Modelling the hydrological impacts of land use change and integrating cultural perspectives in the Waikouaiti Catchment, Otago

New Zealand.

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Abstract

Changes to land use in a catchment impacts the quality and quantity of water as well as affecting Māori relationships with water. However, cultural effects are often considered in isolation to the more easily quantifiable effects on water quality and quantity. As such, the aim of this research is to explore how scientific and cultural data can be integrated in a freshwater management setting to inform decision making in the Waikouaiti catchment, Otago.

The impacts of land use change on flow regimes and water quality were modelled using the Soil and Water Assessment Tool (SWAT) and the Catchment Land Use for Environmental Sustainability (CLUES) model. A cultural stream health assessment survey was undertaken by whānau members to articulate cultural perspectives. The SWAT model was calibrated for baseline conditions at two locations in the catchment; Bucklands and Lawsons. Monthly Nash Sutcliffe efficiency values for the calibration periods were 0.68 and 0.83.Water quality was modelled at Bucklands and Orbells. Total nitrogen (total N) and total phosphorus (total P) loads and concentrations for the baseline were overestimated at Orbells but reasonable at Bucklands. Six land use simulations were run in SWAT and CLUES. The cultural stream health assessments were conducted over a ten month period at two culturally significant locations; Bucklands and Orbells, individual scores were averaged and compared to mean flow on the sampling day.

Replacing existing mixed native and exotic forestry with woody biomass (scrub) at Lawsons resulted in a significantly altered flow regime; 7-day mean annual low flows (7-day MALF) were increased by 68% and peak flows by 45%, with the highest proportion of surface runoff compared to other land uses. In contrast, 7-day MALF decreased by 53% in a fully afforested scenario whilst the impacts of partial conversion to tussock or low producing grassland were smaller; ~12% increases in annual yield primarily due to lower evapotranspiration. At Bucklands (predominantly low producing grassland) the largest decreases in mean annual runoff were from native forest (42%) and tussock (26%), decreases in both scenarios were a result of high evapotranspiration and low surface runoff, groundwater and lateral flow. 7-day MALF and peak flows decreased by 86% and 73% under the native forest and tussock scenarios whilst peak flows increased by 17% in the intensive dairying scenario which had a high proportion of total runoff from lateral and surface flow.

The intensive dairying scenario was predicted to have the most profound effects on water quality at both locations; total N loads more than doubled and total P loads doubled compared to the baseline although there was no change in sediment loads. The lowest total N loads were modelled in the native forest scenario whilst woody biomass and tussock yielded the lowest sediment loads. Cultural satisfaction was not exclusively determined by flow as an unsatisfactory score in one cultural theme did not always correlate with an unsatisfactory score in all the other themes for that surveying day. Proportionately more themes were scored unsatisfactory at Bucklands than at Orbells. Although more days with flow less than 0.6 m^3s^{-1} were scored unsatisfactory, themes were scored poorly across all flow. The themes with the most unsatisfactory scores at Bucklands were Wai Māori and health whereas at Orbells the landscape and overall theme scored poorly more frequently. By integrating hydrological and water quality modelling with cultural data a broader understanding of the impacts on cultural health and the suitability of various land use scenarios for aquatic life was achieved. This approach provides a template to meet legislative objectives and the outcomes are applicable in local decision making.

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List of Abbreviations

CHI	Cultural Health Index
CLUES	Catchment land use for environmental sustainability
COMAR	Cultural opportunities, mapping, assessment, and responses
HRU	Hydrological response unit
FDC	Flow duration curve
GIS	Geographical information system
NPS	National Policy Statement
ORC	Otago Regional Council
RMA	Resource Management Act
SWAT	Soil and Water Assessment Tool
Total N	Total nitrogen
Total P	Total phosphorus
MfE	Ministry for the Environment
MAF	Ministry of Agriculture and Forestry
MPI	Ministry of Primary Industries
NRWQN	National River Water Quality Network

Chapter 1: Introduction

Changes to the variety and composition of land use within a catchment alter the quality and quantity of water flowing through a river, which impacts river functions and utility. The general effects of land use on river characteristics are well understood but the specific impacts vary between catchments. Changes in land use alter flow regime (the variability of flow between days, seasons, and years) and modify the source and delivery of nutrients to water ways. These changes affect aquatic ecosystems and the human and cultural uses of, and relationships with, a river. Research has often considered the impacts of land use change on water quality and water quantity in isolation to the impacts on cultural values and relationships. In New Zealand an integrated approach is motivated by concerns surrounding the impacts of historic and current land use changes and as a response to regulatory obligations. The focus of this research is to integrate Māori cultural values in the assessment of the impacts of land use change on hydrology in the Waikouaiti catchment.

Land use changes are an important and often controversial topic in environmental management. Land use poses a genuine threat to the integrity of New Zealand water ways (Elliott, 2008) and regulatory authorities are responsible for the sustainable management of resources; that is balancing social, cultural, economic, and environmental aspirations. This includes considering not only individual effects of land use changes but cumulative and future impacts at catchment and even regional scales. The recent Parliamentary Commissioner for the Environment's report on land use and nutrient pollution in New Zealand highlighted the increasing pressures land use represents for water quality under projected land use changes to 2020. It concludes that despite mitigation measures and best farming practice, water quality will continue to deteriorate due to time lags and continued land intensification (PCE, 2013). Additionally, moves towards national limit setting for both water takes and the acceptable quality of water within management units reflects the need for understanding, accountability, and careful allocation of resources (MfE, 2013). The first land use changes in New Zealand resulted from Māori and then European settlement whereas recent and current land use changes are in response to market pressures (PCE, 2013). Many catchments in New Zealand have been transformed with often un-quantified impacts on hydrology. Today land development continues but closer is attention paid to the impacts on water ways in response to increased environmental awareness and the regulatory environment.

The Resource Management Act (RMA) (RMA, 1991) governs land use in New Zealand and delivers sustainable management objectives through a hierarchy of national, regional, and local plans, policies, and statements. The processes described and followed in environmental management are primarily based in legislative and planning conventions, where scientific knowledge is the principal basis for understanding the environment (Ayre and MacKenzie, 2013). Nevertheless, there is an obligation to recognise and account for Māori rights and responsibilities; "... to provide for the involvement of iwi and hapū, and to ensure that tangata whenua values and interests are identified and reflected in the management of fresh water..." (NZG, 2011, p10). Although the RMA (1991) and National Policy Statement (2011) clearly define the expectations of local authorities to involve Māori, few tools have been provided to meet statutory obligations (Townsend *et al.*, 2004) and there is limited literature concerning the mechanisms and strategies for integrating indigenous interests in resource management (Ayre and MacKenzie, 2013).

Traditionally the impacts of land use on water quantity or quality have been explored through physical measurements (Chicota and Snow, 2009) or paired catchment experiments contrasting two land uses in physically similar catchments (Brown *et al.*, 2005). However, physical measurements can be time consuming and costly whilst paired experiments can be confounded by other influencing factors such as soils, geology, or climate (Duncan and Collins, 2013) and are generally limited to small catchments (<5 km^2) (Andréassian, 2005). Thus, computer simulated hydrological models are a useful tool for isolating the effects of land use change (Yang *et al.*, 2007) and allow for the comparison of multiple scenarios. The impacts on Māori values cannot be easily measured using conventional scientific indicators and variables and are often difficult to communicate in non-Māori, environmental management contexts. Cultural stream health assessments were developed in New Zealand as a way to quantify and communicate cultural perspectives (Tipa and Nelson, 2008). Data is collected through surveys and different cultural themes are scored based on cultural satisfaction with flow and other stream attributes, essentially providing an index of cultural satisfaction. Modelling and cultural assessments present two contrasting methodologies in the investigation of land use impacts on rivers but individually and collectively provide a wealth of information. Together scientific and Māori knowledge can inform environmental management, aid decision making, and promote better environmental outcomes but the challenge lies in integrating the two in format that makes the information understandable and accessible to all stakeholders regardless of their background. Thus, this study aims to model the effects of land use change on both quantity and quality, but to also consider broader impacts to the cultural health of a water way and its suitability for sustaining aquatic health. To achieve this, a case study approach is undertaken using the Waikouaiti catchment.

The Waikouaiti catchment is a hilly East Otago catchment with an interesting history of land use change and provides an ideal location to investigate how cultural values can be integrated in the assessment of land use change impacts on hydrology. Early Māori used fire to clear native bush for Moa hunting followed by the clearance of native forest and regenerated tussock for agriculture by European settlers (Campbell, 1977). The coastal catchment is culturally significant to local Māori because of its traditional trails and routes and the mahinga kai resource (ORC, 2005). Equally the Otago Regional Council (ORC) has a management interest in the catchment as it lies within the council's jurisdiction boundary and has identified low flows as a particular concern in the catchment (ORC, 2012a). The catchment landscape is dominated by low producing grassland (sheep and beef), whilst the remaining area is a mix of native and exotic forestry, dairy pasture, and scrub (ORC, 2011). There is a modest amount of data available on catchment but little research has focused on the catchment aside from investigations and reports published by the council.

1.1 Thesis Outline

This research investigates the impacts of land use change on water quality, quantity, and cultural values in the Waikouaiti catchment using a combination of hydrological modelling and cultural surveys. Chapter 2 provides a theoretical review of the current understanding and research in each of the literature themes. It provides a background to the impacts of land use change on water quality and quantity in New Zealand and the physical controls of different vegetation cover. Hydrological models and their use in land use investigations are evaluated and the unique relationship Māori maintain with water is described. Chapter 2 explores methods used to quantify and integrate cultural perspectives into science based resource management processes and the research aims and objectives are outlined. Chapter 3 describes the research strategy, field area, and methodology. Model calibration and validation, the land use scenarios, and the cultural stream health assessment are explained. Model performance is evaluated in Chapter 4, and Chapter 5 presents the results of the hydrological simulations and cultural assessments. Chapter 6 discuses and analyses the results of the hydrological modelling and cultural assessments and draws linkages between scientific and cultural perspectives. Techniques to integrate scientific and cultural data are explored and the direction of future research is suggested. Finally, Chapter 7 summarises the principal outcomes and findings.

Chapter 2: Hydrological responses to land use change: a theoretical review

2.1 Introduction

Land use changes in a catchment affect water resources in terms of water quality and quantity (Beven, 2012) but can also impact cultural relationships with water resources. This chapter explores the physical and cultural impacts of land use change and examines the tools used to assess these impacts. Section 2.2 reviews the current understanding of land use impacts on water quality and water quantity focusing on forestry, pasture, and tussock grasslands. In Section 2.3 the hydrological models used to quantify the impacts of different land uses on flow regime and water quality are evaluated. Section 2.4 explores the Māori perspective of water resource management and Section 2.5 analyses different methods of communicating and qualifying cultural views. A background to land use changes and current management concerns in the Waikouaiti catchment is described in Section 2.5 and finally the research aims and objectives are presented in Section 2.6.

2.2 The impacts of land use on flow regime and water quality

A river is directly and indirectly influenced by its catchment. Evapotranspiration, interception, infiltration, percolation, and absorption of the vegetation cover can modify land surface characteristics, the water balance, and the hydrological cycle (LeBlanc *et al.*, 1997). Precipitation falling in a catchment interacts with soil and vegetation to produce runoff from hill slopes or percolate into groundwater before entering a stream (Parkyn and Wilcock, 2004). These interactions transport residue from the landscape into a stream. Therefore, land use within a catchment affects water quality as well as water quantity. Water quantity and quality are closely linked because high flows can either dilute or flush out contaminants while conversely concentrations are elevated in low flows. Changes in stream water quality and quantity have implications for water users and aquatic ecosystems as well as influencing downstream water bodies such as lakes and estuaries. Although other factors such as geology and climate influence water quality and quantity much research has focused on isolating the effects of specific land uses.

The impacts of land use on hydrology and water quality have traditionally been investigated through paired catchment experiments. Paired catchment experiments require two catchments with similar characteristics, slope, aspect, soils, area, climate, and vegetation located in close proximity (Brown *et al*., 2005). The two catchments are monitored for a calibration period and then land use in one watershed is altered whilst the other remains a control. Paired experiments were first initiated in the late 1800s and continued to be popular through to the 1990s. Internationally (for example the Plynlimon study in Wales (e.g. Calder, 1977; Archer, 2007)) and in New Zealand (for example the Glendhu experimental catchment (Otago) (e.g. Fahey and Jackson, 1997b; Fahey and Watson, 1991)) there are examples of long running experiments which provide invaluable information and insights into hydrological responses to land use. Typically these studies focus on afforestation, deforestation, re-growth, or conversion.

2.2.1 Afforestation and conversion of pasture to forestry

Annual water yields from forested catchments are held to be lower than similar pasture catchments although the magnitude of difference varies. In New Zealand water yields are reported to be between 25% and 80% lower in forested catchments than pasture (e.g. Pearce *et al.*, 1982; Smith, 1987; Rowe, 2003; Duncan, 1995; Fahey *et al.*, 2004). For example, in the schist dominated Berwick forest, east Otago, runoff from two forested catchments was on average 43% lower than that from two pasture catchments (Smith, 1987). In contrast, comparing runoff from the forested catchment after canopy closure in an afforestation example was 81% lower than expected from pasture in the Moutere Hills near Nelson (Duncan, 1995). At Purukohukohu, central North Island in pumice dominated catchments, in the 23 year period from planting to harvesting average annual runoff decreased by 30%. The variation reported in New Zealand is similar to that reported internationally; Farley *et al.* (2005) reviewed several international paired catchment experiments including examples from New Zealand, Australia, and South Africa. They calculated an average decrease in annual yields of 44% for grassland to forest conversions when multiple forest types were included and a 40% reduction for grassland to pine conversions. Although, the calculations were not scaled for the portion of forest converted, Farley *et al.* (2005) concluded scaling affected the magnitude of changes but the patterns were not altered.

The impacts of land use on annual yields are reasonably well understood but the impact on flow regime is less certain (Lane *et al.*, 2005). Peak flows were 77% lower in the pine catchments than pasture at Berwick forest (Smith, 1987) whilst at Purukohukohu afforestation decreased small flood events by 50% and large events by an order of magnitude (Rowe, 2003). At Moutere (near Nelson) large flood events in mature pine catchments were 65% smaller than pasture catchments (Duncan 1995). It is often assumed differences in soil moisture are small in large events but Duncan (1995) demonstrated the difference in flood volume was due to differences in soil moisture in the Moutere example. The effects on low flows are harder to predict as they are dependent on the amount and distribution of rainfall as well as other hydro-geological variables (Fahey *et al.*, 2004). In Berwick forest, East Otago, conversion from pasture to pine decreased the average 7-day mean annual low flow (MALF) by 20%. In comparison, in the ephemeral Moutere catchments days without flow increased from 2 to 5 months following pine planting.

Trees have higher evapotranspiration rates than pasture due to greater interception losses and larger root systems leading to more transpiration. Therefore, the reduction of forest cover results in lower evapotranspiration and thus higher runoff (Baldyga *et al.*, 2007). New Zealand studies have reported interception losses in pine to be 20-30% of gross rainfall (e.g. Rowe and Pearce, 1994, Duncan, 1995, Fahey and Watson, 1991) whilst transpiration estimates are harder to obtain. In Moutere, near Nelson, transpiration losses for pine and pasture were similar (76.9 and 72.7%) compared to interception loses of ~ 21% for pine and ~5% for pasture (Duncan, 1995). However, interception and transpiration loses cannot be extrapolated to other catchments unless there is a high degree of similarity in rainfall distribution, permeability, and moisture storage characteristics of regolith and seasonal distribution, duration, and magnitude of soil moisture deficit (Pearce and Rowe, 1980).

2.2.2 Deforestation and conversion of forest to pasture

As noted in the previous section pasture catchments return higher annual yields than forests (Cooper and Thomsen, 1988). Harvesting of forests results in a general increase in yields but fewer New Zealand studies have focused on the effects of harvesting non-indigenous forests. Harvesting of three small catchments planted in mature pines resulted in 30-40% increases in water yield in the post harvesting bare catchment under average rainfall at the Glenbervie Forest North of Whangarei. Smaller changes were observed in years with lower rainfall. In the Waiwhiu Stream, Wellsford water yields increased by 35% after harvesting and in the pumice dominated Purukohukohu, central North Island water yields increased by 70% (Rowe, 2003). Annual water yields for the four years after harvesting when the land was regenerating at Big Bush forest south west of Nelson were 68% higher than the native control catchment. In Whatawhata hill country, Waikato, comparisons of adjacent catchments in pasture and native vegetation estimated water yields to be 7% higher from pasture which is small but possibly a consequence of unmatched rainfall in the two catchments (Quinn and Shroud, 2002). Comparing similar pasture and native forest catchments in Purukohukohu showed annual streamflow yields from pasture were between 32 and 47% higher. However, contrary to expectations one pasture catchment had lower yields than the native catchments (up to 44% lower) which may have been due to drainage characteristics (Rowe, 2003) or issues determining the true catchment area (Dons, 1986). The water requirements of different tree species is reported to affect the changes in yield after deforestation (e.g. Zhou *et al.*, 2002) but studies from New Zealand suggest that stream responses to deforestation are similar for indigenous and radiata pine forests, the two dominant forest types (Fahey *et al.*, 2004). Thus, results from pine and indigenous forest studies should be applicable in both contexts. For example, after an initial increase in water yield at Big Bush forest south west of Nelson following an indigenous to pine conversion, water yields returned to pre-treatment levels after approximately eight years (Fahey and Jackson, 1997a).

The impact of deforestation and conversions on flow regime varies. In deforestation studies, mean peak flows were elevated by 60% for small events and 30% for large flood events at Maimai in the three years' post harvesting before the replanted trees were fully established (Rowe and Pearce, 1994) and at Donald Creek, Tasman mean flows increased by 77 and 52% in small events after harvesting (Fahey and Jackson, 1997a). At Glenbervie forest, increases in MALF ranged between 32 and 100% during the post harvesting period when land was clear. In Whatawhata hill country, Waikato, low flows from pasture were 17% higher than an adjacent native catchment (Quinn and Shroud, 2002).

The absence of trees causes a higher proportion of rainfall to be converted directly to surface runoff instead of infiltrating into the soil as a result of decreased surface roughness and litter (Barker and Miller, 2013). An exception to this trend is sometimes observed in forest canopies where a high portion of total precipitation is processed as 'fog drip'. Fog drip occurs when fog droplets condense on leaves or needles and fall to the forest floor. In these cases, deforestation decreases discharge (Harr 1982; Bruijnzeel, 2004). Additionally, trampling by livestock, particularly heavy animals such as cows, compacts soil and reduces infiltration (Trimble and Mendel, 1995) further promoting overland flow, thus increasing water yields. Variation in the magnitude of change between studies is often due to other confounding factors such as geology, soil type, and climatic variation (Duncan and Collins, 2013).

2.2.3 Water quality in forested and pasture catchments

The physical properties of trees and grass as well as land use related activities impact water quality as well as flow regime. Afforestation generally improves water quality whilst deforestation can result in a deterioration of water quality. Improvements in water quality following afforestation are due to decreased inputs, nutrients, fertilisers, and the absence of grazing stock (e.g. Cooper and Thomsen, 1981; Quinn and Shroud, 2002). Additionally, tree root systems help to stabilise soils, trapping and reducing sediment delivery to waterways (Davies-Colley, 1997). However, the effects vary with management and the time since planting (Monaghan *et al*., 2010). Predictions for Lake Taupo estimated nitrogen yields from pines would reach a long term equilibrium of 2-3 kg N ha^{-1} yr^{-1} which is small compared to the estimated loads for dairy and non-dairy pastures of 29 and 9 kg N ha^{-1} yr^{-1} (Environment Court, 2008).

In contrast to planting trees, deforestation increases erosion from surface runoff and mass movement on slopes generates and delivers more sediment to waterways reducing clarity (Fahey and Jackson, 1997a). On erodible hill country north of Napier suspended sediment yields in a forested catchment were half those of pasture but after harvesting the situation was reversed (Fahey and Marden, 2000). Livestock activity can also increase sediment loads to waterways. Cattle, more so than other livestock due to their size and affinity for water can reduce bank stability and directly input sediment by trampling stream banks and riparian soils (Trimble and Mendell, 1995) reducing sediment and contaminant trapping capabilities (Belsky *et al*., 1999). In a coastal Hawkes Bay catchment on tertiary marine sediments, pasture generated 250% more sediment than a mature pine forest (Fahey and Marden, 2000). Elevated sediment affects clarity, light for photosynthesis, and vision for feeding (Davies-Colley *et al*., 1992; Quinn *et al*., 1992).

After deforestation nitrogen and phosphorus losses are amplified as harvesting disrupts forest nutrient cycling (Fahey *et al*., 2004). Fahey and Jackson (1997b) found total nitrogen yields were 10 times higher than the control when beech was harvested and 3-5 times higher after 4 years whilst total phosphorus loads were 2-3 times higher. At Purukohukohu, central North Island nutrients levels increased relative to the nearby native catchments in the first year but decreased below pre-treatment levels after 2-3 years. This was attributed to the rapid development of underground weed and soil microbial biomass which retained the nutrients (Parfitt *et al.,* 2002). This highlights the often case specific effects of land cover change which make predicting the nature and magnitude of potential impacts difficult.

Agricultural activity in pasture catchments degrades water quality through point and non-point sources of pollution but impacts vary between farming systems. Points sources e.g. wastes from piggeries, dairy sheds, dairy factories, and freezing works (Elliott *et al.,* 2005) are easier to identify and were the first sources investigated in early agriculture-waterway research (e.g. Rutherford *et al.,* 1987). These can provide a major source of nutrients (nitrogen, phosphorus, and organic materials) to New Zealand waterways (Wilcock *et al.,* 1999). Erosion, animal wastes, and fertilisers are the main sources of phosphorus whilst, animal waste, particularly urine is a major input of nitrogen (Parkyn and Wilcock, 2004). High water yields in pasture compared to forest accommodate the easy transport of nutrients and sediments to waterways (Quinn and Shroud, 2002). Non-point pollution is transported via surface and subsurface runoff, fertiliser drift, and animal contact with a stream (Hatch *et al.,* 2002). Dissolved substances such as nitrate can be leached into the groundwater and eventually enter the stream via seeps and springs (Vant and Smith, 2002). Using modelling, the reversion of extensive sheep and beef farm land to scrub on hilly clay in Gisborne is estimated to decrease total nitrogen and phosphorus losses by a factor of 4 whereas converting intensive sheep and beef farm land to agriculture on alluvial soils in Canterbury would more than double total nitrogen loads and quadruple total phosphorus loads. In contrast, replacing plantation forest with dairy on pumice soils in the Volcanic plateau would increase nutrient losses by an order of magnitude (PCE, 2013). Surplus nitrogen and phosphorus in waterways can cause toxic algal blooms and eutrophication which impairs human use and affecting aquatic life and habitats (Schallenberg *et al*., 2000).

2.2.4 The hydrology of tussock grassland catchments

In New Zealand tussock grasslands (bunch grasses) together with native forest made up the original vegetation composition of the country. The relationship between tussock and water is unique and in New Zealand research has focused on tall snow tussocks. Paired catchment experiments and lysimeter experiments have shown that tussock grasslands have higher water yields than forested catchments. However, the cause of higher water yields from tussock grasslands has been debated for the last 40 years. One hypothesis is that low evaporation rates cause higher yields as demonstrated by lysimeter experiments (Campbell, 1989, Campbell and Murray, 1990, Fahey *et al*., 1996), whereas others argue fog interception contributes to increases in water yield based on lysimeter studies and confirmed by isotopic evidence (Holdsworth and Mark, 1990, Ingraham and Mark, 2000). Davie *et al*. (2006) reviewed evidence to date and highlighted several issues and uncertainties with lysimeters that could bias results. Davie *et al*. (2006) also notes that studies by Fahey *et al*. (1996) and Campbell and Murray (1990) attributed very small amounts of fog deposition to total precipitation, less than 2%. Ingraham and Mark (2000) argue that fog is generated close to the ground at an early stage of condensation which gives it a higher proportion of heavy isotopes which when observed in groundwater samples signal fog deposition. However, Davie *et al*. (2006) suggested two other plausible explanations for a high proportion of heavy isotopes in groundwater; enrichment of heavy isotopes through evaporation and isotopic exchange and/or the water were resident in the soil profile for longer than the rainfall collection period. Recently a modelling experiment by Fahey *et al.* (2011) argued that fog did not have a significant contribution at the catchment scale. Fog deposition is important in a range of other ecosystems outside New Zealand yet in no other places is its role disputed as it is in New Zealand (Ingraham *et al*., 2008). However, as Davie *et al.* (2006) point out, the actual mechanism causing low water use in tussocks is of little to concern to resource managers who are more interested in the fact streams feeding from tussock landscapes have a high water yield. Little research has focused on the influence of tussock grasslands on water quality but it is thought to have little impact on water quality (Mark, 2003).

2.3 Methods of assessing the hydrological impacts of land use change

Paired catchment experiments have provided a wealth of information on the effects of land use change on hydrology in New Zealand and equally so internationally. Periodic synthesis and review of paired catchments experiments has found general agreement with the conclusions of Hibbert (1967); 1) the reduction of forest cover increases water yield, and 2) the establishment of forest cover on sparsely vegetated land decreases water yield (e.g. Hibbert, 1967; Bosch and Hewlett, 1982; Hornbeck *et al.*, 1993; Fahey, 1994; Stednick 1996; Scott and Smith, 1997, Smakhtin, 2001; Andréassian, 2004; Brown *et al.*, 2005; Farley *et al.*, 2005). However, there are limitations to the paired catchment methodology. It is difficult to compare results from different experiments (Andréassian, 2004) due to the lack of key statistics in reported results (Sahin and Hall, 1996) and insufficient detail of site characteristics (Stednick, 1996). Despite the extensive range of paired catchment experiments generalisations are often based on short term (~5 year) experiments. Experiments are generally restricted to small scale investigations (~5 km^2) with practical and theoretical limitations for large catchments (>1000 km^2) (Andréassian, 2004). The few studies that have focused on medium (>100 km^2) to large catchments (>1000 km^2) reported conflicting results to the general patterns described by Hibbert (1967) (e.g. Buttle and Metcalfe, 2000; Wilk *et al.*, 2001; Robinson *et al.*, 2003; Legesse *et al*., 2003; Siriwardena *et al.*, 2006; Lin and Wei, 2008; Fohrer *et al.* 2001). Inconsistency is attributed to the variety of land uses, strong spatial variability in rainfall and/or, water withdrawals often apparent in larger catchments (Bruijnzeel, 2004). In addition, the compensating effects of complex water storage and release mechanisms such as the coexistence of ponds, wetlands and lakes (Robinson *et al*., 2003) often result in little or no change in large scale catchments (Fohrer *et al.*, 2001). Therefore, hydrological responses to disturbance in large scale catchments may be watershed specific (Lin and Wei, 2008). It remains inconclusive if a there is a well-defined relationship between land use type and runoff generation mechanisms (Hundecha and Bárdossy, 2004) and Van Dijk *et al*. (2009) argue the empirical evidence and theoretical debate is not convincing.

2.3.1 Hydrological modelling of flow

Computer simulation addresses some of the weaknesses identified in paired catchment experiments and is particularly useful in large catchment investigations where physical experiments are often not practical. Modelling reduces time costs and eliminates underlying differences between catchments (Yang *et al*., 2007) that may confound results. It also allows for the comparison of multiple land use types and the simulation of different land use scenarios in one catchment. A number of models exist reflecting different approaches to modelling the hydrological cycle but unfortunately no single model has been collectively accepted (Beven, 2012) limiting universal comparisons.

There are several classifications and types of hydrological model. Most rainfall-runoff modelling uses deterministic models, although a model may include a stochastic error (Beven, 2012). Deterministic models simulate physical processes involved in the transformation of rainfall to stream flow in a catchment. A further division of model types is between lumped and distributed models. Distributed models offer a representative description of catchment scale processes useful for investigating the hydrological impacts of land use change where the position of a particular land use may affect the hydrological response. (Gosling and Arnell, 2011). Predictions are distributed in space with variables that represent local averages of storage, flow depths, or hydraulic potential by dividing the catchment into a large number of elements (or grid squares) and solving equations for the state variables associated with every element of the grid square (Beven, 2012).

All distributed models are based on the Freeze and Harlan (1969) blueprint which describes the physics of all the surface and subsurface flow processes in a catchment but is a simplification of reality. Models range from fully distributed models such as the Système Hydrologique Européen (SHE) model (Abbott *et al.*, 1986) which has Danish (MIKE SHE) and United Kingdom (SHETRAN) versions, the Australian THALES model (Grayson *et al*., 1992), and the Integrated Hydrologic Model (InHM) (VanderKwaak and Loague, 2001) which is one of many USA models to semi-distributed models such as TopNet (Fahey *et al.*, 2010) or the Soil and Water Assessment Tool (SWAT) (Arnold *et al.*, 1998) to intermediate complexity models such as WATYIELD (Fahey *et al*., 2010). Fully distributed models are complex and computationally and parametrically demanding which makes simplified forms more attractive (Beven, 2012).

The simplified distributed model attempts to maintain the distributed description without the detailed process representation of fully distributed models. It uses some distribution function to represent the spatial variability of runoff generation. For example, the Geographical Information System (GIS) derived hydrological response unit (HRU) model (e.g. SWAT (Arnold *et al.,* 1998)) is widely used. The HRU approach applies conceptualisations developed at the catchment scale to smaller spatial units, utilizing the modern capabilities of GIS. It allows for the mapping of distribution responses back into the catchment space using GIS and can assess spatial model parameters, and the variability of parameters at a required scale (Beven, 2012). The increasingly ready availability of the data required for these models, such as digital elevation models (DEMs), land use and soil information in addition to the power of computer hardware and geographical information systems (GIS) technology makes these models more accessible and user friendly (Liu et al., 2006). The publication of more than 1300 articles of which SWAT is a component of is evidence of the wide applicability and credibility of the semi-distributed model.

Model performance is verified by comparing model estimates with real world observations. SWAT applications vary in both model performance; often measured by the Nash Sutcliffe efficiency (NSE) criteria where a value of 1 indicates perfect agreement and 0 is poor and in the threshold considered acceptable for model performance (e.g. Guo *et al*., 2008; Stehr *et al*., 2008; Francyzk and Chang, 2009; Pisinaras *et al*., 2010; Palamuleni *et al*., 2011). Wang *et al.* (2012) reported strong model performance for the Three Gorges Reservoir, China (NSE = 0.94 and 0.98) and used partial least squares regression to investigate the relationships between land use changes and hydrological processes. Despite limited historic data Baker and Miller (2013) achieved a NSE of 0.94 for annual runoff and studied how land use changes altered hydrological responses in the River Njoro, Kenya by changing the partitioning of excess rainfall into surface discharge and groundwater recharge. In the Zanjarood basin, Iran a NSE of 0.79 for monthly runoff was deemed suitable to simulate land use modifications and determine changes in different components of flow over time (Ghaffari *et al.,* 2010). In another application, SWAT was used in conjunction with a specifically developed tool, Landuse Update and Soil Assessment (LUPSA) to assess responses to land use change in the Choke Mountain Range, Ethiopia. Due to poor data daily NSE was 0.39 but monthly NSE was >0.8 which was still considered suitable for the study (Koch *et al.,* 2012). In the only

New Zealand example SWAT was applied in the Moteuka catchment, near Nelson to evaluate land cover change impacts on total water yields, groundwater flow, and quickflow (Cao *et al*., 2009). The model performed well for the entire catchment but was variable in the tributaries, the NSE for daily flows ranged from 0.36 to 0.78. Despite the variation reported in model performance, SWAT has been applied in a plethora of studies reflecting the utility and reliability of the model.

2.3.2 Water quality modelling

Early knowledge about water quality in New Zealand also relied on physical measurements but computer simulated models now provide an alternative approach. Whist direct measurements offer insight into the impacts of a specific land use on water quality, measuring all the possible impacts at a catchment, regional, or national scale is time consuming, costly, subject to large variability (Cichota and Snow, 2009), and often not practical (Fahey *et al*., 2010). Modelling is robust and reliable and despite few tools being used to predict the effects of land use change at the catchment scale (Elliott, 2008) the use of hydrological models has increased in recent years as the benefits for both research and environmental analysis are recognised (Chicota and Snow, 2009). The main catchment scale models used in New Zealand are Spatially Referenced Regression on Watershed Attributes (SPARROW), CLUES, AquiferSim, Environmental Sustainability (EnSus), ROtorua and TAupo Nitrogen (RoTan), and the nitrogen leaching model (NLE). These models were all developed and/or calibrated in New Zealand catchments. The main difference between models is how the nutrient balance is calculated. Some models use complex mechanisms or process orientated descriptions of a large number of nutrient processes whilst other models use simpler, typically empirical descriptions of processes and may consider fewer elements (Cichota and Snow, 2009).

ROTAN was developed in New Zealand specifically to model water quality in the central North Island lakes area. ROTAN is a daily time step GIS-based catchment hydrology and water quality model (Kerr and Rutherford, 2008). It estimates nitrate leaching into groundwater and then to streams and further to the lakes (Cichota and Snow, 2009). It has been extensively calibrated in the central North Island lakes (Kerr and Rutherford, 2008), but unfortunately its applicability in other areas has not been tested, and may be limited (Anastasiadis *et al.*, 2011). Using a modified version of ROTAN Rutherford *et al.* (2011) achieved RSME for observed and predicted nitrogen concentrations in nine streams between

0.270 and 2.841 and found the model was suitable for scenario modelling (Rutherford *et al*., 2011).

The AquiferSim and NLE models both focus on groundwater quality but are limited by the knowledge and understanding of groundwater. AquiferSim is part of the International Research for Aquifer Protection (IRAP) project (Lilburne *et al.,* 2006) and incorporates FarmSim, which models farm activities. It has been applied in the central Canterbury plains groundwater zone (Bidwell *et al.* 2009); however, it is limited by the quality and amount of detailed knowledge available on land use, vadose and aquifers in New Zealand (Bidwell *et al.*, 2009). In a hillslope aquifer system the simplicity of AquiferSim 2DV (Woodward *et al.,* 2011) precluded reasonable agreement with concentration patterns under an average water table profile; predictions of oxygen and nitrate under low summer and high spring water table conditions were poor (Woodward *et al.,* 2011). In contrast to AquiferSim, NLE is a simple, semi-empirical model used to estimate nitrogen leaching losses and critical nitrogen application rates into groundwater from different land uses. It can be applied at both the farm and catchment scale but is not widely used (Chicota and Snow, 2009). Di and Cameron (2000) had reasonable success using the model; N leaching losses estimated by the model were in the same order of magnitude as those measured. However, the NLE model has only been used in a few studies and would need further calibration before it was applied to regions outside Canterbury (Cichota and Snow, 2009).

SPARROW and EnSus are both models which have been incorporated into the CLUES model. SPARROW was developed in the United States but has been adapted by NIWA to estimate nitrogen and phosphorus loads from most catchments throughout New Zealand (Elliott *et al*., 2005). It is a semi-empirical model developed for estimating the supply of nutrients to streams in larger catchments (Alexander *et al*. 2002). Elliott *et al*. (2005) used the model to estimate mean annual loads of nitrogen and phosphorus to the 77 New Zealand National River Water Quality Network (NZNRWQN) sites. The model performed reasonably compared to observed data; the nitrogen model measured N loads well (R^2 =0.956) whist P load estimates were not as close but still had a high R^2 value (R^2=0.900). Although the model has performed reasonably it does not include pasture management variables and the relationship with the model must be calibrated to the catchment in the study. In addition, the model does not account for time lags, past changes in land use, and resulting changes in loading in streams (Elliott *et al.,* 2005). EnSus is a framework model used for assessing and mapping the relative risk that different land uses represent to soil and water quality (Hewitt and Stephens 2002). EnSus identifies the soils and land management practices where there is a risk of soil degradation or nitrate leaching and sediment runoff. Its use is limited but increasing as it has been incorporated into CLUES (Chicota and Snow, 2009).

2.3.3 The Catchment Land use for Environmental Sustainability (CLUES) model

An increasingly used catchment scale model in New Zealand is CLUES. CLUES is a quasi-empirical farm and catchment scale model which incorporates components from several models (EnSus, OVERSEER, SPARROW, Soil Plant Atmosphere System (SPASMO) and HARRIS) and links community, social, and economic inputs to assess the effects of land use on water quality (Woods *et al*., 2006). CLUES is simple but has several useful features for planning and policy making (Cichota and Snow, 2009). The CLUES project was initiated by the Ministry of Agriculture and Forestry (MAF) (now Ministry for Primary Industries (MPI)) and the Ministry for the Environment (MfE) and is used by several regional councils in New Zealand. The initial application of CLUES was for early identification of catchments where the receiving surface water bodies are at risk from nitrate sources and since then has been utilised in a range of investigations. These include investigating the effects of land use change and interventions on *E. coli* in Waikato (Anon, 2010) to determining the effects of hypothetical mitigation measures on nutrient loads in Southland (Monaghan *et al.*, 2010). In a recent publication from the Parliamentary Commissioner for the Environment CLUES was used in conjunction with the land use model Land Use in Rural New Zealand (LURNZ) to predict the nutrient losses to water in different parts of the country for modelled land use in 2020 (PCE, 2013).

Research and feedback from CLUES users has resulted in model development and the third version was released in 2012. The model was originally calibrated to National Network of Water Quality Monitoring (NRWQM) sites and errors were generally less for nitrogen loads than phosphorus loads (Elliott, 2011). In a Southland application the estimates of total nitrogen loads, concentrations, and yields generally matched well with observations. In contrast, estimations of total phosphorus were mixed; total phosphorus concentrations were significantly over predicted. This reflects the calculation of median concentrations from flow weighted concentrations which in turn are calculated from the load and flow rate (Monaghan, 2010). A recognised limitation of CLUES is the exclusion of groundwater, which can lead to under or over estimation in catchments where groundwater-surface water interactions occur.

However, to date there is no funding available to develop this part of the model (Elliott, 2011). Nevertheless, the performance of CLUES in a range of applications has been reasonably good (Elliott, 2011) and its ease of use is increasing its popularity and use by researchers and councils alike in New Zealand.

2.4 Embedding cultural perspectives into hydrology

2.4.1 A comparison of scientific and indigenous methods

Contrary to the scientific methodology discussed in Section 2.2 and 2.3 different strategies are employed to conceptualise cultural values. There are several types of knowledge (Agralwal, 2009), and within each knowledge system are various ways of generating, defining, and using knowledge which is centred on the knowledge holders own epistemological perspective and ontology. This can be challenging when a problem transects two, or more, knowledge systems. An example often encountered in environmental management is the interface between scientific knowledge and indigenous knowledge. The scientific frame used to conceptualise the impacts of land use change on hydrological responses in the previous sections may not conceptually encompass values and beliefs that are culturally embedded. Much of the problem stems from the disenfranchisement of the 'indigenous voice' from permissive-based planning and consenting processes. In New Zealand, the RMA (1991) states that the sustainable management of resources will provide for the "social, economic and cultural well being" of people and their communities, and the National Policy Statement (NPS) for Freshwater Management (2011) recognises the importance of an 'indigenous voice' in freshwater management. Objective D of the NPS is "To provide for the involvement of iwi and hapū, and to ensure that tangata whenua values and interests are identified and reflected in the management of fresh water" (NZG, 2011 p.10). Thus, considering the impacts of land use change on hydrological responses from an indigenous perspective not only provides insight, but it is mandated as best practice in nation-wide decision-making processes.

The definition of scientific knowledge systems and indigenous knowledge systems is not straightforward, and has been widely debated for both (Anon., 2010). Scientific knowledge is generated when analytical methods are used to explore data to determine the confidence in the possible explanations of cause and effect. Science is based on the principles of repeatability, rationality, validity, and universality (Raffles, 2002; Ellis, 2005). It aims to be objective and quantifiable (Harmsworth *et al.*, 2002) and the experiments are often synchronic capturing information about many places over a short period of time (Lyver *et al.*, 2009). Generally assessments are carried out with the aim of assessing the impact of human activities on a resource or system and its ability to provide goods and services (Harmsworth *et al.,* 2011). In contrast, the indigenous perspective has been described using a variety of terms from indigenous knowledge (Wohling, 2009) to traditional ecological knowledge (Usher, 2000). Indigenous knowledge is broadly defined as ‘‘all types of knowledge about the environment derived from the experience and traditions of a particular group of people’’ (Usher, 2000, p185) but it also includes traditional knowledge that is distinct from western knowledge (Weiss *et al.,* 2012). Berkes (2009) identifies a knowledge–practice–belief complex encompassing four interrelated levels of analysis: (1) local knowledge of land and animals (factual or empirical), (2) land and resource management systems (applied knowledge), (3) social institutions (norms and values), and (4) worldview (conceptual knowledge, belief system). A distinguishing point of difference between the two systems is that many indigenous knowledge systems include a spiritual or religious element that does not make sense to science (Berkes, 2009). Whilst science is delivered using written communication, indigenous knowledge is typically conveyed through narrative, song, dance, or artistic expression.

The challenges encountered in cross-cultural research include accessing indigenous knowledge which can be particularly difficult for a non-indigenous person to gain. Indigenous knowledge is comprised of layers (Kruger, 2009 cited in Lyver *et al.*, 2009). For example, in indigenous Māori knowledge whakatauki (ancestral sayings), pūrākau and kōrero (myths and stories), karakia (prayers), and waiata (songs) all make up the “records of tribal memory” (Kawhau, 2008 cited in Wehi *et al*., 2009). The knowledge is embedded in idiom, dialect, and tribal identity markers, and is dependent on the structure, meaning, and function of their context (Steiner, 1998 cited in Wehi *et al*., 2009). Thus, access to that knowledge can be difficult, time consuming, and require extensive contextualisation (Wehi *et al.,* 2009). Similar issues were echoed in interviews of participants working on a marine co-management case in Australia. Participants acknowledged the utility of empirical information within each knowledge system, but engaged less with the beliefs and worldviews framing knowledge (Weiss *et al*., 2012). As Ellis (2005) argues, most researchers have a solely scientific background and so are enmeshed in their own cultural values, perceptions, practices, and institutions. Nevertheless, a collaborative study on titi populations on Patauhinu Island, south-west of Rakiura/Stewart Island found that a short term scientific study was able to complement and assist inference from longer term traditional ecological knowledge. The study found that traditional ecological knowledge and science often agreed on pattern, but were more likely to disagree on why the pattern existed (Moller *et al.*, 2009).

In practice indigenous and scientific knowledge are not always considered equally and opinions vary. On one hand some argue indigenous and scientific knowledge cannot and should not be integrated (e.g. Stephenson and Moller, 2009;). There is evidence to suggest that science often receives a superior status to indigenous knowledge (e.g. Jacobson and Stephen, 2009; Williams, 2009) whereas Berkes (2012) argues that indigenous knowledge should hold a higher status. On another level, Agralwal (2009) explores the qualifiers 'indigenous' and 'scientific' questioning the need for contrast between them whilst Berkes (2009) suggests the debate could be more usefully reframed as a partnership and dialogue. Indigenous knowledge is often perceived as anecdotal and unproven (Lyver *et al*, 2009) and rarely recognised as adaptive and dynamic assets for building diverse trajectories that reflect local needs and aspirations (Robson *et al.*, 2009). Indigenous knowledge is usually diachronic, based on observations at a few places over a long time period (Lyver *et al.*, 2009), and indigenous knowledge and perspectives do not exist as one discrete entity. Indigenous perspectives may vary between hāpu (subtribe), and can be regionally diverse. Conversely, synchronic scientific experiments can have small sample sizes, short time frames, and poor replication when resources are limited, weakening their inferential power (Rafaelli and Moller, 2000 cited in Lyver *et al.*, 2009). Thus, each system will undoubtedly be better for certain tasks, but neither is intrinsically superior to the other (Lyver *et al.*, 2009).

Better integration of scientific and cultural perspectives is strongly emphasised in the literature and several common messages are reiterated. Many authors warn against using scientific method to assess traditional ecological knowledge or guide cross-cultural research (e.g. Chambers, 2009; Jacobson and Stephens, 2009). Themes of equity, justice and the need to genuinely embrace, respect, and learn from one another and challenge previous assertions about applications of knowledge are recommended for better cross-cultural collaboration (e.g. Lyver *et al.*, 2009; Allen *et al.*, 2009; Berkes *et al.*, 2009; Robson *et al.*, 2009; Moller *et al*., 2009; Jacobson and Stephens, 2009). In addition, the importance of relationships, on-going involvement, and alignment with community goals is stressed (Allen *et al.*, 2009).

2.4.2 Māori perspectives on freshwater management

The indigenous perspective of Māori in New Zealand is encapsulated in the term Mātauranga Māori. Broadly, Mātauranga Māori is the knowledge, comprehension, or understanding of everything tangible or intangible that exists across the universe from a Māori viewpoint. It incorporates te reo (Māori language), taonga tuku iho (treasure handed down), mātauranga (traditional environmental knowledge) and knowledge of cultural practices such as rongoa (healing and medicines) and mahinga kai (hunting, fishing, and cultivation of food) (Harmsworth, 2002). The popularity of this term has increased in recent years but the definition and its application varies widely (see Royal, 2004 for examples). Interestingly, it was not a term familiar to pre-European Māori (Royal, 2004). In traditional Māori culture, certain individuals were selected and trained to transmit vital knowledge (Holland *et al.,* 2011). Whilst some information could be freely shared such as details of landmarks and topography, other knowledge like the location food gathering places was considered tapu (sacred). Accurate transmission is essential in oral culture, as understanding of traditional resource management strategies ultimately equated to survival (Wehi *et al.*, 2009). However, there is not one worldview shared by all Māori (Anon., 2010). The nature of Mātauranga Māori means it is often specific to iwi or hapū (Harmsworth, 2002). In addition Mātauranga Māori is a living concept, continually changing in response to new experiences, technologies, language, and worldviews (Royal, 2004).

Māori have a unique relationship with the environment (Harmsworth *et al.,* 2011). According to the traditional Māori worldview, the universe has a natural order, fabricated by living and non-living, with the central belief that all parts of the universe are interconnected through the domains of Atua. As such, small shifts in the mauri (life-force) of any part of the environment will cause shifts in the mauri of immediately related components, which could eventually affect the whole system (Harmsworth *et al.,* 2011). Williams (2009) describes the Māori approach to environmental management using a formula, Knowledge base + Sound practice + Sound regulation + Ritual control = Group morality. But it is only when there is faith in the knowledge base that the community will adhere to it. In this context, resource use is guided by spiritual qualities based on an elaborate system of ritenga/kawa (customary rules), with goals to regulate and sustain the wellbeing of people, communities and natural resources (Harmsworth *et al.,* 2011). This approach is reflected in five key Māori values; mauri, mahinga kai, kaitiakitanga, wai taonga, and ki uta ki tai (Table 2.1) (Townsend *et al.,* 2004; Harmsworth *et al.,* 2011).

Table 2.1: Explanation of five key Māori values: mauri, mahinga kai, kaitiakitanga, wai taonga, and ki uta ki tai

Value	Explanation
Mauri:	Māori believe that forests and water and all life supported by them possess a mauri or life force. A key objective of resource management is protecting the mauri of a resource. (Townsend *et al*., 2004)
Mahinga kai	Mahinga kai incorporates the ability to gain access (physical and legal) to a resource, the site where gathering occurs, the activity of gathering, the fitness of the resource for cultural use, and the spiritual and mental well-being associated with being able to access the resource (Townsend *et al*., 2004) as well as knowledge transfer during mahinga kai activities (ORC, 2005).
Kaitiakitanga	It is the responsibility of an iwi and its members to be custodians, protectors, and guardians of their taonga (treasures), the spiritual and physical waterways within their rohe and other resources (Townsend *et al*., 2004).
Wai Taonga	Wai taonga refers to waters that are of cultural significance to whānau, hapu or iwi (Townsend *et al.*, 2004).
Ki uta ki tai	The Māori approach to resource management is described by Ki uta ki tai, a holistic, mountains to the sea approach. For Māori any resource, such as a river is not viewed as an independent entity but rather as a connected component of the wider environment (Thompson, 2011).

2.4.3 Tools for the assessment of cultural stream health

The definition and setting cultural flows has been used internationally in cross cultural resource management applications. The idea of a cultural flow is that the indigenous people themselves decide on where and when water should be delivered based on traditional knowledge and their aspirations for their people (Morgan, 2006). Cultural flows are water entitlements that are legally and beneficially owned by indigenous people and are of sufficient and adequate quantity and quality to maintain the spiritual, cultural, environmental, social, and healthy livelihoods of the people. A cultural flow was set in the Murray Darling basin where members of the indigenous community engaged in negotiations and discussions with the Australian governments through the Murray Darling initiative (MLDRIN, 2008).

In New Zealand cultural tools have been developed in response to a lack of tools available to meet resource management objectives and to enhance the recognition of Māori values in management. Based on the five significant cultural values identified in Table 2.1 and the need for a representative measure of Māori values in environmental monitoring and resource management, the cultural health index (CHI) was developed in the late 1990s (MfE, 2003). A CHI assessment incorporates Māori knowledge, cultural values, and customary practices in the evaluation of stream health (Townsend *et al.,* 2004). Following this cultural opportunities, mapping, assessment, and responses (COMAR) was introduced by Tipa and Nelson (2008). A COMAR assessment identifies and assesses opportunities for Māori to engage in a range of cultural experiences under different environmental conditions. Both type of assessment are intended to be conducted independently by a cross section of iwi or runanga/whānau members. Scores are collated and an overall index of stream health is calculated for each site (Tipa and Teirney, 2006). Cultural indicators provide a holistic assessment of river health and utilise collective skills but need consistency in method. The goals of cultural health assessments encompass the health of waterways and health of the community (Harmsworth *et al*., 2011).

Studies by Townsend *et al.* (2004) and Harmsworth *et al.* (2011) compared the results of scientific and cultural monitoring in the Taieri and Kakaunui catchments and the Motueka and Riwaka catchments respectively. Both found correlations between cultural indicators and scientific equivalents, for example, the macroinvertibrate community index (MCI), the Stream Health Monitoring Assessment Kit (SHMAK) and land development. Both studies concluded the CHI performed comparatively in providing a measure of stream health.

Scientific and cultural monitoring were complimentary and contributed to shared learning, resulting in a wealth of knowledge and understanding of overall river health (Harmsworth *et al.*, 2011).

2.5 Land use changes in the Waikouaiti catchment

Land clearance in the Waikouaiti catchment followed a pattern typical of many catchments in New Zealand. Native forest was cleared by fire for Moa hunting followed by European settlers clearing tussock and regenerated bush for agriculture (Campbell, 1977). Located in East Otago, the Waikouaiti catchment falls under the jurisdiction of the ORC. The river and surrounding landscape are held in high esteem by Kai Tahu ki Otago who also have a vested interest in sound management of the catchments resources. It is valued as a traditional route into the Maniototo and Strath Taieri, as well as being a part of the behaviours of mahinga kai resource gathering, and hapū and whānau bonding (ORC, 2005). The phrase "Waikouaiti te awa waiora o o tātou tini tīpuna, rere tonu, rere tonu" is used to describe the river and translates to "The Waikouaiti is a river that embodies our health and vitality passed on by our many ancestors, may it continue to flow strong" (Prebble *et al.*, 2004 p.14). The history of the catchment, its current water resource situation, and a shared interest by council, the local community, and Māori make it an ideal case study to investigate the integration of cultural values in the assessment of land use change impacts on hydrology.

The Waikouaiti catchment has undergone extensive change since human settlement. Occupation in the area was initiated by Māori approximately 500 years ago, which had little impact on the landscape due to the migratory movement of the local hapū between different pa in the Otago region (ORC, 2005). However, there is evidence to suggest Māori cleared native bush, although the location or extent of this is unknown (Mark *et al.,* 2003). European settlers were first attracted to the catchment for whaling and several whaling stations lined the coast in the early 1800s. In 1838 land was cleared in Waikouaiti for the first organised settlement on the East Coast of the South Island (Campbell, 1977). During the late 1800s to mid-1900s there were brief periods of gold rush and finally land was cleared from the 1850s for agriculture and the eventual growth of a small township (Campbell, 1977).

Unfortunately, little formal documentation of the original vegetation composition exists but several historical accounts include observations of the landscape. Recollections from early settlers describe a wilderness of bush, swamp, tussock, flax, tutu, fern, matagouri, grass, reeds of raupo, and toetoe (Buchan, 1927; Malloch, 1940; Campbell, 1977) although retrospective observations could have been biased by nostalgia and were not grounded by scientific method (Mark *et al.*,2003). It is likely the original catchment consisted of mainly coastal broadleaf forest (Campbell 1977; Mark *et al*., 2003). Today, sparse amounts of indigenous forest remains and many areas have regenerated to kanuka or manuka woodlands. Tussocks were depleted due to aerial over-sowing of the drier and lower country resulting in rapid replacement by pasture species. A combination of fire and grazing since settlement has weakened the tussock grassland cover, inducing invasion by manuka scrublands (Mason, 1989). In the period between 1865 and 1948 extensive 'paddocking' for gold in the South Branch took place with some underground mining on the valley side. However, this was concealed by subsequent reversion to bush. These changes are likely to have substantially altered the water balance of the catchment, as well as modifying the natural loads of sediment and nutrients delivered to the coastal margin.

2.5.1 Waikouaiti catchment management

The Waikouaiti catchment is under the jurisdiction of the ORC and national obligations under the RMA (1991) and NPS (2011) described in Section 2.5.1 are implemented through local plans. The Regional Plan: Water for Otago (the Water Plan) "seeks to enable people and communities to provide for their social, economic and cultural well being [*sic*] through the appropriate use, development, and protection of lakes and rivers and their margins, and other water resources" (ORC, 2012a, p36). It outlines the issues associated with use, development, and protection (ORC, 2012a) and describes the objectives, policies, rules, and other methods to address them. The fourth chapter entitled 'Kai Tahu Ki Otago freshwater perspective' describes water management objectives, expectations, and issues of Kai Tahu. The chapter is informed and complimented by the Kai Tahu Ki Otago natural resources management plan (KTKO plan) (ORC, 2005) which describes Kia Tahu management objectives for all resources including freshwater.

The Water Plan identifies several important cultural values but does not specify direct actions for monitoring and maintaining cultural values. For example, a responsibility to exercise kaitiakitanga is a core component of resource management for Kai Tahu. The Water Plan states that the effectiveness of opportunities to exercise kaitiakitanga will be measured against environmental outcomes. Environmental outcomes include the continued health and wellbeing of water resources and cultural usage of these resources. However, Kai Tahu believes the traditional relationship of Kai Tahu and their associated values with the water resource has been overlooked in the monitoring of the region's water resources (ORC, 2005). Although the ORC monitor various variables relating to water quantity and quality in rivers across the region there is no cultural monitoring/assessment programme. The KTKO plan identifies surveys and data collection systems as suitable methodology to provide a comprehensive information base on water resources and threats to the life sustaining capacity of water. The KTKO plan stresses the need to establish a management regime that identifies water quality and quantity standards consistent with Kai Tahu cultural and spiritual values. Cultural stream health assessments such as COMAR or the CHI could be adopted to meet the objectives of both the Water Plan and the KTKO plan as the values assessed in cultural surveys match closely with those identified in the plans.

The Water Plan also details several resource management concerns for Kai Tahu. These include concerns about the impact of land use on adjacent water, especially in lower catchment areas. In some catchments this has already adversely affected Kai Tahu cultural and spiritual beliefs, values, and use. The concern stems from Kai Tahu's ki uta ki tai (mountains to the sea) approach to resource management. Ki uta ki tai focuses on land use throughout the whole catchment because mahinga kai species are migratory and occupy different areas of a catchment in different stages of their lifecycle and similarly Kai Tahu have different uses for different areas of the catchments throughout the year. Kai Tahu is afraid an emphasis has been placed on the use and development of land without sufficient consideration being given to the resulting impact on the water resource, thus compromising traditional use options and relationships with water resources. Without the necessary conversations and careful planning, future development in the Waikouaiti could result in similar anxieties.

In addition to land use concerns voiced by Kai Tahu, low flows have been identified as a management concern in the Waikouaiti catchment. This is an issue that crosses cultural and scientific boundaries, prompting integration. Low flows have implications for human use (e.g. community supply, irrigation, and stock water), aquatic species, water quality, and cultural values. From each perspective extended periods of low flow have negative implications, however, the degree of impact, the point at which low flow is considered problematic, and the appropriate solution differs between parties. Thus, low flow management could be both a binding issue and present opportunities for shared learning and better environmental outcomes.

2.5.2 Waikouaiti summary and challenges

Scientific and indigenous knowledge systems present contrasting approaches to resource investigation and management. Whilst hydrological modelling is widely recognised as a useful and reliable tool for assessing hydrological responses to land use change, cultural stream health assessments shows promise as an indigenous method to measure impacts from a Māori perspective but are yet to be widely utilised. These contrasting methodologies contribute valuable information about resource use, protection, and management. However, to date no published studies have investigated the integration of cultural values in the assessment of land use change impacts on hydrology. Cultural values, until recently were often ignored and it remains unclear if cultural values and scientific measures are compatible or complementary. The concept of a report that considers both indigenous and non-indigenous views equally to be used for decision making is rare globally (Anon., 2010). International literature presents a call for better integration of science and indigenous knowledge in resource management. Integration capitalises on the breadth of knowledge from both perspectives and can result in better environmental outcomes. The Waikouaiti catchment provides a setting to investigate and integrate these two perspectives.

There are strong practical and theoretical factors motivating an integrated approach to freshwater management in the Waikouaiti catchment. However, the real challenge lies in the practical implementation of embedding cultural values. In traditional resource management, quantifiable data is valued for its understandably and applicability in decision making. However, quantifying cultural values is only part of the picture; only after careful analysis can data become useful in real world applications. Unfortunately many resource managers are inherently embedded in their own cultural backgrounds (Ellis, 2005). Generally resource management training or qualifications focus on the collection, analysis, and interpretation of scientific data whilst cultural considerations are not taught to the same level. Therefore, whilst a resource manager may be quite comfortable in processing raw scientific data and translating it into information useful for decision making they may have difficulty when presented with a set of cultural scores or indices relating to a particular river. Indeed any data is of little use without some background of how the data was collected, what it represents, how it should be processed and finally interpreted.

1.1 Research Aims and Objectives

The aim of this research is to integrate cultural values in the assessment of land use change impacts on hydrology in the Waikouaiti catchment. This research contributes to existing debate on the impacts of land use change on hydrological processes and water quality and explores an area where less research has been conducted; integration of cultural and scientific data. The findings will provide valuable information for Māori, local authorities and the community to assist in the management of freshwater resources in the Waikouaiti catchment.

The objectives of this research are:

1. To develop a representative hydrological model of the Waikouaiti catchment using a semi-distributed HRU hydrological model, SWAT.
2. To model water quality in the Waikouaiti catchment using the CLUES model.
3. To apply a pre-human land use scenario and other land use combination scenarios to the calibrated and validated Waikouaiti catchment models in order to assess the impacts of land use change on flow regime and water quality.
4. To measure and quantify cultural values and relationships with the Waikouaiti River water resource using cultural stream health assessments.
5. To analyse the relationship between, and explore how, cultural stream health measures, flow variables, and water quality can be integrated in freshwater management.

Chapter 3: Field Area and Methods

3.1 Research Strategy

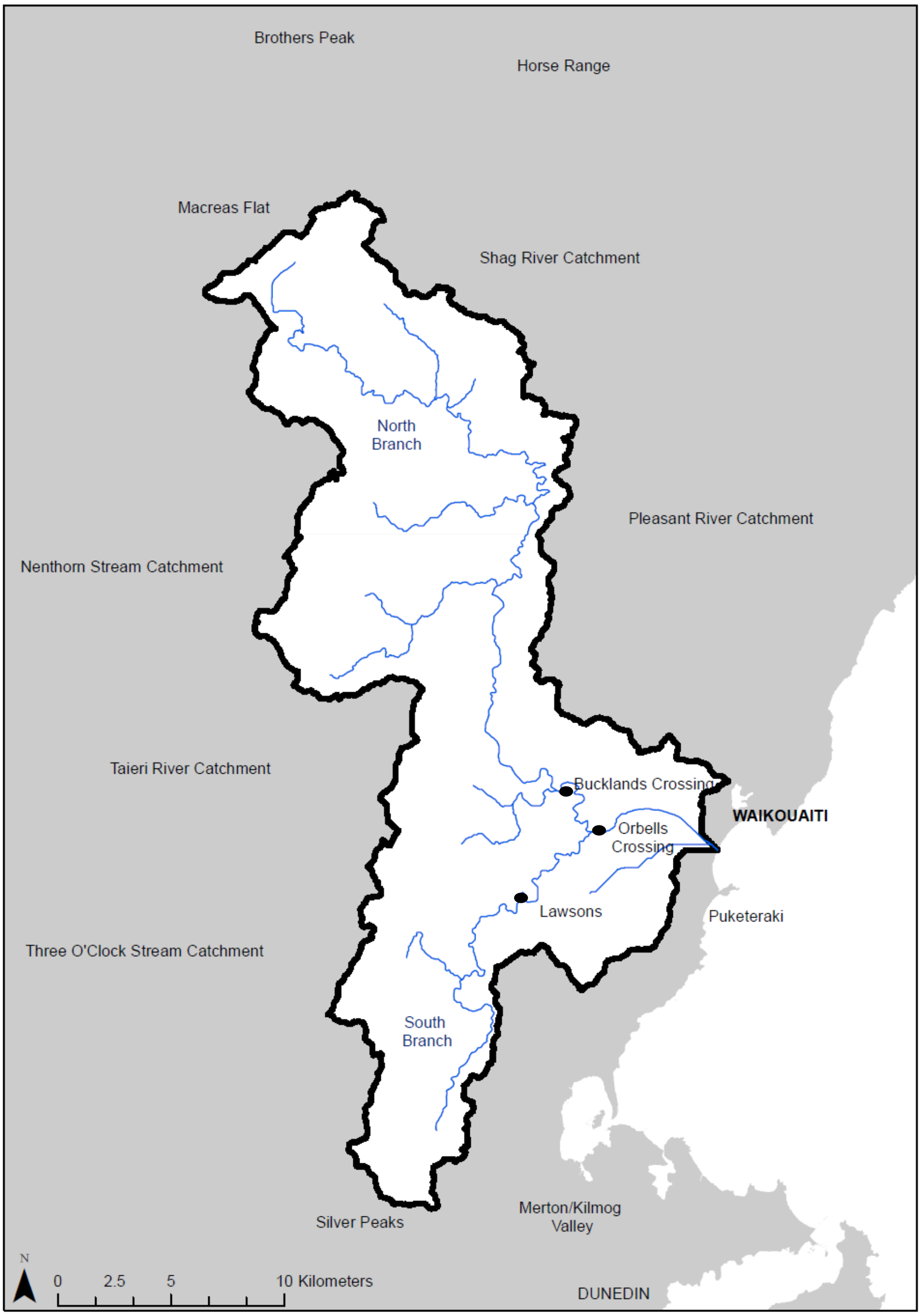
Integrating cultural and scientific knowledge in resource management applications is often hindered by the fact that cultural information is typically qualitative and scientific information is generally quantitative. Thus, combining scientific knowledge and indigenous knowledge is difficult. In the context of freshwater resources, the literature review in Chapter 2 demonstrated the popularity and utility of hydrological modelling in land use impact assessments on both water quality and quantity. This approach typifies conventional scientific method whereby outputs are quantifiable, a characteristic considered important in decision making. The development of cultural stream health assessments demonstrates potential to quantify cultural values. Thus, the CHI and a cultural flow assessment were used to measure Māori associations with waterways. The strategy used in this research is to develop hydrological models that assess the impacts land use change has on water quantity and quality in the Waikouaiti Catchment, and embed a Māori perspective by using cultural assessments. The first part of the chapter details the study location followed by a description of the hydrological models; SWAT (Section 3.3.1, 2) and CLUES (Section 3.3.4) and the calibration/validation of SWAT in Section 3.3.3. The collection of the cultural health data is explained in section 3.5.

3.2 The Waikouaiti Catchment

The Waikouaiti River is located north of Dunedin between 45.42 and 45.71 ^{o}S and 170.447 and 170.493 ^{o} E. The catchment area totals 425 km^2 and the river flows in two distinct branches; the North Branch and the South Branch (Figure 3.1). The two branches converge approximately 8 km inland from the Pacific Ocean outlet (ORC, 2008) and each is supplied by several small tributaries (Campbell, 1977). The North Branch covers approximately 283 km^2 whilst the South Branch is a smaller 86 km^2 (ORC, 2008). A small estuary at the coast causes the river to be tidal for approximately 5 km upstream (ORC, 2008).

The catchment boundary is defined by the inland Horse Range and the Brothers Peak in the south. The catchment extends around the eastern flank of the Strath Taieri to the Silver Peaks then down to the Kilmog/Merton valley, reaching the coast at Puketeraki (Figure 3.1) (ORC, 2005). The absence of neighbouring mountain ranges between the Waikouaiti catchment and the adjacent catchments make boundaries indistinct. The bordering catchments are the

Nenthorn Stream Catchment in the west, the Taieri River, the Three O'Clock Stream, the Pleasant River, and the Shag River catchments. The North Branch headwaters are shared with the Shag and Pleasant Rivers in the north and east (ORC, 2011).



z

Figure 3.1: Location of the Waikouaiti catchment, Otago, New Zealand. The map shows the two main branches of the Waikouaiti River (the North Branch and the South Branch), neighbouring catchments and location of hydrological gauging stations (Bucklands Crossing, Orbells Crossing, and Lawsons).

3.2.1 Relief

The catchment relief ranges from flat and undulating (0-3°) to steep (26-35°). Most of the catchment is moderately steep (21-25°) (Landcare Research, 2010). The ORC (2008) classify four terrain zones; 1) the western plateau, 2) a central area of dissected hills and steeplands, 3) coastal downs and 4) terraces, river flats and sand dunes which are similarly defined by Campbell (1977) (Figure 3.2). The fairly flat western plateau has high elevation (500-700 masl) in the headwaters of the North Branch, near Macraes Flat, and stretches along the western edge of the catchment. Inland from the confluence, the central area of the catchment is divided by tight gullies and a dissected landscape. The coastal hills and downs are rolling and less dissected due to differences in underlying geology. At the downstream end of the confluence the low lying terrain is dominated by a river plain and estuarine system with sand dunes and river terraces (ORC, 2008).

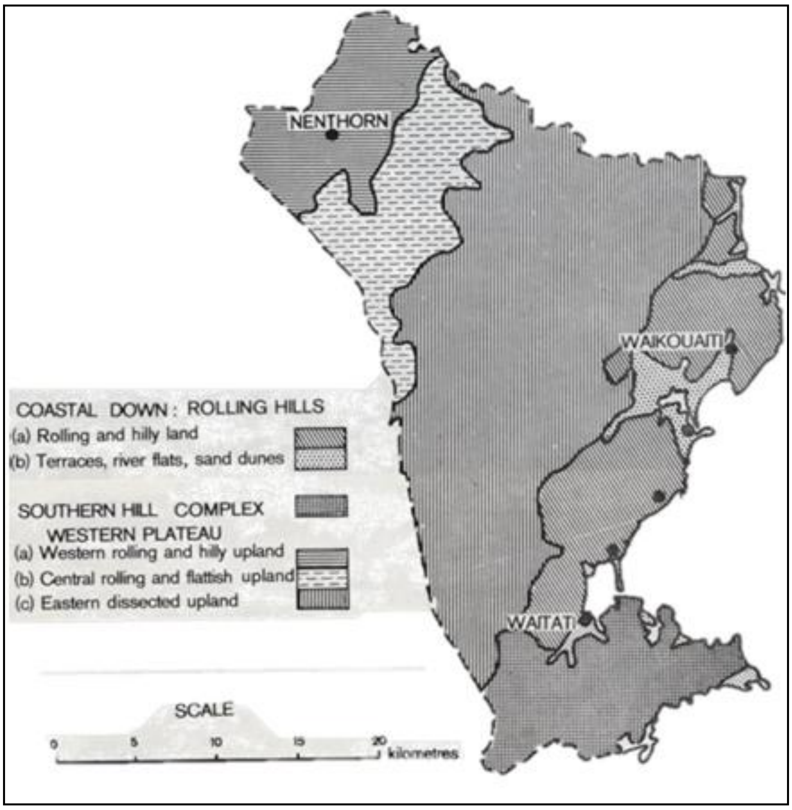


Figure 3.2: Map of Waikouaiti catchment terrain showing rolling and hilly land, terraces, river flats, and sand dunes, western rolling and hilly upland, central rolling and flattish upland and eastern dissected upland. Source: Campbell, 1977.

3.2.2 Geology and Soil properties

Catchment geology is varied. The inland rock layers are dominated by schistose rocks in the torlesse supergroup; quartzofeldspatic schist with minor greenschist and metachertz. There are small patches of terrestrial conglomerate and bereccia (Kyeburn formation) and alkaline volcanic rocks. In contrast to the inland area, the underlying geology of the coastal downs and flood plains includes more recent sedimentary beds; schistose, sandstone, limestone and carbonaceous mudstone as well as some volcanic deposits; alkali basalt and bassanite occurring as lava flows, agglomerate, tuff, and shallow intrusions (Park, 1904; Forsyth, 2001).

Soil character is fairly uniform across the catchment, comprising mainly of brown soils (Figure 3.3). The South Branch is characterised by orthic-brown soils, whilst the North Branch mainly consists of firm brown soils. Particles are typically 'silty' with very few rocks in the topsoil and no rock outcrops. Soil drainage is classified as 'moderate well' with potential rooting depths of 0.45-0.59 m and deeper potential rooting depths in the north and near the coast. No permeable layer is observed in the South Branch and parts of the North Branch, whereas in other parts of the north the depth to the slowly permeable layer is between 0.45-0.59 m. Closer to the coast the depth to the permeable layer ranges between 0.0 and 0.89 m. Movement through the saturated soil (permeability) is moderate in the south and moderate to slow in the north. Profile available water reflects the soil's capacity to hold water assessed for the soil profile to a depth of 0.9 m and is mostly 'moderately high' (90-149 mm), whilst profile readily available water, also assessed to a depth of 0.9 m is generally 'moderate' across the catchment (50-74 mm) (Landcare Research, 2011).

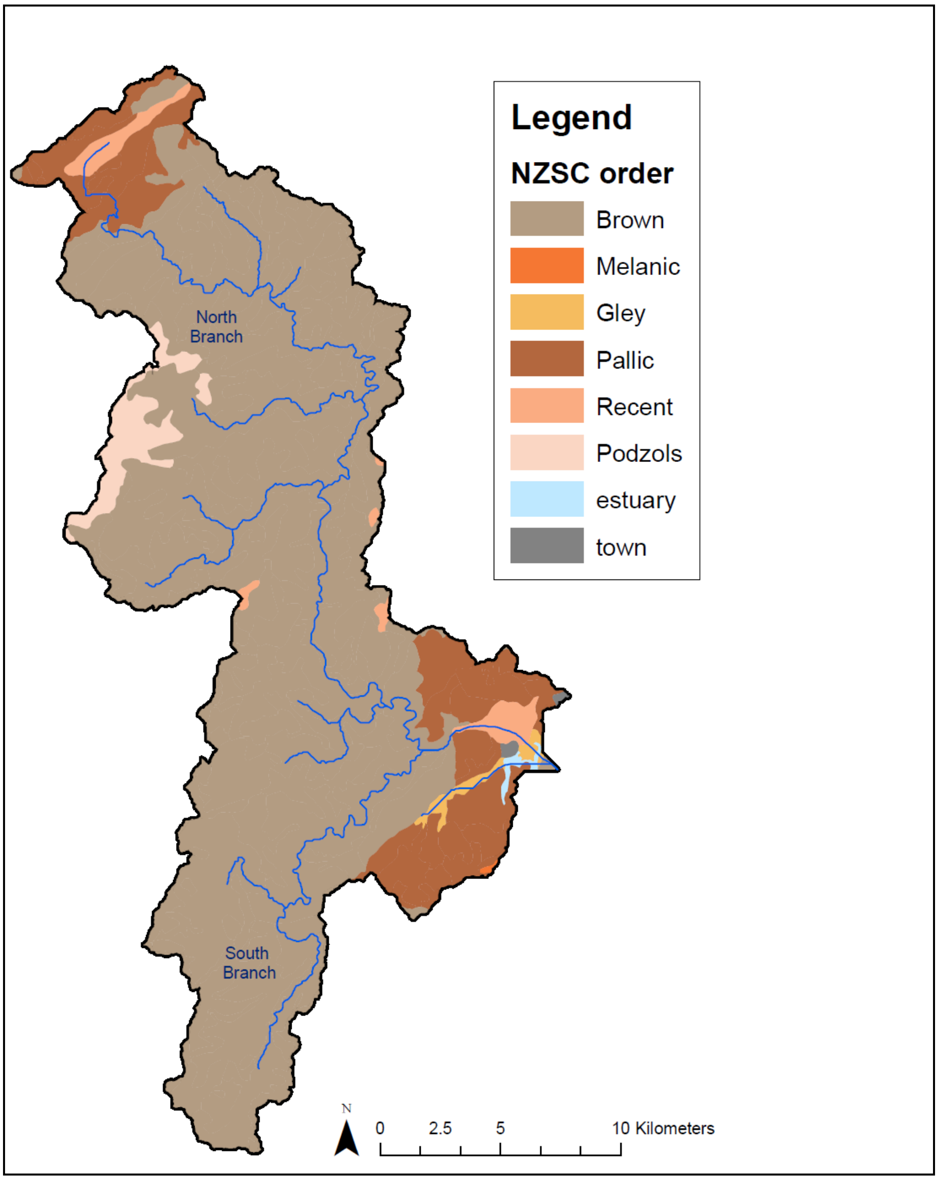


Figure 3.3: Waikouaiti catchment map showing the distribution of soil orders. Data source: Landcare Research, 2011). The dominant soil orders are Brown (B), Pallic (P), and Podzols (Z).

3.2.3 Land cover

Low-producing grassland typifies catchment land use (~94% cover) and includes low fertility grassland on hill country and tussock grasslands. The remaining catchment is a mixture of natural forest, high producing grassland, and some exotic forestry (Figure 3.4, Table 3.1). Native kanuka/manuka and introduced scrub grow in the gullies, whilst natural forest consists of native manuka/kanuka remnants and broadleaf indigenous hardwood forest/scrub in the headwaters of the South Branch near the Silver Peaks. Sheep and beef farming make up the primary agricultural activity whilst there is some dairy activity in the lower catchment, assisted by irrigation downstream of the confluence (ORC, 2008).

In contrast to the current landscape, Campbell (1977) suggests the original catchment was largely coastal broadleaf forest. Evidence of remnant forest in the current North Branch supports this. The few remaining stands of podocarp-broad leafed forest are characterised by kahikatea and totara with little matai and rare stands of rimu and miro, and ground cover contains shrubs typical of relatively dry eastern forests (Mark *et al.*, 2003).

Table 3.2: Land cover in the Waikouaiti catchment by area (hectares) and percentage, in descending order (MfE, 2010).

Land cover	**Area (hectares)**	**Percentage (%)**
Grassland-low producing	350,998.50	93.71
Natural forest	14,002.16	3.74
Grassland- high producing	4,701.55	1.26
Planted forest pre 1990	1,780.99	0.48
Grassland with woody biomass	1,106.43	0.30
Planted forest post 1989	781.29	0.21
Other	622.18	0.17
Settlement	186.95	0.05
Wetland- open water	161.29	0.04
Wetland- vegetated non forest	119.36	0.03
Cropland annual	70.82	0.02
Cropland perennial	7.77	<0.01
Total Area (ha)	**374,539.26**	

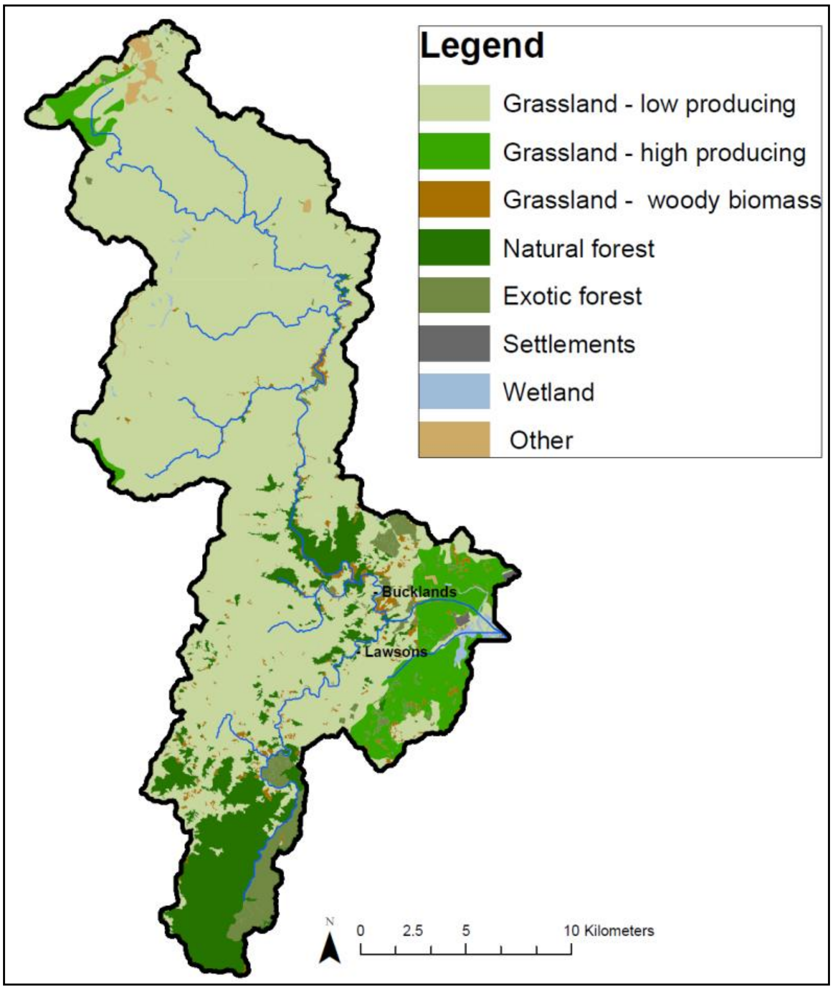


Figure 3.4: Waikouaiti catchment map showing the distribution of current (2007) land use. Data source: the MfE, 2010.

3.2.4 Climate

The catchment exhibits two distinct climatic zones. The south and south-western zone typically has moderate temperatures and a higher annual rainfall; mean annual rainfall is 982 mm. Conversely, the north and northwest extents experience greater temperature extremes, lower annual rainfall and larger temperature moisture deficits; there are twice as many days with temperatures >25° (a median of 8 days per annum) and mean annual rainfall is 592 mm (ORC, 2010). Frosts are not unusual in most parts of the catchment and snowfall or hail is a common annual occurrence. The coastal areas generally have fewer sunshine hours than further inland. Prevailing winds are from the west and south-west in inland areas and north-east and south-west on the coast (Campbell, 1977).

The catchment shows large variation in maximum and minimum monthly precipitation totals. Although average monthly rainfall is generally consistent throughout the year, there is wide variation between the maximum and minimum monthly totals recorded over time for any particular month (Figure 3.5) (ORC, 2010). Some years have monthly totals close to 0 mm and others over 200 mm. Rainfall displays a north-south gradient. The northern headwaters have an average rainfall of 50 mm month^{-1} with higher totals in December and January attributed to thunderstorms. In contrast, average monthly totals in the southern part of the catchment are closer to 80 mm month^{-1}.

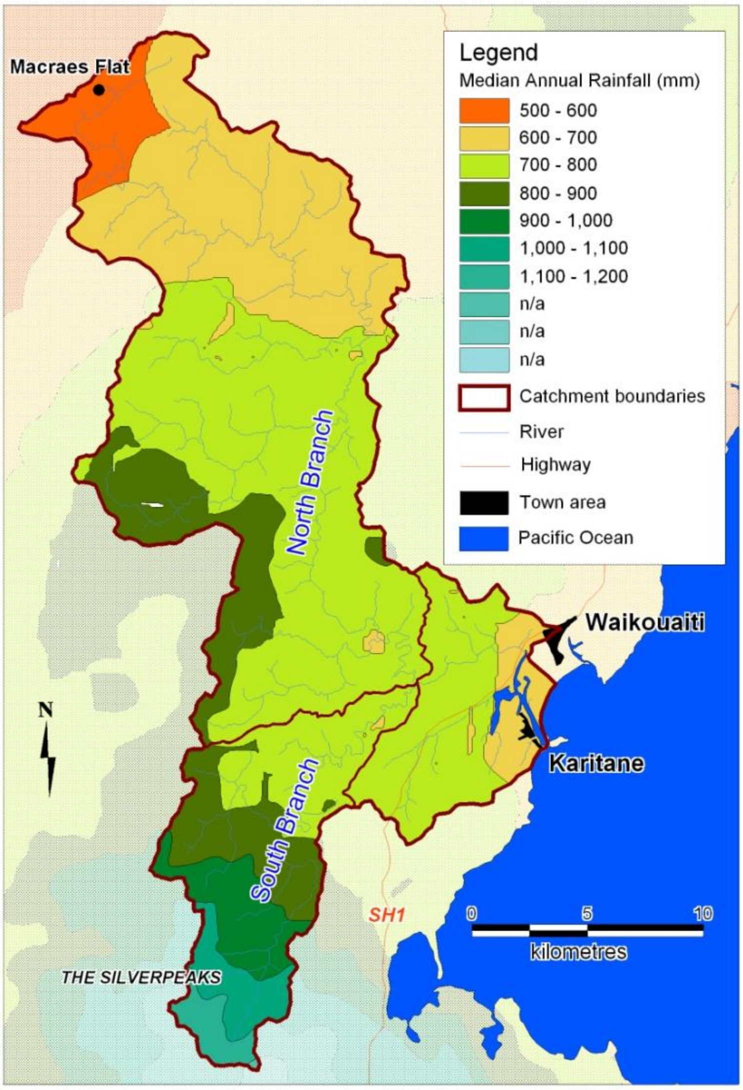


Figure 3.5: Modelled median annual rainfall in the Waikouaiti catchment (ORC, 2010).

3.2.5 Hydrology

Despite draining an area less than a third of the North Branch size, the South Branch has similar flow to the North under normal conditions. In times of low flow the South Branch supplies most of the flow to the main stem. This is caused by higher, more dependable rainfall in the South Branch headwaters in the Silverpeaks. Monthly flow levels are highly variable, especially in the North Branch. The lowest average flows occur at the end of summer/early autumn (the median February flow between 1991 and 1999 was 0.30 m^3s^{-1}) with the highest average flows in winter (the median July flow between 1991 and 1999 was 2.36 m^3s^{-1}). This variation is attributed to changing evapotranspiration as rainfall is relatively consistent during the year. During low flow, the South Branch provides most of the water to the main stem of the river (ORC, 2010).

Of most concern for management in the Waikouaiti catchment is that of low flows. The lowest flow recorded in the river was 0.05 m^3s^{-1} in the summer of 2003/2004 and anecdotal evidence suggests flow ceased in the North Branch during this period. On average instantaneous flow drops below 0.10 m^3s^{-1} once every five years. The 7 day mean annual low flow (MALF) is 0.258 m^3s^{-1} (ORC, 2011). At the other extreme, flooding is infrequent and typically caused by storms with different characteristics to the normal weather patterns (Pearson and Henderson, 2004). A string of easterly quarter winds blowing moist air from the Pacific Ocean generates storms, typically lasting less than 48 hours. The largest flood in recent history was in June 2013, peaking at 425 m^3s^{-1}. The previous maximum flood in terms of flooding extent was observed in June 1980. Other large floods occurred in 1986, 1987, 1993, 1994, and 2006, all of which exceeded 70 m^3s^{-1} in the North Branch (ORC, 2008).

The existing total primary allocation in the Waikouaiti River is 0.129 m^3s^{-1}. Three consents downstream of the confluence supply irrigation, stock drinking water and town supply. In the North Branch there is a small rural supply take and a few indirect takes for mining activities at Macreas Flat, which are considered insignificant (ORC, 2008). Consents are subject to minimum flow thresholds of 0.150 $m^3 s^{-1}$ in November to April and 0.350 $m^3 s^{-1}$ in May to October. The community water use is not restricted to minimum flow requirements according to schedule 1B in the Water plan (ORC, 2012a).

3.2.6 Water Quality

In the estuary, build-up of toxic hydrogen sulphide during long periods without flushing flows is a potential threat to the overall river health (ORC, 2011). Water quality based on measurements taken at Orbells, downstream of the confluence and as rated by the water quality index (WQI), is 'very good' (ORC, 2012b). The WQI considers thresholds for median values of nitrite-nitrate nitrogen (NNN), ammoniacal nitrogen (NH_4), dissolved reactive phosphorus (DRP), *Escherichia coli* (*E. coli*), turbidity, and dissolved oxygen (DO). Guideline thresholds for DRP were exceeded on 6.8% of monitoring days, 11.8% for *E.coli* and 25.8% for DO (ORC, 2012b). Heavy rainfall often causes *E.coli* bacteria levels to exceed contact recreation guidelines in the catchment, a trend typical in many agriculture dominated catchments (ORC, 2008). In addition, water temperature often exceeded 20 °C, a consequence of poorly shaded river reaches and low summer flows, which causes stress for aquatic species (ORC, 2008). Non-adjusted flow trend analysis revealed a meaningful increase in DRP and total P for the period 2001-2011 and turbidity for 2006-2011. Mann-Whitney tests showed a statistically significant improvement in NH_4 concentrations over this period (ORC, 2012b).

3.3 Hydrological Modelling

3.3.1 SWAT model description

SWAT 2009 (Arnold *et al.*, 2012) was used because it is suitable for assessing the relative impacts of land use change on hydrologic response and has been successful in other applications as a method to increase understanding of watershed responses to land use change. It is a deterministic model so each successive model that uses the same inputs will produce the same outputs. This allows the effect of a single variable e.g. land use/cover change on hydrologic responses to be isolated (Barker and Miller, 2013). The physically based, basin scale, continuous time model operates on a daily time step. SWAT was developed as a management tool to evaluate the impact of different management practices on water, sediment and agricultural chemical yields in ungauged catchments (Arnold *et al.*, 2012).

In SWAT runoff is estimated using physically-based algorithms. Watersheds are divided into sub-watersheds, defined by outlets, which are further distributed into hydrological response units (HRUs). A HRU is a homogenous block of land use and soil properties. SWAT uses a HRU as a unit to model the water balance and quantifies the relative impact of vegetation management, soil and climate change in each (Arnold *et al*., 1998). The hydrological processes modelled in SWAT are surface runoff, soil and root zone infiltration, evapotranspiration, soil, and snow evaporation, and base flow (Arnold *et al.*, 1998). Watershed hydrology is divided into two phases; land and water. The land phase controls the amount of water, sediment, nutrient, and pesticide loadings into the main channel of each sub basin and is governed by the water balance equation (equation 3.1). Complementing this, the water phase defines the movement of water, sediments, and nutrients through the channel network to the watershed outlet (Neitsch *et al.*, 2011). Simulation of the hydrologic cycle in SWAT is based on the water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \quad (3.1)$$

where SW_t is the final soil water content, SW_o is initial soil water content, t is time (days), R_{day} is the amount of surface runoff, Q_{surf} is the amount of surface runoff, E_a is the amount of evapotranspiration, w_{seep} is the amount of water entering the vadose zone from the soil profile and Q_{gw} is return flow (Neitsch *et al.*, 2011).

The algorithms used in SWAT are based on common methods and widely accepted hydrological science. A brief description is provided here and more comprehensive detail of the SWAT method and theory can be found in the SWAT documentation (Winchell *et al.,* 2010; Neitsch *et al.,* 2011; Arnold *et al.,* 2012). Runoff is calculated using the Soil Conservation Service Curve Number (SCS CN) method (e.g. Bondelid *et al.,* 1982). Landuse classification includes choice of 102 land types stored in the SWAT database, each which has a CN2 value (curve number for antecedent soil moisture II) assigned to it. Soil interflow is calculated using the kinematic storage model (Sloan and Moore, 1984) which accounts for soil hydraulic conductivity, topographical slope and the temporal and spatial change of soil moisture. Crop yield is determined using a simplification of the EPIC model which utilises the degree day approach (e.g. Williams, 1990). Potential biomass is estimated using Monteith’s approach, coupled with water temperature and nutrient stress adjustments. Leaf area index is simulated as a function of heat units and varies between plant-specific potential minimum and maximum values. Potential evapotranspiration (PET) can be estimated using one of three methods: Priestley-Taylor (Priestley and Taylor 1972), Penman-Monteith (Monteith, 1965), Hargreaves (Hargreaves and Allen, 2003) or by user input data. Canopy evaporation is modelled as a function of potential evapotranspiration, maximum interception capacity and the ratio of the actual potential maximum leaf area index. Plant water uptake from the soil is simulated as a function of potential evapotranspiration, leaf area index and rooting depth, and is limited by soil water content (Neitsch *et al.,* 2011).

3.3.2 SWAT data preparation

Flow was modelled at two locations in the catchment; Bucklands Crossing (hereafter referred to as Bucklands) and Lawsons because these are the only two sites with long term flow records. The Bucklands record is 9 years long (1991-1999) and represents flow in the North Branch capturing a 248.7 km^2 area. The longer Lawsons record (1991-2010) is representative of the southern extent of the catchment (55.2 km^2). The observed flow records were compared to the modelled flow in the calibration and validation stages. Gaps in the Bucklands flow record were filled using a regression with flow at Craig Road in the Shag River, a neighbouring catchment with similar flow characteristics (ORC, 2011). There were four gaps in the data; two short gaps (2 and 7 days) and two longer gaps (70 and 100 days). Linear regression was used to fill the missing data and the R^2 values (0.84 and 0.96) showed a good fit between the Bucklands and Craig Road data.

To build a hydrological model SWAT requires a digital elevation map (DEM), land use and land cover information, soil data, and basic climate data which can be user-defined or SWAT generated. The spatial boundary of the SWAT model was set to match the Waikouaiti catchment boundary. The boundary was delineated from a 15 m resolution DEM (Table 3.2) and the catchment had 16 sub-basins and 101 HRU's. HRU's were defined by landuse/soil/slope coverage thresholds of 5/20/5 %. Land use information was extracted from the land use and carbon analysis system (LUCAS) map which classifies land cover as best known on the 31st December 2007 and the soil order was derived from the New Zealand Fundamental Soil Layer (NZFSL).

Climate data included 24 hr precipitation totals (9am-9am), daily maximum and minimum temperatures, relative humidity, and solar radiation (Table 3.2). Three locations; Stoneburn (VCSN 19860), middle (VCSN 19654) and bottom (VCSN 19442) (Figure 3.6) were chosen to capture the spatial climate variability. The climate data were all sourced from the National Institute of Water and Atmospheric Research (NIWA) Virtual Climate Station Network (VCSN) (Tait *et al.*, 2006; Tait *et al.*, 2012) except for the precipitation data for Stoneburn. Daily precipitation data for Stoneburn was recorded by an automatic weather station (AWS). Gaps in the observed precipitation record at Stoneburn were directly filled with data from the nearest VCSN station. There was a strong correlation between observed Stoneburn records and the nearest VCSN station (R^2= 0.95) thus a direct fill was suitable.

Despite a good network of precipitation gauges in the catchment, most of the records either do not match the period of available flow data or have been collected from manual gauges with a monthly resolution. The VCSN was originally developed for precipitation records to be an input for hydrological models but was extended to include 11 variables. The data is operationally interpolated into a regular grid of points covering all of New Zealand to a resolution of ~5 km. End users and published studies have generally concluded the estimates of daily rainfall are reasonable in elevations less than 500 m but not as reliable in complex mountainous terrain (Tait *et al.*, 2012). For elevations less than 500 m, comparison with regional council records throughout New Zealand not used to calculate the VCSN, the mean absolute error for rain days only (≥ 1 mm) is 2-4 mm. Similarly, a comparison between the VCSN data for Stoneburn (not used to run the model) and the AWS record for Stoneburn (collected by ORC) found a close agreement (R^2= 0.95). Therefore the VCSN data was considered suitable for the SWAT model in the Waikouaiti with elevations mostly less than 500 m. Errors in VCSN data for elevations above 500 m are greater (5-15 mm) (Tait *et al.*, 2012). When additional weather data were used during model calibration the model performance was not improved. Thus, no data from VCNS above 500 m was used.

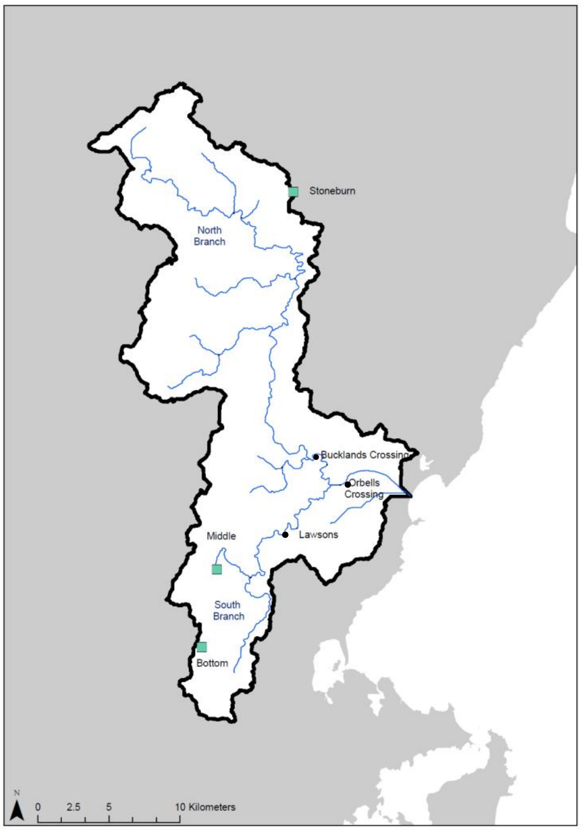


Figure 3.6: Location of weather stations used to run the SWAT model: bottom, middle and Stoneburn.

The Priestley–Taylor model was used to estimate PET because it requires less data (precipitation, maximum and minimum temperature, relative humidity, and solar radiation data) than the more extensive data requirements of the Penman–Monteith method. The Priestley-Taylor method is also used to calculate potential evapotranspiration in the New Zealand distributed hydrological model TopNet (Clark *et al*., 2008). McNaugton *et al.* (1979) recommended the Priestley-Taylor method for short vegetation, not under water stress and where advection enhancement is not great. When compared to the VCSN estimates of PET, the values calculated in SWAT using the Priestley-Taylor method were more accurate than the SWAT estimates obtained using the Hargreaves method.

Discharge data were converted to runoff depth per unit area to normalise for areal differences. This allows for the comparison between sub-catchments and with other hydrological variables. The SWAT output includes information on a range of variables describing water yield, sediment yields and water quality. Evapotranspiration and the runoff components were the main variables of interest. SWAT defines three contributing components to runoff; surface runoff (surf), groundwater (gw) and lateral flow (lat). Surf is the surface runoff contribution to stream flow during the time step, whereas gw is the groundwater contribution to stream flow. It represents water from the shallow aquifer that returns to the stream during the time step. Lastly, lat is the lateral flow contribution to stream flow for the time step and is similar to through flow.

Table 3.2: Data type, description, and source used to run the SWAT model for the Waikouaiti catchment

Data type	**Data description and scale**	**Source**
DEM	15 m spatial resolution, NZGD 2000	UO-NSS, 2011
Land cover	LUCAS (2008)	MfE, 2010
Soil type	The New Zealand fundamental soil layer, WGS 84	Landcare Research, 2010
Precipitation	Middle -19442 (VCSN) Bottom -19443 (VCSN) Stoneburn (AWS)	NIWA, 2013
Other climate data (min and max temperature, solar radiation, relative humidity)	Middle -19442 (VCSN) Bottom -19443 (VCSN) Stoneburn-196522 (VCSN)	NIWA, 2013
Flow records	South Branch at Lawsons (1991-2010) North Branch at Bucklands (1991-1999)	ORC, 2013

3.3.3 SWAT sensitivity analysis, calibration, and validation

The initial parameter values in SWAT did not produce accurate simulations of stream flow and needed to be modified by a parameter calibration process. A sensitivity analysis was conducted to evaluate how different parameters influence the predicted output using the built-in sensitivity analysis function in SWAT. The method combines latin-hybercube (LH) and one-factor-at-a-time (OAT) sampling (e.g. van Griensven *et al*., 2006). SWAT runs $(p + 1) \times m$ times, where p is the number of parameters being evaluated and m is the number of LH loops. In each loop, a set of parameter values representing a unique area of the parameter space is selected. That set is used to run a baseline simulation for that unique area. Using OAT, the value of a randomly selected parameter is changed from the previous simulation by a user-defined percentage. SWAT runs using the new parameter set and the process is repeated. When all the parameters have been varied, the LH algorithm locates a new sampling area by changing all the parameters (Veith and Ghebremicheal, 2009). The sensitivity analysis was performed using only modelled data to identify the impact of adjusting a parameter value on some measure of simulated output (Veith and Ghebremicheal, 2009). The 10 most sensitive parameters are listed in Table 3.1.

Table 3.1: Ten most sensitive parameters determined using a sensitivity analysis.

Rank	Parameter	Description
1	ESCO	Soil evaporation compensation factor
2	CANMX	Maximum canopy storage
3	GWQMN	Threshold depth of water in the shallow aquifer for return flow to occur.
4	SOL_AWC	Available water capacity of the soil layer
5	SOL_Z	Soil depth
6	SOL_K	Saturated hydraulic conductivity
7	BLAI	Leaf area index for crop
8	SLOPE	Average slope steepness
9	CN2	Initial SCS curve number for moisture II
10	ALPHA_BF	Baseflow alpha factor

SWAT was calibrated and validated using a daily time step. The calibration parameters were selected based on sensitivity analysis results (Table 3.1). The determination of model parameters was done by manual trial and error, using a process adapted from Neitsch *et al.* (2011) (Figure 3.7). The built-in automatic calibration routine in SWAT was not used as it is relatively time consuming and testing of this function gave poor simulation results. For each parameter a realistic range was determined based on prior knowledge of the catchment and values reported in the literature. Model calibration and validation was evaluated at two locations using observed discharge data; Bucklands in the North Branch and Lawsons in the South Branch. Using a split sample the calibration period for Lawsons was July 1991 to December 2001 and the validation period was January 2002 to April 2010. The shorter record at Bucklands confined the calibration period to July 1992 to January 1996 and the validation period was January 1996 to January 1999.

Model performance in the calibration and validation periods was evaluated using the Nash Sutcliffe Efficiency (NSE) criterion (Nash and Sutcliffe, 1970). Modelled daily, monthly, and annual flow was compared to observed records. The NSE criterion determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970), so measures how well the plot of observed verses simulated values fit to the 1:1 line. NSE is calculated as:

$$NSE = 1 \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i-1}^{n}(O_i - \bar{O})^2}\right] \quad (3.2)$$

where O_i is the *i*th observation for the constituent being evaluated, P_i is the *i*th predicted (or simulated) value for the constituent being evaluated, $\bar{O}$ is the mean of the observed data of the constituent being evaluated and *n* is the total number of observations (Moriasi *et al.,* 2007). NSE values range between -∞ and 1.0 (Nash and Sutcliffe, 1970). A NSE of 0 indicates the model is no better than using the mean observed runoff volume as a predictor of runoff whereas a NSE of 1 represents a perfect fit of the observed and simulated flow (Moriasi *et al.,* 2007; Krause *et al.,* 2005). A limitation of the NSE is the squaring of differences between observed and predicted. This can overestimate the larger values in a time series and neglect lower values (Legates and McCabe, 1999), thus overestimating model performance in peak flows and underestimating low flow performance. This limits the sensitivity of NSE to systematic model over or under prediction especially during low flows (Krause *et al*., 2005). As an additional statistical comparison, the logarithmic formulation of NSE was calculated. It uses logarithmic values of O_i and P_i. The logarithmic transformation flattens peaks and low flows are kept at approximately the same value. This improves the sensitivity to low flows but does not entirely eliminate the impact of peak flows (Krause *et al*., 2005).

Figure 3.7 illustrates the manual ‘trial and error’ calibration process. The most sensitive parameters were adjusted first followed by the next most sensitive parameter. The range considered for each parameter value was determined using values reported in the literature and catchment data. After each adjustment the model was rerun for the calibration period and model performance was assessed using the NSE criterion.

The validated model was accepted when the NSE value was within 0.1 of the NSE value for the calibration period. If the validation model was unsatisfactory, the model was re-calibrated using the steps described in Figure 3.7. Model performance was rated according to the scale devised by Henriksen *et al.* (2008) and ranges from very poor to excellent (Table 3.2)

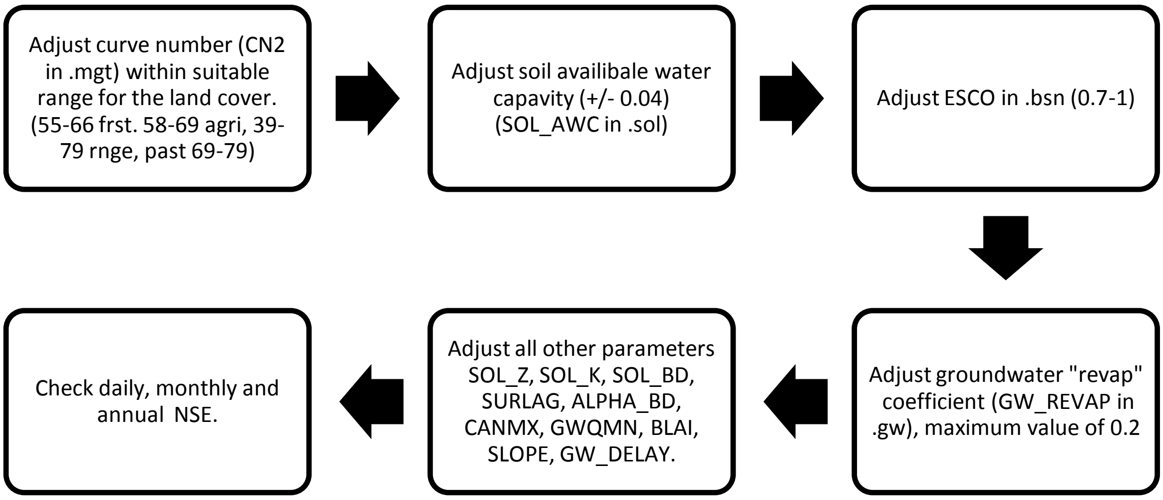


Figure 3.7: Calibration procedure for SWAT in the Waikouaiti River Catchment. Adapted from Neitsch *et al.* (2011).

Table 3.2: Performance indicator based on NSE values (Hendrickson *et al*., 2007)

NSE	Performance indicator
<0.2	Very poor
0.2-.05	Poor
0.5-0.65	Fair
0.65-0.85	Very good
>0.85	Excellent

3.3.4 CLUES model description and use

CLUES is a modelling tool that assesses the effects of land use change on water quality and socio-economic factors at catchment, regional and national scales. CLUES was developed by NIWA in collaboration with Lincoln Ventures, Harris consulting, AgResearch, HortResearch, Crop and Food Research, and Landcare Research for the MAF (now MPI) and the MfE. The water quality variables simulated in CLUES include annual average loads, concentrations and yields of total N and total P, sediment loads and *E. coli*. loads as well as socio-economic factors. CLUES runs through ArcGIS and combines a number of models and geospatial databases; SPARROW, SPASMO, OVERSEER, TBL and EnSus (Semadeni-Davies *et al.*, 2011).

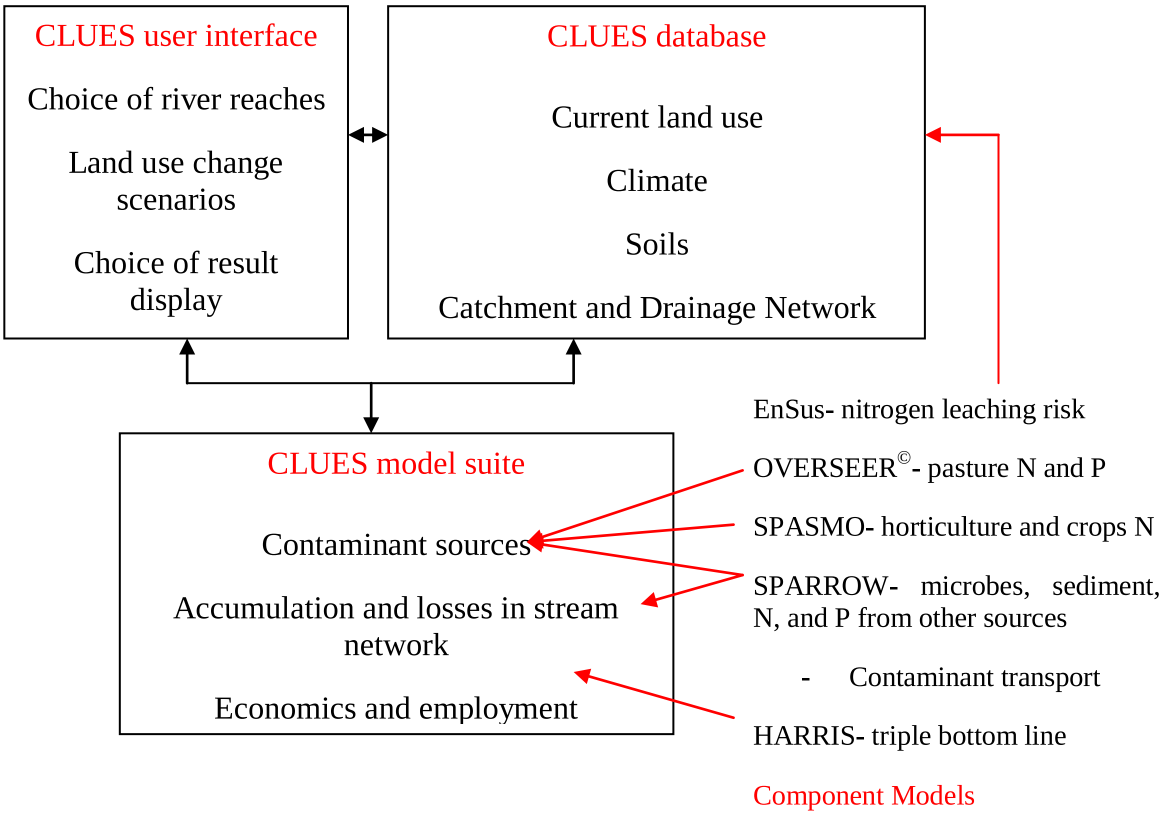


Figure 3.7: CLUES modelling framework (Semadeni-Davies *et al*., 2011).

In CLUES the base areal unit is a sub-catchment (~10 km^2 and above) as defined in the NIWA River Environment Classification (REC) national stream and sub-catchment network. Each sub-catchment is associated with a uniquely numbered river reach and estimations of water quality variables can be made for a reach or sub-catchment. The geo-spatial data integrated in the CLUES model includes a 30 m resolution DEM, current land use developed with reference to the Land Cover Database (LCDB2), Agribase (Asure Quality Ltd) and Land Environments of New Zealand (LENZ), soil data from the Land Resources Inventory (LRI) Fundamental Soils layer, runoff (rainfall less evapotranspiration), slope, point sources and lakes. The output from CLUES includes water quality results displayed as maps, tables or bar graphs (Semadeni-Davies *et al.*, 2011). CLUES does not model groundwater which is a known limitation (Elliot, 2011) but as there is no known groundwater sources in the Waikouaiti catchment this is not considered to be problematic. CLUES assumes water percolating into the ground will emerge in the same surface water catchment. The modelling framework is discussed in detail by Woods *et al.* (2006).

CLUES was run using default settings but the CLUES land use layer was replaced with the LUM (2008) land use layer used in the SWAT modelling to provide consistency across models. Additionally, the CLUES land use layer misclassified native forest in the catchment as scrub. This discrepancy between observed land use and the CLUES layer was also apparent in modelling of the Silverstream catchment, a small native catchment south of Dunedin (Fountain, 2013, pers. comm.)

The water quality variables focused on in this research were nutrient loads (kg $year^{-1}$); the instream cumulative loads for total nitrogen (total N) and total phosphorus (total P) for each river reach, sediment load (kilo-tonnes $year^{-1}$); instream cumulative loads for total suspended sediments (TSS) for a particular river reach, and nutrient concentrations (mg m^{-3}); instream nitrogen and phosphorus concentrations for a particular river reach. Long term measurements of water quality made by the ORC are available for two locations in the catchment; Orbells Crossing (hereafter referred to as Orbells) and Bucklands. The records are patchy but cover 1983-2010 at Orbells and 1983-2012 at Bucklands providing a reasonable data set to compare CLUES estimates for baseline conditions and thus assess model performance.

Model performance was evaluated by comparing CLUES estimates of total N and total P loads to observed loads. Loads were generated from the observed data using LOAD ESTimator (LOADEST) developed by the USGS (Runkel *et al.*, 2004). LOADEST is a FORTRAN program for estimating constituent loads in streams and rivers. Using a time series of stream flow and ORC spot measurements LOADEST developed a regression model to estimate loads for the given time interval. For further comparison median total N and total P concentrations estimated by CLUES were compared to long term medians at each of the monitoring sites.

3.4 **Land use scenarios**

Flow regimes and water quality under different land use scenarios were estimated by running land use scenarios in the calibrated SWAT model and in the CLUES model. Six land use scenarios were created (Table 3.3). The native forest scenario is representative of pre-human settlement; thought to be a largely coastal broadleaf forest (Campbell, 1977). In the native forest scenario the catchment has 100% native afforestation. The tussock scenario is an intermediate scenario between burning of the bush for moa hunting and clearing land for agriculture where tussocks replaced the burned bush (Campbell, 1977). The intensive dairying scenario is an extrapolation of national agricultural trends of increasing dairy farm conversions (PCE, 2013); in this scenario land best suited to dairying (slopes < 20°) was converted to dairy. Dairy farming in the catchment increased from 7% to 42% coverage. The intensive dairying scenario did not include the likely increases in water withdrawals associated with irrigation due to model and information restraints. The indigenous headwaters scenario evaluates the effects of native afforestation in a small area of the catchment. The southern extent of the catchment is not well suited to dairying because of the steeper slopes but is suitable for sheep and beef farming. The Southern agriculture scenario increases low producing grassland by 12%. The woody biomass scenario explores the consequences of ceased agricultural activity on a large scale which would result in generation of scrub or woody biomass. Vegetation on slopes greater than 21° is replaced with woody biomass.

The original land use layer was adjusted to represent each scenario using ArcMap tools. Simulations were carried out using the calibrated models and the only component altered was the land use layer. The meteorological forcings were the same for all land use scenarios. In this way, the effects of vegetation change on basin hydrology were isolated from the effects of climate variability. All other parameters remained unchanged. A simulation period of 19 years was used for Lawsons and seven years for Bucklands in SWAT.

Table 3.3: Description of each of the land use scenarios and the scenario name.

Scenario name	**Description**
Baseline	Current land use (as best known at 31st December 2007, used for model calibration and validation).
Native forest	A scenario where the catchment has 100% native forest cover.
Intensive dairying	A scenario where farming practices intensify, all land with a slope <20 ° is converted to dairy farming.
Southern agriculture	A scenario representing increased agriculture (sheep and beef) replacing native forest in the South Branch.
Indigenous Headwaters	A scenario representing increased native forest replacing some agriculture with native forest in the North Branch headwaters.
Woody biomass	A scenario representing an increase of grassland with woody biomass (scrub) on slopes >21°.
Tussock	A scenario representing a combination of short tussock, snow tussock, and native forest in the catchment.

3.4.1 Flow threshold Analysis

A variety of optimum flow conditions for various fish species were investigated. Thresholds were only analysed for species known to be present at, or near, the gauging site. Thresholds are based on optimum flow levels recommended by ORC (2011) for fish in different parts of the Waikouaiti River (Table 3.4). The main species present in the North and South branches include short and long fin eel, lamprey and adult and juvenile brown trout.

Table 3.4: Flow thresholds for different fish species present in the North and South Branches.

Species	**Optimum flow**
Shortfin and Longfin eel Lamprey (juvenile)	0.050 m^3s^{-1}
Adult brown trout	0.203 m^3s^{-1}
Juvenile brown trout	0.115 m^3s^{-1}

3.5 Cultural stream health assessment

The impacts of land use on cultural values were determined by analysing cultural stream health data. The cultural data was provided by Dr Gail Tipa of Tipa and Associates Ltd who undertook a preliminary cultural stream health assessment survey with members of the runanga at culturally significant locations within the catchment. Assessments were carried out at Bucklands and Orbells which are both deemed culturally significant over a ten month period in 2011/2012. The raw data was provided by Dr Tipa and the individual scores were averaged to give an overall measure of stream health at a particular site. The assessment comprises two components; questions relating to flow and a cultural health index (CHI) (MfE, 2006). As described in Section 2.4.3, a cultural assessment is a participatory process that allows for the identification of preferred flows and specification of other management actions necessary to recognise, provide for, and protect cultural interests in respect to freshwater. The process and questions are grounded in cultural beliefs, values, and practices and use technical methods to monitor effects (Tipa and Nelson, 2012). The CHI is also based on iwi perspective of stream health and the assessment applies cultural values determined by iwi. It uses indicators that express Māori values for the environment and their relationship with it (MfE, 2006). Thus, the flow assessment and CHI allow for the collection of data specific to cultural values that can be used to diagnose issues, and decide on priorities or remedial actions necessary to restore or enhance cultural values at the site (MfE, 2006). At each site the assessors independently answered a series of questions under different themes. The flow assessment has four sections; mahinga kai, wai Māori, health, landscape, and an overall section. Each section has a series of questions which are scored on a 1-7 likert scale by the individuals, 1 being little or no satisfaction and 7 very satisfied. The CHI is divided into three themes; surface of the water, water, obstructions or litter, plus an overall section. Questions in the cultural health index are ranked on a 1-5 likert scale. At the time of the assessment, assessors were unaware of the measured flow. Individual scores for each theme and day were averaged and compared to measured flow.

3.6 Consequence table

A consequence table was used to draw together and integrate the scientific and cultural data. A consequence table is a flexible, visual tool that can be simplified or extended to cater for the intended audience (Failing *et al.,* 2007). A consequence tables consists of values or variables of interest and a measure of consequence or impact on the value or variable of interest under different scenarios. Measures include percentage change in mean annual runoff, 7-day MALF and peak flow, percentage change in sediment, total N and total P loads, percentage of days flow is below species habitat thresholds, and impacts on feel, pride, access, and the overall resource. The four cultural values (feel, access, pride, and overall resource) were chosen to condense the themes assessed in the cultural assessments and were considered reflective of interrelated values common across themes. The impact or consequence on each of these measures under each land use scenario is depicted using graphic symbols. A consequence table was created for Bucklands and Orbells.

3.7 Summary

In order to maintain data integrity and reliablity of data, scientific and cultural data were generated indepentenly rather than applying scientific method to genrate cultural data or *vice versa.* The SWAT model was callibrated at two locations in the Waikouaiti catchment, representative of the North and South branch flow regimes. Water quality was modelled in the North Branch (Bucklands) and downstream of the confluence (Orbells) as dictated by the availiable data. Cultural stream health assesments were also conducted at Bucklands and Orbells a reflection of the cultural significance of each of these two locations.

Figure 3.8 summarises the key steps in the methodology and links each process to the objectives outlined in section 2.6. The calibration and validation of the SWAT model for the Waikouaiti River meets objective 1: to develop a representative hydrological model of the Waikouaiti catchment using a semi-distributed HRU hydrological model, SWAT and the water quality modelling meets objective 2. The application of land use scenarios described in Section 3.4 meets objective 3: to apply a pre-human land use scenario and other land use combination scenarios to the calibrated and validated Waikouaiti catchment models in order to assess the impacts of land use change on flow regime and water quality. The use of cultural stream health assessments partially fulfills objective 4 and were carried out by members of the runanga. The final step was to integrate all the data and make inferences about the hydrological impacts of land use change on flow, quality, and cultural values (objective 5) and was aided by the use of consequence tables.

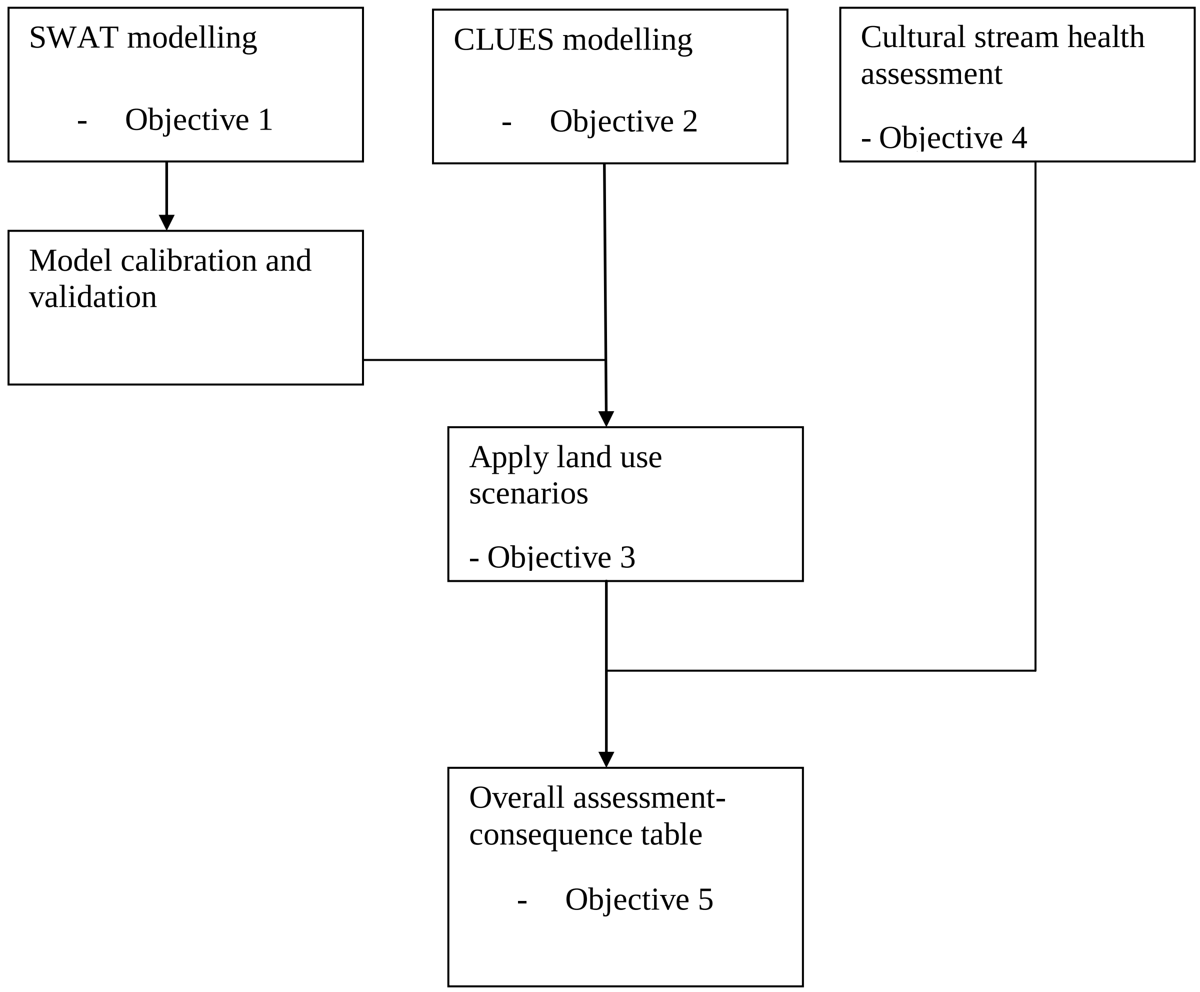


Figure 3.8: Summary of the links between research objectives and key steps in the methodology.

Chapter 4: Model Performance

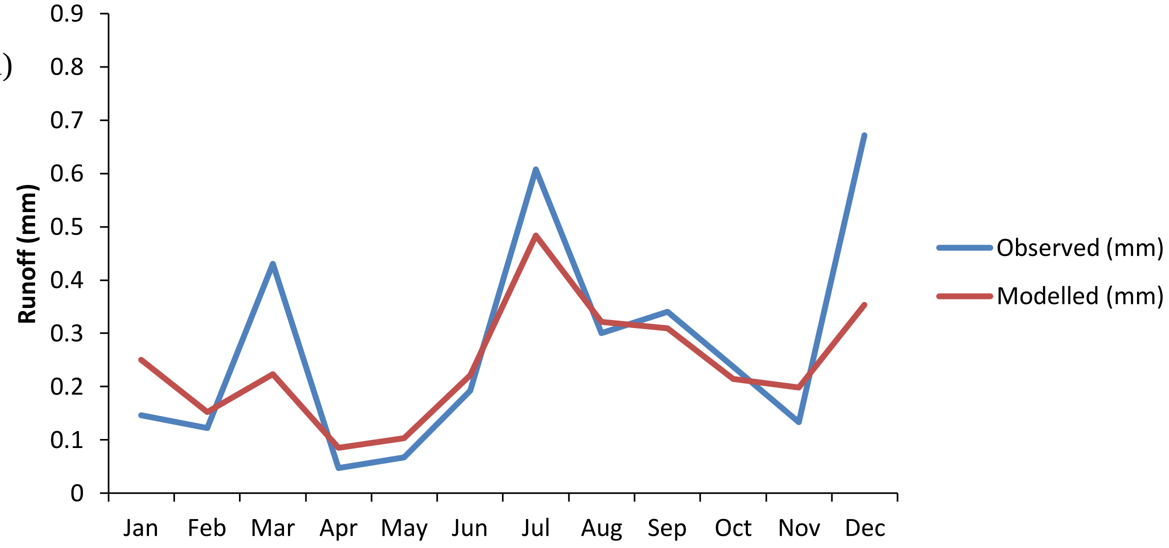
4.1 Introduction

Chapter 4 describes and evaluates the performance of the SWAT and CLUES models. In Section 4.2 the performance of the SWAT model is evaluated using the NSE criterion and Henriksen *et al.* (2008) performance criterion. The model performance is analysed and its applicability outside of the calibration conditions (i.e. for simulating land use scenarios) is justified in Section 4.3. The performance of CLUES is described in Section 4.4 and the results are described and explained in Section 4.5.

