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Assessment of nature-based flood management (NBFM) approaches in the upper Waimatā Catchment, Gisborne

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Abstract

This research evaluates the impact of nature-based flood management (NBFM) solutions in the upper Waimatā Catchment in Gisborne, New Zealand. The Soil and Water Assessment Tool Plus (SWAT+) was used to model the hydrological relationships and processes that define the catchment today. SWAT+ was then used to test the effective reduction in peak flow volumes for an 85-percentile event, as well as the effective reduction in volumetric sediment transport associated with the range of NBFM interventions proposed. A spectrum of small to larger scale interventions are evaluated to support targeted catchment planning efforts in the future. A peak-flow reduction of ~35% was observed for an intervention comprising wetlands (runoff attenuation features (RAF)) and strategic retirement of 'unsuitable' land to native broadleaf forest (Jessen et al, 1999). A peak flow reduction of ~35% translates to a ~74% reduction in bedload volumetric sediment transport. Findings from this study offer a perspective and rationale for scaling the current forest and wetland management efforts in the upper valley to achieve a reduction in flood risk that is commensurate with the scale of intervention. The solutions proposed also simultaneously address erosion issues while providing ancillary water quality treatment, biodiversity enhancement and steering for potential biogeomorphic recovery pathways.

Key words: *floodscapes, catchment hydrology, nature-based flood management, SWAT+ water modelling, applied fluvial geomorphology*.

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Chapter 1 Introduction

1.1 Global context – nature-based flood management (NBFM)

Water plays a multifaceted role in the landscape, essential for both the emergence of new life, and for sustaining and supporting existing ecosystems and communities. Across many regions worldwide, the natural flow of water has been significantly altered by human development, including both historic and current land use activities (Fryirs and Brierley 2012; Forest and Bird 2022; Hack and Schröter 2021). Flooding, despite being a natural process, is often exacerbated by human factors. Water passage over land is often sped up and re-routed in catchments where significant vegetation clearance has taken place; where impervious areas such as roads or buildings are developed; or where the river itself has been laterally constrained or channelised (Fryirs and Brierley, 2012). It is in these catchments, typically in urbanised or agricultural lowland areas, where flooding 'impacts' are realised. According to the Emergency Events Database (EM-DAT) from the Centre for Research on the Epidemiology of Disasters (CRED), flooding disasters caused an annual average of 5,518 deaths worldwide from 2003 to 2022. However, in 2023 alone, flood-related deaths increased significantly to 7,763 (CRED, 2023). Each year, an average of 75.6 million people are affected by floods, with associated damages costing an estimated 41.1 billion USD annually (CRED, 2023). In addition to developmental change, climatic changes due to increasing greenhouse gas emissions are expected to 'substantially increase the severity and frequency of the risk of flooding' (Forest and Bird 2022). The scope of these issues is complex, multi-scalar and requires 'systems-thinking' approaches (Piegay and Lamouroux, 2017).

To mitigate the impacts of fluvial and pluvial flooding, tactful, place-based interventions are required to balance the passage of water in supported and adjacent ecosystems, and to protect community values within a given catchment. The implementation of NBFM is an emerging field worldwide, showing great promise in redefining traditional approaches by working with river dynamics to mimic historical hydrology and manage flood-related impacts (Wren et al., 2022; Merz et al., 2010). This research looks to evaluate possible NBFM approaches in the Waimatā catchment, Gisborne (Tairāwhiti), New Zealand.

1.2 Project study area - site context - Waimatā

During early phases of European settlement (1865 – early 1900s), the hydrological and geomorphic regimes of the wider Tairāwhiti landscape were altered in significant ways through processes of land clearance and land cover conversion (Salmond, 2016). Today, Waimatā locals face immediate meteorological hazards associated with flooding, erosion, landslips and fluvial aggradation/deposition in the lower reaches of the catchment.

By 1865, large portions of the Waimatā catchment were surveyed and sold off (Gundry, 2017). Intensive deforestation, exotic forestry, and agriculture in the late 19th century had lasting impacts on river hydrology, marked by severe flooding events such as in March 1880 and May 1916, which led to extensive sedimentation and harbour shallowing (Grundry, 2017). The sense of identity and belonging that the Waimatā catchment offers to mana whenua (local Māori) was, and is, challenged by the ecological, physiographic and spiritual imprint of this colonial land use history (Thomas, 2024; Brierley et al 2022).

The Waimatā Catchment (226 km^2) drains into and is a tributary of the Tūranganui River (shortest river in the country at 1200 m long). The Waimatā adjoins the Taruheru River near Gisborne City, before transitioning to the Tūranganui River which flows directly into Tūranganui-a-Kiwa (Poverty Bay) (Figure 1) (Cullum, Brierley & Marden, 2017). The main channel of the Waimatā River meanders through terrace-confined valley settings. In both the upper and middle reaches, it is deeply incised due to 'flashy' flood events, and resultant downcutting into highly erodible Holocene valley fill material (sandstone and mudstone deposits) (Marden et al., 2014). Today, the Waimatā catchment still has significant blocks of active forestry (*Pinus radiata*), as well as active hill country beef and sheep farming. The upper Waimatā catchment is dominated by exotic grassland (50.6%) and plantation forestry (29.8%), with smaller areas of native scrub (7.6%), broadleaf forest (4.9%), and deciduous hardwoods (2.4%) (Landcare Research, 2019). Fast-response flooding will continue to generate high sediment yields, carry forestry debris (slash), and disrupt both human and ecological communities if management actions do not intervene at the root of this issue.

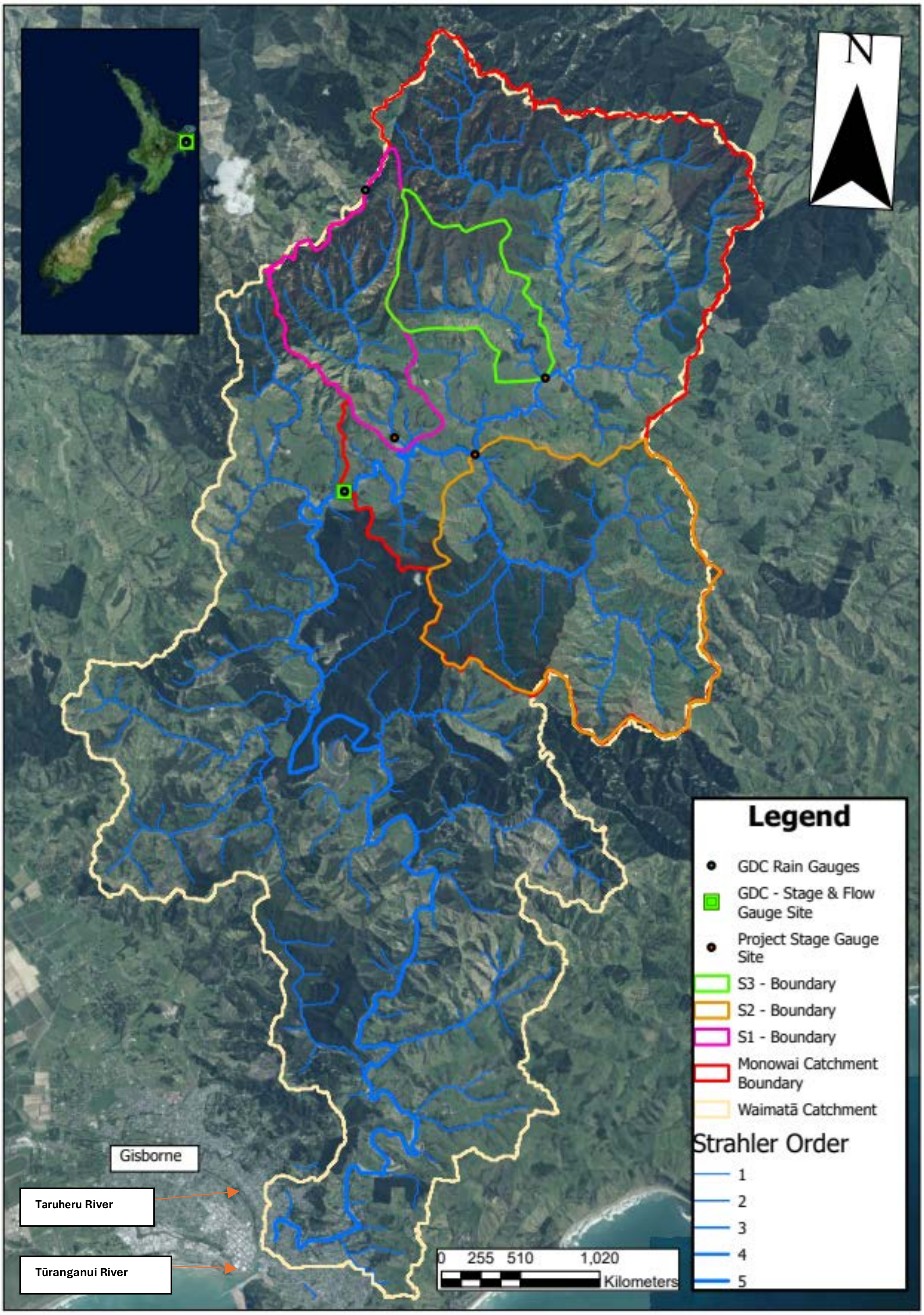


Figure 1 The Waimatā Catchment

The Waimatā Catchment experienced significant flood damage from both ex-tropical Cyclone Gabrielle (2023) and Bola (1988). During Cyclone Bola, over 800 mm of rainfall was recorded over 4 days, which was the largest event ever recorded in the North Island of New Zealand (at the time). On the 13-14th of February 2023, ex-tropical Cyclone Gabrielle hit Tairāwhiti causing widespread destruction. During Gabrielle, 250-400 mm of rain was estimated to have fallen over the region, with the Waimatā rain gauges collecting 257 - 310 mm of rain in 48 hours (MetService 2023; Figure 1). Damage included the destruction of municipal water infrastructure, bridges, and homes; prolonged power outages lasting weeks; and widespread inundation of silt and forestry debris across beaches, productive land, and roads (RNZ, 2024; GDC, 2023; Figure 2).

Figure 2 Photo mosaic of flood damage in Tairāwhiti (source: Thomas, 2024; NZ Herald, 2020)

The impacts of flooding are directly related to the land use history of the catchment and the resultant changes to hydrological responsiveness (efficiency of water conveyance). The current extent of pasture and exotic forestry land use have shown to directly influence the hydrological responsiveness of sub catchments in the Waimatā (Burgess, 2023). The hydrological impacts of land use change in the Waimatā Catchment are now well-documented, and frustrations about a clear path to recovery and industry accountability have been expressed in the affected community (Gundry, 2017; Salmond, 2016; RNZ, 2024). Work is needed to evaluate the hydrological influence of specific and practicable NBFM interventions, considering subbasin sensitivities and maximal impact for investment long-term (Fuller et al., 2023; GETS 2024; Cairns, Brierley & Boswijk, 2021).

1.3 Research aims

The main objective of this research is to develop and evaluate practicable nature-based flood management (NBFM) options for the Waimatā River, Gisborne. The first step is to model and understand the catchment hydrology of the upper Waimatā River (Figure 1). Interventions in the upper catchment would seem to offer the greatest potential for generating a beneficial cumulative impact and for improving conditions in the lower valley (Wren et al, 2022; Fuller et al 2023).

In the case of the upper Waimatā, a judiciously selected and well-calibrated model will offer some insight into the relative effectiveness of specific NBFM interventions, taking into consideration localised variation in soil, topography, current land cover and rainfall. This research will build upon work by Burgess (2023) in evaluating sub-basin hydrological sensitivity and highlighting areas with the highest potential for positive outcomes following specific NBFM interventions. The time constraints on this research have allowed for only informal community consultation and consideration of current catchment planning initiatives. For this reason, the study assesses a spectrum of NBFM interventions (smallest –to largest effort) with the hope of informing and supporting future management actions.

With conversion of developed land back to either shrub or native forest, flood peaks, bank erosion and transport of bedload sediments (including woody debris/slash) could be reduced over management timeframes (~5-10+ years) (Burgess, 2023, Jones et al, 2022). Furthermore, the reinstatement of wetland systems within the upper reaches has potential to influence the rate and quantity of peak runoff during flood events (Fennel et al 2022; Nicholson et al 2012; Wren et al, 2022; Auckland Council, 2016).

This research seeks to understand the relative influence of current and potential landcover extents on the hydrological regime in the upper Waimatā catchment. Prospective landcover planning will be based on Landcare Research land use capability (LUC) mapping of the region (Jessen, 1999; Landcare Research, 2023). This study will evaluate the relative influence of different land use arrangements (including RAFs) on cumulative flood peaks by comparing changes across the modelled hydrographs (pre- and post-intervention). Specific RAF interventions are developed using NIWA's technical guidelines for constructed wetlands (NIWA, 2021). The RAF interventions are designed to achieve flood control while also providing water quality treatment and extending a critically endangered freshwater habitat type (Salmond, 2016). The effective reduction of flood peaks for the design event will be translated into an ad-hoc estimate of the effective reduction in volumetric bedload sediment transport (%). The reduction in geomorphically effective work presents an empirical insight into the potential for NBFM to influence the current biogeomorphic trajectory of the Waimatā (Fryirs, 2024).

The research question posed is:

Can strategic conversion of land use (including RAFs) change the flood peak magnitude of event-based flooding as recorded at the Monowai bridge monitoring station?

The hypothesis for this test is that selective land use conversion will result in:

a) a 15% reduction in flood peak at project gauge sites (compared to observed).
b) a reduction in bedload sediment transport at Monowai (~20%).

The modelled interventions explored in this research are provided in Table 1.

Table 1 Modelling Simulations proposed to test NBFM.

	W0	W1
T0	Baseline (calibrated model)	Wetland interventions (15.7 ha)
T1	LUC Class 8 - converted to native broadleaf forest	W1T0 + W0T1
T2	LUC Class 7 & 8 - converted to native broadleaf forest.	W1T0 + W0T2
T3	LUC Class 7 & 8 - as above. LUC Class 6 - converted to selective 'mixed' forestry.	W1T0 + W0T3
T4	LUC Class 7 & 8 - as above. 30 m - riparian buffer.	W1T0 + W0T4

Note*: further information about the wetland design and site selection process is provided in Appendix A.*

Chapter 2 Literature review

2.1 Introduction

This section outlines and synthesises key literature on the topic of NBFM and modelling assessment frameworks, both across NZ and worldwide. The section will cover key aspects of the hydrological cycle and how these are understood during the scoping, model parameterisation and operational refinement stages of NBFM intervention. The following topics are covered in sequence:

- Modelling the influence of land use on hydrological responsiveness
- NBFM approaches
- Quasi-estimation of reduced bedload sediment transport under NBFM scenarios
- Geomorphic trajectories – NBFM
- Modelling frameworks – selection process
- Current research gaps – *floodscapes* and their management

Overall, the review highlights established and emerging techniques, as well as operational learnings from river managers, practitioners and scientists from the past 20 years.

2.2 Modelling the influence of land use on hydrologic responsiveness

Urbanisation, cyclic exotic forestry operations and agricultural/pastoral land use are responsible for significant changes to river systems in Aotearoa and worldwide (Larned et al., 2020). Land use changes alter the runoff characteristics by altering the path of water to the channel network. Modelling of these processes requires accurate representation (parameterisation) of the physical processes which constitute these stark differences in water storage and transport.

The roughness elements in the landscape (i.e., forest canopy, understory, grasses, woody debris, soil condition) act as resistance features working to delay the concentration of water flows through the landscape (Beven, 2012; Wren et al, 2022). Therefore, the configuration of land use in a catchment has a direct influence on the extent of alteration to the historic flow regime (in addition to local scale factors such as geology, soil depth, ecology and changing climate) (Gao and Yu, 2017). Change of land use can lead to additional modification of the following processes: infiltration (soil compaction), canopy effects (throughflow, interception, stemflow, evapotranspiration (ET)) and erosion (soil texture, soil depth). In addition, the impact on these processes changes through time, and in response to specific land impacts as well as weather trends. The complex influence of landcover change on flooding is illustrated by the conceptual diagram in Rogger et al., (2017) (Figure 3).

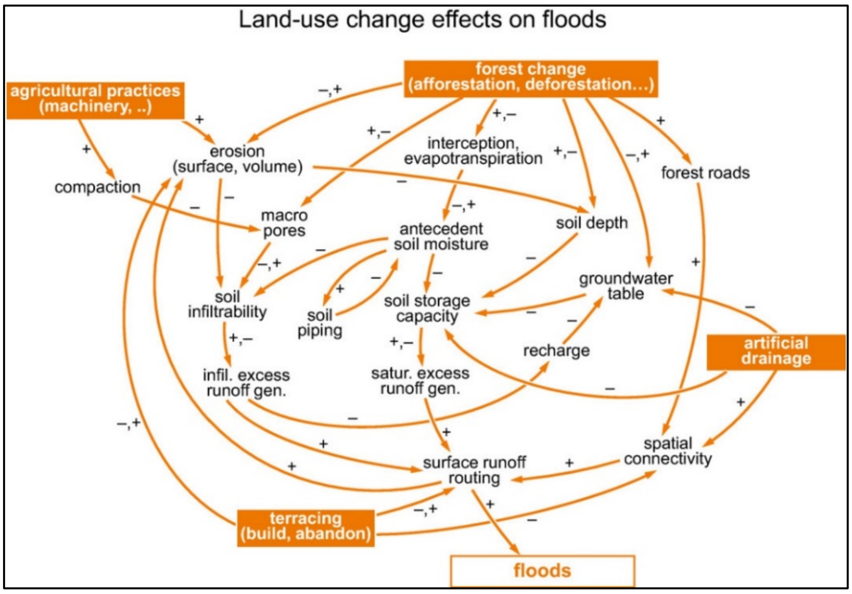


Figure 3 Pathways and feedbacks that govern flood magnitude (Rogger et al., 2017)

2.2.1 Infiltration

One vital aspect of understanding land use conversion hydrology is understanding the influence that land use activities have on soil permeability, both in the short and long-term. Research by Hansson et al (2019) conducted in the Boreal Forests of Sweden outlines the impact that forestry traffic has on soil water transmissivity, specifically hydraulic conductivity and bulk density. They found that soil water content was highest in vehicle tracks, indicating that soil compaction (mechanical) decreases the key properties of total porosity, pore connectivity and saturated hydraulic conductivity (‘K_{sat}’) (Hasson et al., 2019; Hasson et al., 2018; Ebeling, Lang & Gaertig, 2016). Ebeling et al. (2016) found that bulk density in compacted soil groups remained significantly higher than in unimpacted control sites, even 10-20 years after traffic flow had ceased along the routes.

Compacted soils are typical of agricultural land use (trampled by livestock), urban land use (mechanical) and forestry (degraded soils – cessation of microbial and faunal aeration processes, homogenous root systems) (Alaoui et al, 2018). Kim et al. (2010) found that an 8% increase in bulk density and a 69% reduction in K_{sat} would translate to increased surface runoff in silty loam substrates. Similarly, a study in the Devon River (UK) had observed a 53% conversion of rainfall to surface runoff with grazed pastures, compared with a 7% conversion when land was left ungrazed. The above literature suggests that soil infiltration is greatly influenced by land use practice and remains a highly sensitive parameter in land use modelling approaches. Using the SWAT model, Burgess (2023) identified moist bulk density, saturated hydraulic conductivity and curve number (CN2) as key sensitive parameters in representation of the hydrological processes defining Waimatā Catchment. Similarly, Kumar et al., (2017) identified K_{sat} as the second most sensitive parameter (second to CN2).

CN2 (or SCS curve number) is a parameter in hydrological modelling representing how rainfall is divided between runoff and infiltration, specific to each soil and land cover combination. This approach is popular as CN2 values can be derived from observed flow across various catchments and events. In semi-distributed models like SWAT/SWAT+, CN2 is dynamically updated during rainfall events by referencing the gamma unit hydrograph (GUH), which tracks effective rainfall for each hydrologic response unit. The 'cn3_swf' parameter further adjusts CN2 based on soil moisture conditions, informed by GUH positions. Curve numbers have been modelled for diverse land cover and soil types, making this method widely used in SWAT, SWAT+, and TOPMODEL (Beven, 2012; Burgess, 2023). A key limitation of the curve number approach is the uncertainty of antecedent soil moisture at the start of simulations, often addressed by including a warm-up period. Additionally, CN2 values can vary with storm size and slope (Ajmal et al., 2016).

2.2.2 Roughness elements

Another vital component of land cover hydrology is understanding the variability in both terrain and channel roughness. Terrain roughness influences the resistance acting on overland flow and influences the effective time of concentration at the channel outlet. Similarly, channel roughness is a direct control on the speed of flow transportation through the channel network. Accurately representing these parameters in a model is often a key step in calibration (Kumar et al., 2017; Kalyanapu et al., 2009). The Manning's roughness coefficient (n) is a commonly used approach for characterising a surface resistance factor for different landcover settings (Dingman, 2009). Kalyanapu et al. (2009) suggest that the simplification of terrain roughness by land use type is a significant source of uncertainty in common hydrological models. They derive a spatially continuous representation layer of (n) and compared flood peak results to that of the aggregated land cover input. The results translated to a ~13% difference in flood magnitude and a 16% difference in peak timing for smaller catchments (23 km^2) (Kalyanapu et al., 2009). They suggest that for medium to large catchments the default land cover (n) values return acceptable and comparable results to the manually derived values (Kalyanapu et al., 2009).

Kumar et al. (2017) modelled the Tons River Basin (17,000 km^2) in India using SWAT, they found that overland flow roughness (ov_n) was more sensitive than channel roughness (ch_n) for the predominantly agricultural catchment. However, with respect to other parameters, ovn_n and ch_n were not considered sensitive (10^{th} and 18^{th} most sensitive respectively). Being a very large catchment, this result concurs with what was discovered by Kalyanapu et al. (2009).

Manning's coefficients for typical land cover types in the landscape can be referenced from literature (Dingman, 2009). Additionally, the modeler may conduct targeted measurements of channel roughness by accounting for particle size distribution (PSD) on the bed (Dingman, 2009). The Strickler Equation (Eq.1) is a common method for translating median particle size into a skin friction value, aiding in the assessment of hydrological resistance (Strickler, 1923, as cited in Dingman, 2009).

$$n_M = 0.0150 * D_{50}(mm)^{1/6} \qquad (1)$$

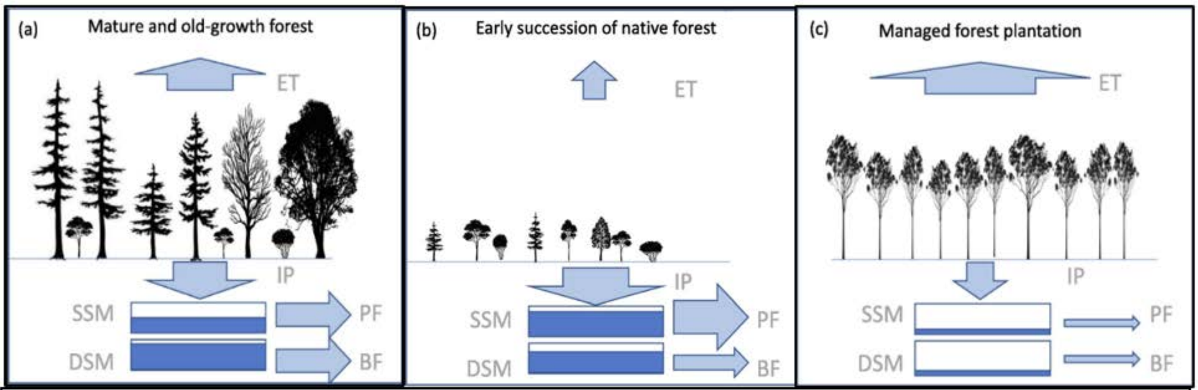
Several empirical formulas exist for accounting skin friction effects from sediment size; however, these all vary based on the specific intended application. Some use D_{90} and some are specific to grain size ranges (classes). Although for Strickler-type equations, experience has shown the computed values tend to be smaller than actual values (Dingman, 2009). This is for several reasons, including the variable exposure to fining sediment sizes as water levels rise in a channel, vegetation effects on roughness, geomorphic units and armouring effects resulting in wider PSD (Dingman, 2009; Fryirs & Brierley, 2012). The above equation is suited to uniform gravels and sands and uses the D_{50} (median) particle size (Dingman, 2009).

Topographic roughness (including channel, terrain, and land cover) is closely linked to catchment geomorphic evolution (Doane et al., 2024; Fryirs et al., 2023). In this study, roughness is viewed as a balance between roughening and smoothing processes, tied to the current hydrological regime and geomorphic trajectory (Doane et al., 2024). Examples include pool-riffle sequences prior to sediment infilling after floods or woody debris that gradually breaks down. Doane et al. (2024) emphasises the temporal changes in roughness elements that may introduce significant uncertainty in long-term modelling.

2.2.3 Vegetation effects on hydrology

Land-use effects have myriad interactions with water-balance and thus, flood dynamics. Several studies in New Zealand have focused on the implications of canopy changes on catchment hydrology. Beets & Oliver (2007), Hughes et al (2020) and Duncan (1995) assessed the differences in hydrology between forested and non-forested catchments in New Zealand. Beets & Oliver (2007) compared pasture, indigenous evergreen forest and exotic forestry (*Pinus radiata*) in the water yield they produce in the receiving channel network. Annual flows from pine catchments were found to be 400mm lower than pasture after the canopy filled out (160-260 mm average). The study highlights the temporal variability of rainfall interception, throughflow, evaporation and ET with tree growth and similarly, harvest (Beets & Oliver, 2007). Their findings suggest that pine stand leaf area index (LAI) is linearly related to evaporation and ET, but this was not statistically significant for transpiration rates. Similarly, Hughes et al (2020) found that seven years after converting 62% of an upland pasture catchment to pine, peak river flows were reduced by ~50%.

Active forest management and restoration of marginal scrub forest to stages of secondary succession have marked implications for hydrological response. Jones et al (2022) define forest restoration along primary objectives of 1) establishing new forest 'reclamation', 2) achieving structure, composition, or ecological process goals 'rehabilitation', or 3) conversion of land from other land use activities to native forest 'reconstruction'. Notions underpinning forest 'restoration' include the return of an ecosystem back to a pre-disturbance state, thus assuming stationarity of boundary conditions that control forest development. Most forest restoration efforts are targeting increased canopy cover; however, effective interception by canopies has been shown to vary with precipitation (event-magnitude and duration), tree density, species composition and understory structure (if any) (Jones et al, 2022; Figure 4).



ET = evapotranspiration (transpiration and evaporation from the canopy and soil), including of water intercepted by the canopy, IP = infiltration and percolation into the soil, SSM = shallow soil moisture in the rooting zone, DSM = deep soil moisture/ shallow groundwater, PF = peak flows, BF = base flow.

Figure 4 Generalised model of water budget associated with forest types (source: Jones et al, 2022)

A systematic review by Bonnesoeur et al. (2018) found that forestation efforts significantly impacted degraded soil by reducing surface erosion and mitigating moderate floods. Forestation increased soil infiltration rates eightfold, though soil water storage and surface runoff did not fully recover to native forest levels within the 20-year timeframe (Bonnesoeur et al., 2018). This suggests that previous land use duration and type are key determinants of a site's hydrological and ecological recovery potential.

Pearce et al. (1987) studied the hydrological effects of exotic reforestation with *Pinus radiata* just before Cyclone Bola. They found that average soil water content was lower under pine forest compared to pasture, with soil moisture remaining high for 6-8 months under pasture but only 3-4 months under pine. Rowe (1999) conducted a 3 year-long study on regenerating kānuka (*Kunzea robusta*) forest hydrology in the Waimatā catchment. Their study found that this common pioneer native typically resulted in 57% throughfall (water hitting the ground) and 1% stemflow, leaving 42% as interception losses (i.e., evaporation off tree structures). This was shown to be comparable to the rainfall attenuation capacity of a closed stand of *Pinus radiata* (exotic). In Tairāwhiti, kānuka is a primary coloniser of landslide scars (successional species) and is actively planted as a precursor to tall forest restoration projects (Rowe 1999). Similar research has been done in Taitā (NZ) for mānuka (*Leptospermum scoparium*), with results showing that 40-50% of the rainfall hit the ground as throughfall and 39% was estimated as interception losses across multiple observed events (Aidridge and Jackson, 1968).

These papers highlight the variable effect of planted species on resultant hydrological response across a range of settings. The age of the stand and the species composition determine the water yield from the forest system, with exotic pine forest reaching native pre-clearance levels after approximately a decade (for some settings). This is a major source of model uncertainty due to the lack of data on tree stand ages and the complex mosaic of successional layers in native broadleaf and deciduous systems.

2.3 Nature-based flood management

Traditional flood protection methods often include static, hard-structural approaches to increasing flood conveyance, storing flood waters and protecting sensitive receptors (Fryirs et al, 2023). Examples of these include stop banks, detention basins, levees dams and culvert/piped solutions – all of which are expensive to install/maintain, are linked to poor environmental outcomes and give the community a false sense of permanent and infallible flood protection (Fryirs et al, 2023).

Nature-based solutions (NBS) or nature-based flood management (NBFM) are emerging approaches in catchment science, focused on reducing flood risk by working with natural processes (Wren et al., 2022). These measures are place-based and often implemented at scale (Figure 5). Interventions in the upper catchment are shown to generate cumulative benefits downstream (Wren et al., 2022; Fuller et al., 2022).

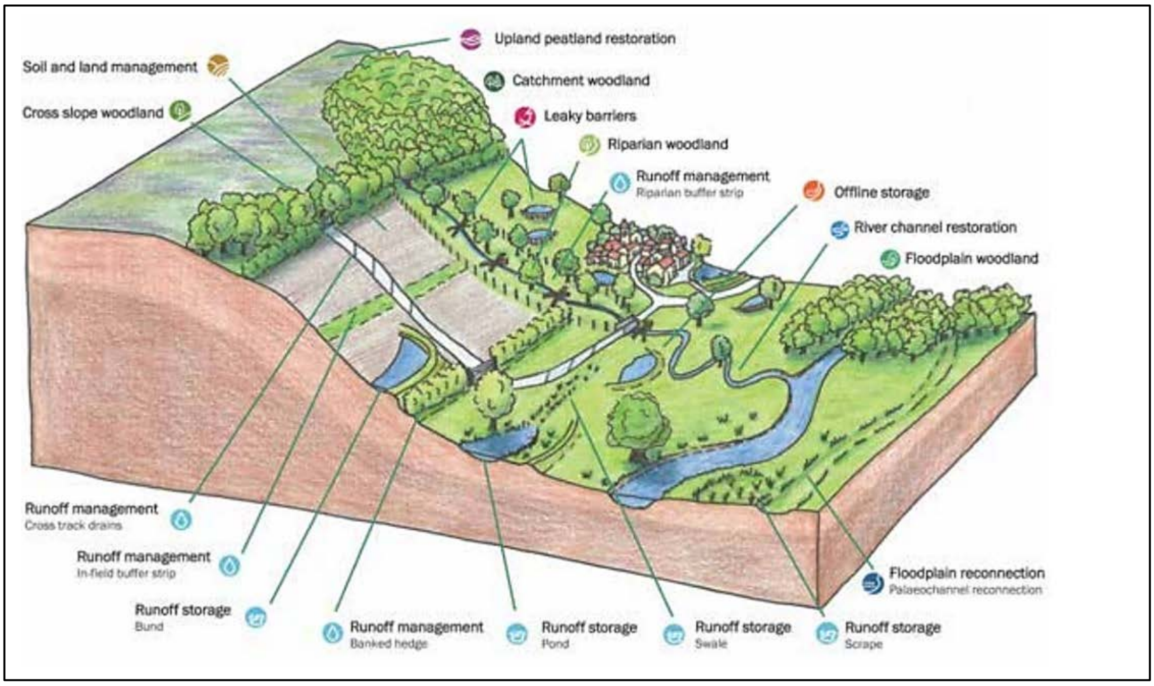


Figure 5 NBFM – common approaches (source: Wren et al, 2022)

Nature-based flood management strives to achieve one of three outcomes (Wren et al, 2022):

1) **Protect** – steps to retain things in the current landscape that are functioning well in terms of natural processes.
2) **Restore** – work at the source of the problem and reinstate hydrological processes across the landscape.
3) **Mimic** – discrete features that work to emulate natural hydrological processes to achieve flood risk reduction (i.e., stormwater detention).

