Land Use and Climate Change Impacts on Water Quality and Quantity in the Waipara River Catchment North Canterbury, New Zealand

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Abstract of a thesis submitted in partial fulfilment of the requirements for the Degree of **Doctor of Philisophy.**

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In New Zealand, degradation of water quality due to land use activities is perceived as the largest and most threatening environmental issue. The primary aim of this thesis was to assess the impact of land use and climate change on water quality and quantity of the Waipara River catchment. The Soil and Water Assessment Tool (SWAT), constituent load estimator program (LOADEST) and remote sensing techniques were used. The SWAT model was calibrated and validated for hydrology on monthly time-step using flow data (2001-2012) from the Teviotdale gauge station. Water quality data from the same station was used in calibrating for nutrients - nitrate (N) and phosphorus (P). Due to the shorter period (2001 - 2006) of the available water quality records, LOADEST was used in generating time series water quality data to match the flow records. SWAT model parameters were estimated and ranked for their sensitivity. Model performance was assessed using the Nash Sutcliffe efficiency index (NSE) and Regression Coefficient (R^2). The NSE and R^2 obtained for the study are 0.82, 0.85 and 0.73, 0.74 for flow calibration and validation respectively; while the NSE and R^2 values for N and P calibration and validation were 0.77, 0.80 and 0.71, 0.72 respectively. Land use/cover change scenario analyses were implemented on three Landsat image data sets, and using Markov and Cellular Automata (MCA) to project for land uses in the years 2020, 2025 and 2030. The trend in land use change is based on the 2013 land cover which is considered as the baseline. Among seven land use classes identified, two potential fast growing land use types are vineyards and beef/dairy. Based on these analyses, they are expected to increase by 2.2%, 9.3%, 13.5%, and 1.8%, 7.3%, 13.0%

in 2020, 2025 and 2030 respectively, assuming that current trends continue. The SWAT simulations of catchment average N yield in surface water is 4.73kg/ha/yr and will increase by 3.6%, 17.4% and 29.7% in year 2020,2025 and 2030 respectively. P yield of 0.78kg/ha/yr is estimated to increase by 2.5%, 6.3% and 9.4% respectively for years 2020, 2025 and 2030. Sediment yield is also predicted to increase from the current 0.71T/ha/yr by 7.0%, 15.9% and 21.4% in 2020, 2025 and 2030 respectively. The spatial distribution of pollutant sources: nitrogen, phosphorus and sediment in the catchment are also revealed by this study.Estimates of water demand showed that 113,805,329.4m^3, 145,417,920.9m^3 and 189,675,549$m^3$of water would be required by the increasing dairy land use in year 2020, 2025 and 2030 respectively.The extent of increase in temperatures due to climate change from years 2016 to 2050 will range between approximately +0.6°C and +1.0°C; and +1.2°C and +3.3°C in the period 2065–2099 relative to the strength of radiative forcing (Representative Concentration Pathways - RCP 8.5. 6.0 and 4.5). A decrease in surface flows of approximately 1% - 9% according to RCP strength is expected over winter in years 2039–2050. Winter months of same period will experience 4%, 1.6% and 0.5% reductions in groundwater levels under RCP 8.5, 6.0 and 4.5 climate scenarios respectively. The study showed that the projected land use changes, especially increase in beef/dairy operations, will increase nitrate and sediment loadings to the Waipara River in the future. It has also determined the amount of water required to meet the water demand for potential increases in dairy land use in the catchment, which could be vital to the Regional Council in resolving future water needs. Meanwhile, changing from predominantly grazing activities to forestry and vineyard scenarios indicates that N and P yields will decrease generally under RCP 4.5 and RCP 6.0 climatic conditions. Rate of reduction in N yield under the two climatic conditions for the respective land use change scenarios ranges between 30% and 70% while P yield will decrease by approximately 40 to 52%.

Keywords: Land use change, climate change, SWAT model, water quality, water quantity, environmental degradation, remote sensing, GCM, RCP, hydrology, nutrients, scenario.

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Chapter 1

INTRODUCTION

1.1 Background to the Study

Diffuse or non-point source contamination has been the primary cause of pollution for water bodies in many parts of the world. In New Zealand, the quality of surface water bodies has been declining over the past decades (Deans and Hackwell, 2008; New Zealand Conservation Authority, 2011; Ministry for the Environment and Stats NZ, 2017) while land use change and intensification, coupled with fertiliser application and irrigation have been found to be increasing (Ford and Taylor, 2006; Parliamentary Commissioner for the Environment, 2015; Ministry for the Environment, 2017a). Current and past land use activities, especially agricultural land use, have been blamed for heightened nutrient, sediment and pesticide discharges into waterways and groundwater resources (Lord, 1996; Hanson, 2002; Ford and Taylor, 2006; ECan, 2014; Morgenstern et al., 2015; Wells et al., 2016; Ministry for the Environment, 2017b). These higher concentrations are associated with problems of euthrophication and contamination that may impact the health and quality of the water for aquatic and human lives (Novotny, 2003). Consequently, aesthetic, recreational, pollutant mitigation and water treatment costs have been incurred (Blennerhassett, 1998; Novotny, 2003; Ahmadi, Records and Arabi, 2014; Ministry for the Environment, 2017a).

Nutrient enrichment, especially by nitrogen (N) and phosphorus (P) in Canterbury Rivers has over the years been a growing source of concern. Both small spring-fed and large rivers flowing from the mountains are impacted by nutrient input, directly or indirectly from the intensifying land uses within their surroundings, creating potential health risks to water users (Stevenson et al., 2010). This issue has drawn attention to the need for reduction of nitrogen and phosphorus inputs to waterways. Nutrient availability, however, varies in space, time and consistency of land use practice. Contemporary research findings in New Zealand show varying levels of N and P concentration according to seasonal flows (Ausseil, 2008; McArthur et al., 2010; Monaghan, 2014; NIWA 2016; Smith et al., 2016).

Land use and water quality are no doubt intricately related. Numerous research findings have established that land use and both water quantity (Bultot et al., 1990; Krause, 2002; Ranjan et al., 2006; Li et al., 2007; Kibria et al., 2016; Yin et al., 2017), and water quality (Tong and Chen, 2002;

Baker, 2003; Ahearn et al., 2005; Heathwaite et al., 2005; Giri and Qiu, 2016; Shi et al., 2017) are strongly related.

Land use practices are closely connected to evapotranspiration rates, generation of surface runoff, washing-out of soil nutrients, as well as other hydrological processes (Tang et al., 2011; Li et al., 2015).As is usually the case, land use changes can have many implications for water and nutrient cycles within river basins (Tang et al., 2011; Wang et al., 2017). For instance, converting farmlands or grazing lands into woodlands may lead to decreases in water and nutrient yields (Legesse et al., 2003; Guo et al., 2008; Cunningham et al., 2015). Change in land use and variation of climatic conditions have been found to be the most influential factors controlling changes in hydrological systems (Mander et al., 1998; Chang et al., 2001; Tomer and Schilling, 2009; Zhang et al., 2016).

A change in climatic condition such as rising temperatures could lead to decrease in dissolved oxygen and consequently aggravating algal blooms in waterways (Reisinger et al, 2014). Climate change also creates spatial and temporal variability in rainfall, such that certain regions of the world experience irregularities in rainfall pattern (e.g. frequency and amount) thereby influencing stream flows and fresh water supply (Gluckman, 2017). As climatic conditions of places change, evidenced by variability in hydrological system components like precipitation, temperature and evapotranspiration, both surface and subsurface water resources are affected. Great variations could result into long periods of low or high streamflow and groundwater levels (Kumar, 2012; Kumar et al., 2017). Studying these factors is the focus of this thesis.

1.2 Problem Statement

The Waipara River catchment in North Canterbury has experienced increasing changes in land use, primarily conversions from pastoral farming to viticultural, horticultural or lifestyle activities. There is also interest in developing dairy farming within the catchment which has particularly informed the special interest of this thesis, namely to studying the Waipara River catchment. The inherent variability in environmental factors and land uses within a catchment could potentially influence the rate of pollutant discharge. It is a challenge to isolate and establish the effect of individual land use types on water quality in a catchment, especially in dynamic land use and climatic situations without good quality data and a robust catchment modeling tool(s) *(*Deans and Hackwell, 2008). In New Zealand, the sensitivity of aquatic systems to nitrogen and phosphorus is such that small increments in either can lead to significant negative impacts. Dairy farming in particular has generally been held responsible for the leakage of nitrogen and phosphorous to the surrounding environment. However, there is still a wide knowledge gap in determining who and what exactly is responsible for the pollution in a catchment. In other words, where are the pollutants coming from? And what is the share of various land use /cover constituting the source of nutrient or pollutant discharge to the Waipara River? Answering these questions requires a modeling approach that is capable of simulating nutrient/pollutant loading based on individual land covers in the catchment, putting all relevant environmental processes into perspective. That is the issue this thesis is addressing.

1.3 Research Aim and Objectives

This research aims to understand the impact of land use and climate change on pollutant generation in the Waipara River catchment in Canterbury, New Zealand. The specific objectives that address this aim are as follows:

1: Determine the spatial distributionof pollutant/nutrient sources within the Waipara River catchment;

2: Quantify the nutrient/pollutant fluxes from the land use/cover types in the Waipara River catchment using an appropriate model;

3: Analyse how current land uses influence the concentrations of nitrogen and phosphorus in surface water flow of the Waipara catchment;

4: Determine the relationship between future land use changes and pollution loading in surface flow for the catchment;

5: Quantify the impact of climate change on surface flow and water quality for the catchment.

1.4 Layout of the Thesis

The thesis has eight chapters, organised as follows:

Chapter two focuses on the review of literature on hydrologic and water quality models. The characteristics features, strengths, limitations and classification of models that are used for estimating Catchment hydrology and water quality are discussed. An overview of hydrological models is also presented in chapter two. The models chosen for further application are described.

Chapter three discusses the study area with emphasis on:

- geographical location,

- climate,
- geology and soil,
- land use,
- water resources of the area,
- the eco-habitat and cultural values as well as the management strategy for the Waipara River catchment. The status of the water quality of the catchment is also discussed.

Chapter four outlines the background modelling approach. It discusses the primary input data requirements for setting up and implementation of the chosen model.

In order to ensure that the model accurately represents the physical processes occurring in the Waipara River catchment, calibration and validation procedures are implemented in chapter five for streamflow and nutrients respectively. This work is presented in chapter 5.

Land use/cover change scenario analyses are undertaken in chapter six. The chapter highlights trends in land use change and makes projections for the future. The consequent impacts of nutrient yield from the projected land use changes are also forecasted.

Chapter seven presents an analysis and discussion of climate change impacts on water resources. The impacts on both surface and subsurface water resources are analysed and projections made into the future.

Lastly, chapter eight presents the conclusions and recommendations and also highlights the significance of the study. Areas of further research are also identified.

1.5 Significance of the Study

The thesis findings are important with respect to management of the Waipara River catchment, including impact analysis of land use change and contaminant fluxes, climate change impact on availability and quality of water resources. They are expected to be also important for revealing information about water demand and supply to sustain the potential increase in dairy land use in the catchment.

Chapter 2
LITERATURE REVIEW

2.1 Introduction

In chapter one, declining water quality and quantity associated with land use activities and climatic variability was identified as a global phenomenon. In the absence of sufficient measurements, resolving water quality and quantity related problems is made easier with the use of a suitable modeling approach. This chapter provides a review of information available in the literature and briefly discusses the different approaches to hydrologic modeling. The contents of this review are arranged as follows: section 2.2 deals with the general background to land use and water resource relationships. Land use impacts on water quality and quantity are presented in section 2.3. Section 2.4 and 2.5 highlighted on climate change and its implication for New Zealand. Section 2.6 presents a brief review on nutrient modeling and estimation tools. Information about classifications (types) of hydrological models is presented in section 2.7. A brief discussion of some widely applied catchment models with more emphasis on the selected model of application is also reviewed in section 2.7. Concluding remarks which provide a justification for the choice are given in section 2.8. A summary of the literature review process is presented in section 2.9 while section 2.10 highlights the gaps in literature.

2.2 Background to Land Use and Water Resources

Land use and water resources are intricately related. The type of land use, method of use, and the intensity and extent of its use will have a substantial effect on both the quantity and quality of available water resource. Numerous researchers have identified how land use is related to water quantity (Bultot et al., 1990; Krause, 2002; Ranjan et al., 2006; Li et al., 2007; Yira et al, 2016; Kibria et al., 2016; Yin et al., 2017), and also water quality (Tong and Chen, 2002; Baker, 2003; Ahearn et al., 2005; Heathwaite et al., 2005; Zonderland-Thomassen and Ledgard, 2014; Giri and Qiu, 2016; Shi et al., 2017; Malan et al., 2018). Land use is said to be closely associated with the way water evaporates from soil and other surfaces including transpiration from plants, generation of overland flow, reduction of soil fertility, and movement of water within the hydrologic cycle (Tang, et al., 2011; Kaspersen et al., 2016; Teutschbein et al., 2018). Land use changes can bring about irregular surfaces and soil compactness, and influence the opening and closing of plant stomata as well as impacting the fertility of the soil (Hormann et al., 2005; Yang et al., 2012; Mohawesh et al., 2015).

The observed changes in quantity and quality of surface water often result from climatic variability, change in land use, and other forms of pressure from human society. Studies from many parts of the world show that land use changes and climate variability are the chief cause of changes in the occurrence, circulation, distribution, and properties of the waters of the earth and its atmosphere (Mander et al., 1998; Chang, 2004; Tomer and Schilling, 2009; Zhang et al., 2013; Dwarakish and Ganasri, 2015; Bosmans et al., 2017). Lettenmaier et al. (1994), Kent (1999), Juckem et al. (2008), Lee and Kim (2017), and Hou et al. (2018) however noted that the way land use and climatic variability affect hydrological responses, especially stream flow and hydro-chemical responses, is very complex and difficult to separate.

Notwithstanding the cause of the pollution, whether natural or man-made, the effect of any activity involving land use on water resources can be very serious. The next section of the chapter therefore explores ways by which land use can impact on water quality and quantity.

2.3 Land Use Impacts on Water Quantity and Quality

Land use (such as forestry, farming and urban) is known to be an important factor that greatly impacts on river water quality and quantity. Aichele (2005) and White and Greer (2006) reported a significant impact from land use changes, especially those caused by urbanization, on hydrology. Choi et al. (2003), Aichele(2005), Brandes et al. (2005), White and Greer (2006) and Zaharia et al. (2016) identified a positive relationship between urbanization and trends in stream water quality and flow characteristics, while Tang et al. (2005) identified impacts of afforestation on reducing both flow and non-point source pollution. Other studies revealed that land use change may alter the frequency of flood events (Crooks and Davies, 2001; Brath et al., 2006; Rogger et al., 2017; Hou et al., 2018)), severity (De Roo et al., 2001; Environment Waikato, 2007, 2009), baseflow (Wang et al., 2006; Price, 2011), and mean annual discharge (Costa et al., 2003; Cao et al., 2009; Chu et al., 2013). There is general agreement among scholars that an increase in urban land area uses usually triggers increased high flows, decreased low flows, and increased variability in stream-flow due to the increased impervious surfaces brought about by urbanization leading to decreased infiltration of precipitation, resulting in increased runoff. Several international studies have also indicated that land use can have a great impact on water quality (Sliva and Williams 2001;Woli et al., 2004;Schoonover et al., 2005; Chu et al., 2013). Tu et al. (2007) found climate change and land development impacts on seasonal stream flow and nitrogen loadingin eastern Massachusetts, USA. Rhodes et al. (2001) reported that increase in the number of people in conjunction with alteration of the land environment are connected with loss in quality as well as reduction in surface and groundwater resource availability in New England (USA). They demonstrated that nitrogen and sulphate concentrations correlated positively on the average with percentage catchment area transformed by anthropogenic activities, especially urbanising land uses. Wilson and Weng (2011) predicted the future impacts of city growth and change in climate on stream water quality within the Des Plaines River watershed, Illinois, using Land Change Modeler (LCM) and the Soil and Water Assessment Tool (SWAT) to illustrate three future city growth situations. The scenarios modeled showed that with the right urban development plan appropriate for the climatic conditions, deterioration in water quality could be reduced.

2.4 Climate Change

The reality of global climate change has long been established (IPCC, 2007). Notable impacts of future climate changes are evidenced in increases in global temperatures resulting from alterations in atmospheric circulation patterns. The melting of polar ice, rising sea levels, increased evaporation and precipitation, severe draught in some places, changes in mean stream discharge, and severe hydrologic events are some implications of climate change (Praskievicz and Chang, 2009). The complexities associated with the global climate as well as the nature of the future pressures on it made the determination of the actual effect of change in climate to be highly uncertain. In other to appreciate the impact of climate change, various scenarios *have been constructed based on three separate global climate models (GCM). The predictions of climate change for each scenario are different and the predictions from each model are also different. This results in a very large variance of predictions for future climate change (*Renwick et al., 2010).

Future atmospheric concentrations of aerosols and greenhouse gases explain to a large extent the degree to which change in climate will occur. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) shows that global mean temperature increased between 1.1–6.4°C during the 21st century. Two families of scenarios are commonly used for future climate projections: the 2000 Special Report on Emission Scenarios (SRES) and the 2010 Representative Concentration Pathways (RCP). The SRES scenarios are named by family (A1, A2, B1, and B2), where each family is designed around a set of consistent assumptions: for example, a world that is more integrated or more divided. In contrast, the RCP scenarios are simply numbered according to the changes in radiative forcing (from +2.6 to +8.5 watts per square meter) that may result by 2100.Climate change predictions based on "A1B" scenario revealed mid-range changes in global mean temperatures as well as in other climatic parameters. The A1B scenario predicted an increase in global mean temperature to a little below 3°C by the end of the 21st century, compared to that of the late 20th century (or about 3.5°C relative to pre-industrial temperatures) *(*Renwick et al., 2010).

The pattern of distribution of future warming is not well understood. There is however a likelihood of -non-uniformity, in wich the greatest warming occurs over the Arctic and the higher-latitude regions of the Northern Hemisphere *(*Renwick et al., 2010; Hansen et al., 2006; 2007). The southern oceans are expected to experience the least warming, while the tropical regions will record alteration in rainfall patterns (Seidel et al., 2007). Increased rainfall is likely to occur around the Equator, middle and high latitudes of the northern and southern hemispheres. Meanwhile, as the subtropical high pressure belt spreads towards the poles, regions within latitudes 30° to 40° may experience decreased rainfall (IPCC, 2007). Changes in climate are also predicted to induce increased evaporation and acceleration in the hydrological cycle globally (Ramanathan, 2001; Wentz et al., 2007).

2.5 The Implication of Current Climate Change for New Zealand

Mullan et al. (2008) estimated the current 3°C global warming under the A1B emissions scenario, to imply a 2.1°C mean warming over New Zealand (about 70% of the global mean). They also reported increases in the westerly wind circulation in winter and spring over New Zealand. It is however uncertain whether a reduction in westerly winds would result during summer periods. Based on this there are expected to be relatively higher evaporation rates in winters than summers (Renwick et al., 2010).The western parts of New Zealand are likely to experience increases in annual mean rainfall, while decreases in rainfall in the east are expected due to the predicted changes in winds. Such changes may be more significant in winter and spring. There is also the possibility of a reversal in the trend, such that, the eastern regions would experience increased precipitation; and the west recording a decrease during summer months (Mullan et al. 2008). These changes may lead to climatic extremes, among which are: *reduced frost frequency and increased risk of heat waves over the wholecountry; reduced soil moisture and increased risk of drought in the east of the country; increased risk of forest fires in many eastern and northern regions, and increased risk of heavy rainfalls in most places* (Renwick et al., 2010).

2.6 Nutrient Modeling and Estimation Tools

Pollution of rivers and lakes by nutrients and sediments can have negative impacts such as algal blooms, fish kills, and dead zones. Given the increasing awareness of the need to manage or reduce nutrient and sediment pollution in New Zealand and elsewhere in the world,there has been a growing interest in the search for tools capable of estimating and tracking nutrient losses to support policy and investment decisions.Several estimation tools have been developed, each of which can vary based on the scale of application, purpose, land use, data requirements, required details and level of uncertainty,and the complexity of their estimates (Cichota and Snow, 2009; USA-EPA, 2018). Krovang et al. (2009) applied a group of nutrient models in 17 European watersheds to understand the variabilityin net N and P loads and partitioning of N and P loads. Eight models for N and five models for P were utilised in three important European watersheds with varying climate, topography, soil and land use types (Vansjø-Hobøl (Norway), Ouse (Yorkshire, UK) and Enza (Italy)). Theirstudies showed great variabilities in annual N and P losses from agricultural land use within the 17 watersheds in the rage of 19.1–34.6 kg N ha and 0.12–1.67 kg P h. The observed variation in net N and P loads and gross N and P losses was attributed to regional factorsand existence or non-existence of large water bodies within the watershed. Determining which tool that is appropriate for a particular project depends largely on the aim and objectives of the project, level of required detailsand accuracy as well as quality of available data. The previous research suggests that models are useful tools and modeling studies have been carried out to understand various aspects of land and water environment relationships. The following sections evaluate models used for hydrologic applications.

2.7 Overview of Hydrologic Models

Various authors have reviewed the range of hydrologic and water quality models. Some have provided detailed information about the capabilities, attributes, weaknesses and popularity of models (Donigian et al., 1991; DeVries and Hromadka, 1993; Novotny and Olem, 1994; Donigian et al., 1995; Tim, 1996a, 1996b; US EPA, 2008; Moriasi et al., 2012; Liangliang and Daoliang, 2014). These hydrology and water quality models differ greatly in the way they are structured and in their scale of operation. Generally, however, models are designed to achieve two primary goals. The first goal is to enable a good interpretation of hydrological processes occurring in the catchment, as well as the potential impacts any changes in the catchment may have on these hydrological processes (Xu, 2002). They are therefore very valuable for studying the potential effects a change in catchment land use activities and climate may have on river water quality and quantity (Putro et al., 2016). The other purpose is for generating synthetic sequences of hydrologic information which are useful for facility design and forecasting (Xu, 2002). Models therefore come in diverse levels of sophistication and can be classified in different ways.

Two popular ways of classifying hydrologic models are by taking into account the physical processes or by the spatial description of catchment processes. In the first approach, hydrologic models are considered as conceptual or physically based, and in the second approach, as lumped or distributed. Conceptual and physically based models are representations of essential components (e.g., features, events, and processes) that connect hydrologic inputs and outputs. The components display the fundamental operations of the hydrological system or Catchment, and are usually built using structures (stores of water) and the interconnection between the structures (e.g., storage, discharge, and transmission of water) (Fenicia et al., 2011). A lumped model regards individual sub-catchments as a single unit, homogenous in its characteristics, while a distributed model divides each sub-

Catchment into smaller units, accounting for the differences in soil, slope, vegetation and land use (Brirhet and Benaabidate, 2016). The lumped conceptual and the distributed physically based models constitute two typical categories of these models. The Stanford watershed model (Crawford and Linsley, 1966), the Hydrologiska Byråns Vattenbalansavdelning (HBV) model (Bergström, 1976) and the Sacramento model (Burnash et al., 1973) are examples of lumped conceptual models. MIKE SHE (Abbott et al., 1986a, b), the Institute of Hydrology Distributed Model (IHDM) (Beven et al., 1987) and the Thales (Grayson et al., 1992) are examples of distributed physically based models. TOPMODEL could be described as being conceptual and distributed (Beven and Kirkby, 1979). A summary of selected lumped conceptual and distributed physically based models are listed in Appendix 1.

Similarly, model input and parameters, as well as the extent of the physical principles underlying the model structure define the approach to hydrologic model classification. In this respect, hydrologic models can therefore be classified as lumped and distributed when model parameters are influenced by spatial and temporal variability. They are described as deterministic or stochastic models when the classification is based on the extent of the underlying physical principles. Where different values of output are generated from a single set of input variables, the model is described as stochastic. It is a deterministic model if a single set of input variables consistently produces the same output value (Devi et al., 2015). Lumped models do not consider variability in spatial characteristics of the catchment; they treat the entire basin as a homogeneous unit. As a result, the generated output does not reflect variability in the prevailing spatial processes in the different parts of the basin (Moradkhani and Sorooshian, 2008, Devi et al., 2015). Distributed models on the other hand aggregate the catchment into homogeneous units; for example, square cells and triangulated irregular networks, such that variability in the spatial phenomena of the catchment is better represented (Moradkhani and Sorooshian, 2008).

Another form of model classification which, based on time, is static versus dynamic models. A dynamic model includes time while a static model does not. Hydrologic models can also be categorised as event based or continuous models (Sorooshian et al., 2008). Time specific events are best modeled using event based models while events that are continuous in nature require continuous models.

A very common classification approach (Jajarmizadeh et al., 2012; Devi et al., 2015) as adopted in this review is by categorising models as empirical, conceptual or physically based. The following sections review this adopted categorisation, with emphasis on their merits and drawbacks. Discussions on three examples of physically based hydrologic models (MIKE SHE, TOPMODEL and SWAT) to be considered and evaluated for application in the study of the Waipara River catchment then follow in section 2.5.

2.7.1 Empirical Black-Box Models

According to Devi et al. (2015) empirical black-box models can also be described as data driven models because they are based only on the information content of available observed data without any regard for the characteristics and physical processes of the hydrological system. These types of model do not take physical processes into account – just input/output relationships. In other words, they entail mathematical equations rooted in the input and output time series observations. Empirical models are most useful especially in river basins where there are insufficient hydrological data to run either a conceptual or physically based model (He et al., 2014). That is to say empirical models become useful tools where it is impossible to find the essential data for running either conceptual or physically based models. Examples are the simple linear model (SLM) (KachrooandLiang, 1992) and the Takagi-Sugeno fuzzy system model (Zhang et al., 2009). Another example is the unit hydrograph method, which uses regression and correlation statistics to derive the functional relationship existing between input and output variables (eg. Ramírez, 2000; Bereziartua et al., 2005; Singhet al., 2013).These models cannot be extended beyond the catchment under study, as their validity is limited to the confines of the area of available data (Devi et al., 2015).

Merits

The main advantages of empirical models are the ease of model development without having to understand the underlying physical characteristics and processes of the hydrologic system, the possibility of surmounting complex causal relationships associated with catchment physical processes and their cost effectiveness due to the opportunity to utilise collected data without unnecessary time spent trying to find out the logical relationships between variables and parameters (Klemes, 1982).

Drawbacks

Hydrologic processes are known to occur in very complex environments while collected hydrologic data are usually fragmented (both temporally and spatially). As a result, the derived empirical relationships based on these data, may not yield very accurate results but only give approximations (Klemes, 1982).

The validity of an empirical model is only found within the range of the underlying data, and so could be seen as a mere interpolation formula which present great uncertainty when used in studies requiring making of inference, such as in water resource management applications involving considerable extrapolation of the hydrologic information in both spatio-temporally and in the range of values (Klemes, 1982).

A major drawback in empirical modeling is the lack of a theoretical (physically based) explanation for model behaviour which creates doubt around the reliability of the model structure (Klemes, 1982). The availability of data in conjunction with a lack of basic knowledge of the relationships among things being explained is said to be the generally accepted scientific reason for empirical modeling (Klemes, 1982). This rationale led to the acceptance of the axiom "let-the-data-speak-for-themselves" and became popular among many hydrologists especially in the evolution of black-box modeling (Klemes, 1982).

2.7.2 Conceptual Methods (Parametric Models)

A conceptual hydrologic model is a simplified representation of perceived important hydrological process components of a catchment, such as the generation of overland flow from a rainfall event (Ekenberg, 2016). This type of model is referred to as parametric or grey box model. The conceptualisation of the hydrologic system and processes (e.g. rainfall, runoff, infiltration, percolation, evapotranspiration) is schematised with the use of a variety of interconnected reservoirs that can be used up and replenished (Devi et al., 2015).

TOPMODEL (Beven et al., 1979) is an example of a conceptual but spatially distributed model developed originally for the purpose of studying small catchments in the UK (Beven et al., 1984). The model has had a widespread application across many parts of the world (Lamb et al., 1997; Scanlon et al., 2000; Cameron, 2006; Gallart et al., 2007, Peng et al., 2008). Other examples of conceptual models include the Xinanjiang (XAJ), mix runoff generation (MIX) and Northern Shannxi (NS), models (Zhao et al., 1980, Zhijia et al., 2008).

Merits

Conceptual models are very useful for simulating catchment hydrological processes and prediction of flood events (Kan et al., 2016, 2017). The potency of conceptual models compared to other types of models lies in their effective mathematical algorithms, the fact they are easy to understand, their relevance in many situations (e.g., arid and semi-arid conditions), and having more real-life interpretation in relation to model parameters than most empirical and physically based models (Zhao et al., 1980, Kan et al., 2012, 2017).

It is not unusual to use conceptual models to treat the catchment as a single homogeneous unit. These lumped-conceptual models do not require large amounts of input data and therefore are generally easier to operate (Ekenberg, 2016). Lumped conceptual models have been known to perform well especially in water management studies despite their simplicity. These models take less time to run and therefore support concurrent modeling and comparative analysis of several catchments (Perrin et al., 2001). Pedruco (2005) identified a major strength of conceptual models to be that they take into account non-linear processes, such as evapotranspiration, and can therefore work well on continuous time series.

Drawbacks

Perhaps the main issue with conceptual models is that the conceptualisation of the model structure requires an in-depth knowledge, and the skill of the modeller to correctly define the hydrological phenomena being represented (Wagener, et al., 2004). This modeling technique is based on semi empirical equations and involves the use of large amounts of field data (meteorological and hydrological) through calibration processes to evaluate the model parameters (Beven, 2001; Devi et al., 2015). According to Devi et al. (2015) the calibration process entails curve fitting, amongst other techniques, making it hard to interpret outputs. Consequently, forecasting the effects of land use change cannot be made with absolute reliability.

2.7.3 Physically Based Model

Interest in physically based hydrologic modeling developed in order to find solutions to the weaknesses associated with conceptual models. Physically based hydrologic models utilise numerical functions to depict river catchment hydrological characteristics and processes such as conversion of rainfall to surface and subsurface flows (Singh et al., 2013). Generally, the principal elements of the land phase of the water cycle such as interception, snowmelt, evapotranspiration, surface and sub-surface flows and stream flows are represented. The modeling procedure is based on fundamental concept of physics along with the conservation of energy and the conservation of mass (Wagener, 2003). They are also known as mechanistic or white box models, and are based on principles of the physical hydrological processes of water movement (Abbott et al., 1986b). These models employ state variables that can be measured and are time and space dependent. The fundamental pathways of water circulation in the catchment are presented in mathematical functions. The model can be operated using short periods of hydrological and meteorological data for its calibration, but requires extensive parameterisation to adequately represent the physical characteristics of the catchment (Abbott et al., 1986a). Srinivasan R. of Texas A&M University, USA (one of the SWAT model developers) (personal comm. 2014) stated that “one to five years of observed flow and water quality data is sufficient for calibrating the SWAT model”. A physically based model is described as fully distributed when the entire Catchment is divided into small rectangular grid shapes, and is referred to as semi-distributed when the catchment is split into sub-catchments which in turn are defined by topography and stream networks.

Merits

Physically based models, e.g., the SHE/ MIKE SHE model (Abbott et al., 1986a, b) are more attractive tools and address many limitations of empirical and conceptual models. This is because of their ability to represent the catchment characteristics with the use of parameters having physical interpretation. Physically based models are applicable in a wide range of situations. They can be relevant to other catchments of similar characteristics and so can give information beyond the limits of the modeled Catchment (Devi et al., 2015). They take into account the non-uniformity of the landscape features such as soil types, topography, climate and land use. They are capable of estimating runoff at ungauged locations within Catchments (Brirhet and Benaabidate, 2016). They are able to simulate or estimate the influence any alteration in catchment land use may have on the water cycle. The development of physically based models was motivated by the desire to have models that can avoid calibration, which are suitable for ungauged catchments (Arnold et al., 1998) or where there is insufficient data to run the other two model types.

Drawbacks

A major issue with physically based or mechanistic models (especially fully distributed models) is that they require extremely large data needs (so many variables e.g. weather parameters, soil, topography), suffer from scale-related problems, as well as over parameterisation (Beven, 1989). They still need to undergo some calibration processes to arrive at essential parameter values (Wagener, 2003). Physically based models also require much time to run algorithms, giving rise to their unsuitability, for instance, in real-time flood prediction (Beven, 2012). Sometimes, the determination of physical parameters, especially the subsurface processes, involves small scale laboratory experimentation, and the results extrapolated to the catchment scale leading to inaccuracies and loss of heterogeneity in catchment characteristics (Beven, 2012). Appendix 2 presents a summary of the general characteristics of the three categories of hydrologic models presented from the foregoing discussions.

Although the literature on hydrology offers good descriptions of the characteristic features of existing models, the usefulness, applicability and suitability of each hydrologic model to a given situation is a function of several factors. It has been known that the result of a modeling exercise can only be as good as the actual input data and that the reliability of model output depends on a number of factors. Among such factors are:

- the theoretical basis of model construct,
- how the Catchment is classified to reflect the physical characteristics of soil, climate and topography,
- comprehensiveness, representativeness and quality of input data,
- the effectiveness of inbuilt techniques for filling missing data gaps (Mantel and van Engelen, 1997),
- cost consideration of the software and availability of user support opportunities,
- a model's capability of integrating hydrology and water quality modules in the same model framework,
- capability of generating outputs for a location of interest within a catchment under study,
- ability to simulate the effects of management practices on water quality and quantity.

As argued by Klemes (1982), there is no best model; the suitability of a model for a case study depends largely on the goals and objectives to be achieved by the study. A common practice among hydrologists (Davie, 2004; Brirhet and Benaabidate, 2016; Sharifi et al., 2017) is to test or review two or more models of the same category and compare their suitability for application to the problem.

The physically based hydrologic model is chosen for use in this study not only because of its capabilities of representing the physical characteristics of the catchment under study, generation of outputs for location of interest within the catchment, but also the ability to simulate or estimate the influence any alteration in catchment land use may have on the water cycle.

The following sections of this review examine three similar physically based hydrologic models (MIKE SHE, TOPMODEL and SWAT) with a view to evaluating their suitability for use in the study of the Waipara River catchment.

2.7.4 MIKE SHE Model (Systeme Hydrologique European)

The MIKE SHE is a physically based hydrologic model developed by the Danish Hydraulic Institute (DHI) (http://www.mikebydhi.com; accessed October 17, 2017) for the integrated simulation, analysis and management of river catchments. The model is structured in modules. The hydrologic modules include, among others, the Nedbor Afstromnings Model (NAM), Unit Hydrograph Model (UHM), and Water Movement (WM) which is the central hydrologic component connecting other stand-alone modules. The water quality components of MIKE SHE are independent units including advection-dispersion, particle tracking, sorption and degradation, geochemistry, biodegradation, and crop yield and nitrogen consumption modules.

MIKE SHE is deficient in channel simulation (Thompson et al., 2004) but can be coupled with other modules with channel simulation capabilities. Yan et al. (1998, 1999) combined the WM module of MIKE SHE and channel simulation module of MIKE 11 to successfully build a joint surface and ground water model for the South Florida Water Management District (SFWMD) to enhance the efficiency of MIKE SHE. Besides channel simulation, other constituents of MIKE 11 include flow simulation, nutrient and sediment modules. MIKE SHE and MIKE 11 have often been used jointly or separately (Mike 11 Reference Manual, 2009).

Extensive physical parameters which may not always be available are required to operate MIKE SHE, thereby limiting the applicability of the model, especially in catchments with insufficient data. A major strength of the model is its capability of simulating a wide range of catchment hydrologic processes, e.g., precipitation, evapotranspiration, interception, river flow, saturated ground water flow, and unsaturated ground water flow (Butts et al., 2004; Sandu and Virsta, 2015). The MIKE SHE framework can effectively represent catchment hydrodynamics including nutrients, sediment and agro-chemical movement and so has been widely used for water resources management studies in both small and large complex river systems (Refsgaard and Knudsen, 1996; Brun and Engesgaard, 2002; Müller-Wohlfeil and Mielby, 2008). The model employs the Kristensen and Jensen's (1975) technique for estimating evapotranspiration. Complete information about MIKE SHE is contained in the reference manual (MIKE SHE - DHI, 2017). Refsgaard and Storm (1995) also presented the characteristic features of MIKE SHE including the pre/post processing and alternative output representation approaches.

Several MIKE SHE projects have been implemented to analyse catchment water resources management related problems and the general conclusion is that MIKE SHE is a very robust modeling tool. Refsgaard and Knudsen (1996) implemented a comparative modeling study of MIKE SHE, NAM and WATBAL on three Catchments in Zimbabwe to forecast overland flow, utilizing a minimum of one year monitored flow record for calibration and found that MIKE SHE performed better than the other two models. Thompson et al. (2004) combined MIKE SHE and MIKE 11 to assess the periodic changes in groundwater and ditch water levels in the Elmley Marshes of South-east England and found that the model perfectly simulated the macropore flow of the wetland as well as the periodic changes in groundwater and ditch water. Similarly, Liu et al. (2007) employed MIKE SHE and MIKE 11 to examine the effects of subsoil water and topography on overland flow frequency, diffusion and fluctuation in groundwater levels in an arid environment. The outcome of their study also shows the robustness of the MIKE SHE framework in groundwater resources management.

Evaluation

MIKE SHE has the capability of providing detailed analysis of hydrological processes, resulting in high level accuracy of rainfall-runoff modeling if accurate data are available. It can be considered a complete modeling package. Its input requirements are however very large and could be hard to meet and handle, thus constituting a problem in setting up the model. Focusing on modification of a few parameters during calibration is a possible solution to handling the large input parameters required (Refsgaard and Storm 1995).

Although the model has high level processing power, modification of its code to meet user specific modeling needs is not possible. Pre and post processing of MIKE SHE outputs is supported by extensive graphical capabilities, making the modeling easier. It has therefore been concluded that MIKE SHE compares well or even has superior ability over other models with similar codes/framework (Yang et al., 2000, and Abu El-Nasr et al., 2005). High-level technical and conceptual knowledge of hydrological and water resources are essential requirements to effectively use MIKE SHE.A major consideration in the use of MIKE SHE is accessibility due to high costs. The MIKE SHE model code is patented to DHI with the sole distributorship right. Although anybody can apply for the licenses, the cost implications for software procurement and training are quite high.

2.7.5 TOPMODEL (TOPographic MODEL)

TOPMODEL is a semi distributed conceptual hydrology model that utilises information about the physical characteristics of the landscape to compute the topographic index distribution capacity of the Catchment (Beven et al., 1986; Gumindoga et al., 2014). In other words, it takes advantage of topographic information related to runoff generation to determine sources of overland or subsurface flow generation across the Catchment (Beven, 1997). The approach involves estimation of the level of the water table or storage deficits across the Catchment. The storage deficit value is dependent on the topographic index (a/tanβ) (Beven and Clarke, 1986), where ***a*** is the drained area of each contour length and ***tanβ*** is the slope angle of inclination (Devi et al., 2015). The topographic index indicates hydrological similarity, and places with similar digits can be considered to be of similar hydrologic characteristics. Locations with higher topographic index figures are presumed to get saturated before others and so potentially stand to be the flow generating sites (Beven, 1997). Since the topographic index is based on basin topography, the model gives calculations only for representative values of indices. This therefore implies that the model may not be able to correctly estimate values of data or a function between two known values.

The model uses the exponential Green-Ampt technique (Green and Ampt, 1911) for computing flows and it is advisable to consider utilising fewer parameters for the computation (Beven et al., 1984). The output comes in the form of area maps or simulated hydrographs. The parameters of TOPMODEL can be measured theoretically, so it is therefore considered as a physically based model (Beven and Kirby, 1979; Beven et al., 1986). The theoretical interpretation of the model is that surface and subsurface flows are associated with topography and soil. As such, surface and subsurface flow generation zones and the hydrologic behaviour of a Catchment can be determined when the nature of surface topography and rate of soil transmissivity are understood. This knowledge aids in forecasting flooding in river basins.

TOPMODEL is applicable in Catchments with shallow soil depths and flat terrains. Nourani et al. (2011) applied the model in studying the runoff response of Ammammeh River basin in Iran and found the model could represent both event based and daily flows. More accurate results were obtained in daily modeling as it uses soil moisture conditions. The classical version of TOPMODEL disallowed direct use of water quality data in order to perform hydrograph separation and to estimate chemical concentrations in the stream water. In order to do this, a modified version has to be employed (Talamba et al., 2010). The model cannot run on gridded data coarser than 1 km^2 (Kauffeldt et al., 2016). In other words, the need for a finer grid or high resolution data of a large river catchment implies huge amounts of spatial data, thereby requiring substantial amount of computing storage and processing time.

Evaluation

The most interesting feature of TOPMODEL is the approach used in representing a catchment. Since the index is based on basin topography, the model gives calculations only for representative values of indices. It can be obtained by manual analysis of contour maps. The model cannot simulate water quality (nutrients and sediments) together with hydrology within the same model framework. A positive aspect of TOMODEL is its availability and cost. Demonstration versions of the software for teaching and educational purposes are available free of charge, but user support from model developers involves high costs.

2.7.6 Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) was developed (Arnold et al., 1998) as a catchment scale hydrologic model to run on daily time steps. The main objective of the model development was for the assessment of the impacts of sediment and agricultural chemical discharges on water due to anthropogenic activities in large complex, and ungauged river basins (Anaba et al., 2017).

The main constituents of the model framework include catchment hydrology, climate, sediment, plant growth, soil nutrients, agrochemicals and management. The hydrological processes represented involve overland flow, subsurface flow, channel flow, potential evaporation, snow melt, infiltration percolation etc. There are several options in SWAT for users to select from in simulating hydrologic processes based on data availability. For instance, the Penman–Monteith (Monteith, 1965), the Priestley-Taylor (Priestley and Taylor, 1972) or the Hargreaves equations (Hargreaves et al., 1985) can be applied in simulating potential evapotranspiration (PET) (Li et al., 2009), and infiltration can be modeled with the use of Curve Number (USDA-SCS 1972) or Green-Ampt methods (Green and Ampt, 1911). According to Ponce and Hawkins (1996), the CN technique is simple to use, is responsive to soil type, land type and state of land use, soil moisture content and has high predictability giving it a wider applicability. In SWAT, the computation of actual evapotranspiration is influenced by available water content of the various storage media such as soil moisture and canopy. The essential climatic elements or information required in SWAT modeling include: daily rainfall, sunshine, relative humidity, temperature, and wind speed. These elements control the hydrological component, and in river basins where historical records of this information are not available, an in-built weather generator is capable of estimating the values using monthly statistics. The model relates climatic information to geographic locations across the basin and so is able to output results according to spatial disparity of the catchment.

Various SWAT applications have been undertaken in modeling the effects of agricultural management practices on surface and subsurface water quality. The model has a very robust capability for creating scenarios for predicting pollutant losses associated with various land uses and their management practices. It has been applied widely across the globe in the analysis and evaluation of land use practices, estimation of total maximum daily nutrient loads, sediment yield, nitrogen and phosphorus losses, fertiliser application, and change in land use impacts on water resources. The literature contains many studies that demonstrate the utility of the model. For example, Das et al. (2013) evaluated the performance of SWAT model in simulating hydrological processes in the Yarra River basin (Australia) for the 1990-2008 period, for the purpose of adopting SWAT in determining the impact of land use change on water quality. SWAT was found to have sufficiently replicated the hydrology of their study area, and would be capable of capturing other water quality related catchment processes. Lee et al. (2010) evaluated non-point source pollution reduction using SWAT and found that the model performed in simulating streamflow at 63% (Nash-Sutcliffe model efficiency); and estimated total phosphorus (TP), total nitrogen (TN) and suspended solids (SS) at 88%, 72% and 68% (coefficient of determination, R^2) reliability rates respectively. Bossa et al. (2014) undertook a scenario-based analysis of land use and climate change impact on land and water degradation from the meso- to regional scale in Benin Republic, using the SWAT model. They revealed that increasing land use change over the years has had significant impact of between -8% and 50% on surface runoff, groundwater flow, sediment and organic nitrogen load; water yield and evapotranspiration were affected by climate change at the rate of −31% to +2%.

SWAT has also been employed in understanding catchment phosphorus movement and establishment of critical source areas (CSAs) (Srinivasan et al., 2005, Ouyang et al., 2007, Busteed et al., 2009, Pai et al., 2011; Winchell et al., 2015). Michaud et al. (2007) undertook a scenario analysis of the impact of land use and crop production techniques on phosphorus movement using SWAT, to determine the best crop production approach that supports reduction in phosphorus loading within the Pike River Catchment of southwestern Québec, Canada. Additional work by Ghebremichael et al. (2010) involved a high-resolution approach to modeling CSAs of phosphorus discharge in the Rock River Catchment of the Missisquoi Bay, using the SWAT model. Similar research was carried out by Winchell et al. (2015), where the SWAT model was applied in identifying the phosphorus CSAs of the Vermont sector of the Missisquoi Bay Basin (MBB) (USA/Canada). Their finding was that 20% of the MBB contributes a total of 4% of the total phosphorus loading from the area, which again shows the utility of SWAT in catchment nonpoint source pollution studies.

Wei et al. (2016) in their study of land use change effects on overland flow found that the SWAT model had good applicability during calibration, and was capable of simulating runoff responses to land use change in Qiaoyu River basin in the southwest of Henan province in China. Cao et al. (2009) employed SWAT in evaluating the effects of land cover alteration on total water yields, surface and subsurface flows in the Motueka River catchment, New Zealand. Their analysis suggests that SWAT successfully simulated the effects of land cover alteration on the water resources of the catchment. Cao et al. (2007, 2009), LERNZ (2015) employed the SWAT model in representing the hydrological processes in New Zealand river catchments and found more realistic results in both the hydrological processes and in spatial representation. The findings of these studies suggest that SWAT can predict catchment hydrology which to a very large extent controls the movement of pollutants with reasonable accuracy. A study of pollutant fluxes in the Waipa catchment, New Zealand considering various irrigation scenarios was undertaken using SWAT (Me et al. 2017). The results showed that the model is an invaluable decision tool for treated wastewater irrigation. Pereira et al. (2014) also concluded in their study of the implications of forest depletion on the hydrology of a river catchment on the Brazilian east coast that SWAT performed satisfactorily in simulating stream flow.

Other research on the effects of land use activities on streamflow, sediment, and agrochemical discharges were also carried out using the SWAT model, with results in good agreement with observed data (Chen et al., 2005; Chu et al., 2004; Guo et al., 2008; Qin et al.,2009; Wu and Johnston, 2007). Zhang and Zhang (2011) integrated climatic parameters and land use information in SWAT to model the effectiveness of agricultural best management practices (BMPs) to reduce sediment load and agrochemicals in overland flow. In the same vein, Ficklin et al. (2010) employed SWAT in assessing the implication of climate change on soil nutrients, sediment, and agrochemical discharge in the San Joaquin Catchment and found that agricultural runoff is sensitive to climatic variability. Du et al. (2006), Kannan et al. (2006), Vazquez-Amabile et al. (2006), Gassman et al. (2007), Larose et al. (2007) and Luo et al. (2008) have applied different kinds of catchment scale hydrologic models (including SWAT) for simulating hydrology and related pollution problems and concluded that the rate of agrochemical diffusion in surface water is not only influenced by their rate of applications and physiochemical characteristics, but is also associated with the variability of physical environmental characteristics like climate, land use and soil.

Water yield prediction using the SWAT model is found to vary according to climate change model resolution. Stone et al. (2003) found that hydrologic analysis with SWAT using the Regional Climate Model (RCM) scenario produced a higher yield than that obtained from Global Climate Models (GCMs) data. The variation in water yield was noted at both the catchment and sub-catchment levels. Different climatic scenarios using just one climate change model yielded different runoff output (Arnell et al., 2003).

Evaluation

The Soil and Water Assessment Tool's capability of operating on limited available data made it possible for its widespread application to a variety of river catchments, and calibrated for various purposes in various countries using both very long and short periods of available time series data. A limited direct calibration of the model is usually required to obtain good hydrologic predictions (Easton et al., 2010). SWAT could possibly be qualified as the benchmark for any catchment hydrologic, land management and water quality relationship modeling (Droogers et al., 2006). In other words, the model has every necessary capability for simulating hydrology and predicting pollutant losses associated with various land uses and their management practices. The SWAT model belongs in the public domain and is therefore accessible without any associated cost. There is also a diverse user support from both the developers and a functional user group. Training workshops for both experienced and inexperienced users and conferences are also organised at regular intervals each year across the globe.

2.8 Choosing a Model for Case Application

There is a range of hydrologic models that can be used in assessing the effects of land use and climate change on catchment water resources. Each model has its own unique characteristics and respective applications. The models also possess their own deficiencies, for instance difficulty of use, high data demand, or imprecise expression and documentation of model weaknesses. Several of these models are quite elaborate in representation of physical processes (lumped, distributed, process oriented). They implement basic laws of nature that govern catchment hydrological processes and can be spatially and temporarily distributed. It is also important to know that the characteristics of the catchment under study, the objectives and degree of accuracy of desired outcome of the modeling exercise determine to a large extent the selection of lumping or distributing models (Jajarmizadeh et al., 2012). From the enormous amount of process oriented models available now, three of the most widely applied have been reviewed in this chapter for the study of the Waipara River catchment. A crucial decision to make here is to determine the model that could best aid the achievement of the objectives of the current study. A number of screening questions have been raised to ascertain the suitability of each of the three models for the study:

1. Has the model got an in-built climate generator to simulate required climatic data where observed data is missing, unavailable or insufficient, and also to compute required weather parameter statistics?
2. Can hydrology, sediment and nutrient simulation be integrated in same model?
3. Are climatic data considered spatially distributed or lumped?
4. Can the model simulate the effects of management practices on hydrology and water quality?
5. Is the model able to generate outputs for a location of interest within the catchment?
6. Is there any support from model developers and user groups?
7. Is the model freely available without cost?

A critical analysis of the three models undertaken in this chapter against seven criteria (Table 1) has shown that SWAT performed best in a catchment like the Waipara and for these reasons it will now be used as the basis for the rest of the thesis.

Table 1 Evaluation of model suitability for the study of Waipara River catchment

Name of Model	In-built climate generator	Hydrology, sediment and nutrient integration	Spatial distribution of climatic data	Incorporation of effects of management practices on hydrology and water quality	Ability to generate outputs for a location of interest within a catchment	Availability of user support	Availability and costs
MIKE SHE	0	0	+	0	++	+	0
TOPMODEL	0	+	+	+	++	+	+
SWAT	++	++	++	++	++	++	++
***++** = most suitable,* ***+** = suitable,* ***0** = less suitable*							

2.9 Summary

Three categorisations of hydrologic models as empirical, conceptual and physically based were reviewed. The physically based models were considered best because of their capability to represent the physical characteristics of the catchment under study, generation of outputs for location of interest within the catchment, and also the ability to simulate the impact any change in catchment land use may have on the water cycle. Seven criteria were then applied to three specific physically based models including the MIKE SHE, TOPMODEL and SWAT. A critical analysis of the set criteria showed that SWAT performed best and is therefore chosen for use in the Waipara case study.

2.10 Gaps in Literature

This review of literature has established the importance of models, especially the physically based hydrologic models in the assessment of river basin hydrologic processes and catchment land use management. The review has also shown the widespread application of the SWAT model world-wide, as well as the scope of applications. While the application of SWAT in New Zealand is not new, the New Zealand based SWAT model applications are limited in scope to hydrology and nutrients/contaminant simulation of river catchments (Ekanayake and Davie, 2005; Cao et al., 2007; Cao et al., 2009; LERNZ, 2015; Me et al., 2017). There is no known application of the SWAT model in the study of the combined land use and climate change impacts on water resources that have been made in New Zealand. Integrated SWAT and GCMs application studies of climate change impacts on water quality and quantity in New Zealand are also unknown. Another aspect of SWAT model application in climate change impact analysis which has not featured among the New Zealand studies is the assessment of the atmospheric CO_2 concentration pathways (RCP 4.5, 6.0, 8.0). The use of SWAT to evaluate climate change effects via different land use scenarios has also not featured in the literature in New Zealand. The current study will fill these gaps in the literature.

Chapter 3
STUDY AREA

3.1 Introduction

This chapter describes the Waipara River catchment which is the study area of the thesis. Sub-section 3.2 describes the physical characteristics of the Waipara catchment location. Section 3.2.1 takes a brief overview of the climate of the region while geology and soil characteristics are outlined in section 3.2.2. The subsequent sections 3.2.3 to 3.2.6 describe terrestrial vegetation, agricultural land use of the catchment, water resources, aquatic life and eco-habitat values. The significance of the river system to Maori cultural values and the water quality status of the river are highlighted in sections 3.2.7 and 3.2.8. The concluding section 3.3 presents a brief summary of the importance and benefits of the Waipara River catchment as a valuable sustainable resource for supporting the cultural, social, environmental and economic well being of the area. The problem of water quality degradation resulting from intensification of land use activities as well as a potentially useful approach for helping put in place a more effective and sustainable pollution control and management strategy which is a core objective of the thesis are also highlighted.

3.2 Catchment Description

The Waipara catchment located in North Canterbury Region of the South Island, New Zealand, is a relatively small river system compared to other river basins of the Canterbury Plains (Waipara River Working Party –WRWP, 2012). The catchment encompasses an area of 726 km^2 and extends some 40 kilometres from the eastward slopes of the Southern Alps to the coast by the northward side of Pegasus Bay (Figure 1). The landscape of the catchment is physically variable, with a substantial amount of flatland areas on the one hand, and mountain ranges of over 1000 metres in height on the other (some notable places/features are indicated on the map as locations). This variability is not limited to Waipara alone; it is typical of other catchments in the region (Chater, 2002; Mosley, 2003). The region comprises of relatively low mountains, flat land, and a number of coastal uplandsand can be divided into two: the upper Waipara and lower Waipara. The upper Waipara catchment is rugged, steep and traversed by four main branches: the North, South and Middle Branches of the Waipara River and Tommys Stream (Lloyd, 2002a; WRWP, 2012). A wide flat alluvial plain then makes up a greater portion of the lower Waipara catchment, with coastal hills forming its eastern boundary. Weka Creek and Omihi Stream constitute the two main tributaries of the lower Waipara River (flowing from the north) catchment (Lloyd, 2002a).

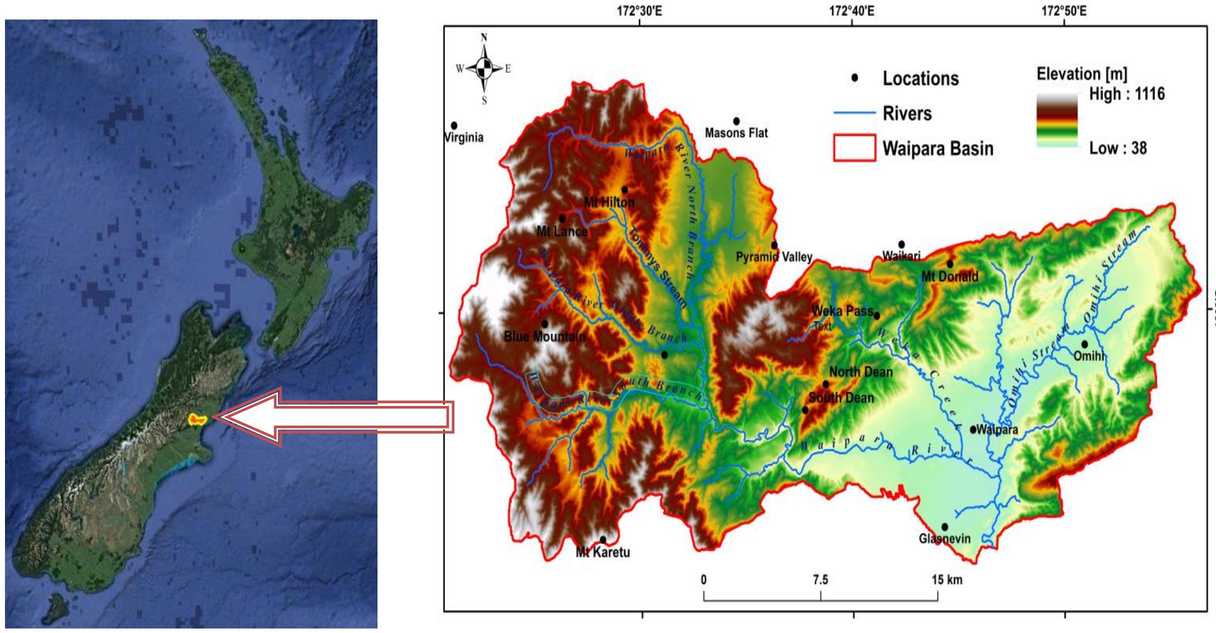


Figure 1 Waipara River catchment

The North Branch of the Waipara River near its headwater flows eastwards from the hills and then changes direction south across Masons Flat. The North Branch is joined by the Middle and South branches below Masons Flat and then flow into the main stem of the Waipara River (Lloyd, 2002a; Chater, 2002; WRWP, 2012). The Waipara River, flowing through Ohuriawa Gorge, enters the greywacke/argillite bedrock that formed the Doctors Hills. The Doctors Hills as well as Mt Grey to the south, create a visible demarcation separating the upper catchment and the lower catchment (Chater, 2002).

3.2.1 Climate

Seasons in the Waipara catchment, as in the Canterbury region, vary dramatically, due greatly to the effect of the Southern Alps. The region is characterised by three meso-scale wind systems which include: westerly fronts, blowing from the Tasman Sea that bring rainfall across the Southern Alps to the western parts of the catchment (Sinclair et al., 1997; Chater and Sturman, 1998), moist southerly cold wind blowing across the Tasman Sea and Southern Ocean across the South Island (Smith et al., 1991) and the easterly fronts typically from the north over the Pacific Ocean (McKendry et al., 1987). Long dry spells are common in summer when hot dry north-westerly winds set in leaving the temperature ranging from 21°c to 32°c, creating dry microclimatic conditions but are often cooled by a north-easterly sea breeze (Sinclair et al., 1997). It is also common to have snow in the mountains during winter (Sinclair et al., 1997) bringing the daytime winter temperatures down to about 7°c to 14°c (http://www.northcanterbury.co.nz/NorthCanterbury/location-climate/).It is also very common to see the climate changing considerably over short distances. Finkelstein (1973) estimated the annual average daily temperature for the region to be 12°c**.** Distinct rainfall distribution patterns are also identifiable in the region despite the overlapping coverage area of the wind systems (Sturman, 1986), with the western parts of the region receiving more rainfall.

3.2.2 Geology and Soil

The landscape of the Waipara catchment is comprised of limestone cliffs, alluvial terraces as well as steep sided rocky hills and cliffs. The structure and the geology of the landscape have greatly influenced the flow of the river system. The upper catchment is characterised by moderate to steep topography consisting of greywacke and argillite sedimentary bedrock formation. The gorge area is made of stunning landforms such as concretions created from limestone by the action of running water. Deposits of glacial outwash, river gravels, marine siltstones and sandstones that occurred during the Quarternary period created a predominantly large alluvial basin in the lower catchment (Chater, 2002). Sedimentary rock formation of the tertiary age composed of sandstones, limestones, mudstones and conglomerates bound the alluvial basin of the lower catchment.

The Waipara River is of national and international significance especially for its historically and scientifically important sites in the upper sections of the river system. This area contains a wealth of information about the past geological events of New Zealand (WRWP, 2012). The geological processes that have occurred over the years in the region can be understood from the exposed rocks in the area. The region is popular for its rich deposit of marine reptile fossils formed in large, almost spherical shapes. The discovery of the first fossil bones in New Zealand was made here in 1859 (WRWP, 2012). It is also of historical significance to note that the entire Waipara area (including other parts of the South Island) was part of the ocean bed millions of years ago (WRWP, 2012).

The type and spatial distribution of soils within the catchment is to a very large extent influenced by the geology of the area which also defines the vegetation and land use (Lloyd, 2002b). Griffiths (1980) reported that deep fertile clay loams as well as shallow stony silt loam soils cover the valley floors of the catchment. Because the soils of the Waipara river catchment were formed from sedimentry rock materials, there is a very high probability that they possess similar chemical characteristics (Roberts et al., 1994). Figure 2 shows the soil types and distribution in the catchment.

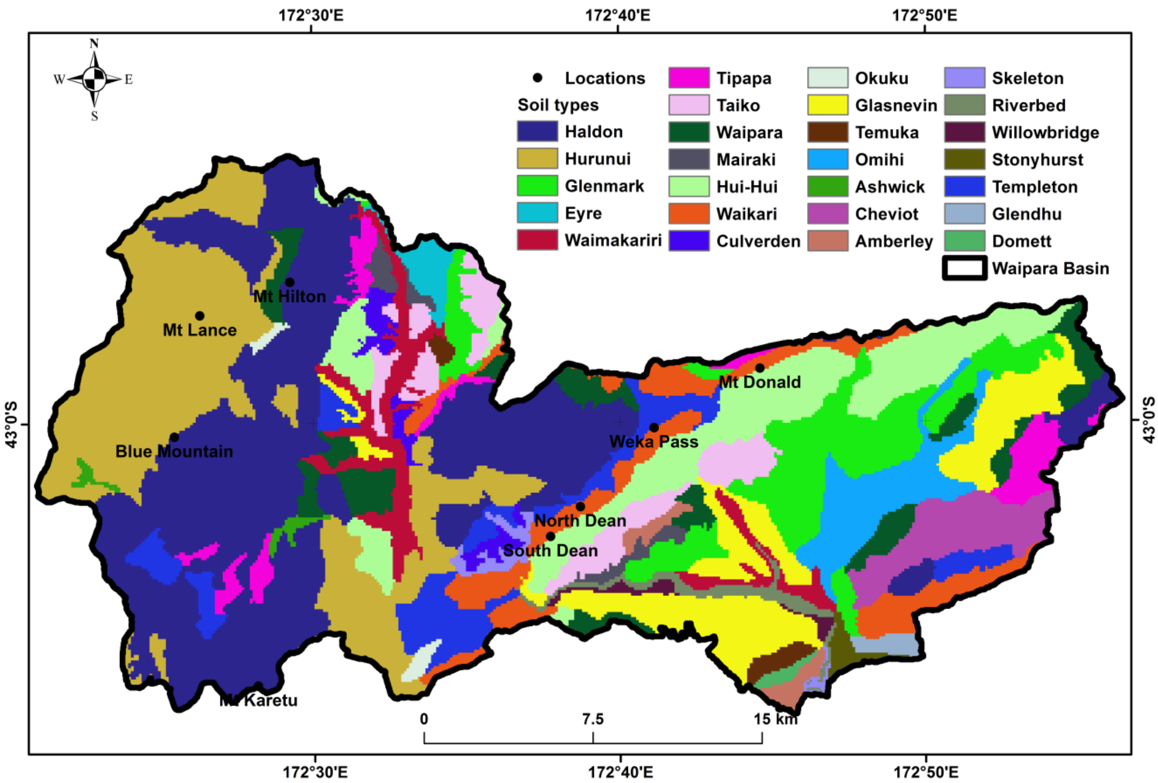


Figure 2 Waipara River catchment soils and distribution.

3.2.3 Terrestrial Vegetation

The Waipara River catchment supports a range of ecosystems. The nature and extent of terrestrial vegetation in the catchment especially along the river channels is largely determined by natural ecological processes, human activity (such as agriculture, intentional and indelibrate ingress of non-native plant breeds), and fluvial processes during periodic high flows which removes vegetation cover (Mosley, 2003). The upper parts of the catchment are generally dominated by undeveloped pasture, and native shrublands. Remnants of indigenous forest and exotic shrubland also occur along river channels and are designated as significant natural sites by the Hurunui District Council. There has been extensive invasion of exotic vegetation of the region which include non-native grasses and other flora, shrubs (gorse and broom), and woody plants (mainly willows, some of which were for the purpose of protecting river banks) (Mosley, 2003).

3.2.4 Agricultural Land Use

Agriculture is the primary landuse activity in the Waipara Catchment, and has supported the development of small rural settlements. Exotic forestry and extensive dry land pastoral farming are the dominant land use activities in the middle and top segments of the catchment. The characteristically more fertile soils, warmer temperatures and relatively flat terrain of the lower parts of the catchment favour intensive livestock grazing as well as cultivation of exotic horticultural and arable crops (Lloyd, 2002a). Cultivation of grapes (viticulture) and olive plantations started in recent years. Grapes were first planted in the Waipara valley in the 1980s (nzhistory.govt.nz/keyword/waipara). The intensification of land use activities and change from pastoral land use to expanded forestry in the upper catchment and the growing viticultural, horticultural and small-scale farm settlements in the lower catchment has brought about greater demand for water in the catchment (WRWP, 2012). The growth and development in land use activities witnessed over the years thus pose huge pressures on water resource (especially water quality and quantity) management in the Waipara Catchment (Charter, 2002). In view of this, the Canterbury Regional Council has reviewed the policy on water take from the Waipara River and has set environmental flows (WRWP, 2012). The Waipara catchment environmental flow and water allocation plan came into effect on 10 June 2012 (WRWP, 2012).

3.2.5 Waipara River Catchment Water Resources

The Waipara Catchment's dry microclimatic conditions as well as its water resources are extremely variable. The flow pattern of the river is characterised by high flows and floods in winter and extended durations of low flows especially in summer and autumn months. Durations of low flows of less than 100 l/s during the summer months can last for several weeks and sometimes extend into the next winter. Hayward et al. (2003) estimated the annual mean and median flows of the river as 3.0 m^3/s and 1 m^3/s respectively. High volume flash floods are also common especially during winter but can occur at any other time (Hayward et al, 2003). The Waipara catchment however possesses some amount of underground water reserve deeply buried within the confined and unconfined aquifers of the Quaternary gravel formation of the sedimentary alluvial basin (Chater, 2002). The existence of the limited hydraulic connectivity between subsurface and surface water resources enhances the utility of the groundwater reserves in the catchment. The hydraulic connectivity helps in-stream water recharge as well as the depletion of ground water.

Generally, groundwater resources in the Waipara Catchment are recharged by precipitation infiltration. Due to less rainfall and excessive evapotranspiration rates, and the presence of dense clay layers within the gravels, recharge rates from precipitation are low, leading to somewhat poor groundwater storage capacity of the catchment (WRWP, 2012). The lower part (Weka Creek, Home Creek and Omihi Stream) of the catchment, which has some degree of hydraulic connectivity, experiences surface water recharge from groundwater (Chater, 2002). Detailed information about the amount and rate of groundwater withdrawal for irrigation purposes within the catchment is undocumented, primarily due to absence of water meters on most pumps (Chater, 2002). Although the Resource Management (Measurement and Reporting of Water Takes) Regulations 2010 stipulates that any water use/take as much as 5, 10 or20 litres/sec that would not return water back to the source must be measured and reported to the Regional Council, the problem of undocumented water takes still exists. Forest and Bird (2016) reported an "environmental crime wave" in Canterbury, where farmers illegally took large volumes of water using non-functioning water meters. Recorded amounts of consented water allocated for abstraction by Environment Canterbury has been the only way for estimating actual abstraction rates. Chater (2002) found such estimation to be imprecise when attempting to naturalise flows in the catchment, thus affecting the results of flow estimations. Chater (2002) and WRWP (2012) however noted that the total authorised amount of water taken from the Waipara River and its branches by Environment Canterbury is approximately 1300 l/s. Out of this amount, 1149 l/s abstracted during high flows are meant for offstream storage facilities such as reservoirs (e.g. Glenmark Irrigation Scheme; Mosley, 2003).

3.2.6 Aquatic Life and Eco-habitat Values

The aquatic life of the Waipara River is comprised of native fish species including longfin and shortfin eels, Canterbury galaxias, upland bluegill and common bullies, torrent fish, and inanga (Richardson et al.,2003). Evidence of a limited population of trout also exists, even though the river is not a well known brown trout fishery (Mosley, 2003). The Waipara River mouth is also an important habitat for native birds such as the endangered wrybill, black-fronted tern, banded dotterel and bittern (Mosley, 2003; Hughey et al., 2010). The Department of Conservation’s rating of the river and river mouth wildlife habitat status in 1983 to be of “moderate” and “moderate to high” value (O’Donnell and Moore, 1983). O’Donnell (2000) classified the river mouth as “High-3” on the bases of its national and international importance as a habitat for endangered species, and the river as “High-6” due to its use by <10% of the existing endangered species population. The river system is also used for recreational purposes such as swimming, camping, off-road operation, picnicking and fossil-hunting (Mosely, 2003).

3.2.7 Māori Cultural Values of Waipara Catchment

The Waipara River catchment is of great importance to the Māori as it provides a life sustaining resource (mahinga kai). The concept of *mahinga kai* refers to places and resources (e.g. food and other natural materials) valuable for supporting the cultural, social, and economic well being of *mana whenua* (Crengle, 2002, p.12). Local land areas, forests, rivers, lakes, sea and sky constitute places for food production (Waitangi Tribunal, 1991, p.150). *Mahinga kai* resources are not only important to *iwi* for physical life, health and wellbeing, cultural artworks or economic/commercial support (MfE, 1998, p.87), they also have other cultural significance such as *“whanau experience and knowledge, and transmission of cultural values and tikanga practices between generations”* (Crengle, 2002, p.12).

Māori have therefore maintained a strong relationship with the Waipara River as it was once a significant *mahinga kai* and as well as a channel of commercial transport and merchandise along the coast. The place of the Waipara River and lagoon in Māori culture featured in the Statutory Acknowledgement under the *Ngāi Tahu* Claims Settlement Act 1998.

> *"The [Waipara] river and associated coastline was a significant mahinga kai, with kai moana [sea food], particularly paua, being taken at the mouth. The tūpuna had considerable knowledge of whakapapa [genealogy], traditional trails and tūranga waka [places for gathering food and taonga], ways in which to use the resources of the river, the relationship of people with the river and their dependence on it and tikanga [customs] for the proper and sustainable utilisation of resources. All of these values remain important to Ngāi Tahu today. The mauri of the Waipara River represents the essence that binds the physical and spiritual elements of all things together, generating and upholding all life. All elements of the natural environment possess a life force, and all forms of life are related. Mauri is a critical element of the spiritual relationship of Ngāi Tahu Whānui with the river"* (Schedule 74 Ngāi Tahu Claims Settlement Act 1998).

3.2.8 Water Quality Status of Waipara River

Water quality measurement of the Waipara River is undertaken by the Canterbury Regional Council once every three months at Laidmore Road, Stringers Bridge, Mt Cass Road and Greenwoods (Teviotdale) Bridge sites. Collected water samples are subjected to laboratory analysis for dissolved oxygen, pH, conductivity, turbidity, suspended solids, dissolved organic carbon, nitrate-nitrite nitrogen, ammonia-nitrogen, total nitrogen, dissolved reactive phosphorus, total phosphorus and E. coli (WRWP, 2012). The high concentrations of dissolved organic nitrogen and dissolved reactive phosphorus have led to the Waipara River being defined eutrophic (Hayward et al., 2003).

A study of the chemical, physical, biological, and radiological characteristics of the Waipara River by Hayward et al. (2003) reported that periphyton growth and consequent depletion in aesthetics and the freshwater ecosystem values present the major water quality concerns for the Waipara River catchment. Plant nutrients such as nitrogen and phosphorus play crucial roles in the growth and development of periphyton (benthic algae) or macrophyte (plant) species. Development of macrophytes is often enhanced by the stability of a river flow regime and presence of smooth sediment deposits, whereas streams with gravels on their beds support periphyton growth (Hayward et al., 2003). The proliferation of these plant communities is however determined by the presence of light and nutrients, as well as the rate at which flood events occur. Periphyton growth and development in particular involve a multiplex relationship between nutrient discharge and stream flow pattern. Controlling nutrient input and suitable flow levels is an essential periphyton management strategy. MfE (2000; Snelder et al., 2013) nutrient guidelines for the prevention of periphyton proliferations are therefore based on the frequency of flood events.

The recent state of the Waipara River water quality as reported by (Ecan, 2017) shows that the water quality status measured for nitrogen and phosphorus concentrations, and bacteria at Teviotdale and Laidmore sites are in the best 25% of like sites across New Zealand. Mosley (2003) also suggested that the water quality in the Waipara River is far better than any other Canterbury foothill rivers. Ecan (2017) however sounded a health warning of the possibility of toxiccyanobacteria occurring at a number of popular freshwater recreation sites in Canterbury including the Waipara River system.

A great proportion of the catchment is made of soft sedimentary deposits of the tertiary marine sandstone and limestone, constituting a natural source of inorganic nutrients (e.g. Phosphorus). Total phosphorus (TP) discharge has been known to be associated with sediment loading during floods. Concentrations of total phosphorus were generally low. Median TP concentrations were found at all sites to be below the detection limit. Relatively highconcentrationscorrelated withflood eventswhichcorrespond with low turbidity and limited amount of sedimentation of the river. Mean dissolved inorganic nitrogen (DIN) concentrations in the river according to Hayward et al. (2003) are very high, although generally lower than other similar hill-fed rivers in the region. Hayward et al. (2003) also identified a spatial pattern in DIN concentrations in the river with high concentrations around Laidmores Road, Stringers Bridge, and lower concentrations around Mt Cass Road and a rise in concentration at Teviotdale Bridge. Total nitrogen (TN) concentrations are also found to be high across the catchment (more so after flood events) but still lower than what is found in other hill-fed streams. Total organic nitrogen (TON) is about 60-90% of TN concentration (Hayward et al., 2003).

As algal biomass prolifirates in the Waipara River, nutrients are increasingly taken up from the water column. Periphyton cellular nutrient enrichment and conductivity are other indicators of water quality status (MfE, 2000). Past studies showed thathigher percent cellular N and P occur at the Stringers andTeviotdale bridge sites than the Laidmores Road and Mt Cass Road sites (Hayward et al., 2003). Biggs (1995) suggests that cellular nitrogen value less than 5% and cellular phosphorus value below 0.5% is an indication of N and Plimitation. The analyses showed that the median values of percent cellular Nat Laidmores Road and Mt Cass Road were 4.7 and 4.8% respectively, indicative of nitrogen limitation. Median percent cellular N at Stringers Bridge and Teviotdale Bridge were 6.6 and

7.7%, showing N enrichment. On the contrary, P limitation (with median percent cellular values ranging from 0.32 to 0.52%) was observed at all the sites over the study period.

The reported cellular N and P values showed that nutrient enrichment at Stringers Bridge and Teviotdale Bridge sites was the greatest among all the sites. DIN concentrations were also highest at these sites but differ with DRP concentrations. DRP enrichment was found to be low at the Stringers Bridge site. The nutrient status as shown by the cellular nutrient values was also found to have correlated withthe periphyton biomass enrichment status of the river. The occurrence of high periphyton biomass frequently observed at the Stringers and Teviotdale Bridge sites is an indication of eutrophication of the river (Hayward et al., 2003).

Concentration of dissolved elements in water especially dissolved salts can be determined by conductivity. Conductivity is therefore an alternative indication of nutrient supply to streams or lakes, and is correlated to periphyton biomass (MfE, 2000). The reason for this is that the major ions (e.g. calcium, sodium, bicarbonate and chloride), which are notused by plants, are leached from the rocks and soils in same proportions to plant nutrients remain in the water, even though plants have taken up the nutrients. New Zealand streams with conductivity values higher than 20 mS/m are characterised by high periphyton growth (MfE, 2000). The conductivity values of many Canterbury gravel rivers ranged betweed 5-25 mS/m. In the case of the Waipara River, the values ranged from 21 to 34 mS/m. The conductivity of the Waipara River is notably higher and generally increased downstream because some of the major tributaries feeding into the river are dominated by tertiary marine sediments (limestone and sandstones) which influence the water chemistry (Snelder et al., 2002).

Someother water quality status determinants (listed in table 2) include dissolved oxygen concentration, temperature, turbidity, pH, ammonia toxicity and faecal coliforms. In the Waipara River, values of percent saturation of dissolved oxygen were found to be generally above (better than) the guideline value of 80% saturation. Measurements of Spot temperature at all sites were less than the Resource Management Act guideline of 25°C. Similar to other hill-fed rivers in Canterbury, turbidity in the Waipara River was generally low. About 3 – 6% of water samples from all the sites showed increased turbity above the aesthetic guideline value, which was consistent with periods of high flows. