Hydrological Responses to Differing Land Cover Scenarios to Better Inform Farm and Catchment Planning Initiatives for the Waimatā River, Gisborne, New Zealand

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Abstract

This research examines the impact of land cover on hydrological relationships in the Waimatā River Catchment in Gisborne, New Zealand. A hydrological model (The Soil and Water Assessment Tool (SWAT)) is used to model flow in the Waimatā River Catchment in its present state. Results from this analysis are then used to simulate a hydrograph for multiple afforestation and deforestation scenarios. Appraisal of surface runoff, water yield and flow rate show which sub-basins contribute the most to flow in this watershed. Comparison of results between sub-catchments shows how land cover changes in one or more sub-basins impacts on flow through the system, highlighting the variable sensitivity of sub-basin discharge to changes in land cover across the catchment. Terrain, groundwater, and soil characteristics, linked with vegetative cover, also influenced this sensitivity. Sub-basins identified as the most responsive were subsequently subjected to alternative land cover scenarios to assess potential improvements and anticipate the impact of deforestation. Findings from this study could help river restoration decisions by the local community and the Council, thereby supporting farm plans to better inform catchment plans.

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Chapter 1: Introduction

1.1 Context

History of urbanisation, agricultural intensification, deforestation, and plantation forestry operations in the Waimatā River Catchment have caused significant geomorphic changes (Coombes, 2000; Salmond, 2016). The catchment experienced a conversion of 1882 hectares of grasslands to exotic forestry between 1996 and 2018 (LAWA, 2022b). The current land cover comprises 32% plantation forest, 6% indigenous forest, 11% shrubland, 49% grassland and 1% cropland and 1% urban. Anthropogenic activities triggered large-scale deforestation in the catchment, accelerating erosion and causing excessive river sedimentation. The downstream effects are flooded land, damaged property, siltation, and driftwood clogging the river (Salmond, 2016). Land use change has also degraded freshwater biodiversity as it is challenging for fish and invertebrate species to survive in an ecosystem overloaded with fine-grained sediments and forestry slash, causing changes in habitat structure (Cullum et al., 2017; Salmond, 2016). The Waimatā Catchment has experienced significant flood damage in recent years. In March 1988, ex-tropical Cyclone Bola recorded 800mm over four days, with some of the largest rainfall totals for a single storm event ever recorded in the North Island of New Zealand at some high-country stations. Cyclone Bola was long considered the worst storm to hit Gisborne until ex-tropical Cyclone Gabrielle broke records and caused widespread destruction on the 13th and 14th of February 2023. Mass sediment deposition is a consequence of most significant storm events in the Waimatā Catchment, but the presence of forestry slash intensified the damage caused during Cyclone Gabrielle compared to Cyclone Bola.

The hydrological effects of land use change in the Waimatā Catchment are well documented, and frustrations are felt across the community (Coombes, 2000; Cullum et al., 2017; Gundry, 2017; Salmond, 2016). Land cover alters the hydrological cycle by modifying evapotranspiration, soil infiltration and surface runoff (Cao et al., 2008; Marden et al., 2012). Deforestation has led to significant erosion and adjustments to the flow regime in the Waimatā Catchment. Less water is intercepted and transpired by the tree canopy, increasing rainfall-runoff (Marden et al., 2012). Increasing vegetative cover in a catchment has the opposite effect by intercepting rainfall in the canopy and increasing evapotranspiration (Rowe et al., 1999). River discharge is the primary transporter of substantial volumes of sediment and woody debris. This combination devastates the Waimatā Catchment by flooding land, scouring out banks and washing away infrastructure, riparian vegetation, crops, and livestock (Salmond, 2016). Understanding the hydrological implications of land cover within specific catchments is essential to make better decisions on managing and living with our natural resources. Many physical, chemical, and biological characteristics influence a river's health, all interacting and depending on each other. This makes improving the conditions of New Zealand rivers a complex task. Land cover change can be a source of hydrologic problems, and management must take careful steps to protect rivers from degradation (G. Brierley & Fryirs, 2009; Larned et al., 2020; Saher et al., 2020). Hydrological analyses play a vital role in uncovering relationships within catchments, although they are not the sole determining factor.

River restoration is a scientific and social process that benefits local communities living and working within a river catchment (Salmond et al., 2022; Wohl et al., 2015). There are strong cultural and generational connections to the Waimatā River. The river's value extends beyond its physical attributes, as it is deeply intertwined with the cultural identity and heritage of the people (Salmond et al., 2022). Cairns et al. (2021) investigated how the local community relates to the Waimatā River and how that shapes their aspirations for restoration. Residents aspire for improved water quality and scenic beauty to protect the river's environmental value and improve swimmability. The Waimatā Catchment Group and Waikereru Ecosanctuary put considerable time and effort into engaging the local community with its protection and restoration efforts. The catchment also has a large group actively involved in farm environment planning (WRRP, 2019).

In New Zealand, regional councils and unitary bodies are responsible for reporting water quality information. This is achieved through individual monitoring programmes. The 2020 National Policy Statement for Freshwater Management (NPSFM) and the Resource Management Act 1991 (RMA) direct regional councils to manage freshwater systems. They provide a framework to set regional policy statements and plan management objectives. NPSFM also includes Te Mana o te Wai, and together they aim to implement sustainable management, protect freshwater ecosystems, and maintain a balance between freshwater, the environment, and communities. Freshwater monitoring is also conducted by some Crown Research Institutes, environmental groups and local community groups depending on their aspirations of a particular water body. The Gisborne District Council is designing a broader catchment plan that includes the Waimatā River (GDC, 2022). It aims to provide a clear direction of sustainable management and ensure the mauri and values of the river are protected and enhanced. Proactive management plans are integral for effectively improving our life with the river (G. Brierley & Fryirs, 2009; Wohl et al., 2015). The recent events of Cyclone Gabrielle have also highlighted the importance of flood risk assessments and mitigation. This has become a focus area for local councils as the Gisborne and

Hawkes Bay regions recover. Hydrological analysis aids in flood risk assessments and indicates areas where flood damage could be reduced. Farm Environment Plans are also essential to consider as they are becoming the new norm for landowners. Freshwater farm plans play a crucial role in broader catchment management, and it is important to establish reasonable procedures that can benefit the entire catchment. Land management decisions for river restoration are often applied at the farm scale; therefore, understanding how a catchment's whole watershed behaves opens the opportunity to integrate these farm plans into a coherent catchment plan.

1.2 Study Aims

The main objective of this study is to show the hydrological relationships with land cover in the Waimatā River Catchment in Gisborne. It focuses on how different land cover scenarios, such as afforestation and harvesting of plantation forestry, can affect the flood regime. Previous research has shown that rainfall interception can be improved by increasing forest canopy, shrubs, and wetlands, slowing down rainfall runoff. This could potentially reduce flood peaks, bank erosion and overland transfer of contaminants into the system. The study also aims to identify the sub-basins most sensitive to land cover changes, providing insights into where restoration efforts should be prioritised to have the most significant impact on the flow of the river system. The analysis uses water yield and surface runoff to demonstrate how land cover influences the hydrological behaviour of each sub-basin. These processes directly affect the resulting discharge in a peak event. Flow rate shows how the river discharge changes between the scenarios. Discharge influences the kinetic energy of a river and is responsible for the impact the river will have on the watershed.

Land cover change will alter the flood hydrograph, so this research focuses on determining whether these changes are significant and what they indicate. The annual averages of the discharge metrics were not expected to vary much because of the consistent meteorological data between scenarios. Therefore, there is a closer examination of the changes to flow peaks. Planting areas in natural vegetation has the potential to reduce flood risks downstream. Deforestation is anticipated to do the opposite by decreasing evapotranspiration and increasing rainfall runoff and river flow rate. Due to land cover and terrain variations, differences between sub-catchments are expected rather than a uniform response throughout the catchment. Therefore, establishing natural water interception, such as regenerating forests, will be more successful in some parts of the landscape than in others. This knowledge could then be used to target specific areas for interventions that will make a positive difference to flood resilience and the river's health. This project, combined with other projects on the Waimatā River, will hopefully help paint a broader, more holistic picture of how the catchment behaves. Therefore, it can support farm plans in the Waimatā River Catchment to inform catchment plans better.

Chapter 2: Literature Review

2.1 Introduction

This study examines the hydrological relationships between land cover and the Waimatā River Catchment in Gisborne. The following chapter critically reviews the use of hydrological models to assess the impact of land use change on river catchments. The importance of river and flow management is explained, and hydrological models are explored to determine their suitability for simulating watershed processes to demonstrate sub-basin sensitivity. There is an overview of hydrological modelling software and the criteria and justification for deciding on SWAT, the model used in this thesis. An assessment of the current approaches in the field is conducted, and the primary themes are highlighted. This review also highlights how modelling applications can be used as a tool for river management. The question is then posed as to why we should not be satisfied with the current approaches and how we can address deficiencies in the research. Hydrological responses to land cover changes are summarised and related to the Waimatā River Catchment.

2.2 Catchment Management and River Restoration

Catchment management is important for rivers affected by anthropogenic activities to allow them to sustain functional ecosystems. Restoration initiatives aim to improve rivers' hydrologic, geomorphic, and ecological processes. A wide variety of management activities can enhance river processes and overall health, which usually involves structural modification of streams and their surrounding areas (Wohl et al., 2015). River management focuses on fixing compromised elements of a natural system, but this is often difficult when a river's geomorphic structures and functions have been highly modified and constrained (G. Brierley & Fryirs, 2009). Proactive management plans are integral for effectively improving how we live with the river (G. Brierley & Fryirs, 2009; Wohl et al., 2015). While hydrological analyses are not the only determinants of relationships within a catchment, they are a vital component that can provide a more holistic picture of catchment processes when combined with other assessments. Restoration is also a social process, benefiting local communities who live and work within a river catchment (Salmond et al., 2022; Wohl et al., 2015).

As with any environmental field, climate change affects the hydrological cycle and river limits are constantly being tested. Extreme rainfall events are projected to become more frequent and severe, with a warmer atmosphere causing heightened flood risk. Relying solely on modelling scenarios that use historical and present rainfall data may no longer be adequate in predicting future flood events (Brunner et al., 2021). Mean annual floods (MAF) are expected to increase in Tairawhiti (Ministry for the Environment, 2018). Therefore, flood risk analysis has become an integral part of flow management, and mitigations are usually aimed at addressing this.

The Waimatā Catchment has experienced significant flood damage in recent years. River discharge is the primary transporter of substantial volumes of sediment and woody debris (Fuller et al., 2023). This combination devastates the Waimatā Catchment by flooding land, scouring out banks and washing away infrastructure, riparian vegetation, crops and livestock (Salmond, 2016). This has many knock-on effects on the cultural and recreational value of the river (Cairns et al., 2021). Climate change is a source of uncertainty that must be considered in all management approaches to make appropriate decisions for restoring river resilience and protecting vulnerable land and communities.

2.3 The Influence of Land Use on Hydrologic Response

Urbanisation, agricultural intensification, and production forestry operations are responsible for significant changes to New Zealand rivers, affecting the structure and function of freshwater ecosystems (Larned et al., 2020). These land cover changes can be a source of hydrologic problems by changing runoff characteristics. This can substantially impact floods, particularly in areas where natural landscapes have undergone significant modification. Understanding the hydrological implications of different land uses within specific catchments is essential to make better decisions on managing and living with our natural resources (Larned et al., 2020; Saher et al., 2020).

Changes in land cover can disrupt the natural hydrological cycle by altering rainfall interception, evapotranspiration, surface runoff, infiltration, and soil water storage capacity (Buechel et al., 2022; Cao et al., 2008; Marden et al., 2012; Rogger et al., 2017). However, the effects of land use change on the flood regime can be ambiguous because it is only one of several factors affecting discharge. Land cover type is just one component of a complex hydrological system, making it challenging to anticipate its impacts on a catchment (Gaál et al., 2012; Rogger et al., 2017; Sanyal et al., 2014). For example, deforestation can decrease rainfall interception and evapotranspiration. This increases antecedent soil moisture, which reduces soil storage capacity (Brown et al., 2005). These interactions are illustrated in Figure 2.1 by Rogger et al. (2017). Obtaining specific data for each catchment is crucial in addressing this and getting more accurate conclusions.

Many experimental studies still show that catchment discharge can be reduced with increasing forest cover, but it is more difficult to isolate the effects that land cover change has on flood peaks. However, some studies have shown delayed flood peaks with afforestation scenarios (Bathurst et al., 2011; Belmar et al., 2018; Khaleghi, 2017; Lestari et al., 2019). Increasing vegetative cover in a catchment reduces rainfall runoff by intercepting rainfall in the canopy and increasing evapotranspiration (Bergin et al., 1995; Rowe et al., 1999). Tree cover also provides a greater rooting depth than pasture, increasing soil moisture storage potential (Duncan, 1995; Rowe & Pearce, 1994).

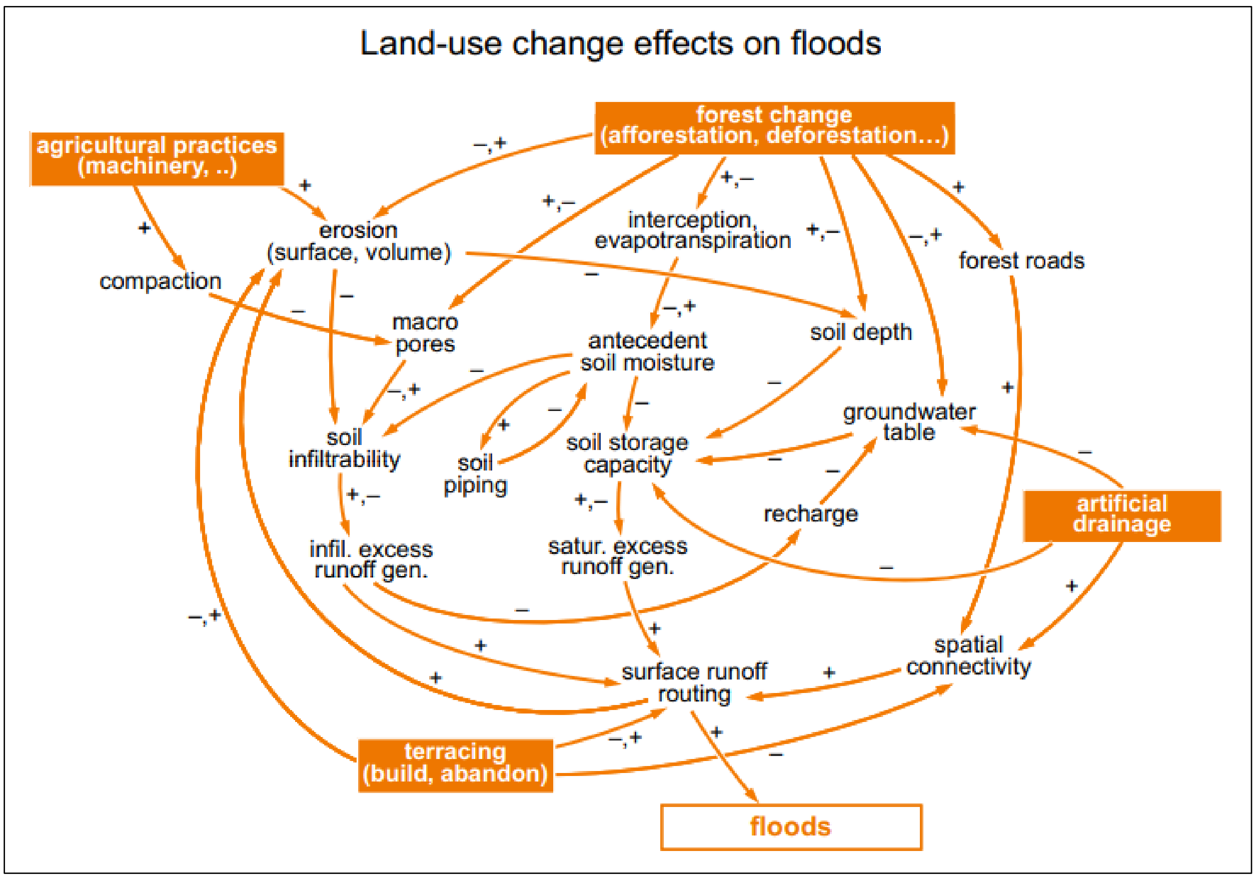

Figure 2.1: Process interactions in land use change effects on floods at the catchment scale. Source: Rogger et al., 2017

2.4 Overview of Hydrological Models

Reviews of hydrological models were assessed first to understand the current modelling environment (Beven, 2012; Horton et al., 2022; Sood & Smakhtin, 2015). Case studies were then investigated to show what models can be applied to land use change scenarios. Due to the vast range of hydrological models available, the most common models were analysed in more detail based on their popularity with studies evaluating the impacts of land use change and their ability to be applied to a New Zealand hill country catchment.

Hydrological modelling is one of river management and research's most common analytical frameworks. Catchment models help quantify existing conditions, aiding managers in identifying critical zones where land use impacts are substantial. Hydrological models are typically used to examine the effects of management practices on water quality, but they have also proved helpful for assessing how land cover configurations shape the flood hydrograph. Hydrological measurement techniques often have limitations, so models present the opportunity to widen analysis as multiple processes can be examined simultaneously, most of which can be done from a desktop (Beven, 2012). Horton et al. (2022) investigate why there are so many different hydrological models, using Switzerland as an example. The wide range of model applications is the key driver to the diversity of models available, so focusing on the outcomes for a particular project will help to refine what model should be selected for a specific purpose. There is usually a preference for local methods; however, adapting international models is becoming more popular as technology improves. The study also reaffirmed that as technology improves, models are continuously adapting.

Beven (2012) describes the main steps of the modelling process. The first step is to decide on the processes important for the research question, resulting in the perceptual model. Next, the equations that can help achieve this are revised to develop a conceptual model. The modeller can move on to utilising the software in their procedural model to start testing the output capabilities. Calibration and validation are the final stages of fine-tuning parameter values to improve the accuracy of modelled processes. Hydrological models are constantly adapting as GIS technology and computer capabilities progress. The current state of the art is complex, physically based models that are distributed and coupled with GIS systems (Beven, 2012). Distributed models split a watershed into smaller sub-basins and simulate their hydrological processes separately, allowing for a more detailed catchment analysis. However, simple lumped parameter models, such as IHACRES (Identification of unit Hydrographs and Component flows from Rainfall, Evaporation and Streamflow data), can still provide good simulations if only discharge prediction is required (Beven, 2012).

Topography-based Hydrological Model (TOPMODEL) is an example of a physically based, distributed model that uses physical laws and equations to simulate hydrological processes at the catchment scale. TOPMODEL has been used to assess land cover change on flood peaks (J. Gao et al., 2018). TOPMODEL uses a distribution function of characteristics rather than calculations at every point in the catchment (Beven, 2012). Therefore, the model's limitations arise from its inability to generate multiple outcomes from a simulation using a single set of parameters and input values.

The Hydrologic Modelling System (HEC-HMS) was designed to simulate rainfall runoff with the foresight that no one model would be universally applicable. Therefore, it must be constantly adjusted and adapted to different landscapes and scenarios (Scharffenberg et al., 2010). HEC-HMS is a strictly hydrological tool that simulates watershed response to specific events, predicting flow, stage, and timing. HEC-HMS has been used globally to investigate the impacts of land use change on watersheds (Azizi et al., 2021; Y. Gao et al., 2020; Khaleghi, 2017; Saher et al., 2020). HEC-HMS is a physically based, lumped parameter model that splits a watershed into sub-basins and calculates the water balance for each one with a set of equations. HEC-HMS's original design was for application to civil engineering processes (Scharffenberg, Fleming, et al., 2010).

The Soil and Water Assessment Tool (SWAT) was created by the US Agricultural Research Service to predict runoff and improve agricultural management. It has since been applied internationally and used outside the scope of just agricultural land use. SWAT was designed for land management, so it is suitable for assessing land use change. SWAT can be categorised as a numerical model, a type of model within the geosciences that uses a system of equations to represent natural systems and their interactions (Bokulich & Oreskes, 2017). SWAT is process-based and requires source inputs for each sub-catchment and all the factors influencing its distribution, such as climate conditions, soil characteristics and management practices. A key signature of SWAT is that it considers different land uses and soils using Hydrological Response Units (HRUs). In contrast, other models, such as HEC-HMS, are purely hydrological. Modifying parameter values or inputs to model changes within a catchment is relatively simple. This simplicity comes from pre-set assumptions and parameters being available. However, Beven also notes that this could be considered a weakness in some cases, so the user must carefully evaluate the assumptions. For example, SWAT assumes that each HRU responds homogenously to inputs. SWAT has been widely used to assess the impacts of land use change on hydrology (Cao et al., 2008; Fohrer et al., 2001; Ghaffari et al., 2010;

Kibii et al., 2021). A review of SWAT studies by Tan et al. in 2019 found that most calibration and validation results using the model were very good and that availability of reliable data was one of the main problems with using SWAT.

Catchment models help quantify the effects of interventions (Parshotam & Robertson, 2018). This type of complex model can be difficult to apply over large areas, but in catchments that have the detailed information required, the model has a better capacity to accurately depict processes for specified areas (Parshotam & Robertson, 2018). Using a numerical model to create simulations gives opportunities to run multiple scenarios and compare between them, as there are limitations to physical hydrological measurement techniques (Beven, 2012). It also allows for exploring future changes through forecasting and predictions. This makes models effective for assessing the differences between past, current and future scenarios using existing data. Another advantage of using catchment models is they can interpolate data from existing monitoring locations across large areas with no data (Parshotam & Robertson, 2018).

No model can entirely represent the complexity of a natural system (Beven, 2012; Oreskes et al., 1994). Errors and discrepancies may occur in various aspects, such as input data, model parameters, structure, and spatial and temporal scales. All models carry some degree of uncertainty, which can be challenging to quantify and communicate effectively. Models are not closed systems; therefore, understanding each model's assumptions helps us interpret its results' reliability. All the articles reviewed expressed that calibration was essential to the accuracy of the model's results and that collecting adequate and unbiased data is vital. Veith et al. (2010) found higher uncertainty for groundwater than for surface runoff parameters. They also found that the level of uncertainty varied between the catchments they were evaluating but that the overall degree of uncertainty was moderate.

2.5 Approach to Analysis Using SWAT

The choice of model depends on the required outcomes and the specific purpose of each study. Each case study and scenario have unique factors contributing to the type of model chosen. It also depends on what data is available and the background knowledge and capabilities of the modeller (Horton et al., 2022; Parshotam & Robertson, 2018). The Soil and Water Assessment Tool (SWAT) was chosen for this thesis because a distributed model is required to look at sub-basin processes. SWAT presents the opportunity to evaluate individual sub-basin flow sensitivity to land cover changes. Various land use scenarios can be run, and their impacts compared. The Waimatā Catchment has enough detailed input data for this; therefore, SWAT provides more detailed outputs than other hydrological model types. This is especially important when analysing the impacts of land cover change. SWAT was designed for land management and has successfully assessed land use change impacts internationally and in New Zealand. SWAT meets the research criteria as it is open source, links easily to GIS databases and is relatively simple to modify parameter values or inputs to model changes within a catchment (Beven, 2012). This simplicity comes from pre-set assumptions and available parameters, which is valuable to help fill the gaps where input data is limited. This helped with the parameterisation of soil data for the Waimatā Catchment, which was limited in places. A review of SWAT studies by Tan et al. (2020) found that most calibration and validation results using the model were very good, and the availability of reliable data was one of the main problems with using SWAT.

2.6 Current Research Approaches

Many physical, chemical, and biological characteristics influence a river's health, all of which interact and depend on each other. This makes improving the conditions of New Zealand rivers a complex task, and numerous tools and datasets are available for analysis.

A review by Brown et al. (2005) found that scenario-based modelling approaches could be grouped into afforestation, deforestation, regrowth, and forest conversion experiments. The central theme of the reviewed research involved quantifying how historical land use change has adjusted the hydrological characteristics of a catchment (Azizi et al., 2021; Ghaffari et al., 2010; Kibii et al., 2021). Many studies expand on this and use scenario-based modelling to predict future land use change impacts, aiming to improve management and monitor land degradation within a catchment. Most research scenarios modelled large-scale afforestation, deforestation, or reforestation within a watershed. There are fewer that involve restoration projects to specific sub-basins.

Flood risk emerged as a prevalent theme since it directly impacts people, particularly urban communities near rivers, often within their natural floodplain. Hajian et al. (2019), Lestari et al. (2019), and Sanyal et al. (2014) are examples of papers discussing these flood implications, providing risk assessments, and simulating past, present and future flood events. Some studies also integrate a changing climate with future land use change, such as Chim et al. (2021) and Wang et al. (2021). The question of location vs scale of afforestation for flood mitigations often appears in the literature. Buechel et al. (2022) did a study across Great Britain and found the extent of afforestation was more important than its location within a catchment. The hydrological impacts of urbanisation are better documented internationally as their processes are better understood and easier to measure (Rogger et al., 2017).

A few published studies in New Zealand assess the hydrological impacts of land use change. Beets & Oliver (2007) and Duncan (1995) compare the difference in hydrology between forested and non-forested catchments. Much of New Zealand's research has looked at the hydrological impact of converting different land uses to plantation forestry (Cao et al., 2008; Duncan, 1995; Fahey & Payne, 2017; Hughes et al., 2020; Pearce et al., 1987; Rowe & Pearce, 1994). Most of these studies only presented hydrological information on changes in water yields. Duncan (1995) found that water yield did not immediately increase from forest harvesting; it occurred in the second year after. This is likely because the replenishment of soil moisture was required first before any noticeable increases in surface runoff occurred.

In recent years, SWAT has been applied to catchment modelling in New Zealand to monitor nutrient and sediment fluxes (Ekanayake & Davie, 2004; Me et al., 2015), but its use for modelling land cover change is limited. Cao et al. (2008) used SWAT to show that the Motueka River's flow rate and total water yields decreased in native and plantation forestry scenarios. National Institute of Water and Atmospheric Research (NIWA) is currently applying SWAT as part of the Whatawhata Integrated Catchment Management Project (NIWA, 2020). The study is designed to analyse land use change's impacts on water quality, stream flow and ecosystem health, including forestry harvest operations. Most studies were conducted in the South Island, which experiences different climatic patterns to the current study area and has very different soil processes to the East Coast of the North Island. This highlights a lack of diversity in New Zealand hydrological studies.

The reviewed papers present reasonably consistent results. Most studies focus on the negative impacts that occur as a result of deforestation and urbanisation. While some differences in details were observed, they mostly confirm the hypotheses that land use change has significant effects on a catchment's hydrological response to rainfall events. These changes subsequently have knock-on effects on ecosystem processes and the local communities that rely on the freshwater resources in a catchment. Residents are also exposed to physical danger from heightened flood risk. Deforestation decreased evapotranspiration and increased surface runoff and annual water yields, whereas revegetation did the opposite and had restorative effects. Noticeably fewer papers ran future afforestation and restoration scenarios in their models. However, those that did found that best management practice scenarios could significantly influence the flow regime of their catchments to reduce the impacts of floods. (Alarcon et al., 2017; Y. Gao et al., 2020; Khaleghi, 2017; Rodrigues et al., 2019; Saher et al., 2020).

All New Zealand studies that focused on establishing plantation forests found that annual water yields decreased. However, these reductions varied depending on the age of the trees. Forest harvest operations increased both surface runoff and the soil water balance. The studies mentioned are essential for understanding the current situation of New Zealand rivers, but they do not always give specific recommendations on how those river catchments can improve.

2.7 Research Gaps

The critical review has revealed the main gaps in hydrological research for catchment management are future predictions of impacts of land use change, analysing sensitivity of sub-basins, and a lack of coherence between catchment management and river research. Wohl et al. (2015) describe two themes in river restoration: limited monitoring of restoration projects to show whether goals have been achieved and a high proportion of projects that don't improve the river.

The hydrological modelling studies all achieve their aims of quantifying past and present hydrological behaviour within specific catchments. However, scenario-based modelling should be applied more to predicting the impacts of future land use change alongside a warming climate and higher flood risks to make this information more valuable to managing and restoring rivers (Dwarakish & Ganasri, 2015).

Most studies included a sensitivity analysis of parameters as part of the calibration process, but there were no studies that assessed the sensitivity of individual sub-basin discharge to changes in land cover. Instead, this sensitivity was discussed for the whole catchment response or comparing catchments within regions. Looking at how sensitive sub-basins are to changes within a catchment is integral to understanding the watershed processes and helping prioritise areas for river restoration. This refined scale was not always an option for most of the research mentioned because it requires more spatially detailed input data, which is not as easily accessible.

Another issue that has been identified is a lack of coherence between catchment management models and river research models. Hydrological models are mainly used in academia to test hypotheses and run experiments. Hydrological models can also inform catchment management by predicting the outcome of landscape manipulations at the policy and farm-level (Parshotam & Robertson, 2018). Management projects often use peer-reviewed research to inform their planning, but there is a gap in research designed explicitly for this. The assessment of sub-basin sensitivity is not commonly found in the literature, as this approach is often implemented through management projects that are not extensively documented

(Parshotam & Robertson, 2018). The hydrological nature of a catchment is fundamental to understanding most other processes, so filling this knowledge gap would help validate existing understanding of the river and better inform farm and catchment planning.

2.8 Study Area

The critical review has revealed research gaps in hydrological modelling, creating an opportunity for new methodological approaches. This can be applied to the Waimatā River Catchment, which serves as the case study for this thesis. A history of deforestation in the Waimatā Catchment has caused high sediment loads and geomorphic changes (Coombes, 2000; Salmond, 2016). Deforestation caused mass erosion in the catchment and modifications to the flow regime as tree roots no longer stabilise soil, and there is no interception of rainfall by forest canopy (Marden et al., 2012) (see land use changes in regional setting, Chapter 3). Although the impacts of land use change in the Waimatā Catchment are well documented (Coombes, 2000; Cullum et al., 2017; Gundry, 2017; Salmond, 2016), there has been no formal research to quantify the hydrological effects of future land use change. The Gisborne District Council records meteorological and discharge data for management purposes; however, this is spatially limited and mainly used to show historical trends (GDC, 2020).

The Waimatā Catchment has a solid base of data and research that covers the river's social-economic, physical, and ecological processes. However, a hydrological model has never been applied to the catchment, and SWAT has never been used within the Gisborne region. The Waimatā River Catchment has available data, which makes this scale of analysis possible. The hydrological nature of a catchment is fundamental to understanding most other processes, so filling this knowledge gap would help validate existing understanding of the river and better inform farm and catchment planning. Developing a hydrological model for the Waimatā Catchment is a crucial milestone towards bridging the gap between scientific research, effective catchment management, and community aspirations.

There is increasing community interest in protecting the Waimatā River, with the Waimatā Catchment Group and Waikereru Ecosanctuary putting considerable time and effort into engaging landowners and the local community in protection and restoration efforts. The catchment also has a large group actively involved in farm environment planning (WRRP, 2019). Freshwater farm plans are key elements to broader catchment management, so it is crucial to have reasonable procedures in place so these can be useful and benefit the whole catchment. Understanding how a catchment's entire watershed behaves opens the opportunity to integrate these farm plans with a coherent catchment plan. This information would then be available for community groups to use and help make decisions based on their goals and aspirations. Although the effects of forest cover on the flood regime are usually quite ambiguous, this research can still isolate the impacts of land cover change on specific sub-basins due to the case study's availability of all input data. As a result, there is less generalisation of assumptions.

Chapter 3: Regional Setting

3.1 Introduction

The Waimatā River Catchment is in the Gisborne region, located on the East coast of the North Island, New Zealand. For the purpose of this research, the catchment is defined by the yellow outline illustrated in Figure 3.1 and does not include the urban area of the lowest reaches. The river drains an area of approximately 220 km^2 of hill country, and most of the catchment is under 600 meters in altitude. The headwaters consist of steep hill country, mainly pastoral agriculture, and some exotic forestry. This eventually transitions to more gentle slopes in the lower catchment, primarily forestry and areas of higher quality pastoral land. It then levels out to flats with some horticultural and cropping practices and a coastal plain of urban settlements where the river flows through Gisborne City. Here the river joins the Taruheru to form the shortest river in the Southern Hemisphere, the Tūranganui River, which flows into Poverty Bay. The regional setting chapter introduces how geology, climate and human activities influence the behaviour and health of the Waimatā River. Land use change, flood characteristics and the river's history are also discussed, with examples of past events (see Cullum et al., 2017).

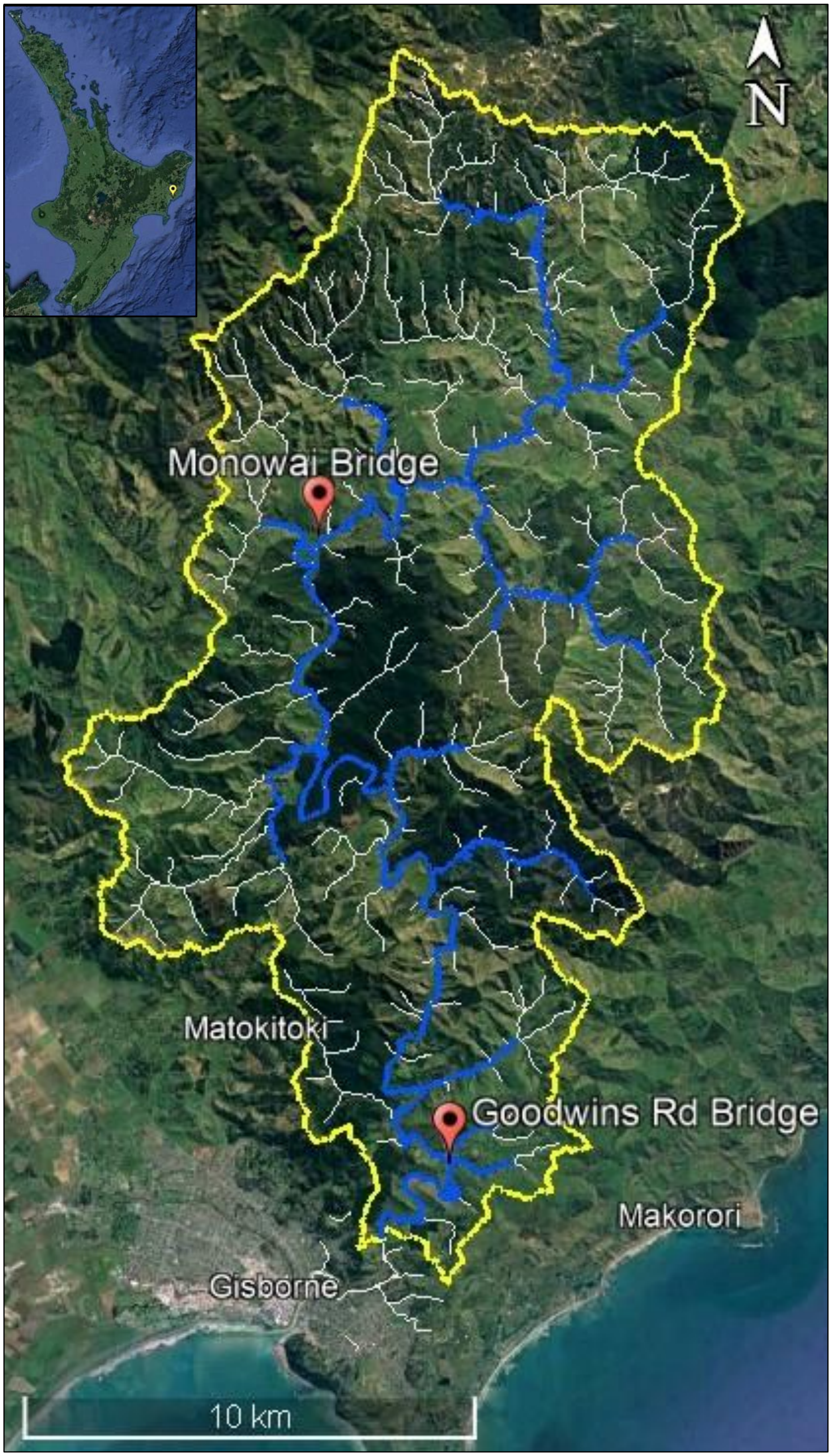

Figure 3.1: Waimatā Catchment Boundary, Watershed Network and GDC Flow Gauges

3.2 Geological Setting

The headwaters of the Waimatā Catchment are at the bottom of the Raukumara Ranges. Adjacent to the catchment is the Hikurangi subduction margin, where the Pacific Plate is moving under the Indo-Australian plate (Wallace et al., 2009). A high tectonic uplift rate has created steep slopes and narrow valleys, limiting the river's width and concentrating its flow. The catchment is primarily mudstone of different ages, easily weathered, along with some areas of alternating mudstone and sandstone (Mazengarb & Spenden, 2000; McLeod et al., 1999). The weak lithology, combined with the removal of indigenous vegetation, causes the catchment to be highly prone to erosion and generates large amounts of sediment as the rocks are uplifted and eroded (Cullum et al., 2017).

As shown in Figure 3.2, the Waimatā Catchment mainly comprises weakly developed Recent soils. Down-slope movement on steep slopes continuously reworks the soil profile, limiting time for in-situ soil development. These soils have variable textures and high available water capacity. Tephric material from volcanic ash is found in some areas of the Recent soils (Harvey et al., 2021). There are some areas of Pumice soils where the tephra is more coarse and Brown soils where the tephra has less sand (McLeod et al., 1999). The lowlands consist mainly of Pallic soils, identified by their pale subsoils, low iron oxide levels and weak structure. These soils tend to be dry in summer and wet in winter (Harvey et al., 2021). The lower catchment also contains some Pumice soils in the parts experiencing earth flow, which are weak due to their low clay content. The upper catchment has more Brown soils, the most common in New Zealand. Iron oxides are present, and they have a relatively stable, well-developed topsoil (Harvey et al., 2021). Some Gley soils are found in the upper catchment and more in the lower catchment. They are grey in appearance due to waterlogging and chemical reduction and usually indicate the presence of wetlands or swampy areas. They have high groundwater levels, giving them a high bulk density.

The underlying lithologies of the Waimatā Catchment are uniform, so there isn't much variation in infiltration rates. A study by McLeod et al., 1999, found that the total available water capacities of soils in the Gisborne region were generally high. The Tephric soils tend to have higher available water capacity than soils with similar textures.

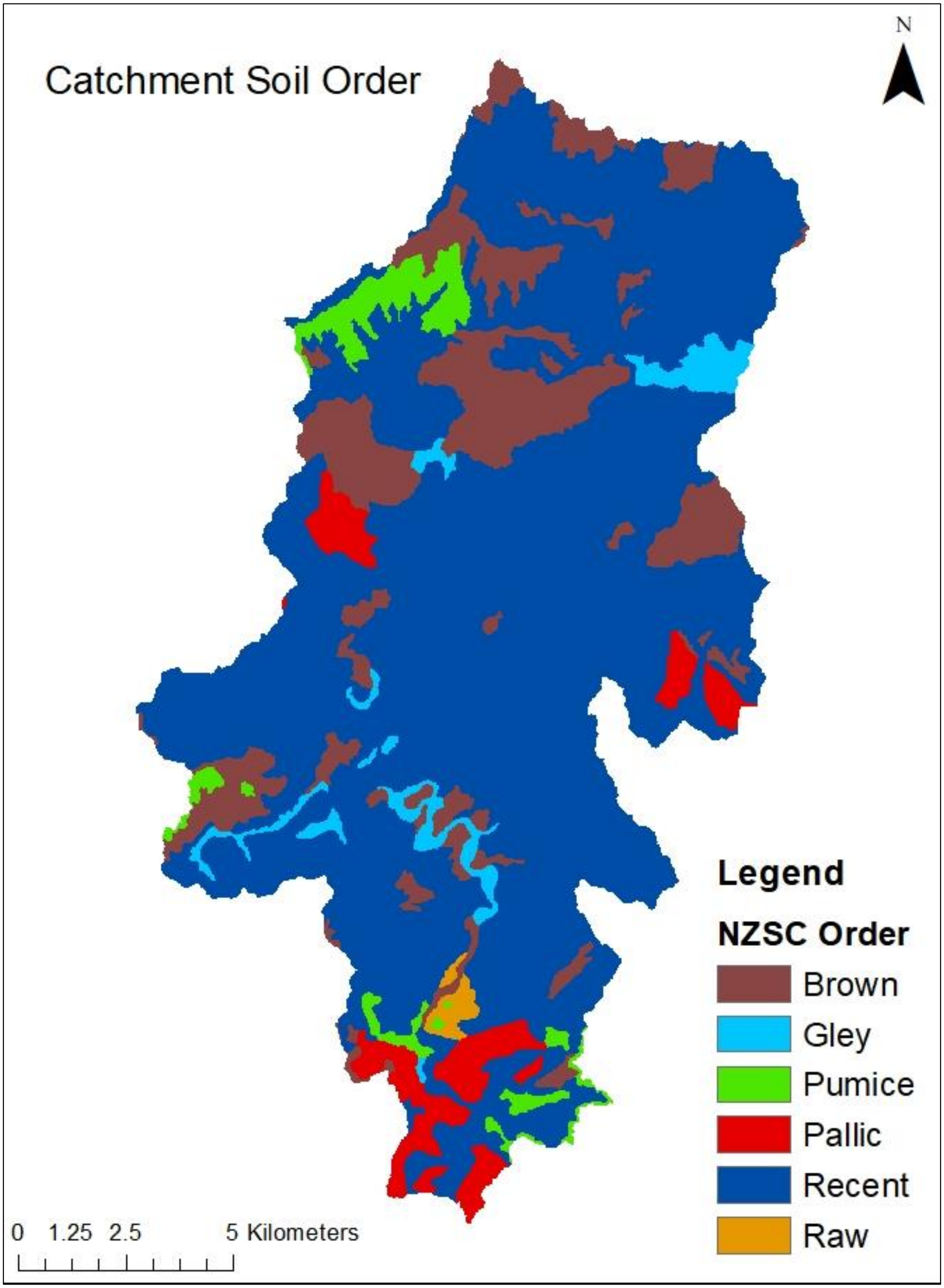

Figure 3.2: Waimatā Catchment Soil Map (Fundamental Soil Layers NZ Classification)

3.3 River Geomorphology

Geology, landscape history, and position in the catchment influence the character and behaviour of the Waimatā River. The river is unique to the rest of the east coast region as the bedrock and terraces have caused a fixed river position, which gives no space to accommodate large volumes of sediment (G. J. Brierley et al., 2023). Steep headwater reaches of the Waimatā are in poor geomorphic river condition, with forest harvesting causing an overload of fine-grained sediments (Harvey et al., 2021). These inputs from upstream have infilled some valleys. The Waimatā system is highly confined, so there is little systematic change throughout the catchment. Therefore, the river acts as a chute, and most sediment and woody debris are flushed out to the ocean (Harvey et al., 2021). Even though this does not impact channel morphology, it does cause large amounts of sediment to accumulate at the river mouth (Cullum et al., 2017). Rainfall runoff from this type of hill country is high, and if there is little vegetative cover, then high rainfall events can cause flooding of a flashy nature where water levels rise very quickly. Quaternary changes to flow regimes have left old terraces behind, so the floodplain has been confined to narrow pockets adjacent to the river (Cullum et al., 2017; Salmond et al., 2022). Human settlement and industry in Gisborne city have modified and limited the wider natural floodplain at the river's lower reaches (Cullum et al., 2017). Stream power is determined by position within the catchment, which generally decreases downstream as slope reduces and the valley widens. All these factors result in the Waimatā River having a low capacity for adjustment. The recovery potential of the river is high as materials are easily flushed downstream due to the relative confinement of the river. Hence, materials only overload the system temporarily (Cullum et al., 2017).

3.4 Land Use Change

Historically the Waimatā Catchment mainly comprised of tawa, kohekohe, titoki and podocarp forest (Salmond, 2016; Wilmhurst et al., 1999). Kahikatea, tōtara and matai dominated the river terraces of the upper catchment, and the kahikatea-pukatea forest was prevalent at the top of the lower catchment in the poorly drained areas of alluvial terraces and wetland margins (Salmond, 2016). Māori land clearance and settlement were mainly confined to the flats for cultivation and infrastructure purposes, so the majority of the steep land, especially in the headwaters of the Waimatā Catchment, remained native forest that provided resources such as timber, fruits and birds (Coombes, 2000; Ewers et al., 2006; Salmond, 2016; Wilmhurst et al., 1999). Deforestation accelerated upon European arrival for timber harvesting and to expand pastoral agriculture. This resulted in the clearance of indigenous vegetation across most of the catchment. By 1900 an area of 9700 hectares had been cleared between the Taruheru and Waimatā rivers (Coombes, 2000). The replacement of soil-stabilising vegetation with pasture, in combination with the geological nature of the catchment, triggered a major sedimentation issue that has continued to the present day, reducing water quality (Coombes, 2000; Wilmhurst et al., 1999). The first exotic pine forest was planted in 1960 (Salmond, 2016), and these areas remained small until Cyclone Bola caused significant erosion and flood damage in 1988. Subsequently, there was an emphasis on planting Pinus radiata as a means of erosion control and to prepare for potential future extreme rainfall events. Many pine plantations were initially established as soil conservation initiatives that were government subsidised, but now most are commercial forestry, and many have been sold to overseas owners (Cullum et al., 2017). These plantations covered large areas of the Waimatā Catchment over a short period, resulting in mass harvesting in the catchment when the trees matured 25-30 years later (Marden et al., 2012). When a pine forest is harvested, the ground is left bare and vulnerable until the next rotation of trees has matured and re-established a canopy cover. This contributes to sediment and slash issues evident in the Waimatā Catchment. Fuller et al. (2023) suggest that the geomorphic river stories of East Coast landscapes need to be considered when managing land use in vulnerable catchments.

The most recent land cover survey was done in 2018 and is summarised for the Waimatā Catchment by LAWA, 2022, as shown in Figure 3.3 and Table 3.1 below. The primary land use of the Waimatā Catchment is pasture for livestock production, making up 49% of the total area. The next largest is exotic forestry production at 32%, and in 2018, 3.58% of that was classed as harvested. With an additional 6% indigenous forest, 38% of the catchment is in forest cover (LAWA, 2022). The established indigenous vegetation is mostly on steep land unsuitable for farming, with areas of mānuka/kānuka scrub left to regenerate to prevent erosion (Salmond, 2016). Whakaroa Reserve, located at the top of the catchment, is the largest area of native vegetation (Salmond, 2016). Gisborne District Council has identified Protected Management Areas (PMA) under their planning process for much of the remaining indigenous vegetation. There are also 13 covenants in the catchment covering 313 hectares that protect native bush via Ngā Whenua Rāhui Kawenata (NWR) or Queen Elizabeth the Second covenants (QEII) (Salmond, 2016). More lifestyle and horticultural blocks are found in the lower catchment. As the river flows through Gisborne City, it is surrounded by urban development and parkland. A survey by Forbes et al. (2018) of Waimatā riparian vegetation covering 457 ha of the riparian zone found that 67% was forested, with 78% being exotic forest. Figure 3.4 illustrates that the most extensive land cover change in the catchment since 1996 has been an increase of exotic forestry by 35%, mostly converted from pasture, which has decreased by 16%. However, with less than 40% of the catchment in forest cover, rainfall runoff and total water yields will increase alongside deforestation in the catchment (Salmond, 2016).

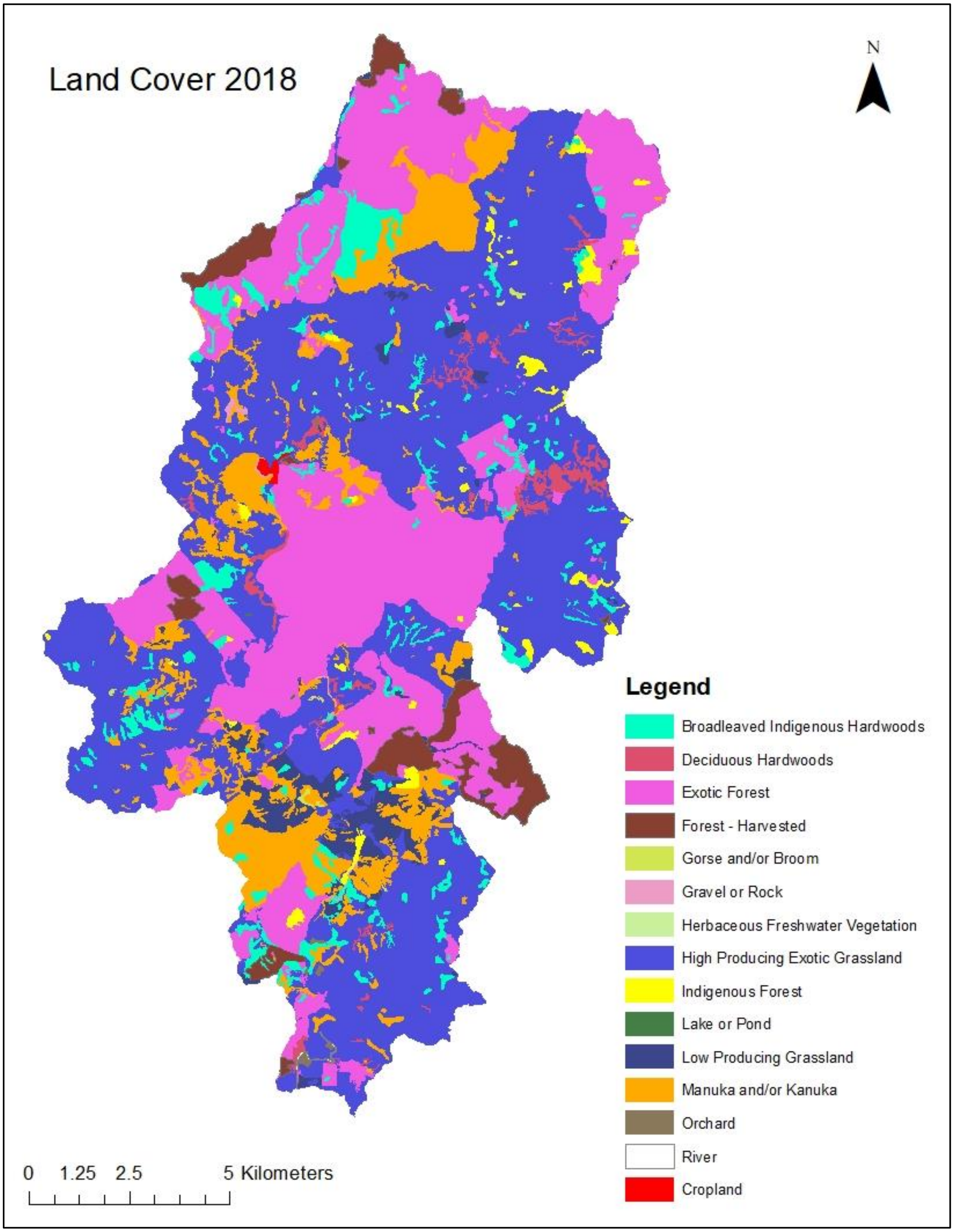

Figure 3.3: Waimatā Catchment Land Cover 2018 (LAWA)

Table 3.1: Waimatā River Catchment Land Cover Breakdown 2018 (LAWA)

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%

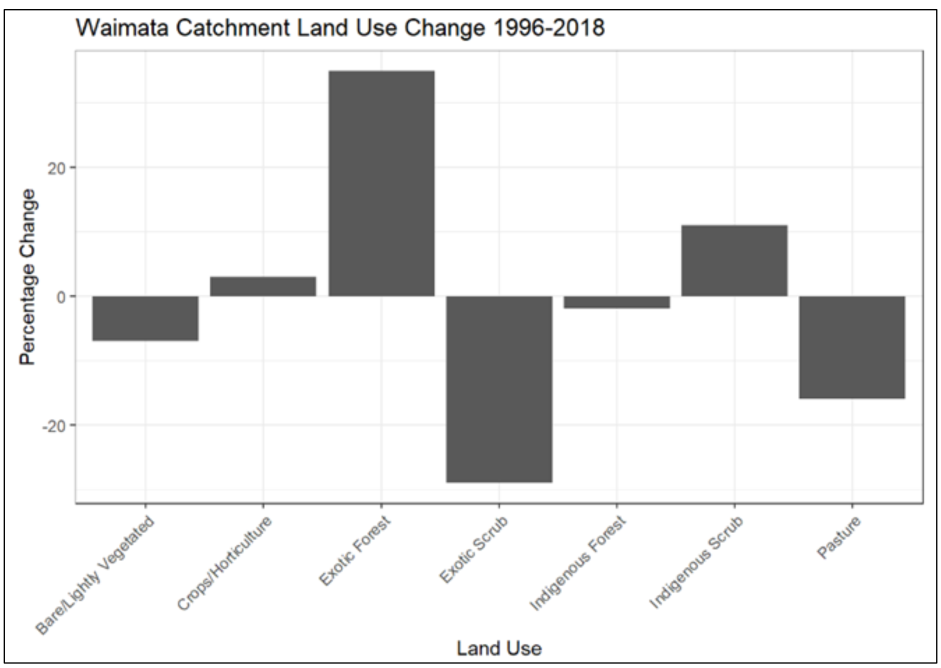

Figure 3.4: Waimatā Catchment Land Use Change 1996-2018 (%)

3.5 River Health and Catchment Ecology

Historically the Waimatā River was a source of mullet, shellfish and tuna (eel) for local people (Coombes, 2000; Salmond et al., 2022). It would have also been a habitat for kakahi (freshwater mussels), giant and banded kokopu, koaro, torrent fish, inanga and bluegill bully (Salmond, 2016). Wetlands and swampier ground alongside the river would have been a source of harakeke (flax) and raupō used as fibres (Salmond, 2016). The indigenous forest that covered most of the catchment supported a range of bird and insect life, all interacting as part of the broader ecosystem of the catchment. Early Māori described the river as running clear and named it Waimatā because its water was black, like obsidian (Cairns et al., 2021).