4.2 Comparison of SWAT predictions and flow observations

Comparison of the modelled and observed hydrographs shows that monthly trends in runoff are reasonably well simulated for the calibration and validation periods at Bucklands (Figure 4.1). During the calibration period, mean monthly runoff is overestimated in January (~70%) and underestimated in March and December (~48%) but reasonably close during the rest of the year (Figure 4.1a). In the validation period the model generally overestimates runoff, especially in the summer and autumn months (e.g. 159% in January) (Figure 4.1b). At Lawsons the model reproduces mean monthly runoff very well in the calibration period; the main discrepancy is overestimation in January (~44%) (Figure 4.2a). The fit between observed and modelled mean monthly runoff during the validation period is slightly weaker but still very reasonable; runoff is underestimated in January (~47%) and overestimated in June (~66%) (Figure 4.2b). Although the percentage differences between observed and modelled mean monthly runoff seem large, in absolute terms the differences are smaller. For example, in January mean monthly observed runoff was 0.6 mm compared to the modelled runoff of 1.0 mm (a ~70% overestimation). The annual regime differs between the calibration and validation periods at Bucklands and Lawsons and this can be attributed to two factors. Firstly, the calibration and validation periods at Bucklands are shorter than Lawsons meaning different time frames and lengths are represented at each site. Secondly, as described in Chapter 3, the South Branch supplies most of the water to the main stem during times of low flows which also contributes to the differences in flow regime.

(a)



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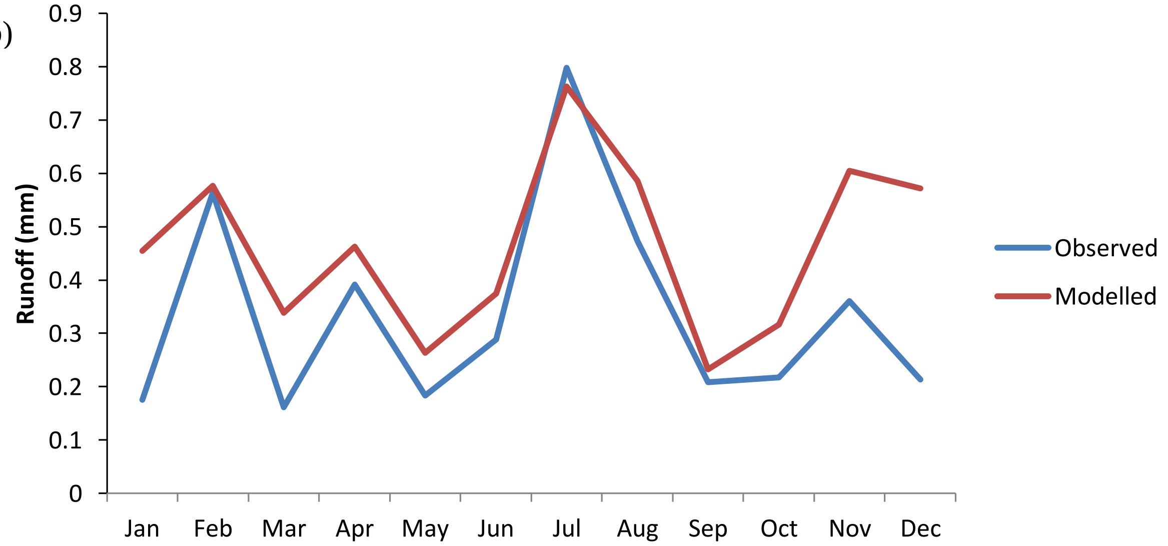
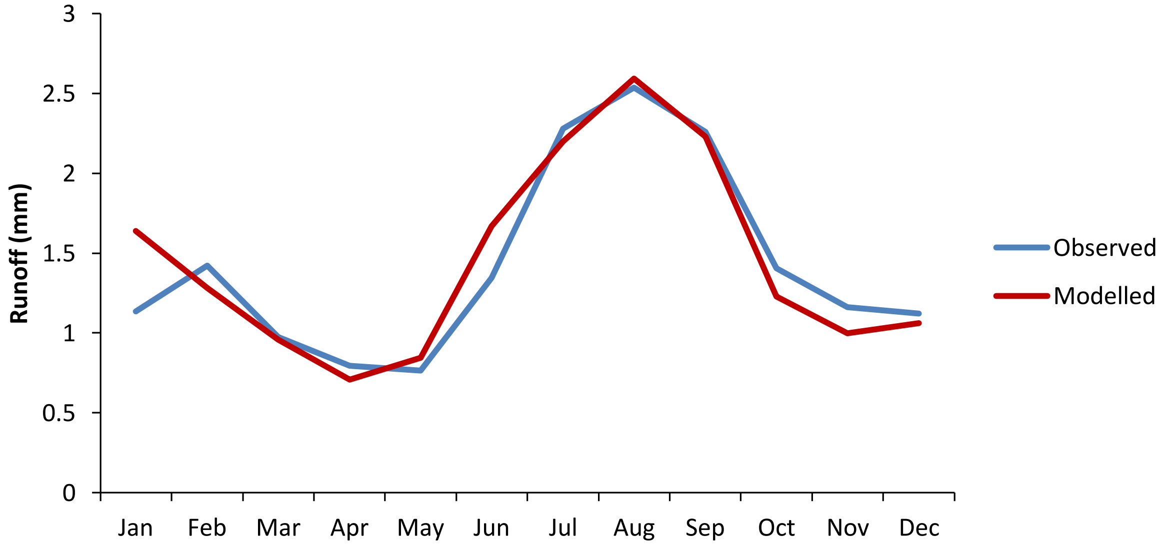


Figure 4.1: Comparison of observed and modelled mean monthly runoff at Bucklands in the North Branch for (a) the calibration period 1992-1996 and (b) the validation period 1996-1999.

(a)



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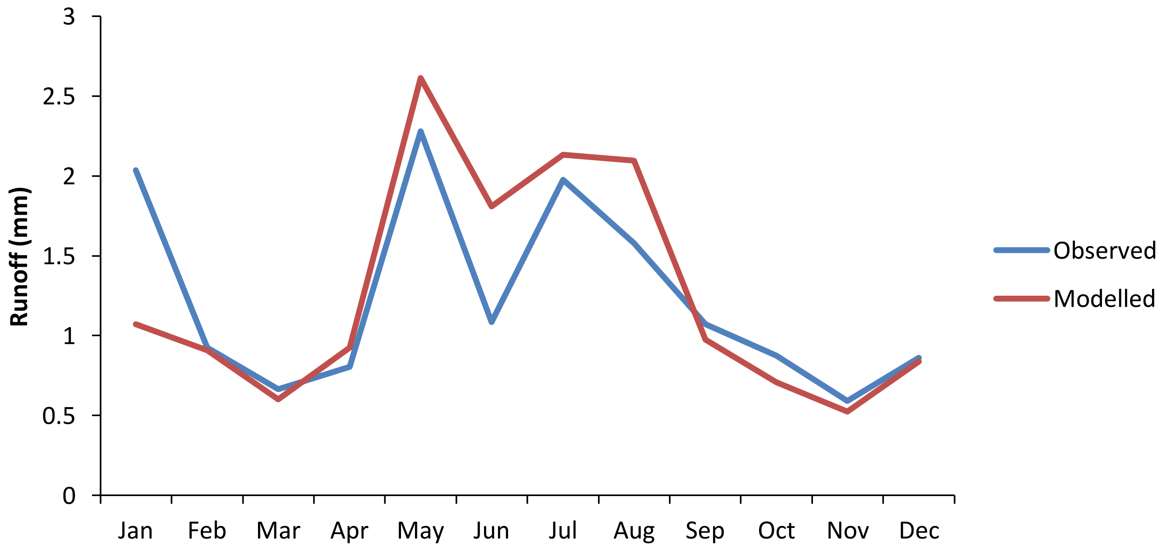


Figure 4.2: Comparison of observed and modelled mean monthly runoff at Lawsons in the South Branch for (a) the calibration period 1991-2001 and (b) the validation period 2002-2010.

The statistical evaluation of model performance for the daily, monthly, and annual calibration is shown in Table 4.1. Daily Ln NSE values were excluded because of days with 0 flow and annual performance was not assessed at Bucklands due to the relatively short calibration and validation periods (3 and 4 years respectively). Calibration of daily flow was very similar at both sites but monthly performance was better at Lawsons. Performance during the validation period was similar to the calibration period at Bucklands, but at Lawsons performance in the validation period was slightly weaker than the calibration period. The best monthly performance was in the Lawsons calibration period (NSE=0.86), which also had the best daily performance (NSE=0.57). Typically the annual model performance is better than monthly and the daily model performance is the weakest. The monthly Ln NSE values ranged between 0.52 and 0.84 across sites and calibration/validation. The Ln NSE values show that although the model was calibrated with the aim of maximising the standard NSE values, the model also performs reasonably for low runoff.

Table 4.1: NSE and Ln NSE values for the calibration and validation periods at Bucklands and Lawsons and the Henriksen *et al.* (2008) model evaluation criteria (Very Good to Poor). *= daily NSE excluding 1-12 January 2012 and **= monthly NSE excluding January 2012. Missing Ln NSE cannot be calculated with zero values.

Bucklands				
	Calibration period		**Validation period**	
	NSE	**LnNSE**	**NSE**	**LnNSE**
Daily	.56	-	0.56 Fair	-
Monthly	0.68 Very good	0.84 Very good	0.630 Fair	0.58 Fair
Lawsons				
	Calibration period		**Validation period**	
	NSE	**LnNSE**	**NSE**	**LnNSE**
Daily	0.57 Fair	-	0.52 Fair (0.66*)	-
Monthly	0.83 Very good	0.64 Fair	0.63 Fair (0.81**)	0.68 Very Good
Annual	0.92 Excellent	0.86 Excellent	0.66 Very good	0.75 Very Good

4.3 Analysis of the SWAT model performance

Although the model performance was reasonably good, it could not be classified as 'excellent' at all temporal scales and locations. This may be due to several factors. Figure 4.1-4.2 illustrate a discrepancy between seasonal patterns in the validation and calibration period at both sites. At Bucklands both the cycle of runoff and the volume of runoff differs significantly. The drier validation period could explain the general overestimation of runoff at Bucklands. Similarly the weaker performance at Lawsons in the validation period is partly attributable to the difference in seasonal patterns between the calibration and validation period.

Most of the input climate data was derived from NIWAs VCSN (Section 3.6.2). These measurements are estimates of daily values based on spatial interpolation of actual observations made at automatic weather stations around New Zealand. As the data is synthetic and not observed there will be some degree of error in the data. As described in Chapter 3 Tait *et al*. (2012) compared VCSN data for rainfall with independent data collected by regional councils. The agreement between the virtual records and observed records were good, particularly for elevations less than 500 m (2-12 mm). The discrepancies between the synthetic data and actual conditions would likely have contributed to model performance particularly at the daily scale.

The detail and spatial scale of information available on soil types and land use may have further hindered model results. The SWAT database contains detailed information on USA soils and land use. The same information and level of detail is not available for New Zealand soils and land use. The New Zealand land uses were matched as closely as possible with the USA land use categories and New Zealand parameter information was used where available but in some instances default values had to be used. Similarly all the available information on soil parameters was used in the model but again default values were used for some properties. This hindered the level of detail available to describe certain physical properties potentially contributing to weakened model performance.

Another potential source of error is sample size. The calibration and validation periods at Bucklands are very short, four and three years respectively. The plot of accumulated runoff at Bucklands shows departure above and below the straight line (Figure 4.3). The plot shows a gentler gradient during the validation period. The annual rainfall totals in 1998 and 1999 were lower than the long term average when many parts of New Zealand, particularly in the Otago Region experienced a severe drought (Caruso, 2002). Thus, two out of the three validation years were drier than the long term average which may explain the why model performance was weaker during the validation period.

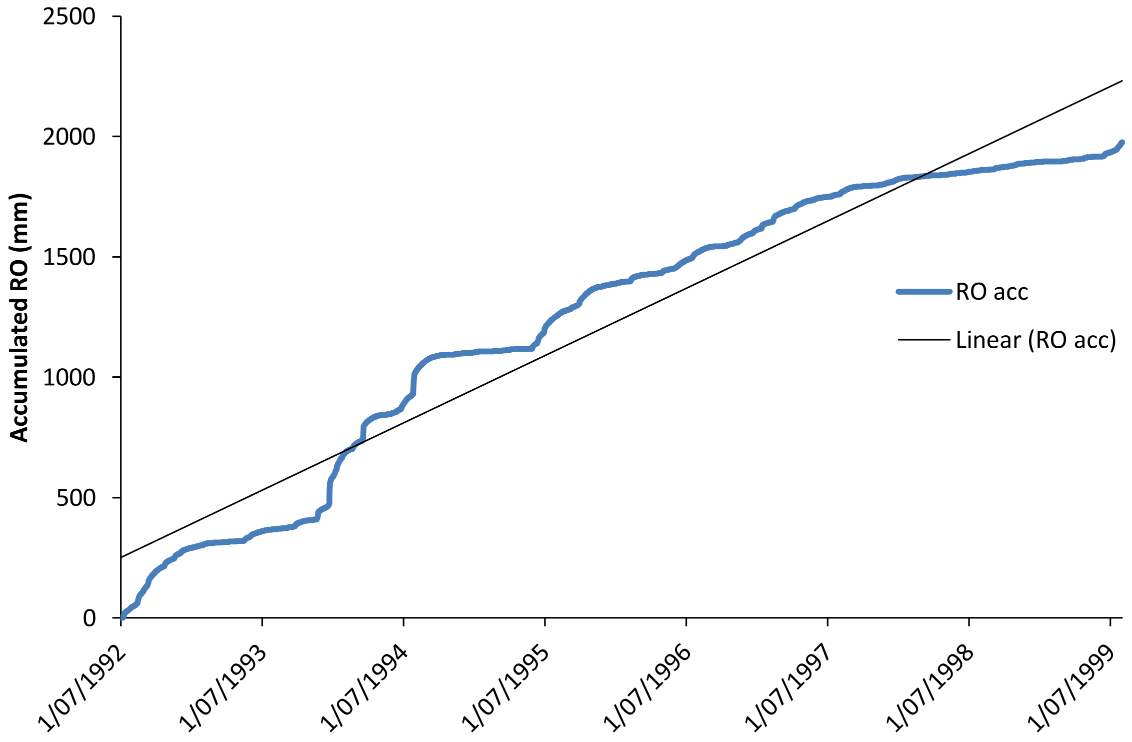


Figure 4.3: Accumulated runoff at Bucklands for the entire period 1992-1999 fitted with a linear trend line.

At Lawsons, model performance during the validation period is not as strong as the calibration period. The weaker model performance during the validation period at Lawsons is partly attributable to an unusually large flood event in January 2002 at the start of the validation period (peak 77 m^3s^{-1}); when this event is excluded model performance improved (daily NSE=0.66 and monthly NSE=0.81) (Table 4.1). The poor annual performance during the validation period at Lawsons may also be partially attributable to a smaller sample size; seven in the validation period, compared to ten years in the calibration period.

According to the model evaluation guidelines of Moriasi *et al.* (2007), a NSE value greater than 0.5 is considered 'satisfactory'. Comparatively, model performance at all temporal scales is 'fair' or better according to the guidelines of Henriksen *et al.* (2008). Therefore, performance of the SWAT model was considered sufficient to apply the model outside the calibration conditions. The model was run at a daily timescale but the results are reported on a monthly scale because these results are more reliable according to the model performance criteria. Where daily results are presented, the results should be interpreted with caution as the model performance is slightly weaker at the daily resolution. In any case the results should be considered an indicative rather than an estimation of absolute values.

4.4 Comparison of CLUES predictions and water quality observations

The CLUES model performance was assessed by comparing the CLUES predictions for the baseline with long term nutrient data for Orbells and Bucklands. The estimation of total N at Bucklands was not considered because there was not enough observed data to calculate loads. Model performance in CLUES was mixed (Table 4.2). Total P loads are slightly overestimated at Bucklands (33%) and largely overestimated at Orbells (1042%). The CLUES estimate of total N load at Orbells is 313% higher than actual observations. At both sites total N concentrations are overestimated, whereas total P concentration is very close to observed levels at Bucklands but slightly overestimated at Orbells. The CLUES estimates of total N loads at Bucklands could not be compared due to a lack of observed data.

Table 4.2: Comparison of CLUES estimates of annual loads of total N and total P to LOADEST estimations (based on spot measurements) at Orbells and Bucklands. Comparison of CLUES estimates of total N and total P median concentrations with long term median concentrations at Orbells and Bucklands.

	Predicted Output CLUES	**Observed Output LOADEST (CI)**
Orbells		
Total P load (t/yr)	4.34	0.38 (0.29,0.49)
Total N load (t/yr)	23.62	5.72 (5.36, 9.2)
Bucklands		
Total P load (t/yr)	2.87	2.15 (1.67,2.64)
	CLUES prediction	**Long term median (range)**
Orbells		
Total N conc (g/m^3)	0.319	0.18 (0.17,0.22)
Total P conc (g/m^3)	0.038	0.01 (0.01,0.012)
Bucklands		
Total N conc (g/m^3)	0.286	0.18 (0.12-0.25)
Total P conc (g/m^3)	0.033	0.039 (0.008-0.075)

4.5 Analysis of the CLUES model performance

Although the CLUES predictions do not match particularly well with the observed data, the observed concentrations were also estimates. The LOADEST estimations were calculated from spot measurements measured by the ORC under baseflow conditions. Additionally, the calculation method of loads and concentrations in CLUES may affect the accuracy of predictions. In CLUES the concentration predictions are based on the load estimates, therefore, an error in the load prediction is compounded in the concentration prediction (Elliot, 2011).

During development of the model, CLUES was calibrated to the 77 NRWQN sites. Each site is classified by climate, source of flow, geology and land use. The Waikouaiti River is classified as cool-dry / hill / hard sedimentary / pastoral (CD/H/HS/P). Of the 77 NRWQN sites used in the model development five are classified CD/H but only one is CD/H/HS/P; the Mataura River at Otamita Bridge. Although the two locations have the same classification, they are very different rivers. The Mataura River in total spans a 5400 km^2 catchment and further upstream of the Otamita Bridge is classified as cool-wet/hill (CW/H) and cool-wet / mountain (CW/M). Thus, data collected in the Mataura River at the Otamita Bridge may not be entirely representative of a CD/H/HS/P catchment. Therefore, it is possible CD/H/HS/P catchments with characteristics more similar to the Waikouaiti River than the Mataura River have been under represented in the development of CLUES. This under representation may in part be responsible for the mixed model performance in the catchment and is an issue to consider in future modifications of the CLUES model.

Other studies using CLUES also had mixed results as described in Section 2.3.2.1. The over prediction of total P loads and concentrations was also found at some locations in Southland (Monaghan *et al.*, 2010). The over-prediction of concentrations has been attributed to the fact that median concentrations are calculated from the load which results in a compounding of errors. Elliot *et al*., (2011) reported errors in total N were generally smaller than errors in total P which was also found in this study. Given the uncertainty surrounding absolute values some studies have focused instead on the relative change between scenarios (Monaghan *et al*, 2010; Elliot *et al.*, 2011). As with many catchment models, the error in relative change with respect to some baseline is expected to be less than the absolute error in the prediction. For example, if some error in concentration in baseline predictions at a site is due to an error in the flow rate, that same flow rate would likely apply for the other scenarios, so that the percentage change in concentration will be more reliable than the absolute value of the new concentration making the assumption that the errors are carried on between scenarios (Elliot *et al.,* 2011).

For the purposes of this modelling application the CLUES model performance was accepted as satisfactory but used with caution. The CLUES estimates were used to give an indication of the relative magnitude and direction of changes in nutrient and sediment loads and concentrations between scenarios. The absolute estimates were not regarded as indicative of actual outcomes.

4.6 **Summary**

The SWAT and CLUES models both performed reasonably and several factors were identified that potentially contributed to model under or over estimations. Both models gave a fair representation of observed conditions and were considered suitable for use simulating land use scenarios different from the calibration conditions. However, the results of the land use simulations must be considered in relation to the model performance. It was recommended the CLUES estimates were used to give an indication of the relative magnitude and direction of changes in nutrient and sediment loads and concentrations between scenarios. The objectives described in Section 2.6 were to develop and use models suitable to assess the effects of land use change on various hydrological responses. Therefore, both the SWAT and CLUES models were considered suitable to assess the impacts of land use change on flow regime and water quality in the Waikouaiti catchment.

Chapter 5: Results

5.1 Introduction

This chapter describes the results of the hydrological modelling and the cultural stream health assessments. Section 5.2 gives an overview of the modelled baseline conditions. The baseline flow regime for Lawsons and Bucklands as modelled in SWAT is described in section 5.2.1 followed by the CLUES output for baseline nutrient and sediment levels at Orbells and Bucklands (Section 5.2.2.). Section 5.2.3 describes the results of the cultural assessments conducted at Orbells and Bucklands. The third section (5.3) focuses on the modelled predictions for water quantity and quality under each land use scenario. Section 5.3.1 investigates how flow varies under different land use scenarios and examines the components of runoff (5.3.2) as well as the duration of flow and components of runoff (5.3.3). Section 5.3.4 quantifies the effects on aquatic species and Section 5.3.5 describes the changes in water quality under each land use scenario. Finally the results of all three sections are integrated and summarised in section 5.4 through the use of a consequence table.

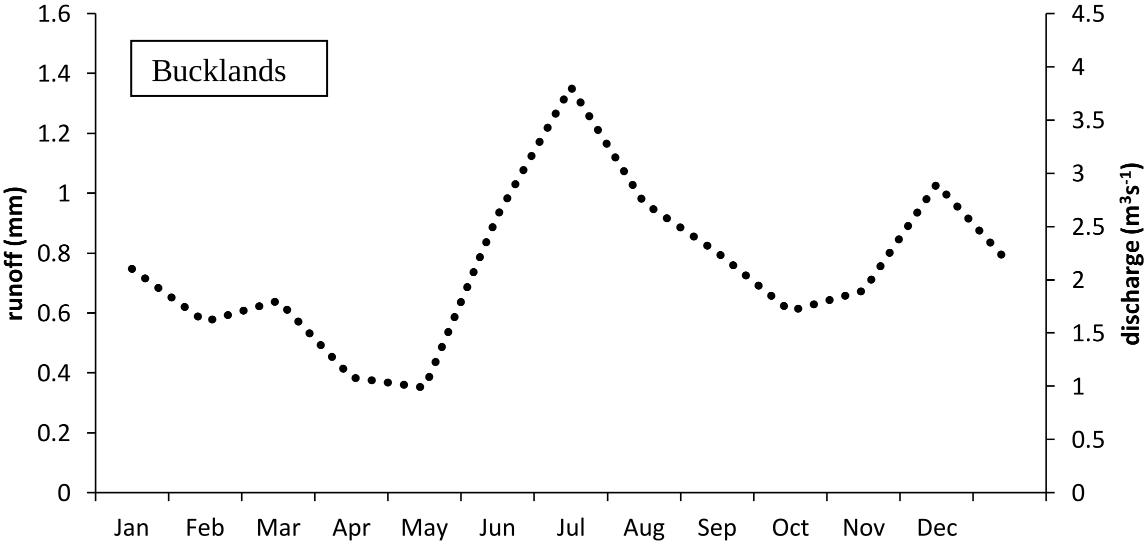
5.2 Baseline characteristics

5.2.1 Modelled flow regimes for the baseline

The mean monthly baseline flow characteristics at Bucklands (predominately low producing grassland) and Lawsons (a mix of native and exotic forest) display similar seasonal patterns. At Bucklands, the highest mean monthly flow is in August and the lowest in May. Mean monthly flow displays a similar seasonal cycle at Lawsons where the highest mean monthly discharge occurs in August and the lowest mean flows are in November and April (Figure 5.1). However, there are some variations between the two locations. For example, mean annual runoff of 279 mm at Bucklands is considerably lower than the 479 mm modelled for Lawsons.

In SWAT runoff components are divided into lateral flow, groundwater and surface runoff as described in Section 3.4. Throughout most of the year lateral flow is the largest component of total runoff at Bucklands, making up between 39 and 54% of total runoff in any month. Groundwater is the next biggest component of runoff at Bucklands and is more influential in August (0.41 mm) than lateral flow (0.28 mm). Finally, surface runoff is the smallest component of total runoff, contributing between 2% and 36% of total runoff throughout the year. The modelled results indicate that surface runoff has a minimal impact on total runoff under baseline conditions, with the exception of March and December when monthly means exceed groundwater contribution (Figure 5.2). Lateral flow is also the biggest component of total runoff at Lawsons and its contributions range between 36% and 56%, a similar range to Bucklands. Unlike Bucklands, groundwater contributions do not exceed lateral flow in any month and range between just 5% of total runoff in December to 22% in September. Lastly, surface runoff is the smallest component of total runoff at Lawsons adding less than 1% to runoff in November and up to 9.6% in May (Figure 5.2). Evapotranspiration displays a typical seasonal pattern at both locations; very high evapotranspiration in the summer months and low evapotranspiration during the winter months (Figure 5.3).

(a)



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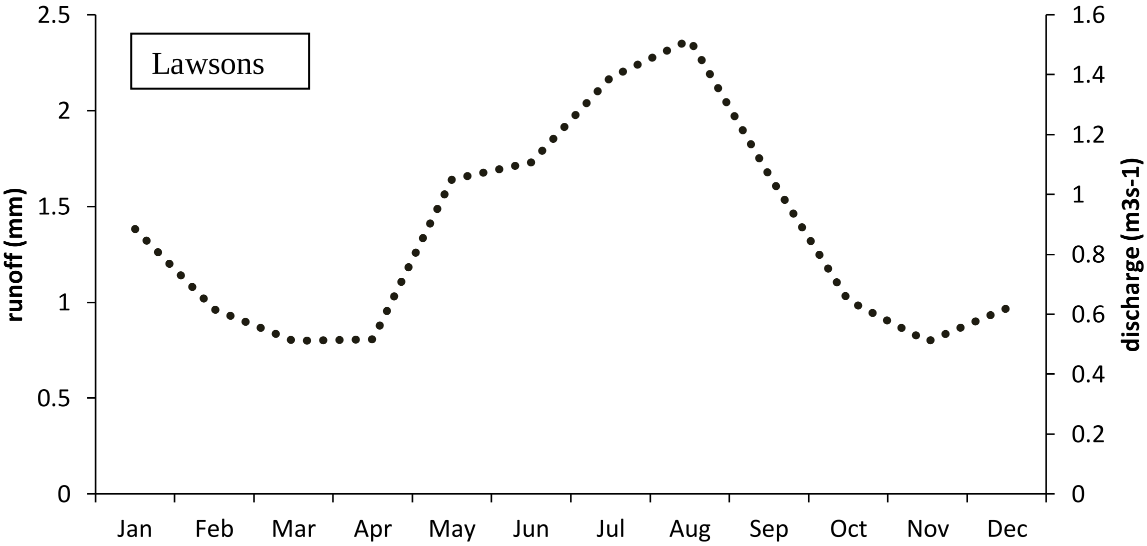


Figure 5.1: SWAT estimates of baseline mean monthly discharge/runoff at a) Bucklands and b) Lawsons.

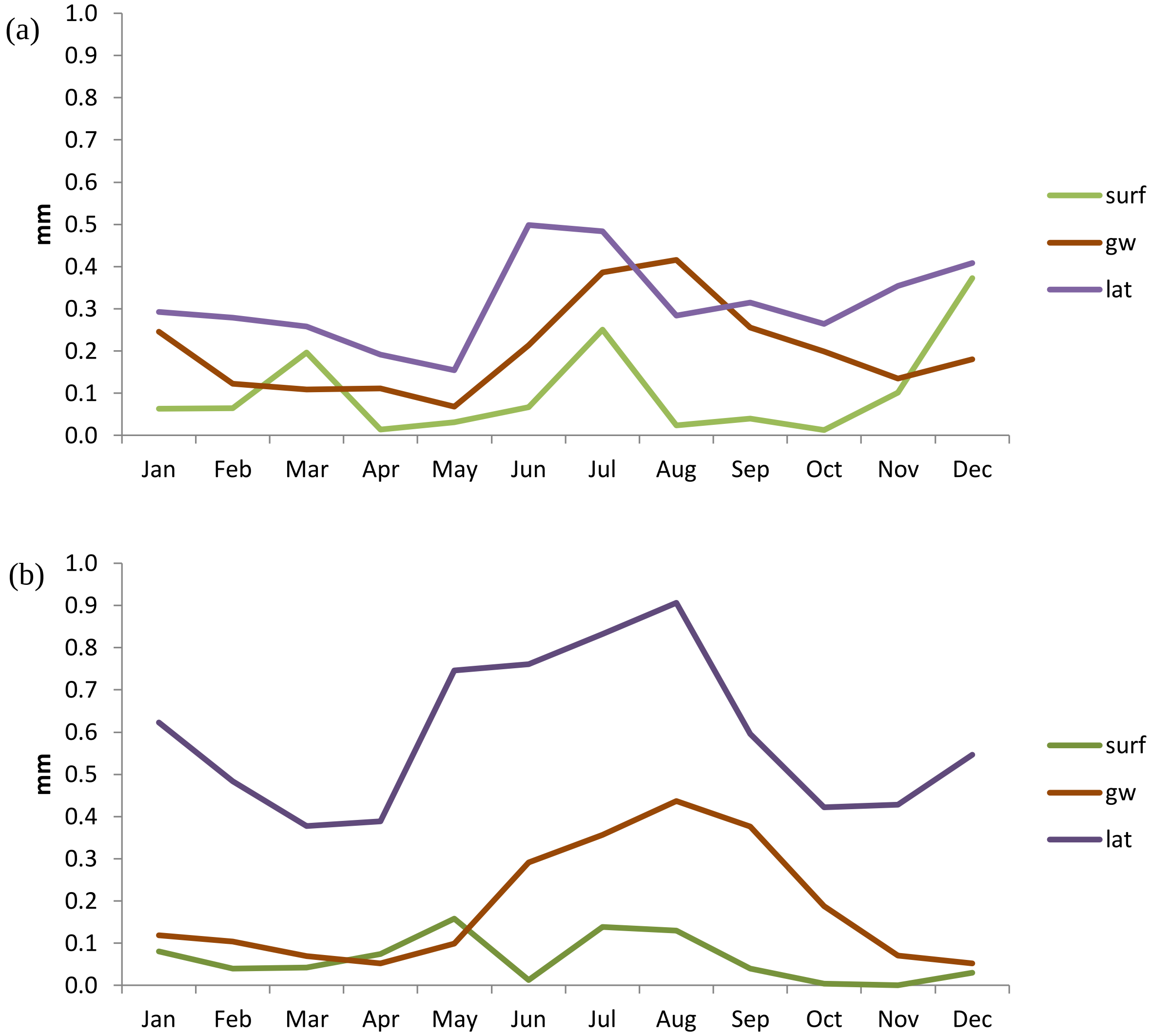


Figure 5.2: SWAT estimates of mean monthly contributions of surface runoff (surf), groundwater (gw), and lateral flow (lat) to total runoff for the baseline a) at Bucklands and b) at Lawsons.

