Investigation of the effects of afforestation on catchment water balance: Case studies in Northland and Waikato

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EXECUTIVE SUMMARY

Forests interact with Earth's water, energy and carbon cycles, resulting in forest management decisions to achieve one outcome (e.g. planting trees for carbon sequestration) that can potentially impact on other aspects (e.g. the water cycle). The processes involved are complex and not well understood. In New Zealand, afforestation is currently largely promoted to mitigate the nation's carbon emissions, but awareness of the potential effects on the water resources is still limited among resource managers. Recently, the Northland and Waikato regional councils expressed interest in improving their understanding of increased afforestation covers and commissioned GNS Science to (i) investigate the potential impacts of afforestation on catchment stream flows and groundwater recharge rates and (ii) advise them on potential consequences for water allocation.

This study builds on Mourot et al. (2020), who compiled a literature review of afforestation effects on water budgets and developed theoretical models. These authors found that trees transpire more water than grass (50–200 mm more) and that afforestation may influence the catchment's water balance, depending on its scale and other local characteristics (e.g. rainfall, geology).

The aim of this study was to ground-truth the models in local case studies. The Mangahahuru Stream (Northland) and Oraka Stream (Waikato) catchments were selected, as they have 30 years of rainfall, stream flow and land-use monitoring data. In these two regions, there were no case study options that also included groundwater-level monitoring data. In addition, there were no catchments with monitoring sites and large-scale afforestation occurring during the monitoring period. Small-scale afforestation (e.g. patches of pasture land converted to pine plantation) and re-planting of forests (as part of the normal forestry cycle after harvesting) were used as 'surrogates' for afforestation. Our ground-truthing approach analysed (a) land-use changes, (b) rainfall and stream flow and (c) evapotranspiration rates and amounts of water potentially available for runoff and/or groundwater recharge. Both local in-situ data and global remote-sensing datasets were utilised and processed in the Google Earth Engine cloud-computing platform, R software and ArcGIS.

Results for the Mangahahuru Stream catchment suggest that, with forest cover increasing by 30% and mean annual rainfall decreased by 8%, mean annual stream flow decreased by 44% over the 2013–2018 period, compared to the 2001–2007 period. The reduction in stream flow is possibly enhanced by trees intercepting / taking up water that otherwise would have been directed to runoff and/or groundwater recharge. In the Oraka Stream catchment, no clear effects of increased forest cover on stream flow were detected, likely due to the larger size of the catchment, the smaller percentage of forest cover and the longer time lags.

Evapotranspiration rates were estimated from satellite data but not validated locally. Observed differences in evapotranspiration between harvested areas and forested areas for the case study catchments were significant (up to 400 mm/yr). This suggests that harvested areas generate more water for runoff and/or groundwater recharge. However, this approach is short-sighted, as it does not account for soil perturbances due to harvesting nor other benefits associated with forests (e.g. soil erosion control, resilience to flood and droughts). Evapotranspiration rates and indication of vegetation health were assessed from high spatial resolution UAV-derived vegetation indices.

Recommendations for refining water allocation in future large-scale afforested catchments are to: (i) start comprehensive monitoring that includes groundwater as soon as possible; (ii) build better hydro(geo)logical understanding; and (iii) consider potential trade-offs between positive and negative impacts and establish catchments priorities. Properties and processes such as climate variability, water scarcity, tree species, tree ages, planting density, place of planting in the catchment (in relation to the groundwater recharge area), percentage of afforested cover, rainfall feedback from increased evapotranspiration and forestry management practices would also have to be considered.

GLOSSARY

Actual evapotranspiration (AET): the actual rate of water uptake by the plant, which is determined by the level of available water in the soil and combines simultaneously both evaporative losses from the soil surface and transpiration from the plant surface.

Afforestation: (as defined by the National Environmental Standards for Plantation Forestry):

a. means planting and growing plantation forestry trees on land where there is no plantation forestry and where plantation forestry harvesting has not occurred within the last five years, but
b. does not include vegetation clearance from the land before planting.

In this study, we have used as a ‘surrogate of afforestation’ both ‘real’ afforestation (defined as per (a) above) but also the planting of trees as normal forestry rotations after harvesting (see explanation in Section 1).

Age class: any interval into which the age range of trees, forests, stands or forest types is divided for classification. Forest inventories commonly group trees into 20-year age classes.

Albedo: the amount of solar radiation reflected from an object or surface, usually expressed as a percentage.

Baseflow (also called drought flow, groundwater recession flow, low flow, low-water flow, low-water discharge and sustained or fair-weather runoff): the portion of the stream flow that is sustained between precipitation events, fed to streams by delayed pathways. Baseflow plays a critical role in maintaining water ecological health and water quality.

Canopy: the more or less continuous cover of branches and foliage formed collectively by the crowns of adjacent trees.

Carbon sequestration: the uptake and storage of carbon. Trees and plants, for example, absorb carbon dioxide, release the oxygen and store the carbon.

Closed canopy: the description given to a stand when the crowns of the main level of trees that form the canopy are touching and intermingled so that light cannot reach the forest floor directly.

Ecosystem: a dynamic complex of plant, animal and micro-organism communities and the non-living environment that interact as a functional unit.

Exotic species (synonyms: introduced species, non-indigenous species): tree species that occur outside of their natural vegetation zone, area or region. In this study, the term refers to Radiata Pine or *Pinus radiata* (called *P. radiata* or ‘pine’ onwards).

Evaporation: the process by which water changes from a liquid to a vapour. The rate of evaporation is dependent on the amount of solar radiation, the temperature of the air and water, humidity and wind speed.

Evapotranspiration: a term that describes the total loss of water by evaporation from the land, including that lost by interception, transpiration and directly from the soil surface.

Forest: a complex community of plants and animals in which trees are the most conspicuous members and where the tree crown density – the amount of compactness of foliage in the treetops – is greater than 10%.

Forestation: the establishment of forest growth on areas that either had forest or lacked it naturally.

Forestry: the profession embracing the science, art and practice of creating, managing, using and conserving forests and associated resources for human benefit and in a sustainable manner to meet desired goals, needs and values.

Google Earth Engine: a platform that combines a multi-petabyte catalogue of satellite imagery and geospatial datasets with planetary-scale analysis capabilities. This cloud-based platform is available for scientists, researchers and developers to detect changes, map trends and quantify differences on the Earth's surface.

Grassland: area in which the vegetation is dominated by a nearly continuous cover of grasses.

Gross precipitation: the precipitation that falls to a watershed, measured above the canopy or in an open area.

Groundwater recharge (also referred to as rainfall recharge to groundwater, (deep) drainage or percolation): the amount of rainfall that vertically drains from the soil to replenish the groundwater.

Hansen Global Forest Change (v1.7): results from time-series analysis of Landsat images in characterising global forest extent and change from 2000 through to 2020.

Harvesting: the removal of produce from the forest for utilisation that comprises cutting, sometimes further initial processing (topping and trimming) and extraction.

Indigenous species (synonyms: autochthonous species, native species): tree species that have evolved in the same area, region or biotope where the forest stand is growing and are adapted to the specific ecological conditions predominant at the time of the establishment of the stand.

Interception: the process by which water held on the surface of leaves, branches and the trunk during and after rainfall is directly evaporated back to the atmosphere; often expressed as a proportion of annual precipitation (interception ratio).

Leaf area index (LAI): one half of the total green leaf area per unit of horizontal ground surface.

Net precipitation: the precipitation that reaches the soil surface, theoretically measured under the canopy and litter.

Overstorey: the uppermost continuous layer of a vegetation cover; for example, the tree canopy in a forest ecosystem or the uppermost layer of a shrub stand.

Potential (Penman) Evapotranspiration (PET): the total loss of water by evapotranspiration from an actively growing, short green plant that is never short of soil water.

Paired catchment studies: these involve the use of two catchments with similar characteristics (i.e. slope, aspect, soils, area, precipitation and vegetation) located adjacent to one another. Following a calibration period, where both catchments are monitored, one of the catchments is subjected to land-use change (e.g. afforestation) and the other remains as a control. This allows the climatic variability to be accounted for in the analysis. The change in water yield can then be attributed to changes in land use.

Plantation forest: forest stands established by planting and/or seeding in the process of afforestation or reforestation, which are either of introduced species (all planted stands) or intensively managed stands of indigenous species, that meet the following criteria: one or two species at plantation, even age class and regular spacing.

Precipitation recycling: the production and transport of upwind atmospheric moisture across land.

Quickflow: the part of storm rainfall that moves quickly to a stream channel via surface runoff or interflow.

Reforestation: the re-establishment of trees on denuded forest land by natural or artificial means, such as planting and seeding.

Runoff: the part of the water cycle that flows over land as surface water instead of being absorbed into groundwater or evaporating.

Runon: surface runoff from an external area that flows onto an area of interest.

Root depth: depth of the soil profile where roots develop (in centimetres).

Shrubland: an open or closed wooded land of vegetation type where the dominant woody elements are shrubs with 0.5–5 m height on maturity.

Stemflow: the precipitation that reaches litter or bare ground by flowing down the stems of trees, shrubs, forbs and grasses.

Thinning: a cultural treatment made to reduce stand density, primarily to improve growth, enhance forest health or recover potential mortality.

Transpiration: the process by which water taken in by tree roots from the soil is evaporated through the pores or stomata on the surface of leaves.

Throughfall: the precipitation that reaches litter, or bare soil, by passing directly through, or dripping from, the canopy.

Understorey: the lower level of vegetation in a forest. Usually formed by ground vegetation (mosses, herbs and lichens), herbs and shrubs, but may also include sub-dominant trees.

Water yield: the amount of freshwater derived from unregulated flow measurements for a given geographic area over a defined period of time. The freshwater flow (yield) is generated from a combination of baseflow, interflow and overland flow originating from groundwater, precipitation and/or snowpack.

1.0 INTRODUCTION

Regional councils have the responsibility to manage their regions' freshwater resources, including preservation of their quality and quantity. To ensure the sustainable management of freshwater bodies, regional councils establish allocation limits.

When assessing allocation limits in catchments, approaches (e.g. water budgets, numerical models) usually include existing land-use and related environmental conditions. However, land-use changes in a catchment can modify water budget components (e.g. evapotranspiration, runoff, rainfall recharge), necessitating revision of allocation limits. For example, HydroGeo Solutions (2000) reported[1] a:

> *"clear pattern of increasing groundwater recharge with distance either side of the forest. Recharge coefficients range from 6.3% in the middle of the forest to 22.9% with the greatest distance of the forest".*

Afforestation is currently highly promoted in New Zealand (e.g. One Billion Trees Programme; Te Uru Rākau [2021]) to help the nation meet its carbon emission targets (He Pou a Rangi 2021). Yet, there is still limited awareness of the potential impact of forest-cover expansion on water resources in New Zealand (Meason et al. 2019).

Understanding the potential effects of afforestation on water quantity has become crucial in the context of climate change and increasing water scarcity issues. The processes are complex and involve the water, energy and carbon cycles (Ellison et al. 2017). Resource managers need to be aware of these potential impacts on groundwater and surface water volumes to ensure that freshwater resources are not inadvertently over-allocated as a result of land-use change.

This study builds on the literature review of Mourot et al. (2020) on the potential effects of afforestation on water yields (stream flows and groundwater recharge) and regional-scale hypothetical models. It aims to complement that work by ground-truthing theoretical scenarios and incorporating local in-situ monitoring and remote-sensing data for two case studies: the Mangahahuru Stream (Northland) and Oraka Stream (Waikato) catchments. The overall purpose is to provide advice to the Northland and Waikato regional councils for the setting of sustainable allocation limits in afforested catchments.

1 On the Aupōuri Peninsula (Northland).

2.0 LITERATURE REVIEW SUMMARY

The literature review of Mourot et al. (2020) reported the following key points.[2]

2.1 Preliminary Notions

To emphasise the role of vegetation in the hydrological cycle and extend the former relatively restrictive definition of water, the notions of 'blue' water (rivers, lakes and aquifers) and 'green' water (consumed by plant growth and production and returning to the atmosphere through evapotranspiration) were introduced.

The partitioning of water flows in the hydrological cycle is determined by biophysical (e.g. water-holding capacity of the soil, rainfall intensity, atmospheric demand, etc.), biological (photosynthesis pathway) and human (e.g. land use, forest management, compaction, etc.) factors (Figure 2.1).

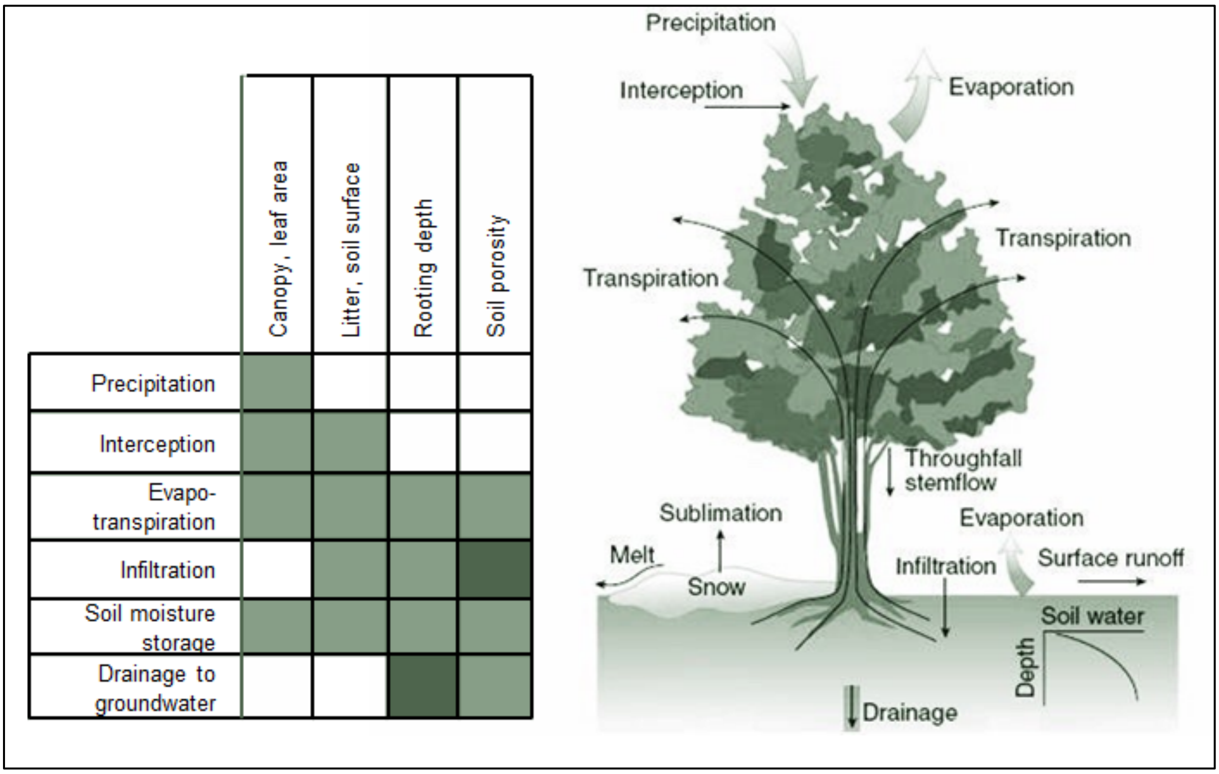

Figure 2.1 Influence of forest characteristics on hydrological processes, after Ekhuemelo et al. (2016) and Jones et al. (2020). Dark green cells of the table have been added to capture recent studies, e.g. Ilstedt et al. (2016).

Trees provide a wide range of ecosystem services (e.g. peak flow buffering, soil erosion control, coastal protection from storm surges and tsunami; Table 2.1). Both the effects on water resources and on their related ecological services should be considered while developing afforestation programmes in order to avoid unintended consequences (e.g. stream flow and groundwater recharge reductions).

2 Full literature references are provided in Mourot et al. (2020). The section on riparian planting was added as part of this study and Northland Regional Council's request.

Table 2.1 Water-related ecosystem functions provided by vegetation and potentially perceived as 'ecosystem services' after Creed and van Noordwijk (2018).

Application	Functions	Metrics
Generic	Water transmission.	• Total water yield per unit rainfall.
	Buffering peak river flows.	• Wet- and dry-season flow persistence or flashiness. • River discharge per unit above average rainfall.
	Gradual release of stored water supporting dry-season flows.	• Dry-season flow persistence. • Aquifer recharge.
	Maintaining water quality (relative to that of rainfall).	• Pollutants per unit volume of water. • Biological water quality indicators.
Site-specific	Stability of slopes; absence of landslides.	• Woody roots for topsoil binding and anchorage. • Non-erosive pathways for overland flow.
	Controlling soil loss by erosion.	• Surface runoff pathways. • Volume of trapped sediment in filter zones. • Infiltration of topsoil and subsoil (macroporosity due to worms and roots).
	Microclimate effects on air humidity, temperature and air quality.	• Wind speed. • Reduction in daily maximum temperature and land surface temperatures.
	Coastal protection from storm surges and tsunami.	• Retardation of wave. • Reduced maximum run-up height.
Frontier of science	Ecological rainfall infrastructure and biological rainfall generation.	• Recycling of atmospheric moisture. • Height above vegetation of rainfall generating events. • Ice-nucleating agents.

2.2 Forest and Water Relationships

Three main common, but somewhat contrasting, views pertaining to the relationships between forest and water exist (Figure 2.2; detailed descriptions in Mourot et al. [2020]):

- 'No forest, no water': forests solve any water-related issues.
- 'More trees, less water': there is a near-universal loss of 'blue' water, with forests using more 'green' water.
- 'It depends': a more nuanced position that considers (i) a full hydrological cycle approach of forest and water, (ii) the local context and (iii) a focus on identifying benefits for particular groups.

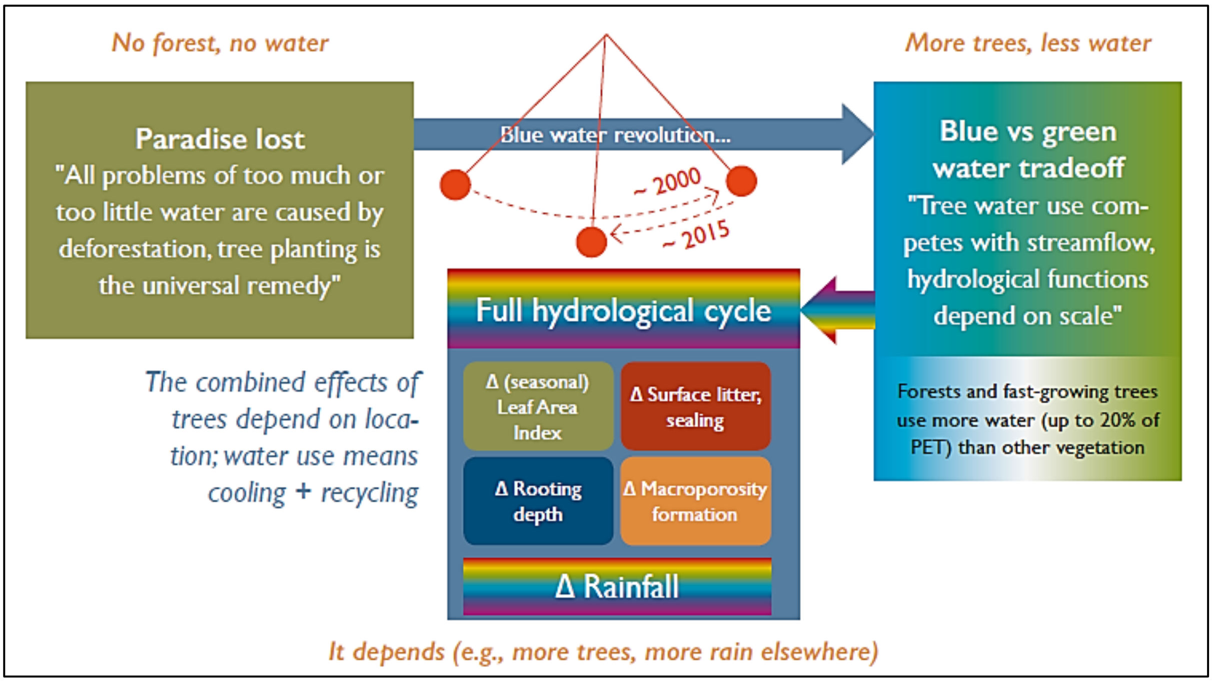

Figure 2.2 The three principal public perspectives of the key forest and water relations (Creed and van Noordwijk 2018).

2.3 Factors Influencing the 'It Depends' Theory

Various factors can be considered in the 'it depends' theory, such as:

- Evapotranspiration, which is a central climate variable that links the water, energy and carbon cycles. Forest evapotranspiration consists of two main components: interception and transpiration of water. Generally, due to the higher evapotranspiration potential of trees, forested catchments have a larger impact on water yield and groundwater recharge than those covered by other vegetation types (e.g. grass and tussock).
- The spatial arrangements of forest stands, which vary with age, density and species composition, affect hydrological cycle yields.
- The water system configurations (i.e. catchment size, storage capacity, inflow and release volumes, evaporative losses) induce scale, space and timing impacts.

The proportional reductions of stream flow following afforestation are larger for low flow than annual flow conditions. These reductions are more severe in drier regions due to limited rainfall and larger relative evapotranspiration rates, reducing the water available for stream flow. Thus, for dry regions, vegetation water use (by transpiration, interception and evaporation) is limited by water availability. In wet regions (not limited by water but more by energy), studies indicate the positive role of forests in re-distributing water from the wet season to the dry season by promoting infiltration-recharging-discharging processes.

The effects of forest-cover expansion on the hydrological cycle differ temporally and spatially:

- The spatial scale of the studies influences the water yield outcomes (small size catchments being more sensitive to hydrological changes than large ones).
- There is generally a time lag between a vegetation land-use change and the establishment of a new equilibrium in the hydrology of the catchment.

A body of evidence, both by observations and modelling, suggests that forests affect local climatology/weather patterns through biophysical changes in albedo, leaf area, canopy structure (roughness) and evapotranspiration. In some cases, precipitation recycling (i.e. the production and transport of upwind atmospheric moisture across land) redistributes and enhances water availability (Figure 2.3).

Increases in both the rate and variability of climate change are anticipated to impact the relationships between forests and water resources.

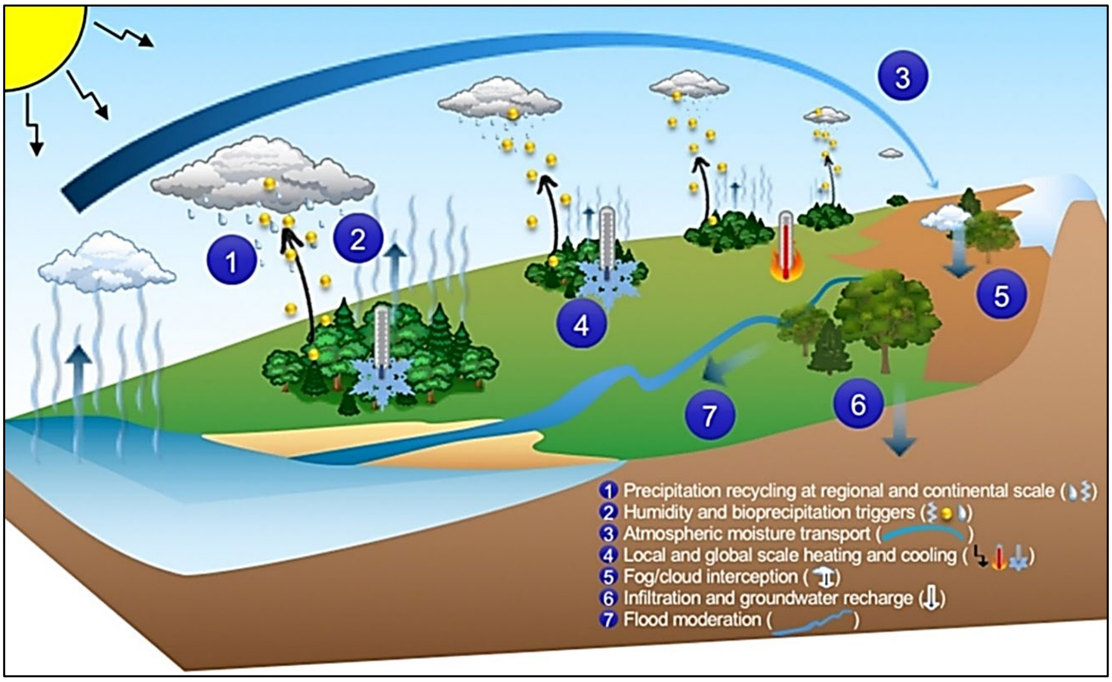

Figure 2.3 Effects of forests on the water cycle at local, regional and continental scales through change in water and energy cycles. (1) Precipitation is recycled by forests and other forms of vegetation and transported across terrestrial surfaces to the other end of continents. (2) Upward fluxes of moisture (evapotranspiration), volatile organic compounds and microbes from plant surfaces (yellow dots) create precipitation triggers. (3) Forest-driven air pressure patterns may transport atmospheric moisture towards continental interiors. (4) Water fluxes cool temperatures and produce clouds that deflect additional radiation from terrestrial surfaces. (5) Fog and cloud interception by trees draw additional moisture out of the atmosphere. (6) Infiltration and groundwater recharge can be facilitated by trees. (7) All of the above processes naturally disperse water, thereby moderating floods (Ellison et al. 2017).

2.4 Climate-Forest-Water-People Nexus

The role of forests in relation to the sustainable management of land and water resources remains a contentious issue in many parts of the world. Emerging perspectives aim to more widely consider the climate-forest-water-people nexus to develop forest-related policies. Resources managers are encouraged to consider the prime regulating role of forests on the water, energy and carbon cycles to better assess, adapt and mitigate changes driven by land use or climate.

Intervention and regulation measures are generally recommended from the catchment to the continental scale, with transboundary integrated water management frameworks (Figure 2.4). These frameworks allow linkages of water management institutions based on their land position (i.e. between up- and downwind position to consider production of atmospheric moisture and between up- and downstream position for surface flow management). They also allow inclusion of the concept of ‘rainfall recycling’ and notions such as ‘precipitation sheds’ (i.e. the area of the catchment from which the precipitation is sourced) and precipitation sinks.

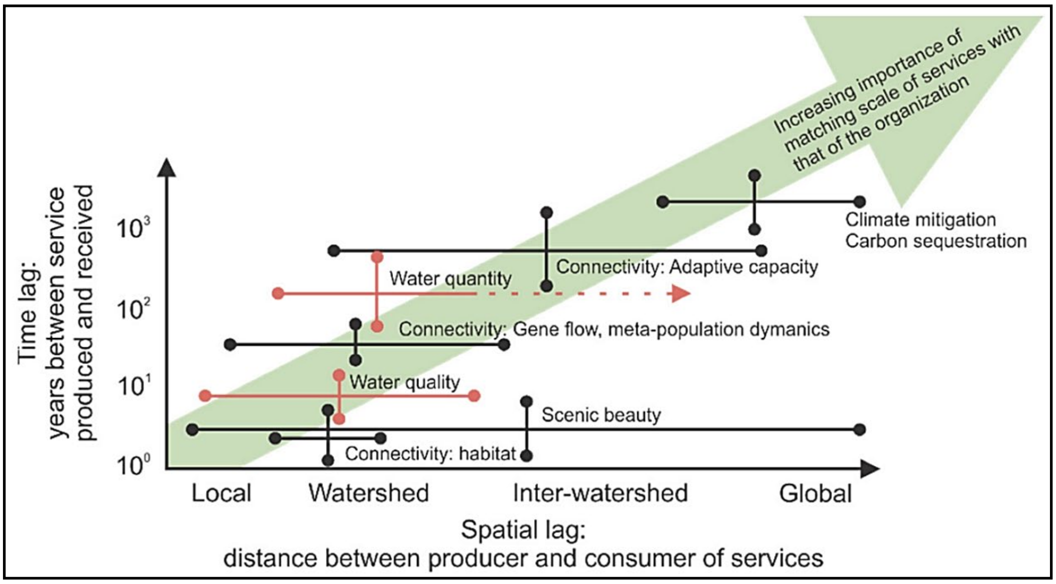

Figure 2.4 Time and spatial relations between forest management decisions and their related aquatic ecosystem services (Creed et al. 2016).

2.5 The New Zealand Context

Most of New Zealand's forest hydrology knowledge is based on studies undertaken 40 years ago, and the learnings from these studies, although providing useful information, cannot systematically be applied to different environments and at different scales.

Four regional councils have introduced measures to regulate reforestation and afforestation projects to address concerns of water quantity reductions, particularly for catchments with low rainfall and/or high demand.

In May 2018, the National Environmental Standards for Plantation Forestry (NES-PF) – a nationally consistent set of regulations for plantation forestry activities – became operative, with two main objectives: (a) maintain or improve the environmental outcomes associated with plantation forestry activities and (b) increase the efficiency and certainty of managing plantation forestry activities. Afforestation is one of the eight core plantation forestry activities covered by the NES-PF.

The One Billion Trees Programme was approved in 2018 and aims to plant one billion trees by 2028 while assisting New Zealand's transition to a low-emissions economy; providing employment and improved erosion and water quality and supporting Māori objectives for their land and forests. The One Billion Trees Programme wants to ensure that the right trees are planted in the right places for the right purpose. Tree planting progress as per April 2021 was approximately up to 259 million trees (Figure 2.5).

Figure 2.5 Tracking the goal of planting one billion trees by 2028, as of 9 April 2021 (Te Uru Rākau [2021]).

2.6 Riparian Planting

Riparian vegetation inter-reacts with baseflow and overbank flows through complex hydraulic interactions (Figure 2.6; Tabacchi et al. 2000). So far, most of the studies have investigated the effects of vegetation on the water cycle at the floodplain and basin scale, yet riparian vegetation is inferred to impact hydrological processes (e.g. water uptake, storage) at the local scale (Pasche and Rouvé 1985).

Exchanges between surface water and groundwater are facilitated by riparian vegetation, as it attenuates the inputs of water from the flood plain and delays drainage from backwaters. Riparian forests add moisture to the air in absorbing energy for evapotranspiration. This effect is most noticeable within and downwind of riparian forests and is often referred to as the ‘oasis effect’ (Tabacchi et al. 2000).

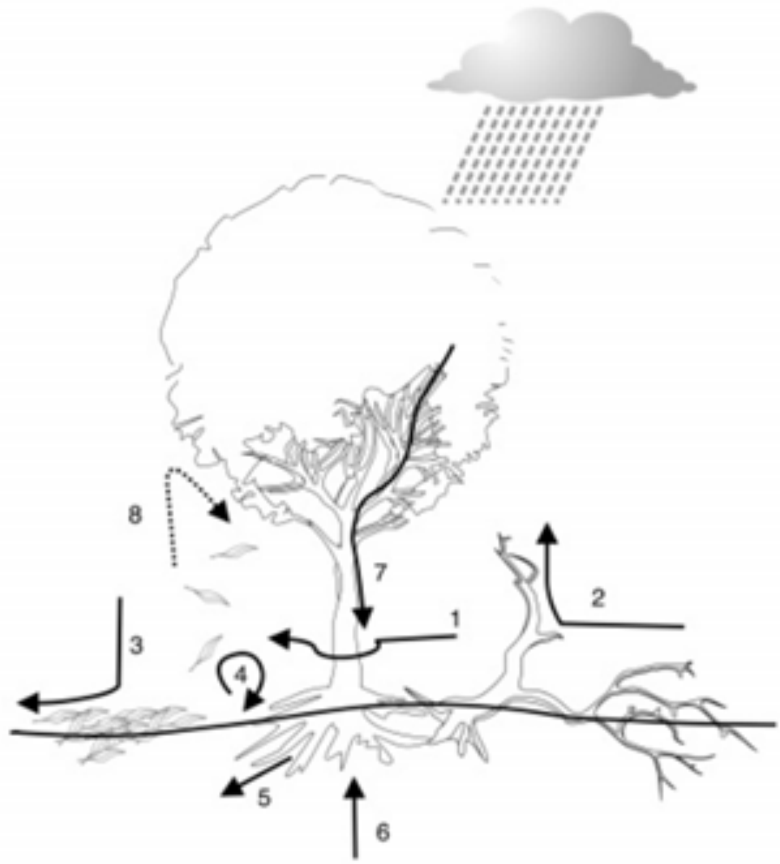

Figure 2.6 The main physical impacts of riparian vegetation on water cycling: (1) interaction with overbank flow by stems, branches and leaves (turbulence); (2) flow diversion by log jams; (3) change in the infiltration rate of flood waters and rainfall by litter; (4) increase of turbulence as a consequence of root exposure; (5) increase of substrate macroporosity by roots; (6) increase of the capillary fringe by fine roots; (7) stem flow (the concentration of rainfall by leaves, branches and stems); (8) condensation of atmospheric water and interception of dew by leaves (Tabacchi et al. 2000).

2.7 Summary of the Effects of Afforestation on Stream Flow and Groundwater Recharge

Historically, the New Zealand science of forest hydrology has been largely based on 'paired catchment studies'. These studies analyse the effects of converting one land cover (e.g. grassland, tussock, native forest) to another (mostly exotic forest) on stream flow and, more rarely, on groundwater recharge. Paired catchment studies integrate the effects of climate variability by comparing changes occurring in another close and non-converted catchment. Since the 1970s, such studies have been carried out in New Zealand, with a main focus on surface water (Table 2.2). Internationally, investigations were undertaken to characterise the effects of afforestation on groundwater recharge (Table 2.3).

Table 2.2 Selection of national studies and their conclusions regarding the effects of afforestation on stream flow (after Mourot et al. 2020).

Location	Study Description	Main Conclusions	Reference
Hunua Ranges (Auckland)	Scrubland to pine forest	Stream flow increased 19% after clearing of vegetation to prepare for planting. Stream flow **decreased 70%** (68 mm/yr) after seven years of afforestation. Summer stream flow decreased by 50%.	Herald (1979)
Mamaku Plateau region	Paired catchment study with afforestation	Geology (ignimbrite jointing controls the drainage). Flows are extremely variable. Could not be related to vegetation types.	Dell (1982)
Tarawera catchment	Native forest to pine forest (large-scale study)	Summer and winter Tarawera River flow reductions of 9.6–1.4 m^3/s (1964–1981). c. 4.5 m^3/s of these reductions (i.e. 13% of the mean flow over the calibration period) could be attributed to afforestation (the remainder is linked to decreased rainfall).	Dons (1986)
Eastern Raukumara Range (Gisborne)	Reforestation with *P. radiata*	Stream flow **reduced by 30%** (170 mm).	Pearce et al. (1987)
Glendhu, Berwick (Otago); Moutere, Big Bush (Nelson); Maimai (Reefton); Purukohukohu (Rotorua); Mangatu (Gisborne)	Pasture to pine forest; Native forest to pine forest; Shrub to pine forest	Stream flow **reduced by 30–50% (**5–10 years after planting). Similar reductions expected in low flows. Storm quickflows and flood peaks can fall by over 50%. Sylvicultural practices and forest harvesting in moderate-to-high areas can increase flows.	Fahey (1994)
Moutere catchment (Nelson)	Paired catchment study: hill country pasture and tall dense gorse to pine forest	Declining surface water yield following 2–3 years with canopy closure (167 mm/yr less after seven years in comparison to pasture). Longer periods of dry streams (+3 months).	Duncan (1995)
Maimai (Reefton), Big Bush (Nelson), Glendhu (Otago)	Paired catchment study: afforestation on pasture or tussock land	Annual steam flow **reduced by 20–50%**.	Davie and Fahey (2005)
Purukohukohu (Rotorua)	Paired catchment study: pasture, *P. radiata*, native forest	Annual stream flow reduced by 400 mm after canopy closure. Stream flow from pine forest c. 100 mm/year less than from native forest.	Beets and Oliver (2007)
Motueka catchment (Tasman)	Predictive model (SWAT): maximum pine potential plantations compared to current land use	Evapotranspiration increased by 6%. Annual surface water yield decreased by **4.5%**. Quickflow decreased by 13%.	Cao et al. (2009)
Glendhu (Otago)	Paired catchment study: tussock to *P. radiata*	Average annual flow **reduced by 33%** (273 mm/yr) and low flows reduced by 26% after canopy closure. Average peak flows reduced by 78% and 37% for small and large events, respectively.	Fahey and Payne (2017)

Table 2.3 Selection of international studies and their conclusions regarding the effects of afforestation on groundwater recharge (after Mourot et al. 2020).

Study Location and Climate	Land-Use Change	Effect on Groundwater Recharge	Reference
South Australia, temperate climate	Paired catchment study: forest and grassland	Recharge rates beneath grasslands (63 mm/yr) were reduced to 0 mm/yr beneath 24-year-old pines.	Holmes and Colville (1970a, 1970b)
South-western Australia, temperate climate	Paired catchment study: pines and woodlands	Recharge beneath pines was estimated to 114 mm / **15% of precipitation**, which is 35% less than the adjacent woodlands.	Farrington and Bartle (1991)
Nebraska Sand Hills, USA, semi-arid continental climate	Native grasslands to dense pine	Overall reduction of groundwater recharge by nearly **17%**.	Adane et al. (2018)
Guarani Aquifer System in south-eastern Brazil, humid sub-tropical climate	Pasture to eucalypt	Average recharge decreased from 407 mm/yr (**27% of mean precipitation**) to 194 mm/year (**13% of mean precipitation**) after land-use change.	Mattos et al. (2019)
Lower Mississippi, USA, humid sub-tropical climate	Afforestation on marginal agricultural lands	Groundwater recharge was only **1.1, 1.2 and 1.4% of the precipitation** for agriculture, forest and wetland, respectively.	Ouyang et al. (2019)
Loess Plateau China, semi-humid climate	Paired catchment study: plantation forest (Black locust) compared with natural grasslands	Groundwater recharge (wet year): **8% and 20% of rainfall** for forest and grassland, respectively.	Schwärzel et al. (2020)
Global analysis	Afforestation	In some cases, afforestation may increase groundwater recharge / low flows due to improved infiltration.	van Dijk and Keenan (2007)
Mirranatwa, south-western Victoria, Australia; low rainfall, high evaporation	Paired catchment study: Eucalypt and pasture for sheep grazing	Little recharge on the topographic heights of the catchment (18 mm/yr), more recharge in the lowland areas (78 mm/yr).	Dean et al. (2015)
Guangdong Province (China), tropical to sub-tropical climate	Large-scale reforestation	Positive role of forests in redistributing water from the wet season to the dry season by **promoting infiltration-recharging-discharging processes**.	Zhou et al. (2010)
Burkina Faso, dry tropical climate	Cultivated woodland with different tree densities	Groundwater recharge is maximised at an intermediate tree density. Percentage of yearly rainfall percolating at 1.5 m soil depth: **16%** around the edges of tree canopies, **1.3%** in open areas and negligible when trees are absent.	Ilstedt et al. (2016)

Note: Only one New-Zealand-based study making comments on the effects of afforestation on groundwater recharge was found during our literature review (Duncan 1993). The author studied afforestation in the Moutere area (Nelson) and found that groundwater recharge had been reduced by up to 70% under pine trees.

3.0 METHODOLOGY

3.1 Input Data

3.1.1 General Summary of Datasets

Three main dataset types were utilised for this study (Table 3.1): local (e.g. rainfall and stream flow), national (e.g. land-cover data) and global (e.g. satellite-derived evapotranspiration). Our rationale was to give priority to local datasets, then to use national data where no local data was available; and, finally, to use global data where there was no New-Zealand-specific data.

3.1.2 Details About Remote-Sensing Datasets

Part of the local and global datasets are remote-sensed images and derived datasets (Table 3.2; description in Sections 3.1.2.1 and 3.1.2.2 for UAV and satellite data, respectively).

3.1.2.1 UAV Data

Multispectral imagery (MSI) was collected by GNS Science using a MicaSense RedEdge 3 multispectral camera, attached to an Altus LRX UAV (Appendix A1.1). Flight lines were created in Altus Planner for a flight height of 120 m above ground level (agl) and flight speed of 8 $m.s^{-1}$ (Appendix A1.2). MSI images were collected with a minimum 75% end-lap and 75% side-lap[3] to improve stitching of the orthomosaics. Images were acquired in stable wind conditions and mainly within 2.5 hours of local solar noon to minimise the effects of sun angle on imagery. Ground control points were collected when possible across the study sites for georeferencing purposes (Appendix A1.3).

3.1.2.2 Satellite Data

Two main sources of satellite data were used for this study (Table 3.2):

- MSI from the Sentinel-2 satellite (European Space Agency) was processed for the study sites. Specifically, we used atmospherically corrected 'Level 2A' data, which are available for New Zealand since December 2018.
- The Penman-Monteith Leuning (PML_V2) algorithm, as described by Zhang et al. (2019), was used to assess actual evapotranspiration. The PML_V2 data estimates evapotranspiration from eight-daily compilations from the MODIS sensors, which are on NASA's Terra and Aqua satellites. PML_V2 data has been proven better than other state-of-the-art satellite evapotranspiration products.

3 End lap is the common image area on consecutive photographs along a flight strip, and side lap encompasses the overlapping areas of photographs between adjacent flight lines.

Table 3.1 Summary of local, national and global datasets used for the project.

Source	Dataset Name	Acronym	Description	Period Used for this Study	Reference
Local Datasets					
Northland Regional Council	Rainfall	$P_{in\text{-}situ}$	Rainfall at Hatea at Glenbervie Forest.*	1/01/1990 – 31/12/2019	N/A
	Stream flow	$Q_{in\text{-}situ}$	Flow at Mangahahuru at County Weir		
	Monitoring sites	-	Location and metadata (e.g. start date, end date, years of recording) for rainfall, stream flow and groundwater level continuous monitoring sites managed by Northland Regional Council.		
Waikato Regional Council	Rainfall	$P_{in\text{-}situ}$	Rainfall at Overdale Road (#669_12) and at Putāruru / Leslie Road (#1122_24).		
	Stream flow	$Q_{in\text{-}situ}$	Stream flow at Pinedale (#669_13)		
	Monitoring sites	-	Location and metadata (e.g. start date, end date, years of recording) for rainfall, stream flow and groundwater level continuous monitoring sites managed by Waikato Regional Council.		
GNS Science	UAV multispectral	UAV MSI	See details in Section 3.1.2.1 and Table 3.2.	19/03/2021 and 22/04/2021	
National Datasets					
Manaaki Whenua Landcare Research	Land Cover Database	LCDB	Multi-temporal thematic classification of New Zealand's land cover, which includes 33 land-cover classes for New Zealand's mainland. Features of this database are described by a polygon boundary, a land-cover code and a land-cover name at five-yearly intervals. Version 5.0 (LCDB v5.0), released in January 2020, was utilised for our analysis.	1996–2018	LRIS Portal (2020)
NIWA	Virtual Climate Station Network Precipitation and Potential Evapotranspiration Data	VCSN	Daily precipitation and potential evapotranspiration data (from 1960 to the present day). Data available for New Zealand in a regular grid (0.05° of latitude and longitude, or approximately 5 km). Data covering the period from 1 January were used in this study.	1/01/2001 – 31/12/2019	Tait et al. (2006)

Source	Dataset Name	Acronym	Description	Period Used for this Study	Reference
Global Datasets					
Accessed from the Google Earth Engine platform	Hansen Global Forest Change	GFC	Global tree-cover extent, loss (allocated annually) and gain maps. Spatial resolution of 30 m.	2000–2020	Hansen et al. (2013)
	Penman-Monteith-Leuning Evapotranspiration V2	PML_V2 ET	PML_V2 ET is partitioned into three components: transpiration from vegetation, direct evaporation from the soil and vaporisation of intercepted rainfall from vegetation. See details in Section 3.1.2.2 and Table 3.2.	2000–2019	Zhang et al. (2019)
	Sentinel-2 multispectral	S2	Level 2A; atmospherically corrected.	2019, 19/02/2021 and 03/05/2021	NA

* Dates with missing data were assumed to have zero rainfall. Dates with multiple totals were added.

Table 3.2 Summary and characteristics of the input remote sensing imagery used for the project.

Vehicle	Instrument	Spectral Bands Used	Spatial Resolution	Study Sites	Study Area / Number of Images Captured	Image Date
UAV	MicaSense RedEdge	Red: 668 nm NIR: 840 nm	8 cm (flight at 120 m above ground level)	Oraka Catchment	Sutcliffe Road / 343	19/03/2021
					MS Farm / 306	
				Mangahahuru Catchment	Upper area / 219	22/04/2021
					Lower area / 252	
Sentinel-2 satellite	MSI	Red: 665 nm NIR: 833–835 nm	Red band: 10 m. NIR band: 20 m.	Oraka Catchment	-	2019 and 19/02/2021*
				Mangahahuru Catchment	-	2019 and 3/05/2021*
Terra/Aqua satellites	MODIS	PML_v2 uses pre-processed MODIS sub-products (leaf area index, albedo, emissivity), which cover a large span of the total 36 spectral bands.	Varying between 250 m and 500 m	Oraka Catchment	-	February 2000 – May 2020
				Mangahahuru Catchment	-	

* Level 2A; atmospherically corrected. The best image in terms of cloud cover within a month of the UAV image collection was selected.

3.2 Data Processing and Analysis

Input data were utilised (Figure 3.1) to ground-truth initial results of Mourot et al. (2020). Data processing was undertaken for the two case studies, with three main work components: (i) land-use change analysis, (ii) rainfall and stream flow analysis and (iii) evapotranspiration and runoff / groundwater recharge estimates. Work components used the software R, ArcGIS and the cloud-computing platform Google Earth Engine (GEE) for data processing and analysis (details in Sections 3.2.2–3.2.5).

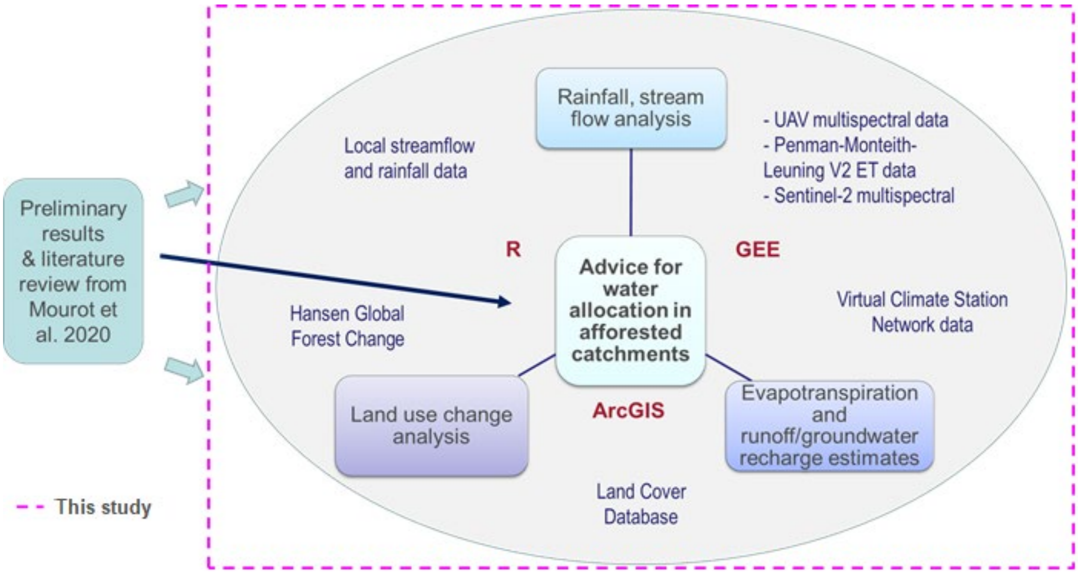

Figure 3.1 Schematic of the project workflow.

3.2.1 Case Study Site Selection

A GIS-based analysis was undertaken using (i) the location of the regional councils monitoring stations for stream flow, groundwater level and rainfall and (ii) LCDB data to detect catchments, with increased forest covers. The best site available for each region was then selected, considering the type of monitoring sites available, the overlap of the afforestation period with the monitoring data, the percentage of afforestation (that needed to be significant) and regional council preference.[4]

Catchments with monitoring sites and significant afforestation occurring during the monitoring period were not available. Therefore, we used both small-scale afforestation (e.g. patches of pasture land converted to pine plantation) and replanting of forests as part of the normal forestry cycle after harvesting as ‘surrogates’ for afforestation.

3.2.2 Forest-Cover Extent and Change Analysis

Forest-cover extents and changes in the catchments were analysed using the GEE cloud-computing platform (Gorelick et al. 2017) and two different sources of data[5]:

- GFC (Hansen et al. 2013) was used to assess (i) forest cover in 2000 and 2020[6]; and (ii) forest-cover gain, loss, and gain and loss between 2000 and 2020.

4 The Aupōuri Peninsula was rejected as a potential case study due to concurrent ongoing investigations (e.g. Forest Flow Endeavour research programme, led by Scion).

5 See details on the approach in Mourot et al. (2020).

6 The GFC dataset has been updated in 2021, with data now available until 2020.

- LCDB classes (LCDB v5.0 2019) were used to track changes in forest cover between 1996, 2001, 2008, 2012 and 2018.[7] The main classes considered in this study are: 'Exotic Forest', 'Indigenous Forest', 'Harvested Forest' and 'High-Producing Exotic Grassland' (description of these classes is provided in Appendix 2).

3.2.3 Rainfall and Stream Flow Analysis

3.2.3.1 Rainfall and Stream Flow Data Processing

A series of data processing was undertaken with the R software for the rainfall and stream flow original time series. Daily mean and rolling mean (over 50–400 days) time series were generated from datasets that originally had multiple measurements per day. Rolling mean time series were generated to 'simplify' the original data and remove 'noise' that can impede interpretation.

3.2.3.2 Baseflow Characterisation

Surface water flow (Q^{SW}_{OUT}) is represented by baseflow (Q^{SW}_{BF}) and runoff or quickflow (Q^{SW}_{QF}) components:

$$Q^{SW}_{OUT} = Q^{SW}_{BF} + Q^{SW}_{QF}$$ Equation 3.1

Baseflow represents the portion of stream flow made by groundwater flow and flow from other delayed sources. This component is particularly important to sustain river ecology and for freshwater resource management (Singh et al. 2019).

The baseflow index (BFI) is represented with:

$$BFI = Q^{SW}_{BF} / Q^{SW}_{OUT}$$ Equation 3.2

Baseflow and quickflow time series were calculated by applying an Eckhardt two-parameter digital baseflow filter (Eckhardt 2005) to the measured stream flow time series:

$$Q_{b,t} = \frac{(1-BFI_{max})\times a\times Q_{b,t-1}+(1-a)\times BFI_{max}\times Qt}{1-a\times BFI_{max}}$$ Equation 3.3

where:

- $Q_{b,\,t}$ and $Q_{b,\,t-1}$ are baseflow at time *t* and *t–1,* respectively;
- *a* is the filter constant; and
- BFI_{max} is the maximum value of BFI.

Eckhardt baseflow filter parameters ('BFI_{max}' and 'a') were set by using:

- values from the national BFI characterisation of Singh et al. (2019) to assess 'BFI_max'; and
- an approach based on recession curves, as per the method proposed by Eckhardt (2008) to assess the filter constant '*a*'.