Land use changes in the catchment have led to the degradation of freshwater biodiversity. An ecosystem overloaded with fine-grained sediments and forestry slash has changed habitat structure, making it difficult for fish and invertebrate species to thrive (Cullum et al., 2017; Salmond, 2016). Monitoring by Gisborne District Council shows that the MCI index of the Waimatā River is in the "Fair"- "Poor" range and has a low composition of EPT species. However, some of the Waimatā tributaries surrounded by indigenous forests are in better condition (Salmond, 2016). The forest ecosystems have changed alongside different land uses. However, remaining native vegetation and even exotic forestry still provide habitats to support biodiversity in the catchment, although at a much smaller scale than before. The river's water quality is poor, and LAWA (2022a) showed that at Anzac Park over the last five years, the water quality was only suitable for swimming 60% of the time. At both Goodwins Road Bridge and Monowai Bridge monitoring sites, E. coli measurements are in the worst 50% of all sites, turbidity is high, and Phosphorus levels are in the worst 25% and likely degrading. However, total Nitrogen is in the best 50% as it is less common for hill country livestock farmers to apply nitrogen fertilisers compared to other agricultural practices. Phosphorus has been found to be naturally high in Gisborne's coastal waters due to its erosive geology (Gisborne District Council, 2020b). High turbidity and high Phosphorus from hill country catchments are generally associated with high sedimentation rates.

3.6 Regional Climate and Flood History

Gisborne's unique climate is directly influenced by its topography and position on the easternmost point of New Zealand. New Zealand is in the hemispheric temperate zone, where weather systems generally move from west to east. Gisborne experiences a higher frequency of extreme weather events compared to the western regions (Chappell, 2016). Low mean wind speeds and high sunshine hours of at least 2200 per year provide Gisborne with a pleasant climate suitable for various agricultural and horticultural practices (Chappell, 2016). Gisborne is exposed to rain and thunderstorms from easterly weather systems, and the Raukumara Ranges cause uplift during these situations, which can intensify rainfall. In contrast, the ranges shelter the region from westerly winds, resulting in higher temperatures and little rain (Chappell, 2016). It is common during summer to have sea breezes that penetrate a substantial distance inland. Rainfall varies across the region, with 1300-1800 mm annual averages in northern coastal areas and Gisborne city and further inland averaging 1000mm and less. 20% of this rainfall is expected during the summer months and 30% in the winter months. The frequency of rain in Gisborne averages 108 rainfall days exceeding 1mm annually (Chappell, 2016).

The Ministry for the Environment (2018) and Woolley et al. (2020) predict high rainfall events in Gisborne will become less frequent but more intense. Total rainfall is expected to decrease by 0-5% by 2040 and 10-15% by 2090. In addition, projections show that the annual number of days of soil moisture deficit and potential evapotranspiration deficit totals will increase, heightening the potential for drought. Combined with a predicted temperature increase of 0.5-1.0 °C by 2040, these factors will likely increase the severity of future droughts. Decreased rainfall will reduce the mean annual discharge of rivers, and some catchments are expected to experience an increase in mean annual low flows. However, further research and modelling are needed to better understand whether there will be changes to high flows. Mean annual floods are predicted to increase for a small proportion of Tairāwhiti rivers by up to 50%, driven by increased rainfall intensity. The Gisborne region is likely to see impacts of this with more flooding and erosion damage. Decreased annual rainfall will lower river base flows, impacting water availability and freshwater ecosystems (Woolley et al., 2020).

High rainfall events are common throughout New Zealand, and the narrow flood plains of the Waimatā Catchment cause water levels to peak quickly as a response to intense rainfall. The water is concentrated in the river chute, moving large amounts of sediment and debris to the coast. However, the clearance of native vegetation in the catchment has increased runoff and enhanced the severity of floods (Salmond, 2016). Since official records of the Waimatā Catchment began in the early 1900s, the frequency and severity of extreme rainfall events and resulting damage has increased. Cyclone Bola and Gabrielle are two significant events that stand out for the Waimatā Catchment due to the extraordinary destruction they caused. Ex-tropical Cyclone Bola hit in March 1988, yielding some of the largest rainfall totals for a single storm event recorded in the North Island of New Zealand. 800mm fell over four days at some high-country stations. The Waimatā Catchment suffered significant land sliding, with some farmers losing up to 30% of their grazing area. The damage costs to the district were $189 million. Cyclone Bola was long considered the worst storm to hit Gisborne until ex-tropical Cyclone Gabrielle broke records and caused widespread destruction on the 13th and 14th of February 2023. The Waimatā Catchment experienced extensive erosion and slips, significant long-term damage to roads and bridges, and flooded houses alongside the river's lower reaches. There was also mass deposition of sediment and forestry slash, which intensified the damage. Recovery from this event is still underway at the time of publication. The recovery cost for the Gisborne roading network alone is nearly $30 million (GDC, 2023). Gisborne experienced a total rainfall of 358mm during February 2023, over five times the monthly normal (NIWA, 2023). Described by locals and media as the worst storm in living memory, Cyclone Gabrielle is an example of what the Waimatā River is capable of and the potential scale of future flood events.

Chapter 4: Methods

4.1 Introduction

To understand how land cover influences hydrological behaviour in the catchment, surface runoff, water yield and discharge were measured using modelling software called the Soil and Water Assessment Tool (SWAT). The analytical techniques examine how land cover change affects these metrics and determine which sub-catchments are most sensitive to land cover change. This chapter explains the rationale of the approach and the justification of the steps used. Figure 4.1 summarises the methods workflow. The methodological approach of this desktop research comprised the following steps:

- Data collection and processing
- Creating a hydrological model for the Waimatā River Catchment
- Calibrating and validating the model with observed flow data.
- Determining alternative land cover scenarios for the catchment
- Using the hydrological model to simulate impacts of land cover changes.
- Analysis of how the land cover changes affected the flow regime.

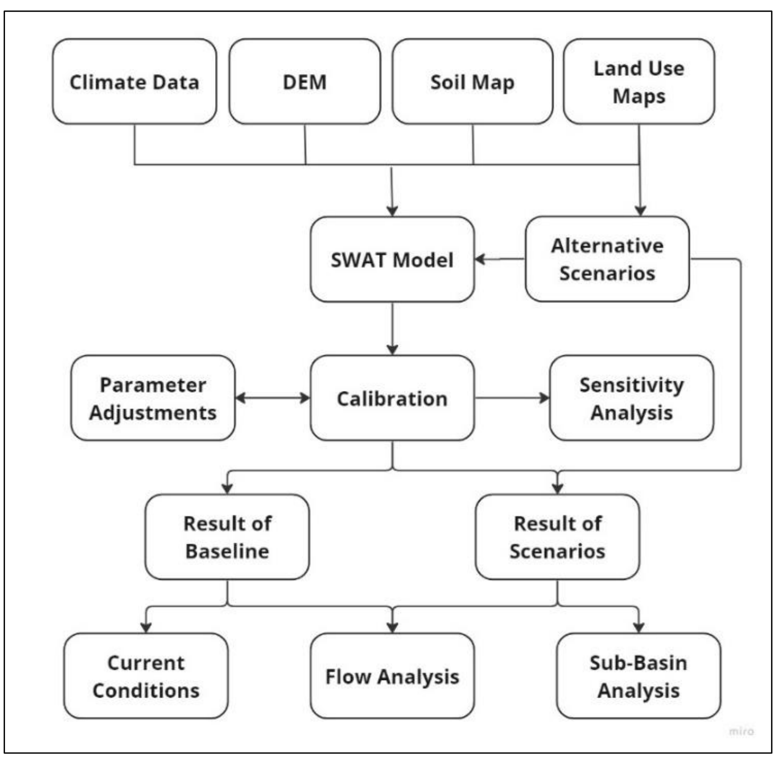

Figure 4.1: Methods Workflow

4.2 Data Collection and Processing

All data required for this research are publicly available and downloadable in formats compatible with GIS software. The data collected are described in the following categories:

- GIS/DEM
- Soil
- Land Cover
- Climate
- Parameter look-up tables
- Observational discharge data

A Digital Elevation Model (DEM) is a grid of elevation values for a specified area. A 1-m resolution DEM was downloaded from the Land Information New Zealand (LINZ) data service portal and clipped to the Waimatā Catchment boundary. It was then aggregated to a 5-m scale so the hydrological model could process it efficiently.

The Fundamental Soil Layers New Zealand Soil Classification was the soil map chosen for this study because it is the only one that covers the entire Waimatā Catchment. It was downloaded from the Ministry for the Environment data service portal and converted from a polygon shapefile to a raster format. Each polygon represents a soil class, and there are 16 soil classes found within the Waimatā Catchment (see Appendix).

A 2018 land cover map was downloaded from the Land and Resource Information System (LRIS) portal and converted from a polygon shapefile to a raster. Each polygon represents a land use class, and the catchment area for this study has 15 in total. The selected map is the most up to date version. The raster values for each land cover class were then reassigned, and some were merged to match the classifications in the SWAT database. This resulted in 11 land classes. The SWAT database does not provide a classification for a recently harvested forestry block, so a new class was created and manually added to the database. The parameters were copied from the *Pine* category, and the parameters that influence rainfall runoff were adjusted accordingly to represent a land class with almost no vegetative cover and scattered debris from harvest operations.

Climate data were collected from multiple sources. Gisborne District Council (GDC) provided rainfall data for five stations and meteorological data for two of those stations. GDC also provided flow data from two gauges along the Waimatā River at Goodwins Road Bridge and Monowai Bridge (located in Figure 4.2).

These flow data were used to calibrate the hydrological model. The remaining meteorological data were collected from NIWA's CliFlo online database. For each station, the daily data were put into separate text files for precipitation, wind speed, temperature, relative humidity, and solar radiation. A different look-up table was created with the monthly means of this data for each station.

Additional soil and land use data was added to look-up tables for calculations in the SWAT database. The model associates these look-up tables with the values in the soil and land use maps to derive spatial differences in the calculations.

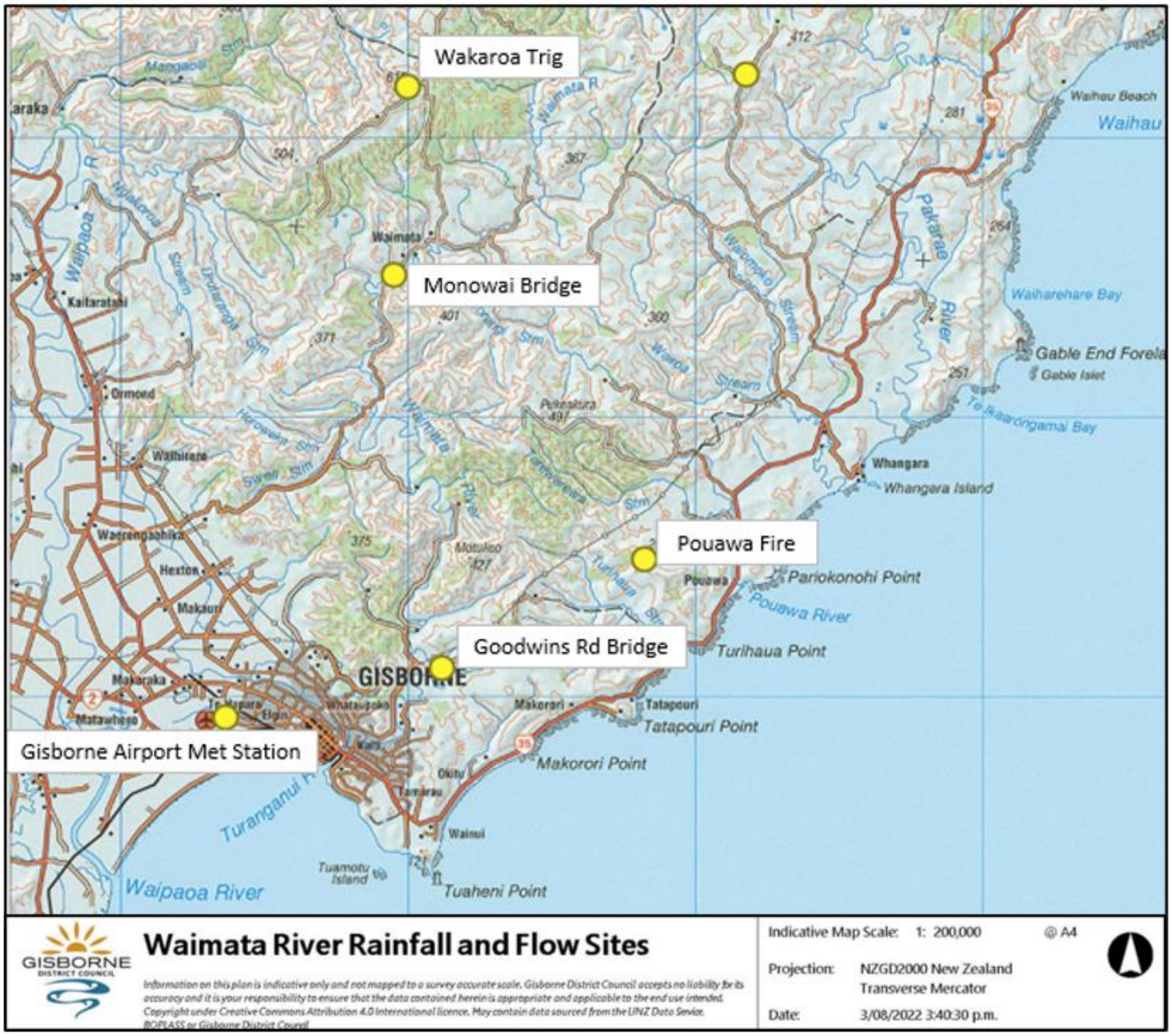

Figure 4.2: Climate Data Site Locations (Gisborne District Council)

4.3 Creating the Waimatā River Catchment in SWAT

The Soil and Water Assessment Tool (2021 version) is a plugin for ArcGIS 10.8. SWAT was chosen because it is open source, compatible with GIS and is relatively simple to modify parameter values or inputs to model changes within a catchment (Beven, 2012). Therefore, it is an appropriate tool for representing the hydrological effects of land use change and has been used successfully for this purpose in New Zealand (Cao et al., 2008). SWAT can also produce soil erosion and water quality metrics, but this study only focuses on the hydrological outputs.

Figure 4.3 is a simplified diagram of a SWAT simulation (see Arnold et al. (1998) and Beven (2012) for more comprehensive descriptions of SWAT). First, an automatic watershed delineation was run using the catchment DEM. This outlined the basin and provided the stream network for the catchment. The catchment was then split into sub-basins depending on the terrain and water channels. SWAT initially identified 101 sub-basins. This was narrowed down to 19 to make the analysis easier by merging the smallest sub-basins into larger ones. This was guided by a river classifications map (Ministry for the Environment, 2010) by only selecting outlet points of third and fourth order reaches. From here, soil and land cover maps were imported into the model, and SWAT calculated a slope map. Then multiple Hydrological Response Units (HRU) were created within each sub-basin based on the land cover, soil, and slope characteristics. The water balance was simulated from these HRU spatial units. The last step was to input observed climate data to run the simulation. SWAT has many output options that allow adjustments to the spatial and temporal scale.

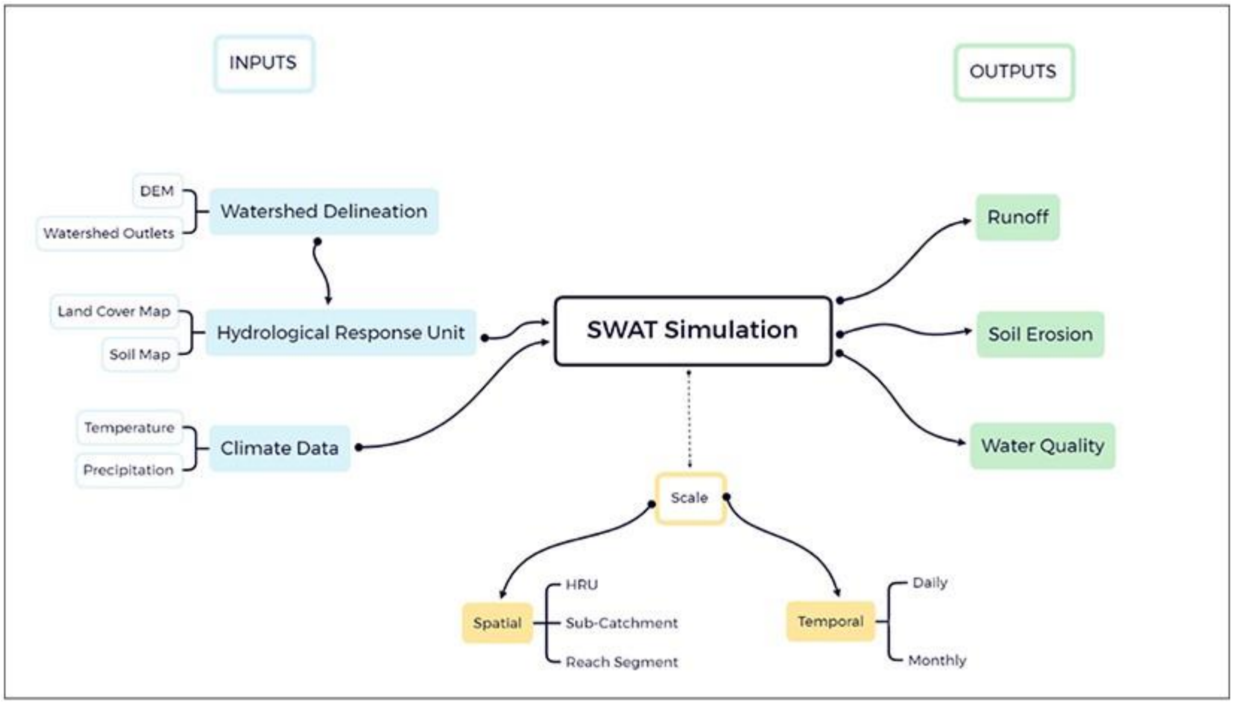

Figure 4.3: SWAT Simulation Diagram

4.4 Calibration and Validation

Many SWAT parameters are fixed based on pre-existing catchment data such as soil and land use maps. Other parameters are only estimated and must be adjusted via calibration to represent better spatial and temporal variations (Me et al., 2015). Having historical discharge data from the GDC allowed for minimising the difference between observations and the modelled simulations to increase the accuracy of output results. Flow rate is the only output calibrated because it has observational data from the catchment. This research used SWAT-CUP, a stand-alone calibration software that reads SWAT output files.

The first step of the calibration was to conduct a manual sensitivity analysis to identify the most critical influence factors in the model. This helped determine which processes are dominant in the watershed and decreased the number of parameters to calibrate (Abbaspour et al., 2017). Manual calibration also revealed that the rainfall runoff and flow metrics are more sensitive to rainfall variation than other climate data. When the first SWAT-CUP calibration was run, the outputs included a sensitivity analysis. The significance of one or a combination of parameters can be determined with respect to the objective function of the model output. The sensitivity analysis results are found in Table 4.1, and parameter sensitivity is ranked by P-value from highest to lowest. The parameter that discharge is most sensitive to is the SCS runoff curve number, a function of the soil's permeability.

Table 4.1: Sensitivity Analysis

Parameter Name	P-value
SCS Curve Number	0.0000
Moist bulk density	0.0004
Threshold depth of shallow aquifer for return flow	0.0336
Moist Soil Albedo	0.0419
Baseflow Alpha Factor	0.0463
Saturated hydraulic conductivity	0.0813
Soil evaporation compensation factor	0.1431
Manning's roughness value for main channel	0.1579
Threshold depth of shallow aquifer for "revap" to occur	0.5168
Groundwater "revap" coefficient	0.5221
Manning's roughness value for overland flow	0.7781
Available Soil Water Capacity	0.9821

To calibrate the model, a three-year period of observational flow data between 2018 and 2020 was input into SWAT-CUP, and simulated results from SWAT were run through it. SWAT-CUP then gave a comparison between observed and simulated flow for each gauge. SWAT-CUP expresses model uncertainty as 95% prediction uncertainty (95PPU) calculated at the 2.5% and 97.5% levels (Abbaspour et al., 2017). The 95PPU accounts for all uncertainties combined, which are mapped onto the parameter ranges. The parameter uncertainty range can be adjusted to get the simulated hydrograph to match the observed data series best, and an example can be found in Figure 4.4.

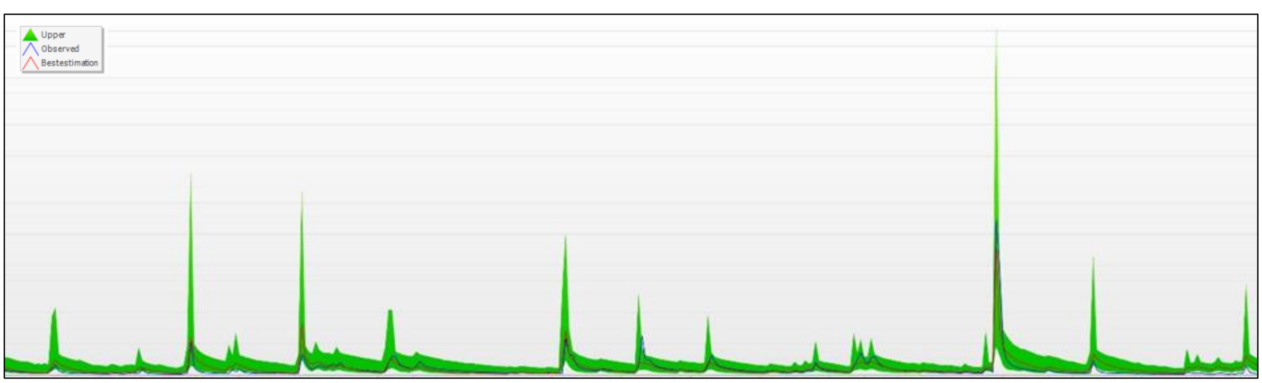

Figure 4.4: Example of how 95PPU from SWAT-CUP Simulation

The R-factor and P-factor are also calculated for each flow gauge to show model uncertainty for each simulation, as shown in Table 4.2. The Nash-Sutcliffe (NS) coefficient assesses the model's accuracy. Feng et al. (2019) found that an NS value around 0.65 to 0.75 is satisfactory for simulating discharge with SWAT. The coefficient of determination (r^2), which varies between 0 and 1, indicates the degree of fit between the calibrated model parameters and the observed data. Based on the results presented in Table 4.2, the calibrated parameters demonstrate a satisfactory correlation with the observed data.

Table 4.2: Calibration Results

	Monowai	Goodwins
p-factor	0.78	0.74
r-factor	1.53	1.72
r^2	0.77	0.76
NS	0.75	0.75

Figure 4.5 shows the best match that was made, and although it is not identical, it is still within reason to use. The study's main focus is the peak event on October 15th, 2019. The simulated outputs are almost identical to the observational outputs in October. However, it is widely accepted that model predictions, calibration and validation are subject to uncertainty as it is impossible to truly reflect all processes involved (Beven, 2012; Oreskes et al., 1994). Calibrations that produce the best match can be used to generate a suite of simulations that capture the effect of possible changes in the catchment. Other studies that used SWAT to assess land use change found that it was common for SWAT to overestimate base flow and underestimate peak flows (e.g., Cao et al., 2008). Considering this, the calibration results in Figure 4.5 and Table 4.2 show that the model parameters are suitable.

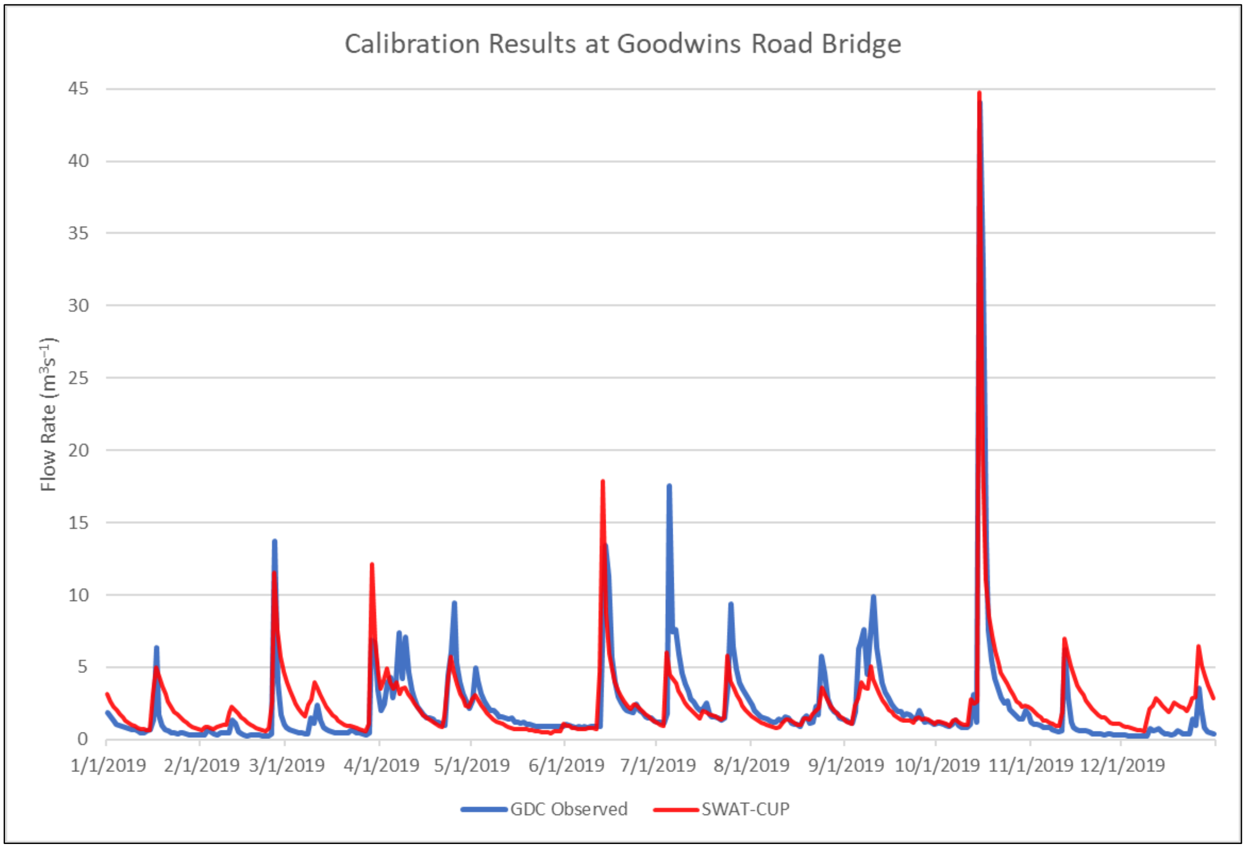

Figure 4.5: SWAT-CUP Calibration Results at Goodwins Road Bridge, 2019

Validation is important to show the consistency of a model between scenarios and build confidence in the calibrated parameters. It also indicates how reliable the model is at representing natural phenomena. As this variety depends on the quality and quantity of input parameters, it can never be assumed that a model is truly reliable at predicting future scenarios. Calibrated parameters were applied to another observed dataset independent of the original to validate the simulated hydrograph. 2021 climate data were run through the model using the calibrated parameters. The results were compared again to the observed flow records for the Waimatā River from that period at both Goodwins Road Bridge and Monowai Bridge. The results illustrated in Figure 4.6 show that the model slightly overestimates base flow and underestimates the flood event in November 2021. However, it still offers a reasonable representation of the catchment's temporal trend of hydrological behaviour. However, it is essential to note that the land use configuration of the catchment area likely changed from 2018 to 2021, with a high chance of blocks of exotic forestry being harvested. Therefore, the 2018 land cover map does not truly represent 2021 when the validation simulation was run.