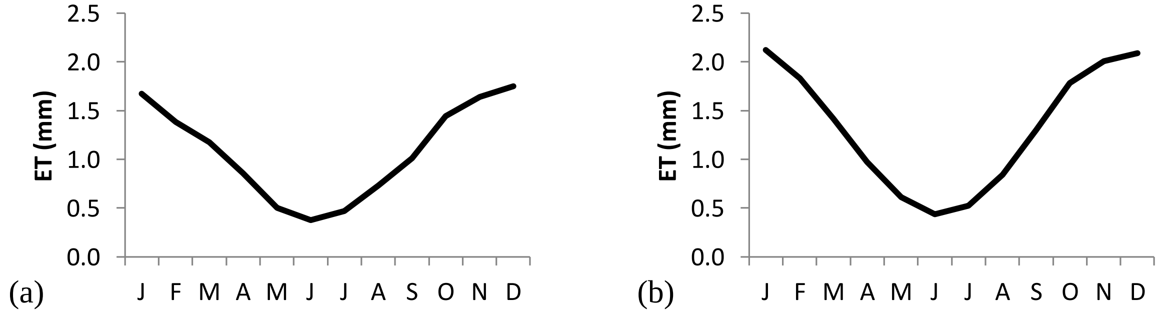


Figure 5.3: SWAT estimates of mean monthly evapotranspiration for the baseline a) at Bucklands and b) at Lawsons.

5.2.2 Modelled water quality for the baseline

Nutrient and sediment loads and concentrations are higher at Orbells than Bucklands reflecting an accumulation at the downstream location. The median annual loads of total N are much higher than median annual total P loads at Bucklands (17 t yr^{-1} compared to 3 t yr^{-1}); Median annual sediment loads are approximately 15 t yr^{-1} at Bucklands. Median total N concentrations for baseline conditions at Bucklands are 286 mg m^{-3} and median total P concentrations are 33 mg m^{-3} (Table 5.1).

Modelled water quality under baseline conditions at Orbells reflects the same trends as Bucklands but the concentrations and loads are greater. As Orbells is located downstream of the confluence it is fed by both branches of the river. Annual loads of total N and total P are 24 and 4 t yr^{-1} respectively, and median sediment loads are ~23 t yr^{-1}. CLUES estimates total P of 38 mg m^{-3} and median total N concentrations of 319 mg m^{-3} (Table 5.1).

Table 5.1: CLUES estimations of median annual loads (t yr^{-1}) and concentrations (mg m^{-3}) of total N, total P and sediment for baseline conditions at Bucklands and Orbells.

	Total N load (t yr^{-1})	**Total P load (t yr^{-1})**	**Sediment (kt yr^{-1})**	**Total N conc (mg m^{-3})**	**Total P conc (mg m^{-3})**
Bucklands	17	3	15	286	33
Orbells	24	4	23	319	38

5.2.3 Baseline cultural assessment

The cultural assessment results displayed variation across sampling days, cultural themes, and sampling location. Analysis of the cultural results did not reveal clear patterns or trends but provided some interesting insights. The cultural assessments were conducted on fourteen occasions at both Bucklands and Orbells for flow conditions ranging from 0.34 m^3s^{-1} to 5.97 m^3s^{-1}. Overall Bucklands had more unsatisfactory scores across all themes and sampling days than Orbells. Generally if at least one theme received an ‘unsatisfactory’ score at one location, then at least one theme was scored ‘unsatisfactory’ at the other location on the same sampling days. However, this was not always the case and it was not necessarily the same themes with poor scores at each site.

Comparing the cultural scores to stream flow suggests that cultural values are compromised more often when flow is less than 0.6 m^3s^{-1}. By contrast, 10% of scores for flows between 0.6 and 1.4 m^3s^{-1} and 25% of scores for flows over 1.4 m^3s^{-1} were unsatisfactory. Of the days with at least one unacceptable score season did not appear to be a factor as they occurred in all seasons, however, the sampling size is too small to make conclusive statements about the influence of season. Analysis of flow conditions preceding the assessment did not expose a consistent link between either a flushing event or constant flow in the fortnight preceding and 'satisfactory' or 'unsatisfactory' results. At Bucklands the flow scores, particularly the wai Māori and health themes had the most unsatisfactory scores, whereas the CHI themes were generally scored above the acceptable level. There was only one unsatisfactory score for the CHI themes at Bucklands; for the overall score on a sampling day with flow < 0.6 m^3s^{-1}. It is interesting to note that the score for one theme was not the same for all the themes on that sampling day (Table 5.2).

In general Orbells had more satisfactory scores than Bucklands. At Orbells the majority of unsatisfactory flow scores were on days with flow < 0.6 m^3s^{-1} (75%). In contrast to Bucklands the intermediate flow days had more unsatisfactory scores (13.8%) than the days with flow above 1.4 $m^3 s^{-1}$ (10%). The landscape and overall flow themes at Orbells had the most unsatisfactory scores; cultural expectations were not met on six days. On one high flow day (>1.4 m^3s^{-1}), Orbells had unsatisfactory scores in all of the CHI themes but was satisfactory overall. In all other cases cultural health as assessed by the CHI was satisfactory. As at Bucklands an unsatisfactory score in one theme did not always correspond to an unsatisfactory score for another theme on a particular sampling day (Table 5.3). Similarly no clear connections between cultural scores and season or preceding flow conditions could be determined.

Table 5.2: Proportion of unsatisfactory cultural scores at Bucklands for three flow categories. On one assessment day an overall assessment was not made.

Theme / Flow range	**<0.6 m^3s^{-1} (low)**	**0.6–1.4 m^3s^{-1} (intermediate)**	**> 1.4 m^3s^{-1} (high)**	**Total**
Flow				
Mahinga kai	3/4	1/6	1/4	5/14
Wai Māori	4/4	1/6	1/4	6/14
Health	4/4	1/6	1/4	6/14
Landscape	4/4	0/6	1/4	5/14
Overall	4/4	0/6	1/4	5/14
% Unsatisfactory	**95%**	**10%**	**25%**	
CHI				
Surface of the water	0/4	0/6	0/3	0/13
Water	0/4	0/6	0/3	0/13
Obstruction or litter	0/4	0/6	0/3	1/13
Overall	1/4	0/5	0/3	1/12
% Unsatisfactory	**6%**	**0%**	**0%**	

Table 5.3: Proportion of unsatisfactory cultural scores at Orbells for three flow categories. On one assessment day an overall assessment was not made.

Theme	<0.6 m^3s^{-1} (low)	0.6–1.4 m^3s^{-1} (intermediate)	> 1.4 m^3s^{-1} (high)	Total
Flow				
Mahinga kai	2/4	0/6	0/4	2/14
Wai Maori	3/4	0/6	0/4	3/14
Health	4/4	1/6	0/4	4/14
Landscape	3/4	2/6	1/4	6/14
Overall	4/4	1/5	1/4	6/13
% Unsatisfactory	**75%**	**13.8%**	**10%**	
CHI				
Surface of the water	0/4	0/6	1/4	1/13
Water	0/4	0/6	1/4	1/13
Obstruction or litter	0/4	0/6	1/4	1/13
Overall	0/4	0/5	0/3	0/12
% unsatisfactory	**0%**	**0%**	**25%**	

5.3 Impacts of land use change on water quantity and water quality

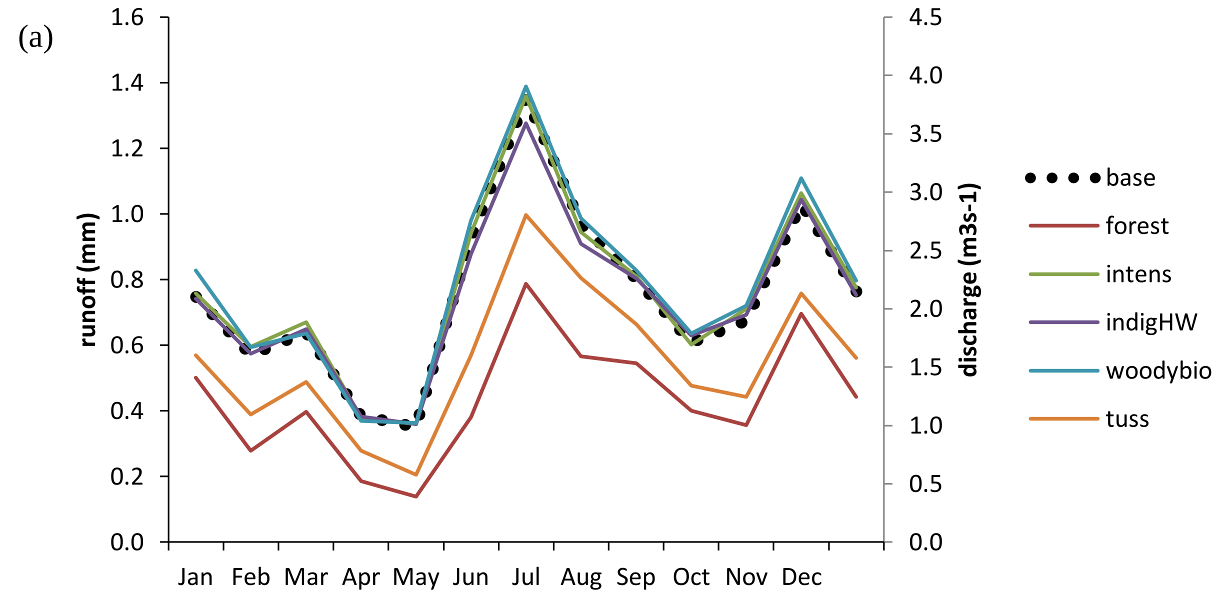
5.3.1 Scenario results for flow modelling in SWAT

Mean annual total runoff shows the most variation between the baseline and the native forest and tussock scenarios at Bucklands. Mean runoff for these scenarios is approximately 42% and 26% higher than the baseline (Table 5.4). In contrast, relatively little difference was detected between the baseline and the other scenarios (<5% difference). However, the magnitude of difference in mean monthly discharge is not consistent throughout the year. Although each scenario follows the same seasonal pattern the relative difference between scenarios is greater in May and April (Figure 5.4).

At Lawsons, the percentage differences in mean annual runoff between scenarios are smaller than Bucklands. The tussock and southern agriculture scenarios resulted in slightly more runoff compared to the baseline scenario (13% and 12% respectively), whilst the woody biomass scenario exerted a stronger influence; runoff was 31% higher (Table 5.4). The highest mean monthly discharge occurs in August across all scenarios except for the woody biomass scenario; discharge is higher in June. Under the woody biomass scenario the differences are more pronounced in November, December and January (Table 5.4).

Table 5.4: Estimates of mean annual runoff (in mm) and the percentage change in mean annual runoff compared to the baseline at Bucklands and at Lawsons.

Bucklands	**Baseline**	**Native forest**	**Intensive dairying**	**Indigenous headwater**	**Woody biomass**	**Tussock**
Mean annual runoff (total) (mm)	279	162	283	275	291	205
Percentage change (%)		-41.9	1.4	-1.5	4.1	-36.1
Lawsons	**Baseline**	**Native forest**	**Intensive dairying**	**Southern agriculture**	**Woody biomass**	**Tussock**
Mean annual runoff (total) (mm)	478	453	482	538	625	543
Percentage change (%)		-5.2	-0.8	12.4	30.6	13.5



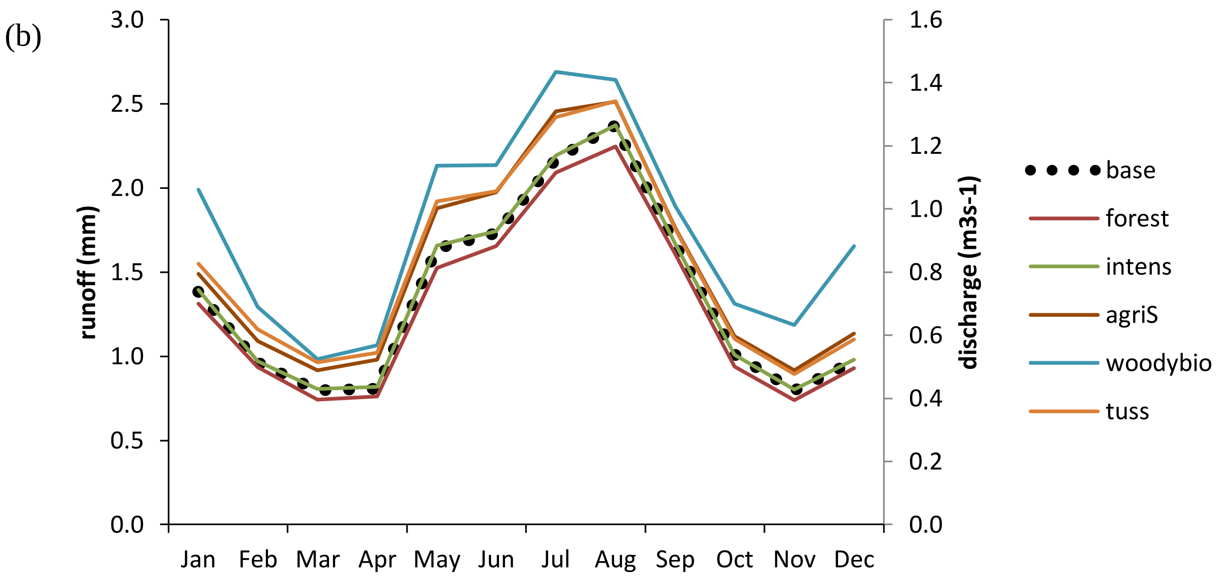


Figure 5.4: Mean monthly runoff /discharge for each land use scenario compared to the baseline (a) at Bucklands and (b) at Lawsons.

5.3.2 Runoff components

Under all scenarios at Bucklands the surface runoff contributions to total runoff are very similar. Surface runoff is slightly higher under the native forest and woody biomass scenarios and slightly lower in the tussock scenario (Figure 5.5). The tussock scenario has the lowest mean monthly groundwater levels; however, the other scenarios are all very similar; the same trend is observed in lateral flow contributions. The main differences in evapotranspiration are in the tussock and native forest scenarios. The shape of the evapotranspiration curve for these two scenarios also differs to the baseline with a peak in November (Figure 5.5).

At Lawsons there is more variation between scenarios in the makeup of total runoff. Surface runoff contributions are significantly higher in the woody biomass scenario but they are very low for the forest scenario. In terms of groundwater and lateral flow contributions to total runoff, all scenarios are very similar with the exception of the native forest scenario, which has significantly lower means. Evapotranspiration is higher in the native forest scenario than the other scenarios throughout the year, except in winter, and slightly lower during spring and early summer in the tussock scenario (Figure 5.6).

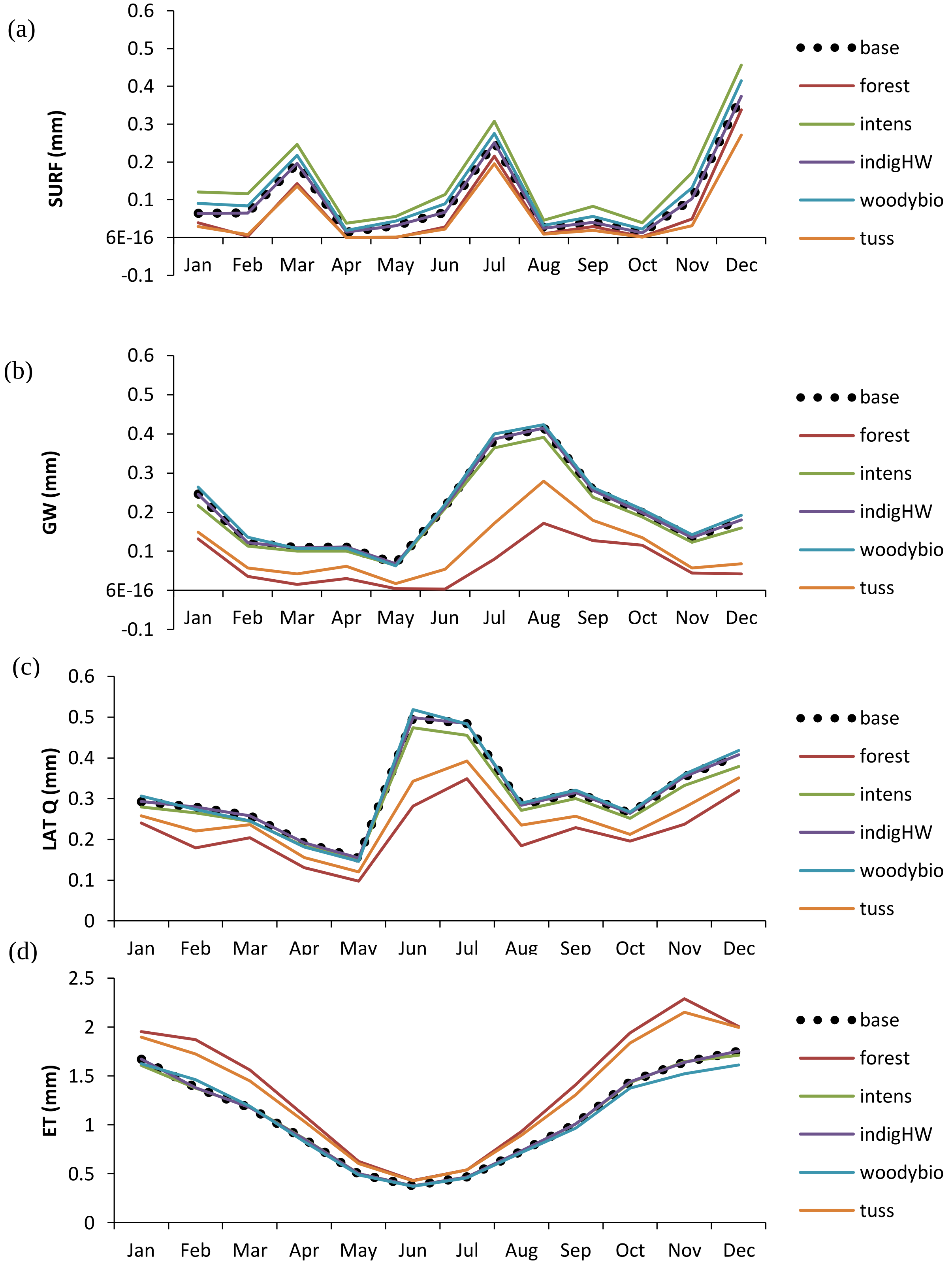


Figure 5.5: Mean monthly contribution of (a) surface runoff (surf), (b) groundwater (gw), (c) lateral flow (lat) to total runoff and (d) evapotranspiration (ET) in mm for each scenario at Bucklands.

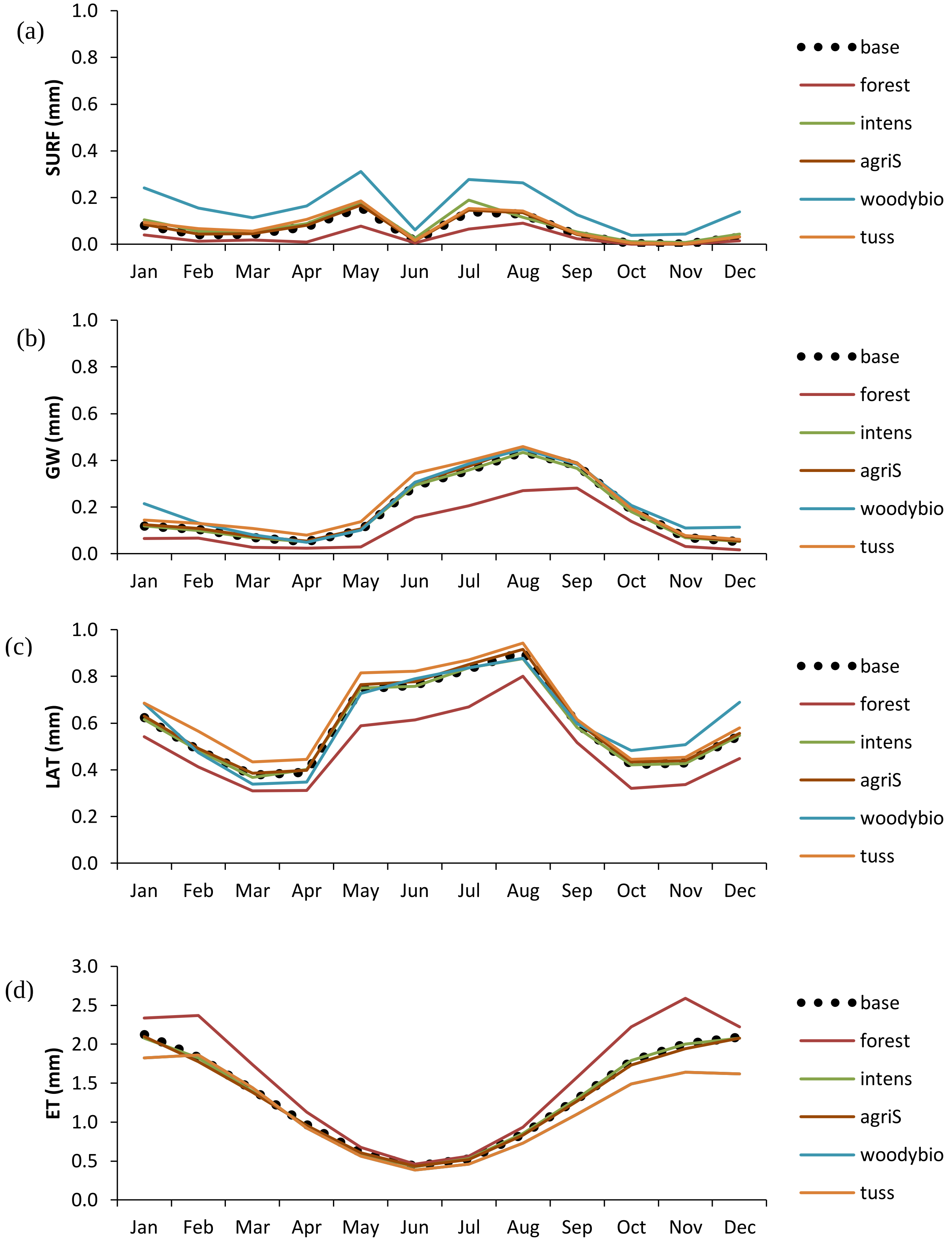


Figure 5.6: Mean monthly contribution of (a) surface runoff (surf), (b) groundwater (gw), (c) lateral flow (lat) in mm to total runoff and (d) evapotranspiration (ET) for each scenario at Lawsons.

5.3.3 Flow variation

The duration of flow varies little between the baseline and intensive dairying, indigenous headwaters, and woody biomass scenarios at Bucklands. Under these scenarios low flows dominate and flows above 1.0 m^3s^{-1} are less frequent (Figure 5.7). The lower flows characteristic of the tussock and native forest scenarios is clearly illustrated in the FDC. For these scenarios, 50% of the flow is ≤ 0.66 and 0.43 m^3s^{-1} (tussock and forest) (Table 5.7). The annual distribution of low and high flows is similar for all scenarios at Bucklands and the low flows typically occur in January and February (Figure 5.4). These low flows typically occur in summer except in the native forest scenario, which has low flows during the winter as well. High flows are more evenly spread throughout the year but more of the peak flows occur in January, July, August and September. Seven-day MALF for the baseline is 0.18 m^3s^{-1}. In the native forest and tussock scenarios the 7-day MALF flow is 86% and 73% lower than the baseline whereas it is 10% higher in the indigenous headwaters scenario (Table 5.4). Mean peak flow at Bucklands is 50.1 m^3s^{-1}. The variation in peak flows between scenarios is smaller than the variation in MALF. The smallest mean peak flow is in the tussock scenario (35.0 m^3s^{-1}) and native forest scenario (39.1 m^3s^{-1}) (Table 5.5).

Lawsons displays more variation in flow duration particularly amongst higher flows. The flow curves can be visually separated into three groups. There is almost no detectable difference between the intensive, indigenous headwaters scenarios, and the baseline but the tussock and southern agriculture scenario curves are steeper, and the woody biomass scenario has the largest high flows (Figure 5.8; Table 5.7). The low flows occur more frequently in March, February, and April. In contrast, high flows typically occur in August, July, and September. However, in the southern agriculture scenario high flows are most often in May and September (Figure 5.5). The baseline has a lower 7-day MALF (0.016 m^3s^-1) than all the other scenarios at Lawsons with the exception of the native forest scenario. The southern agriculture scenario and the woody biomass scenario have the highest 7-day MALF values (0.023 and 0,027 m^3s^{-1} respectively). Mean peak flow is similar in the baseline, native forest, intensive dairying, and southern agriculture scenarios (~21 m^3s^{-1}). In the woody biomass and tussock scenarios peak flows are 45% and 17% higher than the baseline (Table 5.5).

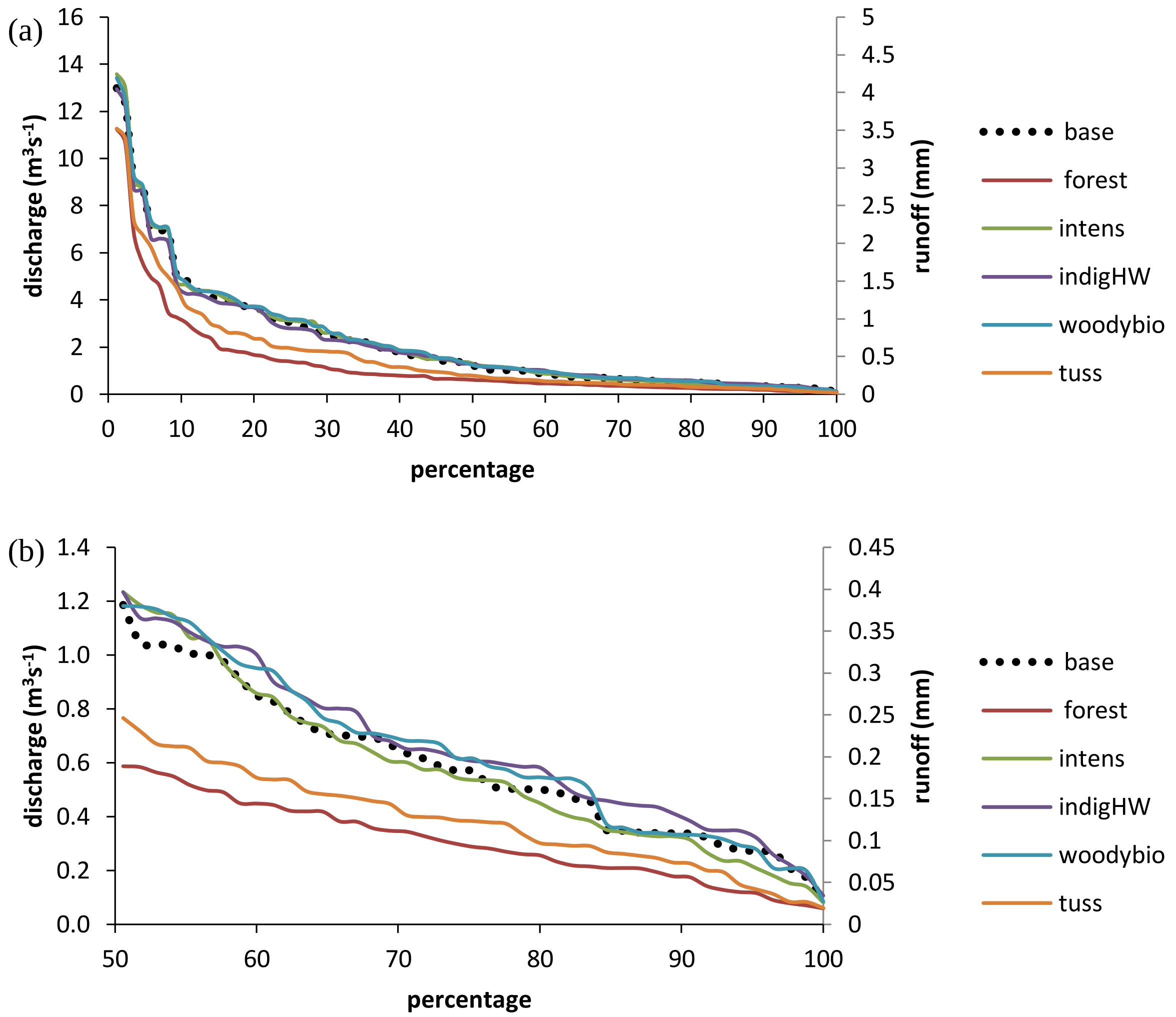


Figure 5.7: Flow duration curves for each land use scenario at Bucklands compared to the baseline using mean monthly discharge (runoff) (b) Flows between the 50th and 100th percentile.

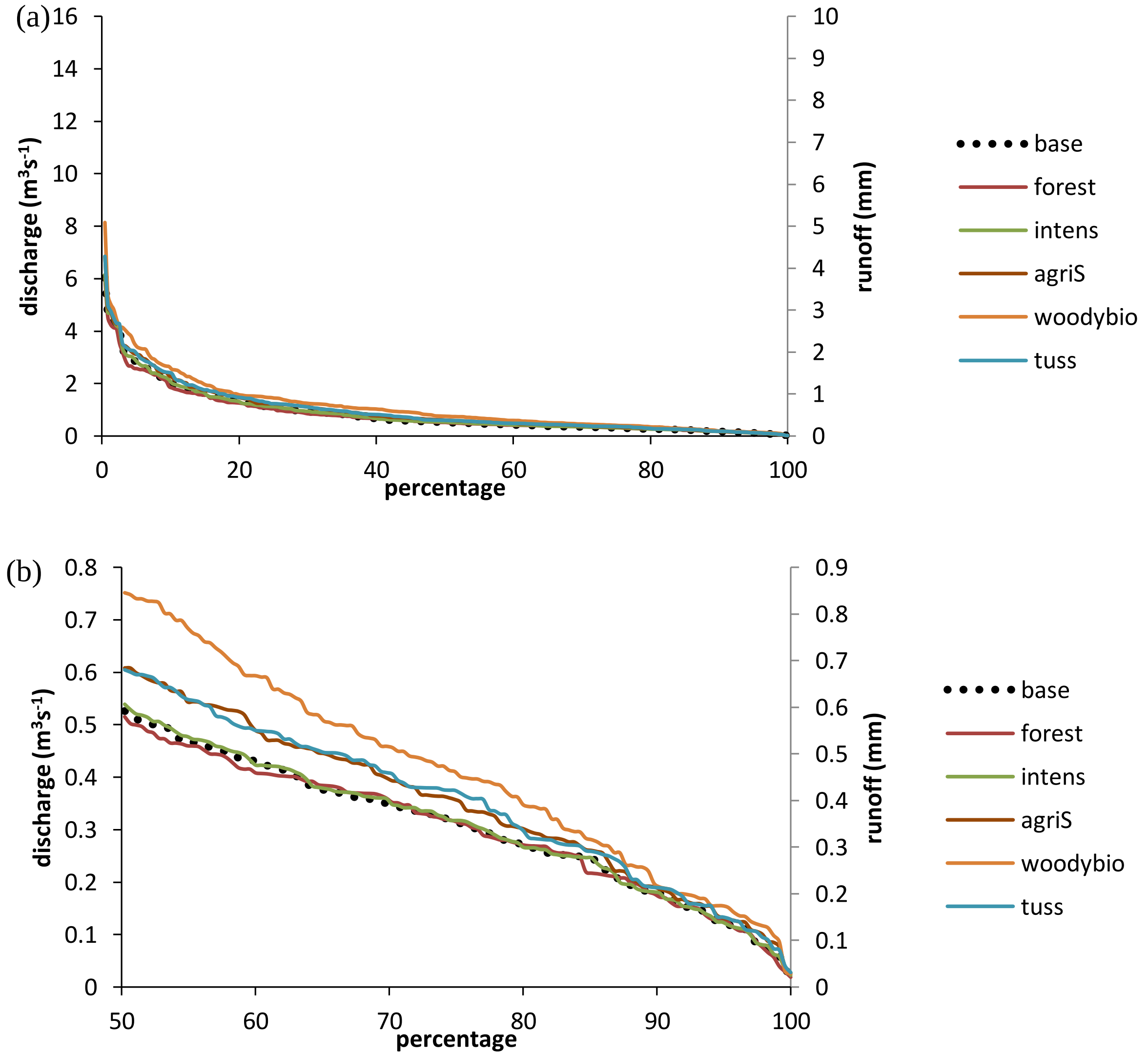


Figure 5.8: Flow duration curves for each land use scenario at Lawsonscompared to the baseline using mean monthly discharge (runoff) (b) Flows between the 50th and 100th percentiles.

Table 5.5: Seven-day MALF, median flow/runoff and mean peak flow for each scenario and the percentage different at Bucklands for the modelling period 1992-1999 and Lawsons for the modelling period 1991-2010.

Bucklands	Baseline	Native forest	Intensive dairying	Indigenous Head waters	Woody biomass	Tussock
7-day MALF (m^3s^{-1})	0.18	0.02	0.16	0.20	0.17	0.05
% difference		**-86.7**	**-13.4**	**10.2**	**-7.7**	**-73.5**
Median flow (m^3s^{-1-})	1.004	0.431	1.005	1.036	1.052	0.657
Median runoff (mm)	0.349	0.150	0.350	0.357	0.366	0.229
Mean peak flow (m^3s^{-1})	50.1	39.1	58.9	48.9	52.7	35.0
% difference		**-22.1**	**17.5**	**-2.5**	**5.1**	**-30.2**

Lawsons	Baseline	Native forest	Intensive dairying	Southern agriculture	Woody biomass	Tussock
7-day MALF (m^3s^{-1})	0.016	0.008	0.017	0.023	0.027	0.023
% difference		**-53.2**	**4.5**	**42.2**	**68.1**	**40.2**
Median flow (m^3s^{-1-})	0.404	0.372	0.406	0.462	0.515	0.466
Median runoff (mm)	0.632	0.582	0.635	0.722	0.806	0.729
Mean peak flow (m^3s^{-1})	21.2	19.5	21.9	23.5	30.9	25.0
% difference		**-8.3**	**3.2**	**10.8**	**45.3**	**17.5**

5.3.4 Impacts on species flow thresholds

The distribution of modelled daily flows for each land use scenario was compared to flow thresholds to meet habitat requirements for certain fish species. The indigenous headwater scenario has the most suitable flow conditions to meet species habitat requirements at Bucklands. Under this scenario, flow falls below the minimum flow level less often; 2.5% for eel and lamprey and 6.1% and 11.2% for juvenile and adult brown trout. The baseline, woody biomass and intensive dairying scenarios also have similar flow suitability. Under the tussock and native forest scenarios flow requirements for adult trout are below the threshold 24.5% and 31.2% of the time (Table 5.6). This also reflects the higher threshold for adult brown trout. In the baseline and tussock scenario adult trout conditions are most likely to be below the habitat preference threshold between December and May. In contrast, in the tussock and forest scenarios flow falls below the thresholds more often between June and September.

At Lawsons the southern agriculture, tussock, and woody biomass scenarios have the most suitable flow conditions for aquatic species. Under these scenarios flow is below the eel and lamprey thresholds about 8.5% of the time, whereas juvenile and adult brown trout flow thresholds are not meet approximately 15% and 26% of the time. The percentage of time flow is lower than the thresholds is slightly higher in the baseline and intensive dairying scenario and highest in the native forest scenario 13% for eel, 23% for juvenile trout, and 35% for adult trout. The species conditions were not suitable more frequently in March and April; for eel and lamprey this occurred mainly in summer whereas flow was below the trout thresholds throughout the entire year.

Table 5.6: Percentage of time flows are below recommendations to maintain habitat for fish species in the Waikouaiti catchment at Bucklands and Lawsons for each land use scenario.

Bucklands	**Baseline**	**Native forest**	**Intensive dairying**	**Indigenous headwaters**	**Woody biomass**	**Tussock**
Short and longfin eel and lamprey (juvenile)	2.6	10.0	2.6	2.5	2.8	7.4
Juvenile brown trout	7.5	22.4	7.6	6.1	7.3	16.6
Adult brown trout	14.2	31.2	14.3	11.2	13.7	24.5

Lawsons	**Baseline**	**Native forest**	**Intensive dairying**	**Southern agriculture**	**Woody biomass**	**Tussock**
Short and longfin eel and lamprey (juvenile)	10.9	13.8	10.7	9.0	7.3	8.9
Juvenile brown trout	20.1	23.9	19.8	17.0	14.8	16.5
Adult brown trout	31.5	35.2	31.2	27.7	24.5	27.2

5.3.5 Scenario results for water quality modelling in CLUES

Annual loads of total N vary more than annual loads of total P at both sites. At Bucklands the intensive dairying scenario resulted in a considerable increase in nutrient levels compared to the baseline. The largest total N load is seen in the intensive dairying scenario (~45 t yr^{-1}) whereas the native forest scenario has a significantly lower estimated total N load of ~2 t yr^{-1}. The other scenarios followed similar trends to the baseline. The total P estimates show less variation; all the scenarios have total P loads around 3 t yr^{-1} except for the intensive dairying scenario (6 t yr^{-1}). Orbells, downstream of Bucklands and the confluence displayed similar trends between scenarios but the nutrient loads were higher. Total nitrogen loads range from 4.76 t yr^{-1} for native forest to >50 t yr^{-1} under the intensive dairying scenario. In contrast, annual total P load ranges from ~ 4 to 8 t yr^{-1}. Sediment loads are quite different for every scenario at Orbells. The woody biomass has the lowest loads (10 kt y^{-1}); native forest is intermediate whilst sediment yields are greatest in the intensive dairying scenario (23 kt y^{-1}). The same trend is noted at Bucklands but the differences between scenarios are smaller (Table 5.7).

Total N concentrations are highest in the intensive dairying scenario and lowest for the native forest scenario at both sites. The median concentrations of total N range between 34 and 750 mg m^{-3} for the scenarios at Bucklands and between 64 and 740 mg m^{-3} at Orbells. Total P concentrations are very similar at both sites for all scenarios with the exception of intensive dairying. Concentrations are ~34 mg m^{-3} at Bucklands and slightly higher at Orbells. The total P concentration for the intensive dairying scenario is 69.2 mg m^{-3} and 73.96 mg m^{-3} at Bucklands and Orbells respectively (Table 5.7).

Table 5.7: Estimates of total N and total P annual loads (t yr^{-1}), sediment (kt yr^{-1}) and total N and total P concentrations (mg m^3) from CLUES for each of the land use scenarios at Bucklands and Orbells.

	Total N load (t yr^{-1})	**Total P load (t yr^{-1})**	**Sediment (kt yr^{-1})**	**Total N conc (mg m^{-3})**	**Total P conc (mg m^{-3})**
<u>Bucklands</u>					
Baseline	17	3	15	286	33
Native forest	2	3	11	34	36
Intensive dairying	45	6	15	747	69
Indigenous Headwater	16	3	14	265	34
Woody biomass	15	3	7	247	36
Tussock	13	3	7	221	34
<u>Orbells</u>					
Baseline	24	4	23	319	38
Native forest	5	5	21	64	41
Intensive dairying	54	8	23	737	74
Indigenous Headwater	23	4	22	310	39
Woody biomass	21	5	10	289	41
Tussock	19	5	12	260	41

5.4 Consequence table

The consequence tables (Table 5.8) combine the results of the flow and water quality modelling and cultural stream health assessments in a visual summary that allows for the comparison of scenarios at Bucklands and Orbells.

At Bucklands low flows are reduced by more than 50% compared to the baseline while runoff and peak flows also decrease. This results in more days with flow below the species thresholds, especially for juvenile trout. The reduction in flow is contrasted with an improvement in water quality; total N loads decrease by >50%. Thus, whilst native vegetation may improve the feel and pride of the site, access could be more difficult and the overall resource only ‘ok’ due to the trade-off between water quality and flow. The intensive dairying scenario has mixed results for flow; mean annual runoff increases slightly, peak flows also increase but low flows decrease by 10.1-30%. The impacts on fish are minor except for adult trout. However, dairy activity results in a major deterioration of water quality; both total N and P loads increase by >50%. This scenario would not be culturally favourable as feel and pride in the site would be diminished. Access could also be restricted by private ownership of farms, compromising the overall resource. Impacts on flow and water quality were minor at Bucklands in the indigenous headwaters scenario. Runoff and peak flow decreased slightly (0.1-10%) whereas low flows increased (10.1-20%.) This impacted most on adult trout (10.1-30% of days below the threshold). Total N and sediment loads were slightly reduced (0.1-10%) but total P loads were unchanged. Lower flows would probably lessen positive feelings at the site but improvements in water quality may improve the overall resource. Impacts on water quantity in the woody biomass scenario are mixed but minor and thus impacts on species thresholds are also small. Total N increases (10.1-30%) whereas sediment loss is significantly reduced (>50%). Therefore, cultural feel, pride and access are probably considered ‘ok’ in this scenario potentially improving the overall water resource. The tussock scenario consistently reduces yield in terms of runoff (0.1-10%), and peak and low flows (30-50%). This affects the habitats thresholds for both juvenile and adult trout. Total N decreases by 10.1-30% and sediment loads by >50%. Thus, tussock would likely improve cultural feel and pride.

At Orbells, improvements in water quality in the native forest scenario would likely improve cultural feel and pride. Total N loads decrease by >50%. In contrast to the native forest scenario, intensive dairying increased total N and P loads by >50% with no change in sediment yields compared to the baseline. As at Bucklands, this scenario would negatively affect cultural values. The indigenous headwaters scenario results in small decreases in total N and sediment loads (0.1-10%) and thus would have minor impacts on cultural values. All values could be considered 'ok' in this scenario. The woody biomass scenario results in decreases in total N (10.1 -30%) and sediment (>50%) but total P is amplified (10.1-30%). This could result in a trade-off between increases in one nutrient but decreases in another. Overall the water resource would be 'ok' in this scenario and other values not significantly compromised. Finally, the tussocks reduce sediment loads (30-50%) and total N (10.1-20%) but total P loads are higher than the baseline (10.1-30%) as in the woody biomass scenario. Feel and pride may be improved by tussock landscapes while the overall resource may be considered ok.

Table 5.8: Consequence table for Bucklands summarising the consequences/impacts of each land use scenario on important flow, water quality, and cultural variables/values. % change (compared to the baseline); ▲ 0.1-10%, ▲▲ 10.1-30%, ▲▲▲ 30.1-50%, ▲▲▲▲ >50%, ▬ no change. % of days below the species habitat flow threshold; ●0.1-10%, ●● 10.1-30%, ●●●● 30.1-50%. Cultural values based on predicted outcomes.

Variable/value	**Consequence/impact**					
<u>Bucklands</u>	**Baseline**	**Native Forest**	**Intensive dairying**	**Southern Agriculture**	**Woody biomass**	**Tussock**
% change in:						
Mean annual runoff (mm)	**247.2**	▼▼▼	▲	▼	▲	▼▼
Average 7- day MALF (m^3s^{-1})	**0.18**	▼▼▼▼	▼▼	▲▲	▼	▼▼▼
Average peak flow (m^3s^{-1})	**50.1**	▼▼	▲▲	▼	▲	▼▼▼
Total N load (t yr^{-1})	**17**	▼▼▼▼	▲▲▲▲	▼	▲▲	▼▼
Total P load (t yr^{-1})	**3**	▬	▲▲▲▲	▬	▬	▬
Sediment load (kt yr^{-}1)	**15**	▼▼	▬	▼	▼▼▼▼	▼▼▼▼
% of days below the species habitat flow threshold:						
Eel and Lamprey	●	●	●	●	●	●
Adult brown trout	●●	●	●●	●●	●●	●●
Juvenile brown trout	●	●●	●	●	●	●●
Cultural values:						
Feel	Improved	Poor	Poor	Ok	Improved	Improved
Pride	Improved	Poor	Poor	Ok	Improved	Improved
Access	Ok	Compromised	Compromised	Ok	Ok	Ok
Overall resource	Ok	Poor	Improved	Improved	Ok	Ok

Table 5.9: Consequence table for Orbells summarising the consequences/impacts of each land use scenario on important flow, water quality, and cultural variables/values. % change (compared to the baseline); ▲ 0.1-10%, ▲▲ 10.1-30%, ▲▲▲ 30.1-50%, ▲▲▲▲ >50%, ▬ no change. % of days below the species habitat flow threshold; ●0.1-10%, ●● 10.1-30%, ●●●● 30.1-50%. Cultural values based on predicted outcomes.

Variable/value	**Consequence/impact**					
<u>Orbells</u>	**Baseline**	**Native Forest**	**Intensive dairying**	**Southern Agriculture**	**Woody biomass**	**Tussock**
% change in :						
Total N load (t yr^{-1})	**24**	▼▼▼▼	▲▲▲▲	▼	▼▼	▼▼
Total P load (t yr^{-1})	**4**	▲▲	▲▲▲▲	▬	▲▲	▲▲
Sediment load (kt $yr^{-}1$)	**23**		▬	▼	▼▼▼▼	▼▼▼
Cultural values:						
Feel	Improved	Poor	Poor	Ok	Improved	Improved
Pride	Improved	Poor	Poor	Ok	Improved	Improved
Access	Ok	Compromised	Compromised	Ok	Ok	Ok
Overall resource	Ok	Poor	Ok	Ok	Ok	Ok

5.5 Summary

In this chapter the baseline hydrological conditions as modelled in SWAT and CLUES and the results of the cultural stream health assessments were described. Modelled mean annual runoff was lower for Bucklands than Orbells. The CLUES modelling showed annual total P loads were similar at Orbells and Bucklands but total N and sediment loads were higher at Orbells than Bucklands in the baseline. Bucklands had more unsatisfactory scores in the cultural stream health assessments than Orbells. The most frequently scored unsatisfactory themes at Bucklands were wai Māori whereas at Orbells the landscape and overall themes received the most unsatisfactory scores. At Bucklands the biggest change in flow was decreases in water yield from the native forest and tussock scenario. In contrast to Bucklands, the biggest impact in quantity at Lawsons was increases in water yield from the woody biomass scenario. At both Orbells and Bucklands water quality was dramatically reduced by large increases in total N and total P loads under the intensive dairying scenario. The woody biomass and tussock scenarios reduced sediment yields at both sites compared to the baseline. The consequence table integrated the different data sources and provided a visual summary and comparison of consequences of each scenario at Bucklands and Orbells. This illustrated both connections and trade-offs for example between improved water quality and reduced flows.

Chapter 6: Discussion

6.1 Introduction

Scientific and cultural data are distinct in generation, processing, analysis, and interpretation but much can be gained by integrating the data as equally informative and valid sources of information. However, integrating such data is challenging and careful consideration is required to ensure neither data source loses integrity by attempting to transform data from one format to match the other data format. On that basis this chapter examines ways to integrate scientific and cultural data from the Waikouaiti case study in a way that will be informative for freshwater management. The results of the land use simulations executed in SWAT and CLUES are first considered using scientific rationalisation to explain the results in Sections 6.2 and 6.3. In Section 6.4 the results of the cultural assessments are interpreted and the potential impacts of the different land use scenarios on cultural values are explored, methods for cultural and scientific data integration are discussed. Finally, the limitations of the research are acknowledged and the direction for future research is suggested.

6.2 The modelled impacts of land use change on flow regimes

Land use changes in a catchment can alter flow regimes due to differences in the interception of rainfall and evapotranspiration in different types of vegetation (Duncan and Woods, 2004). The results of the SWAT land use simulations described in Section 5.3 clearly illustrate that land use has an influence on catchment hydrology in the Waikouaiti River. This section interprets the results, explores explanations for the hydrological differences between land uses, and considers the implications for aquatic species.

6.2.1 Native forestry

Mean annual water yields, low flows, and peak flows at Bucklands were all decreased in a native forest catchment compared to the baseline landscape of low-producing grassland. These results are consistent with experimental studies conducted in a variety of New Zealand catchments which found both pine and native forests typically yield less water than pasture catchments (e.g. Pearce *et al.,* 1982; Smith, 1987; Rowe, 2003; Duncan, 1995; Fahey *et al.,* 2004.) Similarly, increasing native forest coverage also decreased water yields at Lawsons compared to the baseline which is a mix of native forest and low producing grassland. Differences between tall (trees) and short (grassland) vegetation can be largely accounted for by differences in evapotranspiration. The canopy coverage of a forest is larger than grass which results in increased evapotranspiration and therefore less water available for runoff and streamflow. Evapotranspiration is further divided into transpiration (dry leaf evaporation) and interception loss (wet leaf evaporation). Although SWAT does not define transpiration and interception loss, the main differences between tall and short vegetation is transpiration loss (Davie and Fahey, 2005). Trees have a larger leaf area for interception and evaporation and more aerodynamic roughness at the top of the canopy results in turbulence. The evaporated water is easily mixed with the drier from above and thus evaporation rates from wet forest canopies are high (Scotter and Kelliher, 2004).

The SWAT modelling showed a 42% decrease in mean annual runoff under native forest at Bucklands (Table 4.2) which is within the range (30-81%) reported from experimental catchment studies in New Zealand (Pearce *et al.*, 1982; Smith, 1987; Rowe, 2003; Duncan, 1995; Fahey *et al.*, 2004). The modelled difference of 42% under the native forest scenario is very similar to the 43% reduction after the conversion of forest to pasture in another schist-dominated East Otago catchment (Smith, 1987) and is also similar the average reduction of 44% calculated by Farley *et al.* (2004) in the analysis of several international paired catchment experiments. The wide variation in published results (30-81%) reflects differences in regolith, rainfall regime, soil moisture storage (Rowe and Pearce, 1994), climate, forest type, or terrain (Fahey and Jackson, 1997b) between catchments. The lower yields at Bucklands can be attributed to evapotranspiration, evapotranspiration rates in the native forest scenario are 27% higher than the baseline (Figure 4.6) Trees generally have deeper rooting depths than pasture allowing access to more water during dry spells. In SWAT, the maximum rooting depth for native forest was 30% deeper than for grass which in part could explain the water use patterns in the native forest scenario. However, Schenk and Jackson (2002) demonstrate that rooting depth is more closely aligned with climatic variables than life form; that is plants will adapt their rooting depth according to the climatic regime where they occur.

The effects of low flows are difficult to predict as they are dependent on the amount and distribution of rainfall and other hydro-geological variables (Fahey *et al.*, 2004). The modelled results for the native forest scenario at Bucklands showed a large reduction in the 7-day MALF (86%) (Table 4.6) compared to the baseline. This is greater than the 20% decrease reported by Smith (1987) and 11% decrease noted in a hill country catchment in Whatawhata, Waikato (Quinn and Shroud, 2002). Generally low flows are less affected by afforestation than total yields (Davie and Fahey, 2005) but this can vary depending on the low flow measure used and the areas of low flow generation within the catchment. It would appear at Bucklands, the lack of wetland storage areas and lower rainfall compared to the rest of the catchment makes Bucklands susceptible to variation in water balance on the hillslopes (Davie and Fahey, 2005). Another factor to consider is the modelled flows. In the native forest scenario at Bucklands SWAT predicted several days with mean flows close to, or exactly, zero, suggesting flow may cease in a 100% afforested catchment. The large reduction could in part be due to the amount of zero flow days in the native forest scenario, which skews the results and make statistical analysis difficult (Fahey *et al.*, 2004). It is hard to quantify the accuracy of SWATs prediction but SWAT may have under predicted the lowest flows in the native forest scenario given the observed data at Lawsons which is predominately native forest had no days with zero flows yet in the calibration and validation of the model at Lawsons there were days with zero flows, suggesting SWAT under predicts low flows. In contrast to the large reduction in low flows, mean peak flows were predicted to decrease by 22% in the native forest scenario at Bucklands. This is likely a function of comparing percentage changes. A small absolute change in a small number can appear as a large change when converted to percentage and *vice versa* for large numbers. This somewhat limits comparison between the changes in low flows and high flows. It could also limit comparison with other studies where baseline flows are different. Afforestation ameliorates the impacts of precipitation events that cause flooding due to the interceptive and storage capacities of trees. Overall native afforestation has a bigger impact on low flows than peak flows at Bucklands.

At Lawsons, the native forest scenario returns the lowest mean annual runoff but runoff is only 5% lower than the baseline compared to the 42% reduction simulated for Bucklands under the same scenario (Table 4.2). The difference is because the baseline characteristics differ between the two sites. At Bucklands, almost 100% of the baseline grasslands were converted to native forest whereas at Lawsons, only half of the southern extent was converted to native forest as the baseline already comprises mostly native and exotic forests. The relatively small percentage reduction in runoff can be explained by the vegetation similarities between the two scenarios. Therefore, the small change in runoff is consistent with the relatively small change in vegetation. Under native forest at Lawsons the small afforestation results in moderate increases in evapotranspiration, very small decreases in ground water and lateral flows with modest increases to the contribution of surface runoff to total water yield which is reflected in the diminutive impacts on runoff, low flows, and peak flows. The small increase in trees would have only minor effects on ameliorating storm runoff and reducing low flows at Lawsons.

6.2.2 Tussocks

At Bucklands, the tussock scenario yielded lower runoff than the baseline. This finding contradicts the expected water use of tussock compared to pasture. Generally transpiration rates for tussock are lower than grass and thus, runoff higher (Campbell and Murray, 1990). However, this result may be due to the spatial composition of vegetation in the tussock scenario. The tussock scenario comprises a mixture of tussock and native forest. Although the majority of land in the North Branch in the tussock scenario is tussock vegetation, there is a parcel of native forest just upstream of the Bucklands site. It appears the spatial location of the native vegetation is dominating runoff response. This is confirmed by higher evapotranspiration and the lower lateral flow, surface flow and groundwater contributions to total runoff at Bucklands (Figure 4.7), the same controls were exhibited in the native forest scenario described in Section 6.2.2. It appears the interceptive and storage properties of trees described in section 6.2.2 are counteracting the conservative use of water of tussocks further upstream and inland, dominating the runoff response.

The tussock scenario at Lawsons generated the second highest mean annual runoff, a 13.5% increase compared to the baseline, which is predominately native forest (Table 4.2). These findings are consistent with experimental studies in pine and tussock catchments (Fahey and Watson, 1991; Fahey and Jackson, 1997b). Tussock yields high runoff due to a conservative use of water (Campbell and Murray, 1990); however, the exact mechanisms controlling this are debated in New Zealand (Section 2.2.5). At Lawsons, mean evapotranspiration in the tussock scenario is lower than the baseline simulation in all months except February and March; in both cases it is only slightly higher (Figure 4.7, d). This is good evidence to suggest that lower evapotranspiration rates are in part responsible for higher runoff yields under tussock. In terms of total runoff, the surface flow and groundwater contributions under the tussock scenario are similar to the baseline but differ in lateral flow, which is higher than the baseline under the tussock scenario.

The magnitude of low flows in the tussock scenario were also larger than the baseline (Table 4.3), consistent with experimental studies (Fahey and Watson, 1991; Fahey and Jackson, 1997a). Peak flows at Lawsons were 16% higher in the tussock scenario which is smaller than the difference observed at Glendhu between mature pines and tussocks; peak flows were 42% greater. The difference between the two catchments is likely due to differences in initial conditions. At Lawsons the baseline is a mix of grasslands and forestry of which some of the latter remains in the tussock scenario, therefore explaining the smaller percentage difference.

6.2.3 Woody biomass

Woody biomass (or scrub) is an intermediate vegetation structure and the hydrological responses of a woody biomass catchment are expected to fall somewhere between a grass and forest catchment. Water yields should be lower than that from a grass catchment but higher than a forest catchment (Brown *et al*., 2005). The response of tall scrub is closer to forest due to the similarities in interception and water storage capacities although there may be differences for shorter scrub (Fahey *et al.*, 2004). The SWAT simulations estimated the woody biomass scenario would yield higher mean annual runoff than the baseline simulation at Bucklands; although runoff is lower in March and April. Given vegetation such as scrub is expected to use, intercept, and transpire more water than grass resulting in lower runoff (Fahey *et al*., 2004), the modelled results for the woody biomass scenario seemingly contradicts the theory. The woody biomass scenario exhibits higher surface runoff and lower evapotranspiration than the baseline at Bucklands which is causing the higher annual water yields and hence contradicting the theory. To further complicate the results from this scenario, low flows are estimated to decrease slightly (in line with expectations) whereas peak flows would increase, also contradicting theory. One partial explanation for this phenomenon could be the parameterisation of woody biomass vegetation in SWAT. In SWAT woody biomass was represented by relatively short vegetation and has some parameter values that are similar to low producing grassland. It may be that the parameter similarities of the two vegetation types are to similar resulting in mixed and contradicting annual signals whilst at the monthly scale, some of the results are consistent with expectations. Indeed, a Lawsons where the difference in parameterisation between (short) woody biomass and forest are more pronounced the signals in water yield make more physical sense and agree with theoretical expectations.

Runoff from the woody biomass scenario at Lawsons is substantially higher than the baseline (30.6%). Thus, the simulations at Lawsons agree with expectations that woody biomass yields higher runoff than forested catchments. This percentage increase is comparable with the 37% increase observed by Rowe (2003) and the 31% difference reported by Duncan (1995) in experimental studies in New Zealand between scrub and pine dominated catchments. It is interesting to note the similarities in percentage change given the difference in climate between the Waikouaiti, Rowe's (2003) study near Auckland and Duncan's (1995) results in Nelson. Whilst forest and scrub both have a canopy cover, interception and transpiration losses are smaller in woody biomass, resulting in the decreased water yields. Of the components making up total runoff (surf, lat, and gw), the greatest differences between the baseline and the woody biomass scenario is in surface runoff (Figure 4.7, a, d). Evapotranspiration is lower than the baseline especially in August–January, whereas lateral flow is more influential in October–December, whilst groundwater contributions are higher between November and February (Figure 4.7). Average peak flows in the woody biomass scenario are about 33% higher than the native forest scenario which is slightly smaller than the roughly 50% increase in peak storm flows observed by Duncan (1995). So even though the impact on annual yields is similar to other published studies, the smaller vegetation seems to have a lesser impact on peak flows.

6.2.4 Southern agriculture and Indigenous headwaters

The southern agriculture scenario replaces native vegetation in the South Branch with low producing grassland. Based on the trends described in Bucklands for the opposite land use change (grassland to native forest), water yields are expected to be higher in the southern agriculture scenario. A 12% increase in mean annual runoff was predicted by the SWAT modelling and can be explained by reduced evapotranspiration rates in the shorter vegetation converting a higher proportion of runoff directly to surface runoff (Fahey and Rowe, 1992). Evapotranspiration is on average 1.7% lower in the southern agriculture scenario compared to the baseline whilst surface runoff is on average 6.9% higher in the southern agriculture scenario (Figure 4.14). Lateral flow and groundwater contributions to total runoff are also slightly higher than the baseline reflecting the lower water requirements of grass. This is probably also due to shallower rooting depths and lower water requirements of grassland. The impacts of increasing agricultural in the South Branch at Lawsons are more profound for low flows (a 42% increase in the 7-day MALF compared to a 10% increase in average peak flows).

Replacing agriculture with native vegetation in the North Branch headwaters (Indigenous headwaters scenario) had relatively little effect on runoff at Bucklands. The overall effect was a small decrease in mean annual runoff (Table 5.4) but with small monthly increases in February-May and September-December (Figure 5.4). The impacts on floods and low flows were also moderate; 7-day MALF increased by 10% and the average peak flow was 2.5% lower. These mixed results would suggest moderate vegetation changes in the headwaters at this scale have little effect on runoff further downstream. In the upper catchment mean annual runoff is lower in the sub basins draining the area of indigenous forest. This is consistent with the theoretical expectation that runoff is lower from forest than grass as seen in the native forest scenario. In the upper catchment evapotranspiration and surface runoff are similar to the baseline but in this part of the catchment groundwater and lateral flow contributions to discharge are lower. Therefore, although the expected decreases in yields are apparent in the upper catchment, the spatial distant between the indigenous headwaters and the gauging site at Bucklands acts to ameliorate any effects on the hydrological regime.

6.2.5 Intensive dairying

Intensifying dairy farming (intensive dairy scenario) had little impact on runoff at both locations. Intensifying land use at Lawsons only increased mean annual yields by 0.7%. Only a small proportion of land in the South Branch is suited to dairying (slope <20°) so the intensive scenario at Lawsons is very similar to the baseline in terms of land cover; less than 5% of the land area feeding into Lawsons is suited to dairying. In the North Branch more land is converted to dairy farms under the intensive scenario, however, the increase in mean annual runoff was modest (1.5%) (Table 4.2). The physical characteristics of low producing grassland and high producing grassland are very similar. Low and high producing grass have similar water requirements and storage capacities with lower interception and evaporation rates than taller vegetation like trees, so the controls on runoff generating mechanisms are similar. In both cases the amount of evapotranspiration and the contribution of groundwater, lateral, and surface runoff to total runoff are very similar to the baseline scenario (Figure 4.13). This scenario did not account for the likely increases in water withdrawal for irrigation (Section 3.7) which would potentially represent a significant draw on water resources especially in the North branch. Therefore the impacts on low flows and floods was minor at Lawsons but interestingly at Bucklands, the average peak flow increased by 17% whilst 7-day MALF decreased by 13%. The decrease in low flows is inconsistent with the expectation that flows would be similar under dairying and the baseline. Although the percentage difference is 13% in absolute terms mean annual runoff decreases from 0.18 to 0.16 mm which is actually very small. The increase in peak flows is likely due the higher surface runoff under the intensive dairying scenario. This is probably reflective of small areas of forest or scrub in the baseline that are replaced with dairying in the intensive dairying scenario. Overall, increasing dairying has a small effect on peak flows at Bucklands but otherwise little impact on other aspects of the flow regime.

6.2.6 The implications of altered flow regimes on aquatic species

Changes in flow regimes due to land use modifications have a deleterious impact on the aquatic ecosystems within a stream (Duncan and Woods, 2004). The Waikouaiti River is highly regarded for its diverse fish communities comprising both native and exotic species. Changes in flow regime may affect species migration as well as the habitat and feeding of aquatic species (ORC, 2011). An ORC investigation used habitat modelling to recommend optimum flows required to maintain an acceptable habitat for a range of aquatic species found in the Waikouaiti River (ORC, 2011). Comparing the simulated flow to these habitat preference thresholds showed considerable variation between scenarios.

Brown trout are diadronous, which requires part of their life cycle to be spent at sea (Jowett and Richardson, 2003). Trout migration is in spring (McDowell, 1995) and their preferred habitat is the estuary or big pools upstream (ORC, 2011). The average daily runoff was below optimum adult brown trout conditions 14% of the time at Bucklands and 32% at Lawsons in the baseline simulation, indicating that habitat may be naturally limited by low flows (Table 4.4). The optimum conditions are violated most frequently under the native forest scenario. Thus, it can be noted that there is an interesting negative feedback between restoring indigenous forest and its effect on sustaining introduced trout species. Native species are adapted to suit more regular low flow conditions, so conversion to native forest may benefit native species, at the expense of trout, which also compete and displace native species. In the example of the Waikouaiti, the reduced flows occurred more often in summer/early autumn so there may be less of an effect on spring migrations of trout. Furthermore, trout preference for big pools means trout are less affected by low flows in general (ORC, 2011), assuming that stream morphology is conducive to pool formation.

The abundance and biomass of eels is affected by a combination of biological factors including flow regimes. In particular, the variation in quantity and velocity of flows is strongly related to food supplies and instream resting and feeding habitats (Jellyman and Lambert, 2006). However, eels and lamprey are more tolerant to low flows than other aquatic species (ORC, 2011) and have the lowest optimum flow threshold. Under all land use scenarios a higher proportion of days were below the threshold in January and February. In the baseline, woody biomass, and indigenous headwaters scenarios runoff is always suitable during the winter months. Given that short fin eel migrate between between July and November (Jowett *et al.,* 2005) the higher proportion of low flows in January and February would not impact migration. Jowett *et al.,* (2005) found that native species like eel tended to be well adapted to high flows so the distribution of high flows should not affect the eel and lamprey, although this analysis discounts the role of competition with other introduced species, like trout.

Land use changes that affect flow and, therefore, species habitat and distribution also have additional feedbacks that impact aquatic species. The removal of forests, especially in headwaters can homogenise stream habitat conditions. For example, in scenarios such as the southern agriculture scenario at Lawsons, the increase in flow and fewer days below species thresholds may be counteracted by a loss of species adapted to high shade and cool temperatures (Quinn *et al.,* 1997). However, New Zealand fish are thought to have a wide temperature tolerance (Parkyn and Wilcock, 2004). As well as moderating temperatures, shade provided by forests prevents algal proliferations (Quinn *et al.,* 1997; Rutherford *et al.,* 1997). Trees also support bank stabilisation during flood events which preserves habitat in the form of woody debris and tree roots (Parkyn and Wilcock, 2004). Additionally, the removal of trees represents a loss of food; dissolved organic matter and leaf litter are an important energy base in aquatic food webs in forests (Parkyn and Wilcock, 2004).

6.2.6.1 Section summary

In general the modelled results were consistent with experimental studies but there were some exceptions. Yields were lower in the native forest scenarios at Bucklands and Lawsons. Yields were also lower in the tussock scenario and higher in the woody biomass scenario at Lawsons. A number of potential explanations for these results were suggested including under prediction of low flows by SWAT or the spatial variation of and extent of vegetation in a particular scenario in relation to the gauging sites. The biggest impact on species flow habitat preferences was under the native forest scenario on adult brown trout who are least tolerant to low flows although there could be a positive feedback for native species more tolerant of low flows and an enhanced habitat because of more shade.

6.3 The modelled impacts of land use change on water quality

Land use changes in a catchment also impacts water quality. Excess nutrients on the land can be lost to rivers and different vegetation types can be conducive to erosion which delivers sediments to waterways. Water pollutants include point sources like effluent that can be directly traced to a known location or diffuse sources which are harder to trace and understand. Diffuse sources fall into three categories; sediment, bacterial, and nutrients. The water quality modelling in CLUES investigated sediments, and the nutrients; nitrogen and phosphorus. This section focuses first on how these pollutants enter the water in different land use scenarios then describes how excessive concentrations can be detrimental to water quality. Water quality was modelled at Bucklands in the North Branch and at Orbells downstream of the confluence. The trends between scenarios were the same at each location but the loads and concentrations were higher at Orbells downstream of the confluence due to accumulation.

6.3.1 Land use scenarios

The intensive dairying scenario had the greatest impact on nutrient levels at both sites. Total N increased by more than 200% at Bucklands and Orbells and total P loads doubled compared to the baseline indicating a significant change due to land use. The large increases in nutrient loads estimated under intensive dairying can be attributed to excess inputs in the farm systems which when not fully utilized are lost to waterways. A common source of nitrogen from dairy farms is urea in animal urine. The nutrients ingested by animals are poorly utilized in the production of milk so are excreted as waste (Monaghan *et al*., 2010). As nitrogen is generally available in highly soluble forms, in a waterlogged paddock it can filter through the soil profile, leach into groundwater and eventually into streams. Nitrogen can also travel directly to waterways as overland flow. Additionally, cows being a heavy animal trample and pug the soil creating a direct pathway for overland flow and compacting soils which restricts root penetration, slowing plant and the uptake of nutrients.

The increase in phosphorus seen in the intensive dairying scenario is likely attributable to supplemented superphosphate used to boost grass growth (Rutherford *et al.*, 1987) but it is also found in animal effluent in a concentrated and readily available form (Kleinman *et al.*, 2005). As described in Chapter 2 phosphorus is mainly carried by soil particles although some forms are dissolved in water and lost to waterways via leaching. Bound to particles, it is susceptible to the highest loss in areas with high rainfall rates, steep slopes or soil prone to erosion. The cleared, sloping hill country of the Waikouaiti provides ideal conditions for erosion loss and would aid the loss of additional nutrients to waterways if dairy farming increased in the catchment. The elevated levels of total N and total P in the intensive scenario compared to the baseline and all other scenarios are consistent with experimental studies in New Zealand (e.g. Quinn and Shroud, 2002). A conversion from sheep and beef to dairying on a Canterbury farm resulted in a 230% increase in nitrogen yields (PCE, 2013) which is comparable to the 230-265% increase in total N loads predicted in the CLUES modelling (Table 5.1).

Nutrient losses in the intensive dairying scenario were higher than the baseline yet sediment loads were the same. In both scenarios the physical properties of the land uses are similar; both have grasslands (low producing and high producing), it is the inputs to the systems which differ. Dairy farms generally generate more urine and animal waste than a sheep and beef unit due to higher stocking rates and a typically higher fertiliser use. In contrast, sheep and beef operations have limited use of fertilisers and have the lowest non-point source potential (Clothier *et al*., 2007). Therefore, higher inputs in dairying results in higher potential losses of unutilized nutrients than in sheep and beef farming whereas the sediment source and loss is essentially the same. Clearing forested land for grass increases erosion susceptibility, especially in hilly catchments like the Waikouaiti. The susceptibility to erosion on the grassed hilly slopes in the catchment reflects historical land use change of clearing vegetation. In the Waikouaiti catchment, 58% of the catchment is categorised as having a slope greater than 20^{o}, and when combined with a highly weathered regolith, this makes the headwaters susceptive to sustained erosion, particularly under high rainfall. Sediment can be lost to waterways from hill slope instability and reduced entrapment occurs where there is little or no riparian vegetation as is the case in the intensive dairying and baseline simulations. Therefore, in the intensive dairying and baseline scenarios similar amounts of sediments reached the stream but in the dairying scenario. The elevated availability of nutrients allowed more nitrogen and phosphorus to reach the river via sediment transport and other pathways. A conversion from sheep and beef to dairying in Canterbury reports much higher increases in total P yields of ~400% compared to the doubling of total P loads predicted in the CLUES modelling.

Sediment loads were lower in the more vegetated scenario in contrast to the grassy baseline and intensive dairying scenarios. These findings agree with experimental studies in New Zealand that have found sediment loads from pasture are higher than native forest streams (e.g. Dons, 1986; Quinn and Cooper 1997; Quinn and Shroud, 2002). Fahey and Marden (2000) found sediment yields in a pine catchment were less than half the yields for pasture, whereas in these simulations, the intensive dairying sediment load is only 27% higher than in the native forest scenario. It is generally accepted that trees help to bind sediments and stabilise slopes minimising the risk of erosion loss (Quinn and Shroud, 2002). Interestingly, sediments loads were lowest in the woody biomass and tussock scenarios, less than half the baseline. This would suggest the roots systems of tussocks and scrub bind sediments in a similar manner to trees, reducing loss to waterways. The foliage of tussocks and scrub is generally close to the ground which could further trap sediments.

The native forest scenario had the lowest total N loads across all scenarios. This result reflects the absence of grazing stock and fertiliser inputs and reduced rates of nitrogen fixation (Quinn and Ritter, 2003). Comparatively, total N loads in the woody biomass and tussock scenario are in-between the native and the baseline scenario. Little research has focused on nutrient losses from these two land use types. The lower total N levels can be attributed to the removal of stock and other inputs but it would appear the nitrogen fixing scrub species are acting as a source of nitrogen leaching. The decrease in total N loads of around 10% in the woody biomass scenario is much smaller than a 75% decrease in total N yields reported in a Gisborne study of a sheep and beef conversion to scrub (PCE, 2013). The increase in total P at Orbells indicates an opposite trend to the 75% decline in total P yields reported in the Gisborne study (PCE, 2013). Land covered in forestry and scrub is more resilient to soil slipping; carrying sediment and the associated phosphorus into waterways but CLUES does not model this so underestimates the reduction in phosphorus loads that accompany land use changes from pasture to forest (Elliot, 2011). This may explain the marginal differences in total P between the modelled baseline and the native forest, woody biomass, and tussock scenarios.

Based on the discussion of land use impacts above, it would be expected the indigenous headwaters scenario which increases native vegetation in the northern headwaters, would decrease nutrient and sediments loads. The modelled results show marginal decreases in sediments and total N and total P. This suggests that the spatial extend of native forest in this scenario is not large enough to significantly impact water quality. Also, it is upstream of the farming activities that increase contaminants so has no effect in absorbing or intercepting.

Increases in nutrients and sediments are important indicators of declining water quality (McDowell, 1995). There are several consequences of declining water quality for both aquatic ecosystems and human use and values. These can be both temporal and spatial. Although the CLUES model did not define temporal differences such as seasonality, the spatial differences were clear in the elevated nutrient and sediment loads reported downstream of the confluence at Orbells. It is reasonable to surmise that these impacts would further accumulate in the estuary downstream of the confluence near the coast. Under the baseline conditions and the intensive dairying scenario sediment levels are elevated which increases turbidity, reducing the aesthetic amenity of a river and altering habitat and food selection for sighted animals and impairing the gills of fish (Davies-Colley *et al.*, 1992; Quinn *et al.*, 1992). Turbidity reduces light penetration through the water column affecting benthic algae and macrophyte growth and periphyton production and may limit food supply for invertebrates. Fine sediments can smother algae and plants when they settle out or fill the gaps between gravel where fish lay eggs. Silt deposition may also elevate egg mortality due to reduced oxygen. The accumulated effects of excess sediment can cause siltation or eutrophication of estuaries (Schallenburg *et al.*, 2000).

Elevated nutrient levels have differing but equally important effects as sediment on water quality. Whilst nutrients are beneficial for the growth of algae and plants, in excess they may become a nuisance which would likely be the case in the intensive dairying scenario. Aquatic plant and algal growth in a river sustains fish communities, but prolific algal growth due to nutrient oversupply deteriorates the river ecosystem. At nuisance levels, these proliferations adversely affect the ecological, recreational, aesthetic and cultural values of rivers and streams by changing the physicochemical properties of the water, reducing the availability and quality of aquatic habitat and covering the substrate with unsightly algal growths (Biggs, 2000).

6.3.1.1 Section summary

The water quality modelling illustrated that the most extreme elevations in nutrients would result from the intensive dairying scenario. This was consistent with results reported in the literature and attributable to stock and farm practices. The impacts of land use on erosion were clearly illustrated in the dairying scenario and baseline with the highest sediment loads across all scenarios. However, despite theory suggesting trees bind sediments, sediment loads in the native forest scenario were in between the baseline and tussock and woody biomass scenarios. There was more variation in total P loads than total N. The highest total N load was under the native forest, tussock, and woody biomass scenario due to the absence of nutrient inputs from fertilisers or stock. Overall, intensive dairying causes the largest deterioration in water quality.

6.4 Interpreting cultural data and the potential impact of different land use scenarios

The flow and cultural stream health assessments conducted at Orbells and Bucklands were scored on flow attributes and ability to provide opportunities. This section analyses the results presented in Section 5.2.3 and makes linkages between sites, flow, and the cultural scores. Connections between the impacts of land use scenarios on water quantity and quality and the potential implications on cultural uses are analysed and finally, methods for integration of cultural and scientific data in freshwater management are discussed.

One application of satisfaction of whanau in flows being observed is the setting of environmental flows or cultural flows. At the outset of this research it was hypothesised a threshold could be used in the same way as the species habitat preference thresholds to determine how often flow would be above or below the cultural threshold under different land use scenarios. However, statistical analysis of the cultural scores did not reveal a clear threshold about which cultural satisfaction pivoted. There was a concentration of unsatisfactory scores across all flow themes when flow was $< 0.6\ m^3s^{-1}$ at both sites but not all themes were unsatisfactory and there were days with flows above $0.6\ m^3s^{-1}$ that were scored unsatisfactory. Additionally, far fewer CHI themes than flow themes were scored unsatisfactory at any flow level. This would suggest that cultural flow preferences are generally for flows greater than $0.6\ m^3s^{-1}$ but this relationship is not definitive.

Flow conditions affect the cultural use of a site which in turn impacts how a whānau feel about a site (Tipa and Nelson, 2012). The high proportion of unsatisfactory scores across flow themes on lower flow days suggests that scenarios, such as the tussock or native forest scenarios that reduce flow would not be compatible with good cultural stream health. Although, if the location where the cultural survey was being undertaken was situated in either of these landuses, it may be that the overall satisfaction with the site may improve i.e. hapū may be responding more broadly to the overall feeling of the site. Additionally, as highlighted in the consequence tables, while the native forest and tussock scenarios reduced water yields, water quality was improved. This would be beneficial for aquatic species. This could result in a trade off between quantity and quality.

The spread of unsatisfactory scores across all flow levels would suggest flow on the day of the assessment is not the exclusively responsible for unsatisfactory scores. Other variables such as seasonality may impact scores however there did not appear to be a clear seasonal trend as days with unsatisfactory scores occurred in all seasons, as did satisfactory scores. Also, the sample size (14) is too small to determine a statistically significant difference between seasons.

Another influential variable could be the preceding flow conditions. The deposition of flood debris following a flood peak may be considered unsightly or restrictive for cultural use. Analysis of preceding flow conditions for all sampling days could not determine a consistent link between score and preceding flow conditions. More evidence (e.g. photographic) would be needed to support the flood debris hypothesis.

A closer look at the individual themes is useful for making connections between the cultural values and potential implications under different land use scenarios. The low mahinga kai scores could be due to a number of factors and indicative of serious concern for the whānau. Although the trends were inconclusive, the unsatisfactory scores were often on days with low flows. Therefore, land use scenarios that cause a decrease in flow may be unfavourable. At Bucklands, the tussock grasslands or native forest scenarios may contradict cultural values, if they were solely based on flow levels. These scenarios also had the highest percentage of days below species habitat preference thresholds. On the other hand, an unsatisfactory mahinga kai score may indicate inadequate access to the resource; either physical or legal, or that the resource is in a state unfit for cultural use. So when confronted with conflicting indicators about the state of a waterway, it may be of value to interrogate why particular sites have inconsistent scores between the different aspects. A site visited in the catchment but not included in this analysis was a fishing easement in the South Branch. The easement is highly valued and scored well in the cultural assessment. However, the site was only visited once during the surveying period because the difficultly of accessing the site prevented returning for further assessments (Tipa, 2013, pers comm.).

Mahinga kai is a complex value, which can be challenging to communicate to non-Māori audiences. For example, a poor mahinga kai score whether due to access or the actual state of the resource can have negative implications when there is a dependence on it for either sustenance or livelihood support. A more intangible impact is the loss of intergenerational knowledge and custom transfer which is often embedded the practical use and gathering of mahinga kai resources (ORC, 2012a). The implications of an unsatisfactory score extend beyond the assessment site in accordance with the interconnectedness that is central to the Māori perspective. The Waikouaiti River not only provides the mahinga kai resource and ecosystem support for that species but it also supports other significant mahinga kai environments e.g. forest, estuary, and coastal areas (ORC, 2012a).

Cultural and scientific data have several natural and intuitive cross-overs and inter-linkages and previous studies have tested the relationship between cultural scores and scientific measures. The Moteuka ICM study found a correlation between cultural scores and the SQMCI but a mismatch of scale (Yong *et al*., 2008). A semi-quantitative macroinvertebrate community index (SQMCI) score of 6 which indicated an excellent result correlated with a poor cultural score of 2.3. Conversely, Townsend et al. (2004) found a macroinvetbrate community index (MCI) score of 80 (probable moderate to severe pollution) correlated well with a poor cultural score of 1.6. This demonstrates that in some cases scientific and cultural indicators are complimentary and can be informative. For example, if a MCI assessment was conducted on a day when no cultural assessment was carried out it could be inferred a good MCI score would also have been scored well using the cultural index and *vice versa* (given there was a good correlation between the two). MCI modelling could also be used in a predictive capacity to infer likely cultural impacts under different scenarios. Unfortunately, macro invertebrate and fish surveys are only conducted annually on the Waikouaiti River prohibiting correlations between cultural scores and biological indicators. The infrequent sampling regime is likely due to the cost of such sampling. It would be extremely beneficial to conduct some cultural surveys alongside scientific surveys to determine if there is a relationship in the Waikouaiti catchment and then possibly use a more cost efficient cultural assessment to inform and/or trigger the need for a scientific assessment.

Māori tolerance for unclean water is very low. A drinking water sample may show that the water contains some contaminants but is below a toxic level so is still considered safe. In contrast a Māori standard would require that water be protected from spiritual and physical pollution, which requires absolute prohibition of certain discharge activities (MfE, 1998). Although a cultural health assessment, which is mainly observational, cannot usually detect if a waterway has elevated levels of nutrients, the implications of excess nutrient supply may be visible; for example growth of prolific algal or in poor cases eutrophication. Poor water quality can affect the quality and suitability of the mahinga kai resource for human consumption and the health of the river. The majority of unsatisfactory health scores were on low flow days. When flow is low, nutrients are concentrated and if flow has been low for extended periods without flushing flows nutrients can accumulate favouring conditions suitable for algal growth. Māori dislike thick swathes of nuisance growths on banks that impede physical access to a site and diminish the amenity value of the river. The land use most likely to result in poor scores for river health would be an increase in intensive dairying, particularly at the Orbells site which was demonstrated in the CLUES modelling.

The landscape scores were poor on some days but satisfactory on other days. This would suggest that the overall landscape of the two cultural monitoring sites is acceptable but the condition of the landscape during certain flow levels is not. At both sites poor landscape scores generally coincided with lower flows. Low flows can give a river a sluggish or lifeless appearance. Therefore, high flows are generally considered cleansing although unsafe for some cultural uses (Tipa and Nelson, 2012). In general, the days sampled with higher flows had satisfactory landscape scores. Flushing flows can both flush weed or algal growth and redistribute sediment build-ups. The use of mapping by Tipa and Nelson (2012) in the Kakanui revealed that low flows were expected at certain times of the year and a seasonal variability in timing, duration, and magnitude of flow was accepted. A similar mapping exercise could be useful in the Waikouaiti to determine culturally suitable flow regimes and compared and contrasted with the fdcs for different land use scenarios. Other factors that could unintentionally affect scoring could be the weather conditions on the day of sampling. For example, smells could be pushed by the wind i.e. if urea is being sprayed on a paddock nearby this could diminish site satisfaction. These variables should also be investigated in the analysis of scores.

The obstruction or litter theme in the CHI questionnaire is very specific to the actual sampling day. There was one unsatisfactory obstruction or litter score at each site and these were on unrelated days and flow levels. Litter could be disposed of by members of the public using these sites for picnics or camping. If scores were consistently poor due to litter or rubbish dumping this would signal the need for preventative actions. At Orbells, the flow was quite high on the day landscape was scored unsatisfactory and on the same day the surface of the water and water themes in the CHI were also scored poorly. Obstruction or litter is very difficult to predict and cannot be explicitly linked to likely changes in water quantity or quality under different land use scenarios. It is rather a theme that is temporally and spatially specific and would trigger a direct response at the time of the assessment.

6.4.1 Integrating scientific and cultural data

The former paragraphs have interpreted the cultural data and outlined some of the possible connections between water quantity, quality, and cultural values under different scenarios. This is useful and a prerequisite to any decision making. However, it is often at the point of decision making that difficulty in integrating the cultural and scientific data arise, both in how to treat different forms of data and how to combine them. Decision analysis tools have been applied extensively in a variety of disciplines and range from simple diagrams to complex matrices (Failing *et al.*, 2007). A consequence table was utilized as a flexible, visual tool that can be simplified or extended to cater for the intended audience. It aids clear interpretation of and comparison between alternatives. The consequence table presented in Section 5.6 is intended to be illustrative only. It is based on the information available and not reflective of the actual opinions of any stakeholders.

In application, the advantages of a simple approach are numerous. There are often a variety of stakeholders with differing backgrounds, expertise, and preferences, many of whom will be volunteering their own time. Therefore, to engage multiple stakeholders in a productive decision orientated dialogue that considers both facts and values, a combination of analytical tools and facilitated discussion is needed. Using a collaborative approach, objectives and measures of performance are identified, alternatives are evaluated and uncertainty is clearly defined in setting up a transparent platform for decision making (Hammond *et al.*, 2009). This approach provides for values to be included in the decision process rather than focusing solely on scientific objectives and rational economies (Failing *et al.*, 2007). Through a collaborative and facilitated process, those involved in decision making would work together to create a consequence table similar to Table 5.8 that reflects the values, priorities and preferences of the stakeholders involved.

The consequence table presented in Table 5.8 is useful as it provides a starting point for discussions and decision making and can be adjusted and adapted as discussions develop. Scenarios can be compared and contrasted easily. For example, it is easy to identify scenarios with minimal impacts such the indigenous headwaters scenarios in contrast to scenarios with larger impacts such intensive dairying which significantly reduces water quality and thus impairs cultural values. In other cases, trade-offs are highlighted such as the trade off between lower flows and better water quality under native forest. The link between water yield and aquatic habitat is clear and the use of symbols makes it easy to compare the magnitude of effects. A further element could be added to measure scenarios against specific criteria for example a decrease in flow should not be greater than 15% or increases in nutrient load should not be greater than 5%. Thus the consequence table provides a tool that can cross scientific and cultural boundaries and clearly communicate ideas regardless of an individual's expertise of knowledge.

6.5 Summary

Analysis of the modelling results found consistencies between published results from physical experiments and the modelling. The patterns observed in runoff, peak, and low flows could be explained by the hydrological processes modelled in SWAT such as evapotranspiration, surface runoff, lateral flow and, groundwater. In general the taller vegetation types had higher evapotranspiration and therefore lower runoff and stream flow. Trees were generally better at ameliorating peak flows whilst low flows were increased under grass because more precipitation is converted to runoff. Where discrepancies existed between expected results and theory these could be explained by the spatial composition of vegetation in a particular scenario as well as the physical characteristics of the vegetation defined in SWAT. Water quality was poorest in land use scenarios where farming activity took place. The physical characteristics of grass enabled easy transport of excess nutrients to waterways generated from animal wastes, fertiliser applications and other farm inputs. Sediment loads were lower in vegetation with deeper or more complex rooting systems that were able to trap and bind sediment, preventing erosion and sediment loss. Unsatisfactory cultural scores were generally on lower flow days but not consistently. Therefore, while low flow appeared to contribute to cultural dissatisfaction it was not the sole factor. Other factors such as seasonality and preceding flow conditions were investigated but no definitive links could be confirmed. Often scenarios that reduced flow also had improved water quality which would lead to a trade off between values of cultural importance. The consequence table provided a visual summary of links and trade-offs in different scenarios. The consequence table, although created for illustrative purposes only would be a good starting point for discussions surrounding land use, hydrology, and cultural values. This chapter highlighted the benefits as well as the challenges and presented an easily applicable tool for the integration of cultural and scientific data.

Chapter 7: Conclusion

Hydrological impacts from land use change can be defined broadly and in this research encompassed effects on flow regime, water quality, and cultural values. The challenge of this research lay in not simply considering scientific and cultural perspectives but integrating the two in a manner that would assist and enhance decision making in freshwater management. The findings of this research contribute to the literature areas surrounding the topic and provide practical guidance for meeting obligations mandated in national resource management legislation. At a practical level, the results of this study will be useful for stakeholders in the Waikouaiti catchment; facilitating a more comprehensive understanding the water resource and assisting decisions surrounding future use and management options.

Using hydrological modelling and cultural stream health assessments, scientific and cultural data was generated and interpreted independently to maintain integrity and authenticity of the each data type. The result was two distinct products that individually and collectively informed a more comprehensive understanding of the Waikouaiti catchment water resource. The hydrological model SWAT performed well given it was developed in the USA and met the objective to investigate the hydrological impacts of land use changes on flow regime. The New Zealand CLUES water quality model did not perform as well as expected, but provided a useful indication of the relative direction and magnitude of trends in sediment, total P and total N loads for different land use scenarios. The cultural stream health assessments proved to be highly insightful and illustrated the potential for use in a range of applications. Together the two forms of hydrological modelling and the cultural assessment gave a good overview of the water resource in the catchment and the potential impacts under various land uses.

The hydrological impacts of land use change varied between scenarios and whilst some links between cultural and scientific perspectives were intuitive others were more intricate. In the Waikouaiti catchment low flow concerns would be exacerbated under a native forest scenario, especially at Bucklands, but total N loads would be significantly reduced thus representing a trade-off between flow and water quality. The increase in low flows under this scenario would disadvantage adult and juvenile trout but may be beneficial to more low flow tolerant native species, such as eel and lamprey. Additionally, a native dominated landscape may enhance cultural pride and identity at the expense of culturally unsatisfactory flows. Conversely, although an intensive dairying scenario has little effect on flow regime, water quality is dramatically compromised. Increased nutrients would likely negatively impact the mahinga kai resource and human use of the river, inducing algal blooms, which are unsightly, and impact use, access, and ecosystem health. The tussock scenario may also enhance cultural perceptions of the landscape but compromise other cultural values, such as maintaining flow for mahinga kai species. At Lawsons, high evapotranspiration rates appeared to contribute to higher runoff from tussock, however, at Bucklands decreased runoff suggested the spatial variation of tussock and native forest in the scenario was important. In agreement with other studies nutrient levels were low in the tussock scenario and the vegetation acted to bind sediments minimising erosion loss. The woody biomass scenario also presented improvements in water quality although it appeared the nitrogen fixing species scrub species are acting as a source of nitrogen leaching. In the woody biomass scenario increases in runoff were the most pronounced at Lawson in comparison to the native baseline. At both locations the impact on aquatic species was intermediate. The South Branch specific southern agriculture scenario and the North Branch indigenous headwaters scenarios in general had minimal impacts on flow regimes and water quality thus resulting in minimal effects on cultural values and opportunities. It appears small changes in land use have relatively minor impacts on hydrological in the Waikouaiti catchment.

In analysing the cultural and scientific data several links were discernible and often intuitive. Nevertheless, completely integrating the two data sources was challenging. A simplistic approach was chosen over more complex decision analysis tools to enhance the applicability in a resource management context. The consequent table provided a clear visual summary of all the variables and the likely consequences under different land use scenarios. The consequence table can be tailored to a variety of freshwater management decisions and is a truly collaborative approach that meets stakeholder and legislative objectives and obligations.

This study was successful in achieving research objectives, gaining a broader understanding of the Waikouaiti catchment water resource and presenting a unique approach to cross-cultural freshwater management that is replicable and applicable in New Zealand, and possibly overseas.

Integrating scientific and cultural data is an area of current importance and will continue to be a central part of environmental management in New Zealand into the future. Thus, research needs to improve the tools available for generating both cultural and scientific data as well as apply, evaluate, and develop tools for the integration of cultural and scientific data. SWAT proved a valuable tool for assessing the impacts of land use on hydrology but was possibly prohibited by a mismatch of data required for the model and data available in New Zealand. Future use of SWAT for New Zealand applications should focus on bettering model calibration. The CLUES model was useful for developing a broad understanding of the consequences but future model development could benefit from including more catchments with similar characteristics to the Waikouaiti to improve the accuracy of the model predictions for this type of stream. The cultural stream health assessments provided very interesting and useful insights into cultural values surrounding the Waikouaiti water resource. Cultural assessments should be encouraged throughout the country to increase understanding and knowledge of cultural resources and values and aid decision making. Integrating cultural and scientific data was both challenging and beneficial. There needs to be feedback between application and research so methods and tools can be improved. As this is an area where little research has focused, it is still somewhat a period of trial and error. Researchers and resource managers need to work together to achieve the best outcomes. More case study approaches like this one will be useful to test ideas and provide comparisons between locations and contexts.

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Appendix 1: Final parameters used in the calibrated SWAT models

Bucklands		
Soil		
sol_zmx	940	
	Layer 1	**Layer 2**
sol_bd	1.15	1.3
sol_z	400	1000
sol_awc	0.121	0.175
sol_k	0.36	0.35
Clay/silt/sand	22/37/41	23/29/48
sol_abl	0.0001	0.0399
usle_k	0.631	0.2631

HRU	
canmx	0.6 (agrl)
	1.8 (past)
	2.3 (frst)
ESCO	0.95
EPCO	0.75

GW	
gw_delay	16
alpha_bf	0.047
gwqmin	0.36
gwrevap	0.17
rechrg_dp	0.05
gwht	1

WURCH

Sub_7	0.0360
mgt	
CN[2]	66 (agrl)
	66 (frst)
	77 (past)
BSN	
SURLAG	7
ESCO	0.95
EPCO	1

Lawsons		
Soil		
sol_zmx	940	
	Layer 1	**Layer 2**
sol_bd	1.2	1.3
sol_z	400	1000
sol_awc	0.125	0.175
sol_k	0.35	0.35
Clay/silt/sand	22/37/41	23/29/48
sol_abl	0.0001	0.0399
usle_k	0.631	0.2631

HRU	
canmx	0.6 (agrl)
	1.8 (past)
	2.3 (frst)
	2.8(pne)
	1.5(rnge)
ESCO	0.75
EPCO	0.75

GW	
gw_delay	16
alpha_bf	0.048
gwqmin	0.15
gwrevap	0.15
rechrg_dp	0.05
gwht	1

mgt	
CN[2]	58 (agrl)
	55 (frst)
	74(past)
	69 (rnge)
BSN	
SURLAG	1
ESCO	0.9
EPCO	1