7 Details of land-cover classes are provided in Mourot et al. (2020).

3.2.4 Trend Analysis

The Mann-Kendall test, seasonally adjusted where relevant, was used for trend assessment of rainfall and stream flow. The Mann-Kendall test has a long history of use in water resources studies internationally (Helsel et al. 2020) and in New Zealand (Larned et al. 2016; Snelder and Fraser 2018; Moreau and Daughney 2021). Seasonality was tested using the Kruskall-Wallis test, an equally widely used statistical test for environmental data analysis (Helsel et al. 2020). Two seasonality settings were used: monthly and quarterly (Autumn, Winter, Spring and Summer), starting from the 60th Julian day (1 March).

Trend magnitudes were estimated using the Sen's slope estimator, which robustly handles typical water resource data, i.e. non-normally distributed time series containing missing and censored values (Snelder and Fraser 2021). Based on the monitoring data available and the literature, two time periods were tested: 1990–2020 (entire monitoring data period) and 2008–2020 (period where potential effects of increased forest cover were inferred to be meaningful). The results are provided for the seasonally adjusted Sen's slope estimator and Mann Kendall test, where seasonality was detected.

Monitoring data was processed through the R software (Version 3.6.2) using the LWP-Trends (version 2101) library to compute all statistical tests, which are reported using the following metrics:

- **Statistical test p-values**: several statistical tests were conducted to assess the statistical significance of a trend and its seasonality. As per the methodology of Helsel et al. (2020), for each test, a hypothesis was formulated and test statistics calculated. An acceptable error rate was arbitrarily set to reject or accept the hypothesis based on a data-calculated probability value (p-value). For this report, the significance level was set using a symmetric confidence interval of 95% and qualified in terms of uncertainty.
- **Trend direction**: this is a descriptive category based on the sign of Sen's slope; the method was recently developed and applied to river-quality state and trend assessments (Larned et al. 2016; McBride 2019) to replace the use of arbitrary confidence level compared to the trend test p-value to define trend type. In this method, a symmetric confidence interval around the trend is calculated. If this interval contains the zero value, the trend is described as 'uncertain'. If this interval does not contain the zero value, this interval is 'established with confidence' and assigned either a 'decreasing' or 'increasing' trend descriptor.

3.2.5 Evapotranspiration and Water Available for Runoff or Groundwater Recharge Estimates

3.2.5.1 Water Budget Approach

Direct assessments of groundwater recharge rates under different forest covers were not possible due to the absence of groundwater level and rainfall recharge monitoring sites in the case study catchments. Instead, a simplified water budget approach, using both in-situ monitoring data and remotely sensed imagery, was utilised with annual mean values (Equation 3.4). The aim was to assess the amount of water potentially available for runoff or groundwater recharge in the catchments. This was estimated as 'bulk', as differentiation between runoff and groundwater recharge components was not possible.

$$P - ET = Q + \Delta S \quad \text{Equation 3.4}$$

where P is rainfall, ET is evapotranspiration, Q is stream flow and ΔS is the change in groundwater storage.

We utilised mean annual evapotranspiration values from the PML_V2 dataset (AET_{PML_V2} onwards) for the period 2000–2019 for *ET* using the GEE platform. Mean annual values of *P* and *Q* were calculated using in-situ rainfall and stream flow data ($P_{in\text{-}situ}$ and $Q_{in\text{-}situ}$ onwards).

Mourot et al. (2020) established that evapotranspiration for native and exotic forests is, on average for the nation, 120 mm/yr higher than evapotranspiration for high-producing grassland. This value differs per region, depending on climate and landscape (mean values range from 54 to 195 mm/yr, with Northland estimated around 70 mm/yr). They did not find significant differences between exotic and native trees based on the PML_V2 dataset.

3.2.5.2 Approach Based on Evapotranspiration Differences

We derived actual evapotranspiration estimates from Sentinel-2 MSI data ($AET_{Sentinel\_2}$ onwards) based on calculation of a series of vegetation indices (e.g. Normalised Difference Vegetation Index [NDVI]; Leaf Area Index [LAI]), as per the approach of Mourot et al. (2019; Appendix A3.1). Since Sentinel 2 Level 2 (atmospherically corrected) imagery has only been available for New Zealand since December 2018, we used 2019 mean annual values of $AET_{Sentinel\_2}$ for analysis with LCDB 2018 land covers. This informed on the $AET_{Sentinel\_2}$ differences between 'Harvested Forest' and 'Exotic Forest' classes for each case study catchment. Differences in *P* – *ET* were calculated using $AET_{Sentinel\_2}$ as *ET* values for the entire case study catchments and for harvested areas.

3.2.5.3 Insights from UAV Normalised Difference Vegetation Index

UAV MSI imagery was captured for two sites per case study on 19/03/2021 and 22/04/2021 for the Oraka Stream and Mangahahuru Stream catchments, respectively (site description, material used and imagery captured are provided in Table 3.2 and Appendix 4). The purpose of UAV imagery capture was to collect data that could characterise different land covers, including different vegetation types (i.e. exotic forest, indigenous forest and grasslands) and harvested forest covers.

The UAV orthomosaics for four flights were processed in Agisoft Metashape Professional software (version 1.5.1) following the workflow described in the Agisoft aerial data processing tutorial (Agisoft Helpdesk Portal c2021). Alignment quality was improved by gradually removing tie points using the gradual selection tool. Geotiff files were then created for further processing using GEE and ArcGIS Pro. Rudimentary filtering of shadows was undertaken in ArcGIS.[8]

NDVI values were calculated for each of the UAV orthomosaics by Equation 3.5:

$$NDVI = \frac{NIR - Red}{NIR + Red} \qquad \text{Equation 3.5}$$

In addition, NDVI was also calculated for the best-quality Sentinel-2 image (with no or limited cloud cover) collected within a month of the UAV flights for comparison. The best images identified were captured on 19/02/2021 and 3/05/2021 for the Oraka and Mangahahuru catchments, respectively. We hypothesise that NDVI values can inform / be correlated to evapotranspiration values, as per the findings of Goulden and Bales (2019); Appendix A3.2. Thus, high-resolution UAV-derived NDVI values could provide valuable insights on evapotranspiration characteristics from different land covers.[9]

8 More advanced shadow filtering would improve the quality of the images but was not undertaken due to time constraints.

9 This was out of scope of our study but is cited for further work.

4.0 RESULTS AND DISCUSSION

4.1 Case Study Characteristics

Two catchments were identified as the best available options for this study based on selection criteria (Section 3.2.1): the Mangahahuru Stream (Northland; c. 5 km north of Whangārei) and Oraka Stream (Waikato; c. 3 km southeast of Putāruru) catchments. Both catchments have 30-year records of rainfall, stream flow and land cover data; but groundwater is not monitored in either catchment.

The Mangahahuru Stream catchment, with a total area of 2122 ha (Table 4.1; Figure 4.1 and Appendix 4), is predominantly forestry and monitored by the Hatea at Forest Headquarter rainfall site and the County Weir stream flow site. This catchment was previously covered by pasture and was afforested to mitigate soil erosion and sediment discharge issues. The Oraka Stream catchment (Table 4.1, Figure 4.2 and Appendix 4) has a more diverse land use, with forestry being dominant but also with the presence of producing grasslands. This catchment has a total area of 13,268 ha, two rainfall monitoring sites (#669_12 and #1122_24) and the Pinedale flow site. In both catchments, increase in forest cover occurred during the 30-year monitoring period (Section 4.2), mainly due to planting forestry cycles following harvesting.

Table 4.1 Summary of general characteristics of the case study sites.

Item	Case Study Catchment	
	Mangahahuru Stream (at County Weir)	**Oraka Stream (at Pinedale)**
Region	Northland	Waikato
Catchment area	2122 ha	13,268 ha
Elevation range	105.5–303.6 m above mean sea level	136–680 m above mean sea level
Mean slope	31.0°	21.2°
Mean annual rainfall [1,2]	1472 / 1678 mm/yr	1444 / 1310 mm/yr
Mean annual PET [1]	986 mm/yr	867 mm/yr
Mean flow [2]	1089 mm/yr or 0.73 m^3/s	646 mm/yr or 2.72 m^3/s
Geology [3]	Main: Waipapa Group sandstone and siltstone (Waipapa Composite Terrane) Minor: OIS6+ (Early Pleistocene to Middle Pleistocene) estuary, river and swamp deposits	Main: Mamaku Plateau Formation ignimbrite from the Rotorua Volcanic Centre Minor: OIS3–OIS2 (Late Pleistocene) river deposits (Hinuera Formation)
Lithology [3]	Main: sandstone, mudstone, non-clastic siliceous sedimentary rock, basalt Minor: mud, sand, gravel, peat, lignite	Main: pyroclastic rock, lapilli, ash Minor: sand, silt, gravel, peat
Soils [4]	Main: Orthic Brown Soils Minor: Fluvial Recent Soils and Albic Ultic Soils	Orthic Podzols and Orthic Pumice Soils
Pre-forest land cover	Pasture	Pasture, native forest?
Exotic forest cover [5]	56% (1996/2001) – 80% (2012)	31% (2001) – 46% (2012)

[1] VCSN data (2000–2019).

[2] Northland Regional Council and Waikato Regional Council data (2000–2019).

[3] QMAP (Heron 2018).

[4] Fundamental Soil Layer (Hewitt 2010).

[5] LCDB v5.0 data (1996–2018).

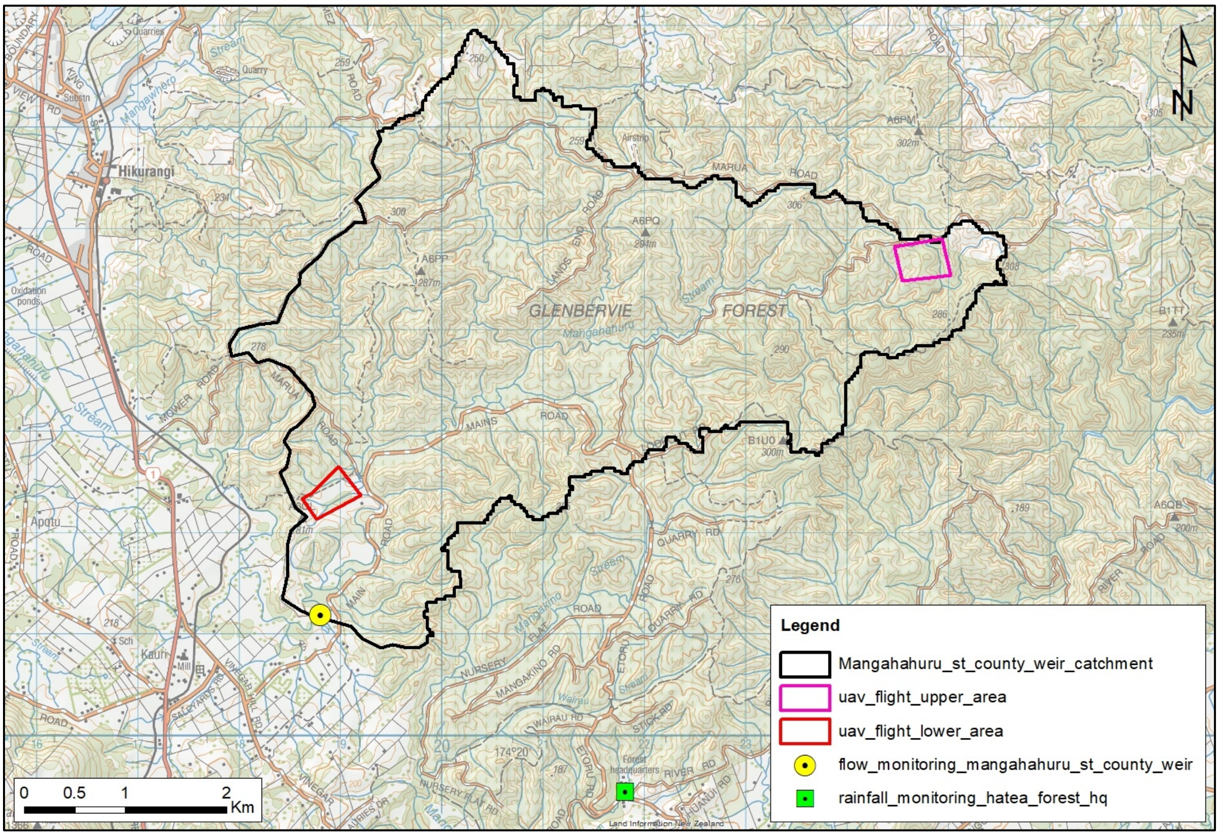

Figure 4.1 Mangahahuru Stream catchment study site, monitoring sites and UAV flight areas.

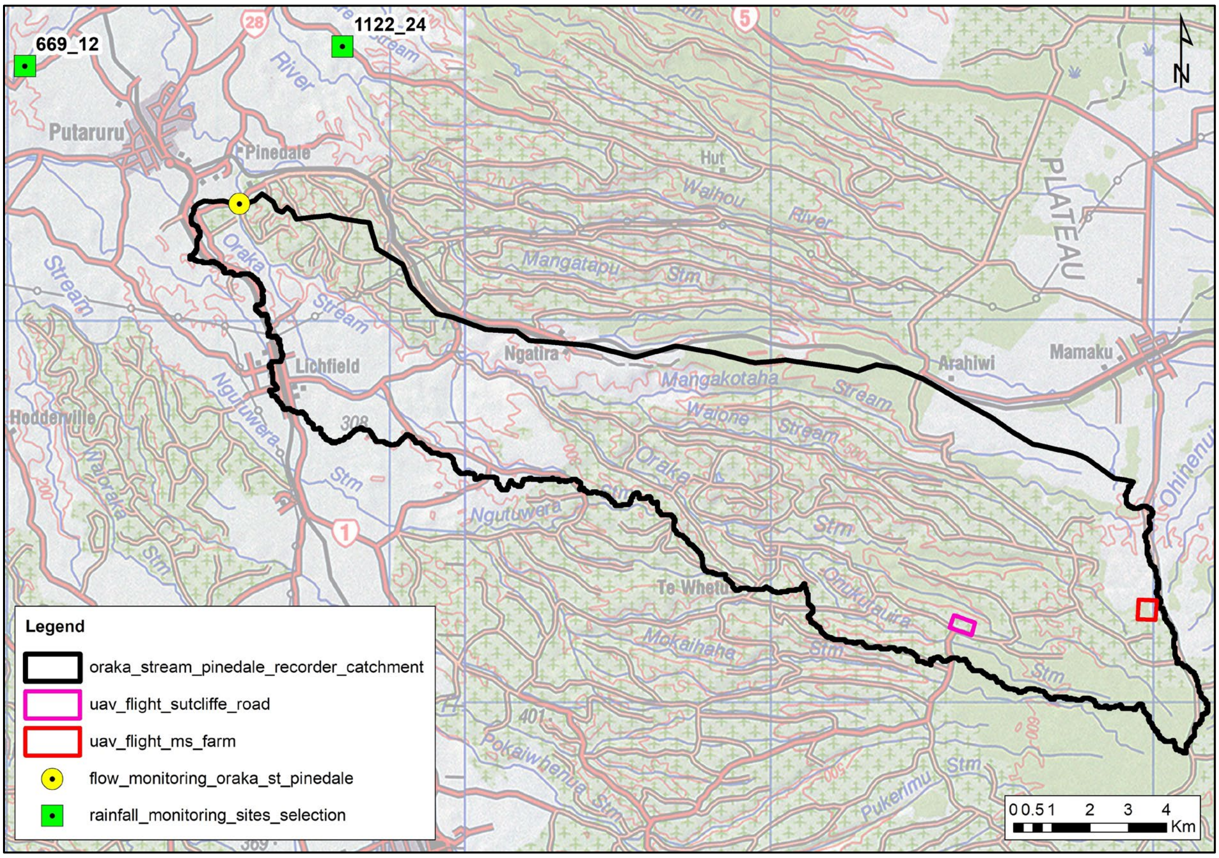

Figure 4.2 Oraka Stream catchment study site, monitoring sites and UAV flight areas.

4.2 Forest-Cover Extent and Change Analysis

4.2.1 Mangahahuru Stream Catchment

The forest cover of the Mangahahuru Stream Catchment was assessed from both the GFC (2000–2020) and LCDB (2001–2018) datasets. Forest cover increased during this period: the GFC estimates a forest cover of 16 km^2 in 2000, extending to 19 km^2 in 2020 (Figure 4.3). The LCDB estimates a cover of approximately 15 km^2 in 2001, extending to 20 km^2 in 2018. The same data indicates that the 'Exotic Forest' class varied between 55.9% of the catchment in 1996 and 79.6% in 2012 (Figure 4.4). The other most-represented classes were 'Indigenous Forest', 'Broadleaved Indigenous Hardwoods' and 'Harvested Forest'.

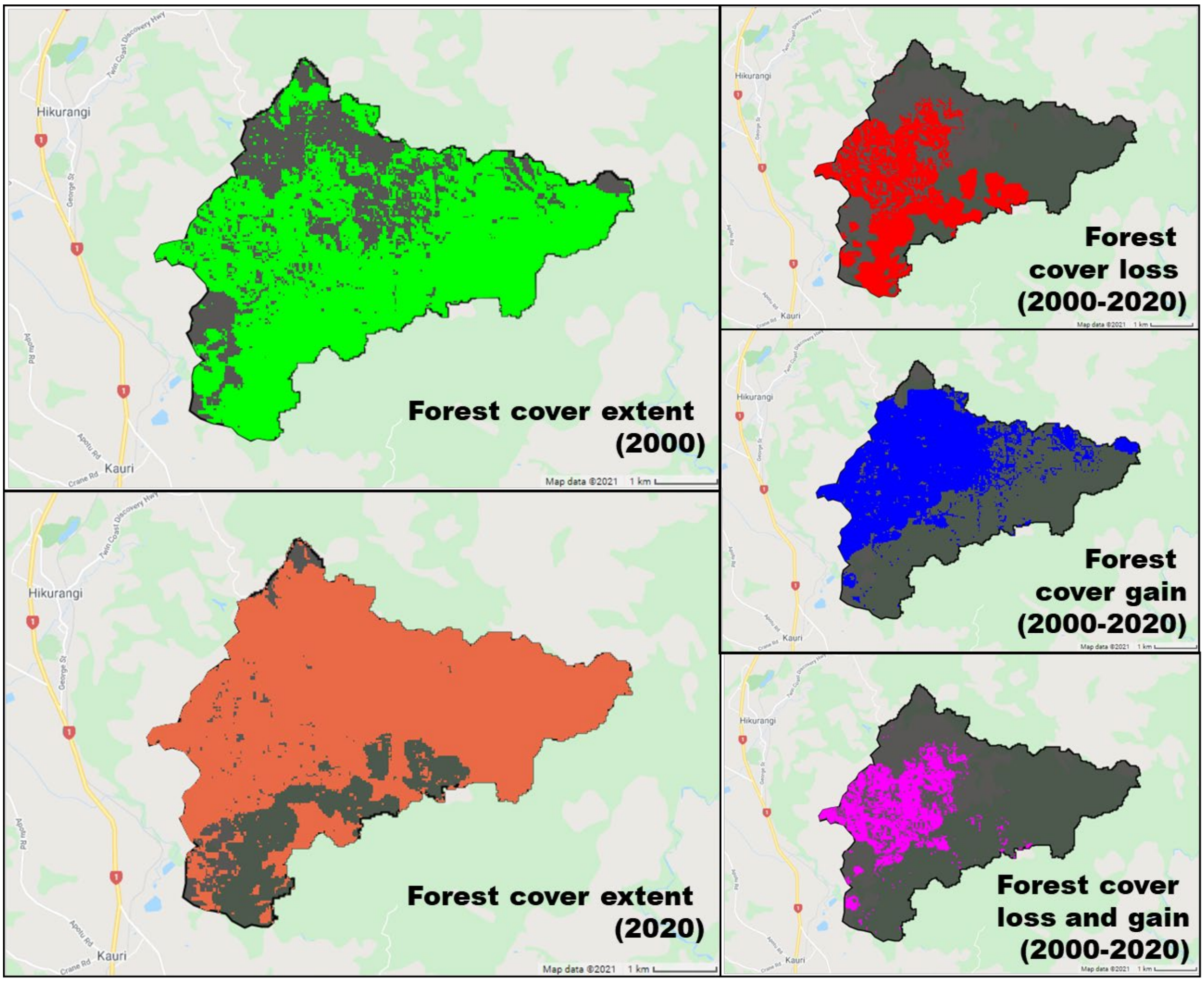

Figure 4.3 Forest-cover change for the Mangahahuru Stream catchment using GFC 2020 data (flow recorder catchment in dark grey. Left: forest cover extents in green and orange; right: forest-cover changes in red [only forest cover loss], blue [only forest cover gain] and magenta [both forest cover loss and gain]).

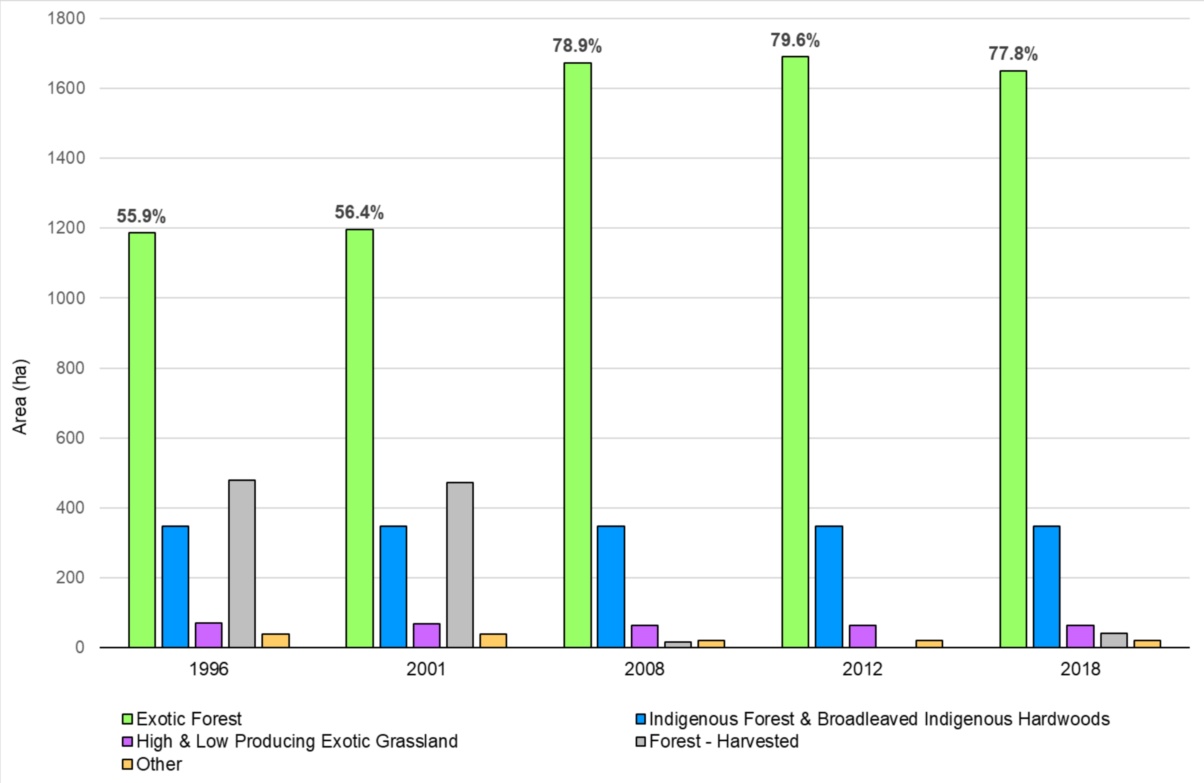

Figure 4.4 Land-cover types and areas in the Mangahahuru Stream catchment between 1996 and 2018 using LCDB v5.0. The values labelled on the chart represent the percentage of exotic forest cover in proportion to the total catchment area.

4.2.2 Oraka Stream Catchment

The forest cover of the Oraka Stream Catchment was also assessed from the GFC (2000–2020) and LCDB (2001–2018) datasets. The GFC estimates similar forest covers (72 km^2) for 2000 and 2020, despite forest-cover loss and gain over this period (Figure 4.5). Part of the forest present in the lower part of the catchment in 2000 seems to have been replaced by plantations in the upper part of the catchment in 2020. The LCDB estimates a cover of approximately 71 km^2 in 2001, extending to 86 km^2 in 2018. The large discrepancy between the LCDB 2018 and the GFC 2020 forest-cover data is inferred to be linked to harvesting after 2018. LCDB data indicates that the ‘Exotic Forest’ class was up to 48.3% of the catchment in 1996, decreasing to 31% in 2001 to then rise again to 46.1% in 2012 (Figure 4.6). The other most-represented classes are ‘High- and Low-Producing Exotic Grasslands’, ‘Indigenous Forest’, ‘Broadleaved Indigenous Hardwoods’ and ‘Harvested Forest’.

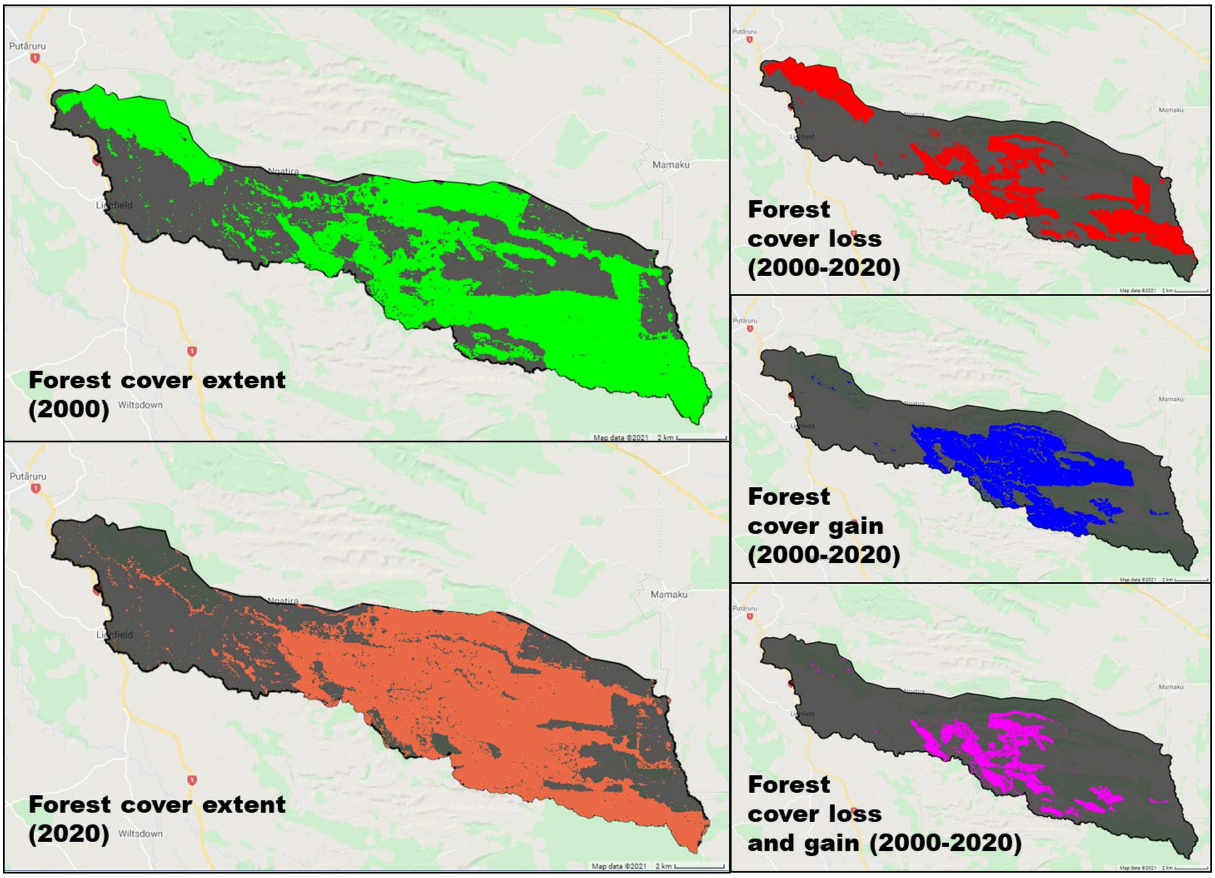

Figure 4.5 Forest-cover change for the Oraka Stream catchment using GFC 2020 data. Flow recorder catchment in dark grey. Left: forest-cover extents in green and orange; right: forest-cover changes in red (only forest-cover loss), blue (only forest-cover gain) and magenta (both forest-cover loss and gain).

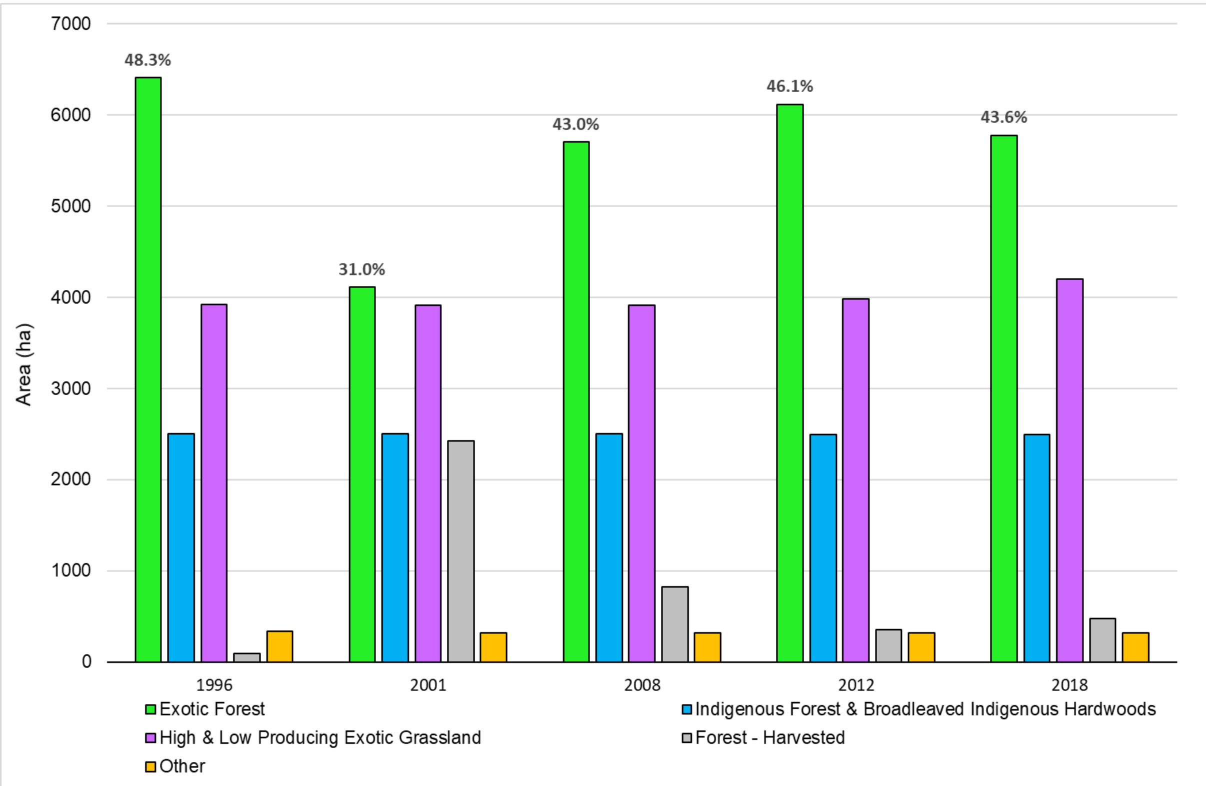

Figure 4.6 Land-cover types and areas in the Oraka Stream catchment between 1996 and 2018 using LCDB v5.0. The values labelled on the chart represent the percentage of exotic forest cover in proportion to the catchment total area.

4.3 Rainfall and Flow Analysis

4.3.1 Daily versus Rolling Mean Time Series

The 400-day rolling mean rainfall and stream flow time series provided the best datasets on which to base our analysis. They were easier to interpret compared to other generated rolling mean (Appendix 5.1) and daily mean time series (e.g. Mangahahuru Stream and Oraka Stream flow time series in Figure 4.7 and Appendix 5.3, respectively).

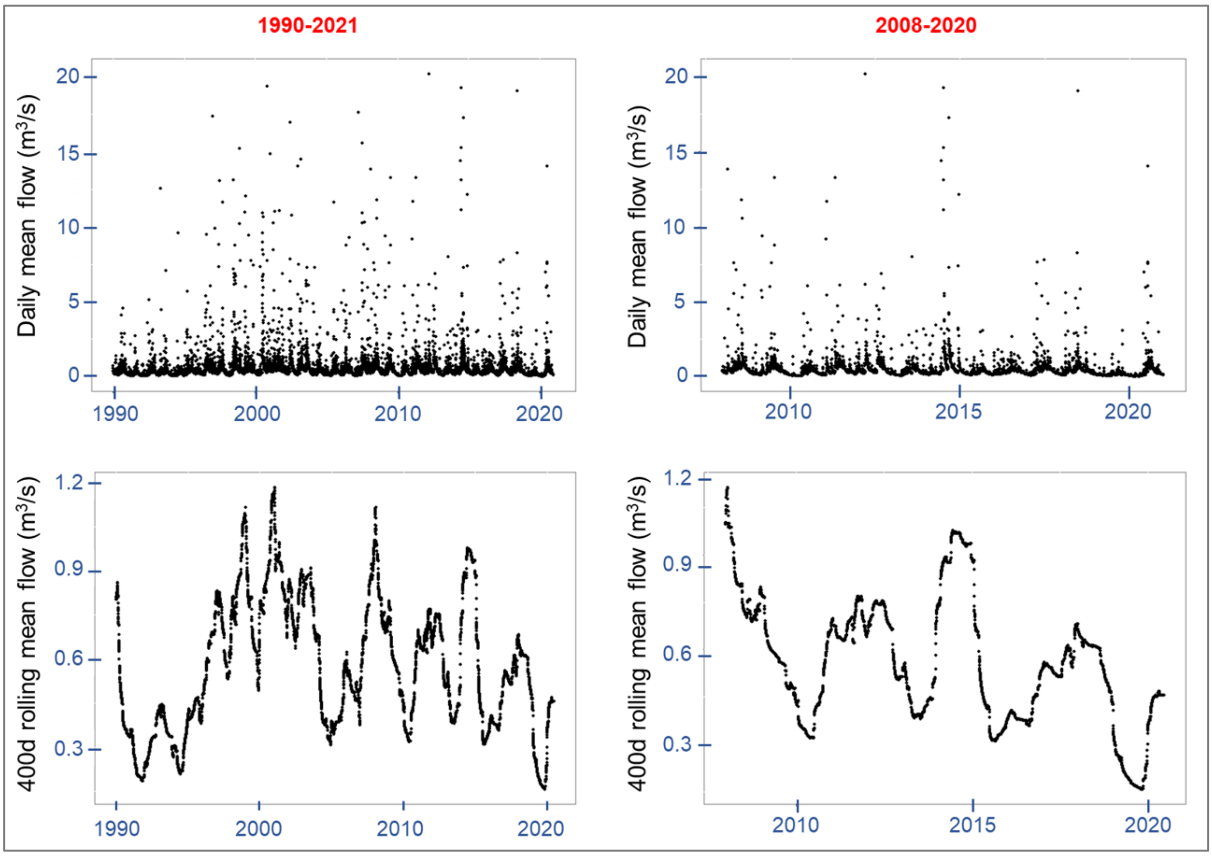

Figure 4.7 Comparison of daily mean flow plots and 400-day rolling mean flow plots for the Mangahahuru Stream over the 1990–2021 and 2008–2020 periods. The scale of the Y-axes was adjusted for the rolling mean plots for readability.

4.3.2 Rainfall and Stream Flow Rolling Mean Time Series

The rolling mean time series for the Mangahahuru Stream catchment indicates a strong relationship between rainfall and stream flow, with probably relatively short time lags in the catchment (Figure 4.8).

The hydrograph for the Oraka Stream catchment seems slightly less ‘responsive’ to the rain signal than Mangahahuru Stream’s hydrograph (Figure 4.9). This could partially be explained by lower rainfall variability in the Oraka Stream catchment compared to the Mangahahuru Stream catchment. Rainfall variability would also likely be less in the ranges, where most recharge is inferred to occur.[10]

10 The rainfall sites that we used are in the plain.

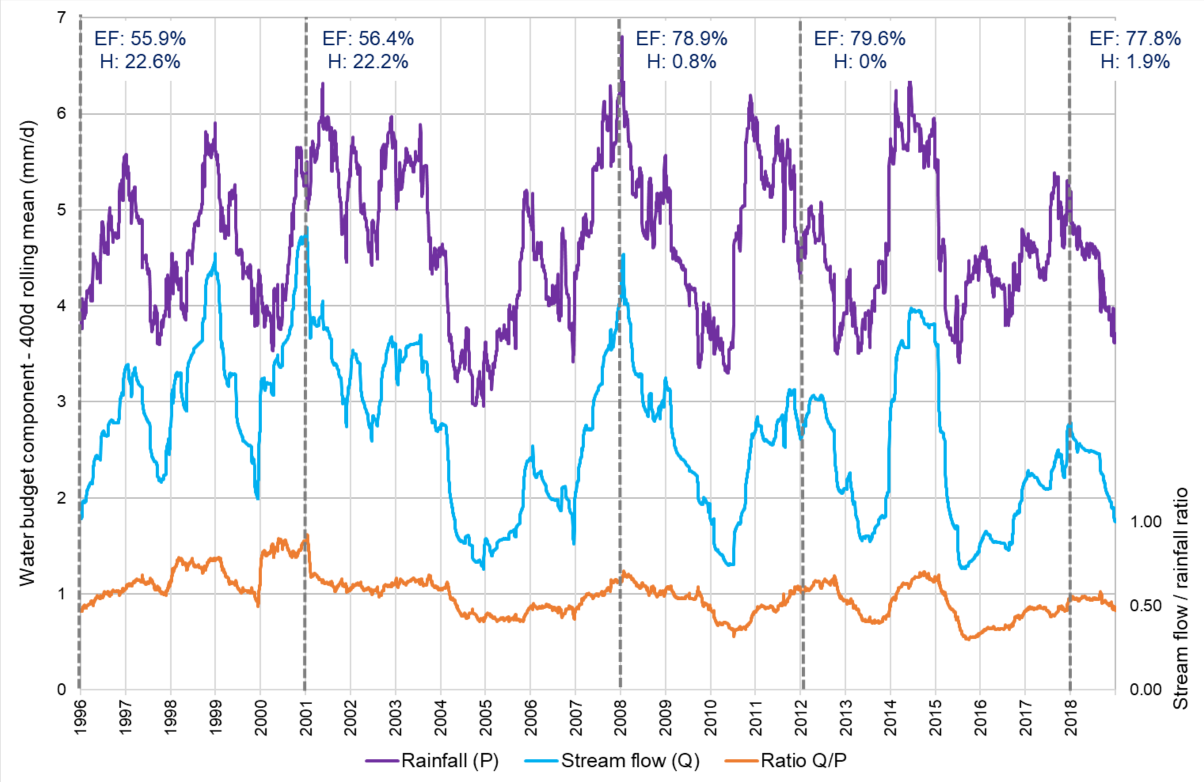

Figure 4.8 400-day rolling mean rainfall and stream flow for the Mangahahuru Stream (1996–2019). The values labelled on top of the chart represent the percentage of exotic forest (EF) and harvested forest (H) covers in proportion to the catchment total area, based on LCDB data.

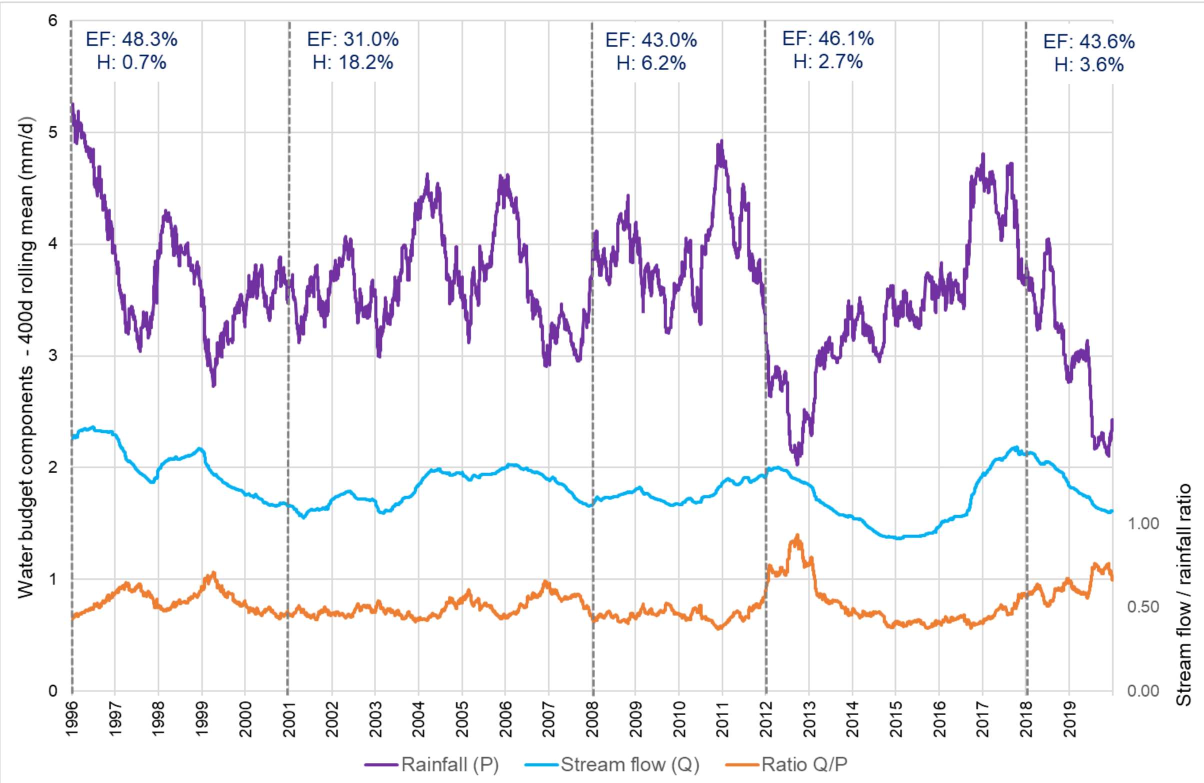

Figure 4.9 400-day rolling mean rainfall and stream flow for the Oraka Stream (1996–2019). The values labelled on top of the chart represent the percentage of exotic forest (EF) and harvested forest (H) covers in proportion to the catchment total area, based on LCDB data.

In addition, looking at the Oraka catchment characteristics, and in particular at the geology (Table 4.1) and baseflow index (Section 4.3.3), it is likely that the Oraka Stream is receiving groundwater discharge from a fractured ignimbrite rock aquifer. Water dating at the Blue Spring, located nearby and also fed by a fractured ignimbrite rock aquifer, provided a mean residence time of c. 56 years (Gusyev et al. 2011). The larger size of the catchment, the smaller forest cover percentage and relatively complex geology of the Oraka catchment could explain the difficulty in correlating forest cover extent to stream flow. Other parameters such as plantation age may also play a role, as young trees (e.g. < 5 years) have less impact on water quantity than mature trees (Farley et al. 2005).

Reeves and Rosen (2002) came to similar conclusions while studying the effects of exotic forest logging in the Waimarino catchment (near Tūrangi, Waikato). The authors concluded that, due to the large mean residence time of the deep ignimbrite aquifer, “any changes due to the effects of land use may take many years to be observed”.

4.3.3 Baseflow Characterisation

Singh et al. (2019) reported long-term average BFI values for 482 river/stream sites in New Zealand. They made the following observations of interest to our case studies:

> *“BFI values were generally found to be higher (0.8–0.96) for the centre-north regions of the North Island of New Zealand (e.g. the Bay of Plenty region and south-west thereof).”*
>
> *“The eastern coastline of the North Island has consistently low values in the 0.2–0.4 range, and the same holds for the Auckland region and the northernmost part of the North Island.”*

These observations were used to set the Eckhardt (2005) baseflow filter parameter ‘BFI_{max}’ with values of 0.5 and 0.8 used for the Mangahahuru and Oraka streams, respectively (Appendix 5.2).

A recession curve analysis (Section A5.2) gave values of 0.45 and 0.78 for the Eckhardt filter constant ‘*a*’. Digital filtering of the stream flow time series with these ‘BFI_{max}’ and ‘*a*’ parameter values indicates a much lower baseflow component for the Mangahahuru Stream compared to the Oraka Stream (Figures 4.11 and 4.12, respectively).

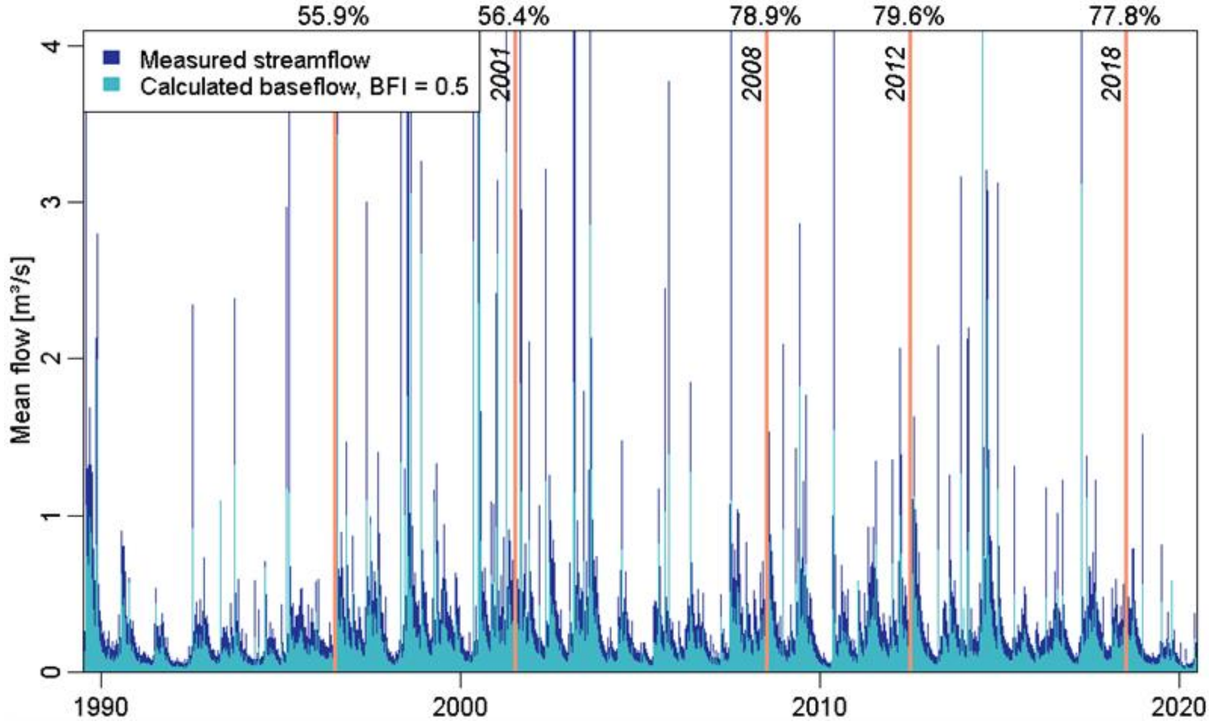

Figure 4.10 Measured stream flow and calculated baseflow (Eckhardt filter) for Mangahahuru Stream at County Weir (1990–2020). The values labelled on top of the chart represent the percentage of exotic forest cover in proportion to the catchment total area, based on LCDB data.

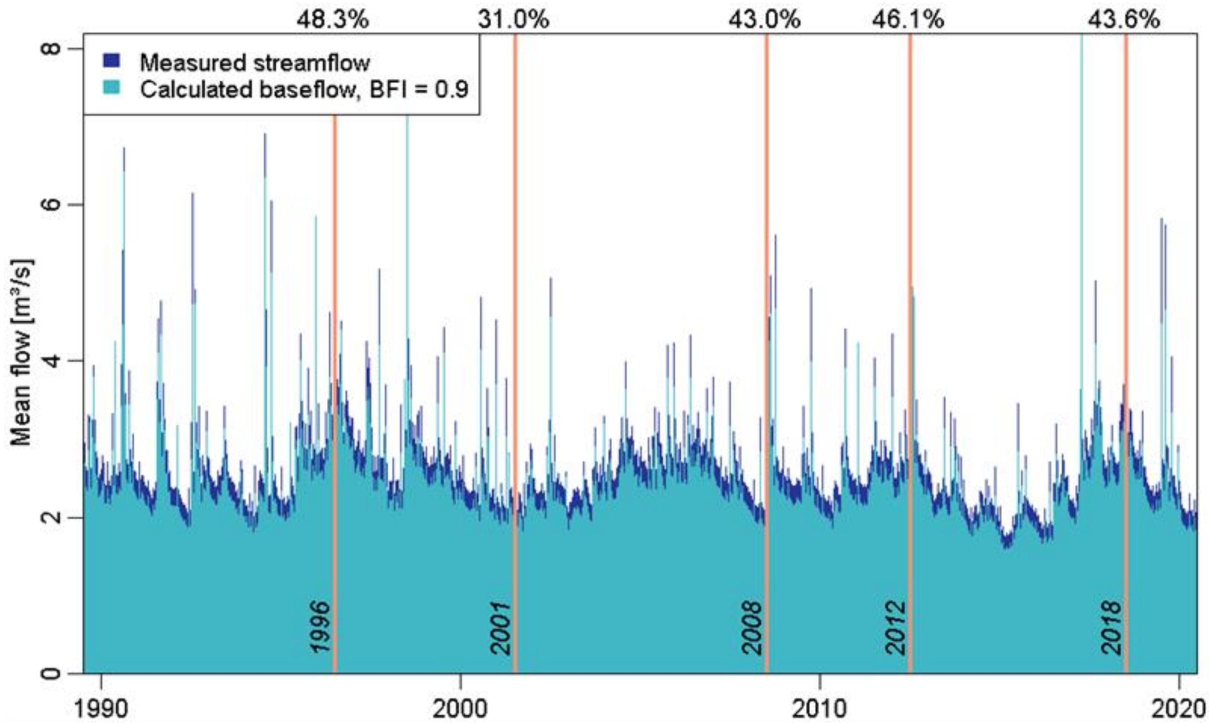

Figure 4.11 Measured stream flow and calculated baseflow (Eckhardt filter) for Oraka Stream at Pinedale (1990–2020). The values labelled on top of the chart represent the percentage of exotic forest cover in proportion to the catchment total area, based on LCDB data.

4.3.4 Trend Analysis

4.3.4.1 Mangahahuru Stream Catchment

In the Mangahahuru Stream catchment, the 400-day rolling mean time series show trends for rainfall: rainfall generally increased over the 1990–2021 period (which is also visible on the monthly total time series for this period) but decreased in the 2008–2020 period (Table 4.2).

For stream flow, no trend was detected over the 1990–2021 period, while a general decrease in all of the time series (daily mean, 400-day rolling mean, baseflow) was observed for the 2008–2020 period (Table 4.2). Sen's slope calculations indicate similar amplitude for the reductions in rainfall and stream flow when converted to the same unit.

4.3.4.2 Oraka Stream Catchment

In the Oraka Stream catchment, the 400-day rolling mean rainfall time series indicate decreasing trends over the two periods of 1990–2021 and 2008–2020. The monthly total time series only indicate a decreasing trend over the 1990–2021 period (Table 4.3).

For stream flow, a general decrease in all of the time series (daily mean, 400-day rolling mean, baseflow) was observed for the 1990–2021 period, while no trend was assessed over the 2008–2020 period (Table 4.3). Sen's slope calculations indicate smaller amplitude for the reductions in stream flow compared to rainfall when converted to the same unit.

Table 4.2 Summary of flow and rainfall trend analysis for the Mangahahuru Stream catchment. Trend directions: black = uncertain, blue = increasing, red = decreasing.

Monitoring Site [1]	Time Series	Season	Period	Number of Observations	Median [2]	Sen's Slope	Trend Direction
Hatea Forest Headquarter rainfall	Monthly total	Quarterly	1990–2021	124	111.89	0.46	?
		Quarterly	2008–2020	52	120.50	-2.32	?
		Monthly	**1990–2021**	**371**	**111.89**	**0.70**	↑
		Monthly	2008–2020	155	120.50	-0.38	?
	400-day rolling mean	**Quarterly**	**1990–2021**	**122**	**133.16**	**0.76**	↑
		Quarterly	**2008–2020**	50	136.42	-2.50	↓
		Monthly	**1990–2021**	**364**	**133.16**	**0.77**	↑
		Monthly	**2008–2020**	**148**	**136.42**	**-2.39**	↓
County Weir flow	Daily mean	Quarterly	1990–2021	125	0.31	0.00	?
		Quarterly	**2008–2020**	**53**	**0.32**	**-0.01**	↓
		Monthly	1990–2021	372	0.31	0.00	?
		Monthly	**2008–2020**	**156**	**0.32**	**-0.01**	↓
	400-day rolling mean	Quarterly	1990–2021	123	0.55	0.00	?
		Quarterly	**2008–2020**	**51**	**0.55**	**-0.03**	↓
		Monthly	1990–2021	366	0.55	0.00	?
		Monthly	**2008–2020**	**150**	**0.55**	**-0.03**	↓
	Baseflow (BFI 0.5)	Quarterly	1990–2021	125	0.31	0.00	?
		Quarterly	**2008–2020**	**53**	**0.32**	**-0.01**	↓
		Monthly	1990–2021	372	0.31	0.00	?
		Monthly	**2008–2020**	**156**	**0.32**	**-0.01**	↓

[1] Location of monitoring sites shown in Figure 4.1.

[2] Median value units are: mm/month for rainfall and m^3/s for stream flow.

Table 4.3 Summary of flow and rainfall trend analysis for the Oraka Stream catchment. Trend directions: black = uncertain, red = decreasing.

Monitoring Site [1]	Time Series	Season	Period	Number of Observations	Median [2]	Sen's Slope	Trend Direction
Overdale Road rainfall [3]	Monthly total	Quarterly	1990–2021	124	92.99	-0.50	?
		Quarterly	2008–2020	52	97.83	-2.75	?
		Monthly	**1990–2021**	358	92.99	-0.53	↓
		Monthly	2008–2020	152	97.83	-1.07	?
	400-day rolling mean	**Quarterly**	**1990–2021**	122	110.59	-0.46	↓
		Quarterly	**2008–2020**	50	107.00	-1.79	↓
		Monthly	**1990–2021**	364	110.59	-0.50	↓
		Monthly	**2008–2020**	148	107.00	-1.67	↓
Pinedale flow	Daily mean	**Quarterly**	**1990–2021**	124	2.63	-0.01	↓
		Quarterly	2008–2020	52	2.50	-0.01	?
		Monthly	**1990–2021**	368	2.63	-0.01	↓
		Monthly	2008–2020	153	2.50	-0.01	?
	400-day rolling mean	**Quarterly**	**1990–2021**	122	2.79	-0.01	↓
		Quarterly	2008–2020	50	2.67	0.00	?
		Monthly	**1990–2021**	363	2.79	-0.01	↓
		Monthly	2008–2020	147	2.67	0.00	?
	Baseflow (BFI 0.9)	**Quarterly**	**1990–2021**	124	2.1	-0.01	↓
		Quarterly	2008–2020	52	2	-0.01	?
		Monthly	**1990–2021**	369	2.1	-0.01	↓
		Monthly	2008–2020	153	2	-0.01	?

[1] Location of monitoring sites shown in Figure 4.2.

[2] Median value units are: mm/month for rainfall and m^3/s for stream flow.

[3] Station ID: #669_12.

4.4 Evapotranspiration and Water Available for Runoff or Groundwater Recharge Estimates

4.4.1 Water Budget Approach

4.4.1.1 Mangahahuru Stream Catchment

For the 2001–2019 period, mean annual measured rainfall ($P_{in\text{-}situ}$) was 1691 mm/yr and mean annual actual evapotranspiration (AET_{PML_V2}) was 800 mm/yr. According to the water balance equation (Equation 3.4), this shows that, globally, water is available in this catchment for stream flow and/or groundwater recharge. On a year-by-year basis, when rainfall minus evapotranspiration ($P_{in\text{-}situ} - AET_{PML\_V2}$) was smaller than the stream flow ($Q_{in\text{-}situ}$), the stream was potentially more supported by groundwater inflow (Figure 4.12) than during years where rainfall minus evapotranspiration ($P_{in\text{-}situ} - AET_{PML\_V2}$) was larger than the stream flow ($Q_{in\text{-}situ}$). In the latter situation, groundwater recharge and increased groundwater storage would have potentially occurred.

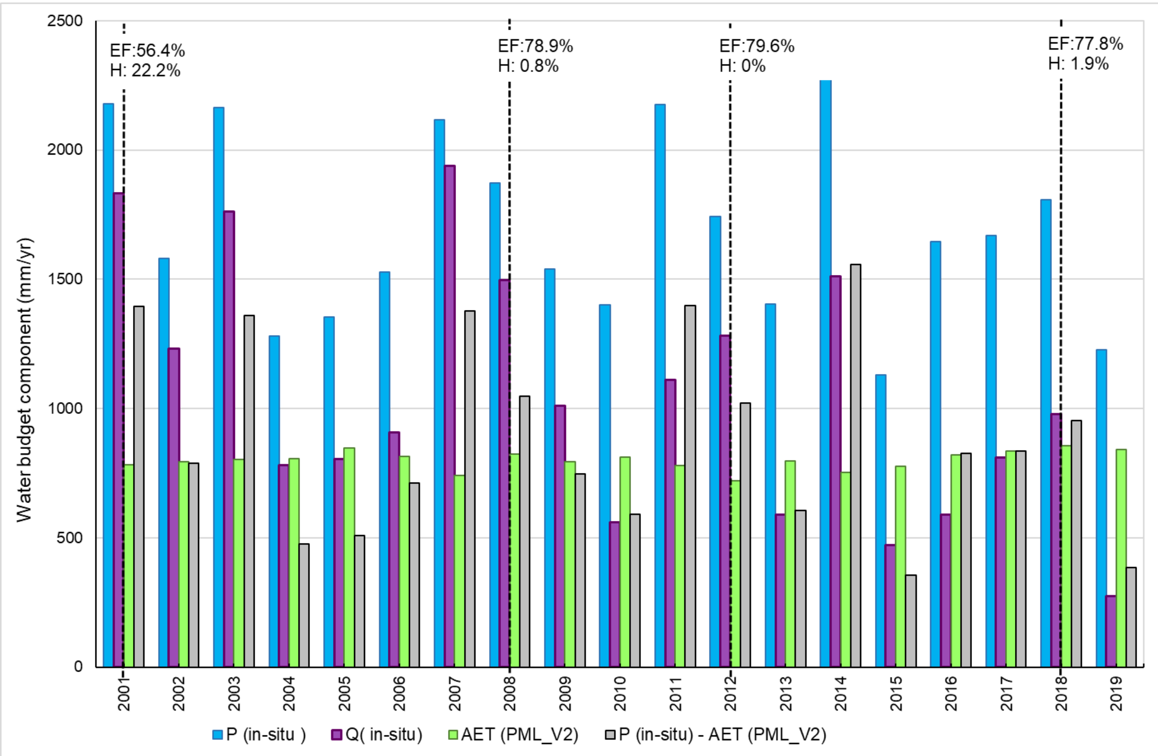

Figure 4.12 Mean annual measured and estimated water budget components for the Mangahahuru Stream catchment (2000–2019). P: rainfall; Q: stream flow, AET: actual evapotranspiration. In-situ: data measured; PML_V2: data estimated based on satellite imagery. The values labelled at the top of the chart represent the percentage of exotic forest (EF) and harvested forest (H) covers in proportion to the catchment total area, based on LCDB data.

For the Mangahahuru catchment:

- $P_{in\text{-}situ} - AET_{PML\_V2}$ was smaller than $Q_{in\text{-}situ}$ over the 2001–2009 period; and
- $P_{in\text{-}situ} - AET_{PML\_V2}$ was mainly larger than $Q_{in\text{-}situ}$ over the 2010–2019 period.

This would suggest that, after 2009, stream baseflow was less sustained by groundwater. A potential explanation could be that most of the trees planted after 2001 had sufficiently grown to take up part of this *P – ET* -derived water. Fahey (1994) reported stream flow reductions 5–10 years after planting. This water uptake by trees would then result in less recharge to groundwater and subsequently reduced baseflow in groundwater-fed streams.

Mean values of $P_{in\text{-}situ}$, AET_{PML_V2} and $Q_{in\text{-}situ}$ and their changes compared to the 2001–2007 period[11] were calculated for LCDB data time periods (Table 4.4). $Q_{in\text{-}situ}$ shows the largest reductions (-18% and -44% for the 2008–2012 and 2013–2018 periods, compared to 2001–2007). Changes for $P_{in\text{-}situ}$ and AET_{PML_V2} are smaller (up to -8% for $P_{in\text{-}situ}$ for the 2013–2018 period). The larger reductions in $Q_{in\text{-}situ}$ could be linked to increased sub-surface water storage due to higher soil water-holding capacity under the trees. These results could also reflect the high uncertainty in rainfall distribution due to one rainfall monitoring site for the catchment.

Table 4.4 Summary of the water budget component changes for the Mangahahuru Stream catchment.

Time Period	Mean					Change Compared to the 2001–2007 Period		
	$P_{in\text{-}situ}$ (mm/yr)	AET_{PML_V2}		$Q_{in\text{-}situ}$		$P_{in\text{-}situ}$	AET_{PML_V2}	$Q_{in\text{-}situ}$
		(mm/yr)	(% $P_{in\text{-}situ}$)	(mm/yr)	(% $P_{in\text{-}situ}$)			
2001–2007	1743	798	46%	1323	76%	-	-	-
2008–2012	1747	786	45%	1092	63%	0.2%	-2%	-18%
2013–2018	1600	811	51%	746	47%	-8%	2%	-44%

4.4.1.2 Oraka Stream Catchment

For the 2001–2019 period, mean annual measured rainfall ($P_{in\text{-}situ}$) was 1311 mm/yr and mean annual actual evapotranspiration (AET_{PML_V2}) was 674 mm/yr, which indicates that, globally, water was also available in this catchment for stream flow and/or groundwater recharge (Equation 3.4). Similarly to the Mangahahuru catchment, the annual comparison between $P_{in\text{-}situ}$ – AET_{PML_V2} and $Q_{in\text{-}situ}$ provides insights regarding years where groundwater storage is augmented or depleted (Figure 4.13). No obvious pattern was observed between $P_{in\text{-}situ}$ – AET_{PML_V2} and $Q_{in\text{-}situ}$ for the Oraka Stream catchment that was possibly linked to increased forest cover. This is not unexpected considering the inferred long water transfers in the catchment and associated time lags between land-use changes and related observed effects (see Section 4.3.2). However, future work should focus on summer periods and low flows, when more contrast is likely due to low rainfall and high evapotranspiration.

Mean values of $P_{in\text{-}situ}$, AET_{PML_V2} and $Q_{in\text{-}situ}$ and their changes compared to the 2001–2007 period[11] were calculated for LCDB data year periods (Table 4.5). No significant change was identified between this reference period and the following ones (2008–2012 or 2013–2018).

11 The forest cover increased the most over this period, mainly due to forestry planting cycles (LCDB data).

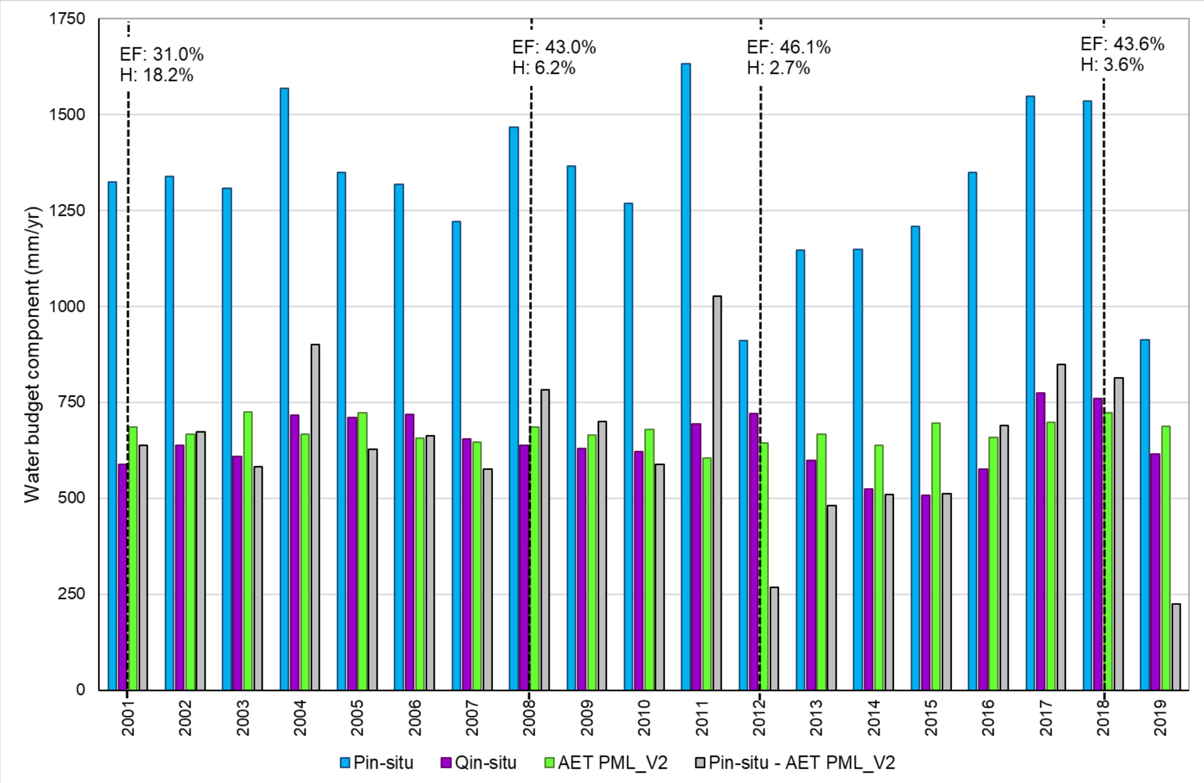

Figure 4.13 Mean annual measured and estimated water budget components for the Oraka Stream catchment (2000–2019). P: rainfall; Q: stream flow, AET: actual evapotranspiration. In-situ: data measured; PML_V2: data estimated based on satellite imagery. The values labelled at the top of the chart represent the percentage of exotic forest (EF) and harvested forest (H) covers in proportion to the catchment total area, based on LCDB data.

Table 4.5 Summary of the water budget component changes for the Oraka Stream catchment.

Time Period	Mean					Change Compared to the 2001–2007 Period		
	$P_{in-situ}$ (mm/yr)	AET_{PML_V2}		$Q_{in-situ}$		$P_{in-situ}$	AET_{PML_V2}	$Q_{in-situ}$
		(mm/yr)	(% $P_{in-situ}$)	(mm/yr)	(% $P_{in-situ}$)			
2001–2007	1347	681	51%	662	49%	-	-	-
2008–2012	1329	656	49%	660	50%	-1%	-4%	0.3%
2013–2018	1336	692	52%	682	51%	-1%	2%	3%

4.4.2 Approach Based on Evapotranspiration Differences

2019 $AET_{Sentinel\_2}$ estimates indicate higher values for 'Exotic Forest' compared to 'Harvested Forest', with differences of c.130–400 mm/yr (Figures 4.14 and 4.15) the highest differences found in harvested/bare soil land. For the 'Exotic Forest' class, differences were observed due to varying characteristics (e.g. plantation age and planting density).

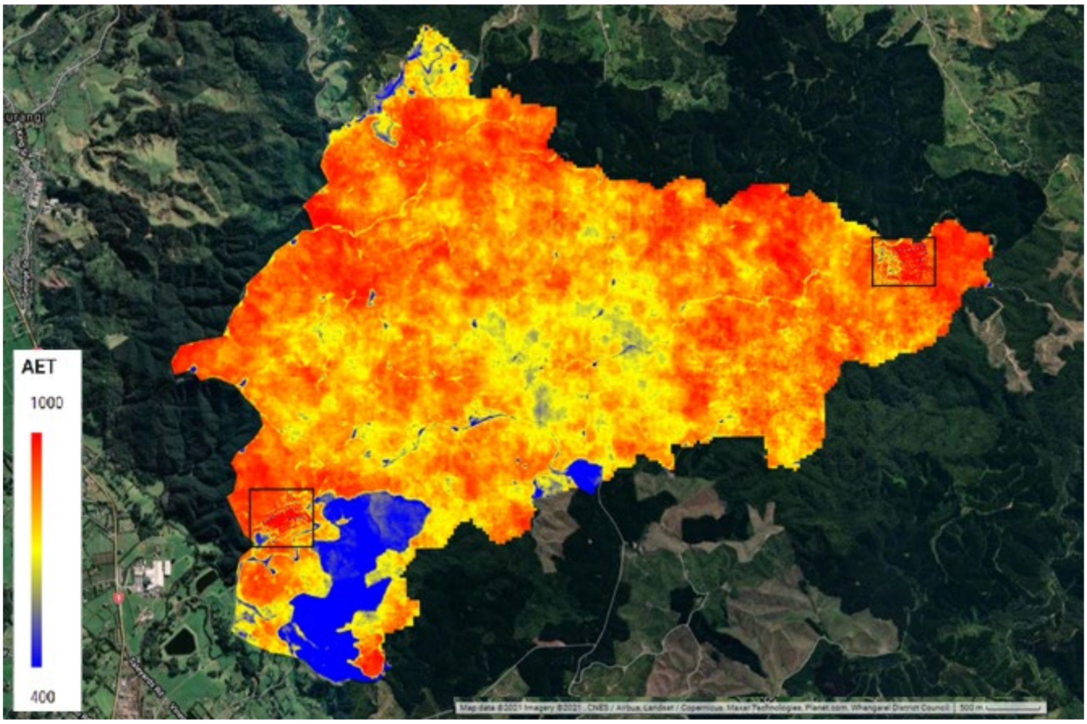

Figure 4.14 2019 mean actual evapotranspiration estimates for the Mangahahuru Stream catchment. Black rectangles show the areas surveyed by UAV. Blue areas are mainly harvested/bare soil land covers. Yellow to red areas are vegetated areas (Figure 4.3 shows forest cover in 2020).

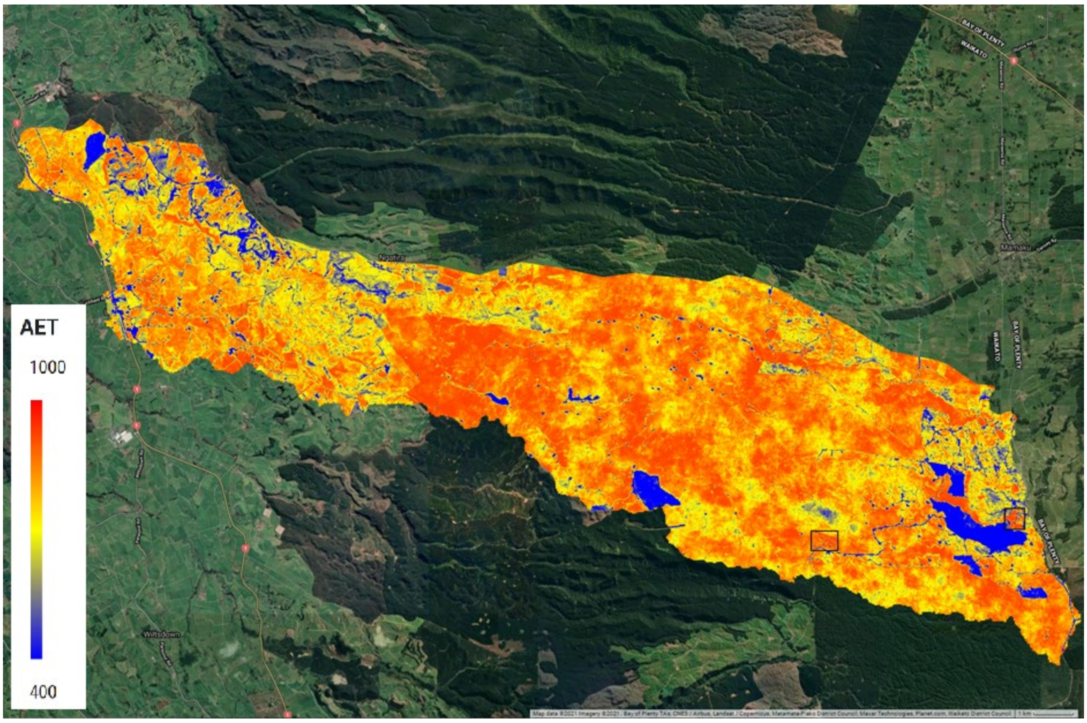

Figure 4.15 2019 mean actual evapotranspiration estimates for the Oraka Stream catchment. Black rectangles show the areas surveyed by UAV. Blue areas are mainly harvested/bare soil land covers. Yellow to red areas are vegetated areas (Figure 4.4 shows forest cover in 2020).

P – ET calculations for the entire case study catchments and harvested areas within these catchments are summarised in Table 4.6. These confirm that the effect of increased forest cover on the *P – ET* flux is significant. Assuming constant *P*:

- In the Mangahahuru Stream catchment, 4% of forest harvesting (in percentage of the total catchment area) caused a decrease in evapotranspiration, translating to a *P – ET* increase of 10%.
- In the Oraka Stream catchment, 1.5% of forest harvesting (in percentage of the total catchment area) caused a decrease in evapotranspiration, translating to a *P – ET* increase of c. 2%.

Theoretically, the *P – ET* -derived water is available for runoff and/or groundwater recharge. It is important to note that harvesting practices and related soil disturbance usually impact on the partition between runoff and groundwater recharge. Additionally, the ‘less trees, more water’ approach, on which these numbers are derived, is short-sighted, as it does not consider other benefits of forests such as aquatic ecosystem services (e.g. flood buffering and soil erosion control; Section 2.1). These services are highly valued and recognised worldwide, and it is anticipated that forests will have a major role to play to build future resilience to climate change (e.g. by helping adapt to climate-change-induced increased hydrological cycle variability and extremes).

Table 4.6 Increase in water potentially available for runoff and/or recharge through recent harvesting in the Oraka Stream and Mangahahuru Stream catchments.

Catchment	Catchment Area (ha)	Recently Harvested Area		$P – ET_{2019}$ Catchment (m^3/s)	$P – ET_{2019}$ for the Harvested Area*	
		(ha)	% Catchment		(m^3/s)	In % of $P – ET_{2019}$ Catchment
Mangahahuru	2122	76	4%	0.1	0.01	10%
Oraka	13,269	194	1.5%	1.6	0.025	2%

* Based on an evapotranspiration difference of 400 mm/yr between forest and harvested forest.

4.4.3 Insights from UAV Normalised Difference Vegetation Index

The NDVI images derived from UAV data have a high resolution (c. 10 cm) and outline the different features (e.g. tracks, water troughs) and land covers present on surveyed sites (e.g. exotic and indigenous forests, grasslands, harvested forest) with related distinctive values. The Sentinel-2 NDVI-derived images (20 m resolution) only capture large size features (e.g. roads) and provide lower contrast between land covers (Figures 4.16, 4.17 and Appendix 6).

Comparisons between the NDVI values obtained from the UAV and Sentinel-2 indicate an offset between the values measured (NDVI values from UAV being lower than from Sentinel-2; Table 4.7). This can be explained by the slightly different technical characteristics of the instruments and, in particular, the wavelengths of the bands captured. Recalibration was not undertaken in this study but would be straightforward to apply.

For both imagery sources, the highest NDVI values measured were for forest, then grassland, then harvested forest. The 2021 NDVI values measured for harvested forest were abnormally high due the presence of trees in the LCDB 2018 polygon.

Contradicting values were obtained for the indigenous and exotic forest classes, with Sentinel-2 capturing slightly higher NDVI values for exotic forest than for indigenous forest, while it was the opposite for the UAV. We infer that the UAV-derived NDVI values are more accurate due to their higher spatial resolution, also confirmed by the indigenous forest looking visually healthier; denser, with understorey vegetation below the native trees; and seeming to have a higher vegetation activity (Figure 4.18). However, UAV data was likely recorded with a different solar angle compared to the satellite data, possibly introducing uncertainty due to tree shapes and shade. According to the work of Goulden and Bales (2019), NDVI values can, in some cases, be correlated to evapotranspiration values (Appendix A3.2), which mostly correlates to the transpiration rate of healthy plants. Hence, the measured NDVI values (Table 4.7) could potentially be used to inform vegetation cover evapotranspiration rates. However, further work, including integration of more parameters (e.g. plantation age, tree density, management practices) and ground-truthing measurements is needed to confirm this.

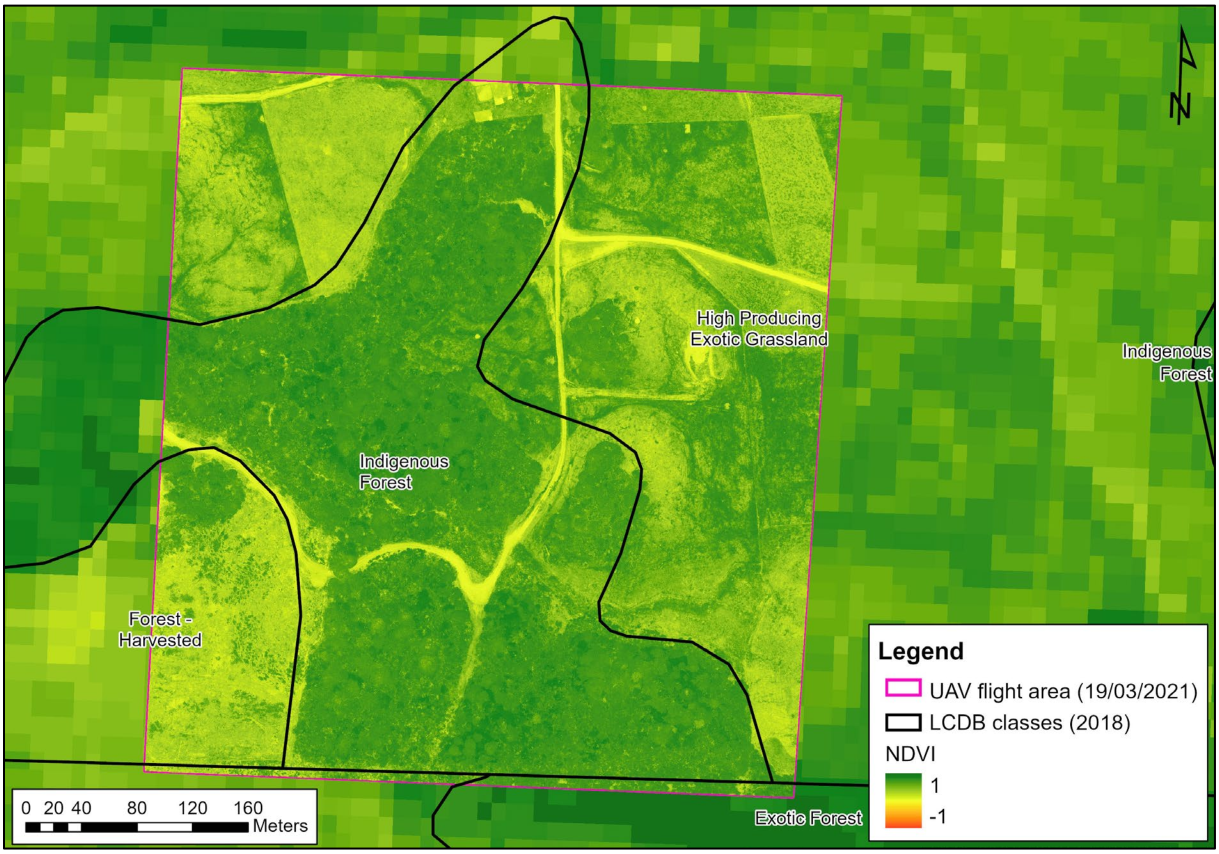

Figure 4.16 Overlay of NDVI images derived from Sentinel-2 image (19/02/2021; background), UAV image (19/03/2021; foreground) and LCDB 2018 cover classes for the MS Farm site, Oraka Stream catchment.

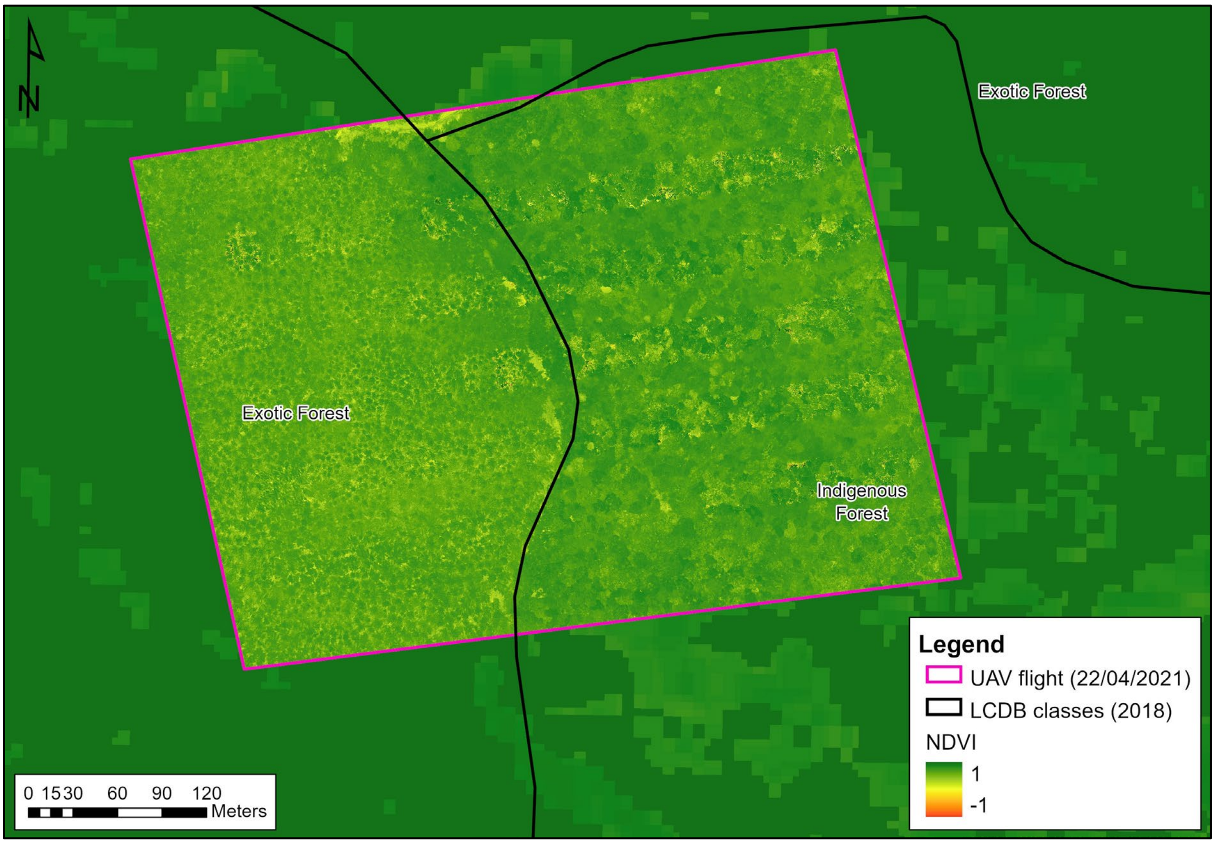

Figure 4.17 Overlay of NDVI images derived from Sentinel-2 image (3/05/2021; background) and UAV image (22/04/2021; foreground) for the Mangahahuru Stream catchment, upper area.

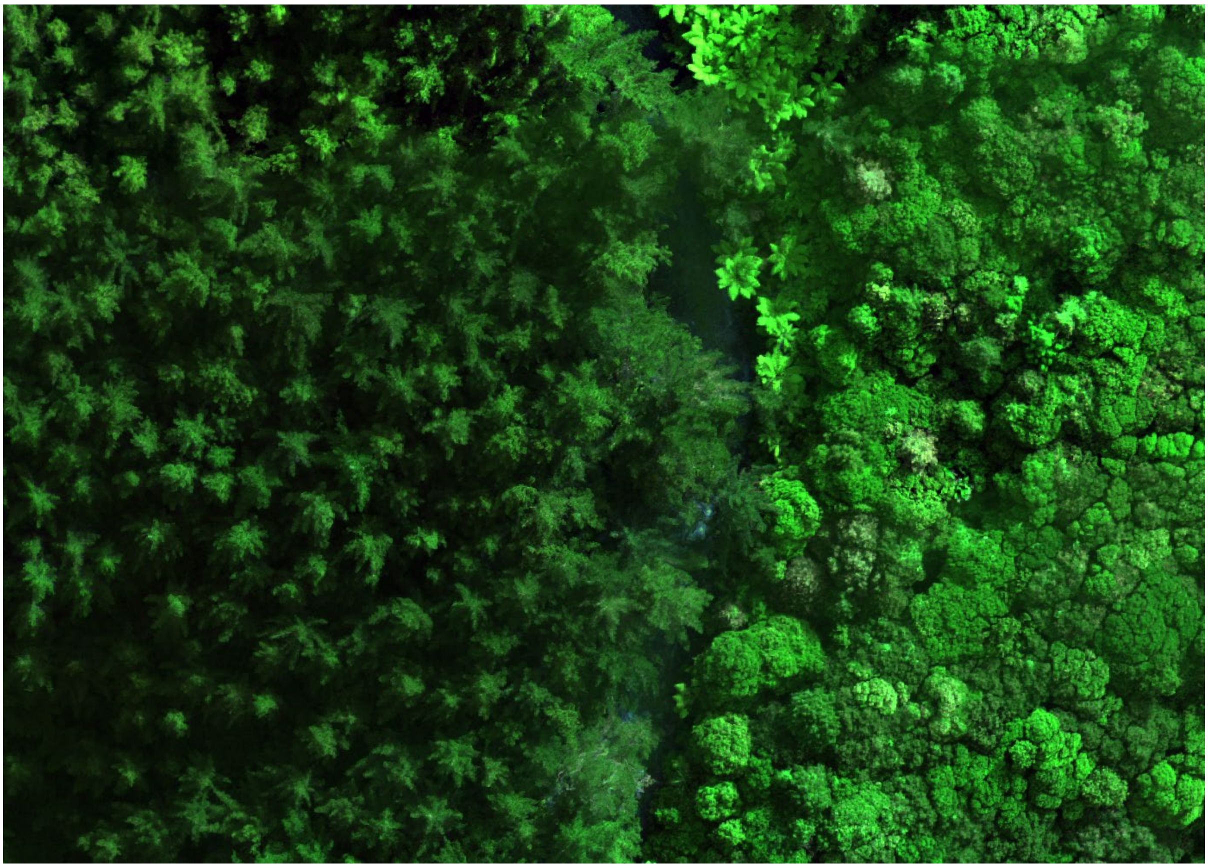

Figure 4.18 RGB UAV image for the Mangahahuru Stream catchment, upper area, showing indigenous forest cover on the right and exotic forest cover on the left (22/04/2021).

Table 4.7 NDVI values inferred for LCDB land-cover classes from UAV and Sentinel-2 images (Autumn 2021).

<table>
<tr><th rowspan="2">LCDB 2018 Class</th><th rowspan="2">Catchment</th><th rowspan="2">Area</th><th colspan="3">UAV [1]</th><th colspan="3">Sentinel-2 [1]</th></tr>
<tr><th>Mean NDVI</th><th>STD NDVI</th><th>Mean NDVI</th><th>Mean NDVI</th><th>STD NDVI</th><th>Mean NDVI</th></tr>
<tr><td rowspan="4">Exotic Forest</td><td rowspan="2">Mangahahuru Stream</td><td>Upper</td><td>0.62</td><td>0.12</td><td rowspan="3">0.64</td><td>0.98</td><td>0.04</td><td rowspan="3">0.99</td></tr>
<tr><td>Lower</td><td>0.63</td><td>0.11</td><td>0.99</td><td>0.04</td></tr>
<tr><td rowspan="2">Oraka Stream</td><td>Sutcliffe Rd</td><td>0.67</td><td>0.12</td><td>0.99</td><td>0.05</td></tr>
<tr><td>MS Farm</td><td>0.77</td><td>0.06</td><td>NR</td><td>0.88</td><td>0.07</td><td>NR</td></tr>
<tr><td rowspan="2">Indigenous Forest</td><td>Mangahahuru Stream</td><td>Upper</td><td>0.68</td><td>0.12</td><td rowspan="2">0.72</td><td>0.91</td><td>0.09</td><td rowspan="2">0.87</td></tr>
<tr><td>Oraka Stream</td><td>MS Farm</td><td>0.76</td><td>0.11</td><td>0.83</td><td>0.12</td></tr>
<tr><td>Broadleaved Indigenous Hardwoods</td><td>Mangahahuru Stream</td><td>Lower</td><td>0.59</td><td>0.14</td><td>0.59</td><td>0.86</td><td>0.14</td><td>0.86</td></tr>
<tr><td rowspan="2">High-Producing Exotic Grassland [2]</td><td>Mangahahuru Stream</td><td>Lower</td><td>0.64</td><td>0.15</td><td rowspan="2">0.65</td><td>0.84</td><td>0.13</td><td rowspan="2">0.74</td></tr>
<tr><td>Oraka Stream</td><td>MS Farm</td><td>0.66</td><td>0.11</td><td>0.63</td><td>0.11</td></tr>
<tr><td>Gorse and/or Broom</td><td>Mangahahuru Stream</td><td>Lower</td><td>0.60</td><td>0.11</td><td>0.60</td><td>0.89</td><td>0.11</td><td>0.89</td></tr>
<tr><td>Forest – Harvested</td><td>Oraka Stream</td><td>MS Farm</td><td>0.58</td><td>0.14</td><td>NR</td><td>0.59</td><td>0.11</td><td>NR</td></tr>
</table>

[1] Image dates are provided in Table 3.2.

[2] The grasslands observed on MS Farm were likely Low-Producing Grasslands; a conversion might have occurred since 2018, hence the low NDVI values.

NR: not representative, i.e. the actual land cover was different from the LCDB 2018 class. In this case, there was a mix of indigenous and exotic trees in the MS Farm ‘Exotic Forest’ polygon, and some trees were left in the ‘Harvested Forest’ polygon.

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The ground-truthing work undertaken in this study illustrates the complexity and the paucity of supporting data to differentiate the effects of climate and afforestation on catchment hydrology. The choice of contrasting case study sites in Northland and Waikato indicated that this complexity is compounded by the local setting. For instance, the geology of the Oraka Stream catchment induces long water transfers and associated long time lags between land-use changes and visible effects in the catchment.[12]

In comparison, the Mangahahuru Stream catchment was less ambiguous due to a larger forest cover and inferred shorter response times. Stream flow reductions following increased forest cover were observed, and water balance calculations suggested a reduction of baseflow that may be a consequence of tree water uptake.[13]

The absence of groundwater-related monitoring data (groundwater level, rainfall recharge) limited our analysis and interpretation. These data would have assisted in better understanding potential changes in groundwater storage due to increased forest cover.

The use of a better spatially characterised evapotranspiration by remote sensing was deemed crucial to improve quantifying the effect of trees on evapotranspiration, as trees transpire more water than grass (in between 50 and 200 mm more) or bare land (up to 400 mm more according to our results). The large evapotranspiration differences that we estimated between forest and harvested areas suggested that larger $P - ET$ -derived water could be available for runoff and/or groundwater recharge at harvested areas. While increased stream flows and groundwater recharge are generally reported following harvesting, we consider this perceived benefit to be short-sighted, as it does not fully consider benefits of forests (e.g. resilience to drought and floods).

Our results and, in particular, the flow reductions observed in the Mangahahuru Stream catchment, inferred to be partially due to increased forest cover, highlight the need to adopt decisions based on a clear understanding of potential trade-offs. This occurred in the Mangahahuru Stream catchment, where pasture was initially converted into forest to address soil erosion and sediment discharges issues. Catchments in which addressing soil erosion is the priority, and for which reduced stream flows is not critical (e.g. for the ecological life, for community supplies), could be used for afforestation development. Similarly, catchments with degraded soils and low permeability due to intensive pasture land use could be afforested to restore soil permeability and groundwater recharge.

The complementary use of in-situ monitoring data and remote-sensing data was beneficial to the understanding of catchment responses to land-use changes. In our water budget calculations for the 2000–2019 period, rainfall and stream-flow components were characterised by in-situ monitoring data, and evapotranspiration was estimated based on satellite imagery. However, this study did not cover the ground-truthing and validation of these remote-sensed derived evapotranspiration estimates, which would inform on their representativeness. In addition, contrasting evapotranspiration values are expected within LCDB classes (e.g. pine evapotranspiration will vary with plantation age) but was not addressed in this study.

12 Dell (1982) came to similar conclusions while working in the Mamaku Plateau area.

13 The baseflow digital filtering approach was unable to capture this effect, as it just applied the same ‘filter’ across time to the flow time series.

5.2 Recommendations

Our study has investigated the local effects of increased forest covers on stream flows and identified several research gaps that hinder a comprehensive understanding of potential impacts of afforestation on the hydrological cycle. This understanding is needed due to increasing afforestation at the national scale to mitigate carbon emissions.

To refine water allocation in afforested catchments, we recommend starting comprehensive monitoring to build understanding as soon as possible. Parameters to be considered are climate variability, water scarcity, tree species, tree ages, planting density, place of planting in the catchment (in relation to the groundwater recharge area), percentage of afforested cover, rainfall feedback from increased evapotranspiration and forestry management practices (thinning, rotation length, understorey control), etc.

Our recommendations for future work include:

- Introduction of complementary monitoring (groundwater level, groundwater recharge) in a few afforested catchments representative of the regional conditions.
- Isotope and water-age sampling and analysis to improve the understanding of water sources, transit times and flows in afforested catchments.
- Ground-truthing of remotely sensed data to optimise its benefits and extend monitoring scale (see Mourot et al. 2021).
- Time-series analysis focused on summer/low-flow periods to inform allocation limits.

Finally, we recommend that water resource managers work closely with forest managers and climate-change advisors to achieve integrated and best-informed decisions at the regional scale.

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APPENDICES

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APPENDIX 1 UAV IMAGERY COLLECTION

A1.1 Equipment Utilised for UAV Imagery Collection

Figure A1.1 Altus LRX UAV with multispectral camera attached (see Figure A1.2 below).

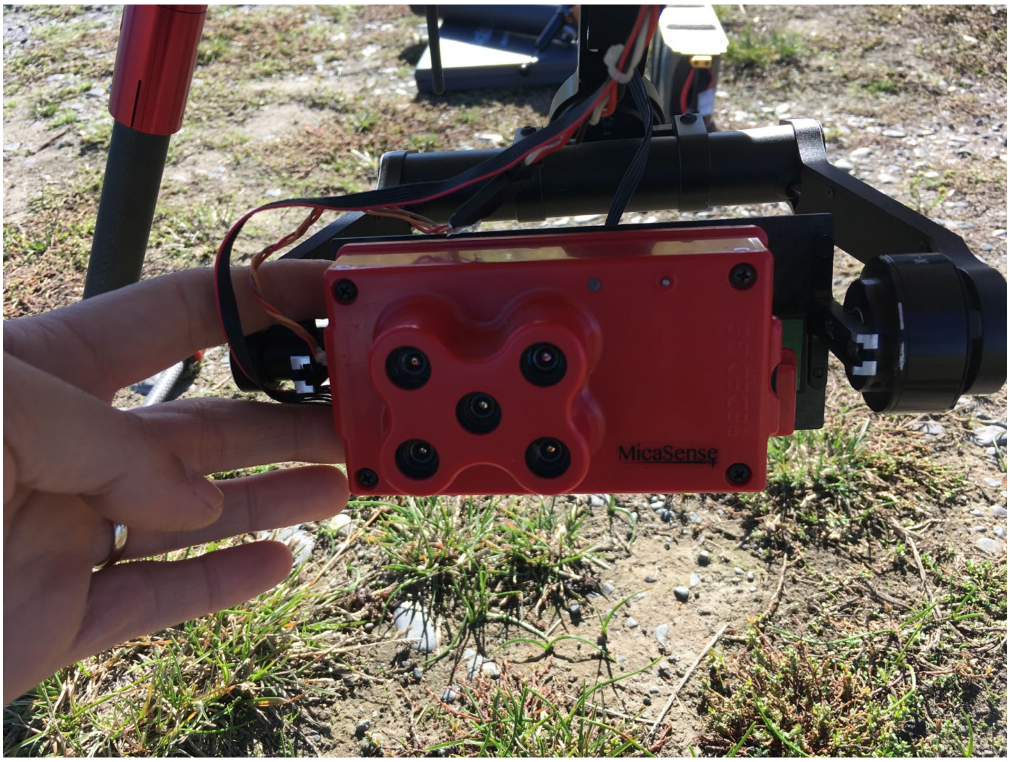

Figure A1.2 MicaSense RedEdge 3 multispectral camera.

A1.1 Flight Lines

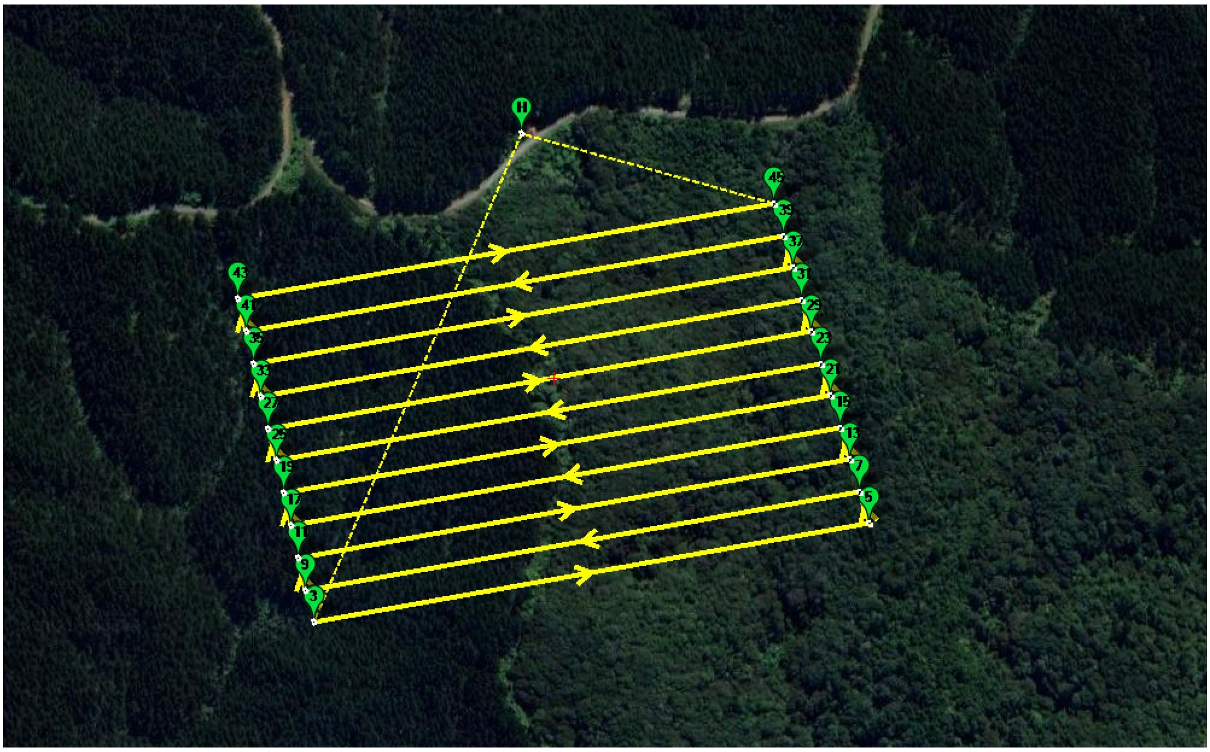

Figure A1.3 Mangahahuru Stream catchment (Northland), upper area.

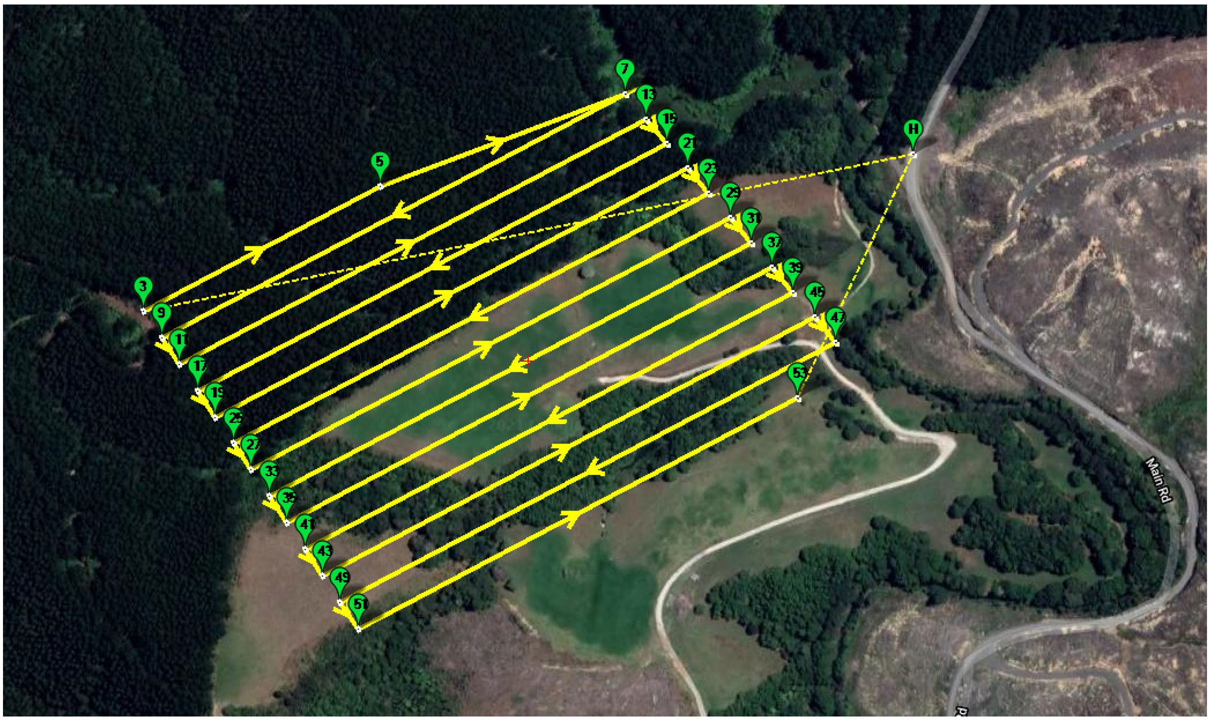

Figure A1.4 Mangahahuru Stream catchment (Northland), lower area.

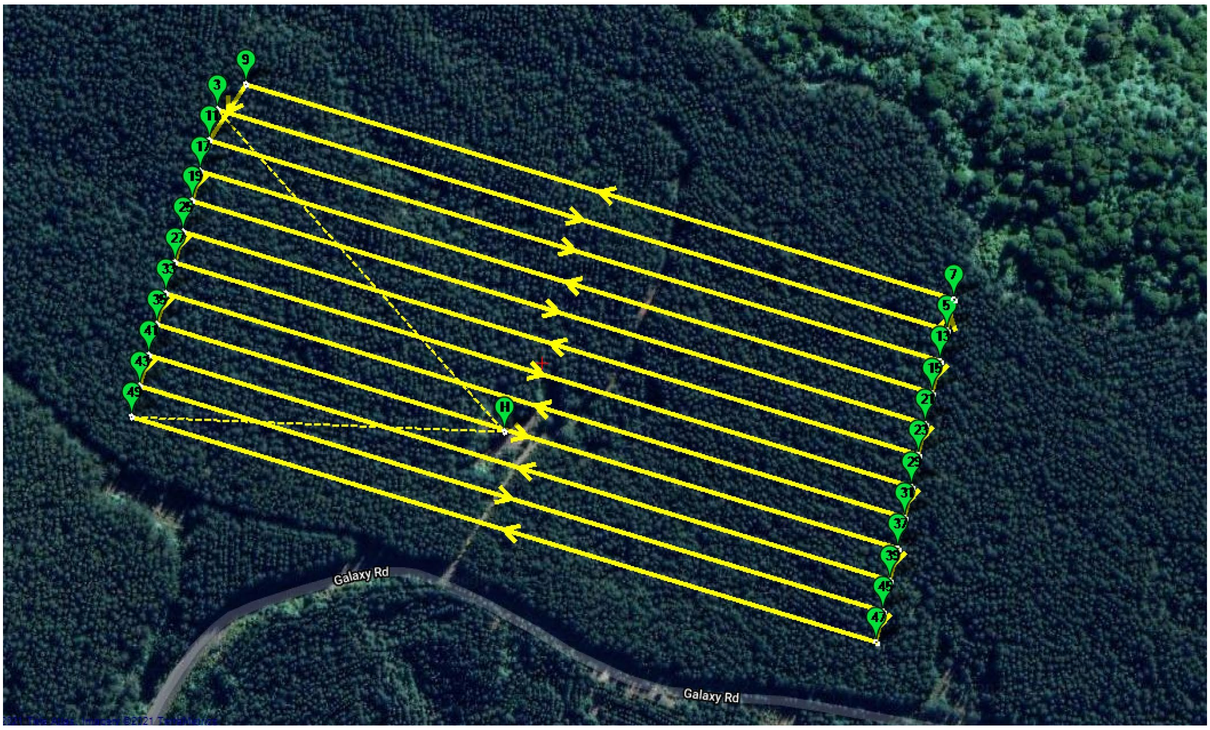

Figure A1.5 Oraka Stream catchment (Waikato), Sutcliffe Road.

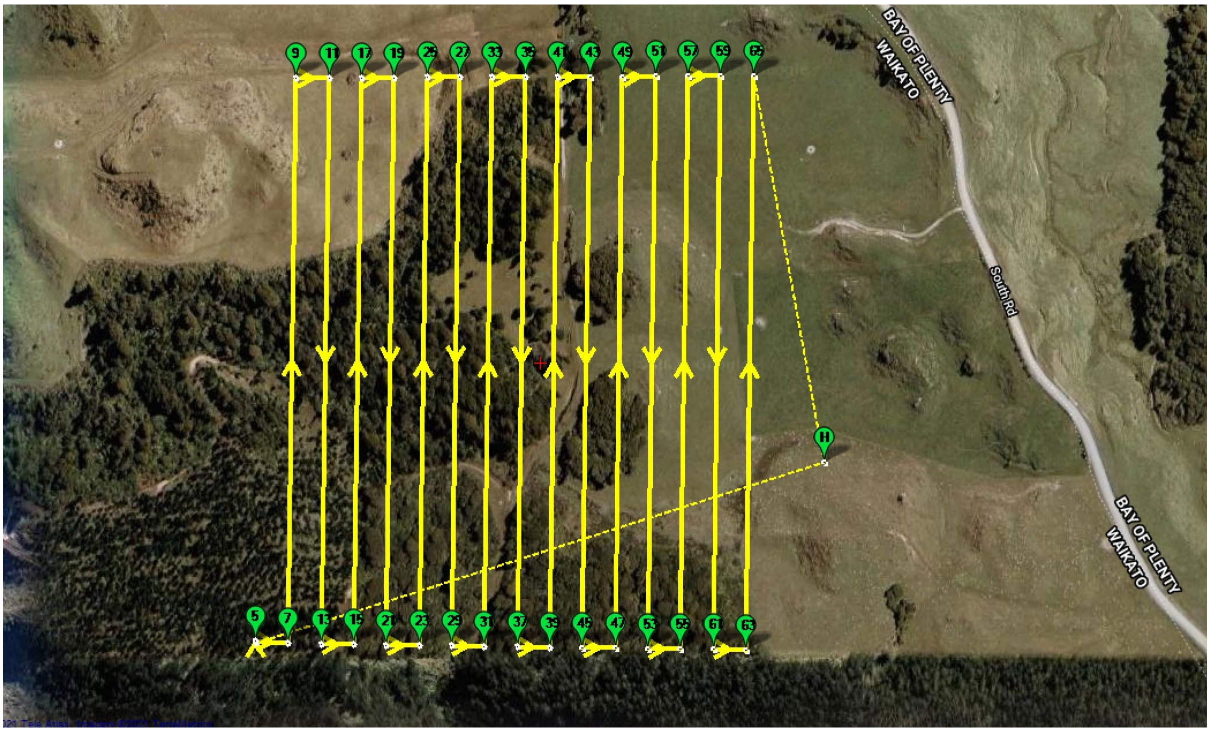

Figure A1.6 Oraka Stream catchment (Waikato), MS Farm.

A1.2 Ground Control Points

Ground control points (GCPs) were collected when possible across the study sites for georeferencing purposes.

MS Farm site (Oraka Stream Catchment)

At MS Farm site, the GCPs included identifiable structures such as water troughs, farm posts and fences.

GCPs were surveyed using a post-processed kinematic global positioning system (GPS) Trimble GeoXH 3.5G GeoExplorer 6000, with an estimated horizontal and vertical error of approximately 10 cm.

GCPs were only surveyed at MS Farm site for grassed areas (5).

Other sites: Sutcliffe Road (Oraka Stream Catchment), Upper and Lower Areas (Mangahahuru Stream Catchment)

It was not possible to collect GCPs for these other sites due to trees obscuring sight of the points or access issues due to the presence of cattle in the grassed area.

For these sites, resulting UAV image orthomosaics were overlaid and visually compared to georeferenced basemaps in ArcMap as a check of georeference accuracy.

APPENDIX 2 NEW ZEALAND LAND COVER DATABASE (LCDB v5.0) CLASSES DESCRIPTION

Table A2.1 Description of the LCDB v5.0 classes mentioned in the study (LRIS Portal 2020).

Class Code	Class Name	Class Description
40	High-Producing Exotic Grassland	Exotic sward grassland of good pastoral quality and vigour, reflecting relatively high soil fertility and intensive grazing management. Clover species, ryegrass and cocksfoot dominate, with lucerne and plantain locally important but also including lower-producing grasses exhibiting vigour in areas of good soil moisture and fertility.
51	Gorse and/or Broom	Scrub communities dominated by gorse or Scotch broom, generally occurring on sites of low fertility, often with a history of fire, and insufficient grazing pressure to control spread. Left undisturbed, this class can be transitional to Broadleaved Indigenous Hardwoods.
54	Broadleaved Indigenous Hardwoods	Lowland scrub communities dominated by indigenous mixed broadleaved shrubs such as wineberry, mahoe, five-finger, *Pittosporum* spp., fuchsia, tutu, titoki and tree ferns. This class is usually indicative of advanced succession toward indigenous forest.
64	Forest–Harvested	Predominantly bare ground arising from the harvesting of exotic forest or, less commonly, the clearing of indigenous forest. Replanting of exotic forest (or conversion to a new land use) is not evident and nor is the future use of land cleared of indigenous forest.
69	Indigenous Forest	Tall forest dominated by indigenous conifer, broadleaved or beech species.
71	Exotic Forest	Planted or naturalised forest predominantly of radiata pine but including other pine species, Douglas fir, cypress, larch, acacia and eucalypts. Production forestry is the main land use in this class, with minor areas devoted to mass-movement erosion control and other areas of naturalised (wildling) establishment.

APPENDIX 3 EVAPOTRANSPIRATION ESTIMATES FROM MULTISPECTRAL IMAGERY

A3.1 Mourot et al. (2019) Study

As part of this study, the approach developed by Mourot et al. (2019) to assess actual evapotranspiration (AET) via a series of vegetation indices calculations was utilised.

Figure A3.1 depicts this workflow. For this study, calculations were processed in the Google Earth Engine platform until the relative evapotranspiration (RET step, noting that RET represents the ratio between AET and PET where evaporation from the soil is also included).

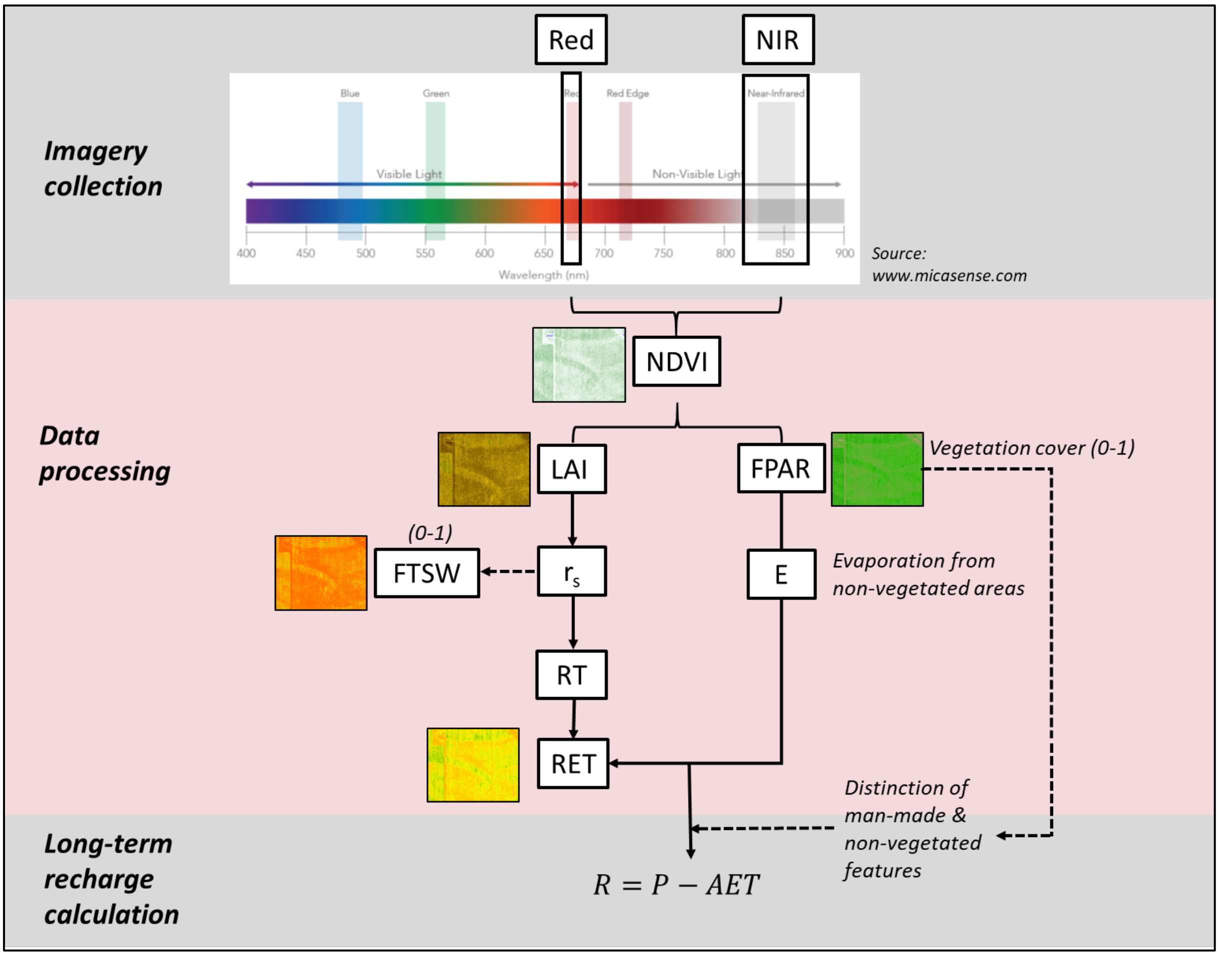

Figure A3.1 Schematic of the actual evapotranspiration calculation workflow (NIR: Near Infrared, NDVI: Normalised Difference Vegetation Index, LAI: Leaf Area Index, FPAR: Fraction of Photosynthetically Active Radiation, r_s: surface resistance, FTSW: Fraction of Transpirable Soil Water, RT: Relative Transpiration, RET: Relative evapotranspiration; R: Recharge, P: Precipitation, AET: Actual Evapotranspiration; dashed lines indicate that task was out of project scope) (Mourot et al. 2019).

A3.2 Goulden and Bales (2019) Study

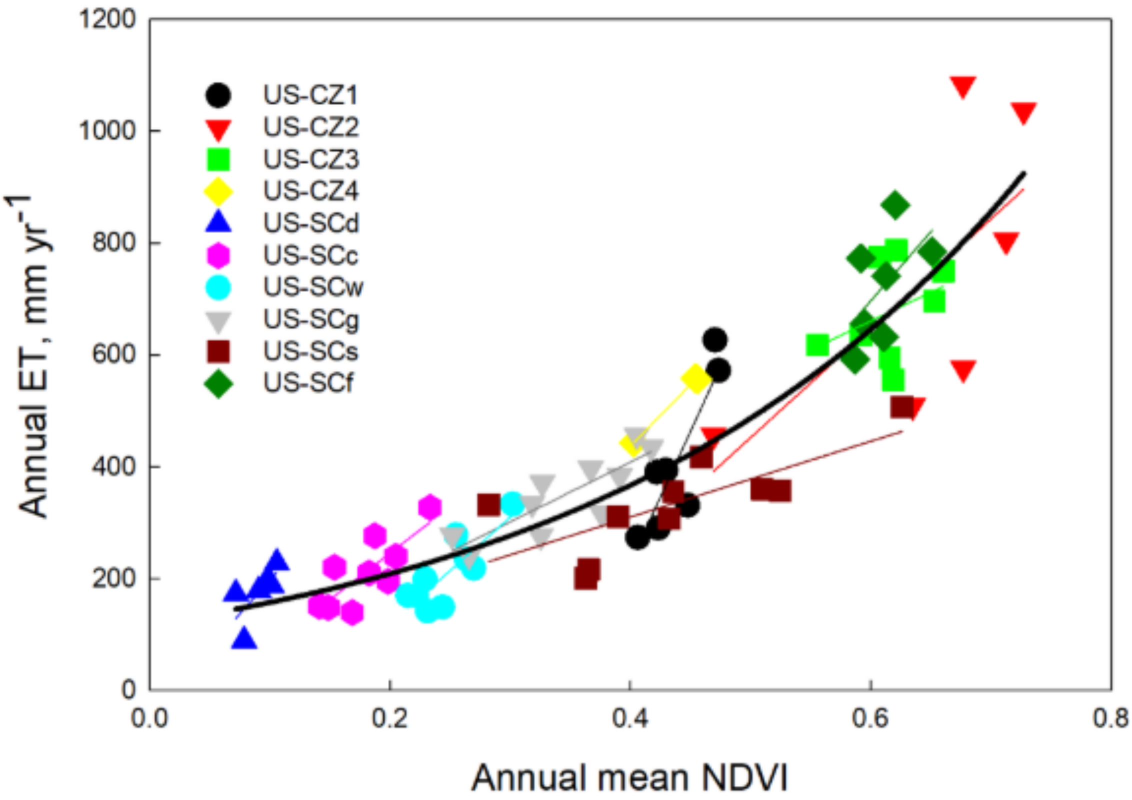

Figure A3.2 Annual water year evapotranspiration by integrated eddy covariance against annual Normalised Difference Vegetation Index (NDVI) from Landsat for nine nearest upwind pixels across multiple years at 10 California flux towers. The solid black line shows the best fit regression through all sites and for all years: *ET* (mm) = 117.16* exp(2.8025*NDVI) (R2 = 0.8386). Symbols indicate individual sites as identified by the AmeriFlux site code (http://ameriflux.lbl.gov/sites). Thin lines show liner regressions based on interannual variability within each site (Goulden and Bales 2019).

APPENDIX 4 SITE PHOTOGRAPHS

A4.1 Mangahahuru Stream Catchment (Northland), Upper Area

Figure A4.1 Photographs of land covers and soils for the Mangahahuru Stream catchment, upper area. Land covers: native forest (A; left side of B), exotic forest (right side of B; C). Soils (D).

A4.2 Mangahahuru Stream Catchment (Northland), Lower Area

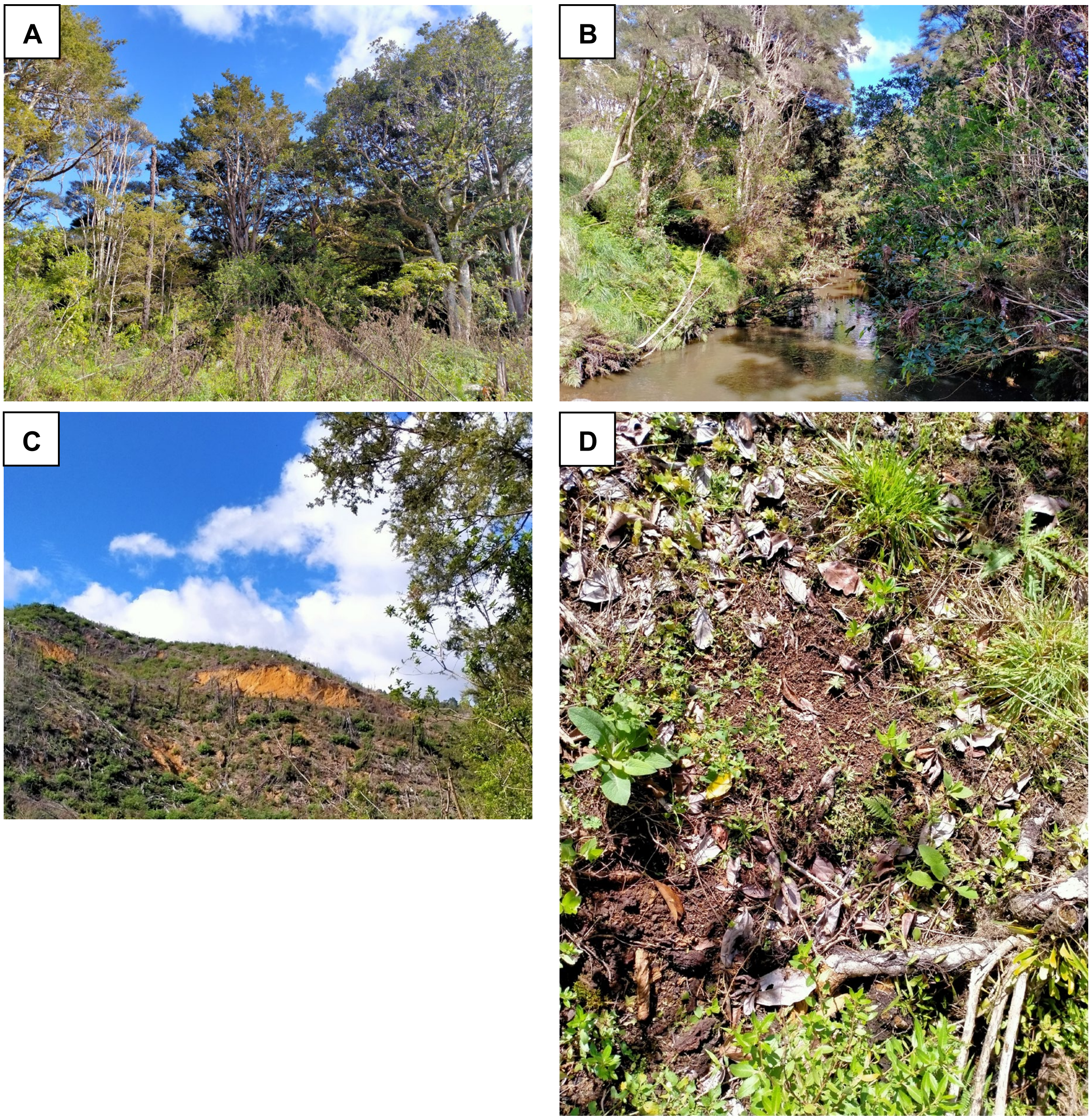

Figure A4.2 Photographs of land covers and soils for the Mangahahuru Stream catchment, lower area. Land covers: native trees (A, B), Mangahahuru Stream at Marua Road (B), harvested forest (C). Soils (D).

A4.3 Oraka Stream Catchment (Waikato), Sutcliffe Road

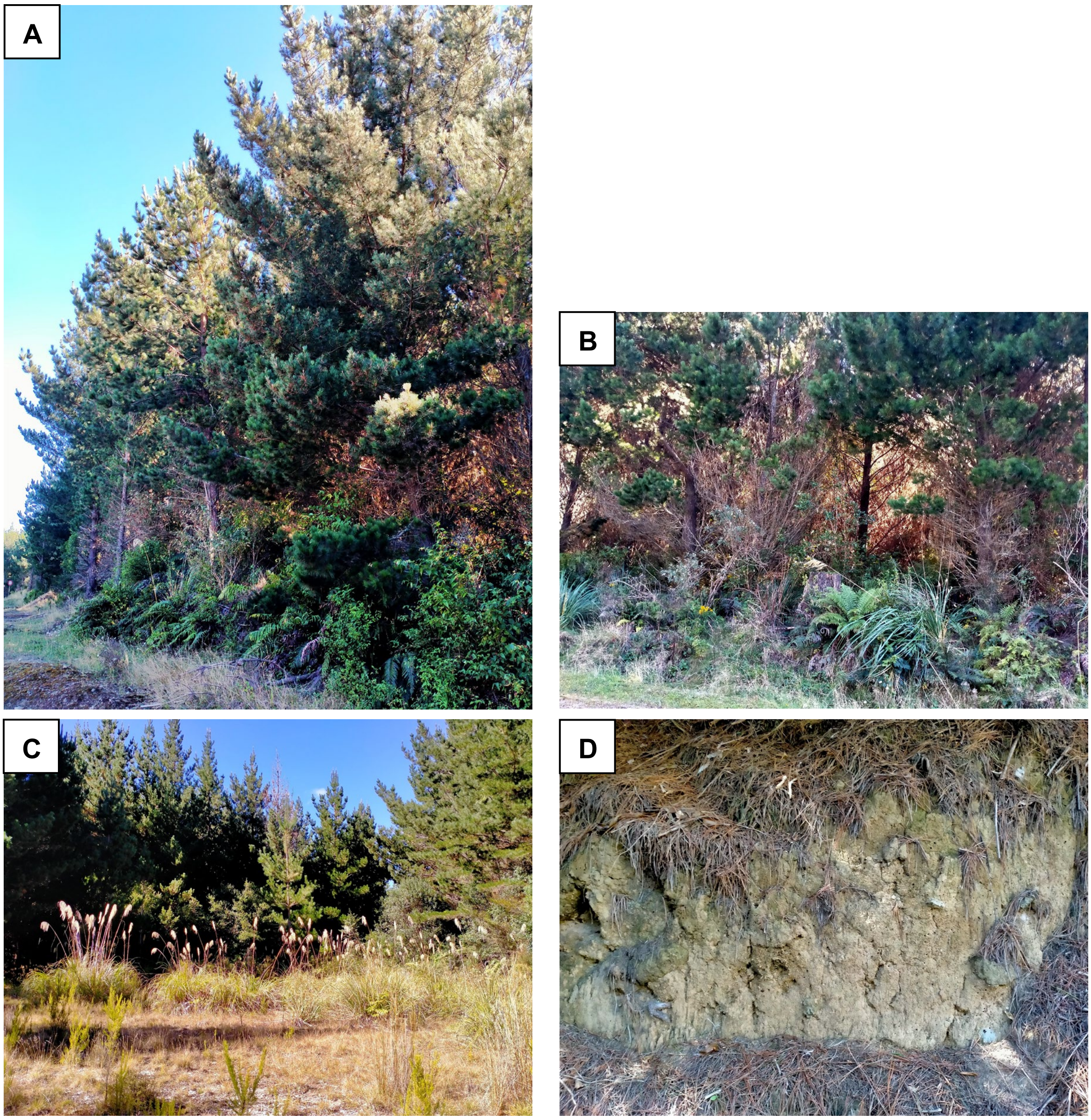

Figure A4.3 Photographs of land covers and soils for the Oraka Stream catchment, Sutcliffe Road. Land covers: exotic forest with understorey (A, B), younger pines and clearing along Sutcliffe Road (C). Soils (D).

A4.4 Oraka Stream Catchment (Waikato), SM Farm

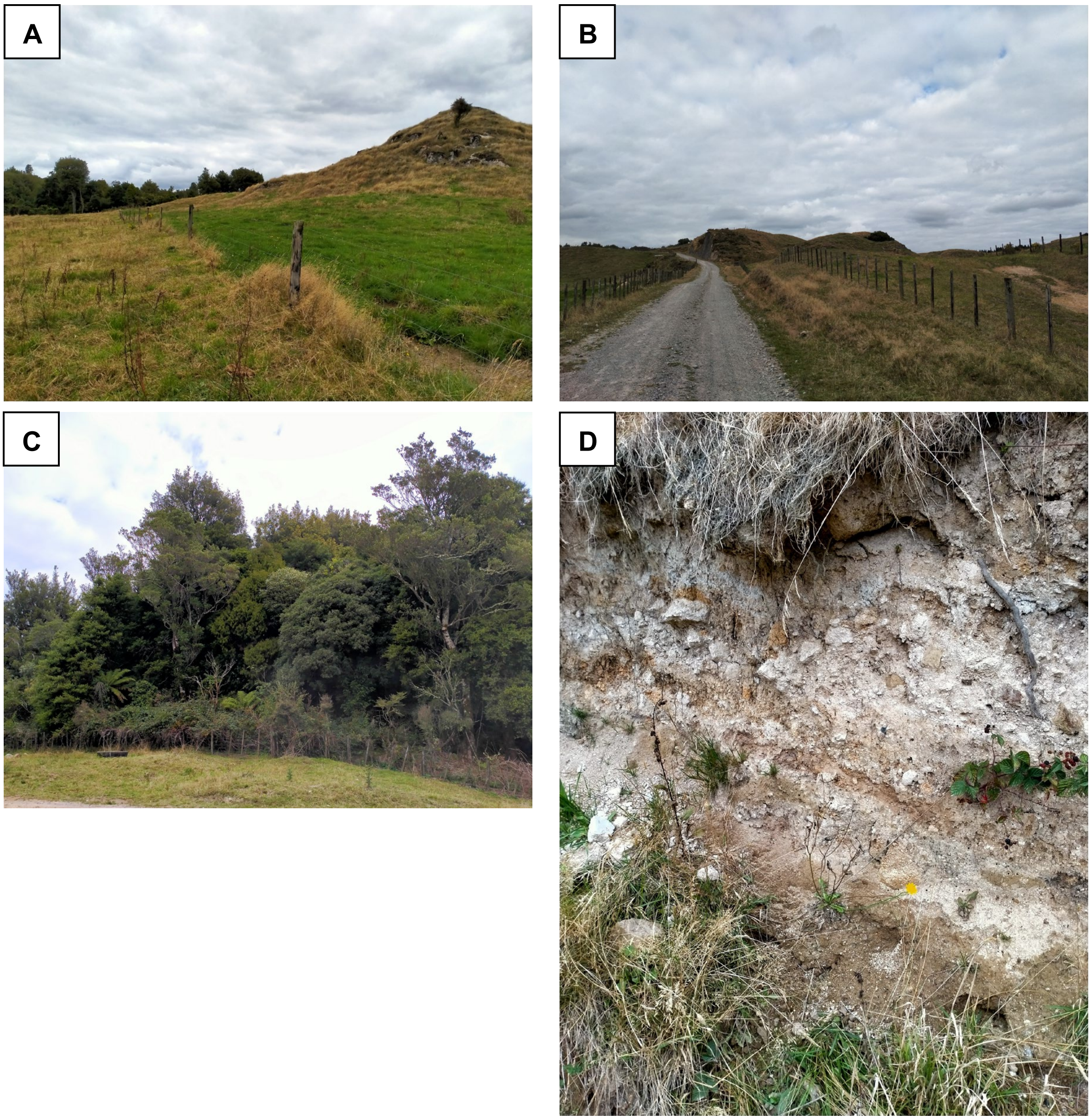

Figure A4.4 Photographs of land covers and soils for the Oraka Stream catchment, MS Farm. Land covers: grasslands (A), grassland and farm tracks (B), native forest (C). Soils (D).

APPENDIX 5 RAINFALL AND STREAM FLOW ANALYSIS

A5.1 Rainfall and Stream Flow Rolling Means

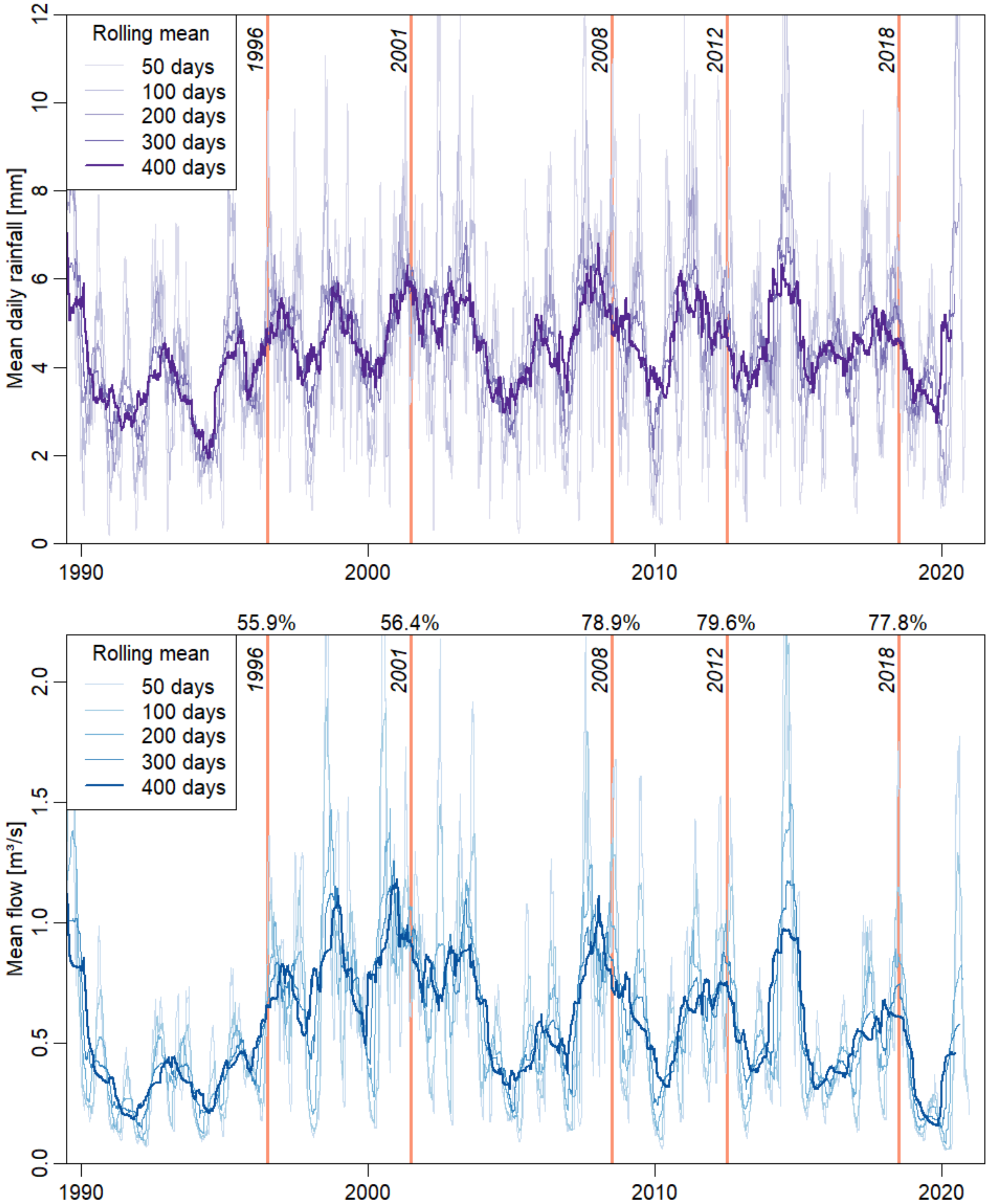

Figure A5.1 Rolling mean values for rainfall (top) and stream flow (bottom) for the Mangahahuru Stream catchment between 1990 and 2020. The values labelled on top of the stream flow chart represent the percentage of exotic forest cover in proportion to the catchment total area, based on LCDB data.

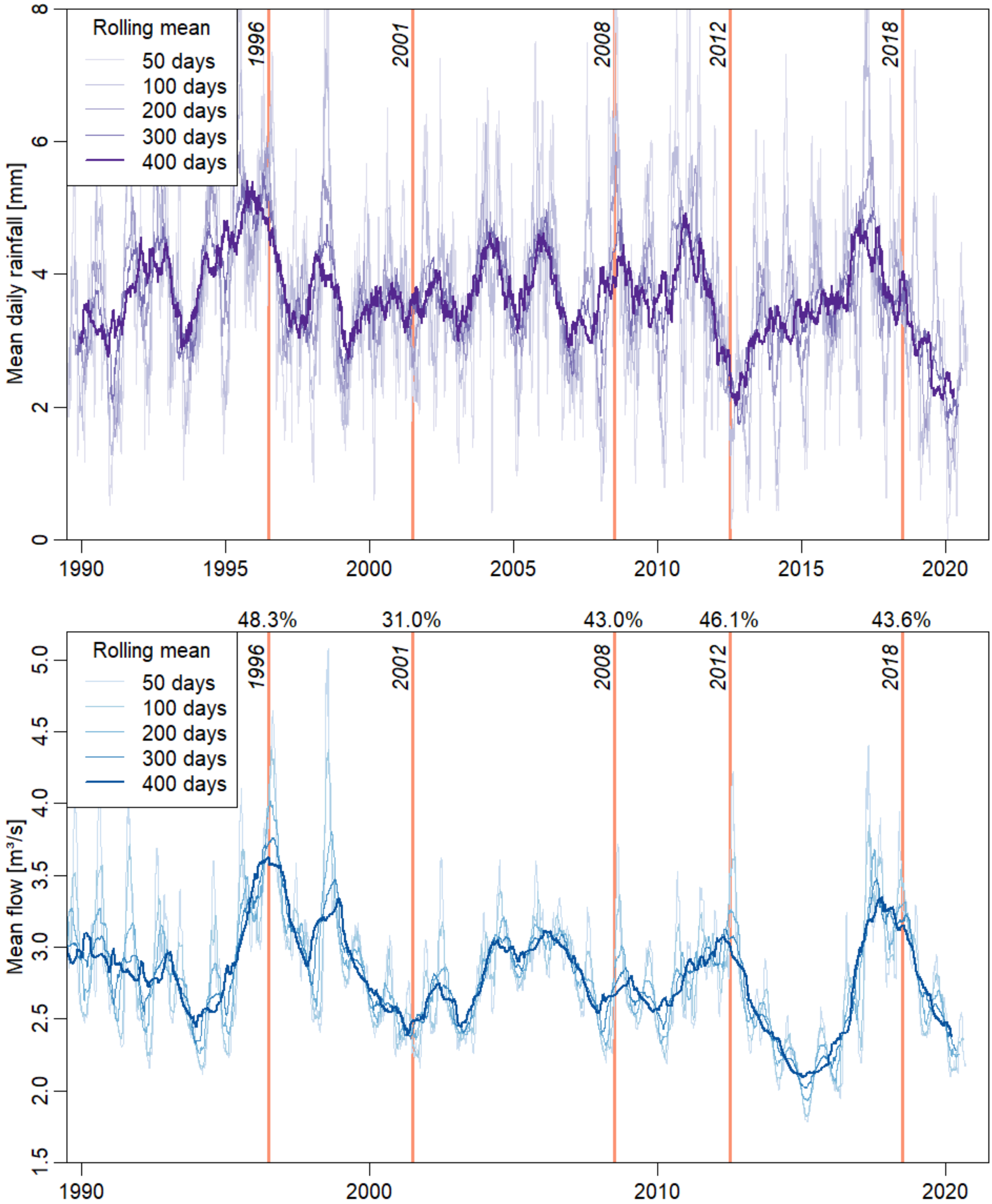

Figure A5.2 Rolling mean values for rainfall (top) and stream flow (bottom) for the Oraka Stream catchment between 1990 and 2020. The values labelled on top of the flow chart represent the percentage of exotic forest cover in proportion to the catchment total area, based on LCDB data.

A5.2 Assessment of Eckhardt Digital Baseflow Filter Constant 'a'

Recession Analysis as per Eckhardt (2008):

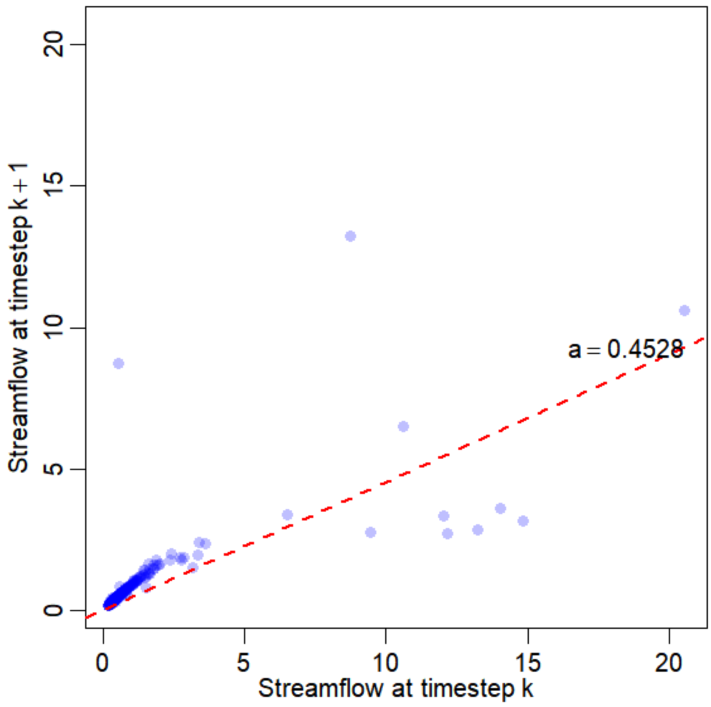

Figure A5.3 Characterisation of Eckhardt filter constant 'a' for the Mangahahuru Stream.

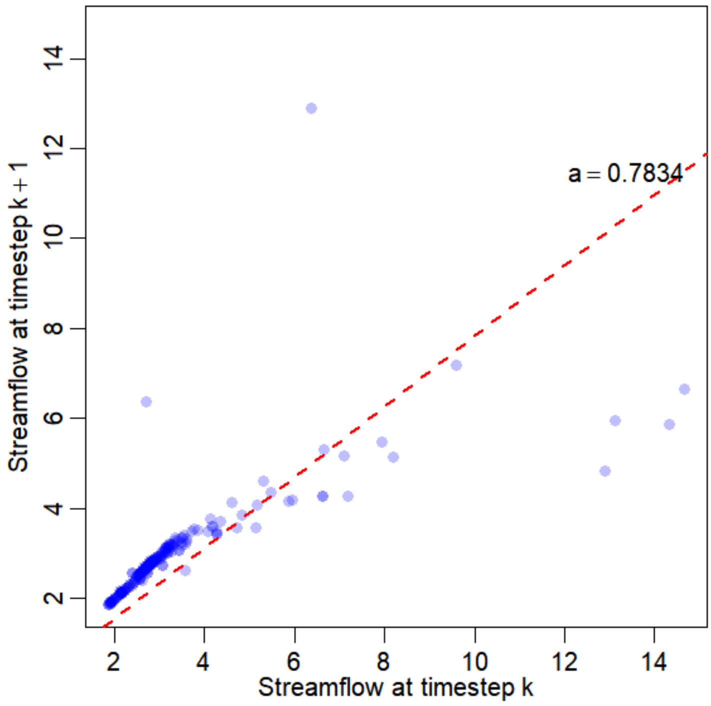

Figure A5.4 Characterisation of Eckhardt filter constant 'a' for the Oraka Stream.

A5.3 Daily Mean versus 400-Day Rolling Mean Curves

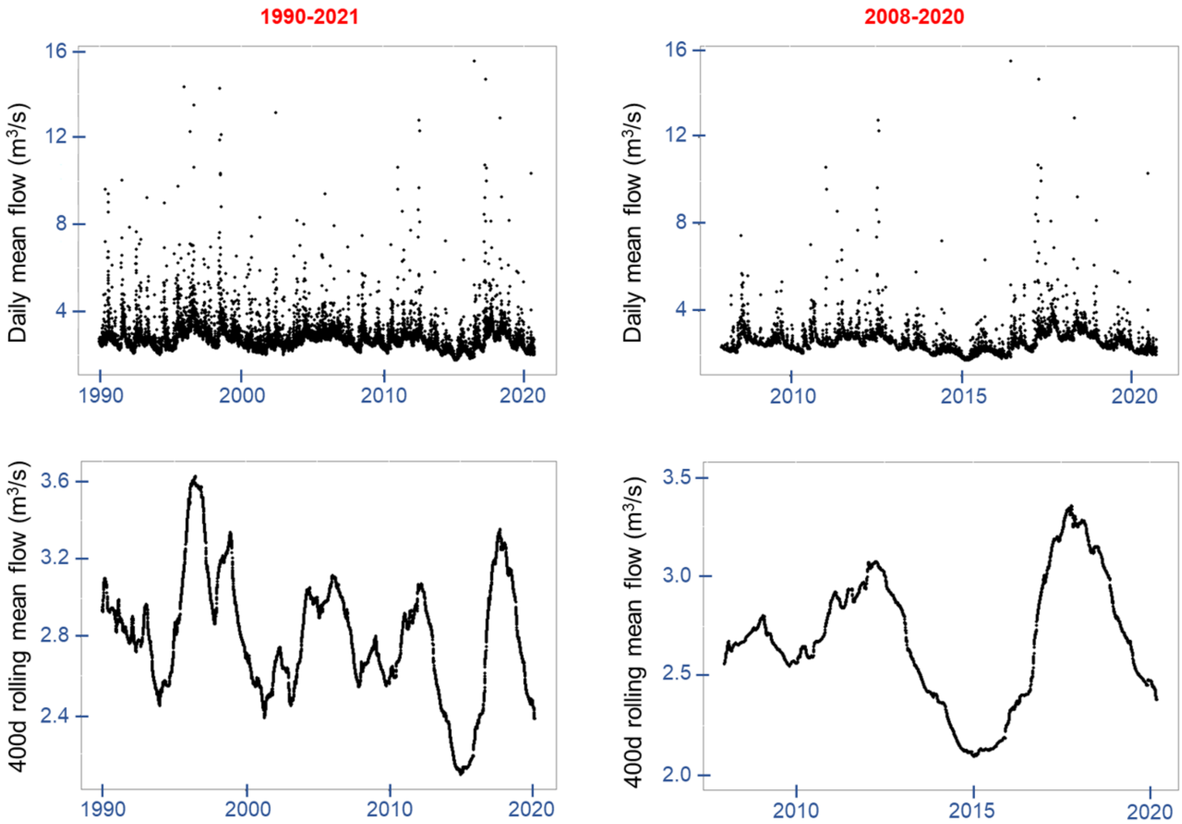

Figure A5.5 Comparison of daily mean flow plots and 400-day rolling mean flow plots for the Oraka Stream over the 1990–2021 and 2008–2020 periods. The scale of the Y-axes was adjusted for the rolling mean plots for readability.

APPENDIX 6 UAV AND SENTINEL-2 NDVI IMAGES

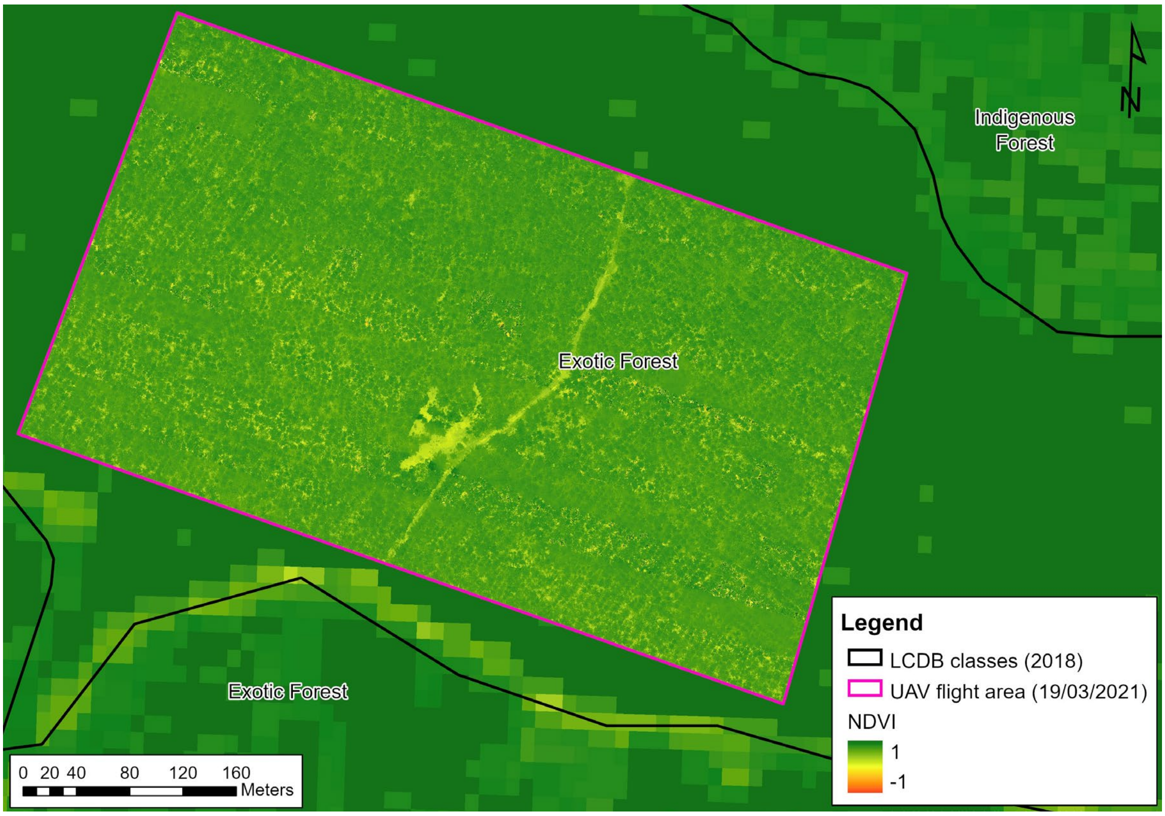

Figure A6.1 Overlay of NDVI images derived from Sentinel-2 image (19/02/2021; background), UAV image (19/03/2021; foreground) and LCDB 2018 cover classes for the Sutcliffe Road site, Oraka Stream catchment.

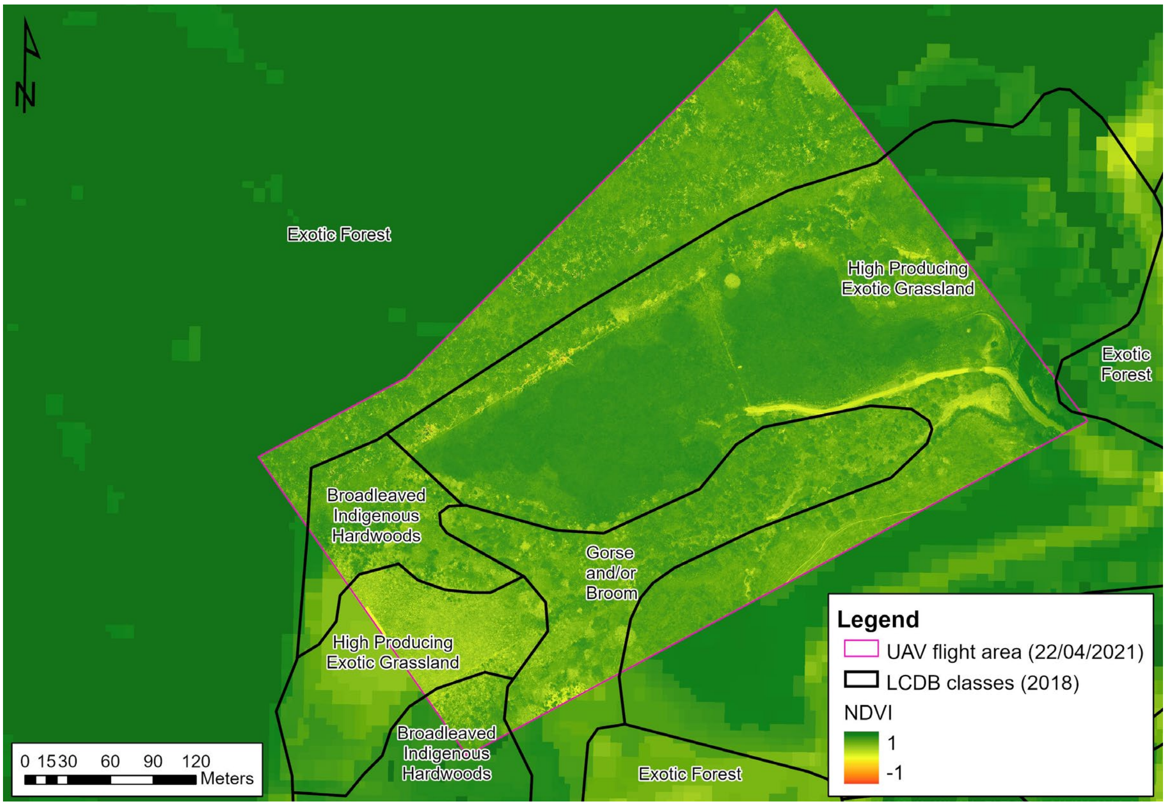

Figure A6.2 Overlay of NDVI images derived from Sentinel-2 image (3/05/2021; background), UAV image (22/04/2021; foreground) and LCDB 2018 cover classes for the Mangahahuru Stream catchment, lower area.

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