Modelling framework approaches aimed at evaluating NBFM performance take many forms. They are often paired with field verification data and enable the continued refinement of approaches amongst the backdrop of local epistemic uncertainty. Examples such as those applied in: Fennell et al (2022); Nicholson et al (2012) and Agarwal et al (2023) take this approach. *See* Appendix B for further information.

2.3.1 Runoff attenuation features (RAF)

Nicholson et al. (2012) evaluated offline diversion ponds using adaptive management, starting small and scaling up over 20 years with ongoing monitoring and adjustments. Their goal was to create 20,000 m^3 of transient storage in the upper Belford Burn catchment, England. Although only half was achieved, results showed clear modulation of flood hydrographs. The study highlights the importance of defining specific goals for runoff attenuation features (RAF) with 'dead storage' designed to fill only during targeted flow events (Figure 6; Auckland Council, 2016).

Salmond (2016) highlights the historic extent of natural wetlands in the Waimatā and Tairāwhiti, noting their significant reduction following drainage by European settlers in the late 19th century. LCDB data indicates that wetlands now cover just 1.75% of their original area in the Gisborne Region (LCDB, 2014, cited in Salmond, 2016). The report calls for wetland reestablishment on flats and damp gullies in the Waimatā, recommending constructed wetlands to trap sediment, filter nutrients, and control flooding. NIWA guidelines suggest converting 1-5% of the contributing catchment area to wetland to achieve significant water quality and hydrology benefits (NIWA, 2021; *See* Appendix A & B for further details on background for wetland intervention design for this project).

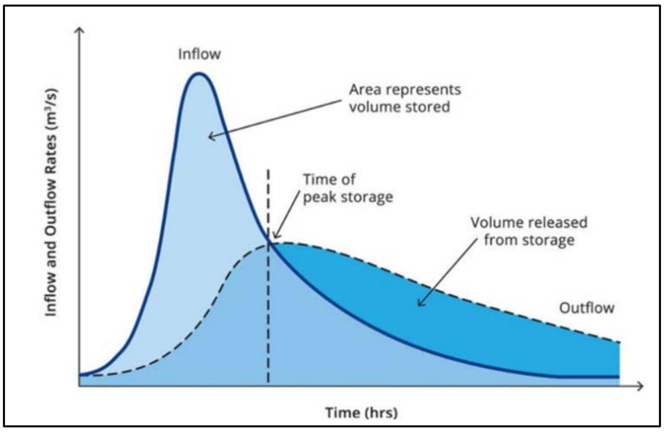


Figure 6 Conceptual flood hydrograph after adding runoff attenuation features (RAF) (dark blue) (source: Auckland Council 2016)

2.3.2 Strategic revegetation of unsuitable land use

Critical review of existing land use activities forms an integral part of NBFM development for soil and land management. Wren et al, (2022) present an international manual for NFM which includes various forms of strategic revegetation of existing pastures/cleared land (Figure 5). The hydrologic rationale for revegetation differs depending on catchment position (i.e., riparian, upland, soil type, rainfall and flow routing) (Figure 5). As discussed in Appendix C, there are ways of approaching land conversion that fulfil multiple goals (i.e., ecological, social and economic values) (Jones et al, 2023).

Wren et al (2022) highlight the importance of designing measures with a consistent approach that identifies and actions upon known issues and opportunities in the catchment. Measures should look to maximise co-benefits by leveraging knowledge of land-limiting factors (i.e., erosion, flooding) and legacy issues. Following ex-tropical Cyclone Bola (1988), concerns of deforestation-induced erosion (gullying, landslides) led to the establishment of several exotic forestry operations on steep hill country blocks in Tairāwhiti which were subsidised by government soil conservation initiatives in the 1990s (Cullum, Brierley and Marden, 2017). Legacies of past land use continue to shape the Waimatā River today – approaches are needed to identify strategic places to approach NBFM design, considering catchment setting but also current land limitations and economic importance. At the regional scale, Manaaki Whenua has categorised and mapped land parcels into eight classes based on long-term land use capability (LUC) (Landcare Research, 2023). LUC mapping identifies physiography, rock types, soils, and erosion susceptibility of landscape units across Tairāwhiti (Jessen et al., 1999), providing insights into agricultural and forestry productivity limitations (Jessen et al., 1999; Landcare Research, 2023). This objective, region-specific framework offers a valuable foundation for developing a coherent NBFM strategy that maximises co-benefits.

2.4 Quasi-estimation of reduced bedload sediment transport under NBFM

River adjustments (morphodynamics) result from sediment movement driven by water flow or wind forces. Zanke & Roland (2020) review 13 common sediment transport functions to aid in selecting appropriate models across varying settings. Similar to Strickler-type equations, numerous sediment transport approaches exist, often creating overlap and complicating the choice for practitioners. Zanke & Roland (2020) found core differences among these functions in their handling of bed-load critical entrainment velocity and applicability to single or multiple sediment classes. They also observed that the non-linear relationship between shear stress and flow depth varies with particle size distribution (PSD) (Zanke & Roland, 2020; Wilcock, Pitlick, & Cui, 2009).

Generally, the 13 transport functions are variations on a single formula with differing simplifications, so model selection often depends on available input and validation data. If PSD is measured at only one point along the river, a D_{50}-based function may be best for qualitative transport rate interpretation. However, D_{50}-only approaches simplify the 'incipient motion' of mixed-sized sediment, potentially overestimating transport due to unaccounted armouring/packing effects (Wilcock, Pitlick, & Cui, 2009). The following approaches were reviewed for their suitability in calculating ad-hoc reductions in volumetric sediment transport for the upper Waimatā:

- Meyer-Peter Müller (1948) (Zanke & Roland, 2020)
- Parker, Seminara, and Solari (PSS) (2003) (Zanke & Roland, 2020)
- Wilcock and Crowe (2003) (Wilcock, Pitlick, & Cui, 2009)
- Einstein-Brown (1950) (Wilcock, Pitlick, & Cui, 2009).

2.5 Geomorphic trajectories – altered hydrology through NBFM.

Each river system retains a unique landscape memory, shaped by the geological, land use, and climatic events that have unfolded over time. These events translate, in physical terms, into distinctive changes in the boundary conditions that control the balance of system adjustments, or process-form relationships. Within this framework, the legacy of catchment changes shapes a river's evolutionary trajectory, linking past and future and enabling the interpretation of 'river trajectories' (Fryirs and Brierley, 2012).

Within the relatively short 'steady' timeframes of months to years, a river system structure (geomorphic form) represents largely the physical characteristics of the valley and the amount of water energy it receives. However, over periods of years to decades, significant system adjustments are observable in response to land use changes (Fryirs et al 2023; Fryirs 2024). A shift in trajectory is the product of emergence – the complex interaction between hydrological and geomorphic elements creating system feedbacks. As shown in the examples above, land cover conversion can significantly influence water yield, erosive power, and sediment load within a catchment. Thus, persistent or large-scale changes in water discharge and sediment supply impact geomorphic behaviours, such as landslides and channel adjustments (Liébault et al., 2005). Over time, these changes can alter the hydrological cycle through positive feedbacks, including:

- Increasing channel surface area exposed to the water table through incision, further concentrating flow.
- Modifying skin friction and surface roughness within and outside the channel, affecting erosion and deposition.
- Hillslope erosion and landslides creating new preferential flow pathways.

As discussed above, roughness elements can be considered the product of competing smoothing and roughening forces (Doane et al, 2024). Thus, changes to the hydrological regime through implementation of NBFM may result in a corresponding shift in coarsening and smoothing relationships over time. Fryirs (2024) discusses the important considerations for planning of biogeomorphic recovery. Development of assisted biogeomorphic recovery approaches should include process-based planning with an appreciation of the resultant impact of interventions on the processes currently underpinning river adjustment (Fryirs, 2024). Biogeomorphic recovery specifically looks at the interplay between vegetation and river structure, with 'assisted' actions comprising intentional planting and seedbank restoration efforts in the context of long-term trajectories (Fryirs et al 2024).

2.6 Modelling frameworks – selection process

Hydrological modelling is an abstraction of reality, often used to address specific questions about complex natural systems (Beven, 2012). Models help answer questions that physical measurements alone cannot, such as predicting the impact of future management actions or understanding process interactions across large or remote areas (Horton et al., 2022). Beven (2012) conceptualises the modelling process as beginning with the hydrologist's initial question (the perceptual model), then translating it into an approximate simulation (Figure 7).

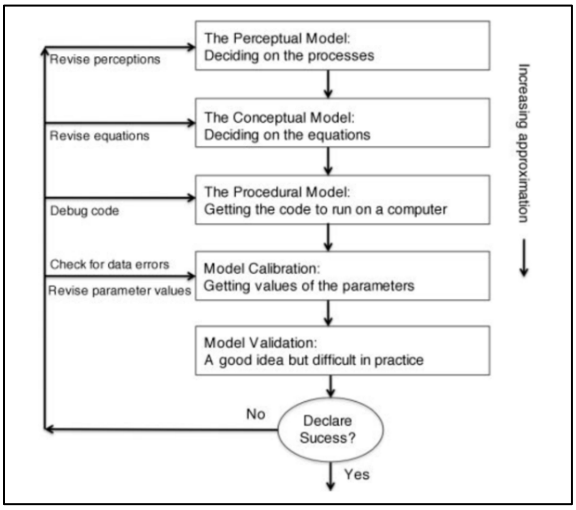


Figure 7 Conceptual steps to modelling process (source: Beven 2012)

Hydrological modelling for rainfall and runoff analysis has historically been constrained by data availability (Blöschl et al., 2024; Beven, 2012; Kumar, 2017). Real-world data is essential for parameter inputs and calibration/validation, making data availability a primary factor in model selection. Additionally, model selection must align with the research question and intended analysis, while considering technical feasibility for both the project and modeler. The goal is to transparently document the learning process rather than follow a rigid stepwise approach (PCE, 2024). To begin model selection for this research, a comprehensive review of modelling frameworks was conducted (PCE, 2024; Blöschl et al., 2024; Beven, 2012; Horton et al., 2022; Sood & Smakhtin, 2015; Burgess, 2023; Beven & Kirkby, 1979; Agarwal et al., 2024). The recent 'Parliamentary Commissioner for the Environment (PCE) review' identified at least 75 biophysical models used by New Zealand regional councils and unitary authorities (PCE, 2024). Although this range cannot be fully explored here, three key distinctions in model types are discussed in the following sections to guide selection for this study.

2.6.1 Physically-based fully distributed model

The first is the physically-based fully distributed model which is a complex mathematical account of the hydrological, meteorological and hydrogeological physics that determine real-world systems (Beven, 2012). This type of model is typically based on partial differential equations which describe 3D surface and subsurface flow interactions across continuous space, often as separate storage zones in a 3D grid with shared and fluid interfaces through which water flux occurs. Examples of this type of model are MIKE Systém Hydrologique Européen (MIKE SHE) by DHI (applied by Fennell et al., 2022), SHETRAN (UK version), and the Integrated Hydrological Modelling System (IHMS) developed by Ragab & Bromley (2010) (Beavan, 2012). These types of models are complex and require a significant amount of input parameterisation data, as well as computational computing power, in order to work effectively. Several papers have suggested a lack of knowledge or data on soil heterogeneity is a fundamental constraint on the accuracy of fully distributed models (Hansen et al., 2007, Bevan, 2001; Blöschl et al, 2024).

2.6.2 Physically based semi-distributed and lumped parameter models

This second model type is a simplified version of the fully distributed model in which similar areas are lumped together to form discrete subunits or 'hydrological response units' (HRUs) (Bevan, 2012). In general, this reduces the computational complexity and requirement of high-resolution continuous parameterisations where every individual point is uniquely calculated for in time and space (Bevan, 2012; Burgess, 2023). Semi-distributed models are ideal when catchments have similar hydrological zones or limited data, allowing for aggregation where continuous, high-resolution data is unavailable. Examples include TOPMODEL (Beven & Kirkby, 1979), SWAT (Burgess, 2023), and SWAT+ (Wu et al., 2020). Discretisation can extend from smaller zones to entire catchments if data constraints necessitate a more generalised approach (Beven, 2012).

2.6.3 Flow routing models (2D)

The third model type reviewed includes routing grid and channel evolution models, the simplest of the three types. Flow routing models track surface water paths without accounting for baseflow, soil depth, variable water tables, or antecedent moisture. Key inputs are a digital elevation model (DEM), land cover, and roughness coefficients. While limited in exploring detailed rainfall-runoff relationships due to the lack of soil water accounting over time, these models are useful for hydraulic or event-based surface routing. Examples of 2D routing models include HEC-RAS 6.5 and HEC-HMS (Xiong, 2011).

2.6.4 Selection of an appropriate modelling approach for the project - SWAT+

SWAT+ is a physically-based, semi-distributed model. Unlike SWAT (2012), SWAT+ (2024) offers enhanced control over wetland and pond hydrology parameterisation (Wu et al. 2020). SWAT+ uses hydrological response units (HRUs) with integrated soil, geology, and hydrogeology layers, allowing for scalable HRU sizes. Wetlands are incorporated directly into HRUs, with storage and retention properties applied at this unit scale (USDA-ARS, 2024). SWAT+ was chosen for this research due to its compatibility with the project's timeframe, data, and academic goals.

2.7 Current research gaps – floodscapes and their management

Considering the academic emphasis on local adaptation of NBFM for desired outcomes, placed-based understanding of catchment hydrology, land use effects and fluvial geomorphology are required. Management of flooding is nuanced, and learnings are often of limited transferability, this sometimes owing to differences in approach/quantification (PCE, 2024). If the model evaluation is transparent and interventions are designed in a practical and scalable manner, the methodology can be used to validate on-the-ground progress, scale up interventions, and develop methods for the design and implementation of NBFM in adjacent catchments. The Waimatā presents a case study of an area with high potential for NBFM interventions at a range of scales. In 2024, GDC issued an RFP for targeted nature-based solutions in the Waimatā to enhance flood resilience and mitigate erosion, woody debris, and runoff (GETS, 2024).

Chapter 3 Regional setting and sites

3.1 Introduction

This section summarises the geological, climatic, and geomorphic settings of the Waimatā Valley and the selected subcatchments (Figure 1). Additionally, it outlines the current land use configuration of the catchment(s) as well as the ongoing conservation efforts. The topics covered, in order, include:

- Geographic and geological setting
    - Soils of the Waimatā
- River geomorphology
- Land use change
    - Land use capability (LUC) mapping
- Regional climate and flood risk variability
- Sub-basin sensitivity.
- The Waimatā – catchment management and river restoration
    - Current research and catchment planning tools

3.2 Geographic and geological setting

The Waimatā hydrological system is located on the southeastern side of the Raukumara Ranges (Figure 12). The catchment lies on the active forearc of the Hikurangi Subduction Margin, an area of frequent faulting activity that results in highly stressed, fractured, and weathered parent rock (Marden et al., 2014). The relatively high uplift rate has shaped steep slopes and narrow valleys, which confine the river's width and concentrate its flows.

The catchment is primarily composed of mudstone and sandstone deposits laid down during the Holocene period (11,700 ya – present) (Mazengarb & Speden, 2000). The East Cape region is largely comprised of deeply incised, erosion-prone hill country with larger catchments constrained by alluvial floodplains and remnant fluvial terraces (Mazengarb & Speden, 2000). Beneath these deposits lies the Torlesse composite terrane basement geology, overlain by thick sequences of early Cretaceous to Oligocene sedimentary and igneous rocks of the East Coast Allochthon.

The surface geology within the Waimatā is mainly Quaternary-aged valley fill comprising mobilised sediments of the above sedimentary sequences. Located approximately 100-200 km east of the central plateau volcanic complex (Figure 8), the Waimatā region has, on average, received deposits of silicic airfall tephra from the Taupō or Okataina volcanic centres every 2,000 years. The Waimatā River Valley flows through, and is constrained by fluvial terraces of differing ages dating back past the last glacial maxima (LGM, ~17,625 cal.yr BP) (Marden et al., 2014) (Figure 9). Since the LGM, the Waimatā is estimated to have transported 2.6 km^3 of sediment to the ocean (Cullum, Brierley & Marden, 2017). High sedimentation rates are common across the East Cape, and the enhancement of sedimentation rates through past land use conversion has brought with it ecological consequences, harbour siltation issues, and damage to core infrastructure (Figure 2).

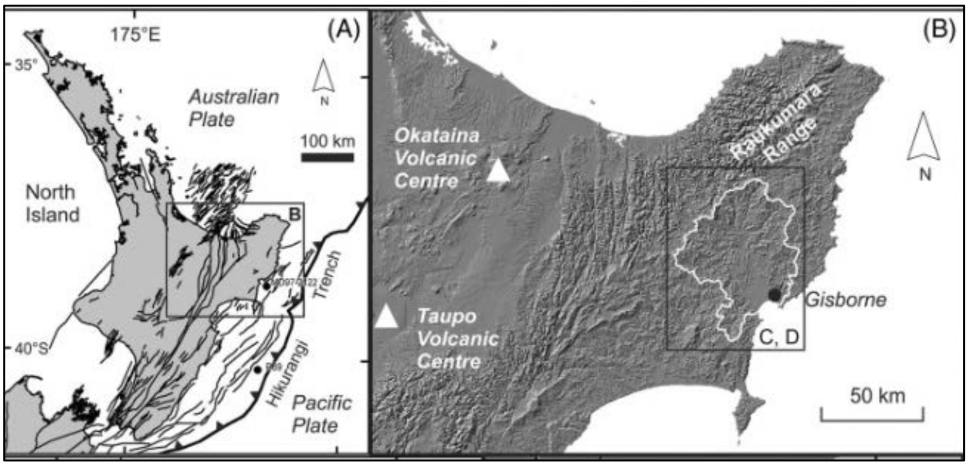


Figure 8 Regional tectonic setting – proximate volcano (source: Marden et al, 2014)

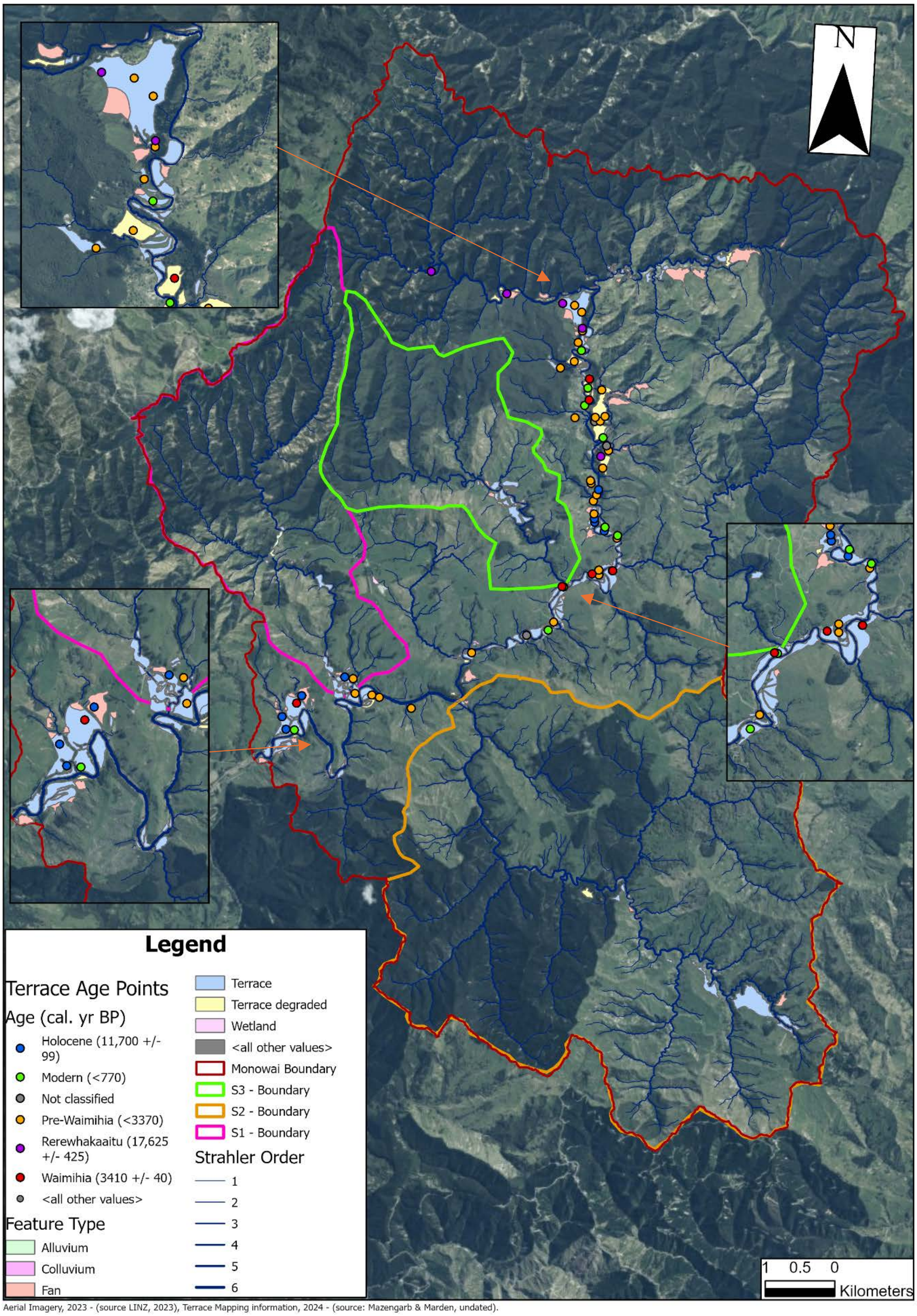


Figure 9 Terrace ages and geomorphic mapping (upper Waimatā)

3.2.1 Soils of Waimatā

Soil types of the Waimatā are shown in Figure 10, primarily consisting of weakly developed Recent soils. Hillslope and gully erosion frequently displace these soils, limiting in-situ soil formation (Cullum et al., 2017;). Other types include coarser Pumice soils, finer-textured brown soils, and tephritic material in some Recent soil areas (McLeod et al., 1999). Gley soils, indicative of past waterlogging and high bulk density, are found in floodplain backswamps of the upper catchment (Salmond, 2016). McLeod et al. (1999) found Waimatā's underlying lithology to be relatively uniform, with little variation in infiltration rates. Although available water capacities are generally high, Tephric soils have slightly higher capacities than soils with similar textures (McLeod et al., 1999).

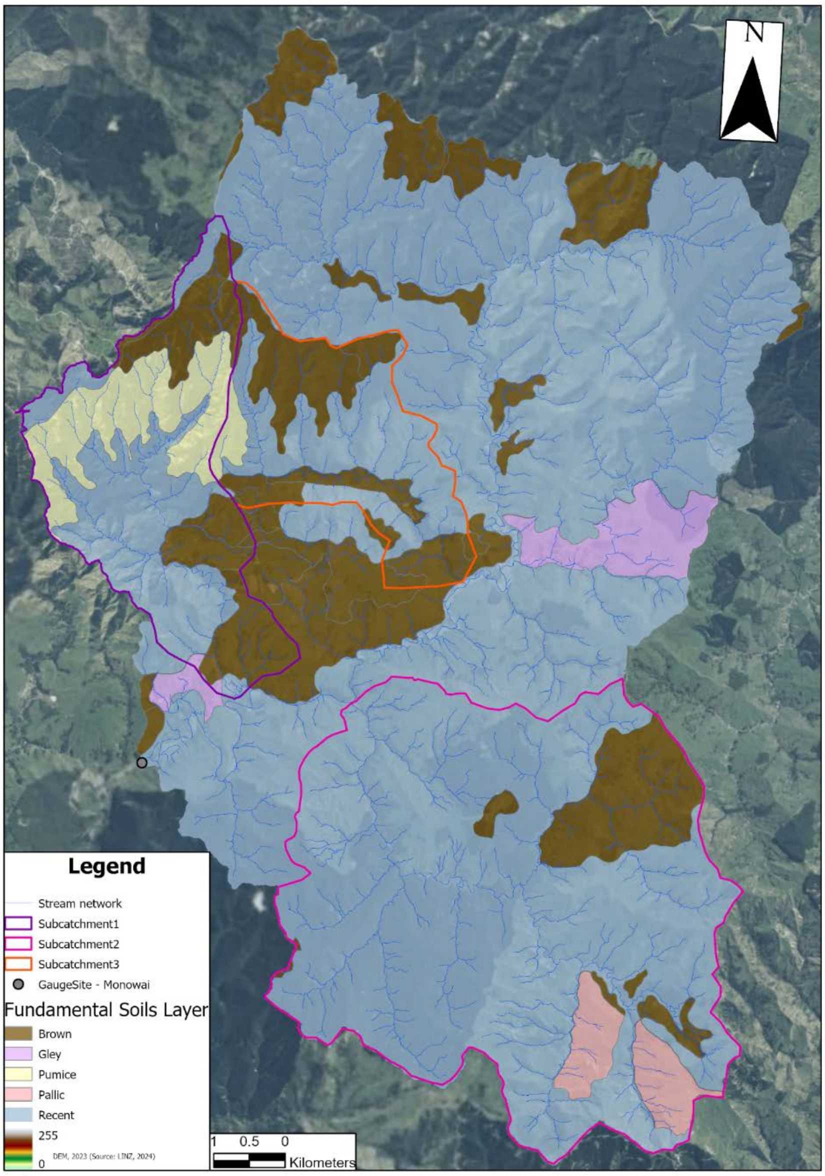


Figure 10 Waimatā Catchment Soil Order Map (Source: Landcare Research, 2023b)

3.3 River geomorphology

Marden et al. (2014) used tephrochronology to identify seven terrace layers in the Waipaoa Catchment, formed by fluvial incision (Figure 9). Their study revealed compositional differences in terrace ages and variations in incision rates over a ~2000-year timescale since the Last Glacial Maximum (LGM). Each terrace layer was linked to known climatic events in New Zealand, reflecting a sequence of terrace formation and incision periods. Although focused on the larger Waipaoa Catchment, these geomorphic insights likely apply to the adjacent Waimatā catchment as well (Figure 9).

Incision of alluvial channels is the key process working to translate tectonic and climatic signals across East Cape, NZ (Marden et al., 2014). Some sections of meandering channel flow through late Pleistocene and Holocene-aged terrace, indicating a terrace confined setting with a reduced capacity for lateral adjustments (Figure 9) (Cullum et al., 2017). Fluvial downwearing and containment by elevated terraces in the Waimatā are intensified by contemporary land use. Expansive pastures and monocultural forestry promote 'flashy' flows in the main channel, increasing channel incision and bank collapse (Fuller et al., 2023). Hillslope deposits of silts and sands are readily mobilised under moderate to high flows, causing the channel to behave like a flume with minimal structural diversity (Fuller et al., 2023). Reducing peak water velocities and restoring geomorphic roughness elements could enhance flow diversity and create habitats for native flora and fauna (Doane et al., 2024; Fuller et al., 2023).

Upland tributaries with lower stream power display a broader, less sorted spectrum of bed grain sizes. Each tributary has unique distributions of mudstone and sandstone clasts, shaped by differences in upland hillslope inputs, faulting rates, and localised geology (Mazengarb & Speden, 2000). Catchment area and channel length in each tributary also influences particle abrasion and sorting. These variations in grain size distribution and sediment characteristics affect roughness, transport dynamics and sorting, ultimately influencing the median particle size (D_{50}) at key locations.

3.4 Land use change

Prior to European settlement, vast expanses of tītoki (*Alectryon excelsus*), tawa (*Beilschmiedia tawa*), kohekohe (*Didymocheton spectabilis*), tōtara (*Podocarpus totara*), and mataī forest covered river terraces (Salmond, 2016). Kahikatea (*Dacrycarpus dacrydioides*) and pukatea (*Laurelia novae-zelandiae*)-dominated forests were common at the top of the lower catchment in poorly drained soils (i.e., lowlands, gley soils, alluvial terraces) (Figure 10). Māori deforestation activities were restricted to the lower-lying land for purposes of cultivation and infrastructure development. Consequently, the upper slopes of the study area were largely intact with native forest up until the late 19th century (Gundry, 2017). By the early 1900s, 9700 ha of indigenous forest had been cleared across the Taruheru and Waimatā rivers (Coombes, 2000). Today, primary native forest covers just 6% of the catchment (Singers & Lawrence, 2017; LAWA, 2018; Figure 11).

Data table - Waimata River Catchment land cover state (2018)

Land Cover Class	Area	
	ha	%
Forest	**8,705**	**38%**
Indigenous forest	1,404	6%
Exotic forest	7,302	32%
Scrub / shrubland	**2,443**	**11%**
Indigenous scrub / shrubland	2,410	11%
Exotic scrub / shrubland	33	<1%
Grassland / other herbaceous vegetation	**11,204**	**49%**
Exotic grassland	11,202	49%
Other herbaceous vegetation	3	<1%
Cropland	**45**	**<1%**
Cropping / horticulture	45	<1%
Urban / bare / lightly-vegetated surfaces	**273**	**1%**
Natural bare / lightly-vegetated surfaces	25	<1%
Urban area	247	1%
Water bodies	**33**	**<1%**
Water bodies	33	<1%

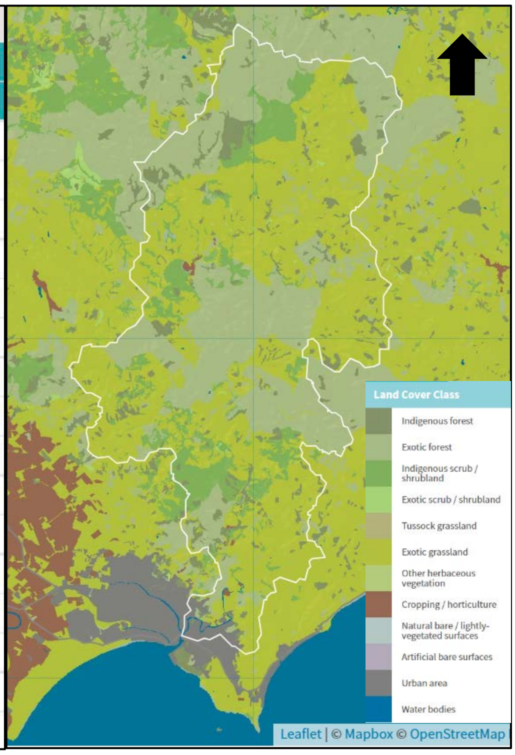


Figure 11 Waimatā land cover map (source: LAWA, 2018)

3.4.1 Land use capability (LUC) mapping – Manaaki Whenua (Landcare Research)

Land use capability (LUC) mapping identifies the physiography, rock types, soils, and erosion susceptibility of landscape units across Tairāwhiti, providing a foundation for assessing limitations on agricultural and forestry productivity (Jessen et al., 1999; Landcare Research, 2023). This framework, specific to the Gisborne Region, highlights widespread erosion and landslides linked to past land use practices.