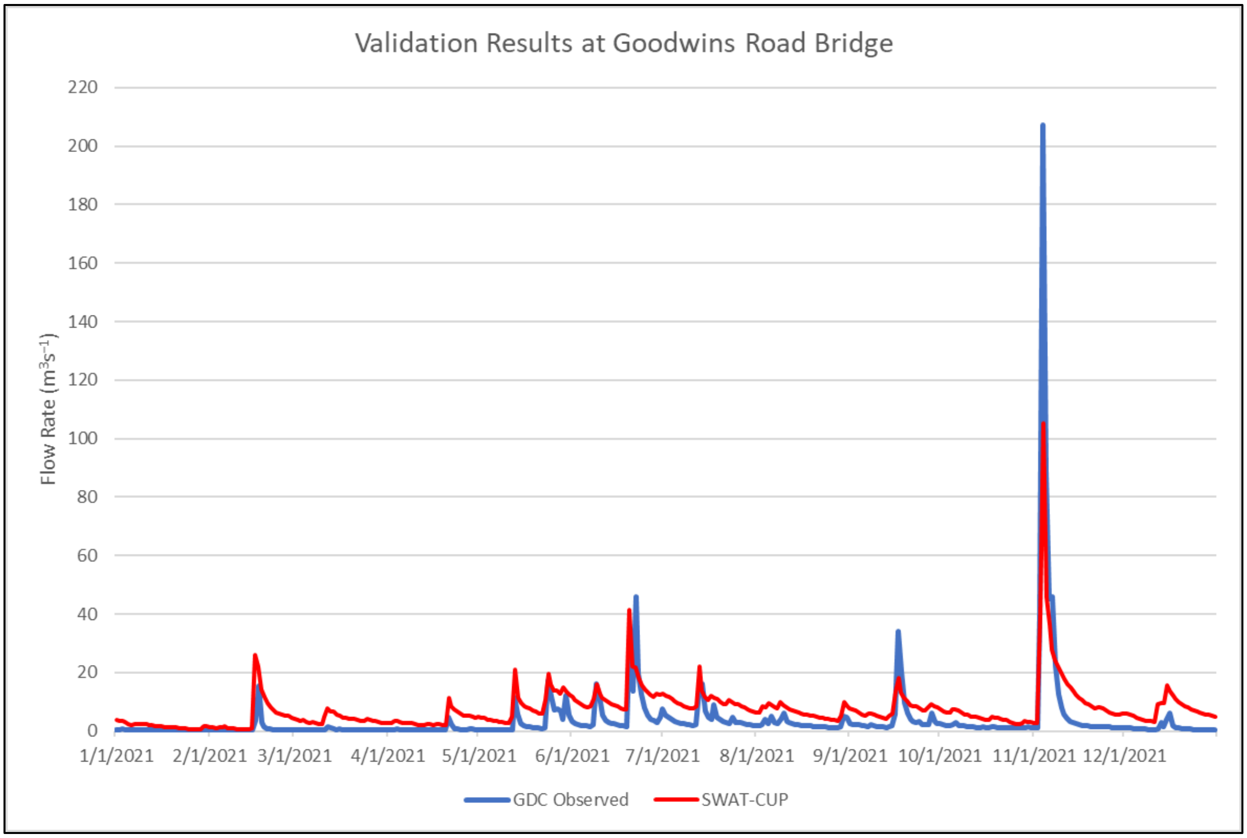

Figure 4.6: SWAT-CUP Validation at Goodwins Rd Bridge, 2021

4.5 Analytical Techniques

The key metrics used in the analysis are total water yield (mm), surface runoff contribution to streamflow (mm) and flow rate (m^3s^{-1}). Total water yield shows the volume of water exiting each sub-basin. This is directly proportional to how much water enters the system by precipitation. Therefore, the annual averages are not expected to alter much since the climate data stays constant between scenarios. Surface runoff is used to show how land cover influences the hydrological behaviour of each sub-basin. Changes in surface runoff directly affect the resulting discharge in a peak event. Flow rate shows how the river discharge changes between the scenarios. Discharge influences the kinetic energy of a river and is responsible for the impact the river will have on the watershed.

The analysis was conducted in three stages. The first step simulated the hydrological behaviour of the Waimatā Catchment in its current state using the most recent 2018 land cover map and 2019 climate data. The water balance was mapped across the catchment to show variations in precipitation, evapotranspiration, and groundwater contribution to streamflow. Surface runoff and total water yield were calculated and compared between sub-basins to understand how this contributes to the resulting discharge of the catchment. Flow rate was assessed at the two GDC gauges, Goodwins Road Bridge to represent the lower catchment and main outlet, and Monowai Bridge for the upper catchment.

The second step revealed how the whole catchment responded to land cover changes and indicated whether there was any significant impact on the overall discharge of the catchment during a high rainfall event. This step includes modelling various afforestation and deforestation scenarios to represent potential land use changes in the catchment (see next section). The last step helped to identify which sub-catchments are the most sensitive to land cover change. A simulation was run for an entire catchment in pasture cover and another for a complete historic indigenous forest. Comparison of surface runoff, water yield and discharge for these extreme scenarios for each sub-basin provided an effective contrast to show which ones changed the most. The larger the differences, the more sensitive the sub-basin. Then the difference between input and output flow for each sub-catchment was measured to show which sub-basins influenced flow rate the most. The larger the difference, the more effect that sub-catchment was. Having identified which sub-basins are most sensitive to flow, a closer look was taken into how the alternative scenarios impacted those sub-basins.

4.6 Simulation of Alternative Land Cover Scenarios

To simulate different scenarios in the Waimatā River Catchment, the only input that was changed was the land cover map. The 2018 LRIS land cover layer was manipulated using ArcMap 10.8. The relevant raster values were reassigned to represent the potential changes in land class for each scenario. All other inputs that were set up in the initial simulation of the Waimatā Catchment remained constant. Alternative scenarios are grouped as vegetation removal and afforestation.

4.6.1 Afforestation

Increasing vegetative cover in a catchment reduces rainfall runoff by intercepting rainfall in the canopy and increasing evapotranspiration (Bergin et al., 1995; Rowe et al., 1999). There are many possibilities for how afforestation could occur in the Waimatā Catchment. This research investigates more realistic options guided by the region's current physical and economic state. It also explores idealistic options such as historic indigenous forest to give a baseline and show how much potential change has happened since deforestation began. Areas of pastoral farmland have the most potential for afforestation, especially bare ground adjacent to the river. Much of the farmland in the catchment has existing mānuka and kānuka scrubland that can grow into established forests if left to regenerate. This can be beneficial for erosion control and enhancing biodiversity. An entire catchment in exotic forestry production is simulated, which is unlikely but not an impossible future scenario if forestry outcompeted pastoral livestock production. Another possible land use change could be planting some areas of pastoral farmland with mānuka for honey and oil production, which was recommended for the Waimatā Catchment in the Te Awaroa Biodiversity Report (Salmond, 2016).

These scenarios include:

- Historic Forest
    - The whole catchment is an indigenous forest.
    - Excludes classes: gravel/rock, water, and freshwater vegetation.
- Scrub to Forest
    - All scrub becomes an established indigenous forest.
    - All other classes remain the same.
- Pasture to Pine
    - All pastoral areas are planted in production forestry.
    - Harvested areas remain harvested.
    - All other classes remain the same.

4.6.2 Deforestation

Removal of vegetative cover decreases rainfall interception and increases runoff, and there are many ways this can occur as land use changes throughout a catchment. Harvesting of exotic production forests is the crucial deforestation scenario to simulate. Harvests constantly happen in the Waimatā Catchment as forests mature, and these events will undoubtedly continue. It is reasonable to assume that some farms' mānuka and kānuka scrubland areas have self-seeded and will likely be removed to clear land back to pasture. Although simulations could also explore what would happen if forestry blocks were converted back to pastoral farmland, this is highly idealistic and less likely to occur with the current economic incentives for forestry in New Zealand.

These scenarios include:

- Forestry Harvest

    - All production forest is harvested.
    - All other classes remain the same.
- Pine to Pasture
    - All production forestry blocks are converted to pasture, including the harvested category.
    - All other classes remain the same.
- Scrub to Pasture
    - All areas of mānuka/kānuka scrub and gorse are cleared for pasture.
    - Excludes Donner’s Bush and Whakaroa Reserve
    - All other classes remain the same.

4.7 Modelling Assumptions

Block classed as soil conservation reserve currently has pasture with poplars and willows for erosion control, so these will never be taken out, but more forest could be established around them.

Orchards, gravel/rock, lake/pond, river, and freshwater vegetation classes will always remain constant.

Scrub not cleared will eventually grow into established indigenous forests.

Harvested exotic forestry blocks will be replanted in exotic pines.

Whakaroa Scenic Reserve and Donner’s Bush Recreation Reserve will never have trees removed, but mānuka/kānuka scrub can be changed to an established forest.

The different maturities of the various forestry blocks are not considered.

Gorse will be cleared alongside scrub.

Harvesting of production forests doesn’t consider riparian buffers that might be present and have potentially been missed by ariel photography.

The model does not consider the effect of the build-up of forestry slash on the river's hydrological nature. This is not something that can be measured, and instead, this research can be used as a guide to show where the river is more likely to carry slash, i.e., which sub-basins are at the most risk to slash transport.

Chapter 5: Results and Analysis

5.1 Introduction

Figure 5.1 summarises how the results chapter is structured. First, the hydrological behaviour of the Waimatā River Catchment in its current state is assessed by reviewing hydrograph records for selected events in 2019. Water yield (mm) and surface runoff contribution to streamflow (mm) are used to explain how streamflow (m^3s^{-1}) behaves throughout the catchment both annually and for a high rainfall event. The second section applies the modelling strategy to analyse how land cover changes might influence streamflow during a high rainfall event. Results are compared against the current land cover configuration. The third section investigates sub-basin sensitivity by comparing discharge under historic indigenous cover relative to complete pasture cover. Changes are expressed as a percentage.

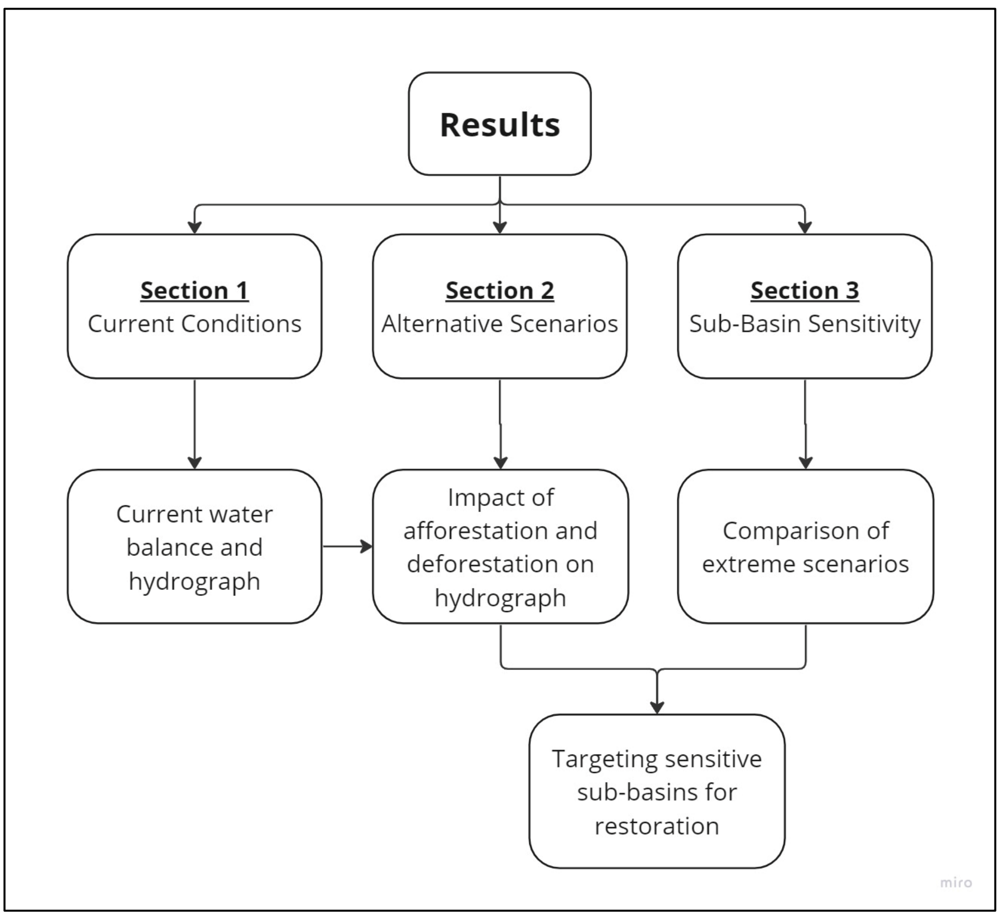

Figure 5.1: Overview of Results Structure

5.2 Current Conditions

5.2.1 Water Balance

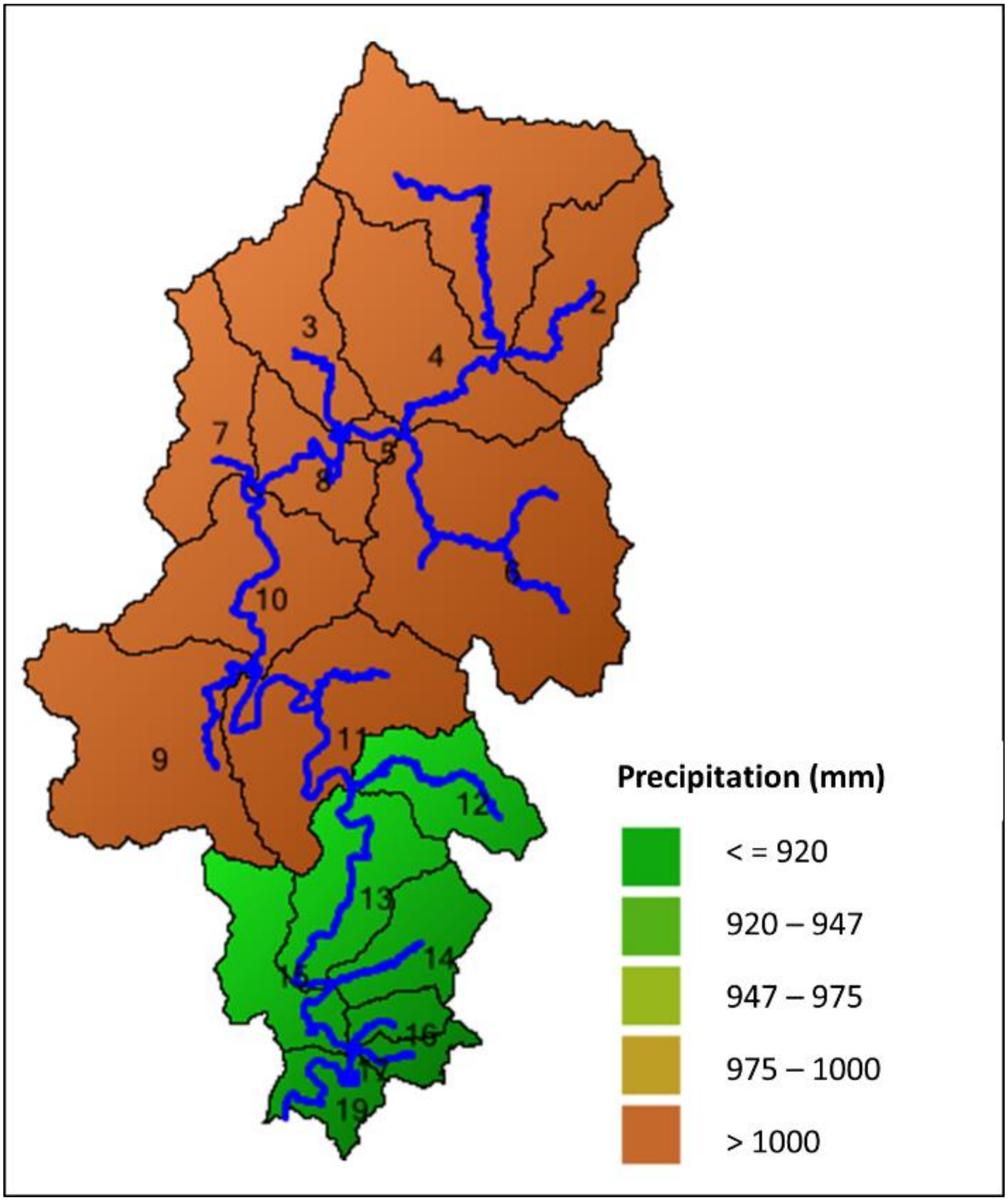

Figure 5.2: Annual Precipitation Distribution, 2019

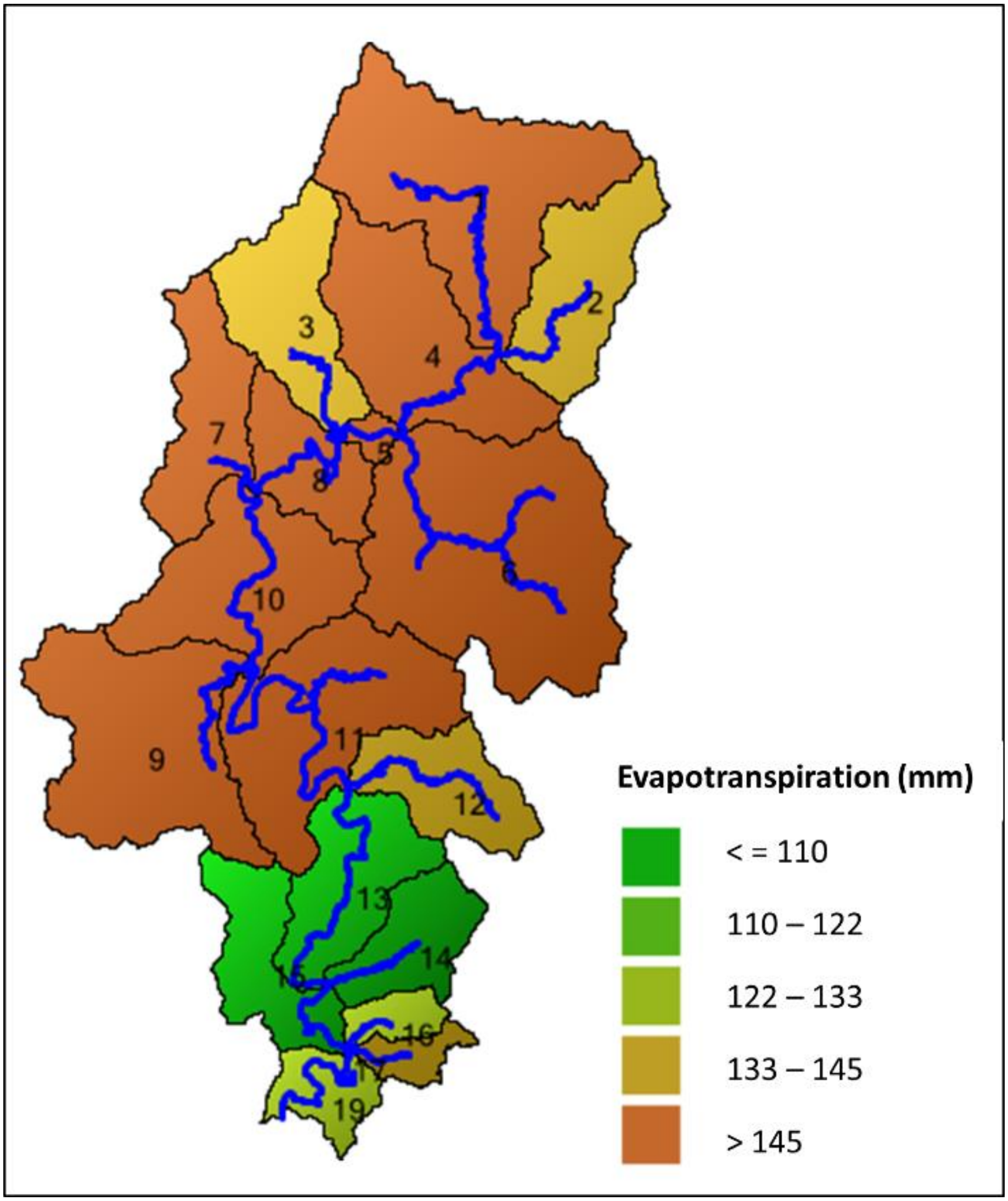

Figure 5.3: Annual Evapotranspiration Distribution, 2019

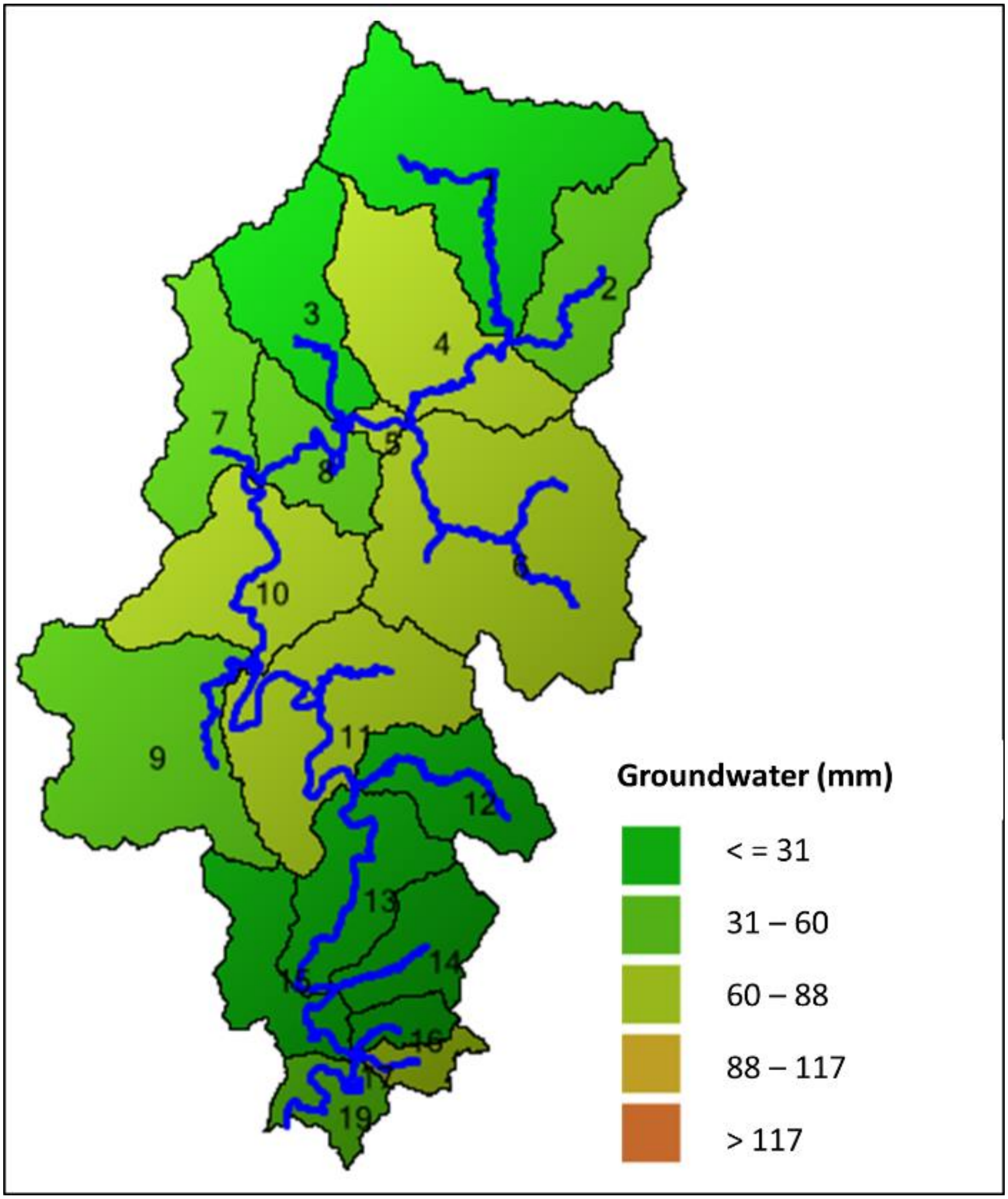

Figure 5.4: Annual Groundwater Contribution to Streamflow Distribution, 2019

Annual Water Balance (mm)			
Sub-Basin	**Precipitation**	**Groundwater**	**Evapotranspiration**
1	1017.45	20.89	156.28
2	1022.66	47.99	144.29
3	1018.73	16.66	144.99
4	1028.69	77.01	151.89
5	1028.88	65.74	155.38
6	1025.02	60.58	153.70
7	1022.28	44.73	145.64
8	1028.88	57.79	153.24
9	1023.88	41.83	147.06
10	1027.57	60.19	150.04
11	1028.21	60.88	148.38
12	897.53	7.78	141.36
13	903.35	9.34	106.69
14	898.48	2.51	101.27
15	898.01	15.64	98.91
16	902.41	20.60	127.80
17	903.74	143.80	122.95
18	893.21	65.66	140.49
19	896.13	42.72	131.09
Total	**18465.11**	**862**	**2621**

Table 5.1: Annual Water Balance Values, 2019

Figures 5.2, 5.3, 5.4 and Table 5.1 illustrate the water balance of the Waimatā River Catchment for 2019. Annual precipitation is higher in the upper and mid-catchment, likely due to its higher altitude. Annual evapotranspiration is more varied but still highest in the upper and mid-catchment, most likely associated with the higher rainfall and greater proportion of forest cover. In contrast, annual groundwater contribution to stream flow is highest in the lower catchment. This is likely due to the lower catchment's less steep terrain, which means less water is entering the watershed from surface runoff, and more is being transferred into groundwater. Additionally, the Pallic and Pumice soils of the lower catchment have a coarser texture than Recent and Brown soils in the mid to upper catchment, resulting in higher permeability, allowing water to move easier through the ground into streams.