LUC maps categorise land into eight broad capability classes, with key limiting factors (e.g., 'e' for erosion, 'w' for wetness) detailed in Table 2 and Figure 12. Common in the upper Waimatā are classes 6e1, 6e2, and 6e3, representing steep Neogene and Quaternary mudstones with varying erosion risks. These classes indicate potential for semi-intensive livestock farming and exotic forestry, though erosion remains a primary constraint (Jessen et al., 1999). Classes 6e10 and 6e16, characterised by high-sloped Neogene sandstone with deep weathering, also pose significant landslip risks. Management guidance for Class 6e suggests restoring ground cover and promoting native regeneration in eroded areas. Classes 7e and 8e/s are classed as unsuitable for agriculture or commercial forestry due to steep slopes and high erosion potential (Jessen, 1999; Landcare Research, 2023). This study will use LUC maps to design NBFM solutions tailored to these limitations.

Table 2 Land use capability mapping – Manaaki Whenua (Landcare Research, 2023)

Key	Classification	Description
	LUC Class 1	Arable. Most versatile multiple-use land, minimal limitations, highly suitable for cropping, viticulture, berry fruit, pastoralism, tree crops and forestry.
	LUC Class 2	Arable. Very good multiple-use land, slight limitations, suitable for cropping, viticulture, berry fruit, pastoralism, tree crops and forestry.
	LUC Class 3	Arable. Moderate limitations, restricting crop types and intensity of cultivation, suitable for cropping, viticulture, berry fruit, pastoralism, tree crops and forestry.
	LUC Class 4	Arable. Significant limitations for arable use or cultivation, very limited crop types, suitable for occasional cropping, pastoralism, tree crops and forestry. Some Class 4 is also suitable for viticulture and berry fruit.
	LUC Class 5	Non-arable. Highly productive pastoral land, not suitable for crops but only slight limitations to pastoral, viticulture, tree crops and forestry.
	LUC Class 6	Non-arable. Slight to moderate limitations to pastural use, suitable for pasture, tree crops and forestry and in some cases vineyards. Erosion is generally the dominant limitation.
	LUC Class 7	Non-arable. Moderate to very severe limitations to pastoral use. High-risk land requiring active management to achieve sustainable production. Can be suited to grazing with intensive soil conservation measures but more suited to forestry.
	LUC Class 8	Very severe to extreme limitations to all productive land uses, arable, pastoral or commercial forestry. Suitable for erosion control, water management and conservation.

Note: this table forms the legend for the below figure, with consistent colour schema representing LUC classes.

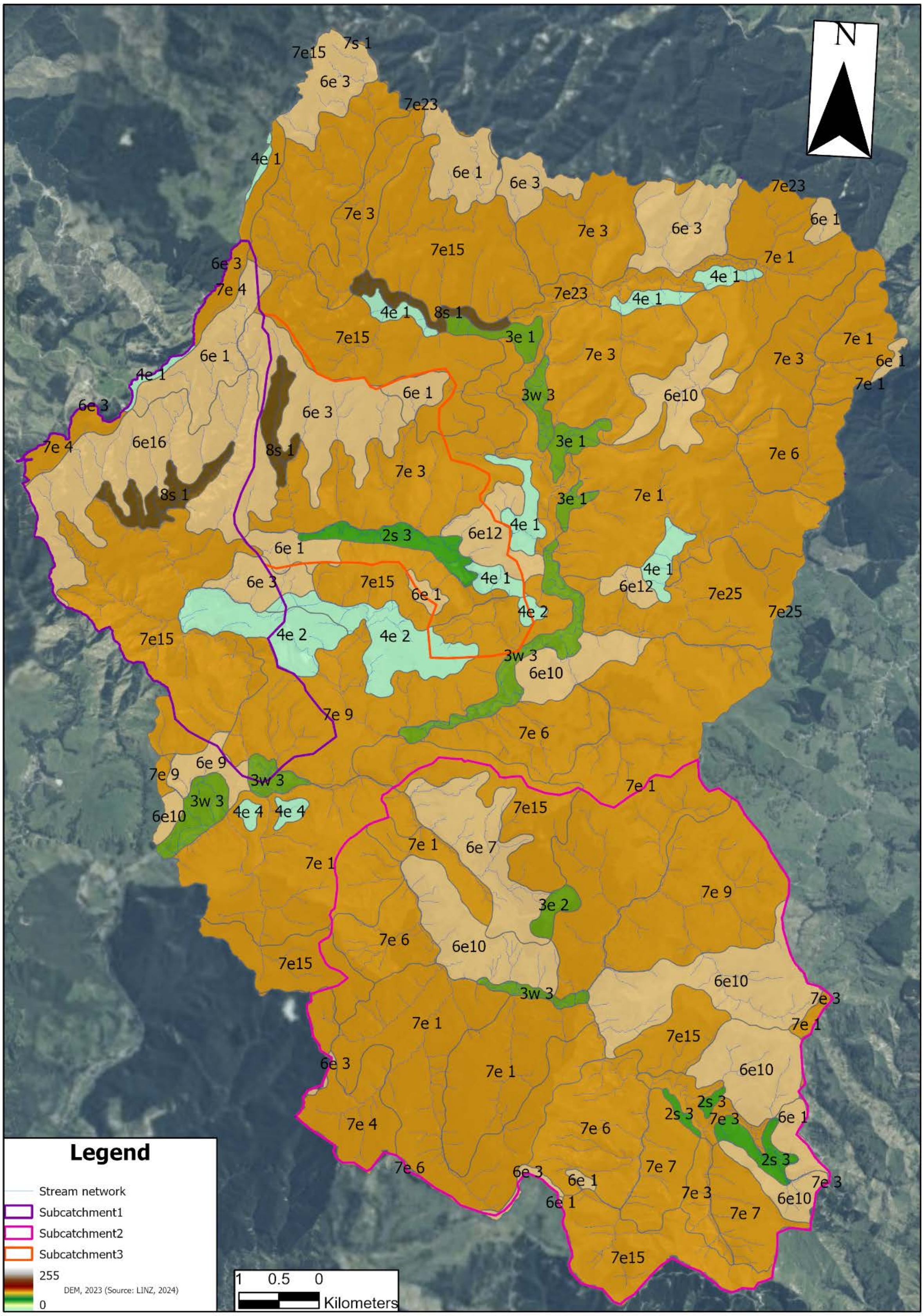


Figure 12 Land use capability (LUC) Mapping of the whole project area (Landcare Research, 2023)

3.5 Regional climate and flood risk variability

The Waimatā Catchment is exposed to periods of significant rainfall due to its coastal exposure to the East Cape of New Zealand. The oceanic range extending out from Gisborne (and much of NZ) has a cooling effect on the lower layers of tropical (northerly) air parcels. This creates layered (stratiform) cloud systems which have the potential to produce large amounts of rainfall, especially when entrained in cyclonic systems (Chappell, 2016).

Warmer saturated winds traveling south collide with the land and foothills of the Raukumara Ranges before orographic effects occur. Air parcels rapidly cool while being forced upward by topography, resulting in short and concentrated rainfall. In Gisborne, rainfall is unevenly distributed throughout the year with a prominent increase during winter months (June-Aug) (Chappell, 2016). The Waimatā Catchment receives around 1600 mm of annual rainfall (Chappell, 2016). Short-period rainfall statistics from the nearest long-term NIWA monitoring site are provided in Table 3.

Table 3 Maximum recorded short period rainfalls and calculated return period from HIRDS (source: Chappell, 2016)

Location		10min	20min	30min	1hr	2hrs	6hrs	12hrs	24hrs	48hrs	72hrs
Gisborne Aero	a	18	29	35	43	69	132	139	215	237	291
	b	55	87	75	39	88	100+	57	90	61	98
	c	7	11	13	19	27	45	63	87	104	115
	d	10	14	18	26	35	59	81	111	133	148
	e	12	17	21	31	42	70	96	131	157	174
	f	14	20	25	37	50	83	113	154	184	204
	g	17	25	32	46	63	103	139	189	226	251

a: highest fall recorded (mm)
b: calculated return period of a (years)
c: max fall calculated with ARI 2 years (mm)
d: max fall calculated with ARI 5 years (mm)
e: max fall calculated with ARI 10 years (mm)
f: max fall calculated with ARI 20 years (mm)
g: max fall calculated with ARI 50 years (mm)

Figures 13-15 show the streamflow precipitation index (SPI), southern oscillation index (SOI), standardised precipitation evapotranspiration index (SPEI), and streamflow drought index (SDI) over 11-21 years at Monowai Station. The data reveal significant climatic variability, with 1-2 year droughts recurring every 6-7 years. La Niña (wetter) conditions occur in ~7 cycles, each lasting around 2 years, including periods in 2004-2005, 2010-2011, and 2020-2023 (coinciding with Cyclone Gabrielle). This climate variability influences flood risk and is critical for assessing the long-term impact of NBFM interventions.

Figure 14 shows a strong correlation between potential evapotranspiration and precipitation during wet periods, indicating high rainfall positively affects the catchment's water balance. SPEI highlights that drought and water stress correlate with higher temperatures, increased evapotranspiration, and lower rainfall. Figure 15 displays streamflow variability (SDI), with La Niña (positive SOI) linked to above-average streamflow, driven by increased rainfall in 2020-2021. The 3–6-month lag between positive SOI and SDI suggests delayed aquifer recharge after drought. These findings emphasise seasonal variability and storage effects, key for interpreting model results and planning NBFM interventions.

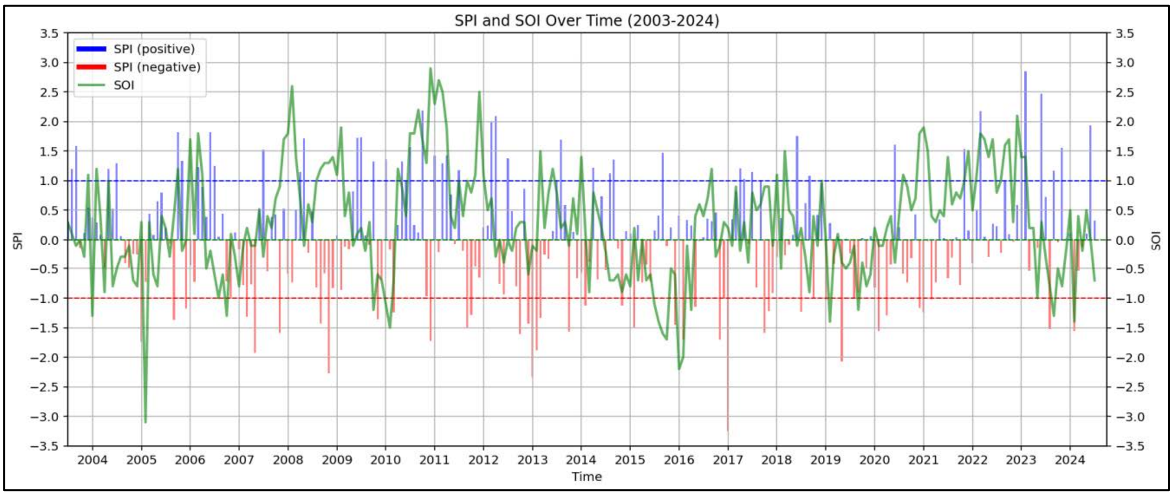


Figure 13 SPI and SOI from 2003-2024 at Monowai Bridge Station

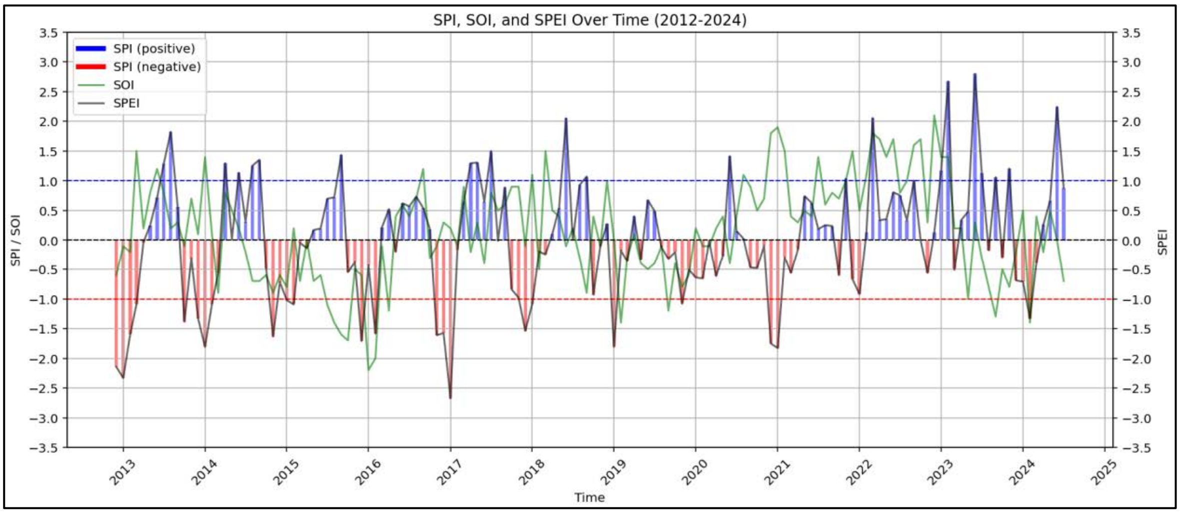


Figure 14 SPI, SOI and SPEI from 2012-2024 at Monowai Bridge Station

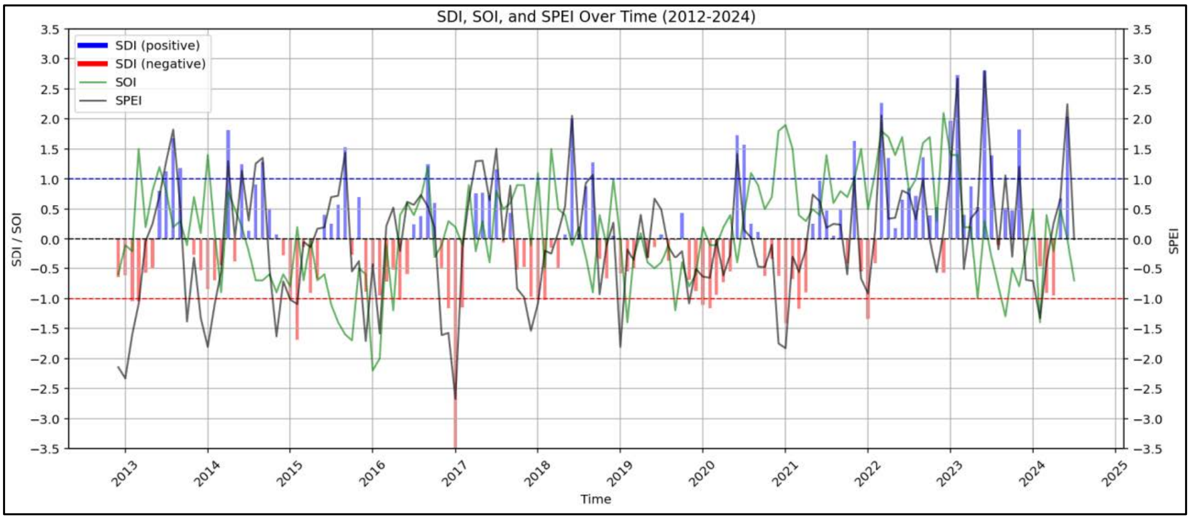


Figure 15 Streamflow Drought Index (SDI) for period 2012-2024

3.6 Sub-basin sensitivity

Subbasins (subcatchments) respond differently to land cover interventions, with physiographic factors such as geology, soil depth, elevation, slope, aspect, existing land cover, and area within the catchment influencing their hydrological sensitivity (Burgess, 2023). Using SWAT, Burgess (2023) assessed the Waimatā Catchment's response to major land use changes, identifying specific subbasins as more suitable for flood resilience interventions.

Figure 16 shows simulated subbasin sensitivity in peak flow (m^3/s) under two land cover scenarios: full pasture and historic indigenous forest. Subbasin 1 was the most sensitive, with peak flow decreasing ~35% under afforestation (Figure 16). Subbasin 3 was the least sensitive to this conversion with peak flows decreasing ~16% (Burgess, 2023). This sensitivity difference likely reflects the upland position, steep slopes, and shallow soils, making canopy structure particularly important in moderating runoff. Steeper slopes often lead to shallower soils and lower rainfall thresholds for Hortonian overland flow (Wang & Chen, 2021), emphasising the role of canopy in water yield control.

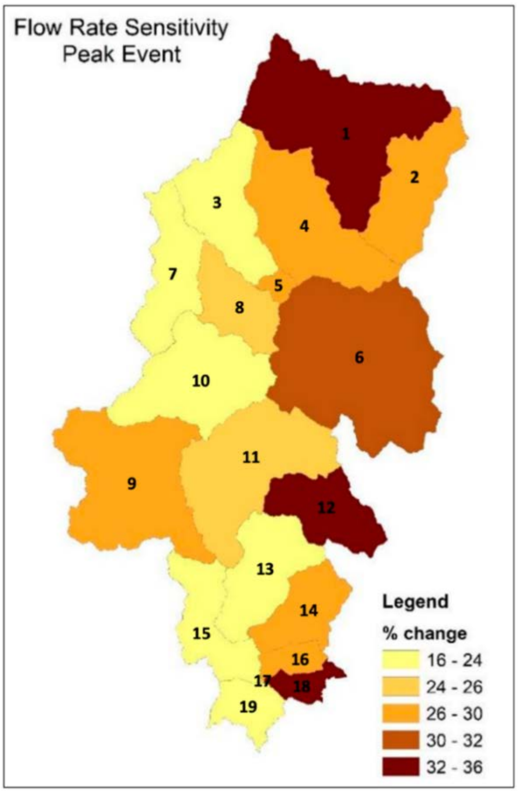


Figure 16 Sub-basin hydrological sensitivity (annual) to bulk changes in landcover (i.e., native / pasture) (source: Burgess, 2023)

3.7 The Waimatā – catchment management and river restoration

Locally there are several groups working to enact change in the Waimatā, with aims of repairing those relational and cultural linkages to the past (*see* Appendix D; Figure 18). Specific relational values include, the ability swim, to gather food, and to live near the river without heightened risk of flood damage and fear of forestry slash (Cairns et al., 2021; Salmond et al, 2024) (Figure 2 & 17). Long-term residents have perceived the health of the river to be in decline, noting forestry impacts that threaten aesthetic values, swimmability, water quality and cultural connection to place (Cairns et al., 2021).

Captured 10/8/2024

Figure 17 Images flood impact at the site – Upper Waimatā (source: authors own)

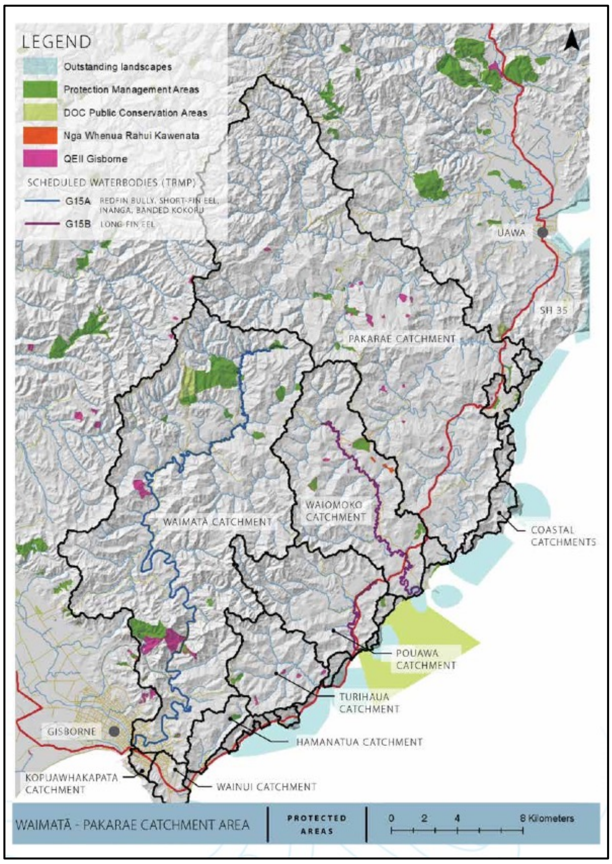


Figure 18 Protected/managed biodiversity areas – Tairāwhiti (GDC, 2022)

3.7.1 Current research and catchment planning tools

Research by Cullum et al. (2017) spurred on the development of the Waimatā Catchment Erosion Management Project in the following year. This report develops catchment-level insights into the landscape and river geomorphological template to which contemporary management actions can be applied (Cullum et al., 2017). The impacts of land use legacies are superimposed on the geological and geomorphic template of the Waimatā system through time. Cullum et al (2017) apply the River Styles framework to map a top down and process-based classification of the contemporary river system (Figure 19). This work sets up a process-level framework for placing interventions, contextualised by imposed boundary conditions (i.e., geological setting) (Harvey, 2021).

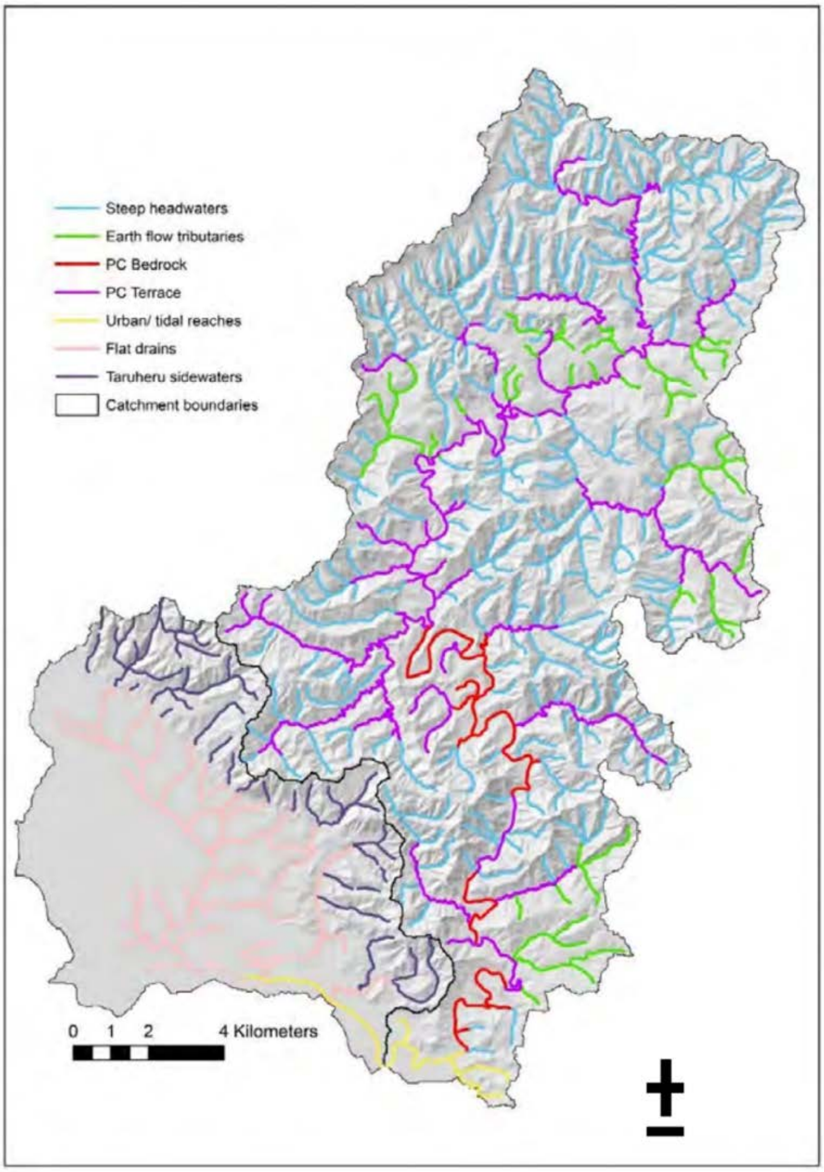


Figure 19 River Styles of the Waimatā River Catchment (source: Cullum et al., 2017)

Following the River Styles mapping work, a series of natural science research has been undertaken, supported by the ‘Let the River Speak’ Marsden research project (Waikereru, 2024b; Harvey et al 2021, Harvey, 2021, Burgess, 2021, Cairns et al., 2021). The Let the River Speak group have recently co-developed a project that bridges mātauranga knowledge and current scientific understanding of the Waimatā (Salmond et al 2022). What becomes apparent in this account is the marginalisation of complex biophysical interfaces when western management considers the landscape as piecemeal domains (i.e., river reaches adjacent to private property boundaries, or ‘estuary’ or ‘coast’). The relational linkages or whakapapa of the Waimatā comprise relationships that transcend the categorical boundaries of western-framed management and technical nomenclature. In Te Ao Māori, rivers are seen as relational nodes in a meshwork of whakapapa that arise from exchanges between earth and land, land and sea, people and other life forms (Salmond et al 2022). This worldview emphasises concepts of balance (or imbalance) through an inherent systems perspective, closely aligned with the principles of geomorphological science (Piegay and Lamouroux, 2017).

Recently the Ruru whānau from Te Aitanga-a-Māhaki (local iwi) have developed a ‘Mauri Compass’ which can be used to guide restoration of Tairāwhiti’s rivers from a mātauranga perspective, considering the actions that separate states of ‘ora’(restored) and ‘mate’ (destroyed) (Mayall-Nahi et al, 2021; Salmond et al 2022; Mauri Compass, 2024). The Mauri Compass will be an important tool for the refinement (design) and operational monitoring of prospective NBFM intervention discussed in this report.

Chapter 4 Methods

4.1 Introduction

This section outlines the methods used in this analysis to answer the proposed research question (*see* Section 1).

4.2 Site selection

The wider study area illustrated by the 'Monowai-Boundary' in Figure 1 was selected for its upland position in the catchment and its proximity to the long-term council monitoring station. The 104.2 km^2 area has a range of land use (Figure 20). Seven large tributary systems drain to the main channel.

S1 (*Mangaehu Stream*), S2 (*Mangaorangi Stream*) and S3 (*Mangahouku Stream*) were selected as study basins due to their relatively similar size, position in the catchment and differing land use compositions (Figure 20; Appendix E). These basins will serve as sites for evaluating the catchment hydrological model and assessing land use parameterisation uncertainty. The variations in land use and size support a semi-quantitative analysis of parameter uncertainty. Appendix E details the area and percent cover of LUC classes within each catchment.

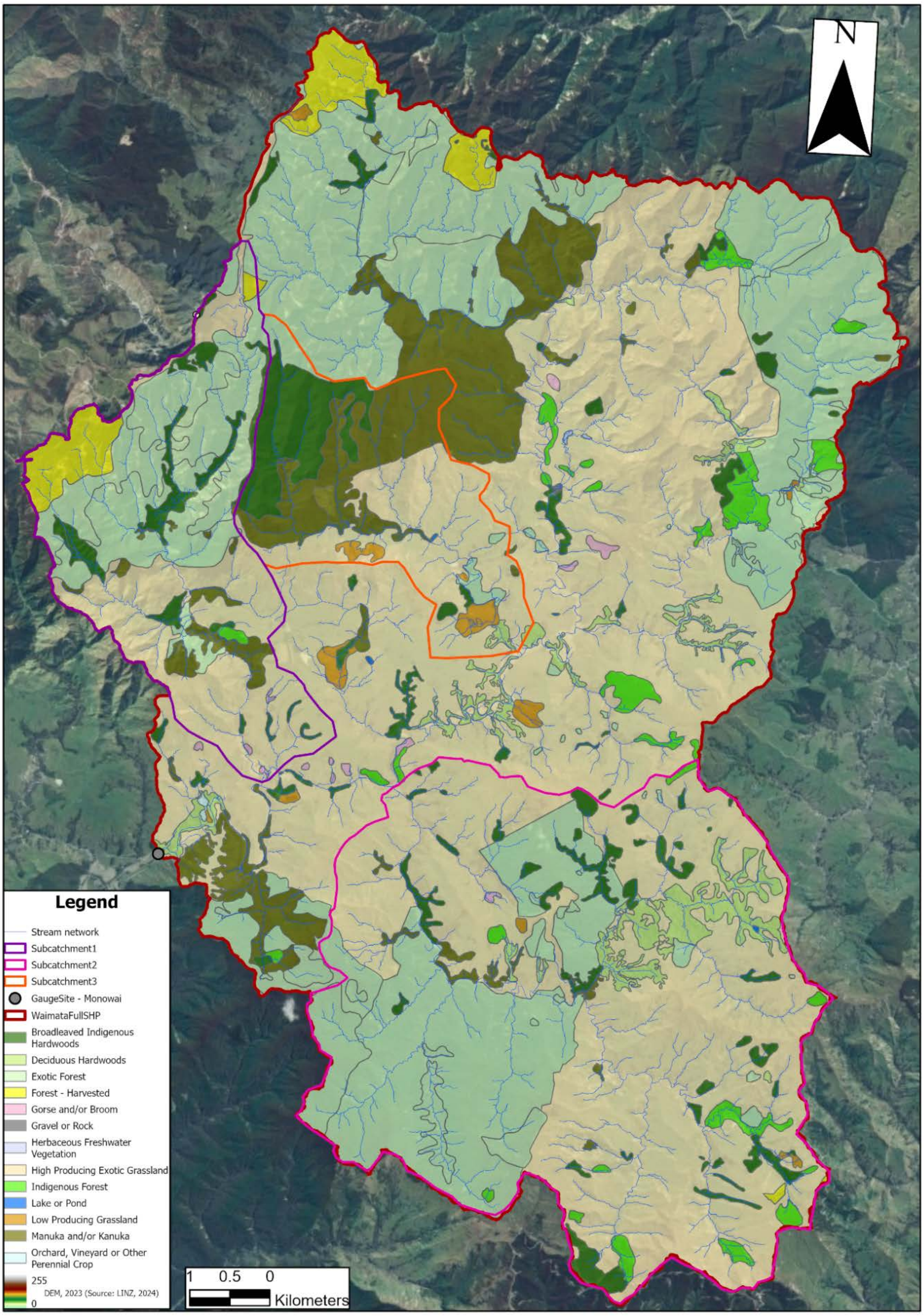


Figure 20 Land use composition of study catchments (Landcare Research, 2018)

4.3 Data collection and processing

The data supporting this research is collated from online sources as well as during two site visits (8-11th August & 4-6 September 2024). Table 4 outlines the field data collected and the intended use for the project.

Table 4 Data collected – fieldwork

Data	Collection method/equipment	Purpose
UAV photogrammetry (SfM) at each study reach (S1, S2 & S3)	**UAV**: Mavic 3 Enterprise (sensor: 48 MP, ½" CMOS) **Survey area**: 200 m reach either side of the river level sensor.	Simulation of a ramped discharge to inform project flow rating curve analysis.
Channel cross sections at each study reach (S1, S2 & S3)	**Survey equipment**: Trimble R10 (base and rover) – PPK static survey. **Location**: 0-5 m upstream of the level gauging sites.	Input into rating curve analysis, accurate representation of channel geometry.
Flow gauging at each study reach (S1, S2 & S3)	**Equipment:** Flow Tracker (FT), tape measure. **Location:** same as cross sections	Flow gauging at one height, contributing to rating confidence.
Wolman pebble count at each study reach (S1, S2 & S3) (Ref)	**Equipment:** Gravelometer, 2x 50m tape measures, notebook. **Survey area**: 100 m reach upstream of the river level sensor.	Calculating skin friction coefficient (Manning's n; Strickler equation)
10-minute continuous river-level monitoring at each study reach (S1, S2 & S3)	**Equipment**: HiLo Monitoring LS1-SAT-R	Model calibration and validation via observed river height. Used to calculate stage-discharge rating curves for each study catchment.
Site photography	**Equipment:** Canon R6 Mk II	Site context for project – cyclone recovery state

4.3.1 Digital data collation and processing

Data sources used in this project are summarised in Table 5.

Table 5 Digital data sources and processing

Data type + unit	Resolution	Processing (if any)	Source
digital elevation model (DEM)	1 m > up sampled to 5 m	see below sections	LINZ (2023)
fundamental soils layer (FSL)	.shp converted to 5 m raster	N/a	LRIS portal (Landcare Research 2023)
landcover layer	.shp converted to 5 m raster	N/a	LRIS portal (Landcare Research 2018)
precipitation (mm/hr)	sub-hourly	aggregated to hourly timestep	Cliflo Database (NIWA 2024)
solar radiation (MJ / m^2)	daily	aggregated to daily timestep	Cliflo Database (NIWA 2024)
wind (m/s^{-1})	hourly	aggregated to daily timestep	Cliflo Database (NIWA 2024)
relative humidity (%)	hourly	aggregated to daily timestep	Cliflo Database (NIWA 2024)
temperature (°C)	hourly	aggregated to daily timestep	Cliflo Database (NIWA 2024)
land use capability (LUC) mapping	regional	N/a	LRIS portal (Landcare Research 2023b)
River flow (m3/s)	daily	N/a	GDC (2024)

Note: where gaps existed in the climate data, a linear interpolation function was used to predict missing values.

4.3.2 Monitoring stations – meteorological data capture

The meteorological data used in this study was collected mostly from the Gisborne Airport Met Station accessed through the NIWA Cliflo Database (Figure 21). Input rainfall was collected at 2 stations, the Wakaroa Trig and the Monowai Bridge rain gauge (Figure 21). The stage record was collected from the project gauging sites and the GDC Monowai Station (Figure 21). The coordinates of the council and NIWA stations used are provided in Table 6.

Table 6 Weather stations (lat, long, height (m))

Station name	**Coordinates** (NZTM; EPSG: 2193)
Waimatā River at Monowai Bridge	-38.51418196, 178.040284222, 49
Wakaroa Trig	-38.453443941, 178.041426907, 606
Gisborne Airport Met Station	-38.62747, 177.9218, 12

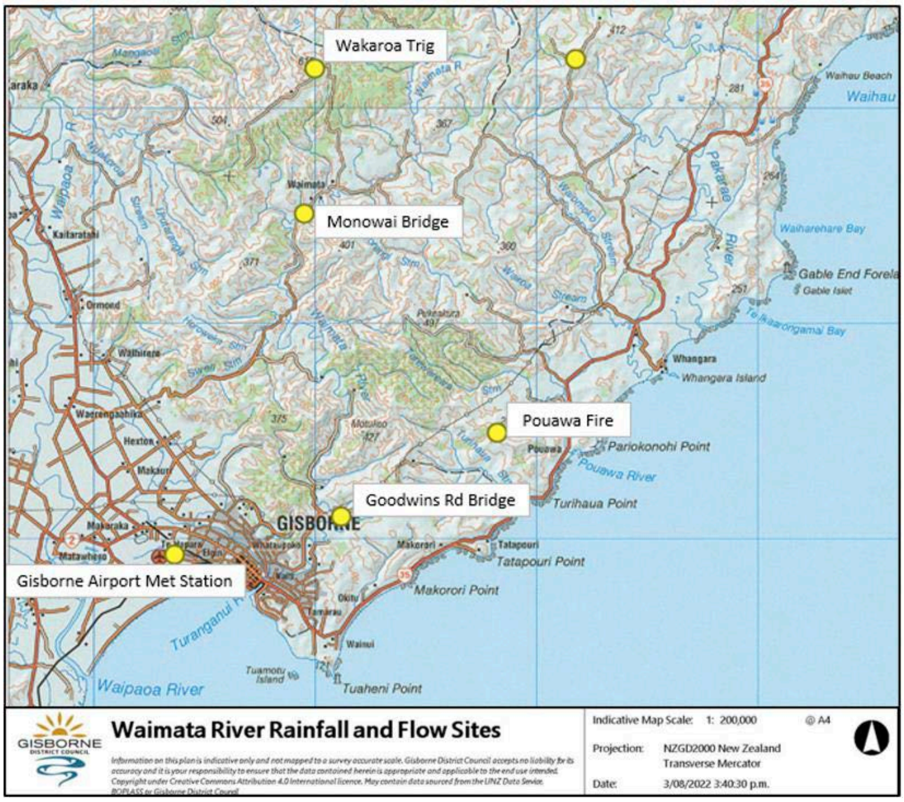


Figure 21 Meteorological and flow gauging stations in the wider study area

4.3.3 Rainfall event selection criteria

The 85th-percentile flood event was calculated from the observed flood history dataset at Monowai Station (1984-2024). The figure below shows the flood events in the top 15% of the record. Note that the baseflow (3 m^3/s) was excluded prior to this calculation being made. The rationale for selecting an 85th-percentile event was that these are more common than the largest recorded events and so, perform more geomorphic work in the system overall (Fryirs and Brierley, 2023) (Figure 22). Additionally, the event size needed to exceed the bed load entrainment threshold, enabling assessment of reductions in effective volumetric sediment transport for D_{50}.

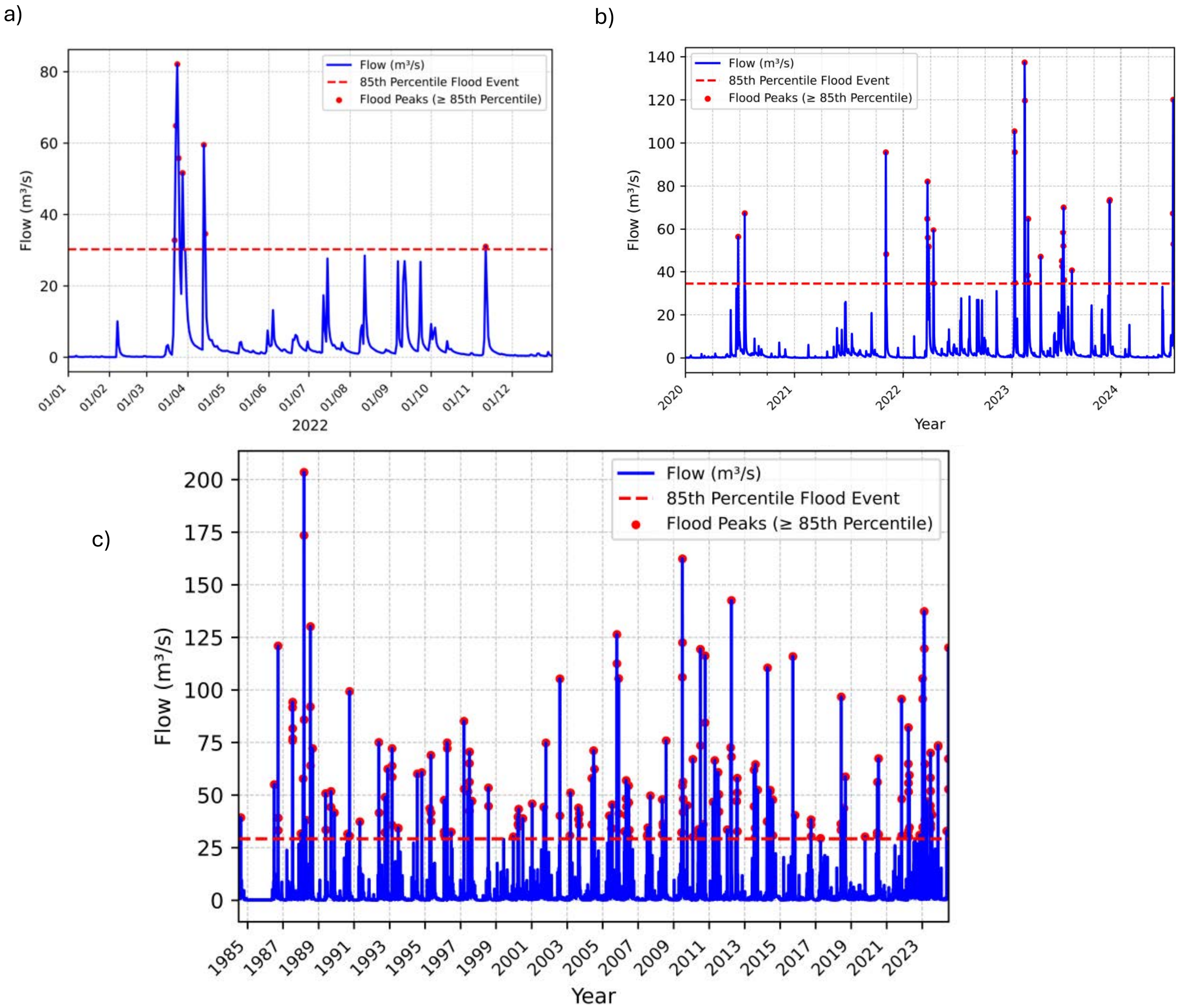


Figure 22 85th Percentile Rainfall – Monowai Rain Gauge

Considering the ARI values in Table 3, the selected 85-percentile test event for this study (11/03 – 05/05/22) was classified with the following rainfall statistics:

- 1-hour maximum rainfall: 26.0 mm, corresponding to a 10-year ARI.
- 6-hour maximum rainfall: 83.2 mm, corresponding to a 20-year ARI.
- 12-hour maximum rainfall: 111.0 mm, corresponding to a 20-year ARI.
- 24-hour maximum rainfall: 132.2 mm, corresponding to a 20-year ARI.

4.4 Model preparation in SWAT+

The modelling workflow in SWAT+ is summarised in Figure 23. SWAT+ used TauDEM to calculate raster functions for the watershed delineation stage of model preparation, this includes:

- flow accumulation raster
- slope raster
- flow direction raster
- stream network vector lines
- sub-basin boundaries
- HRU

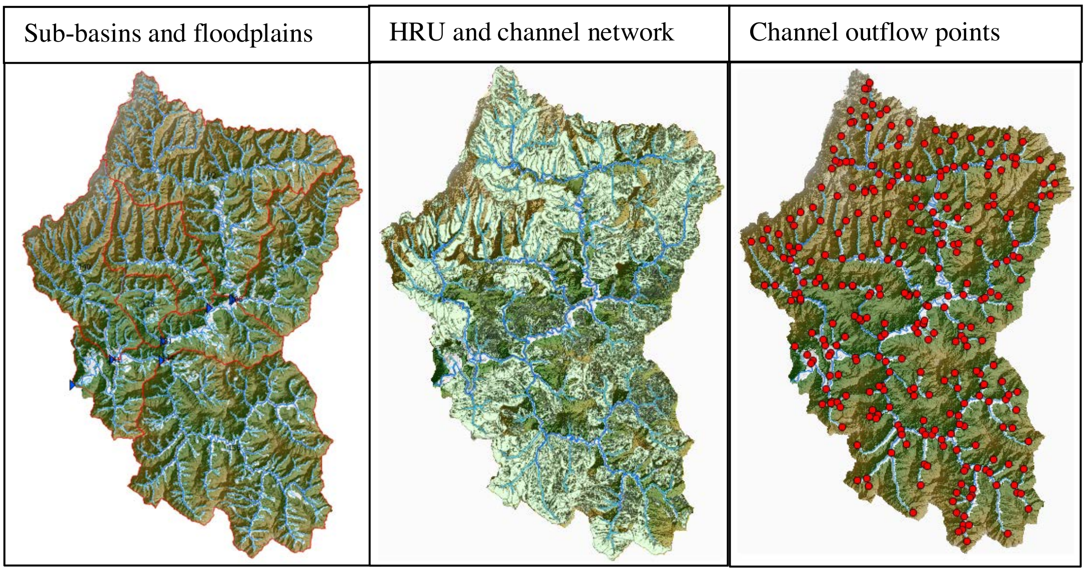


Figure 23 Model environment – watershed delineation - SWAT+

The SWAT+ model operates on a lumped HRU basis, assuming consistent hydrological characteristics within each HRU (Figure 23; Section 2.2). A 1m DEM was downsampled to 5m to improve processing efficiency. HRUs contain information on land cover, slope, soil properties, and position in the catchment. The model tracks soil moisture by adjusting the SCS curve number daily (Beven, 2012) and uses the Muskingum method for flow routing (see limitations section). Sub-daily rainfall data is applied using the Green & Ampt method for estimating infiltration rates, which assumes a non-linear relationship between rainfall and infiltration (USDA-ARS, 2024). This method reflects how infiltration rates decrease over time as the wetting front moves deeper, reducing the capillary potential gradient. Key factors influencing infiltration include soil depth and initial saturated hydraulic conductivity (k). The model was run at the daily simulation time step with rainfall data ingested as hourly (Figure 24).

Climate data was sourced from CliFlo (NIWA, 2024) and GDC to specific request. Monthly data statistics were calculated for 32 years to provided historic averages and better align the model with the climatology of the area. The monthly data is produced by the SWAT+ global weather generator, gridded satellite weather data available for the study area for longer periods than local physical monitoring stations. Note, the model was run with monthly station data spanning 10 years, yielding undesirable results. The monthly data should cover at least 1 full southern oscillation cycle (2-7 years), but longer-ranged data and coverage of more cycles led to more accurate soil moisture accounting (USDA-ARS, 2024). Input climate data for the initial run spanned 4 years, including 2-3 years for model warm up and 2 years of simulated data. The Penman Monteith equation was selected for calculation of the potential ET (PET) within the model, considering mean daily air temperature, wind speed, relative humidity, net radiation, canopy roughness, surface roughness and soil heat flux density (Bevan, 2012). Soil and land cover parameters were then manually collated and put into look up tables for SWAT+ (Landcare Research, 2023b; USDA-ARS, 2024).

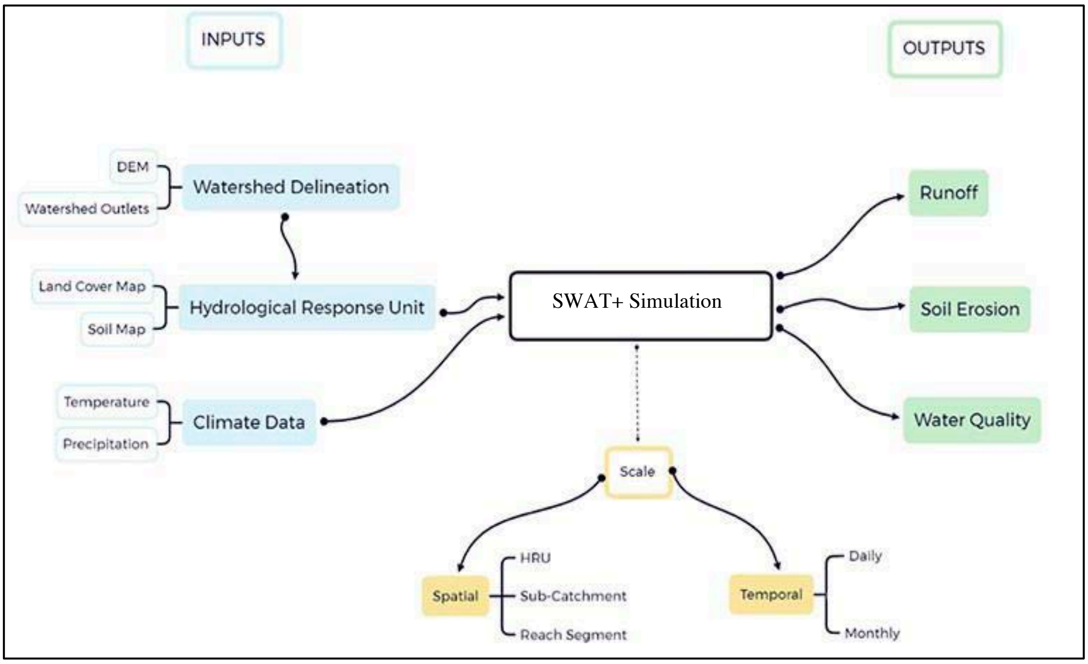


Figure 24 Model set up process – SWAT+ (adapted from Burgess, 2023)

4.5 Calibration and validation

The first step to calibration was to evaluate the model sensitivity to specific change in parameter values. This was done in SWAT+ Toolbox using the Latin Hypercube-One Factor at a Time method and running 60 different models (seeds) (i.e., 1140 samples), recording the magnitude of change to the NSE after each iteration. The parameter sensitivity is shown in Table 7. The dot plots for each parameter and their 'fitted range' are shown in Figure 25.

Table 7 Parameter sensitivity analysis (Latin hypercube-sampling method)

Parameter name	Sensitivity
Condition II curve number (cn2)	0.939
Soil water adjustment factor (cn3_swf)	0.029
Surface runoff lag (surlag)	0.0098
Saturated hydraulic soil conductivity (k)	0.0092
Baseflow coefficient (alpha)	0.008
Soil evaporation compensation factor (esco)	0.004

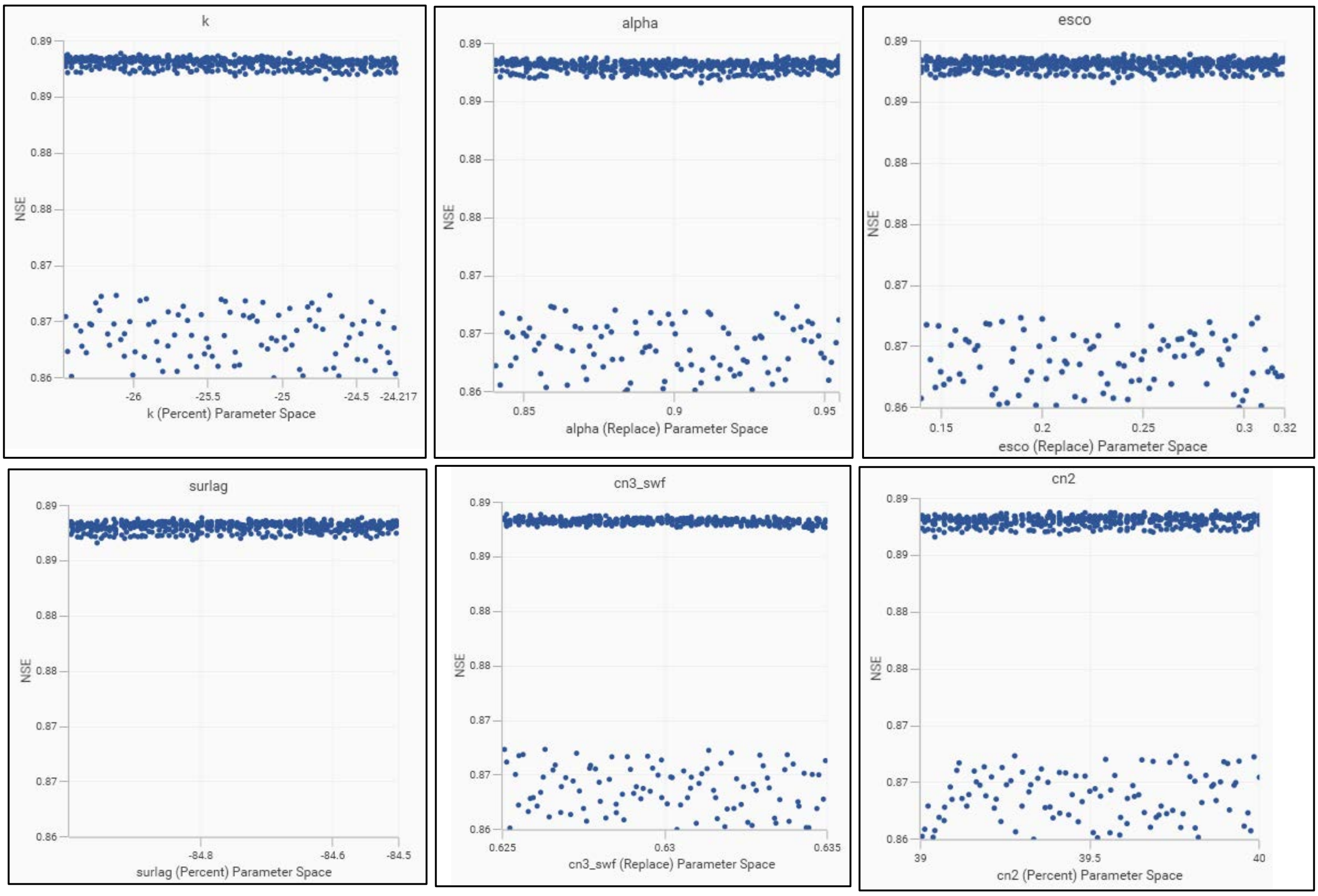


Figure 25 Parameter sensitivity plots – 'fitted range' - NSE

Calibration and validation of the SWAT+ baseline model was achieved by adjusting input parameter values using the Calibration by Latin-hypercube Sampling Iterations (CALSI) algorithm in SWAT+ Toolbox. 500 iterations were run with a batch size of 20 and range refining threshold of 15. The range expansion was set to 7.5% and the global batch size matched the batch size (20). The overall goal of the calibration was to better match the simulated output flow of the model to the observed flows. The Nash-Sutcliffe Efficiency (NSE), Percent Bias (PBIAS) and Regression Coefficient (R^2) equations were used to measure the goodness of fit between observed and simulated hydrographs (Eq.2, Eq.3 and Eq.4). Calibration involves adjusting individual parameter ranges ("fitting"); the final model used the most sensitive parameters (see Table 7).

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - \overline{Y}^{mean}\right)^2}\right] \quad (2)$$

where: Y_i^{obs} are the ground-based measurements; Y_i^{sim} are the model predicted data; and Y^{mean} is the mean of the ground-based measurements.

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) \times 100}{\sum_{i=1}^{n} Y_i^{obs}}\right] \quad (3)$$

where: Y_i^{obs} are the ground-based measurements; Y_i^{sim} are the model predicted data.

$$R^2 = 1 - \frac{sum\ squared\ regression(SSR)}{total\ sum\ of\ squares(SST)} \quad (4)$$

In manual and automatic calibration steps the water balance equation is used to check that the change in soil water is equal to the precipitation minus the other flux areas of the simulated environment (Figure 26). This was used to check the mass balance and any potential unexplained losses in the model.

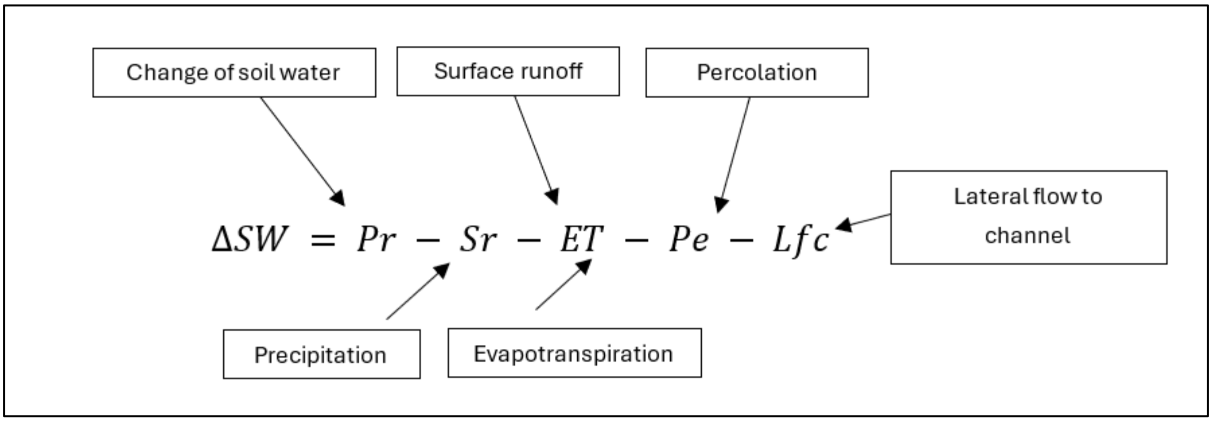


Figure 26 Water balance equation – theoretical underpinnings of calibration

For this research, the software SWAT+ Toolbox was used to determine possible input parameter ranges and parameter uncertainty. This works by running hundreds of iterations of the model with varying input parameters to determine the direction and magnitude of shift in simulated flow (i.e., Latin Hypercube Sampling). The range of NSE results was then used to track parameter uncertainty for the fitted range. The fitted range is the region of that parameter that can provide a comparable and equally acceptable model output. The uncertainty ranges of input parameters are provided in Table 8 and presented visually in Figure 27.

Table 8 Parameter uncertainty ranges – sensitive parameters

Parameter	Fitted range	Change type	Max range	Set value	Parameter uncertainty (%)
Cn2	39.5 to 40	percent	35 - 95	39.8261	1.5%
surlag	-85 to -81	percent	1 - 24	-81.9102	0.521%
alpha	0.84 to 0.955	replace	0-1	0.8844	11.5%
esco	0.14 to 0.32	replace	0-1	0.2408	18%
cn3_swf	0.625 to 0.635	replace	0-1	0.6290	1%
k	-26.468 to -24.217	percent	0.0001 - 2000	-25.4414	0.058%

Note: the parameter uncertainty is calculated by measuring the fitted range against the max range. The mathematical operator (i.e., percent/replace) was considered and applied to the largest number to estimate the most uncertain case.

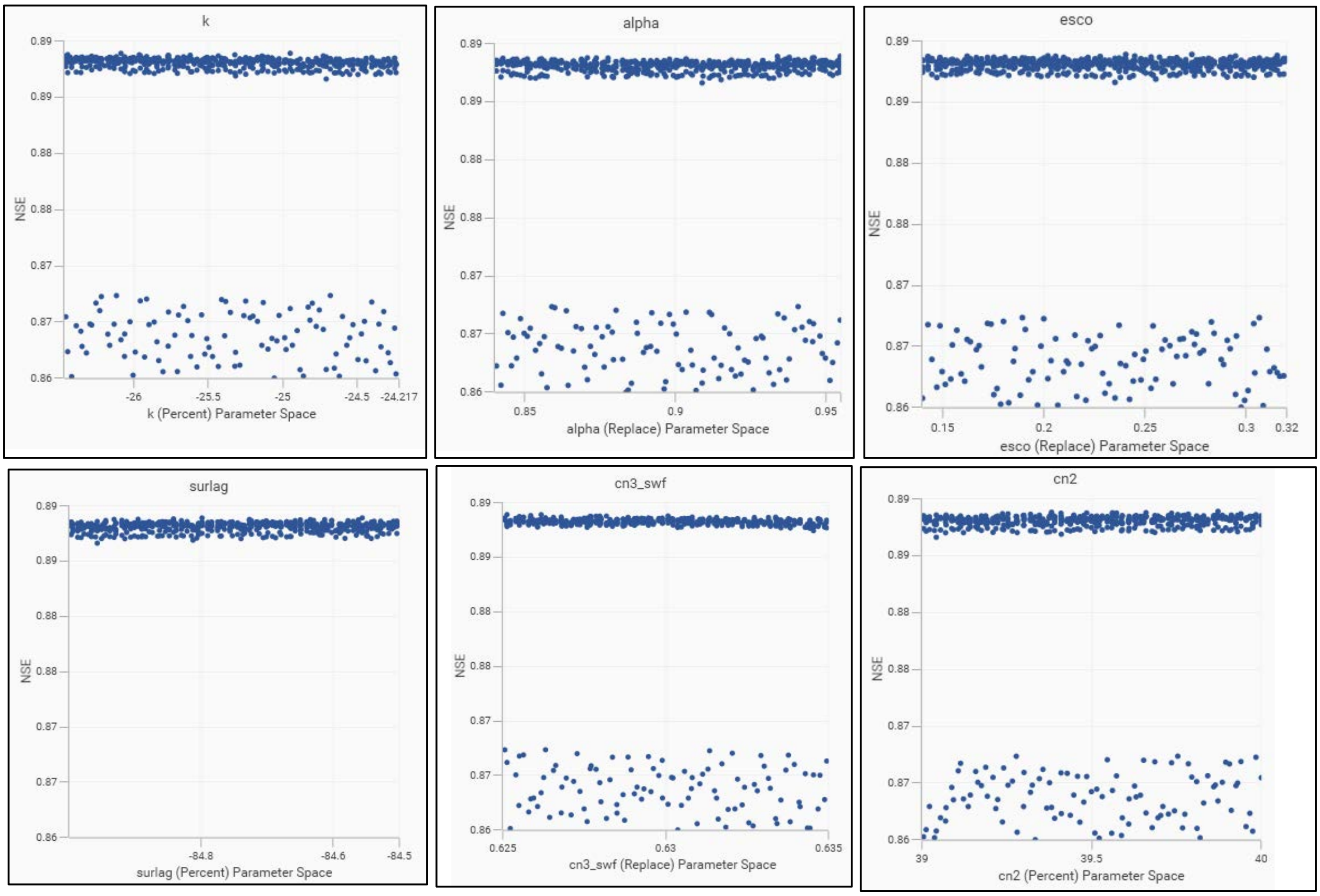


Figure 27 Uncertainty (x-axis) plots for each parameter used in calibration

4.5.1 Sub-catchment validation

HEC-RAS 6.5 was used to model each subcatchment outlet, establishing a mathematical relationship between river level and flow (rating curves). SfM drone data collected in the field was processed into a high-resolution 0.5m DEM, with discharge simulated across this gridded surface (0.5 m resolution). Discharge was ramped up from a 5 m^3/s baseflow, increasing at 0.02 m^3/s per 10 minutes. This simulated flow data was used to interpolate field-collected 10-minute river level data, with the one-time flow gauging record set as the baseline for interpolation (i.e., baseflow). This monitoring enabled calibration and validation of the hydrological regime across subcatchments with varying land use (S1, S2, and S3). The D_{50} values at the gauge locations were measured as 54.5 mm (S1), 77 mm (S2), and 38.5 mm (S3) (Figure 28). The rating curves for S1, S2 and S3 are provided in Figure 29.

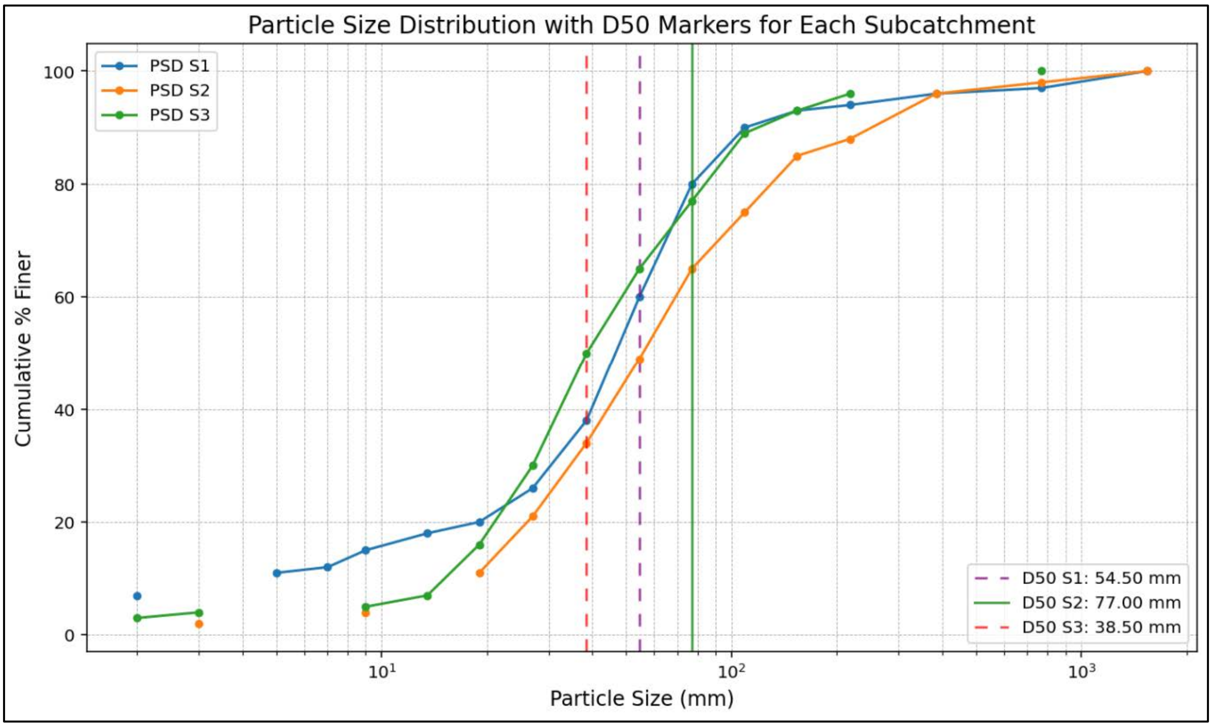
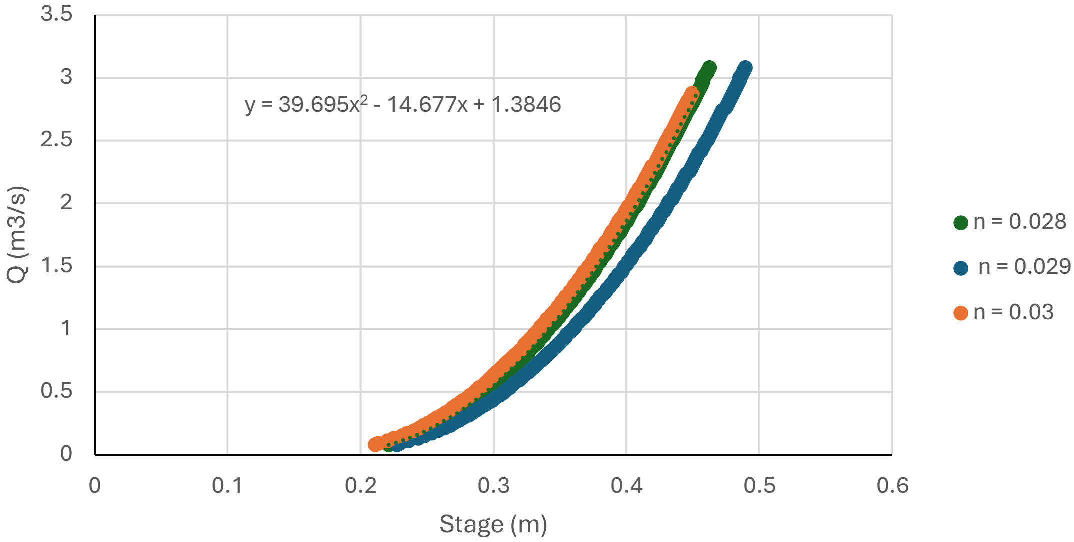
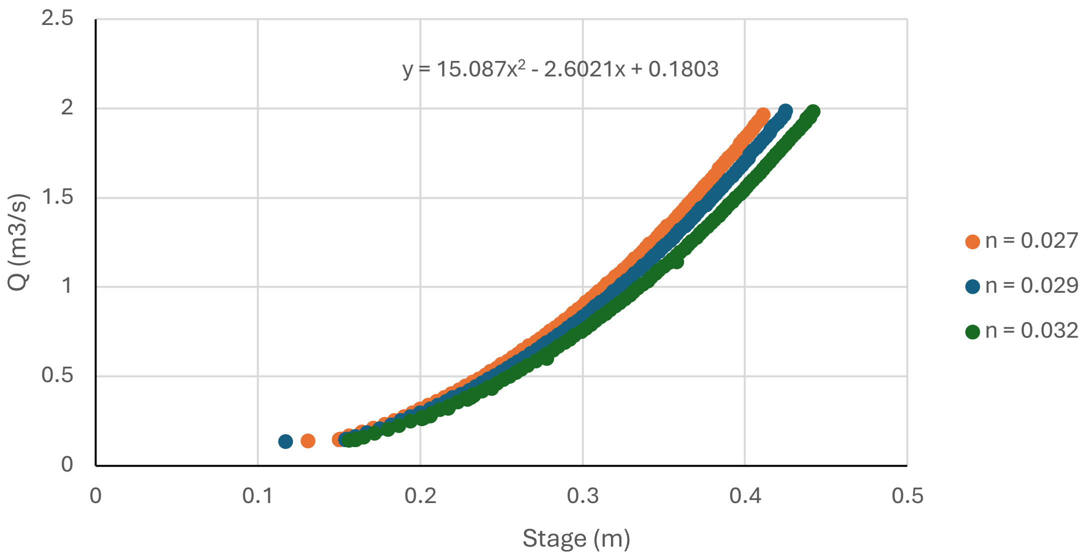


Figure 28 Subcatchment particle size distribution (PSD)

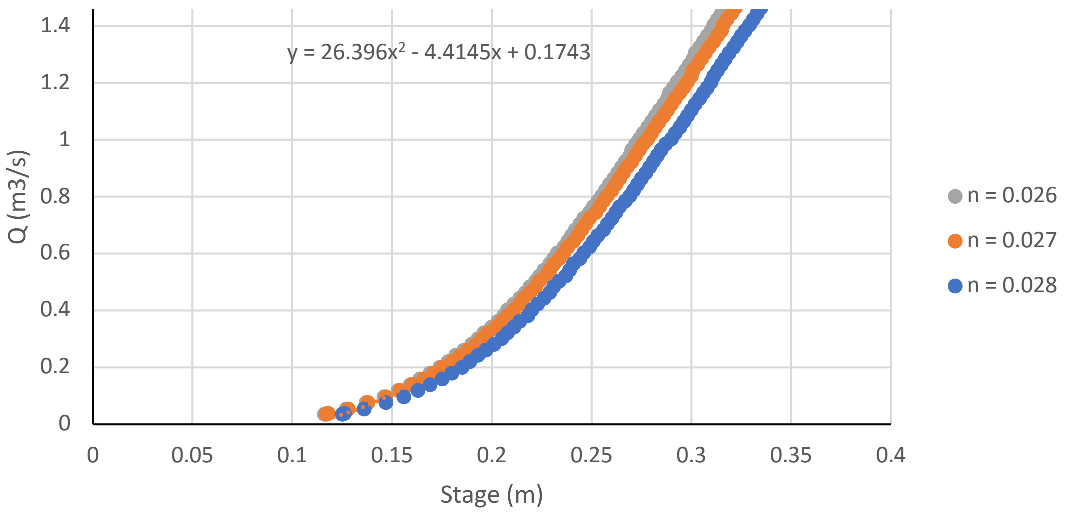
S1


y = 39.695x² - 14.677x + 1.3846
Q (m3/s)
Stage (m)
n = 0.028
n = 0.029
n = 0.03
0
0.5
1
1.5
2
2.5
3
3.5
0
0.1
0.2
0.3
0.4
0.5
0.6

S2


y = 15.087x² - 2.6021x + 0.1803
Q (m3/s)
Stage (m)
n = 0.027
n = 0.029
n = 0.032
0
0.5
1
1.5
2
2.5
0
0.1
0.2
0.3
0.4
0.5

S3


y = 26.396x² - 4.4145x + 0.1743
Q (m3/s)
Stage (m)
n = 0.026
n = 0.027
n = 0.028
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4

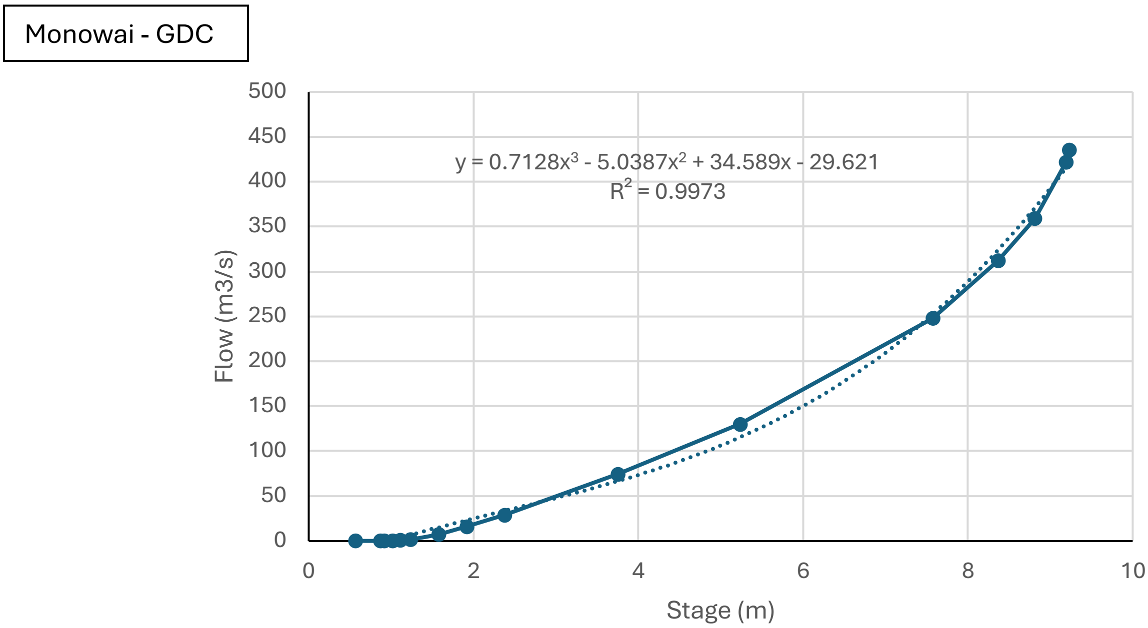


Figure 29 Rating curve analysis (S1, S2, S3 & Monowai)

4.6 Simulation of nature-based interventions

Nature-based flood management interventions were modelled by altering the landcover input layer and forming ‘reservoirs’ (wetlands) at the HRU creation phase of SWAT+ model preparation. This approach to developing NBFM is based on the LUC mapping for the Waimatā (Landcare Research, 2018), as well as flow accumulation, slope and catchment setting. Land classified as ‘unsuitable’ for forestry or agriculture (classes 7-8) were retired in stages to assess the potential range of management outcomes (Landcare Research, 2023; Jessen et al., 1999). Pond design and NBFM approaches from NIWA (2021), Nicholson et al (2012), Burgess (2023), Wren et al, (2022), Jessen et al, (1999) and Fennell et al (2022) were adapted to develop the rationale for strategic intervention of RAF and land use conversion in the study area (Appendix A/B). In total, the transient storage of wetland features in this study totalled 235,000m^3 covering 15.7 ha.

Appendix E details the area and percent cover of each LUC class within Monowai, S1, S2, and S3. Class 7 is the most extensive (~45-70% of each catchment), followed by Class 6 (21-42%). LUC class 6 was converted to ‘mixed forestry’, a blend of exotic and indigenous broadleaf forest classes (Figure 12; Appendix C; see Chapter 2.2.1).

Results of the multi-criteria raster analysis (combining slope, LUC and distance to the channel) for determining wetland suitability are shown in Figure 30. The location of wetland interventions tested in the modelling simulations is a visually selected subset of Figure 30 (Figure 31). A topographic wetness index (TWI) was also calculated to assist in interpreting the conveyance and storage of soil water through the catchment (Figure 32). The TWI was calculated using SAGA GIS plug-in in QGIS 3.32.2. The approach taken is described in the simulation matrix developed to answer the research question (Table 1).

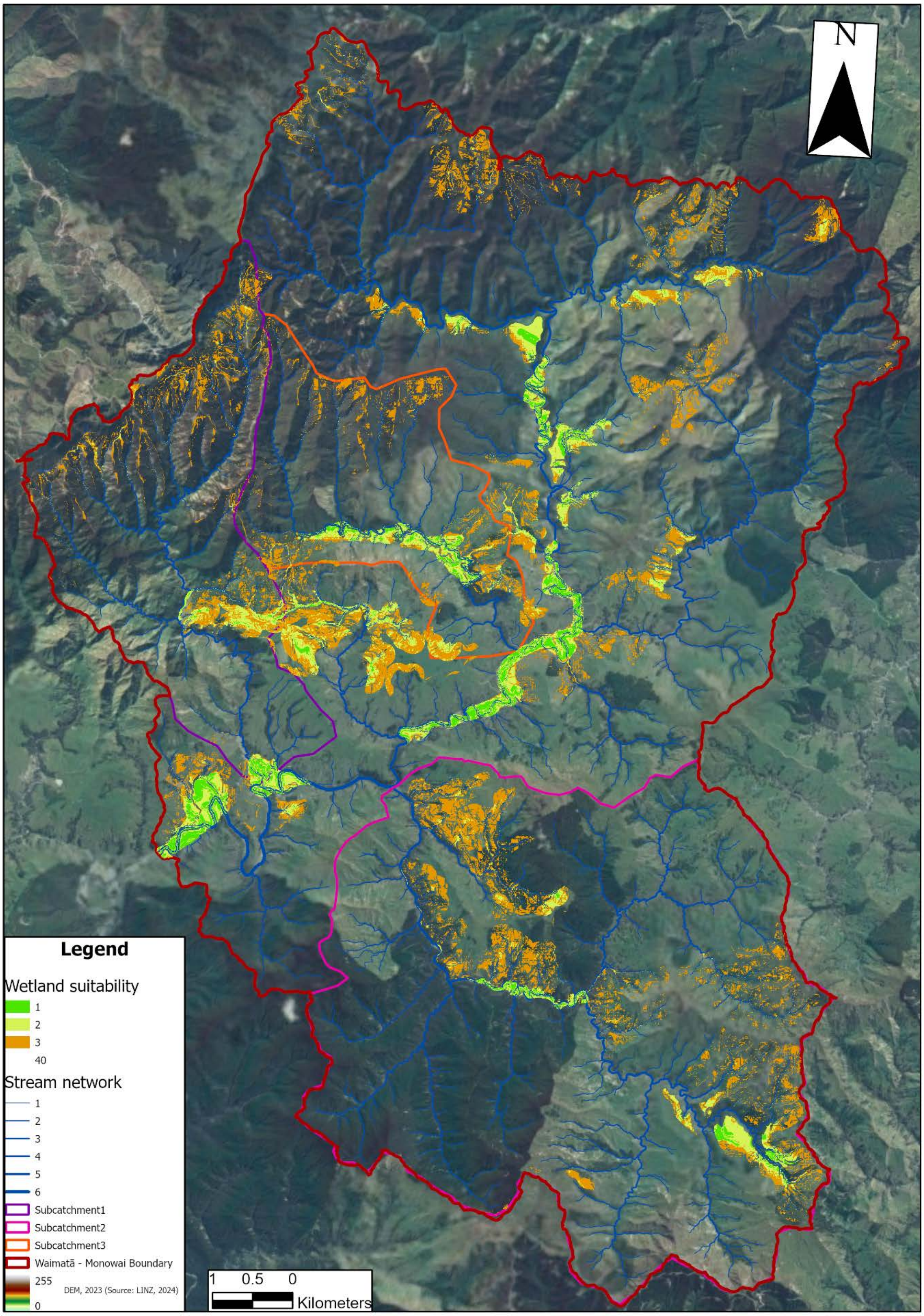


Figure 30 Wetland suitability

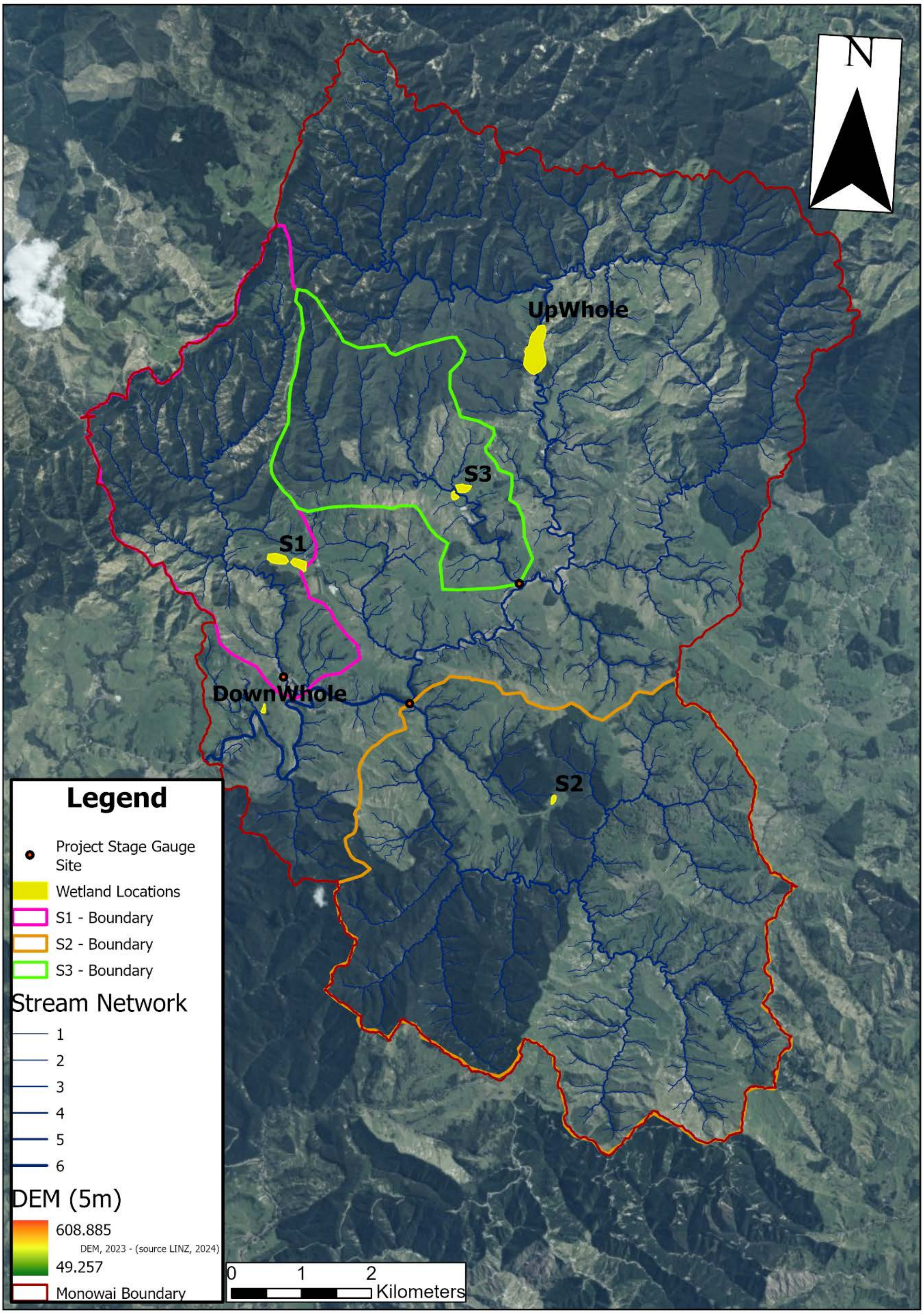
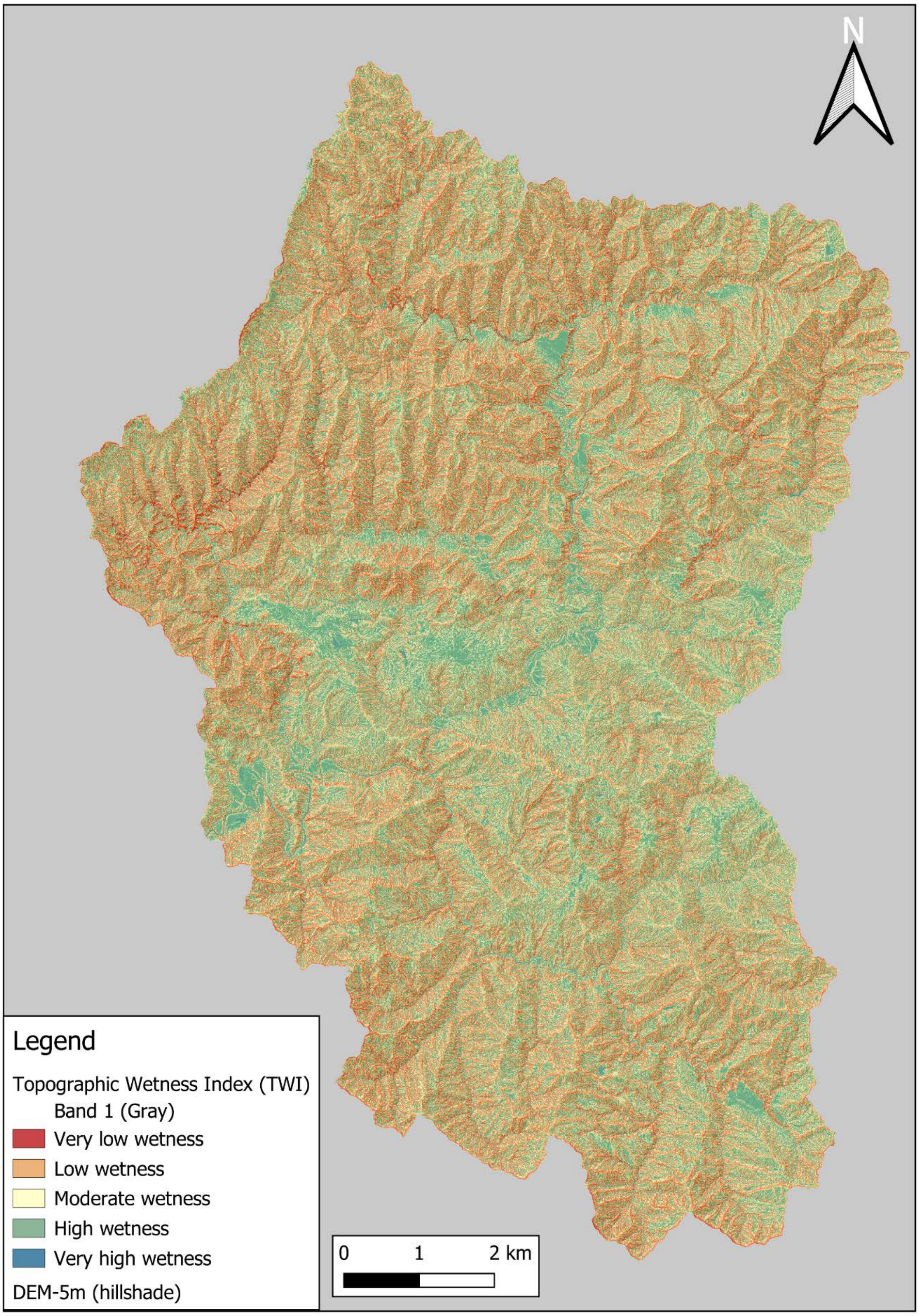


Figure 31 Wetland interventions



DEM sourced from LINZ, 2022.

Figure 32 Topographic Wetness Index (TWI) - Waimatā

4.7 Sediment transport calculations – peak flow reductions

To calculate the reduction in volumetric sediment transport (bedload) the D_{50} particle size was used in the Meyer-Peter Müller (MPM) equation to calculate the bedload transport rate (q_s) (Eq. 5).

$$q_s = 8\left(\frac{\tau_b - \tau_c}{\rho_s * g * D_{50}}\right)^{\frac{3}{2}} \quad (5)$$

Where: q_s is the bedload transport rate per unit width (m^3/s), τ_b is the bed shear stress and τ_c is the critical shear stress for particle entrainment. ρ_s is the sediment density assumed to be 2650 kg/m^3. g is the acceleration due to gravity (9.81 m/s^2) and D_{50} is the median particle diameter (as measured in the field; predominantly coarse gravel).

To estimate the bed shear stress (Pa) for each site the following shear stress formula (Eq. 6) was used:

$$\tau_b = \rho_w \times g \times R_h \times S \quad (6)$$

Where: ρ_w is the density of water (usually around 1000 kg/m^3 for fresh water).
R_h is the hydraulic radius, which is the cross-sectional area of flow divided by the wetted perimeter and S is channel slope (dimensionless).

To estimate critical shear stress (Pa) at each site the shields equation was used (Eq.7):

$$\tau_c = \tau^* \times (\rho_s - \rho_w) \times g \times D_{50} \quad (7)$$

Where: τ^* is the dimensionless Shields parameter (0.03 was used (Buffington & Montgomery, 1997)).

The τ_c was then converted to the flow velocity using the Manning's equation (Eq.8):

$$V = \frac{1}{n} R_h^{\frac{2}{3}} S^{1/2} \quad (8)$$

Where: V is the flow velocity for critical entrainment, n is the Manning's roughness coefficient for D50.

The velocity was then used to calculate the flow depth, and thus shear stress required for particle entrainment of D_{50} using Eq.9:

$$Q = A * V \quad (9)$$

Where: Q is discharge (m^3/s), A is the cross-sectional area (m^2) and V is the flow velocity for critical entrainment as calculated in Eq. 8.

The unit rate of sediment transport (q_s) was then multiplied by the channel width to give an estimate of total bedload transport from the cross section (Q_s). To estimate the sediment volume produced over time, Q_s was multiplied by the duration of flow that exceeded the threshold flow (critical entrainment flow). To compare NBFM interventions the duration of critical flows (i.e., effective reduction) was evaluated against the baseline (T0W0) and presented as a percentage.

4.8 Modelling assumptions

The SWAT+ model is a semi-distributed model which assumes that hydrological characteristics are shared at the HRU unit scale (size depending on soil, slope, landcover and position in the catchment) (*see* Section 2.6). The model assumes no difference in the overall time a land parcel has been under a specific land use activity, meaning the longer-term influences of soil compaction and degradation are not accounted for during the calibration phase. Instead, calibration seeks to find the hydrograph best fit using the average parameterisation of each land use type (i.e., assuming each land cover type is the same overtime). The soil characteristics are inputted using the FSL properties and are spatially varying but regardless, natural complexity has been significantly aggregated and simplified.

Rainfall

The model assumes the rainfall pattern is different within two Thiessen polygon shapes centred around the Wakaroa Trig and Monowai rain gauging sites (Figure 21). In reality, rainfall patterning in this region is likely to be highly varying and influenced by orography.

Flow solver and routing

The Muskingum flow routing method assumes the channel flow volume can be estimated by the combination of wedge and prism storage zones. The wedge space accounts for the upstream advancement of a flood wave atop of ‘normal’ flow rates (i.e., prism). This is a widely used flow routing method and is considered appropriate for the level of detail sought in this research. Two key assumptions (as discussed in the SWAT+ documentation) are the assumption that the flow is uniform in the channel, and that linear storage, inflow and outflow and storage can be approximated linearly (i.e., varying flow does not increase storage through dynamic channel alterations) (USDA-ARS, 2024).

Chapter 5 Results

5.1 Introduction

This chapter presents the results of the initial model (pre-calibration), the post calibration results, and the relative hydrograph impacts of the NBFM interventions developed for the project. The hydrological impact of these interventions is further contextualised in terms of the reduced erosive potential at the Monowai Bridge station (measured as difference in effective volumetric sediment transport of D_{50} particles). Overall, the hypothesis was proved correct, with peak reductions exceeding 15% for most interventions tested (all but T0W1 and T1W0). Similarly, reduction of sediment transport (bedload) was observed above 20% for all of the interventions proposed (Table 1).

5.2 Current conditions

The initial run of the model simulated the hydrograph generally quite well, with an NSE of 0.50 and a PBIAS of 9.16% (Figure 33). The initial daily water balance and flux between zones is shown in Figure 34. The calibrated model results and water balance are provided in Figure 35 & 36 (respectively).

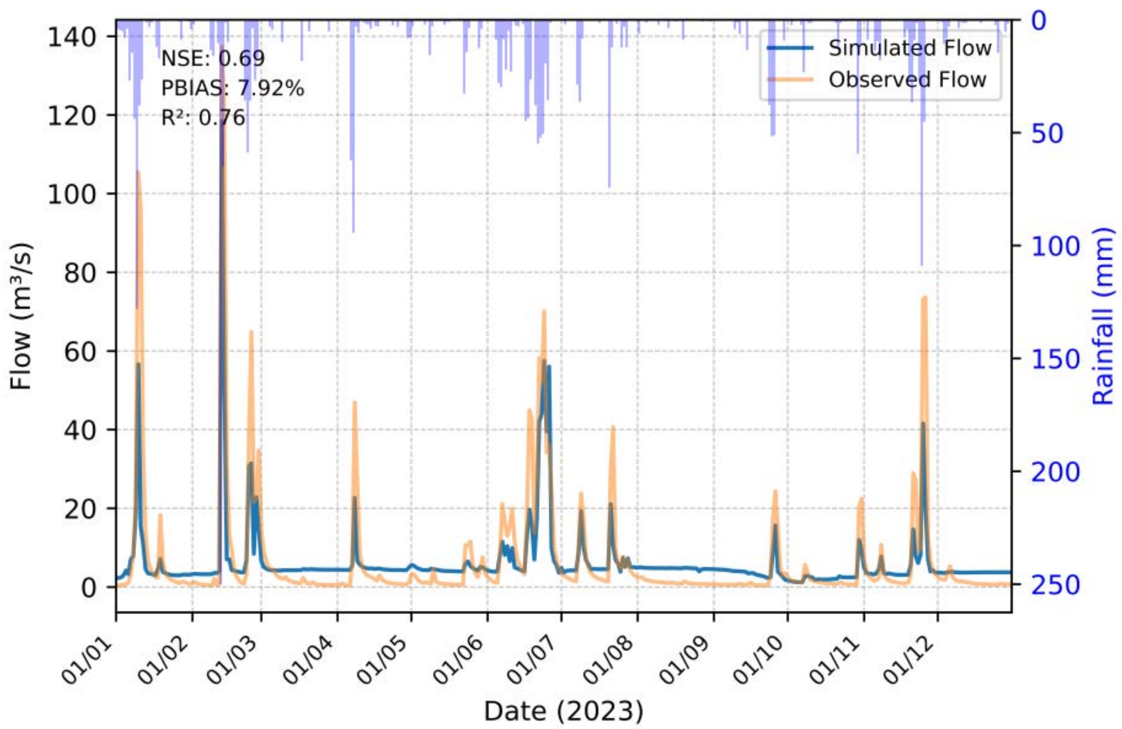


Figure 33 Initial model performance - 2023

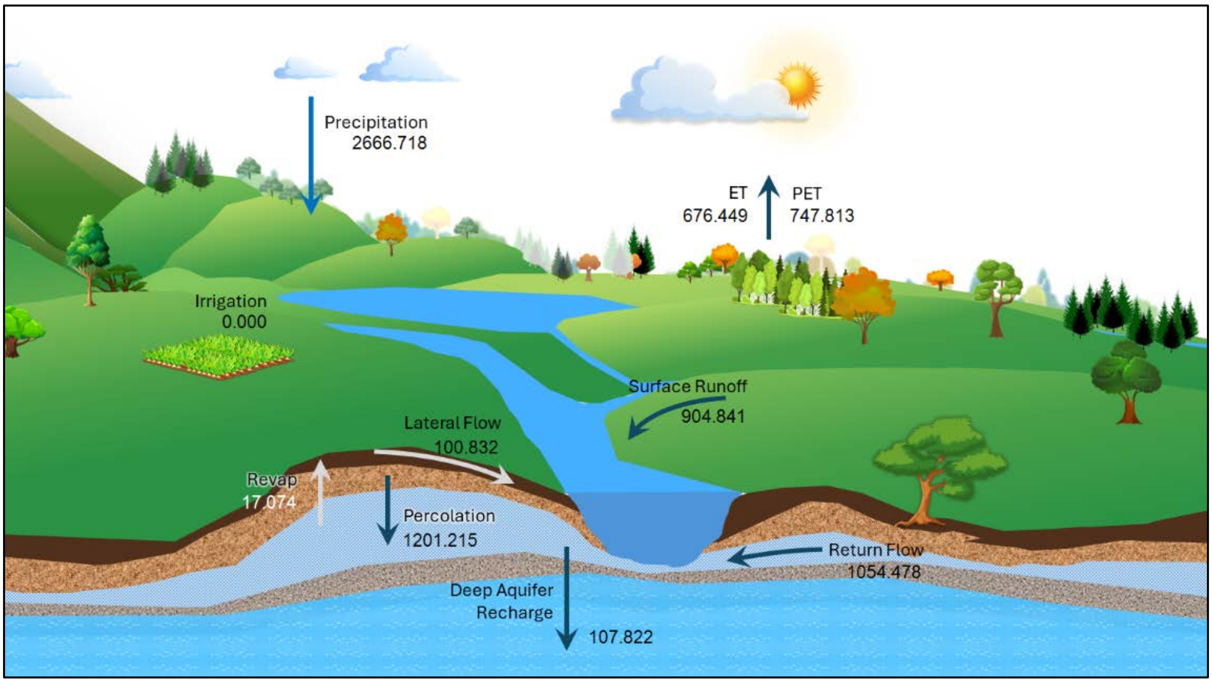


Figure 34 Initial water balance - uncalibrated

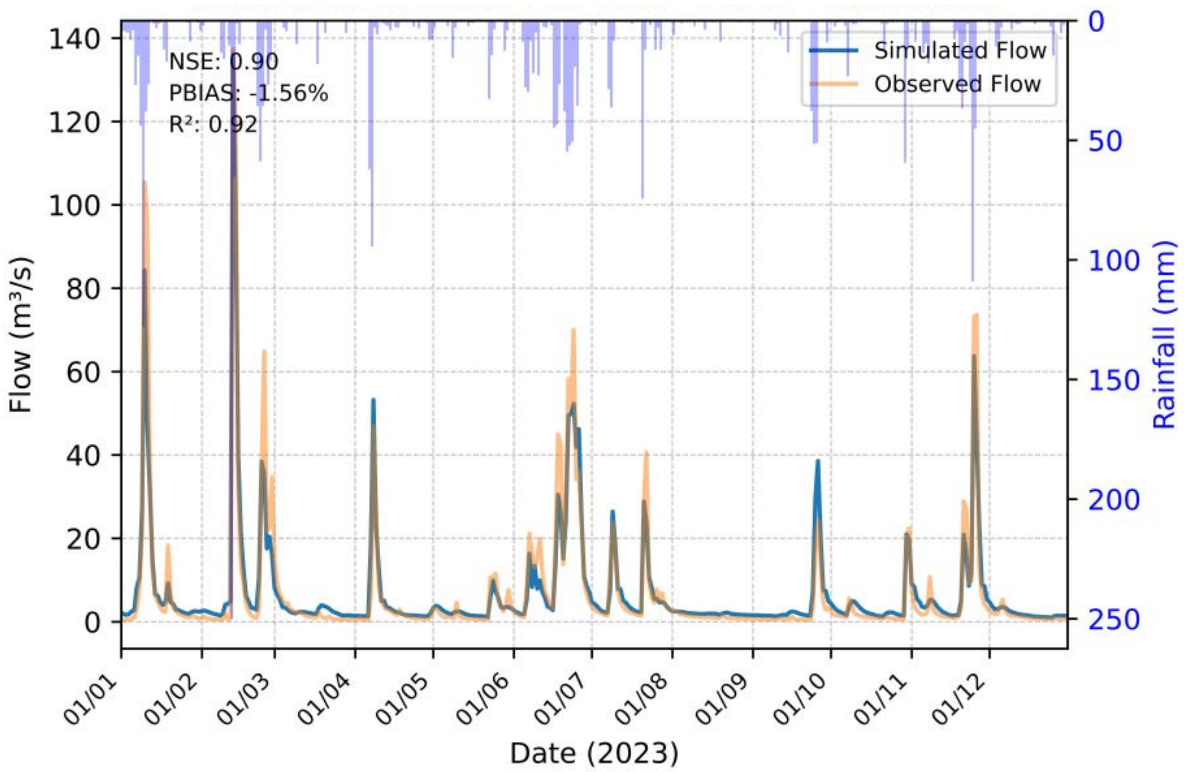


Figure 35 Calibrated model results

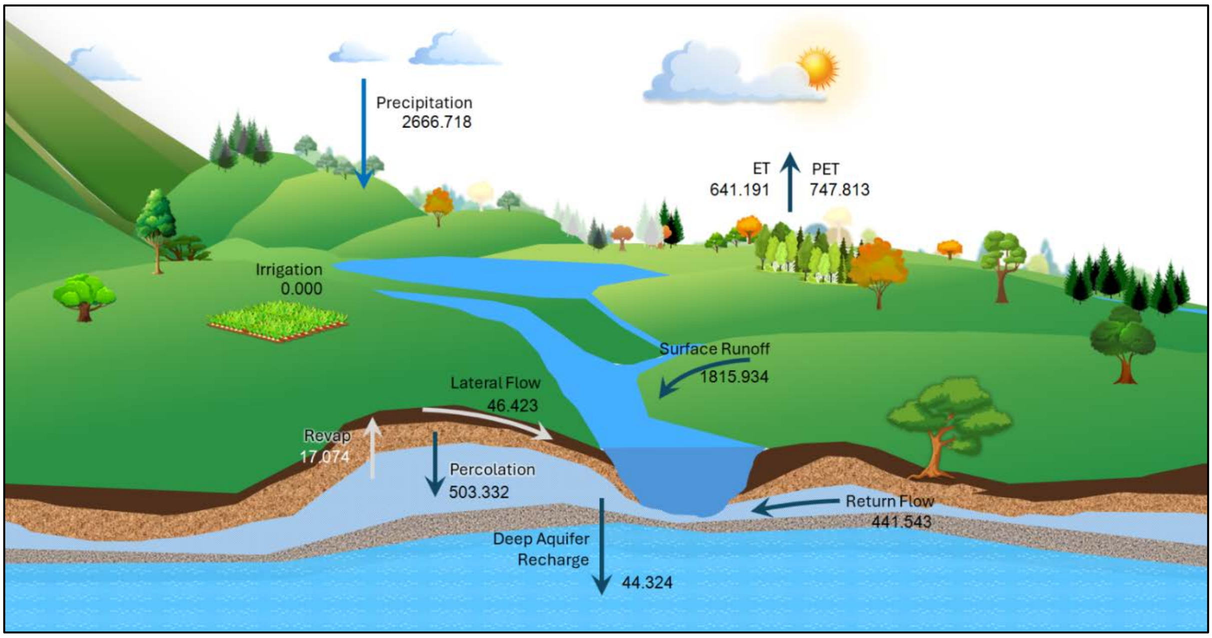


Figure 36 Post-calibration water balance

5.2.1 Validation

After calibrating for the six sensitive parameters outlined in Table 10, the model was validated on year-to-date flow records for 2024; the PBIAS and NSE were 0.87 and 0.9 respectively (Figure 37). An event-based validation was also run for dates 11/03/24 – 05/05/2022 (the 85th-percentile event selected for testing NBFM) (Figure 38).

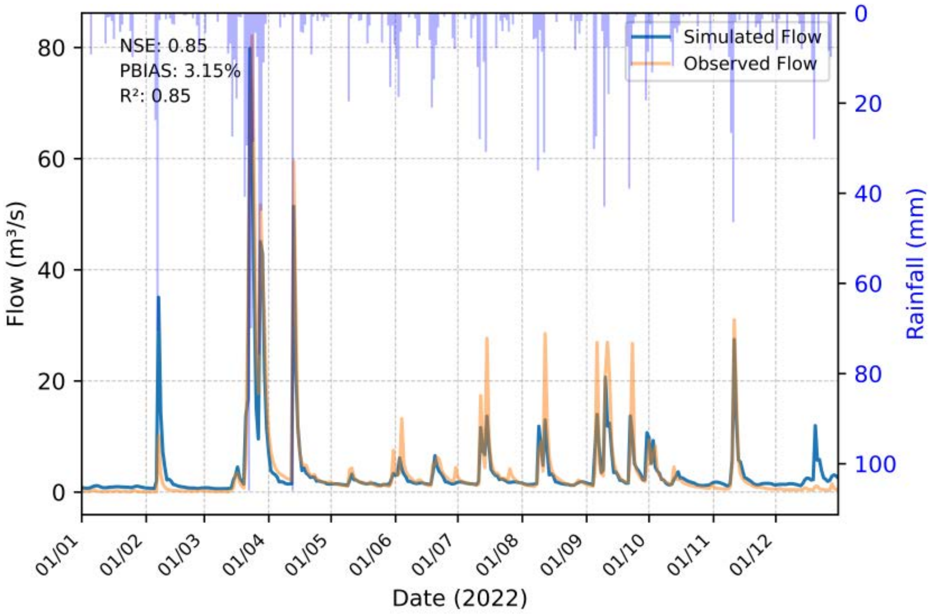


Figure 37 SWAT+ model validation – 2024

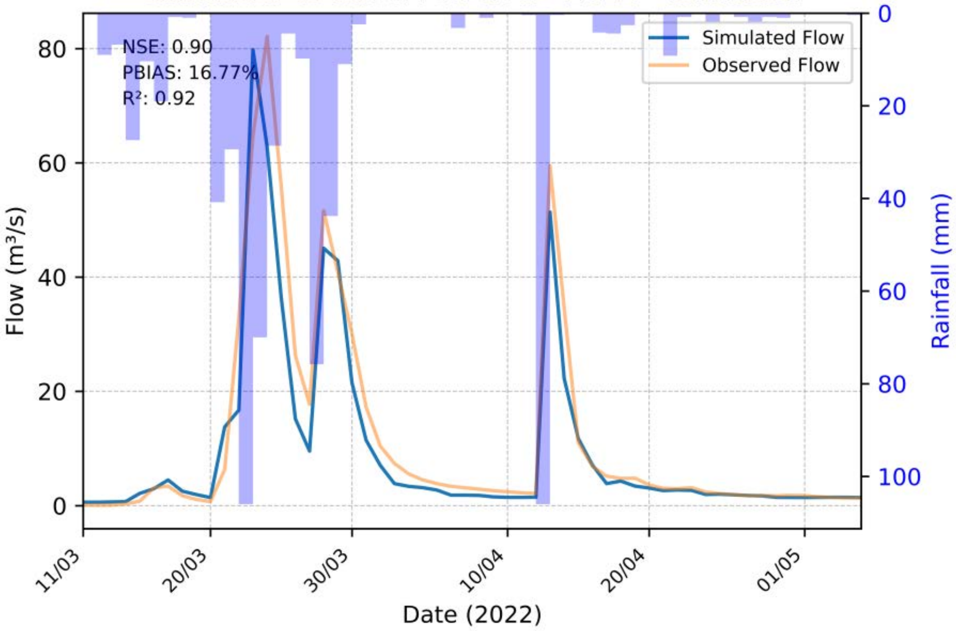


Figure 38 SWAT+ model validation – 85th-percentile event

5.2.2 Sub catchment validation

The sub catchment channel hydrographs for the event-based analysis were assessed using the NSE, PBIAS and R^2 (Table 9). The results of the calibrated model are plotted in Figures 39, 40 & 41. Note that the initial catchment-wide model was not recalibrated for each sub catchment, rather this check was done to observe relative influences of differing land use configurations on the calibrated model.

Table 9 Subcatchment validation differences

ID	NSE	PBIAS	R^2
S1	-5.02	0.19	0.19
S2	-42.63	52.34	0.09
S3	-1.43	36.70	0.61

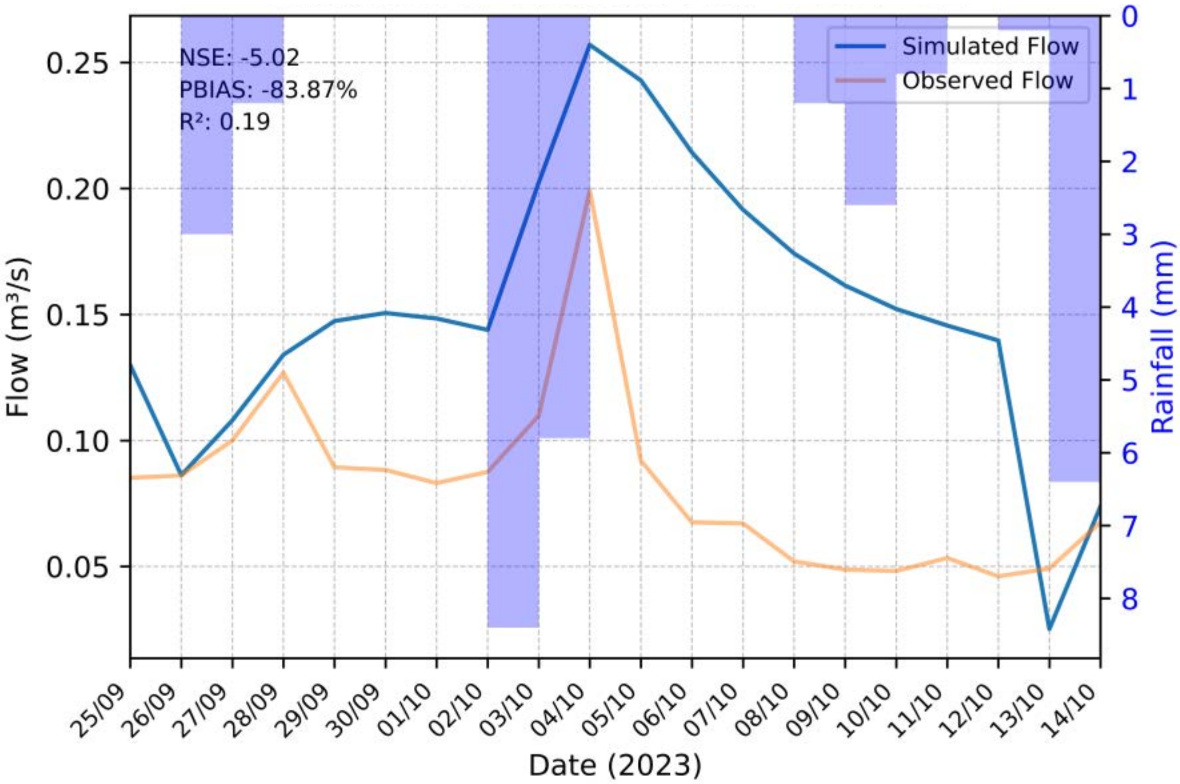


Figure 39 Subcatchment 1 – validation on project observed flow (rated)

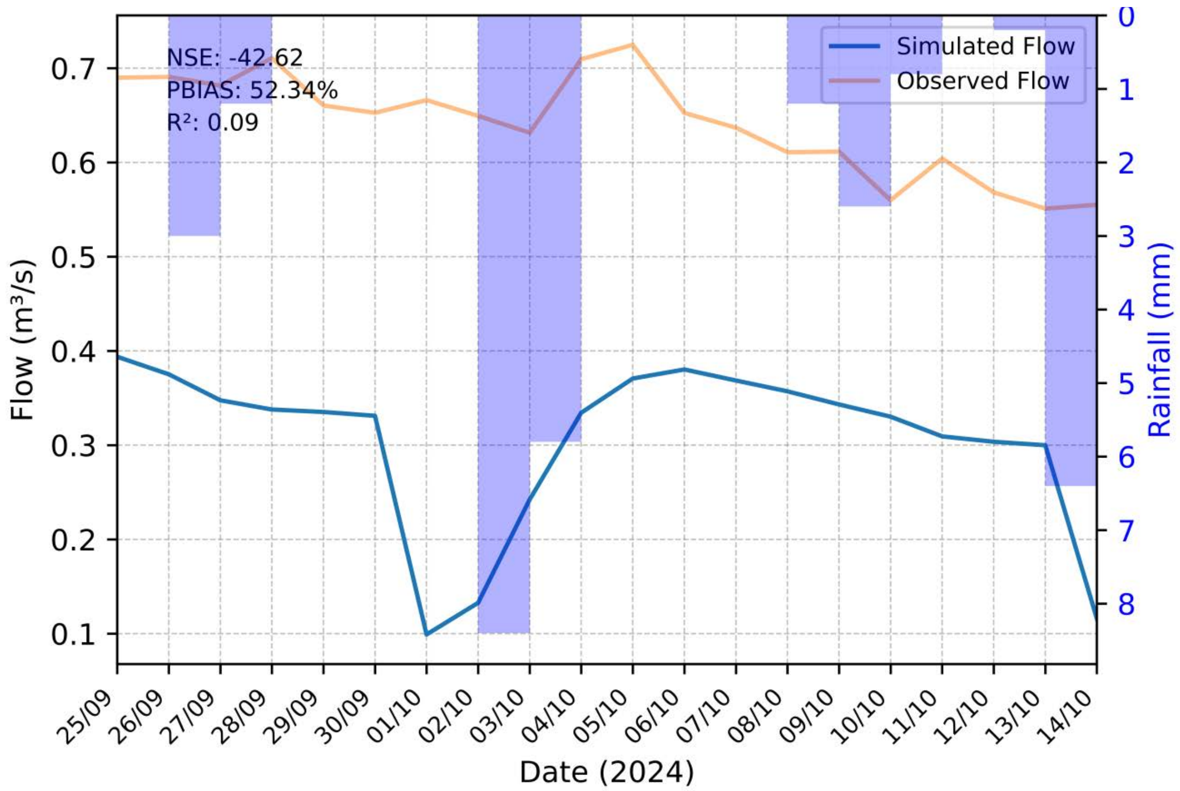


Figure 40 Subcatchment 2 – validation on project observed flow (rated)

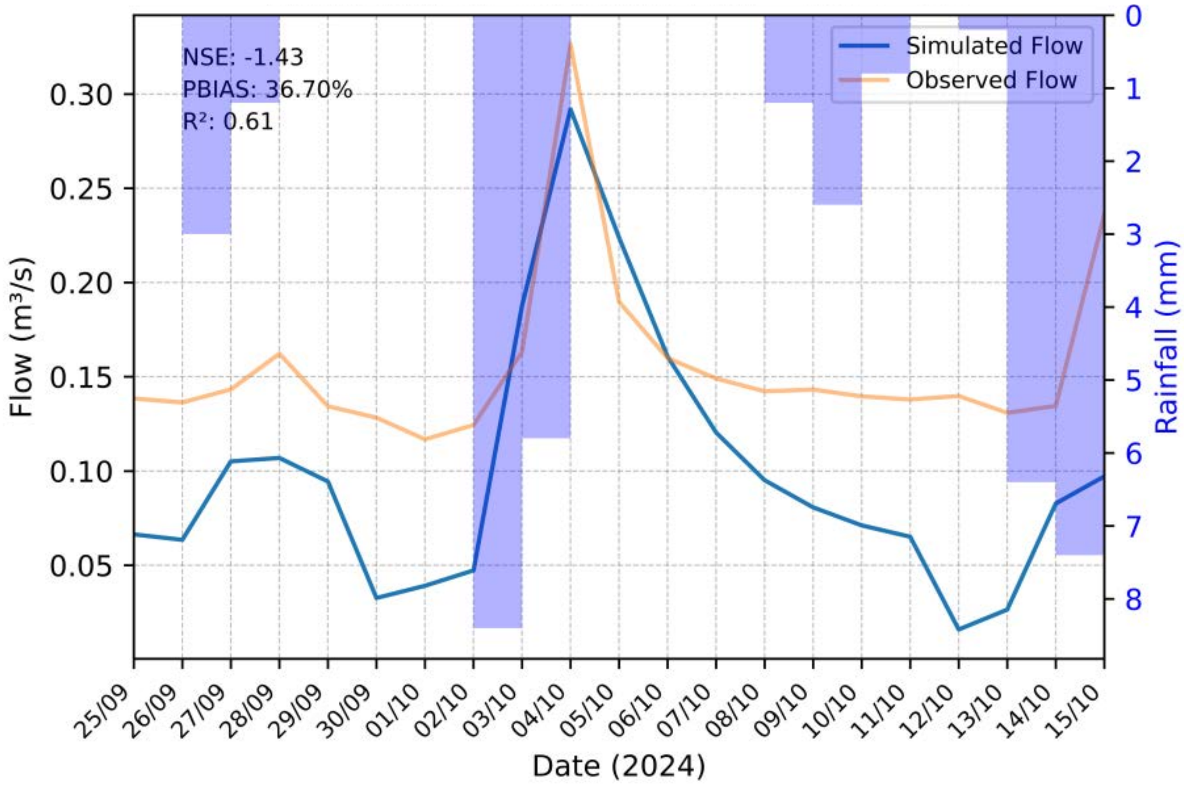


Figure 41 Subcatchment 3 – validation on project observed flow (rated)

5.3 Intervention results

The results of planned simulations (Table 1) are presented below in two parts; Figure 42 presents the land use conversion results, Figure 43 presents the land use conversion results with the wetlands added. The peak-flow reductions are summarised in Table 10.

The peak flow reductions show that the effect is somewhat proportional to the scale of intervention with T3W0 and T3W1 having the greatest effect. The simulated reduction in peak flows should be interpreted with parameter uncertainty (Table 8) and model uncertainty in mind.

Table 10 Peak flow reduction - summarised

Intervention ID	Peak flow reduction (%)
T1W0	-1.8%
T2W0	-27.7%
T3W0	-34.8%
T4W0	-32.5%
T0W1	-3%
T1W1	-3.2%
T2W1	-28.6%
T3W1	-35.6%
T4W1	-33.4%

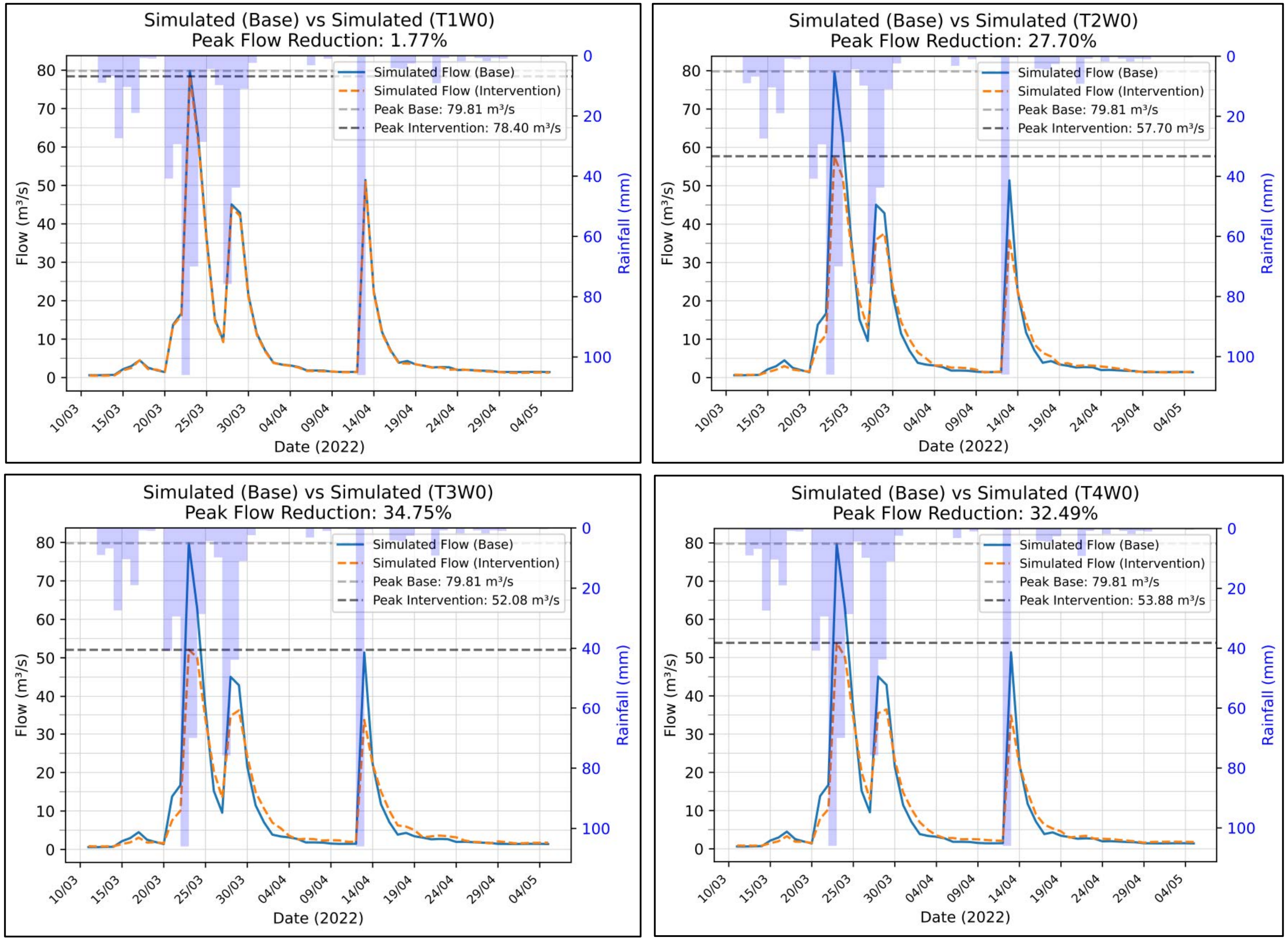


Figure 42 Event-based results on catchment hydrological response (land use - peak flow reductions)

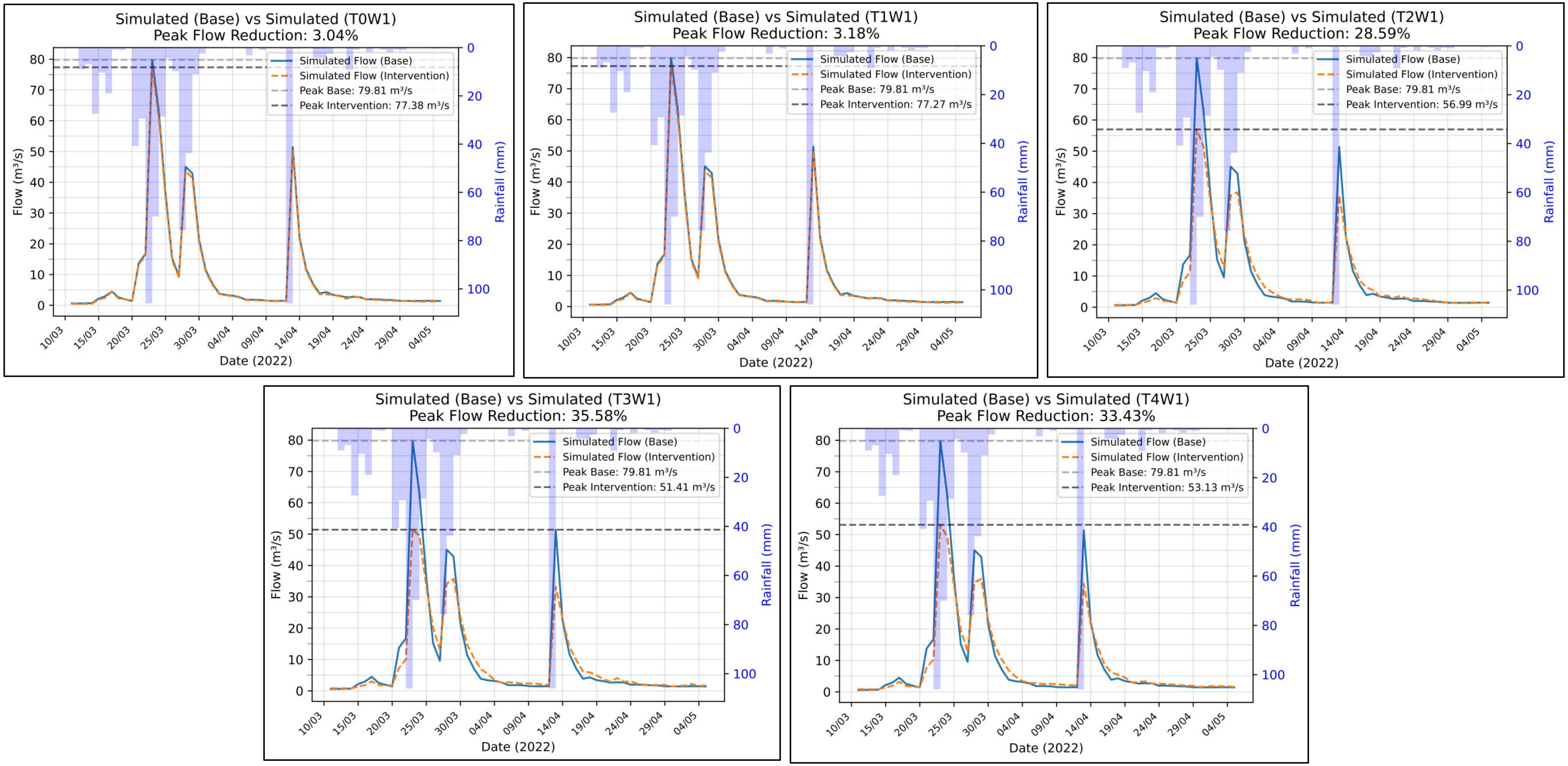


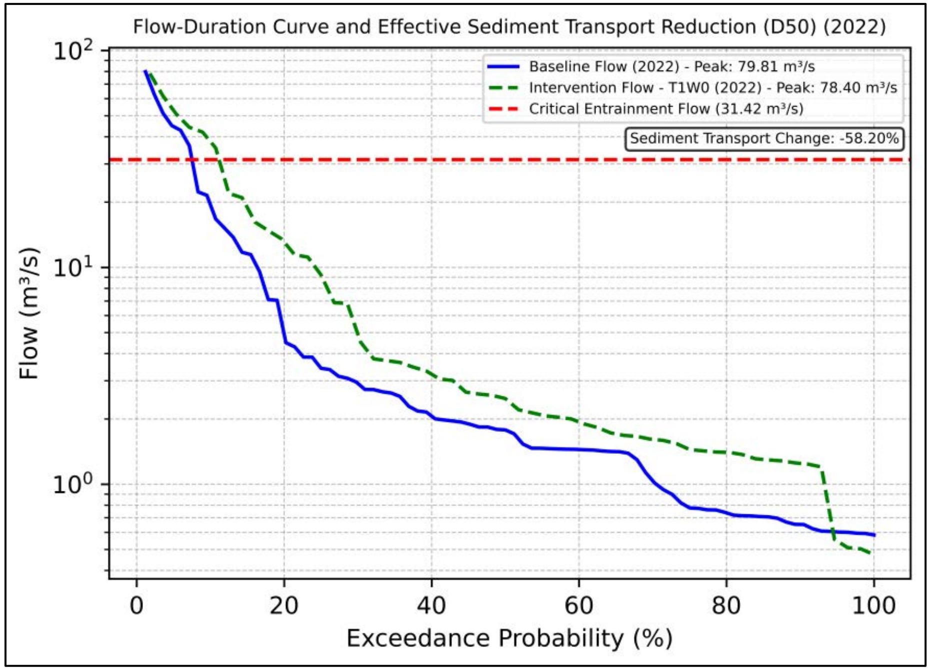
Figure 43 Event-based results on catchment hydrological response (land use + wetland - peak flow reductions)

5.3.1 Sediment transport effects – NBFM interventions

The effective reduction in peak flow was then translated into effective sediment transport reduction (%). The results of this analysis are presented below in two parts; Figure 44 presents the land use conversion results, Figure 45 presents the land use conversion results with the wetlands added. The effective sediment transport reductions of D_{50} are summarised in Table 11.

Table 11 Effective volumetric sediment transport reduction – summarised

Intervention ID	Volumetric Sediment Transport Change (%)
T1W0	-58.2%
T3W0	-74.4%
T0W1	-56.5%
T1W1	-58.2%
T2W1	-69.9%
T3W1	-74.1%
T4W1	-75%



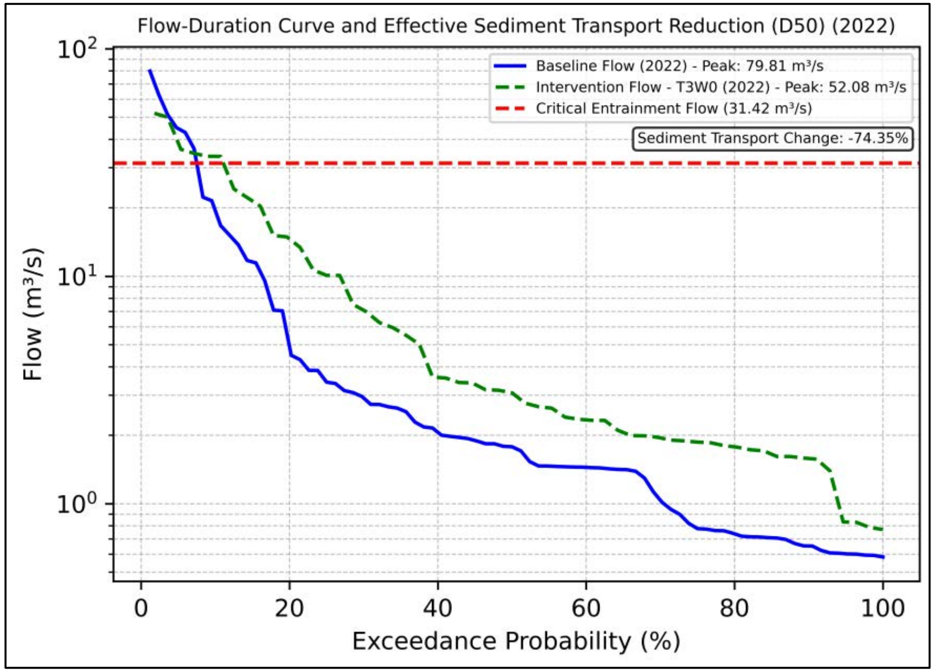


Figure 44 Event-based results on effective bedload sediment transport at Monowai (land use T1W0/T3W0 - peak flow reductions)

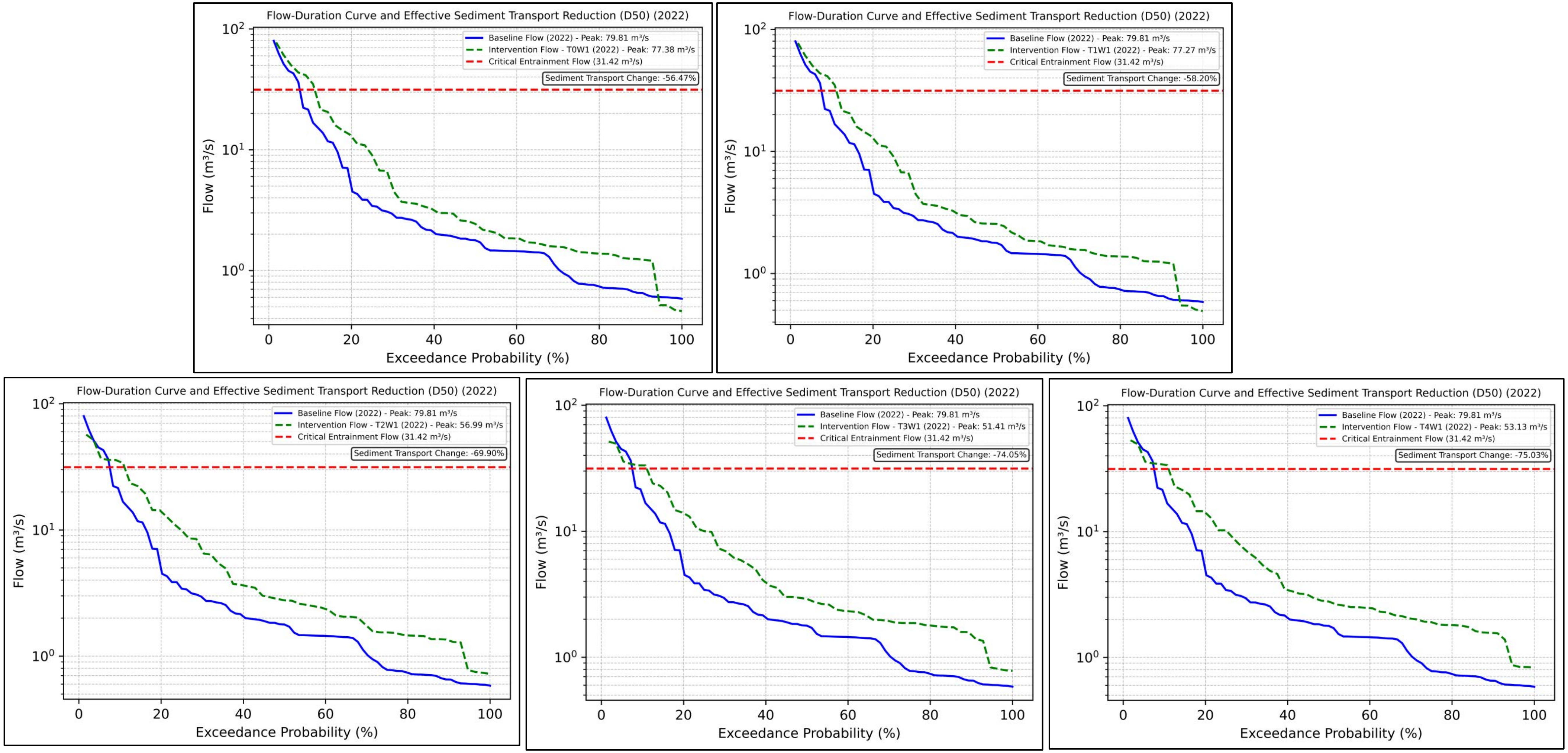


Figure 45 Event-based results on effective bedload sediment transport at Monowai (land use + wetland - peak flow reductions)

5.3.2 Specific wetland hydrological performance – NBFM interventions

The hydrological performance of specific wetlands (Figure 46) is presented below. This was measured at the receiving channel and by comparing the 'flo_out' hydrographs pre and post intervention for the T0W1 case (wetlands only).

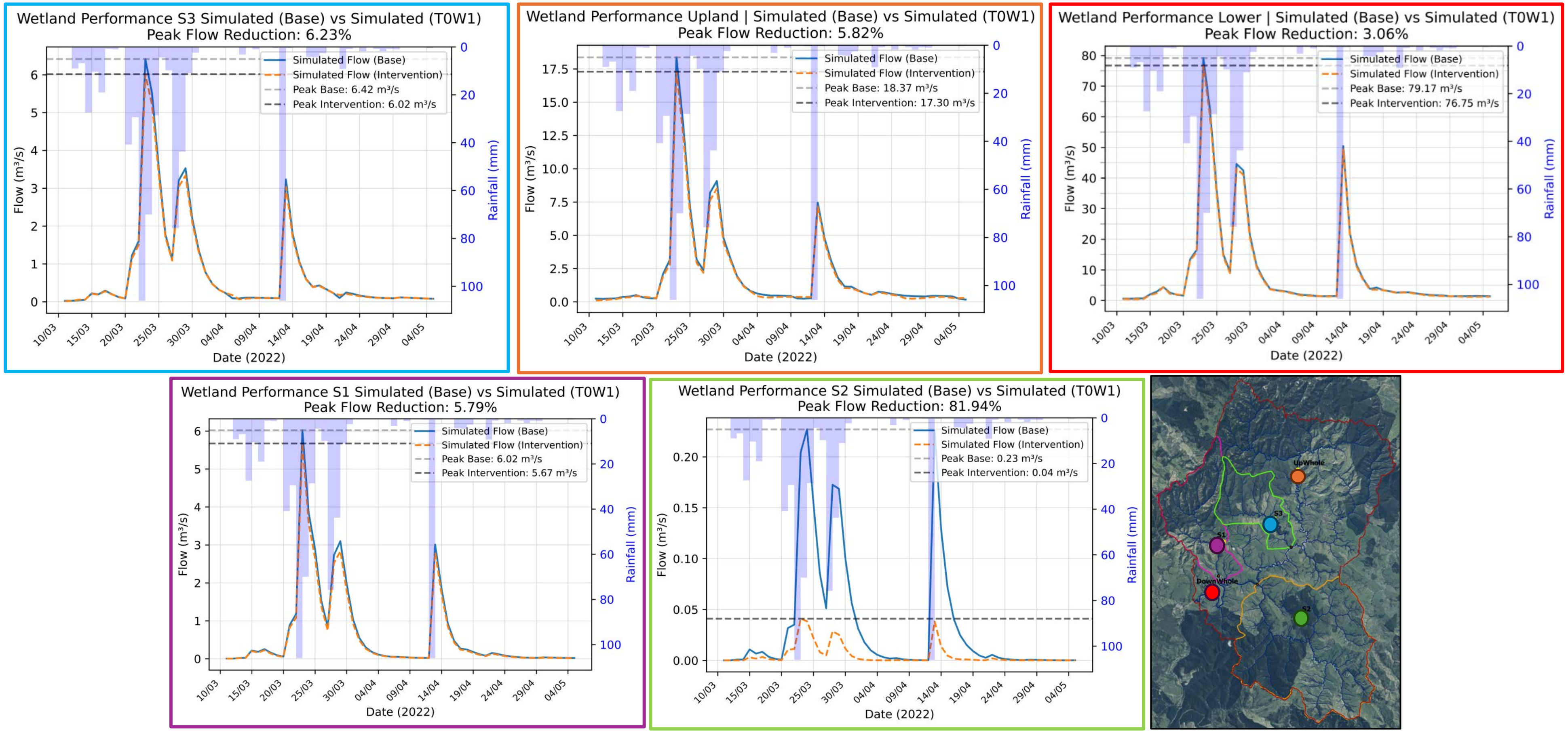


Figure 46 Individual wetland flood peak attenuation, measured from downstream channel flow

Chapter 6 Discussion

6.1 Introduction

This chapter critically discusses model performance and results of NBFM interventions for managing the Waimatā River, focusing on calibration, validation, and their implications for peak flow and sediment transport reductions (Table 1). It examines both epistemic and aleatory uncertainties and their propagation through the analysis. The findings suggest strategic NBFM interventions in the upper valley can reduce flood risk, aiding biogeomorphic recovery and highlighting the role of land cover in shaping current catchment dynamics.

6.2 Model performance

The SWAT+ model deployed for this research performed well once calibrated. A NSE score of 0.85-0.9 for the whole of catchment validation suggests that the model can explain 85-90% of the variance in the observed flow data (Figure 37-38). As SWAT+ is a process-based (distributed) model, this means that most, if not all, complex hydrological processes were accounted for correctly in the calibration stage (Table 8; *see* Section 2.2).

The PBIAS of 3.15% indicates a slight positive bias, meaning that the model systematically over-predicts values by ~3.15% (Figure 38). Figure 38 (event-based validation) has PBIAS of 16.77% indicating moderate-positive bias. This is likely related to the proportion of time that baseflows are being considered in the calculation (relative to peaks); under the yearlong validation test, the model accurately predicts baseflow with observable deviations in peak estimation accuracy. The slightly lower R^2 value observed in the yearlong validation (0.85 instead of 0.9) is consistent with this theory.

Visual interpretation of Figure 37 suggests baseflow contributions are well-represented, with smaller peak events systematically underestimated. However, the selected 85-percentile event is well represented by the model in both Figure 37 and 38. Overall, the event-based validation is well predicted with baseflow recession occurring slightly faster than seen in the observed data – although this is difficult to infer on account of the daily simulation timestep (Figure 6). The literature suggests that a NSE of > 0.75 is an acceptable model from which you can make inferences (Kumar et al, 2017).

6.2.1 Subcatchment validation

The calibrated model has considerably worse performance when simulated hydrographs at the subcatchment outlets were compared to observed data collected as part of the project. Interestingly, Figures 39-41 show a range of over- and under-prediction across the subcatchments selected for testing model performance. Subcatchment S3 had the closest fit to observed data (NSE: -1.43, PBIAS: 36.70, R2: 0.62), with Subcatchment S1 as next best performance (NSE: -5.02, PBIAS:0.19, R2: 0.19). S2 had the worst performance (NSE: -42.63, PBIAS: 52.34, R2: 0.09). The variance in results at each Subcatchment can be explained by several factors including:

1. Land use parameterisation focused on replicating the daily flow hydrograph for the study area. In smaller upland subcatchments, variation within a land use type (e.g., exotic forest) is more significant for runoff generation. Certain land use classes deviated more from the calibrated state, likely due to differences in soil health, water capacity, and roughness characteristics based on the duration of land use.

2. Differences in the relative accuracy of observed data and its translation from raw water level data. The continuous water level data was translated to flow data through a separate hydraulic modelling procedure. While best efforts were made to make this procedure consistent, here lies an assumption that Manning's n value calculated from each site are an accurate representation of the channel roughness (Eq.1; see Section 2.2.2). It is relevant to note that the subcatchments do differ in size, with S2 being approximately 4 times the size of S1 and 3 times the size of S3. This matters as the gradation of particle sizes on the bed is less sorted in smaller subcatchments (typically).

3. Larger catchments have proportionately higher flows and water yield. As discussed, the model calibration for land cover was based upon the average fit (representing the range of variance across and within land cover types in the catchment). With proportionally higher flows to be accounted for, the spatial distribution of rainfall must also be accurately inputted to the model domain. The model used two weather stations (Monowai and Wakaroa Trig), likely missing complex local orographic effects. Rainfall varies with topography and event size (Chappel, 2016); Wakaroa Trig had 15% more rain than Monowai in 2024, though daily averages in 2023 were similar (Wakaroa 7.55 mm/day, Monowai 7.24 mm/day).

4. Calibration (2023) followed a long La Niña phase with high soil moisture and faster flooding responses. Subcatchment validation (2024) started during an El Niño phase with likely lower soil moisture.

5. Local differences in soil type (spatial configuration) or physiography.

S2 likely had worse performance than the others as it was significantly larger and had a higher percentage of pasture (57.8%) and exotic forest (30.5%) land cover (Appendix E). The pasture and industrial forestry landcover types are more likely to have intra-unit variation because of soil degradation and erosion over time.

Overall, the model performed well enough to achieve our aim of assessing the relative magnitude of effect for NBFM interventions proposed. This analysis of relative magnitude is most accurate when evaluated from the Monowai Station (where the model was calibrated). The subcatchment validation suggests that considerable model and parameter uncertainty exists. This indicates that model results should be interpreted within error ranges (*See* Section 6.6).

6.3 Reduction in peak flows

The model results show that the interventions have the potential to offer a wide range of flood attenuation benefits, ranging from lower intervention with lower resultant attenuation, and higher intervention with higher observed attenuation (Table 10). T3W0 offers the greatest reduction in peak flow (~34%) but also comprises the largest areal change from the current state. T4 has a broadly similar effect on attenuation (~32%).

T1 and T2 are the lower end of the intervention gradient and offer ~2% and ~27% reduction, respectively (Table 10). T1W0 being less effective is a function of the reduced area being converted to native forest, as well as the proportion of existing land use already occupied by native forest (no net change). Overall, only 1.2% of the catchment is mapped as Class 8, with approximately two thirds of this already in native forest (Appendix E). The north-west corner of the project area has a section of class 8s1 that is currently primary successional forest (mānuka/kānuka). The results indicate that if this was actively managed to transition to mature forest the resultant flood attenuation effect could be in the order of 2%.

The T2 intervention, including Class 6 and 7 together comprising ~70% of the study area, was intended to show the proportionate effect of retiring steep and unsuitable lands back to native forestry (up to 28% reduction). Acknowledging that this contains a significant portion of the total land, the design of T2 (and T3/T4) may be scaled back in practice. The results show the relative hydrological effect of land use change for different land use capability classes, intended to inform decision making around critical land use planning for flood risk management.

6.3.1 Wetland interventions

The wetland interventions (T0W1) show a ~3% reduction in peak flows as measured at the Monowai gauge site. The individual wetland performance (Figure 46) shows varying effectiveness, and this is broadly explained by the following factors:

1) Position of the wetland relative to upstream land use area. The size of the wetlands is ≤ 5% of the contributing catchment area and each site was developed using a consistent design approach (NIWA, 2021). However, the subcatchments each yield different average daily flow due to land use configuration and relative size of the catchment, this explains the differences in performance.

2) Soil type and saturated hydraulic conductivity (k). Each wetland was set up with the pond bottom reflecting the soil type and k value of the area surrounding the locale.

3) S2 is the only wetland with significantly less contributing catchment area and is placed on a perched ridge. The enhanced flood attenuation capacity (81.94%) is expected, due to the lower input flows from a reduced upstream catchment area.

Overall, the wetland NBFM results highlight a significant reduction in peaks flows. The design and analysis approach used provides insight to scale of intervention required to modulate the hydrograph in the upper Waimatā. The design of constructed wetland features should consider the long-term maintenance of these features, including sedimentation management, weed control, structural integrity of bunding for flood storage. Over longer durations the flood control benefit of constructed wetland may increase on account of maturing wetland flora communities and biomodification of soil (NIWA, 2021).

6.4 Reduction in geomorphically-effective flow rates

The reduced peak flow results were translated to effective reduction in volumetric sediment transport (bedload). Given the non-linear relationship between discharge and sediment transport (Beven, 2012; Wilcock, Pitlick and Cui, 2009), even a relatively modest reduction in peak flow is expected to lead to a substantial reduction in bedload transport potential (Hankin et al, 2019).

The calculation of bedload transport is likely subject to well-documented uncertainties relating to grain size heterogeneity, packing of the bed material and intermittent supply from upstream (see Section 2.4). Nonetheless, for comparison among flood scenarios, a reduction in peak flow leads to lower flow depth and shear stress, making this a vital measure of the erosive potential during a flood event. The upper tributaries of the Waimatā are likely transport limited and therefore have an 'endless' supply of bedload sediment to rework (Whipple & Tucker, 2002). This makes strategic interventions which reduce effective sediment transport even more relevant.

Figure 45 shows T1W0 reduces D_{50} transport by ~58% at the Monowai station, and T3W0 by ~74% (Table 11). The wetland cases offer reductions in the order of ~56% (wetlands only) to ~75% (T4W1). Interestingly, the 30m riparian buffer case resulted a larger reduction in sediment transport than the T3W1 intervention. This may suggest that heightened channel roughness related to streamside vegetation plays an influential role in channel hydraulics and sediment transport (Fryirs et al 2023; Doane et al, 2024).

6.5 Management implications

This section outlines the possible implications of the findings, with an emphasis on nature-based flood risk management, potential cumulative impacts and possibilities of upscaling the approach that was assessed.

6.5.1 Current geomorphic trajectories and management interventions

This section outlines the current geomorphic behaviour of the Waimatā catchment (high-level), discussing possible influences on behaviours, and current trajectories following NBFM intervention. Cullum et al (2017) classify the River Styles of Waimatā, describing the behaviour and capacity for adjustment through each section of river (Figure 19).

The interventions proposed in this report span steep headwater environments, earth flow tributaries and channel sections partially confined by terrace (Figure 13). Currently, the main channel exhibits medium-high energy conditions, with significant storage of sediments that are transported downstream during flood events (Cullum et al., 2017; Harvey, 2021). The flashy flood regime is directly related to a more homogenous in-channel form, where geomorphic roughness elements are broken up and transported downstream under intense flows. Reducing geomorphically-effective flood duration through NBFM is likely to result in the following behavioural adjustments:

1) Earthflow tributaries (with moderate sinuosity) will build geomorphic roughness elements over-time, which act to protect against channel incision. Riparian planting will introduce wood elements into the stream which add to channel roughness and further reduce cumulative flood peaks downstream (Gurnell et al, 2002).

2) Steep headwaters (little/no floodplain) have no capacity for adjustment and are efficient conveyors of flood water. Increasing out of channel storage through implementation of RAF and replanting hillslopes will reduce flood/sediment volumes (peaks) entering the channel. This will contribute to cumulative benefits of reducing flood risk and erosion/deposition downstream (Harvey, 2021).

3) Channels that are partly confined by terraces (alternating floodplain pockets) may build geomorphic structure and increase instream habitat through heterogeneity. Reduced peak flows will support the accumulation and interbedding/interlocking of geomorphic units which provide habitat for instream flora and fauna (Fryirs and Brierley, 2012).

6.5.2 Biogeomorphic recovery potential

Biogeomorphic recovery is an applied river management concept which is underpinned by the mutualistic interactions between physiographic form and ecological process (Fryirs, 2024; see Section 2.5). It differs philosophically from restoration (working to revert to a prior intact state) and instead considers the evolutionary trajectory of a river system, the interactions between form and process and the role that vegetation plays in conditioning physical habitat structure. Necessary to this reframing of management ideals is the acceptance of shifting boundary conditions which control the behaviour of the system (Fryirs, 2024). Boundary conditions in the Waimatā context comprise sediment/vegetation interactions, climatic conditions and tectonic adjustments through time. The peak flow attenuation of wetland and land use conversions must be considered in relation to climatic variability (Figure 13-15), and climatic change in years to come. The assisted recovery potential of NBFM interventions presented in this report likely support a shift towards enhanced instream habitat quality, both from a structure (see Section 6.5.1) and water quality perspective. Constructed wetlands presented in this report are designed to attenuate flood peaks as well as provide water quality benefits (NIWA, 2021).

O'Donnel, Fryirs and Leishman (2015) evaluated the potential for upstream riparian planting efforts in degraded channels to translate cumulative ecological benefits downstream. They found that upstream riparian planting prompted biogeomorphic succession of downstream bars, benches and floodplain units through wind and hydrochory (seed dispersal by river flows). Altered hydrological regimes (reduced peaks and lower sediment transport capacity) will increase the likelihood of natural seed establishment on instream/bank geomorphic units in the Waimatā (especially T4W1/T4W0). Intentional planting efforts in the riparian corridor could be used to ensure that the seedbank has appropriate species present to recolonise downstream banks and instream habitats (O'Donnel, Fryirs and Leishman, 2015; Fryirs 2024). Species selection must include species suited to hydrochorous dispersal and establishment within dynamic in-channel geomorphic units. As well as mānuka, other common native genera include: *Juncus, Carex, Hyrocotyle* and *Veronica* (to name a few). It is important to consider the active management of these riparian ecosystems - separating livestock with stock-proof fencing and regular weed control efforts are fundamental to their success long-term. Potential cumulative impacts of NBFM in the Waimatā are provided in Appendix F.

6.5.3 Possibilities for upscaling in the Waimatā (whole catchment)

Several initiatives/projects already exist in the Waimatā catchment which target forest restoration, erosion management and river recovery (Chapter 2.3; Appendix D). This research offers a perspective and rationale for scaling the active forest management efforts for commensurate reduction in flood risk. Detailed design of these NBFM measures should also consult with the Mauri Compass, to ensure that the whakapapa and relational linkages of the Waimatā are moving toward a state of 'ora' (see Section 3.6.1).

This research provides an appraisal of the prospective outcomes of NBFM actions in the upper Waimatā. A spectrum of low-to-high-cost interventions are provided to give context to likely flood risk reduction resulting from practicable management actions. The findings should be considered in the future planning of land use, reforestation efforts and river restoration in the Waimatā. The information could be used to steer reforestation efforts under the 'Recloaking Papatūānuku' project (Pure Advantage, 2023) as well as align ongoing planting efforts under a holistic catchment perspective (Appendix D).

6.6 Limitations

The research approach, modelling results and insights gained are reflective of both the project time constraints and the word count imposed on this master's research. Nonetheless, the procedural modelling approach deployed presents useful insights into the complexity of the Waimatā hydrological system, especially land cover sensitivity (Figure 7). Overall, the modelling results present a high-level account of the relative magnitude of effect that might arise from strategic NBFM deployment. Considering the uncertainty associated with the model and parameterisation, the results should be interpreted within a suitable range of error (Table 8, Figure 27). To summarise:

- +/- ~10-15% for estimated reduction in peak flows,
- +/-~15-20% for estimated reduction in bedload sediment transport,
- +/- ~50% for evaluation of specific wetland performance higher up in the catchment.

The error ranges presented include model validation metrics (NSE, PBIAS, R^2) and account for parameter uncertainty, measurement uncertainty, computational uncertainty, and epistemic uncertainty (unknowns propagated through the analysis). Examples of epistemic uncertainty include discrepancies between land cover input data and actual conditions, as well as limitations of rainfall data interpolated from only two points, which may not capture complex rainfall patterns. Given these factors, the results should be interpreted within a conservative error margin (as above).

Chapter 7 Conclusion

Marked differences exist between the past and present states of the Waimatā River. A sense of what is realistically achievable must be used to drive future management aspirations, including working with the river as it is today. The communities of Waimatā and Gisborne are living with the river and are actively working towards improved river health (Waikereru, 2024). The local community are demanding action that aligns with resilience and recovery from Cyclone Gabrielle. Their vision including flood prone land being managed sustainably, riverbanks planted with erosion-resistant plants and reprieve from the damage that the forestry industry has caused (slash). In their recent community recovery plan, they call for 'serious interventions – not just band-aiding when situations are serious'.

This research has highlighted that implementing NBFM in the catchment has the potential to provide significant benefits, including effective flood risk reduction (~34%), erosion control (~75%), improved water quality, and enhanced habitats for flora and fauna.

Adaptive management approaches, including regular monitoring of realised success, is a crucial part of the next steps for management of the Waimatā river.

'E kore te pātikie hoki ki tōna puehu'

(the flounder does not return to its dust – we shall learn from our mistakes (and the mistakes of others))

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Appendices

Appendix A: Wetland intervention design

The methodology for selecting wetland sites included a raster multicriteria analysis including slope suitability, distance to the stream and land use capability (suitability). The rationale for selecting wetlands (Figure 1) is described in Table 1 below. Raster calculator was used to combine reclassified layers, final classes 1-3 (Figure 1) represent areas that meet the initial conditions across all three classification layers.

Table 1 Wetland design specifications

Classification type	Rating level	Characteristics
Slope (°)	1	0-3
	2	3-7
	3	7-15
LUC (class; 1-8)	1	1-3
	2	3-5
	3	6*
Distance to stream (m)	1	0-20
	2	20-50
	3	50-150

**Note: LUC class 7-8 were excluded from wetland suitability due to exceedingly high slopes.*

Following raster classification, a visual interpretation of results was undertaken and sites were chosen which directly overlapped with final classes 1 and 2. The sites were developed at high-level to explore the hydrological influence of constructed wetlands on the Waimatā hydrology and flood responsiveness. The wetland sites have a volume derived by the extent, assuming (NIWA, 2021):

- 70% of the wetland area has a water depth of 0.3m (hydrophyte area)
- 30% of the wetland area has a water depth of 3 m (sedimentation pond)
- 1.5 m bunding around the wetland extent (dead storage, flood attenuation capacity)

The final volume considered in the modelling study assumed an average depth of 1.1m for the base pond + 1.5 x area (flood attenuation bund). The wetland site specifications are provided in table 2 below.

Table 2 Wetland design specifications

Id	**Location**	**Area (m^2)**	**Volume (m^3)**
1	S3	19,213.2	31,990.0
2	Up catchment	153,247.0	255,156.2
3	S1	33,470.9	55,729.1
5	Low	4,886.4	8,135.9
6	S2	6,322.6	10,527.1
7	S3	7,726.6	12,864.7

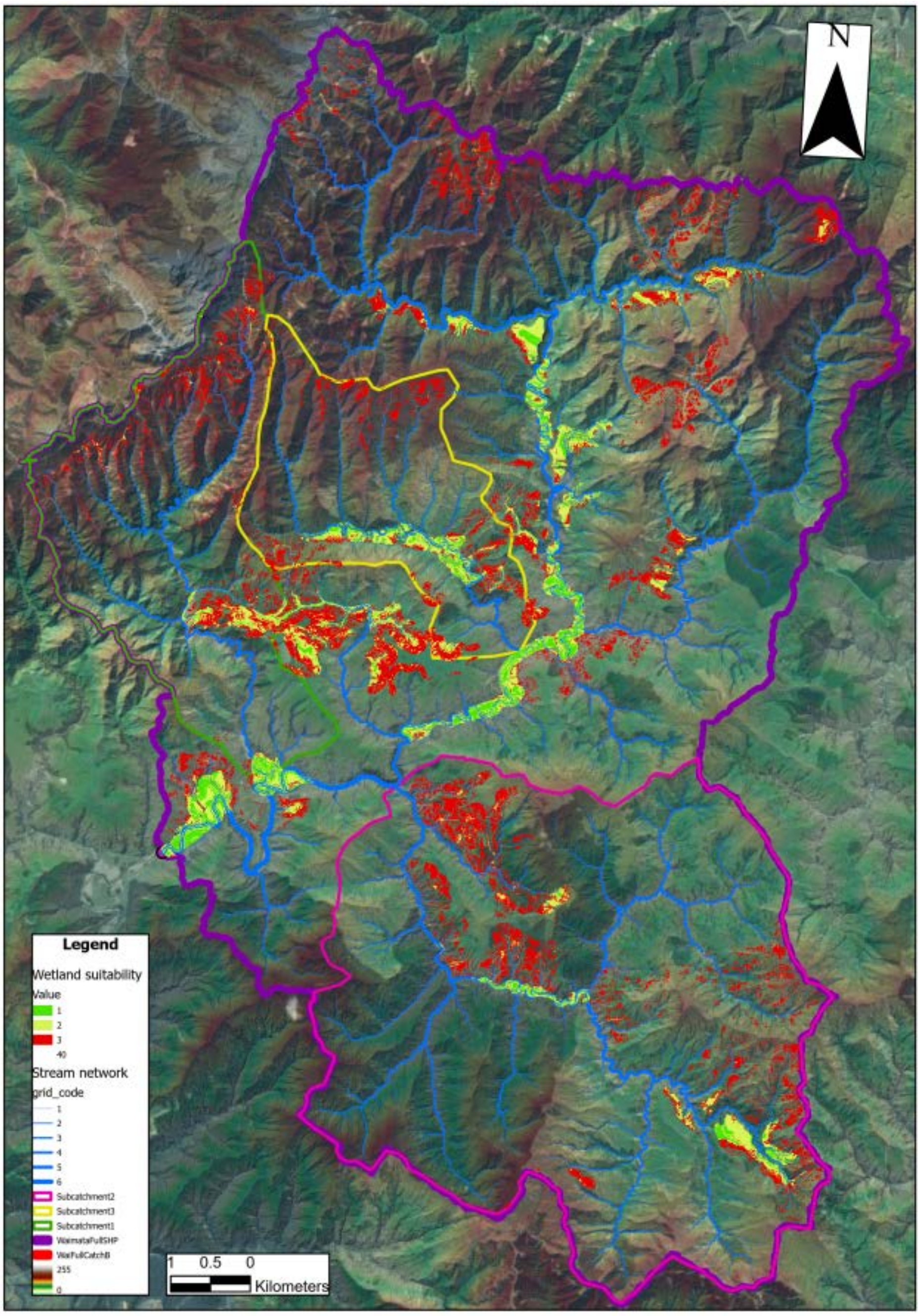


Figure 1 Wetland Suitability Mapping (Classes 1-3)

The conceptual design of wetlands can be extended during the detailed design phase to meet water quality treatment goals and habitat improvement goals by tailoring the pond cell design arrangement and specific planting plans. The reference for wetland design was taken from the technical guidelines for constructed wetland treatment of pastoral farm runoff (NIWA, 2021). The end design should look to maximise the distance travelled by water as well as the dead storage capacity which provides flood attenuation during high rainfall. The intended designs look the below with added dead storage capacity though bunding (Figure 2).

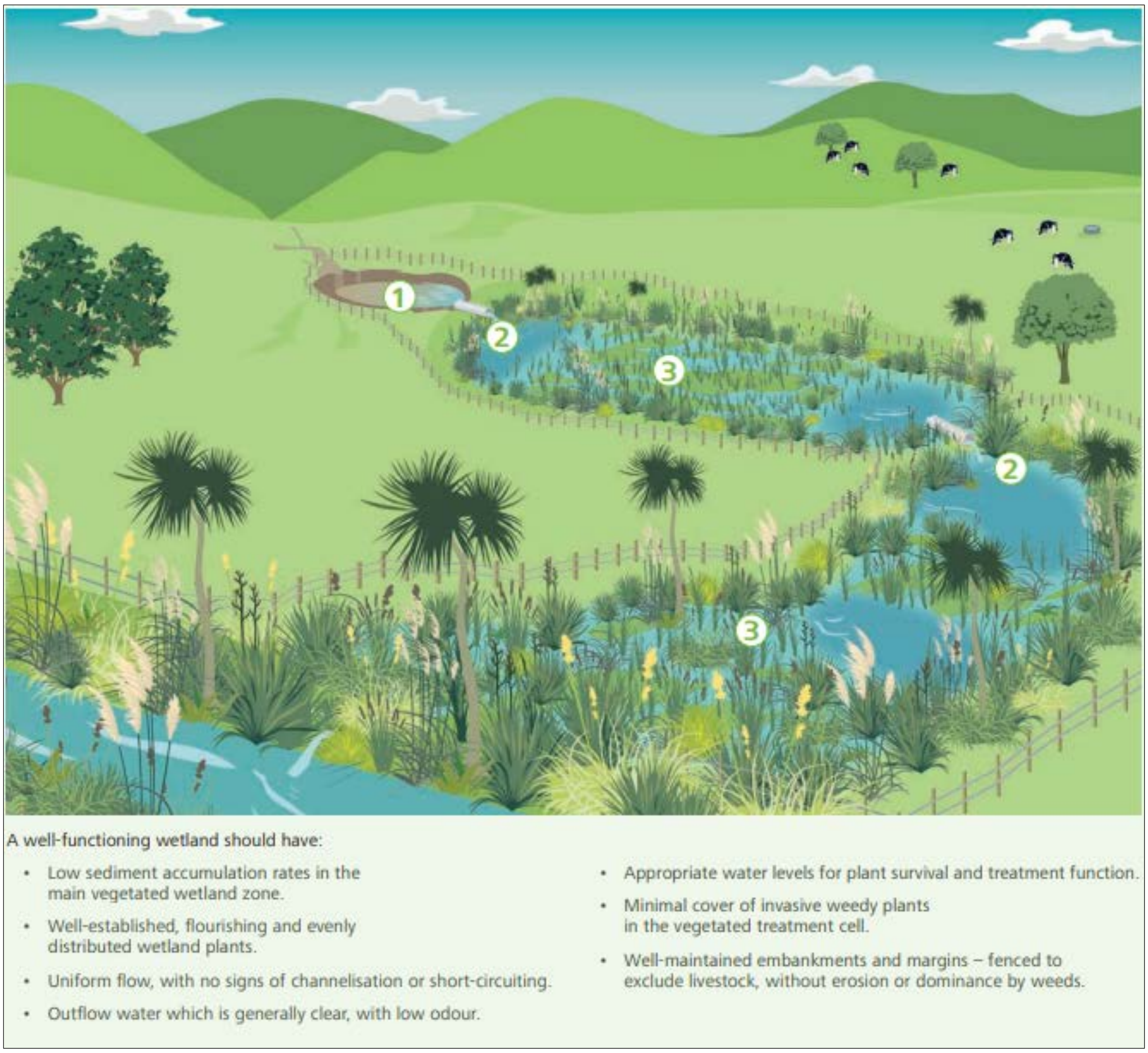


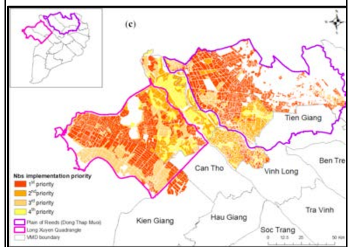
Figure 2 Constructed wetland (NIWA, 2021)

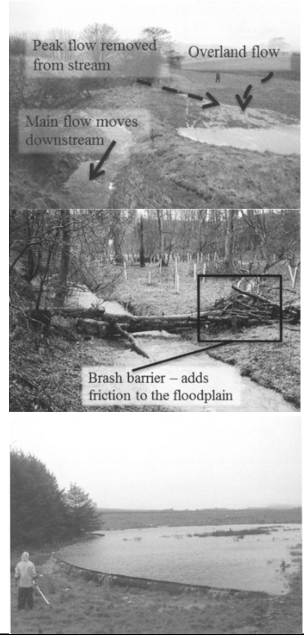
Note: Features of a surface flow constructed wetland in the landscape: (1) A deep sedimentation pond (more than 1.5m deep), size will depend on rainfall intensity and topography but generally up to 20% of wetland size, (2) Deep (over 0.5m) open water zones at the inlet of each cell to help dispersion and mixing, and even out the flow, (3) shallow (average 0.3m deep), densely vegetated zones (at least 70% of the total area). The shallow zone is where most of the nitrogen removal happens via microbial denitrification, fuelled by decaying plant leaf litter. Sunlight penetration in deep open-water areas can promote die-off of faecal microbes in inflowing waters, but shallow water with dense plantings is recommended in the final 20% of the wetland to limit faecal contamination and sediment disturbance in the final outflow by waterfowl.

Appendix B: NBFM literature review

Table 1 presents a summary of international examples of NBFM, how they performed and how they were analysed.

Table 1 Examples of nature-based solutions (NBS) applied to manage flooding and water resources.

ID	Location and context	NBS approach	Results and discussion points	Example and reference
1	**Blairfindy catchment, Scottish Highlands, United Kingdom** • Small subcatchment of the river Livet (~0.9 km^2). • Perennial stream, upper ephemeral tributaries. Mixture of free draining and poorly draining soils. • Community and industry concerns for groundwater recharge and maintenance of baseflows during extended drought periods. • Previous runoff attenuation features (RAFs) were installed by local distilleries to maintain water availability. • Future RAF are being modelled and refined for the catchment area to retain water as well as manage peak flows.	• Optimised locations for additional RAFs were selected via coupled 3D hydrological and hydraulic analysis using MIKE SHE and MIKE 11 models (Fennell et al., 2020 *prior tracer-based hydrology study). • 40 RAFs were installed to increase groundwater recharge and drought resilience. These took the form of 'leaky barriers' promoting slow seepage of surface water to the subsurface (see image to the right). • The results were compared to modelling predictions and learnings were recorded. • Local natural materials were used, such as local timber or till overlain with peat.	• Post-intervention recharge rates ranged from < 0.1 mm/day during dry periods to up to ~15 mm/day following precipitation events. Both this range and the average recharge rate across the calibration and validation period were as expected. • The modelled recharge rate averaged across the catchment increased with the implementation of RAFs and was seasonally variable with a greater increase occurring in late summer (~3–4%) than winter/spring (~0%). • Overall, RAFs reduced mid and high flows (Q_{50} and Q_{10}) and increased low flows (Q_{95}). • Total discharge decreased slightly (~2.7%). • The location and scale of RAFs had clear impact on their effectiveness (namely soil properties, influenced subsurface discharge). • This study has shown that RAFs can be used to manage water storage during low flows while also reducing flood peaks following heavy rain.	(Fennell et al 2022) 
2	**Mekong River Delta, Vietnam** • A vulnerable and ecologically productive river delta supporting myriad species, industries, and communities (3rd largest in the world, 39,000 km^2). • Extreme flooding and climate change events threaten ecosystem services (ES) provided by the delta. • Among others, ES from the delta include flood mitigation, aquaculture/agriculture productivity and climate change. • In deltaic regions, NBS interventions often aim to preserve natural flood benefits while protecting agriculture and aquaculture productivity (Ahn Dang et al 2021).	• The Land Utilization and Capability Indicator (LUCI) model was used at 5x5m resolution to indicate opportunities for NBS within the context of the economic and biophysical ES values. • The Mekong River has an advanced system of dikes and transport and irrigation channels. • The LUCI enabled appraisal of connectivity between flow routing, existing dikes and ES including connections with soil, water, biodiversity (carbon sequestration), industry and groundwater requirements. • LUCI identified existing flood mitigation features of the delta including rice fields, aquacultural areas, mangroves, and other wetlands.	• Comparing ES maps between two timeframes (2010, 2018) reveals how flood control infrastructure accomplishment and regional development strategy updates in 2011 have affected ES across the delta. There are decreases in flood mitigation in the lower stream of the delta and increases in agriculture/aquaculture productivity in the southern parts of the delta. • The increased agriculture/aquaculture productivity has led to a reduction in the carbon stock in the southern Mekong Delta. • Land use/ES/water storage relationships explored in the modelling will aid regional planning efforts in managing natural resources, tailoring the complex dike system and increasing flood resilience.	(Ahn Dang et al 2021) 

ID	Location and context	NBS approach	Results and discussion points	Example and reference
3	**Belford Burn catchment, Northumberland, North-East England** • An investigation of potential attenuation of rural runoff through the application of soft-engineering structures. • Large rural catchment (5.9 km^2) where vegetation clearance, tillage practices, subsurface drainage, ditching works and intensive stocking and cultivation have altered the natural hydrological regime. • The soil is characterised by poorly draining loamy topsoil with clayey horizons. • The village of Belford has been inundated by flooding seven times in the last 7 years; 31 properties are at risk of adverse flooding impacts. • Study ran from 2007-2012 and included field measurements to appraise the performance of over 20 approaches using RAFs.	• Soft engineering approaches include storage ponds, barriers, bunds, and the planting of vegetation and the positioning of woody debris in the riparian zone. • RAFs are ideally positioned in areas of high surface connectivity (lateral connectivity). • A permeable timber barrier was constructed in the headwaters with a storage capacity of 800 m^3 (taking 8-10 hours to fill under heavy rain). • A series of offline diversion ponds were built adjacent to the channel, filled by a 1 m wide inlet structure on the riverbank (330 m^3 capacity). • Overland flow disconnection ponds were built in out of channel areas particularly susceptible to overland flow (made from soil and boulders). These bunds were positioned over natural gullies in open pasture fields. • Large woody debris (LWD) were used in the riparian area to increase surface roughness and slow down water before it enters the main channel.	• To date, the RAF network installed in the catchment is estimated to have a maximum capacity of 10,000 m^3. • Transient storage is expected to have notable impact on peak flows through increased surface roughness and attenuation affects. • Consideration of the overarching goal should be recognised when designing RAF approaches. If reduction of peak flows during large infrequent flood events is the goal, design criteria (i.e., location and size) should be for these features to be empty at the time of flood. • Flood-proofing a catchment can be achieved by installing an appropriately designed network of RAFs. If flood frequency and magnitude are to increase as a result of climate change, more RAFs can be added to the network (i.e., adaptive management approach)	(Nicholson et al 2012) 
4	**Banas River Catchment, India** • Assessing the potential of NBS to mitigate peak discharge rates in Banas Catchment. • Banas is semi-arid and was affected by flooding in 2015, 2017 and 2021. • Study catchments ranged from 54-97 km^2.	• Modelling of different intervention scenarios using HEC-HMS for 4 sub catchments. • Composite NBS approaches were developed for each subcatchment based on potential synergies. • NBS approaches included: reforestation, bioswales, agroforestry and residential parks and plantation. Each intervention was simulated by ascribing 'Manning's N roughness areas' to the affected areas in the modelling domain.	• Modelling enquiries using HEC-HMS showed that in four pilot sub catchments peak discharge could be reduced by 25-81%. • Overall peak discharge at the sink was reduced from 1069 m^3/s to 1033m^3/s in a pilot study in the same catchment (real world intervention). • NBS have positive impacts in different settings (i.e., urban (rainwater harvesting), water body (ecology), cropland (productivity), forests (erosion).	(Agarwal et al 2023). (no images available).

ID	Location and context	NBS approach	Results and discussion points	Example and reference
5	**River Eden Catchment, Cumbria, England** • Optimising NBS placement within a large catchment to manage flood peaks. • Modelling land cover, hydrological connectivity, flood generating rainfall patterns and flow routing to impacted values (communities, property). • Eden Rivers Trust have implemented a range of mitigation schemes to decrease peak flows (soil aeration, riparian planting, river restoration to reconnect floodplain storage). • Modelling has been used to validate initial predictions and refine initial approaches.	• Modelling using SCIMAP-Flood at scale of 5 m (i.e., 5 m DEM). • Combining land cover, hydrological connectivity, flood generating rainfall patterns and flow routing to impacted values (communities, property) to determine best sub catchments for more detailed work to take place (i.e., scoping). • Modelling studies are undertaken to avoid potential risks associated with synchronising delayed flood peaks from adjacent tributaries (*applicable when larger catchments are being considered). • Land use types were weighted based on their potential for flood water generation (inferred from compaction, infiltration, and roughness). • CEH Gridded Estimations of Areal Rainfall (GEAR) was applied to simulate realistic flood pulse timings across a large catchment.	• Through flow travel time calculations, three locations were discovered as key impact points, this was due to the synchronisation of flood peaks downstream of interventions. • Higher elevation areas within the catchment were observed to have less hydrological connectivity and therefore less risk of adverse synchronisation. The spatial distribution of land use influenced this risk significantly. • Exploration of hydrological connectivity patterns requires a grid resolution of 5 m or less. • The topographic dataset used in this study was relatively coarse and can introduce unmeasurable errors in flow direction and routing. • The rainfall patterns used were derived from daily totals and therefore do not represent the hourly or sub-hourly influence of a passing storm event on peak flow discharge. • SCIMAP-Flood is considered an approach that can be tailored to local conditions rather than applied broadly as a fixed solution.	(Reaney 2022) (no images available).
6	**Central Wellington, New Zealand** • Applying an urban biomimicry approach to reduce urban flood risks. • 13.7 km^2 urban water catchment. • 95% of the natural streams have been culverted beneath the city. • Residents are advised to not to swim at least 48 hours after heavy rainfall due to potential water contamination.	• Applying ‘Nature Braid’ a next generation LUCI model to understand relationships between imperviousness, landcover, agricultural productivity, carbon stocks and fluxes, erosion and sedimentation, evaporative cooling, flood mitigation, habitat connectivity/suitability, nitrogen, and phosphorus. • Synergies and tradeoffs were identified with respect to the placement and sizing of Greenroofs (NBS). • LINZ 1 m LiDAR (2019-2020) was used as the topographic input. Building footprints were used as input shapefiles and restricted flow accordingly.	• 59% of the catchment does not contain or benefit from the flood-mitigating landcover features present. • The addition of 0.6 km^2 of green roof space alongside major stormwater flow routes reduced the total flood extent by 11%. • Greenroofs can retain some 10-60% of rainfall directly intercepted and slow runoff.	(MacKinnon et al 2023) (no images available).

Appendix C: Mixed forestry intervention – review and intervention design

Jones et al (2023) presents a critical review of the current forestry industry and highlights the value systems controlling contemporary practice in NZ. The emphasis in NZ over the last 150 years has been on improving production, the highest yield per area (per season) of fast-growing forest stock (mostly *Pinus radiata*). However, adjacent issues of introduced pests, diseases, climate change, erosion and biodiversity loss remain topical around the country. The forestry industry currently comprises 1.8% of NZ's gross domestic product and occupies 8% of the land area, land which is predominantly classed as steep, erosion prone and of poor productivity for agriculture (Ministry for Primary Industries, 2020; Stats NZ, 2021).

Jones et al (2023) posits 'transition forestry' as a means of employing NBS to reform the 'business as usual' industry approach into multipurpose, multifunctional forest systems. There is great potential for planted forestry systems to provide a social, ecological and economic resource if planned and incentivised appropriately. Admittedly there will be trade-offs in economic/ecological productivity which need to be overcome, one option may be co-management of forest blocks with mana whenua, through which planning of implementation and harvest procedures are shared. Messier, Puettmann & Coates (2013) reframe silviculture forest systems as complex adaptive systems, subjected to the same shifting boundary conditions as any managed indigenous forest under 'restoration'. They point to the need for adaptation to changing environments, with the example of regional landscape (forest) plans in northeastern Minnesota (Messier, Puettmann & Coates, 2013). In this research the overarching goal was to restore variability of native forest patch sizes across spatial scales, combatting growing homogenisation in the industrial silviculture industry. The pilot study extended over 450 ha demonstrating the ability to inter-mosaic forest stock with land successional forest comprising long-lived conifers (Messier, Puettmann & Coates, 2013). 40% of the forest cover would be retained to support ecological integrity and reduce typical erosion issues associated with wholesale clearance. In this example the retention of biological legacies within the forest system created long-term habitat for those species with specific symbiotic linkages. Natural forest systems are defined by emergence and a natural range of variability, the selective harvest of mosaiced stock tress could result in a similar dynamism supporting successional process (if scaled correctly). Despite, possible adaptations to the standard silviculture forest system, introduction of late successional natives would require active pest control (e.g., including fencing, trapping).

Although quite abstract, this holistic approach looks to enhance efficiencies of timber production while simultaneously reducing ecological impacts of conventional methods; thus, providing a social, environmental and hydrological asset for the community (Figure 1). In practice this could take many forms but is at high-level, mixed native and exotic plantings combined with a selective low impact harvest regime.

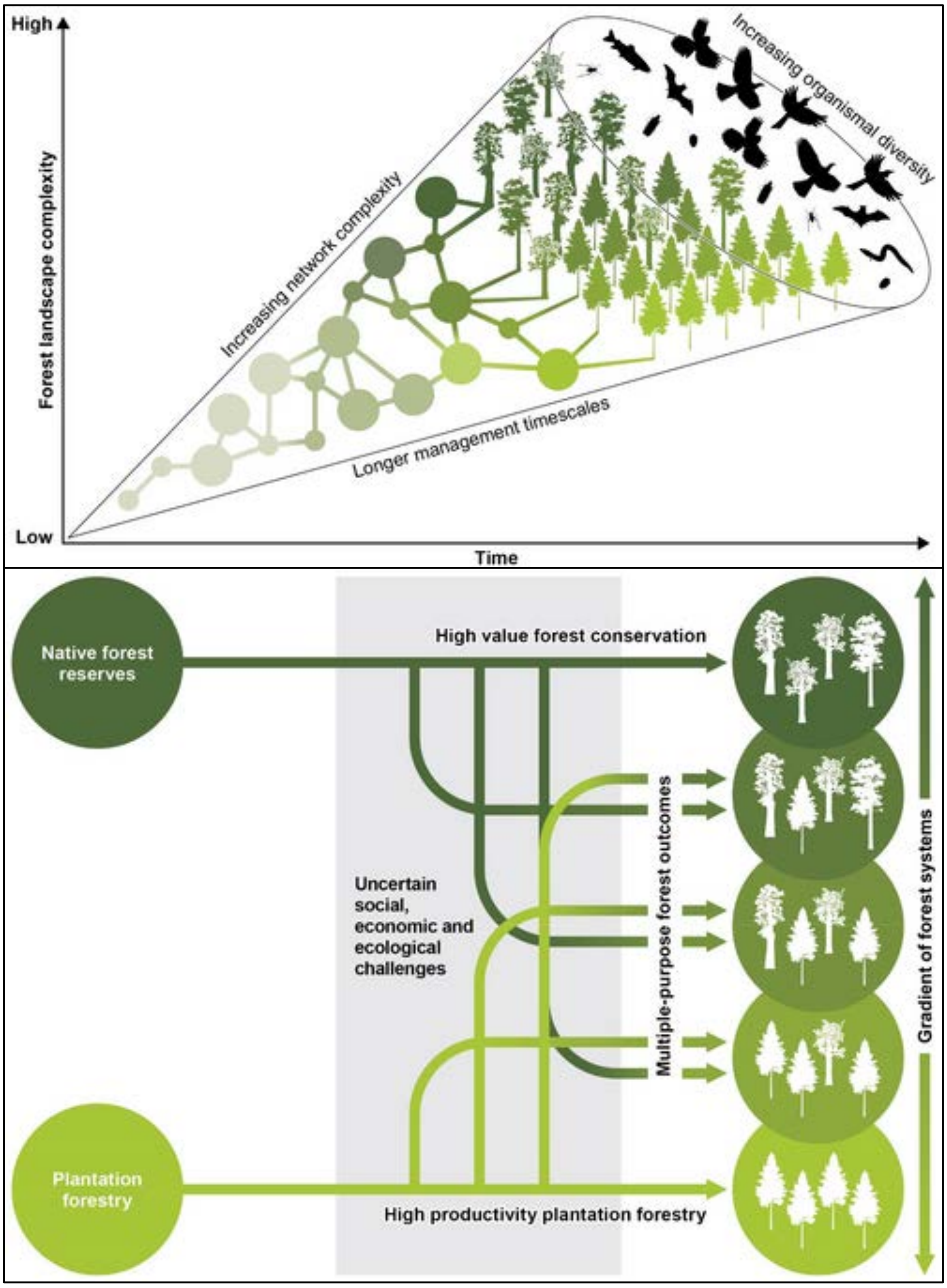


Figure 1 Conceptual reform of forestry industry to 'transition forestry' (source: Jones et al, 2023).

Design of Class 6 intervention for this project included:

- Create a GIS overlay of LUC class 6 extent.
- Reclass existing land use to mixed forest type (pines and native forest).
  - Mixed type differs with respect to: LAI, stem density and species composition.
- Note the understory and terrain roughness of a mixed forest may be highly variable dependent on specific management practices.

Appendix D: Catchment management and forest restoration activities

Three key projects relevant to the Waimatā are summarised below:

1. The Waimatā Catchment Erosion Management Project, launched in 2018, brings together stakeholders including the Department of Conservation (DOC), Gisborne District Council (GDC), Queen Elizabeth II (QEII) Trust, and local conservation groups (i.e., The Longbush Trust). Covering ~6,000 hectares, the project focuses on reducing erosion and downstream sediment buildup (Figure 18). Current efforts include re-vegetation in the lower catchment, pest control, and land protection through fencing, in collaboration with local landowners and the QEII Trust. (Waimatā River Restoration Project, 2018).
2. Waimatā Catchment Restoration Inc (WCRI), established in 2020, leads restoration efforts in the Waimatā Catchment, focusing on erosion control, sustainable land management, and biodiversity support. With funding grants, WCRI has developed farm environment plans, implemented riparian fencing and planting, and carried out pest control to protect native species.
3. The Recloaking Papatūānuku project, initiated by Pure Advantage and Tāne's Tree Trust, aims to regenerate 2.1 million hectares of indigenous forest across New Zealand over the next decade to combat biodiversity loss and climate instability. With 5 million hectares of ecologically promising land identified, the project calls for urgent action to achieve widespread environmental, social, and cultural benefits. Key interventions include enhancing degraded forests, supporting natural reversion on marginal and Crown lands, and reforesting low-productivity and riparian areas (Pure Advantage, 2023).

Appendix E: Land cover, land use capability (LUC) and soil cover summary tables

Table 1 presents the soil cover type and distribution through the catchment; Table 2 presents the land cover type and distribution. Table 3 presents the land use capability distribution of the catchment.

Table 1 Soil distribution and extent – Monowai and Subcatchment

Subcatchment ID	Soil Type	Percent cover (%)	Area (ha)
S1	Weathered Orthic Recent Soils (ROW)	35.4	426.2
	Typic Orthic Pumice Soils (MOT)	27.4	330.2
	Pallic Orthic Brown Soils (BOP)	16.5	199.2
	Typic Allophanic Brown Soils (BLT)	9.4	113.7
	Typic Orthic Recent Soils (ROT)	6.8	82.1
	Typic Orthic Brown Soils (BOT)	3.1	37.3
	Typic Fluvial Recent Soils (RFT)	0.8	9.8
	Typic Orthic Gley Soils (GOT)	0.5	6.4
S2	Weathered Orthic Recent Soils (ROW)	11.1	357.2
	Mottled Tephric Recent Soils (RTM)	5.8	186.6
	Pallic Orthic Brown Soils (BOP)	0.5	17.2
	Pedal Immature Pallic Soils (PID)	1.0	33.4
	Typic Orthic Recent Soils (ROT)	1.4	46.2
	Mottled Orthic Recent Soils (ROM)	65.2	2103.3
	Typic Fluvial Recent Soils (RFT)	14.1	456.3
S3	Pallic Orthic Brown Soils (BOP)	44.18	362.1
	Typic Orthic Brown Soils (BOT)	0.15	1.2
	Typic Orthic Pumice Soils (MOT)	4.53	37.1
	Mottled Fluvial Recent Soils (RFM)	0.01	0.1
	Typic Orthic Recent Soils (ROT)	4.47	36.7
	Weathered Orthic Recent Soils (ROW)	44.37	363.6
	Mottled Tephric Recent Soils (RTM)	2.29	18.8
Monowai (whole study area)	Weathered Orthic Recent Soils (ROW)	56.8	5955.8
	Pallic Orthic Brown Soils (BOP)	16.1	1685.8
	Mottled Tephric Recent Soils (RTM)	12.3	1291.9
	Typic Orthic Pumice Soils (MOT)	3.5	367.3
	Typic Orthic Gley Soils (GOT)	2.5	262.1
	Typic Orthic Recent Soils (ROT)	2.2	226.1
	Typic Allophanic Brown Soils (BLT)	2.0	213.1
	Pedal Immature Pallic Soils (PID)	1.8	186.7
	Typic Fluvial Recent Soils (RFT)	1.0	105.5
	Mottled Fluvial Recent Soils (RFM)	0.9	97.5
	Typic Orthic Brown Soils (BOT)	0.5	53.8
	Mottled Orthic Recent Soils (ROM)	0.3	34.7

Note: naming conventions are adopted from Hewitt (2010).

Table 2 Sub catchment land use

Subcatchment ID	Land use type	Percent cover (%)	Area (ha)
S1	Exotic Forest	41.3	497.8
	High Producing Exotic Grassland	37.8	455.6
	Broadleaf Indigenous Hardwoods	7.9	95.7
	Forest - Harvested	7.6	91.8
	Manuka and/or Kanuka	4.7	56.2
	Indigenous Forest	0.4	5.1
	Gorse and/or Broom	0.2	2.7
S2	High Producing Exotic Grassland	57.72	1862.7
	Exotic Forest	30.45	982.7
	Broadleaf Indigenous Hardwoods	4.57	147.6
	Deciduous Hardwoods	4.28	138.1
	Indigenous Forest	1.79	57.9
	Manuka and/or Kanuka	0.87	28.0
	Low Producing Grassland	0.14	4.4
	Forest - Harvested	0.11	3.7
	Gorse and/or Broom	0.05	1.7
S3	High Producing Exotic Grassland	42.42	347.7
	Manuka and/or Kanuka	28.31	232.1
	Broadleaf Indigenous Hardwoods	20.49	168.0
	Exotic Forest	4.68	38.4
	Low Producing Grassland	3.14	25.7
	Deciduous Hardwoods	0.90	7.4
	Lake or Pond	0.05	0.4
Monowai (whole study area)	High Producing Exotic Grassland	50.62	5304.7
	Exotic Forest	29.82	3125.0
	Manuka and/or Kanuka	7.59	795.6
	Broadleaf Indigenous Hardwoods	4.96	519.5
	Deciduous Hardwoods	2.39	250.6
	Forest - Harvested	2.01	210.6
	Indigenous Forest	1.78	186.6
	Low Producing Grassland	0.59	61.6
	Gorse and/or Broom	0.19	19.4
	Orchard, Vineyard or Other Perennial Crop	0.02	2.4
	Lake or Pond	0.02	1.7
	Herbaceous Freshwater Vegetation	0.01	1.4
	Gravel or Rock	0.01	1.2

Table 3 LUC class dominance – Monowai and sub catchments

Subcatchment ID	LUC Class	Cover (%)	Area (ha)
S1	7	47.2	568.8
	6	42.0	506.6
	4	5.5	65.9
	8	4.5	53.7
	3	0.8	9.8
S2	7	75.0	2419.9
	6	22.5	725.8
	4	12.3	397.7
	2	1.4	44.6
	3	1.1	36.9
S3	7	45.52	373.1
	6	39.38	322.8
	2	6.18	50.7
	8	4.47	36.7
	4	4.44	36.4
	3	0.01	0.1
Monowai (whole study area)	7	70.3	7365.7
	6	21.3	2227.8
	4	3.8	397.7
	3	2.6	270.2
	8	1.2	123.8
	2	0.9	95.3

Appendix F: Potential cumulative impacts of NBFM in the Waimatā

This research was undertaken with the intention of highlighting possible cumulative flood benefits that might emerge from strategic land use change in the upper catchment. The location of the upper catchment has the benefit of management interventions acting on relatively smaller flood volumes (working at the source); thus, the design and maintenance effort is considerably reduced (Fuller et al 2022; Wren et al, 2022). The study area above Monowai is 46% of the total catchment area. If we assume that rainfall depth and effective rainfall (runoff portion) on average is broadly similar the upper catchment, we can conduct an area-weighted analysis of the cumulative impact of upstream actions.

$$Effective\ Flood\ Peak\ Reduction\ at\ \text{Waimatā}\ outlet\ (T3W1) = (0.46 * 35.58\%) + (0.54 * 0\%) = 16.37\%$$

This is a very simplified approach and does not consider variability in soil properties (i.e., storage, depth and conductivity); however, it provides some informed perspective on the potential effective reduction in flood risk for urban and residential areas of Gisborne. The T3W1 interventions in the upper catchment comprised 33% of the total catchment area converted to native broad leaf forest and 10% of the total catchment area converted to mixed 'transition' forestry, to realise 16.37% reduction in flood peaks in the lower urban area.

The NBFM location is important as it slows the flow progression downstream and reduces the time of concentration more effectively than working in the middle or lower reaches (Wren et al., 2022; Nicholson et al., 2012; Lane, 2017). In addition, the development of NBFM interventions in specific sub-basins may have the potential to desynchronise flood peak contributions to the main channel and therefore, reduce the flood peaks downstream (Lane, 2018). This was unable to be verified in this project due to the limitations of SWAT+ outputting results in the daily time step only.