5.2.2 Surface Runoff

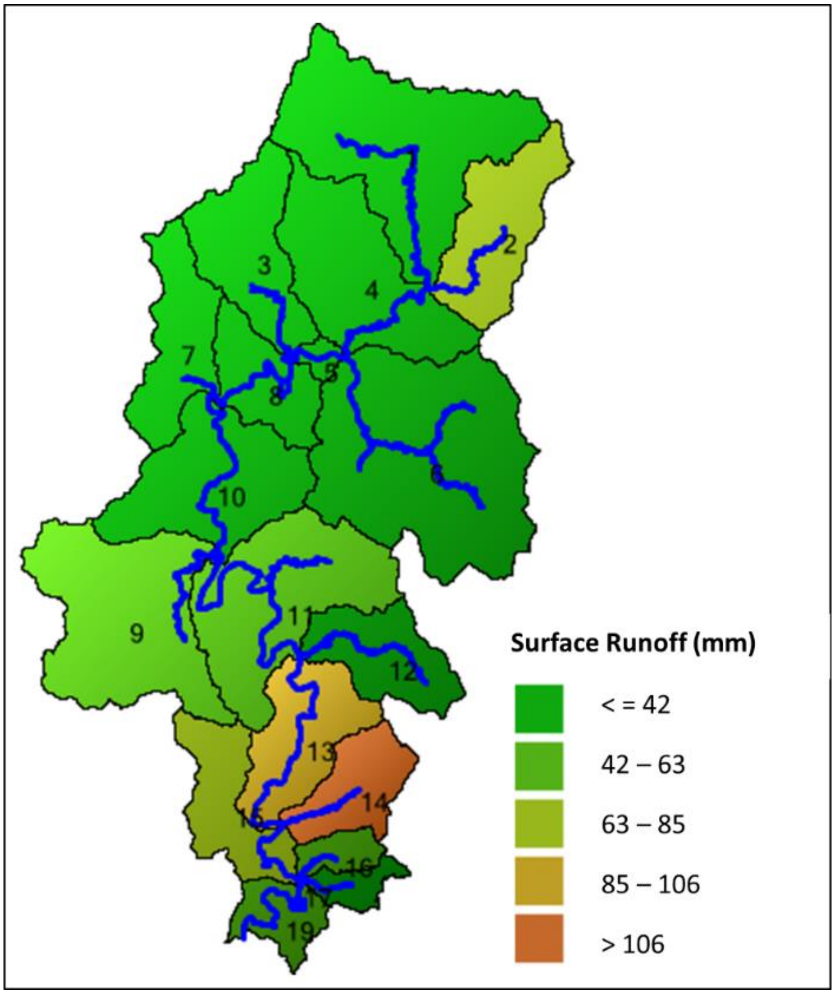

Figure 5.5: Annual Surface Runoff Distribution, 2019

Table 5.2: Total Surface Runoff Values for 2019 and Peak Event

Current Surface Runoff (mm)		
Sub-Basin	**Annual**	**Peak Event**
1	28.03	12.70
2	72.76	26.60
3	23.91	9.36
4	20.75	11.80
5	27.18	15.60
6	30.07	17.80
7	24.10	13.60
8	39.44	18.50
9	53.31	21.90
10	31.31	17.60
11	53.44	21.10
12	26.05	12.90
13	100.85	31.20
14	**127.93**	**36.90**
15	80.49	28.80
16	60.65	20.90
17	29.67	14.40
18	19.95	11.70
19	61.88	23.00
Total	**911.78**	**366.36**

Figure 5.5 and Table 5.2 illustrate the distribution of surface runoff contribution to stream flow per sub-basin. Sub-basin 14 has the highest surface runoff annually and during high rainfall. It is 720 hectares with a land use configuration of 84% pasture, 4% mānuka/kānuka, 8% indigenous forest, 2% exotic pine and 1% poplar. Sub-basin 14 also has steep relief, which, combined with large pasture areas, raises surface runoff. The next highest surface runoff is from sub-basin 13 for similar reasons to 14. It is 48% pasture, 31% mānuka/kānuka and 12% indigenous forest. Even though it has more tree cover than 14, it is steep, with 55% of slopes above a 0.5 gradient. Surface runoff is lowest in the upper catchment, where there is more forest cover, except for sub-basin 2, which is slightly higher than its surrounding basins.

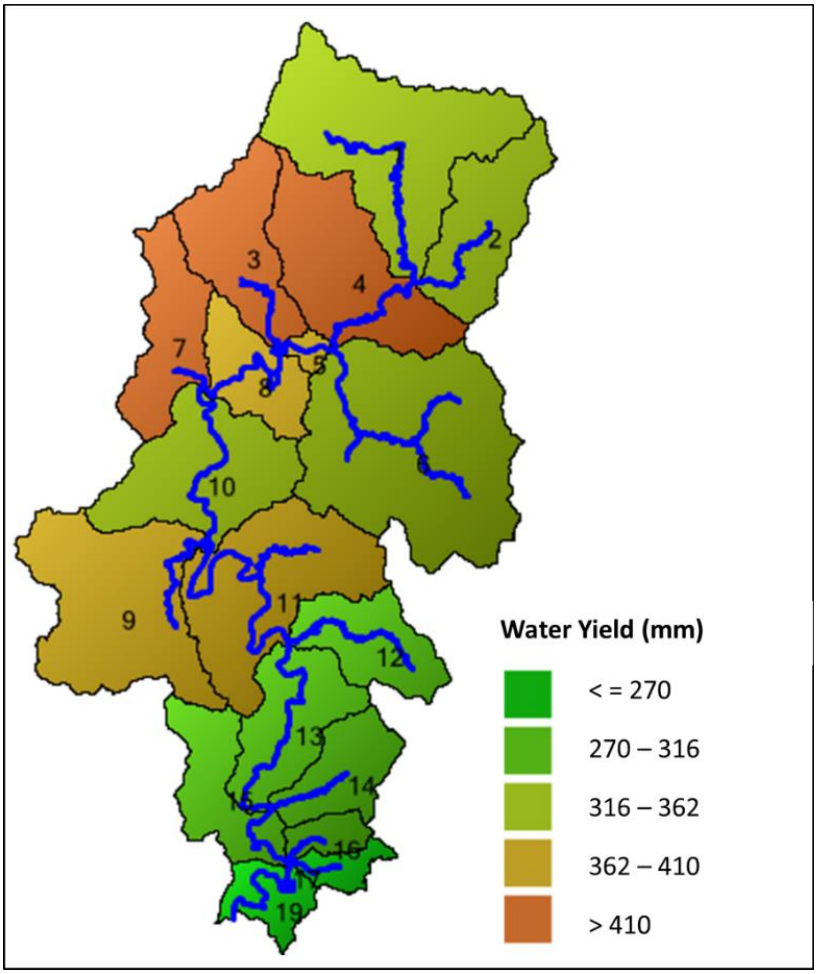

Table 5.3: Total Water Yield Values for 2019 and Peak Event

Current Water Yield (mm)		
Sub-Basin	**Annual**	**Peak Event**
1	352.11	17.10
2	332.13	29.30
3	**455.10**	21.10
4	429.63	17.70
5	388.63	19.80
6	359.26	21.60
7	436.34	21.00
8	386.61	22.80
9	384.45	26.50
10	359.74	21.40
11	370.42	24.60
12	290.15	16.10
13	287.40	33.40
14	294.52	**39.10**
15	287.51	32.00
16	278.53	24.10
17	269.81	17.50
18	222.93	14.30
19	262.32	25.80
Total	**6447.56**	**445.20**

Figure 5.6: Water Yield Distribution, 2019

Figure 5.6 illustrates the distribution of the annual water yield of the catchment and dictates that sub-basin 3 has the highest annual water yield of 455mm. The main land uses covering its 1183 hectares are 41% exotic pine and 38% pasture. The total forest covers 54% of the sub-basin, including 5% of mānuka and 8% of indigenous forest. Even though the sub-basin is only the seventh largest in the catchment, 92 hectares covering 8% of the sub-basin, is classed as harvested forest. This, alongside large pasture areas, will reduce the total rainfall interception and increase surface runoff. It is also reasonably steep, with half the area at a 0.5 gradient or above. The main soil types are Typic Orthic Pumice and Weathered Orthic Recent soils. Sub-basin 4 is slightly larger and has the second-highest water yield at 430mm. The sub-basin is 68% pasture, with 14% mānuka/kānuka shrubland and 13% indigenous forest. The primary soils are Pallic Orthic Brown and Weathered Orthic Recent soils. Slope classes are slightly more varied than sub-basin 3 but still considerably steep. Sub-basin 7 is smaller than 3 and 4 but has a high annual water yield of 436mm. The sub-basin is 63% pasture, 10% mānuka/kānuka and 10% exotic pine. It is also 5% harvested pine, contributing to the higher water yield for its smaller size. The primary soil types are Pallic Orthic Brown and Weathered Orthic Recent, followed by a notable area of Pedal Immature Pallic soils. It is also steep, with 72% above 30% rise over run. The bottom of the catchment has the lowest annual water yields. These sub-basins are not as steep as the upper catchment and are smaller in size. More details of each sub-basins size, soil, land cover, and slope characteristics can be found in the Appendix. Looking at the peak event on October 15th, 2019, in Table 5.3, there are notable changes in the distribution of water yield compared to the annual totals. Specifically, sub-basin 14 has the highest daily water yield, closely followed by 13 and 15 in the lower catchment. This outcome can be attributed to daily water yield predominantly reflecting surface runoff. Consequently, the distribution of daily water yield closely corresponds to the pattern observed in the surface runoff distribution during the peak event, as presented in Table 5.2.

5.2.4 Discharge

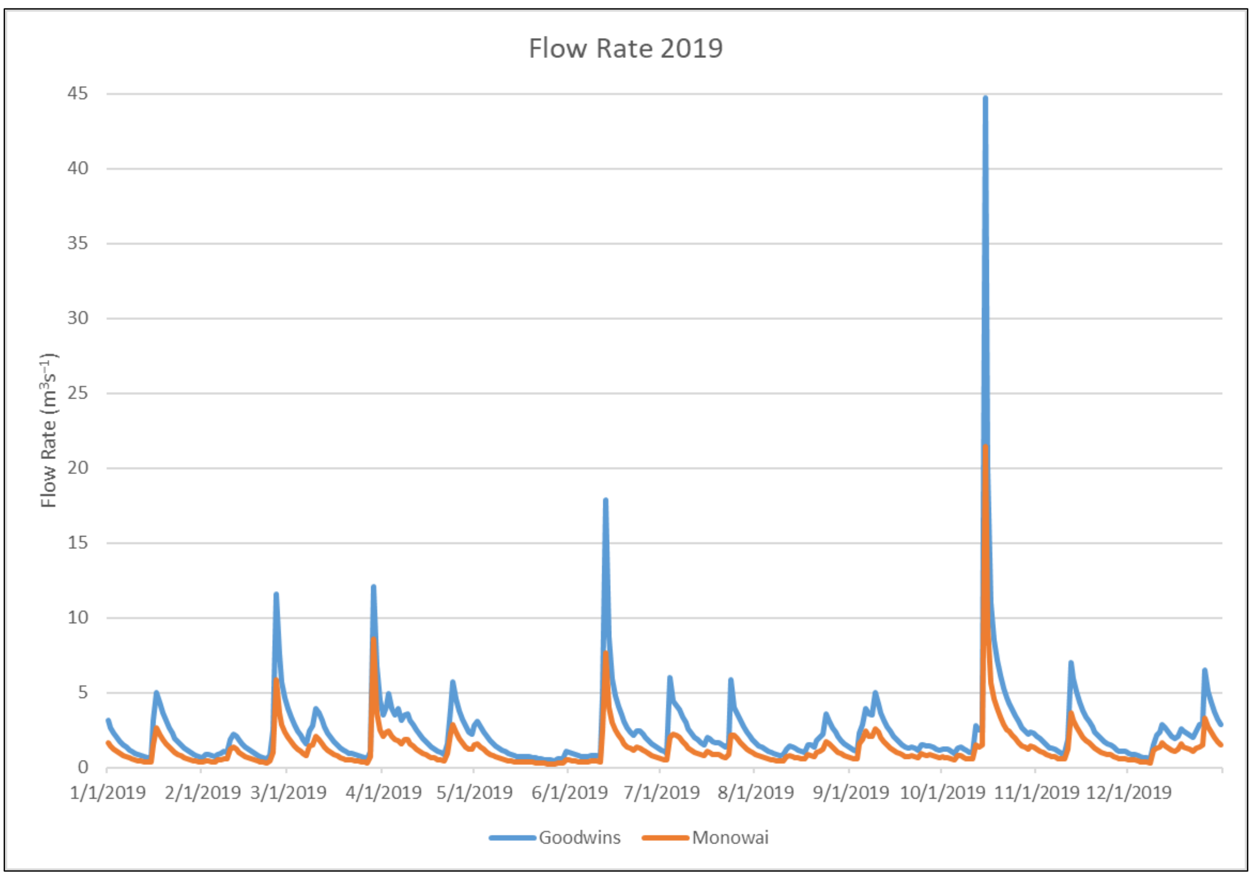

Figure 5.7: Simulated Flow Rate at GDC Gauge Stations for 2019

The configuration of the water balance, surface runoff and water yield throughout the catchment determine the Waimatā River's flow rate. Figure 5.7 depicts the SWAT simulated hydrograph at both flow gauge stations for 2019. Monowai Bridge is in sub-basin 8, and Goodwins Road Bridge is in sub-basin 17. Only these sub-basins are analysed at this step because they are located on the main Waimatā River trunk stream and highlight the contrasting hydrologic response in the upper and lower catchment. Monowai Bridge has lower flow as it captures fewer sub-basins, but its trend is almost identical to the Goodwins Road Bridge gauge. Goodwins has higher peak flows because it is at the bottom of the watershed and experiences a higher volume of water. Four events with high discharge are represented by the most prominent peaks of the hydrograph. There are also consistent smaller peaks throughout the year that are not as significant, and they appear every time there is a period of substantial rainfall. The results use daily averaged data, contributing to sharper peaks compared to hourly data. Base flow typically sits below 5 m^3s^{-1}, which is consistent for the upper and lower catchment gauge stations.

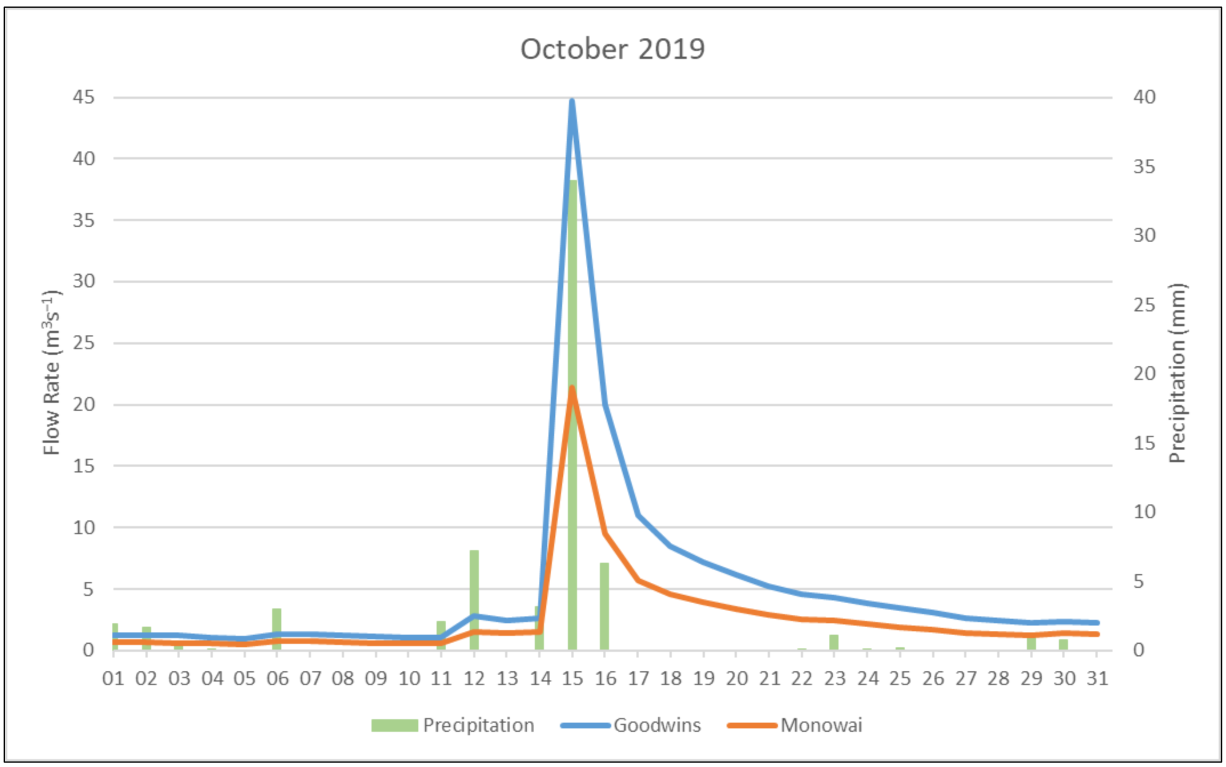

Figure 5.8: Simulated Flow Rate at GDC Gauge Stations for October 2019

Figure 5.8 provides an enlarged view of the hydrograph, highlighting the prominent flood peak on October 15th, 2019. The flow at Goodwin's Road Bridge peaks at a daily average of 44.75 m^3s^{-1}, and Monowai Bridge peaks at 21.42 m^3s^{-1}. A significant rainfall event saw 34mm at Goodwins Road Bridge and 41mm at

Monowai Bridge over 24 hours. Precipitation for the main event starts on October 12th, with peak rainfall on October 15th. The hydrograph's rising limb corresponds with the timing of rainfall accumulation, with a small rise at the start and then a very steep incline to the peak discharge. The falling limb is also steep but takes longer to recede because rain continues until October 17th. There is also a lag time in groundwater flow which takes longer to reach the main tributaries and channels.

5.3 Alternative Land Cover Scenarios

5.3.1 Afforestation

Table 5.4: 2019 daily average streamflow (m^3s^{-1}) and streamflow change (%) from current scenario

2019 daily average streamflow (m^3/s) and streamflow change (%) from current scenario							
Scenario	**Current**	**Historic Forest**		**Pasture to Pine**		**Scrub to Forest**	
Sub-Basin	m^3/s	m^3/s	%	m^3/s	%	m^3/s	%
1	0.29	0.28	-0.52	0.29	0.06	0.29	-0.19
2	0.12	0.12	-1.31	0.12	-0.04	0.12	0.00
3	0.17	0.17	-0.49	0.17	-0.22	0.17	-0.03
4	0.64	0.64	0.91	0.65	1.02	0.64	-0.10
5	1.02	1.03	1.11	1.03	1.43	1.02	-0.06
6	0.37	0.37	1.44	0.38	2.12	0.37	0.00
7	0.14	0.14	0.53	0.14	0.90	0.14	0.00
8	1.28	1.29	0.84	1.30	1.12	1.28	-0.06
9	0.27	0.27	-0.76	0.27	0.02	0.27	-0.14
10	1.60	1.61	0.77	1.62	1.08	1.60	-0.06
11	2.09	2.10	0.36	2.11	0.79	2.09	-0.08
12	0.08	0.08	-1.20	0.08	-0.41	0.08	-0.13
13	2.27	2.26	-0.17	2.28	0.39	2.26	-0.17
14	0.07	0.06	-15.28	0.06	-13.13	0.07	-0.30
15	2.41	2.39	-0.74	2.41	-0.05	2.40	-0.25
16	0.02	0.02	-5.65	0.02	-4.50	0.02	0.01
17	2.43	2.41	-0.79	2.43	-0.09	2.43	-0.24
18	0.02	0.02	4.74	0.02	6.87	0.02	-0.03
19	2.48	2.46	-0.78	2.48	-0.05	2.48	-0.24
Total Average	**0.93**	**0.93**	**-0.89**	**0.94**	**-0.14**	**0.93**	**-0.11**

Table 5.5: October 15th daily average streamflow (m^3s^{-1}) and streamflow change (%) from current scenario

October 15th daily average streamflow (m³/s) and streamflow change (%) from current scenario							
Scenario	**Current**	**Historic Forest**		**Pasture to Pine**		**Scrub to Forest**	
Sub-Basin	m³/s	m³/s	%	m³/s	%	m³/s	%
1	4.85	3.89	-19.74	4.14	-14.69	4.71	-2.97
2	3.69	2.92	-20.73	3.04	-17.53	3.69	-0.03
3	2.84	2.56	-9.87	2.60	-8.28	2.82	-0.60
4	11.21	9.19	-18.05	9.61	-14.26	11.43	1.96
5	18.88	14.95	-20.82	15.55	-17.64	19.08	1.06
6	7.68	5.80	-24.40	5.99	-22.03	7.66	-0.17
7	2.36	1.95	-17.65	2.01	-15.15	2.34	-1.02
8	21.97	18.33	-16.57	19.09	-13.11	22.09	0.55
9	6.34	4.80	-24.25	5.07	-20.06	6.19	-2.29
10	27.05	22.69	-16.12	23.71	-12.35	27.04	-0.04
11	37.21	30.49	-18.06	32.01	-13.97	36.93	-0.75
12	1.57	1.45	-7.71	1.53	-2.55	1.55	-1.15
13	38.55	33.33	-13.54	35.19	-8.72	38.14	-1.06
14	3.13	2.25	-27.94	2.40	-23.37	3.11	-0.67
15	42.65	37.36	-12.40	39.60	-7.15	42.08	-1.34
16	0.68	0.49	-27.88	0.50	-25.26	0.67	-0.18
17	43.31	37.83	-12.65	40.09	-7.43	42.74	-1.32
18	0.40	0.27	-32.66	0.28	-29.22	0.39	-0.80
19	41.03	35.51	-13.45	37.66	-8.21	40.55	-1.17
Total Average	**16.60**	**14.00**	**-18.66**	**14.74**	**-14.79**	**16.48**	**-0.63**

Table 5.4 shows that all afforestation scenarios decrease by less than 1% in the annual daily average flow rate. Table 5.5 presents the results of the streamflow response to the peak event on October 15th, 2019, when the afforestation scenarios were simulated. The first scenario reflects the catchment's historic hydrological response under complete indigenous forest cover, which resulted in an 18.66% reduction in streamflow during the peak event compared to the current land cover configuration. When all pastoral farmland is replaced with pine-production forest, the average daily streamflow is reduced by 14.79%, although some sub-basins have a slight increase. This scenario assumes all forest blocks have matured with a closed canopy cover. The following scenario represents all mānuka/kānuka scrubland in the catchment being left to regenerate into an established, indigenous. The flow rate would be reduced by an average of 0.63% across the catchment. Figure 5.9 provides a graphical representation of the percentage changes in streamflow during the peak event. Sub-basin 18 shows the largest discharge response to the historic forest and pine afforestation scenarios due to its current land cover of 94% pasture. Sub-basin 1 sees the most considerable reduction in flow rate when scrub regenerates into an established forest because of its large area of existing mānuka/kānuka scrub.

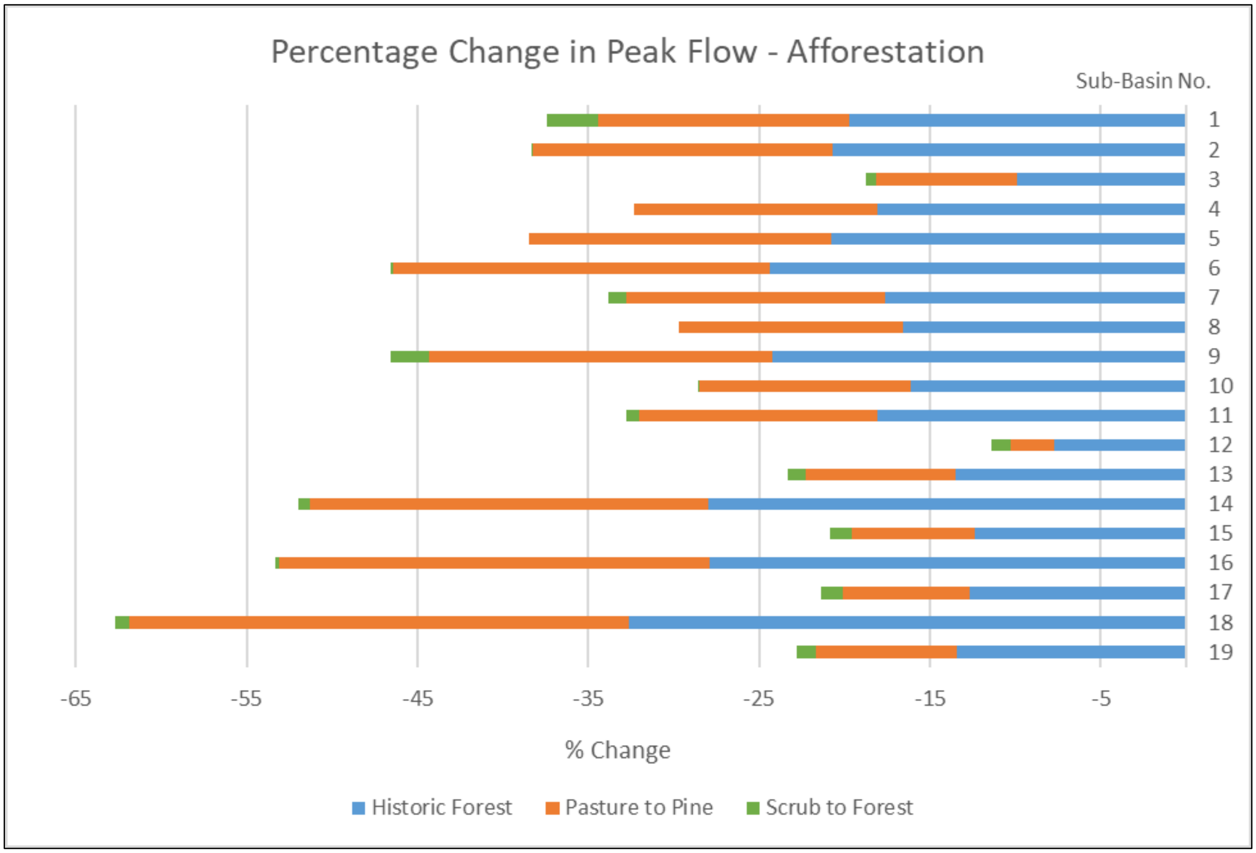

Figure 5.9: Afforestation Percentage Change in Peak Flow from Current Scenario

Figure 5.10 provides a visual representation of how discharge changes across the catchment as a result of each afforestation scenario. The changes are expressed as a percentage. The legend for each scenario is based on the natural breaks in the distribution of percentage change values because there is a variety in how each scenario impacts the catchment. This depends on the land cover that is already present in each sub-basin. For example, there is minimal change in sub-basin 1 for the pasture to pine forest scenario because, under current conditions, the sub-basin already has a large area of plantation forestry present.

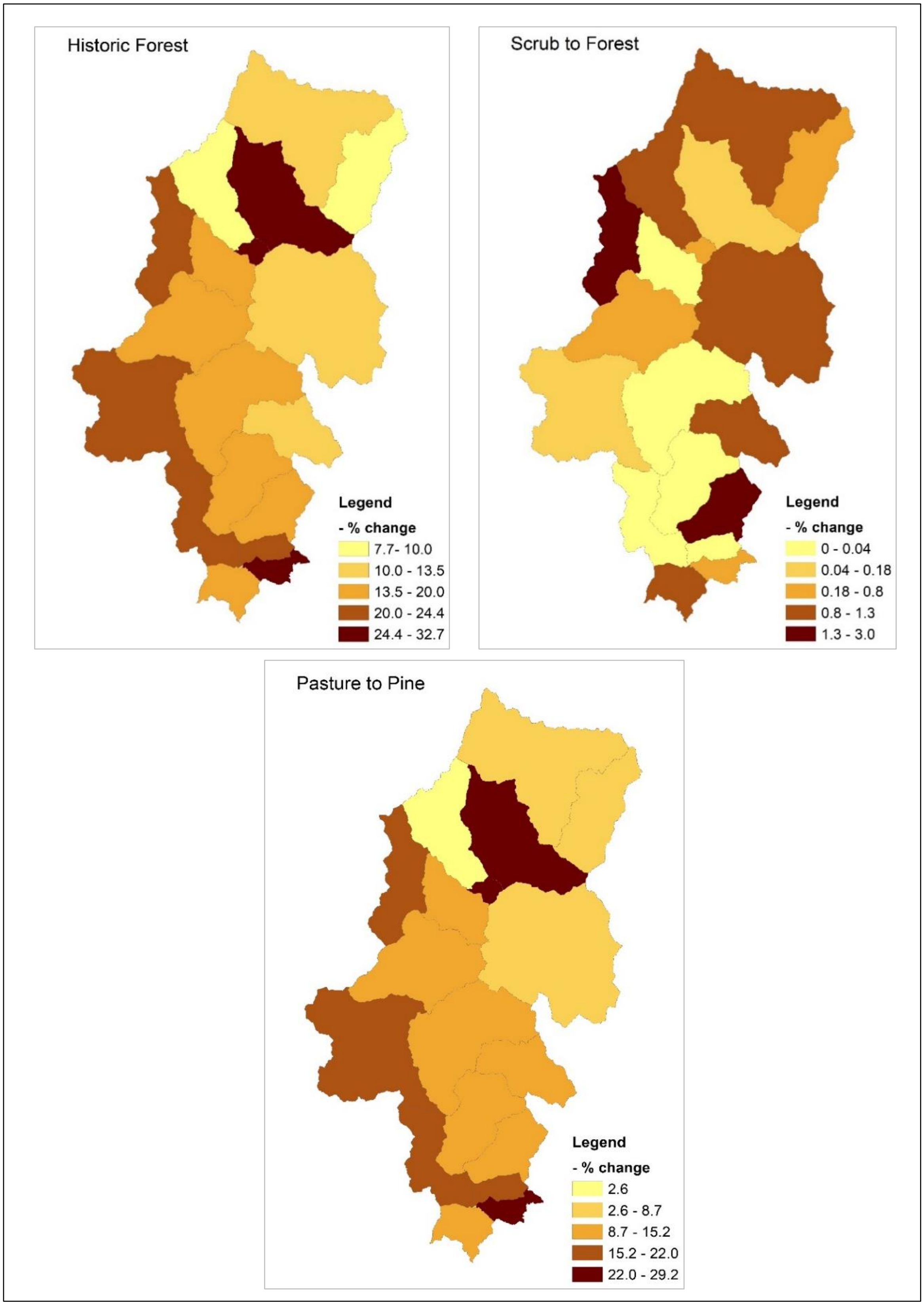

Figure 5.10: Percentage Change in Flow Rate for Afforestation Scenarios

5.3.2 Deforestation

Table 5.6: 2019 daily average streamflow (m^3s^{-1}) and streamflow change (%) from current scenario

2019 daily average streamflow (m³/s) and streamflow change (%) from current scenario									
Scenario	**Current**	**Pasture**		**Pine to Pasture**		**Scrub to Pasture**		**Pine Harvest**	
Sub-Basin	m³/s	m³/s	%	m³/s	%	m³/s	%	m³/s	%
1	0.29	0.29	1.40	0.29	0.94	0.29	0.35	0.29	2.26
2	0.12	0.12	0.78	0.12	0.69	0.12	-0.01	0.12	2.87
3	0.17	0.17	1.08	0.17	0.68	0.17	0.04	0.17	1.37
4	0.64	0.65	1.41	0.64	0.52	0.64	0.10	0.65	1.55
5	1.02	1.03	0.76	1.02	0.20	1.02	0.06	1.03	1.04
6	0.37	0.37	-0.32	0.37	-0.34	0.37	-0.01	0.37	0.21
7	0.14	0.14	0.47	0.14	0.11	0.14	0.03	0.14	0.33
8	1.28	1.29	0.77	1.28	0.26	1.28	0.06	1.29	1.05
9	0.27	0.27	0.25	0.27	-0.15	0.27	0.36	0.27	0.28
10	1.60	1.61	0.77	1.60	0.31	1.60	0.06	1.62	1.24
11	2.09	2.10	0.59	2.09	0.11	2.09	0.15	2.11	1.08
12	0.08	0.08	3.33	0.08	3.09	0.08	0.23	0.09	7.26
13	2.27	2.29	0.95	2.27	0.26	2.27	0.31	2.30	1.36
14	0.07	0.07	1.76	0.07	0.14	0.07	0.57	0.07	0.07
15	2.41	2.44	1.29	2.42	0.40	2.42	0.45	2.45	1.58
16	0.02	0.02	0.84	0.02	0.00	0.02	0.03	0.02	0.00
17	2.43	2.46	1.28	2.44	0.40	2.44	0.45	2.47	1.56
18	0.02	0.02	-0.18	0.02	0.00	0.02	-0.15	0.02	0.00
19	2.48	2.52	1.30	2.49	0.43	2.49	0.44	2.52	1.62
Total Average	**0.93**	**0.94**	**0.97**	**0.94**	**0.42**	**0.94**	**0.18**	**0.95**	**1.41**

Table 5.7: October 15th daily average streamflow (m^3s^{-1}) and streamflow change (%) from current scenario

October 15th daily average streamflow (m³/s) and streamflow change (%) from current scenario									
Scenario	**Current**	**Pasture**		**Pine to Pasture**		**Scrub to Pasture**		**Pine Harvest**	
Sub-Basin	m³/s	m³/s	%	m³/s	%	m³/s	%	m³/s	%
1	4.85	6.02	24.09	5.78	19.02	5.05	4.00	6.36	30.98
2	3.69	4.14	12.37	4.06	10.23	3.69	0.00	4.35	18.01
3	2.84	3.08	8.39	3.05	7.65	2.86	0.67	3.14	10.75
4	11.21	13.02	16.15	12.44	10.97	11.47	2.32	13.31	18.73
5	18.88	21.08	11.65	20.27	7.36	18.73	-0.79	21.72	15.04
6	7.68	8.41	9.51	8.18	6.59	7.27	-5.28	8.78	14.41
7	2.36	2.54	7.49	2.44	3.05	2.39	1.27	2.49	5.54
8	21.97	24.52	11.61	23.60	7.42	21.91	-0.27	25.17	14.57
9	6.34	6.83	7.81	6.61	4.24	6.49	2.46	6.78	6.97
10	27.05	29.46	8.91	28.23	4.36	27.17	0.44	30.32	12.09
11	37.21	41.05	10.32	39.44	5.99	37.63	1.13	41.93	12.68
12	1.57	2.23	41.72	2.20	40.00	1.59	1.46	2.56	63.12
13	38.55	43.23	12.14	41.35	7.26	39.22	1.74	44.01	14.16
14	3.13	3.22	3.07	3.14	0.32	3.15	0.74	3.15	0.54
15	42.65	47.91	12.33	45.69	7.13	43.57	2.16	48.39	13.46
16	0.68	0.69	2.80	0.68	0.00	0.68	0.27	0.68	0.00
17	43.31	48.59	12.19	46.35	7.02	44.23	2.12	49.04	13.23
18	0.40	0.40	1.18	0.40	0.00	0.40	1.13	0.40	0.00
19	41.03	46.12	12.41	44.05	7.36	41.96	2.27	46.61	13.60
Total Average	**16.60**	**18.55**	**11.90**	**17.79**	**8.21**	**16.81**	**0.94**	**18.90**	**14.63**

According to Table 5.6, the annual daily average increases by less than 2% across all the deforestation scenarios. However, Sub-basin 12 experiences a significant annual change, with a rise of 7.26% in the average streamflow. The impacts of the deforestation scenarios on streamflow response during the flood peak event on October 15th are presented in Table 5.7. To contrast the whole catchment afforestation scenarios, a simulation was run to represent what would happen if the entire catchment was cleared for pastoral farmland. The average discharge of the catchment would increase by 11.9%. The following scenario represents the hydrological response if all the pine forests were harvested and replaced with pastoral farmland. The result is an 8.21% increase in stream flow. In comparison, there is only a small change of 0.94% for the scenario where all mānuka/kānuka scrubland is cleared to increase the area of pastoral farmland. However, there is a slight decrease for some sub-basins. The most notable change is seen in the last scenario when all pine forests are harvested. Total stream flow increased by 14.63% during the peak event. However, it must be noted here that looking at the response of individual sub-basins rather than the total effect is more important. In reality, not all pine forestry blocks would be harvested simultaneously. There are significant changes for all the sub-basins with forestry present and sub-basin 12 experiences a 63.12% increase in flow during the peak event. Figure 5.11 provides a graphical representation of the percentage changes in streamflow during the peak event. Sub-basin 12 shows the largest change in discharge as a result of deforestation scenarios due to 51% of its current area in plantation forestry.

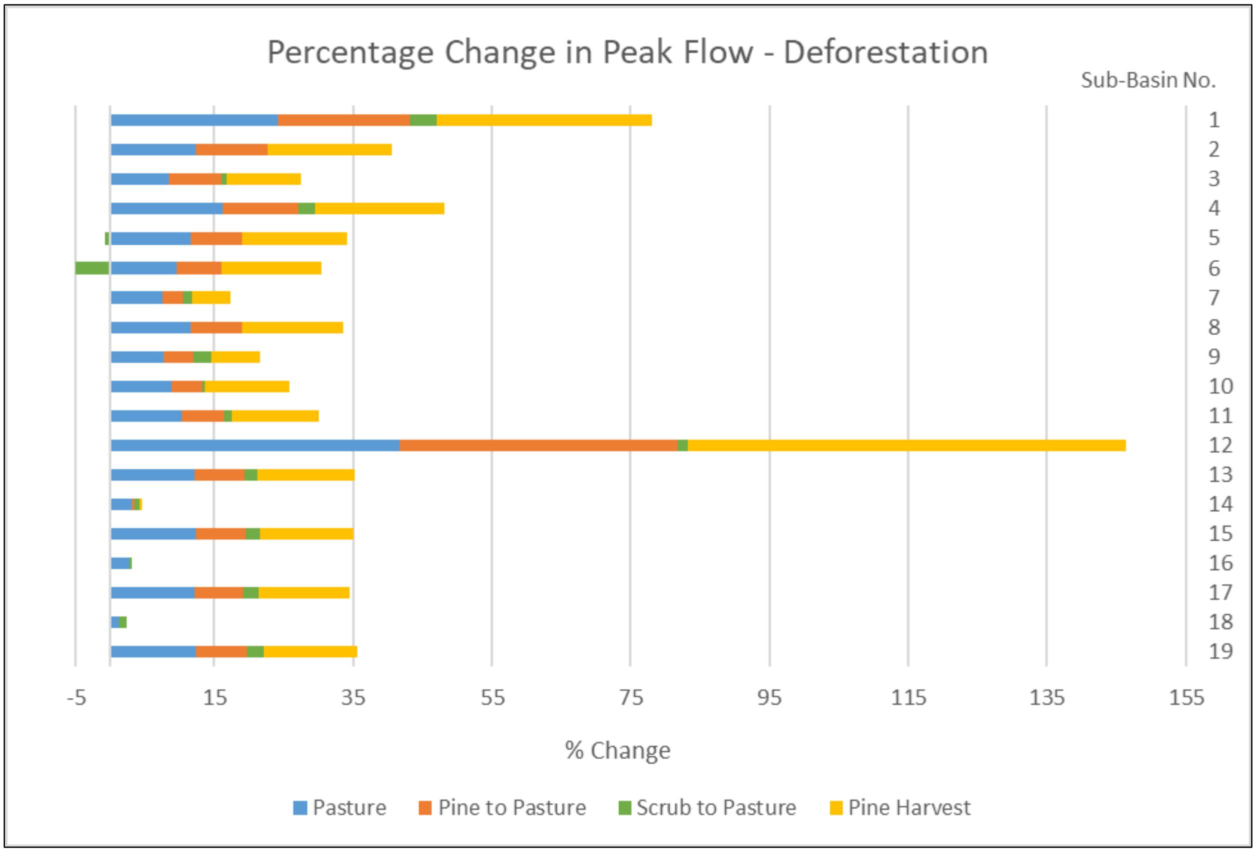

Figure 5.11: Deforestation Percentage Change in Peak Flow from Current Scenario

Figure 5.12 visually represents how discharge changes across the catchment due to each deforestation scenario, expressed as a percentage. The legend for each scenario is also based on the natural breaks in the distribution of percentage change values because there is a variety in how each scenario impacts the catchment. The scrub to pasture scenario shows the most variation in change across the catchment, although these are not hugely significant, as the most noticeable difference is a 4% increase. The most extensive changes for the complete pasture scenario are seen in the sub-basins with the most current forest cover. Comparing the variation in flow change between forestry harvest and converting plantation forestry to pasture emphasises the increase in discharge when harvest operations leave bare ground with not vegetative cover.

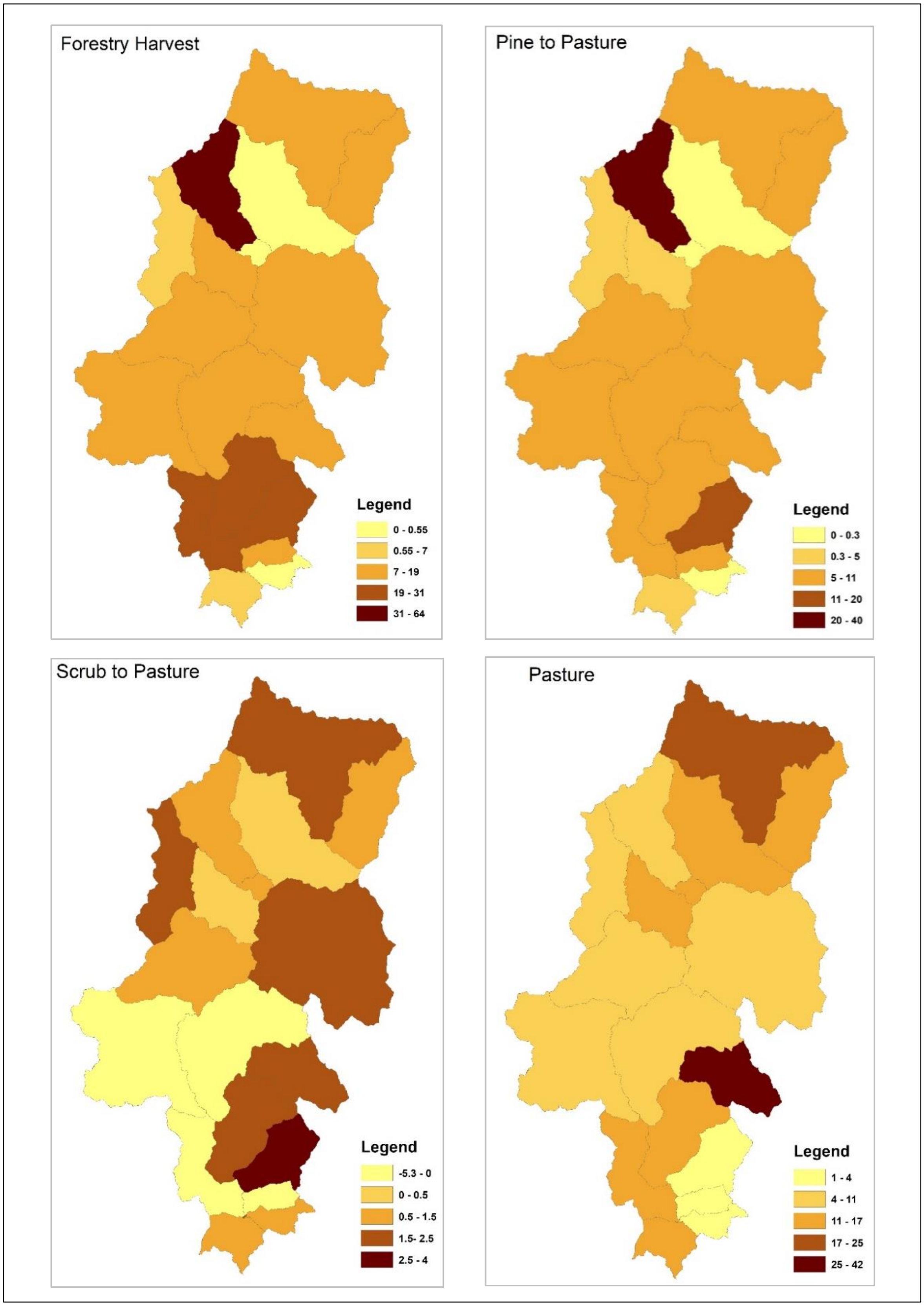

Figure 5.12: Percentage Change in Flow Rate for Deforestation Scenarios

5.4 Sub-Basin Sensitivity

Table 5.8: Annual and Peak Event % Changes from Pasture to Forest

% Change from Pasture to Forest						
	Average Flow Rate		Total Surface Runoff		Total Water Yield	
Sub-Basin	**Daily**	**Peak Event**	**Annual**	**Peak Event**	**Annual**	**Peak Event**
1	-1.9%	**-35.3%**	-51.5%	-45.6%	-1.9%	**-34.9%**
2	-2.1%	-29.5%	-41.7%	-32.8%	-2.0%	-28.9%
3	-1.6%	-16.8%	-49.6%	-40.0%	-1.6%	-18.8%
4	-0.5%	-29.4%	**-55.5%**	-44.6%	2.0%	-28.3%
5	0.4%	-29.1%	-53.0%	-42.1%	1.8%	-31.6%
6	1.8%	-31.0%	-52.6%	-42.5%	1.8%	-34.1%
7	0.1%	-23.4%	-50.7%	-38.5%	0.0%	-24.1%
8	0.1%	-25.2%	-47.5%	-38.8%	-0.1%	-30.9%
9	-1.0%	-29.7%	-47.1%	-36.3%	-1.0%	-29.1%
10	0.0%	-23.0%	-51.0%	-39.6%	-0.5%	-32.6%
11	-0.2%	-25.7%	-47.2%	-37.7%	-0.9%	-32.1%
12	-4.4%	-34.9%	-50.5%	-41.7%	-4.4%	-34.4%
13	-1.1%	-22.9%	-53.3%	-33.0%	-16.0%	-30.1%
14	**-16.7%**	-30.1%	-54.4%	-32.0%	**-16.7%**	-29.6%
15	-2.0%	-22.0%	-54.0%	-32.3%	-14.0%	-28.5%
16	-6.4%	-29.8%	-53.1%	-36.1%	-6.4%	-29.8%
17	-2.0%	-22.1%	-46.7%	**-49.6%**	9.5%	-39.7%
18	4.9%	-33.4%	-47.9%	-47.1%	4.9%	-33.6%
19	-2.0%	-23.0%	-52.4%	-36.6%	-5.1%	-31.3%
Total	**-1.1%**	**-24.5%**	**-50.9%**	**-37.8%**	**-2.4%**	**-30.4%**

Results from simulations of the historic forest and complete pasture scenarios were selected to assess the sensitivity of each sub-basin. Table 5.8 breaks down the changes in discharge, surface runoff, and water yield when the whole catchment in pasture is replaced with indigenous forest cover. The percentage change is expressed for the annual streamflow and peak rainfall on October 15th, 2019.

All sub-basins show significant changes in surface runoff: between 40-55% annually and 32-50% during the peak event. There is a 50.9% reduction in the annual surface runoff for the whole catchment and a 37.8% reduction during the peak rainfall. Sub-basin 4 shows the largest annual decrease of 55.5%, and sub-basin 17 has the greatest reduction during the peak event of 49.6%. There is only a 2.4% difference in annual water yield between the extreme scenarios, which is understandable as the catchment still captures the same amount of rainfall, so it is unlikely to see significant differences in yield. The slight reduction is likely due to the increased canopy cover meaning there is more evapotranspiration. There is, however, a considerable reduction for sub-basins 13, 14 and 15 of 14-16%. Annual water yield seems to be reduced more in the lower catchment than in the upper catchment. When we look at the total water yield for the high rainfall event, we see a total reduction of 30.4%. All sub-basins show a significant decrease between 18% and 40%. The greatest difference in yield is sub-basin 1.

There is little variation in daily average flow between the extreme scenarios, with only a 1.1% average reduction over the whole catchment. There is, however, a noticeably larger change for sub-basin 14 at 16.7%. On average, the entire catchment sees a 24.5% reduction in peak flow during high rainfall. All sub-basins experience a decrease of over 16%, with the most considerable change happening in sub-basin 1 at 35.3%. This is directly linked to the 45.6% reduction in peak surface runoff from the sub-basin. The largest change in the annual flow rate is sub-basin 14 at 16.7%. It is one of the smallest sub-basins in the lower catchment and contributes a tributary stream off the main trunk stream, making it prone to significant fluctuations in streamflow. 42% of its slopes have a gradient above 0.5, and the primary soils in the sub-basin are Typic Orthic Recent and Orthic Raw. In contrast, there is no change in the annual flow rate for sub-basin 10. This sub-basin covers a more extensive area and is situated on the main trunk of the Waimatā River. The sub-basin is steep, with 45% over a 0.5 gradient. Its position in the catchment is the main trunk of the Waimatā River, and its area covers 7.4% of the total catchment. Locating at a lower elevation than its tributaries and receiving water from a larger area helps mitigate fluctuations in the annual average flow rate that smaller tributaries may experience.

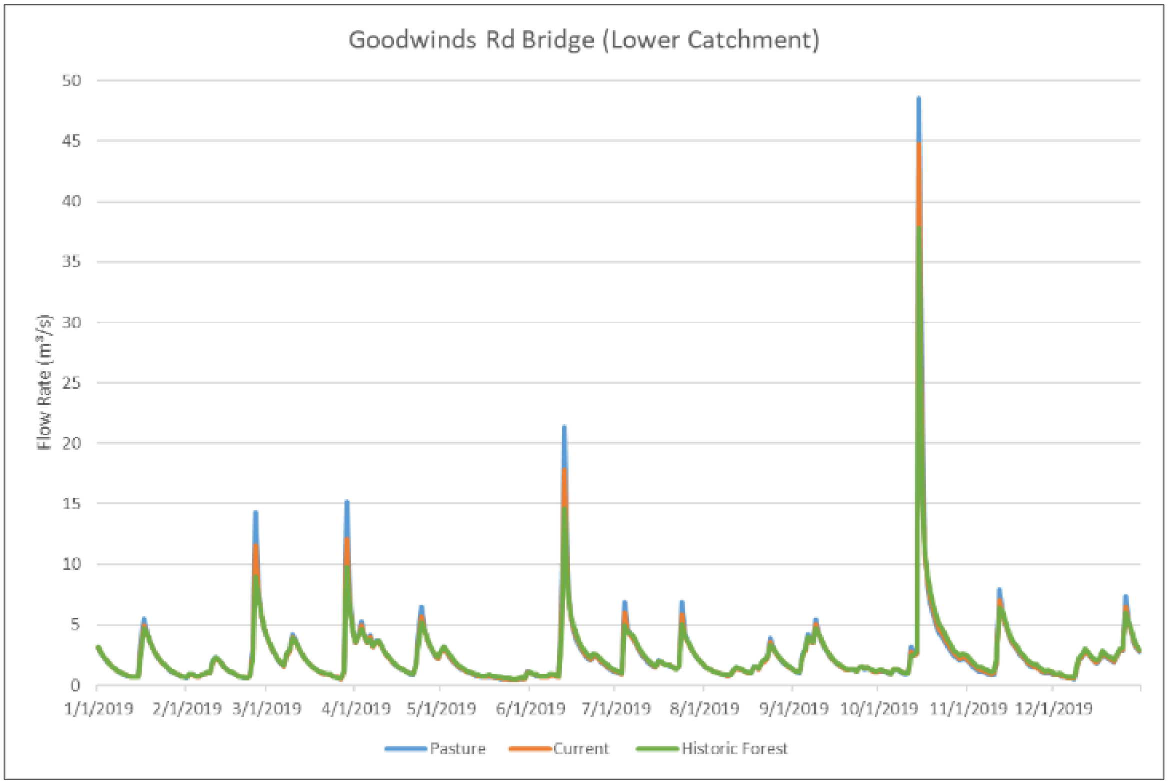

Figure 5.13: Discharge for Extreme Scenarios at Goodwins Rd Bridge

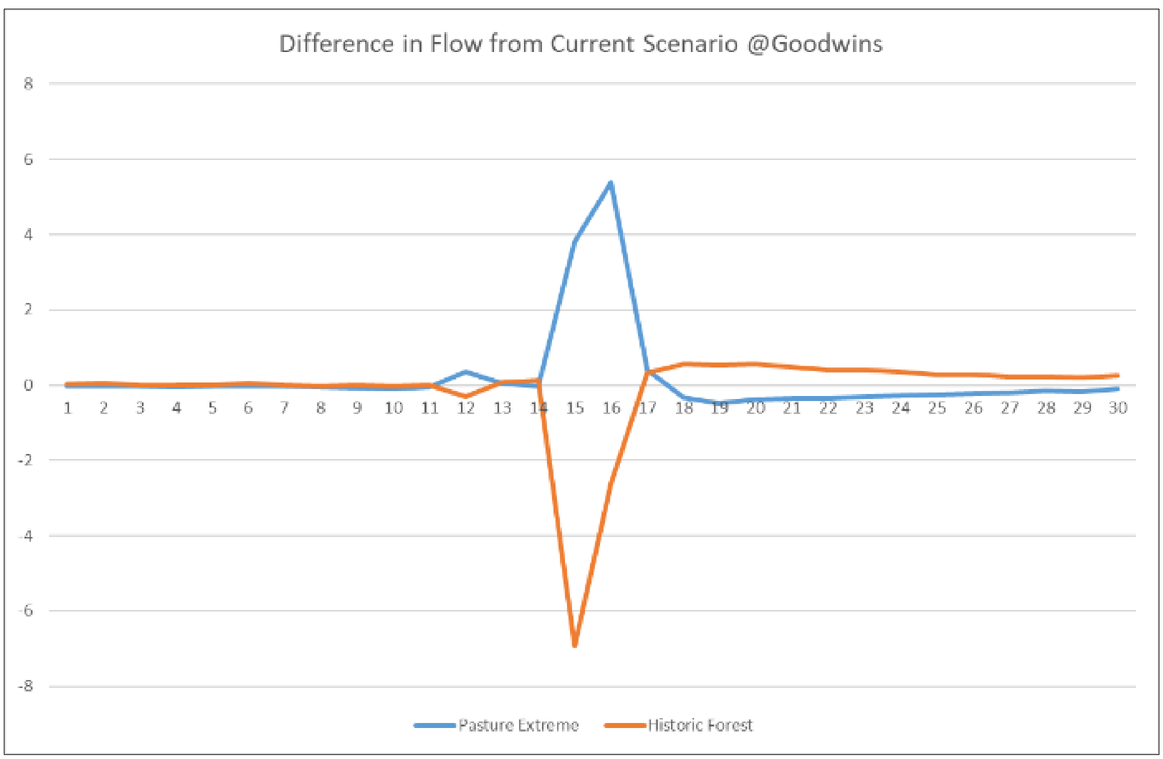

Figure 5.14: Difference in Flow Rate from Current Scenario at Goodwins Rd Bridge

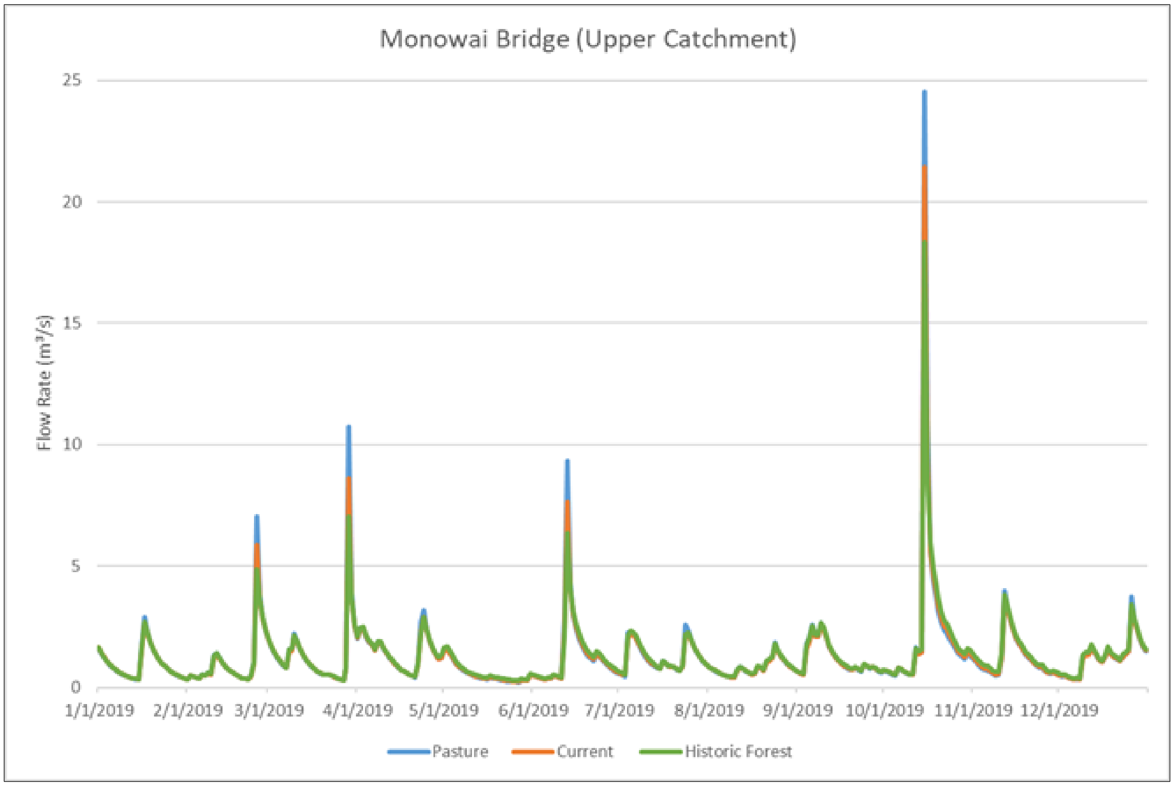

Figure 5.15: Discharge for Extreme Scenarios at Monowai Bridge

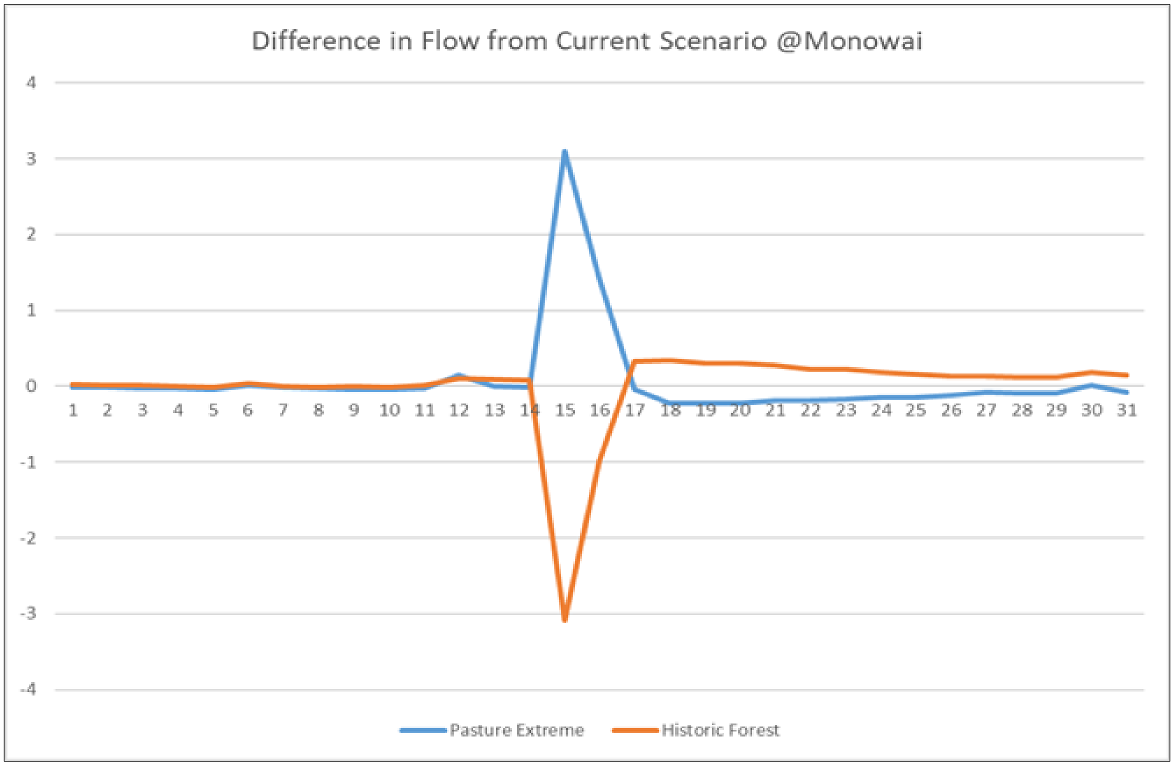

Figure 5.16: Difference in Flow Rate from Current Scenario at Monowai Bridge

Figures 5.13 and 5.15 illustrate the differences in discharge at Goodwin's Road Bridge and Monowai Bridge between the extreme scenarios. Figures 5.14 and 5.16 demonstrate the changes in peak discharge for the high rainfall event. There is a greater change for the forested scenario, reducing peak flow by 15% at Goodwins Road Bridge and 14% at Monowai Bridge. The difference in flow for the pasture scenario is not as dramatic for Goodwins Road Bridge but still considerable, increasing peak flow by 9%. Monowai Bridge experiences a 14% increase in discharge in the pasture scenario. However, even though the forested scenario has a much lower peak flow at both gauge stations, it has a higher recessional limb.

Chapter 6: Discussion

6.1 Introduction

The primary aim of this case study is to explore the hydrological impacts of changing land cover in the Waimatā River Catchment and to determine which sub-basins are most sensitive to these changes. By identifying the sub-basins most responsive to land cover change, this study provides insights into where restoration initiatives can more effectively impact flow through the system. This chapter starts with an overview of the current hydrological behaviour of the Waimatā River Catchment before discussing how modelling alternative land cover scenarios changed the simulated hydrograph. Sub-basin sensitivity is then analysed in more depth with recommendations on how this could help target restoration practices. Management implications and the future direction of hydrological modelling in the Waimatā are covered, and finally, limitations to the study are highlighted.

6.2 Current Hydrological Behaviour of the Waimatā Catchment

The results highlight that sub-basins 14 and 13 have the highest surface runoff contribution to stream flow in the catchment. Even though these are some of the smallest basins in the catchment and don't experience the most precipitation, they are mainly pasture and have steep relief. The combination is a recipe for high surface runoff. Mottled Tephric Recent soils make up the majority of the sub-basins and are reasonably well-drained, so this is unlikely to be a major contributor. Surface runoff appears to be higher in the mid to lower catchment because there is a large percentage of pasture. The upper catchment has more forest cover, so surface runoff is lowest in these sub-basins. Sub-basin 2 is the exception, with slightly higher runoff. This is likely caused by its higher proportion of pasture, less forest cover than the surrounding sub-basins, and a higher percentage of very steep slopes.

Understandably, the highest water yields are in the steeper headwaters of the catchment, where the sub-basins are larger and capture more precipitation. Sub-basins in the lowest reaches of the catchment have the smallest water yields. These sub-basins are smaller and have lower slope gradients and lower altitudes with less rainfall, so less area accumulates precipitation. Sub-basins 3, 4 and 7 have the highest annual water yields in the catchment. There is a combined area of 143 hectares of harvested pine forest between sub-basins 3 and 7 adjacent to each other. This is the main contributor to the high-water yields as surface runoff increases when the forest canopy is removed, especially as the sub-basins also have steep terrain. Canopy cover will change over time as a harvested block is usually replanted. However, it could also be reasonable to assume that there will always be an area of harvested trees within the sub-basin because exotic pines remain that will be cut down as they reach production maturity. Harvesting operations compact soils and disrupt flow pathways in the soil, fundamentally changing runoff. Sub-basin 4 has a small area of pine forest that has not been harvested, but its large proportion of pasture combined with very steep slopes explains why its water yields are some of the highest in the catchment. Sub-basins 13, 14 and 15 in the lower catchment have the highest daily water yields during the peak rainfall on October 15th, 2019. This can be explained by the increased surface runoff of these sub-basins, so a high rainfall event produces the most significant water yield because there is little interception.

Surface runoff and water yield are key discharge components that govern the bulk behaviour of the whole system. These directly influence the flow rate of the Waimatā River. Considerable differences exist between the base flow and peak flows in the Waimatā Catchment, primarily due to its constricted shape, steep slopes, and optimised drainage on farmland. It is further exaggerated by land use configuration, with less than half the catchment having some form of tree cover, resulting in minimal rainfall interception. Therefore, intense rainstorms can produce rapid overland flow and a steep rising limb. The elongated shape of the catchment also means the river's recovery potential is fast, as water is quickly channelled out to the ocean (Cullum et al., 2017). This refers to the river's ability to recover after disturbances such as storm events. All these factors can interact and influence each other and change throughout the catchment.

6.3 Alternative Land Cover Scenarios

6.3.1 Afforestation

The analysis assessed whether alternative land cover scenarios across the catchment would significantly change the flood characteristics of the watershed. The substantial reduction in peak flow for the historic forest scenario shows that the Waimatā Catchment would have shown a less intense response to extreme weather events, with a lower peak and longer recession. More canopy cover to intercept rainfall during intense storm periods delays the time for the water to reach the trunk stream. Peak flow was also considerably reduced when all pastoral farmland was converted to pine production forest. The decline is expected with a whole catchment afforestation scenario and is backed up by other New Zealand case studies investigating the hydrological impacts of pine forests (Cao et al., 2008; Duncan, 1995; Fahey & Payne, 2017; Pearce et al., 1987; Rowe & Pearce, 1994). Hughes et al. (2020) found that peak flows were reduced by ~50% due to delayed surface runoff from canopy interception. Another reason for this significant response to afforestation could be that the case study catchment has steep terrain similar to the Waimatā. This suggests that afforestation scenarios have a larger impact on surface runoff in a steep catchment. However, even though the indigenous forest scenario showed a greater flow rate reduction than the pine forest, their average daily flow rates are almost the same. This is because they represent a whole catchment in closed canopy forest cover.

Inevitably, these are idealistic scenarios. In reality, the pine forest scenario would have different land blocks with trees of various stages of maturity. Therefore, the surface runoff rates would differ across the catchment and lead to higher flow rates than an indigenous forest with constant canopy cover all year round. In a case study on a catchment in Nelson, New Zealand, Duncan (1995) found that when pasture was converted to plantation forest, water yield started reducing in the third year after planting, and this slowly reduced more as the trees matured. Thinning of trees also increases water yields slightly (Duncan, 1995; Hughes et al., 2020).

The SWAT classification for a pine forest has lower biomass and rainfall interception parameters than established indigenous forest. This explains why the simulated flow rates are slightly lower during a peak rainfall event for indigenous forest. There are only subtle changes to the total runoff and discharge metrics for the scrub to forest scenario. This is because mānuka/kānuka scrubland only covers 11% of the catchment, and letting it regenerate into established forest will increase the area of indigenous forest from 6% to 17% of the total catchment. Rowe et al. (1999) used the Waimatā Catchment for a case study on interception and throughfall in a regenerating stand of kānuka. Rainfall interception is high compared to other New Zealand woody vegetation studies, so soils under a kānuka canopy will be much drier than those under pasture. This shows that regenerating mānuka and kānuka scrub to regenerate can be an effective strategy for reducing rainfall runoff in the Waimatā Catchment. This also suggests that there are no large interception increases between native scrub and established forest. Therefore, hydrologically it is better to prioritise establishing areas of no woody vegetation with mānuka/kānuka scrub than it is to try to regenerate scrub land into an established forest.

6.3.2 Deforestation

Deforestation scenarios were also explored for the Waimatā River Catchment, including forestry harvest and scrub clearance. A whole catchment being cleared for pastoral farmland is simulated as an extreme scenario. Results show a significant change in discharge caused by increases in surface runoff. A scenario in which all pine forest production was phased out and replaced with pastoral farmland results in a significant increase in discharge during the peak event due to rapid and synchronous runoff triggered by high rainfall and lack of vegetative cover. The flow rate will increase if all mānuka/kānuka scrubland is cleared to increase farm pasture area. However, this is insignificant because there is only a small proportion of scrub compared to other land uses within the catchment. But there are significant changes for individual sub-basins for those with high percentages of scrub. This shows that the presence of mānuka/kānuka cover is still essential in reducing extreme discharge in high rainfall events and reducing negative impacts associated with high surface runoff (Bergin et al., 1995; Rowe et al., 1999).

The deforestation scenario with the most impact is harvesting exotic forestry blocks. The results show that discharge increases significantly for the sub-basins with forestry because there is a significant increase in surface runoff caused by minimal interception of rainfall as the ground is left bare with scattered debris. Duncan (1995) and Marden et al. (2012) back this up. Their research found that harvesting operations alter hydrologic processes considerably by removing rainfall interception and evapotranspiration and modifying soil water processes. Soils stay wetter for longer when trees are removed, increasing the water table. This can take several years to revert after an area has been replanted. However, the changes in surface runoff after forest harvest are not also immediate. When an area is under mature forest cover, soils tend to have a lower soil moisture content as the trees intercept and transpire water. This means that the soil water capacity must wait to be replenished once trees are removed before more runoff occurs. The forestry harvest scenario results in a significant increase in simulated discharge for the whole catchment. Similar results were found by Cao et al. (2008), Duncan (1995) and Rowe & Pearce (1994). However, assessing individual sub-basins for this scenario is more important than the whole catchment response because forestry blocks will mature and be harvested at different stages. It is improbable that such a large proportion of the catchment will experience bare ground. It does, however, emphasise why staging forestry operations from planting to harvesting is vital in reducing the overall hydrological impact of exotic production forest on the catchment (Marden et al., 2012)

6.4 Sub-Basin Sensitivity

Many factors influence the hydrological behaviour of a sub-basin. Analysis of which sub-basins are most sensitive and contribute most to shaping the flood hydrograph helps better understand which areas to target for restoration. To assess sub-basin sensitivity, two maximally contrasting scenarios were simulated and compared against each other. The first extreme scenario replaced the whole catchment with pasture as the main land cover, and the second replaced the entire catchment with a historical, indigenous forest. The substantial increase in vegetative cover between the extreme scenarios results in a considerable decrease in the surface runoff for all sub-basins. This is caused by increased rainfall interception and evapotranspiration. Surface runoff directly contributes to total water yield, so the reduction also explains why water yield reduces significantly for all sub-basins during the peak event. There is only a minor annual reduction in the total water yield of the catchment because the water balance remains the same between scenarios. Sub-basins 13, 14 and 15 have higher reductions in annual water yields than the other sub-basins. This reflects significant decreases in annual surface runoff of over 50%, likely caused by their steep terrain. These significant reductions in surface runoff and water yield cause a substantial decrease in total discharge during the peak event.

Sub-basin 1 shows the largest reduction in discharge during the peak event. A major contributing factor is a reduction in water yield, the greatest reduction of all the sub-basins. This large sub-basin at the top of the catchment is 11% of the total catchment area and is made up of first and second order streams. Under normal circumstances, flow rates are low, but when there is high rainfall, all the water from the multiple tributaries in the basin rushes together to get to the main reach. The top of the catchment experiences more precipitation because of its higher altitude. It is also a very steep basin, with 33% of its area above a 0.3 gradient and 45% above a 0.5 gradient. All these factors combined cause large fluctuations as a response to high rainfall, making it very sensitive to changes in land cover.

All sub-basins show a minor annual flow rate change except for sub-basin 14. Its reduction in flow rate during the peak event is also significant, and the sub-basin presents the highest contrast between extreme scenarios in annual water yield. This is caused by the substantial reductions in surface runoff when the catchment was simulated in complete forest cover. The results indicate that sub-basin 14 is one of the most sensitive sub-basins to changes in discharge, especially considering that under the current land use regime, it has the highest surface runoff and contributes the highest volume of water to the catchment during a high rainfall event.

A closer look at the peak discharge of the gauge stations on the Waimatā River shows a more remarkable change in peak discharge for the historic forest when comparing the extreme scenarios to the current conditions. However, even though complete forest cover decreased flood peaks, there is a higher recessional limb than the pasture scenario. This is because forests can store water in their canopies. A lot of this water will still exceed soil water storage, contributing to surface runoff, but the lag time is delayed because it takes longer for the water to get to the central reaches. This also reduces peaks because water is in the system for longer. Goodwins Road Bridge and Monowai Bridge have similar peak responses to the historic forest scenario, but Monowai shows a greater increase in discharge under the forested scenario. As Monowai Bridge represents the upper catchment with more forest cover under current conditions, it is more sensitive to reductions in canopy cover.

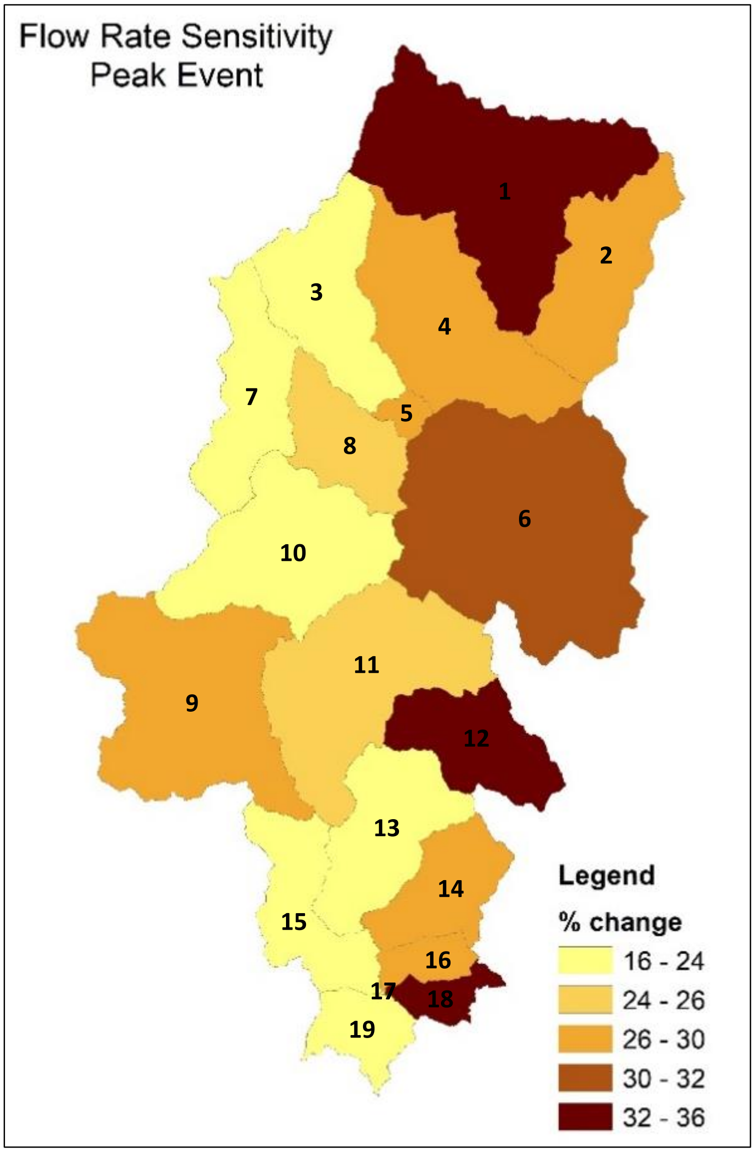

Figure 6.1: Distribution of Percentage Change in Peak Flow Rate Between Extreme Scenarios

Figure 6.1 is an example of the spatial pattern of hydrological response to an extreme rainfall event. This helps visualise the distribution of sub-basin sensitivity across the catchment. The pattern and frequency of tributaries joining the trunk stream are critical in determining downstream flooding impacts. This takes form in the Waimatā Catchment due to its linear shape, which acts like a chute. Similar comments have been made in the adjacent Uawa Catchment (Walley et al., 2018).

6.5 Targeting Sensitive Sub-Basins with Land Cover Changes

We know which sub-basins are the most sensitive to change and those that contribute the most to the catchment. Using this knowledge, we can now examine how the alternative scenarios impacted these sub-basins. Sub-basins 1 and 14 were identified as the most sensitive to changes in discharge when the land cover was altered. During the peak event, sub-basin 1 saw a 35.3% difference between the extreme scenarios, and sub-basin 1 had a 16.7% difference in the daily average flow rate.

As well as being susceptible to fluctuations in flow, sub-basin 14 is one of the most significant contributors of water to the main river reach. The leading cause of this is its limited tree cover and expansive pasture area. Therefore, a deeper analysis of how afforestation scenarios affect the sub-basin is needed. Replacing all pastures with pine forests would reduce the flow rate by 13.13% annually and peak flow by 23.37%. This results from increased canopy interception of rainfall, causing a reduction in surface runoff by 47% annually and 25.2% during the high rainfall event. There are insignificant changes to the flow rate if pastoral production was to remain, and instead, the existing mānuka/kānuka scrub would be left to regenerate into an indigenous forest. The reason is that a low proportion of the catchment (4%) has scrub present, so the area is not influential enough. Therefore, some steeper land is suggested to be set aside for scrub regeneration, which could eventually turn into a forest. When the sub-basin was in a historic indigenous forest, the daily average flow rate was 15% less than under current conditions. The deforestation scenarios have minimal impact on sub-basin 14 because tree cover is already low under current conditions. Therefore, there should be a focus on afforestation scenarios for sub-basin 14 because it can potentially make a considerable difference to river discharge.

Sub-basin 1 was identified as the most responsive to changes in peak flow during a high rainfall event. Given the catchment's potential for afforestation and deforestation, both options are explored. Interestingly, both afforestation and deforestation scenarios had an insignificant effect on the annual discharge. However, during the peak event, there was a significant decrease in discharge of 19.74% for the historic forest scenario and 14.69% for the pasture areas reforested with pine trees. In contrast, leaving the scrub to regenerate naturally into an established forest showed only a small reduction of less than 3%. If the current plantation forest were reverted to pastoral land, the flow rate would significantly increase during the peak event by 19% due to the removal of canopy cover and rainfall interception. The study reveals that following the harvest of a pine forest, a subsequent high rainfall event could trigger a 31% increase in peak flow. This increase from the prior pine to pasture scenario emphasises how stripping all vegetative cover and exposing bare ground can considerably affect discharge. Given the potential downstream consequences, it stresses the value of a gradual harvesting approach in the sub-basin, where feasible.

6.6 Impact of Hydrological Changes

This research has demonstrated how land cover changes impact the discharge of the catchment by altering surface runoff and water yields. Limited response in baseflow is evident between the different scenarios. However, changes to peak flow behaviour are apparent. This likely results in changes to river levels. Reduction in peak flow and river level during a high rainfall event reduces the river's kinetic energy. This can help mitigate flood damage such as bank and channel erosion, scouring and land sliding (Dixon et al., 2016).

Changes in land cover can influence peak flows by altering the runoff behaviour of each sub-basin. There is no way to reduce the volume of water that enters a watershed during a high rainfall event, but changes in land cover can influence the surface runoff behaviour of each sub-basin. Afforestation can prolong the time it takes for water to get to the central reaches of the river by storing water in the forest canopy and intercepting surface runoff (Buechel et al., 2022; Hughes et al., 2020). Soil moisture content is also lower when forests are present (Duncan, 1995; Pearce et al., 1987). The water then gets released over an extended period, reducing peak flows and the damage they cause. The opposite happens when deforestation occurs in the catchment (Hajian et al., 2019; Khaleghi, 2017; Marden et al., 2012; Rogger et al., 2017). Wetlands can also play an essential role in reducing peak flows through retention. Wetlands act as sponges that can absorb excess water and release it over extended periods (Bullock & Acreman, 2003). Wetland areas occur naturally along the valley floor of the Waimatā River Catchment, but the majority were cleared and drained by the end of the 19th century (Salmond, 2016). In 2018, less than 1% of the total catchment area had wetlands present, but this will have increased in recent years as community projects are re-establishing some wetlands (WRRP, 2020). Harvey et al., 2021, identified areas where wetlands could be created and restored in the catchment and recommended this as a non-invasive method of protection.

However, the hydrology of a catchment is only one part of the broader system. Sedimentation is also a problem in the Waimatā River Catchment, and there are extensive sediment depositions during flood events. High surface runoff transports significant volumes of sediment to the trunk stream, and high peak flows readily convey those particles downstream (Harvey et al., 2021). Hydrology also influences water quality. Contaminants can enter the system by being caught up in the overland flow. High E. coli levels are a problem for the Waimatā River, caused by livestock production and birds in the catchment (Salmond, 2016). The river also experiences high levels of phosphorus, which enters the system and attaches to sediment particles (Salmond, 2016). Therefore, reductions in surface runoff and high flows would improve the river's ecological health by reducing contaminants and preventing damage to natural habitats. An ecologically healthy river also improves humans' recreational, cultural, and spiritual interactions with the Waimatā River (Cairns et al., 2021).

6.7 Management Implications

The SWAT simulation results have quantified the hydrological characteristics of the Waimatā Catchment and highlighted sub-basins most sensitive to land cover changes. The model also predicted how specific afforestation and deforestation scenarios would alter discharge. These results give a clearer understanding of the hydrological processes happening in the catchment and could help with policy and management decisions in the future.

River management benefits from having a holistic view of how all processes in a catchment interact and influence each other. The ability to input real-world data into a model provides a valuable tool for in-depth analysis of a catchment that otherwise would not have been possible. SWAT allows river behaviour to be analysed through multiple lenses while comparing land management scenarios. The model also allows digging deeper into which processes are the main influences on river discharge. Catchment managers need to prioritise areas for restoration efforts, especially when they have extensive areas around a watershed that they oversee. SWAT can help to determine the potential for river restoration and provide insights into priority areas for management intervention. The model can also be used to test how river management policy would impact the river by simulating potential land cover and restoration scenarios. It is also a valuable tool for communication between catchment managers, landowners, and local communities (Dwarakish & Ganasri, 2015). Exploring scenarios and visualising hydrological processes can prove vital for deliberative decision making with communities. The model could also be used to test how river management policy would impact the river by simulating potential land cover scenarios.

Scenario-based analysis of surface runoff and discharge in the Waimatā Catchment provides insight into how the river can change. This is especially important for catchments with commercial pine forests as trees will be harvested in the future. Therefore, having predictions of the hydrological impact of harvesting forestry blocks can help better plan when and how to harvest the trees while minimising damage. The study revealed that forestry harvesting significantly increases surface runoff until trees have regrown to a closed canopy. This leads to increased discharge and flood risk, especially if a high rainfall event happens close to the harvest time (Cao et al., 2008). Comparing these results to Harvey et al. (2021), we see other sediment issues become evident as the risk from slash transport to waterways increases. People living and working in those sub-basins should be aware of the effects and increased flood risks these land cover changes could have on them.

Hydrological modelling of the Waimatā Catchment using SWAT is easily implementable into river management given the availability of input data and complementary research (Cullum et al., 2017; Forbes et al., 2018; Harvey et al., 2021; Salmond, 2016). Climate data is thorough across the catchment, land cover maps are detailed, and two river gauge stations aid calibration. Soil data is available, but accuracy could be improved by having a more detailed and easily accessible soil database specific to the catchment. The model should be used with other research and field experience to minimise gaps in understanding the catchment processes.

Prior knowledge of a catchment's characteristics and typical behaviour is required to interpret and convey results accurately. Modelling outcomes can be more successful when complemented with monitoring in a catchment. Monitoring data informs catchment models, while modelling identifies the causes of deteriorated water quality, which can guide restoration efforts. Additionally, modelling can help prioritise future monitoring (Parshotam & Robertson, 2018).

6.8 Future Direction of Hydrologic Modelling in the Waimatā

SWAT has proved successful in modelling the hydrological behaviour of the Waimatā River Catchment. Calibration and validation demonstrate acceptable accuracy while acknowledging the inherent limitations of models. However, they are still a valuable management tool to investigate questions we otherwise would have no way of attempting to answer.

SWAT presents the opportunity to expand on the research of this case study as the model can also produce sediment and water quality outputs. This would require more detailed input data on soil types and land use management practices within the catchment. As the hydrological model has already been established, extending its application to incorporate these processes in the catchment is feasible.

The findings from this study can be used in conjunction with other research in the Waimatā River Catchment. For example, it can be used in combination with Harvey et al. (2021) to conclude the best areas to target for restoration, depending on the goals of community groups and what issues they choose to prioritise. This research can also be used to inform other research projects in the future that require the hydrological building blocks of the catchment.

The future of this field should continue to see hydrological models conducted on a catchment scale to build on the data available for management decisions specific to a region. Understanding this is also key to broader river management, as all the different river characteristics interact and influence each other. For example, this supports work on ecological or chemical functions within a river ecosystem.

There is some support from some authors that a community hydrological model would address the problem of too many hydrological models (Horton et al., 2022). Having consistent analytical approaches and models that provide reproducible workflows is vital for the future of hydrological research because it is essential that results can be compared with other studies to build a broader, more holistic picture of what is happening within regions and countries, not only catchments.

6.9 Limitations

The SWAT model offers analytical and conceptual methods to predict the watershed's response to different scenarios. However, its usefulness may be limited by constraints to data quality, boundary conditions and parameter values (Beven, 2012). Interpretation of a landscape is essential, so a lack of prior knowledge of a catchment is also a source of uncertainty. Therefore, another target should be to address uncertainties in model predictions, and we can continuously improve data accuracy and reproducibility as technology improves.

Model outputs must be evaluated critically because they cannot entirely represent the complexity of a natural system. Models are structurally based, so they don't consider all the possible processes that determine all the interactions within a watershed (Beven, 2012; Oreskes et al., 1994). Errors and discrepancies may occur in various aspects, such as input data, model parameters, structure, and spatial and temporal scales. All models carry some degree of uncertainty, which can be challenging to quantify and communicate effectively. Field assessments would strengthen the validity of the research findings. A combination of field and modelling assessments is the most effective and would be best in the future.

The main limitation of this study was that daily average is the finest temporal scale for SWAT outputs. To improve on this research, SWAT needs to produce hourly outputs to look at how peak events happen in more detail to give better results and more accurate observations. The quality of the soil data was poor as detailed databases are limited, so many assumptions were made. Some other input values had to be estimated from databases and other research articles. To improve accuracy some data could have been collected in the field, but this was not feasible within the scope of this study. The model could only handle a 5-m DEM, so if a 1-m scale is used in the future, it will enhance the accuracy of results by improving delineation precision to identify smaller flow paths and terraces better.

SWAT's simplicity and ease of use are due to pre-set assumptions and parameters. Beven (2012) notes this could also be seen as a weakness, requiring the user to carefully evaluate the assumptions, such as the homogeneous response of each HRU in SWAT. Rogger et al. (2017) found study gaps in understanding artificial drainage while modelling. This study does not map the extent of artificial drainage in the Waimatā Catchment, which could change the runoff and groundwater characteristics.

Another ambiguity that must be considered is using a model developed in another country. New Zealand has unique characteristics that can cause concerns about the applicability of these models. Local parameter values must be added to make SWAT applicable in New Zealand. However, these values are rarely included in catchment modelling reports, so it is usually up to the individual researcher to gather the relevant input data (Parshotam & Robertson, 2018).

Veith et al. (2010) found higher uncertainty for groundwater than for surface runoff parameters. They also found that the level of uncertainty varied between the catchments they were evaluating but that the overall degree of uncertainty was moderate. This supports and adds credibility to the findings of this research which has a central focus on surface runoff characteristics. Acknowledging the assumptions and uncertainties inherent in the baseline model also helps interpret results when alternative scenarios are simulated. Despite some limitations, significant insights have been gained into the behaviour of the Waimatā River Catchment.

Chapter 7: Conclusions

The Waimatā River Catchment is a special and unique part of New Zealand that benefits from a dedicated community working to improve catchment biodiversity and river health. A history of urbanisation, agricultural intensification, deforestation, and plantation forestry operations have caused significant environmental changes in the catchment. Additional inputs of large volumes of sediment and woody debris into the river system cause damage to freshwater ecosystems, infrastructure, and the cultural and recreational value of the river (Salmond et al., 2022). Land cover change alters the hydrological cycle by modifying evapotranspiration, surface runoff, and the resulting discharge. The recent Cyclone Gabrielle has highlighted how sustainable land management is critical for protecting the river and restoring its health. A warming climate adds further uncertainty for the region, so policy and management must stay adaptable and ready to address these challenges. Although the community has strong relations with the river and aspires to restore its health, they are apprehensive about current policy frameworks and forestry operations in the catchment (Cairns et al., 2021). Restoring the river is not just an ecological challenge but also a social process that requires the participation and cooperation of all stakeholders.

The analysis for this research used water yield and surface runoff to demonstrate how land cover influences the hydrological behaviour of each sub-basin. These processes directly impact the discharge during peak events, and the flow rate illustrates how the discharge changes between scenarios. Flow rate influences the river's kinetic energy and is responsible for its impact on the watershed. Sub-catchment analysis can be a valuable complement to catchment analysis in river management as it can uncover local variations that could prove crucial for effective management. The hydrological model SWAT was utilised to conduct this research. Using a numerical model to generate watershed simulations made it possible to run multiple scenarios and compare them. The ability to explore future changes through forecasting and predictions makes models an effective tool for assessing differences between past, present, and future scenarios, all while using existing data.

The afforestation scenarios reduced peak flow rates by increasing rainfall interception and reducing surface runoff. This varied between sub-basins depending on how much woody vegetation was already present. Deforestation had the opposite response, as surface runoff increases when no tree canopy is present to intercept rainfall. This also caused a reduction in evapotranspiration while increasing soil water contents. These findings were expected as a strong foundation of research that confirms these hydrological cycle processes. The sub-basins that contribute the most to the catchment under current conditions are sub-basins 13 and 14 in the upper catchment. These sub-basins had the highest surface runoffs due to their large pastoral areas and steep relief. Once current conditions for the Waimatā River Catchment were quantified, the next step was determining whether these changes were significant and what they indicated. To assess sub-basin sensitivity, two maximally contrasting scenarios were simulated and compared against each other. The first extreme scenario replaced the whole catchment with pasture as the main land cover, and the second replaced the entire catchment with a historical, indigenous forest. Sub-basins 13, 14, and 15 had the highest reductions in annual water yields due to significant decreases in annual surface runoff of over 50%, consistent with their steep terrain. Sub-basin 1 shows the largest reduction in discharge during the peak event due to a decline in water yield. This steep sub-basin at the top of the catchment is 11% of the total catchment area and has some of the highest rainfall totals at the top of the catchment. All these factors cause large fluctuations as a response to high rainfall, making it very sensitive to changes in land cover. Sub-basin 14 in the lower-mid catchment is also very sensitive to changes in discharge. It presents the highest contrast in annual water yield due to a significant reduction in flow rate during the peak event caused by substantial reductions in surface runoff in the complete forest cover scenario. Sub-basin 14 has the highest surface runoff and contributes the highest volume of water during high rainfall events.

Sub-basin analysis is a valuable tool for studying the behaviour of a river catchment. These results provide more detailed information to prioritise areas for restoration interventions to improve river health and flood resilience. It provides insights into the hydrological behaviour of each sub-basin. Additionally, when combined with other projects on the Waimatā River Catchment, this analysis can help to build a more comprehensive understanding of catchment processes and their interactions. Ultimately, this approach can lead to more effective and sustainable management practices that benefit the environment and local communities. This knowledge can also inform farm plans and support catchment planning in the Waimatā River Catchment. Developing a hydrological model for the Waimatā River Catchment is a crucial milestone towards bridging the gap between scientific research, effective catchment management, and community aspirations.

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Appendix

The Fundamental Soil Layers New Zealand Soil Classification		
Soil Class	**Soil Name**	**% of Catchment Area**
BLT	Typic Allophanic Brown Soils	0.91
BOM	Mottled Orthic Brown Soils	0.04
BOP	Pallic Orthic Brown Soils	13.51
BOT	Typic Orthic Brown Soils	0.25
GOT	Typic Orthic Gley Soils	2.72
MOT	Typic Orthic Pumice Soils	3.24
PID	Pedal Immature Pallic Soils	2.45
PIT	Typic Immature Pallic Soils	0.90
RFM	Mottled Fluvial Recent Soils	1.12
RFT	Typic Fluvial Recent Soils	1.30
RFW	Weathered Fluvial Recent Soils	0.49
ROM	Mottled Orthic Recent Soils	1.48
ROT	Typic Orthic Recent Soils	11.60
ROW	Weathered Orthic Recent Soils	49.67
RTM	Mottled Tephric Recent Soils	8.16
WO	Orthic Raw Soil	2.17

New Zealand Land Cover Database Class	Assigned SWAT Class
Manuka and/or Kanuka	Range-Brush
Broadleaved and Indigenous Hardwoods	Forest-Evergreen
Low Producing Grassland	Pasture
Exotic Forest	Pine
Short-rotation Cropland	Agricultural Land-Generic
Deciduous Hardwoods	Poplar
Gravel or Rock	Barren
Orchard, Vineyard or Other Perennial Crop	Orchard
Indigenous Forest	Forest-Evergreen
High Producing Exotic Grassland	Pasture
Lake or Pond	Water
Gorse and/or Broom	Range-Brush
Herbaceous Freshwater Vegetation	Wetlands-Forested
Forest - Harvested	Pine (manipulated)
Mixed Exotic Shrubland	Range-Brush
River	Water
Fernland	Range-Brush

Land Use	SWAT Code	Area (ha)	% Catchment Area
Manuka/Kanuka	MAN	2405.7	11.0
Forest-Evergreen	FRSE	1364.0	6.2
Pasture	PAST	10843.9	49.4
Pine	PINE	6068.5	27.7
Agricultural Land-Generic	AGRL	23.9	0.1
Poplar	POPL	359.5	1.6
Barren	BARR	25.2	0.1
Orchard	ORCD	21.0	0.1
Water	WATR	11.7	0.1
Range-Brush	RNGB	32.9	0.2
Wetlands-Forested	WETF	2.5	0.0
Harvested Pine	HARV	786.7	3.6

Slope (rise over run)	Area (ha)	% Catchment Area
0-10	1266	5.8
10-20	2076	9.5
20-30	2812	12.8
30-50	6896	31.4
50-9999	8896	40.5

Sub-Basin Breakdown

	Sub-Basin	Area (ha)	% Catchment Area	% Sub-Basin Area
	1	**2570.08**	**11.71**	
Land Use	MAN	364.03	1.66	14.16
	FRSE	74.22	0.34	2.89
	PAST	906.05	4.13	35.25
	PINE	1100.98	5.02	42.84
	POPL	1.34	0.01	0.05
	BARR	1.20	0.01	0.05
	WATR	0.20	0.00	0.01
	RNGB	9.00	0.04	0.35
	WETF	1.35	0.01	0.05
	HARV	110.31	0.50	4.29
Soils	BLT	97.71	0.45	3.8
	BOP	351.57	1.60	13.68
	GOT	16.13	0.07	0.63
	RFM	43.21	0.20	1.68
	ROT	72.01	0.33	2.8
	ROW	1496.11	6.82	58.21
	RTM	491.94	2.24	19.14
Slope	0-10	111.70	0.51	4.35

	10-20	195.12	0.89	7.59
	20-30	282.56	1.29	10.99
	30-50	833.54	3.80	32.43
	50-9999	1145.77	5.22	44.58
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	2	**1151.46**	**5.25**	
Land Use	MAN	1.35	0.01	0.12
	FRSE	83.63	0.38	7.26
	PAST	621.22	2.83	53.95
	PINE	402.03	1.83	34.91
	POPL	40.27	0.18	3.50
Soils	BOP	7.17	0.03	0.62
	GOT	201.42	0.92	17.49
	RFM	0.60	0.00	0.05
	ROW	812.90	3.70	70.60
	RTM	126.40	0.58	10.98
Slope	0-10	44.38	0.20	3.85
	10-20	136.46	0.62	11.85
	20-30	204.74	0.93	17.78
	30-50	411.98	1.88	35.78
	50-9999	350.94	1.60	30.48
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	3	**1182.83**	**5.39**	
Land Use	MAN	56.30	0.26	4.76
	FRSE	97.25	0.44	8.22
	PAST	455.16	2.07	38.48
	PINE	480.48	2.19	40.62
	RNGB	2.68	0.01	0.23
	HARV	91.82	0.42	7.76
Soils	BLT	101.8392	0.46	8.61
	BOP	203.445	0.93	17.2
	BOT	36.7453	0.17	3.11
	GOT	6.2467	0.03	0.53
	MOT	326.1894	1.49	27.58
	RFT	11.2566	0.05	0.95
	ROT	70.1465	0.32	5.93
	ROW	427.8178	1.95	36.17
Slope	0-10	55.774	0.25	4.72
	10-20	86.5385	0.39	7.32
	20-30	114.0366	0.52	9.64
	30-50	347.3455	1.58	29.37
	50-9999	579.9921	2.64	49.03
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	4	**1712.26**	**7.8**	

Land Use	MAN	232.15	1.06	13.56
	FRSE	224.38	1.02	13.10
	PAST	1165.84	5.31	68.09
	PINE	41.29	0.19	2.41
	POPL	51.13	0.23	2.99
	WATR	1.05	0.00	0.06
	RNGB	2.08	0.01	0.12
Soils	BOP	704.52	3.21	41.15
	BOT	17.28	0.08	1.01
	MOT	41.53	0.19	2.43
	RFM	54.01	0.25	3.15
	ROT	36.75	0.17	2.15
	ROW	650.42	2.96	37.99
	RTM	213.41	0.97	12.46
Slope	0-10	150.67	0.69	8.80
	10-20	245.57	1.12	14.34
	20-30	278.26	1.27	16.25
	30-50	546.29	2.49	31.90
	50-9999	497.13	2.27	29.03
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	5	**113.09**	**0.52**	
Land Use	MAN	0.11	0.00	0.10
	FRSE	10.55	0.05	9.33
	PAST	99.75	0.45	88.20
	RNGB	3.07	0.01	2.72
	BOP	33.65	0.15	29.75
Soils	RFT	10.66	0.05	9.43
	ROW	69.18	0.32	61.17
	0-10	8.32	0.04	7.36
	10-20	15.50	0.07	13.71
	20-30	21.14	0.10	18.69
Slope	30-50	35.01	0.16	30.96
	50-9999	33.52	0.15	29.64
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	6	**3238.88**	**14.76**	
Land Use	MAN	28.14	0.13	0.87
	FRSE	205.38	0.94	6.34
	PAST	1866.13	8.50	57.62
	PINE	994.53	4.53	30.71
	POPL	138.63	0.63	4.28
	WATR	0.46	0.00	0.01
	RNGB	1.71	0.01	0.05
	HARV	3.02	0.01	0.09
Soils	BOP	354.84	1.62	10.96

	PID	186.46	0.85	5.76
	RFT	17.30	0.08	0.53
	ROM	32.51	0.15	1.00
	ROT	46.33	0.21	1.43
	ROW	2140.45	9.75	66.09
	RTM	460.10	2.10	14.21
Slope	0-10	131.22	0.60	4.05
	10-20	341.39	1.56	10.54
	20-30	520.74	2.37	16.08
	30-50	1126.51	5.13	34.78
	50-9999	1118.14	5.10	34.52
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	7	**978.72**	**4.46**	
Land Use	MAN	98.01	0.45	10.01
	FRSE	87.81	0.40	8.97
	PAST	614.31	2.80	62.77
	PINE	103.36	0.47	10.56
	AGRL	0.03	0.00	0.00
	POPL	7.57	0.03	0.77
	BARR	11.58	0.05	1.18
	WATR	0.43	0.00	0.04
	WETF	1.15	0.01	0.12
	HARV	51.61	0.24	5.27
Soils	BOP	335.45	1.53	34.27
	MOT	71.79	0.33	7.34
	PID	98.00	0.45	10.01
	RFT	6.88	0.03	0.70
	ROT	21.26	0.10	2.17
	ROW	431.58	1.97	44.10
	RTM	10.87	0.05	1.11
Slope	0-10	54.79	0.25	5.60
	10-20	92.85	0.42	9.49
	20-30	124.31	0.57	12.70
	30-50	330.91	1.51	33.81
	50-9999	372.97	1.70	38.11
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	8	**753.29**	**3.43**	
Land Use	MAN	130.73	0.60	17.35
	FRSE	22.86	0.10	3.03
	PAST	419.47	1.91	55.69
	PINE	141.35	0.64	18.76
	AGRL	10.40	0.05	1.38
	POPL	22.97	0.10	3.05
	BARR	0.01	0.00	0.00

	ORCD	2.44	0.01	0.32
	RNGB	0.93	0.00	0.12
	HARV	4.76	0.02	0.63
Soils	BOP	123.10	0.56	16.34
	GOT	37.05	0.17	4.92
	PID	0.00	0.00	0.00
	RFT	93.00	0.42	12.35
	ROW	502.71	2.29	66.74
	RTM	0.06	0.00	0.01
Slope	0-10	54.72	0.25	7.26
	10-20	65.34	0.30	8.67
	20-30	98.91	0.45	13.13
	30-50	250.26	1.14	33.22
	50-9999	286.69	1.31	38.06
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	9	**2196.30**	**10.01**	
Land Use	MAN	306.83	1.40	13.97
	FRSE	114.94	0.52	5.23
	PAST	1451.98	6.62	66.11
	PINE	316.16	1.44	14.40
	POPL	1.16	0.01	0.05
	RNGB	2.16	0.01	0.10
	HARV	0.04	0.00	0.00
Soils	BOP	337.39	1.54	15.36
	GOT	117.92	0.54	5.37
	MOT	61.16	0.28	2.78
	RFM	21.48	0.10	0.98
	RFT	28.38	0.13	1.29
	ROM	127.22	0.58	5.79
	ROT	159.40	0.73	7.26
	ROW	1186.20	5.41	54.01
	RTM	154.11	0.70	7.02
Slope	0-10	95.12	0.43	4.33
	10-20	181.32	0.83	8.26
	20-30	271.45	1.24	12.36
	30-50	762.41	3.47	34.71
	50-9999	882.97	4.02	40.20
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	10	**1614.94**	**7.36**	
Land Use	MAN	251.45	1.15	15.57
	FRSE	72.88	0.33	4.51
	PAST	310.00	1.41	19.20
	PINE	862.87	3.93	53.43
	AGRL	13.44	0.06	0.83

	POPL	37.84	0.17	2.34
	BARR	3.48	0.02	0.22
	WATR	0.80	0.00	0.05
	HARV	65.75	0.30	4.07
Soils	BOP	107.21	0.49	6.64
	GOT	10.63	0.05	0.66
	PID	97.80	0.45	6.06
	RFT	108.17	0.49	6.70
	ROT	113.21	0.52	7.01
	ROW	1063.05	4.84	65.83
	RTM	118.44	0.54	7.33
Slope	0-10	95.74	0.44	5.93
	10-20	117.47	0.54	7.27
	20-30	169.74	0.77	10.51
	30-50	502.52	2.29	31.12
	50-9999	733.05	3.34	45.39
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	11	**1953.67**	**8.90**	
Land Use	MAN	207.76	0.95	10.63
	FRSE	63.99	0.29	3.28
	PAST	825.29	3.76	42.24
	PINE	798.82	3.64	40.89
	POPL	23.41	0.11	1.20
	BARR	4.66	0.02	0.24
	WATR	0.88	0.00	0.04
	RNGB	10.22	0.05	0.52
	HARV	24.18	0.11	1.24
Soils	BOP	180.22	0.82	9.22
	GOT	127.26	0.58	6.51
	RFM	125.60	0.57	6.43
	RFT	9.48	0.04	0.49
	ROM	164.59	0.75	8.42
	ROT	171.53	0.78	8.78
	ROW	966.00	4.40	49.45
	RTM	214.53	0.98	10.98
Slope	0-10	163.84	0.75	8.39
	10-20	180.74	0.82	9.25
	20-30	213.03	0.97	10.90
	30-50	569.19	2.59	29.13
	50-9999	832.41	3.79	42.61
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	12	**875.86**	**3.99**	
Land Use	MAN	39.44	0.18	4.50
	FRSE	6.92	0.03	0.79

	PAST	42.13	0.19	4.81
	PINE	444.54	2.03	50.76
	WATR	0.17	0.00	0.02
	HARV	339.66	1.55	38.78
Soils	BOP	10.21	0.05	1.17
	GOT	4.87	0.02	0.56
	ROT	115.20	0.52	13.15
	ROW	742.60	3.38	84.79
Slope	0-10	19.52	0.09	2.23
	10-20	34.13	0.16	3.90
	20-30	49.38	0.23	5.64
	30-50	182.71	0.83	20.86
	50-9999	587.13	2.68	67.04
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	13	**1087.26**	**4.95**	
Land Use	MAN	332.41	1.51	30.57
	FRSE	133.12	0.61	12.24
	PAST	524.59	2.39	48.25
	PINE	63.36	0.29	5.83
	BARR	4.26	0.02	0.39
	ORCD	4.05	0.02	0.37
	RNGB	1.01	0.00	0.09
	HARV	27.79	0.13	2.56
Soils	BOP	103.07	0.47	9.48
	GOT	66.02	0.30	6.07
	MOT	22.60	0.10	2.08
	PIT	23.31	0.11	2.14
	RFW	100.69	0.46	9.26
	ROT	771.75	3.52	70.98
	ROW	3.14	0.01	0.29
Slope	0-10	70.48	0.32	6.48
	10-20	77.08	0.35	7.09
	20-30	89.68	0.41	8.25
	30-50	254.06	1.16	23.37
	50-9999	599.29	2.73	55.12
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	14	**720.38**	**3.28**	
Land Use	MAN	28.98	0.13	4.02
	FRSE	57.42	0.26	7.97
	PAST	605.21	2.76	84.01
	PINE	16.90	0.08	2.35
	POPL	10.18	0.05	1.41
Soils	BOP	43.90	0.20	6.09
	MOT	26.07	0.12	3.62

	PIT	0.18	0.00	0.03
	RFW	7.64	0.03	1.06
	ROT	489.00	2.23	67.88
	ROW	37.98	0.17	5.27
	WO	113.90	0.52	15.81
Slope	0-10	21.21	0.10	2.94
	10-20	62.58	0.29	8.69
	20-30	102.39	0.47	14.21
	30-50	228.42	1.04	31.71
	50-9999	304.08	1.39	42.21
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	15	**858.99**	**3.91**	
Land Use	MAN	295.74	1.35	34.43
	FRSE	90.07	0.41	10.49
	PAST	189.83	0.87	22.10
	PINE	217.81	0.99	25.36
	POPL	0.08	0.00	0.01
	ORCD	5.15	0.02	0.60
	HARV	57.85	0.26	6.73
Soils	BOM	9.52	0.04	1.11
	BOP	35.95	0.16	4.19
	GOT	8.99	0.04	1.05
	MOT	59.03	0.27	6.87
	PID	63.03	0.29	7.34
	PIT	58.59	0.27	6.82
	RFW	0.05	0.00	0.01
	ROT	437.74	1.99	50.96
	WO	183.63	0.84	21.38
Slope	0-10	52.00	0.24	6.05
	10-20	62.97	0.29	7.33
	20-30	81.88	0.37	9.53
	30-50	224.84	1.02	26.17
	50-9999	434.83	1.98	50.62
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	16	**248.55**	**1.13**	
Land Use	MAN	3.57	0.02	1.44
	FRSE	18.53	0.08	7.45
	PAST	223.93	1.02	90.10
	POPL	3.02	0.01	1.21
Soils	BOP	33.45	0.15	13.46
	MOT	20.03	0.09	8.06
	PIT	4.83	0.02	1.94
	ROT	31.24	0.14	12.57
	ROW	114.32	0.52	46.00

	WO	45.16	0.21	18.17
Slope	0-10	15.55	0.07	6.26
	10-20	40.51	0.18	16.30
	20-30	52.83	0.24	21.26
	30-50	89.04	0.41	35.82
	50-9999	51.12	0.23	20.57
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	17	**1.52**	**0.01**	
Land Use	PAST	1.34	0.01	88.30
	POPL	0.18	0.00	12.05
Soils	PIT	1.53	0.01	100.35
Slope	0-10	0.95	0.00	62.55
	10-20	0.24	0.00	15.51
	20-30	0.12	0.00	7.59
	30-50	0.11	0.00	7.43
	50-9999	0.11	0.00	7.26
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	18	**243.96**	**1.11**	
Land Use	MAN	10.42	0.05	4.27
	PAST	229.96	1.05	94.26
	POPL	1.47	0.01	0.60
	WATR	0.10	0.00	0.04
Soils	MOT	66.20	0.30	27.13
	PIT	1.92	0.01	0.79
	ROW	173.84	0.79	71.26
Slope	0-10	40.85	0.19	16.74
	10-20	71.98	0.33	29.50
	20-30	56.94	0.26	23.34
	30-50	56.26	0.26	23.06
	50-9999	15.94	0.07	6.53
	Sub-Basin	**Area (ha)**	**% Catchment Area**	**% Sub-Basin Area**
	19	**443.32**	**2.02**	
Land Use	MAN	18.24	0.08	4.12
	PAST	291.68	1.33	65.79
	PINE	83.98	0.38	18.94
	POPL	20.31	0.09	4.58
	ORCD	9.38	0.04	2.12
	WATR	7.61	0.03	1.72
	HARV	9.91	0.05	2.24
Soils	MOT	15.33	0.07	3.46
	PID	91.76	0.42	20.70
	PIT	107.94	0.49	24.35
	ROT	10.07	0.05	2.27
	ROW	82.94	0.38	18.71

	WO	133.07	0.61	30.02
Slope	0-10	79.02	0.36	17.82
	10-20	68.26	0.31	15.40
	20-30	79.68	0.36	17.97
	30-50	144.48	0.66	32.59
	50-9999	69.67	0.32	15.72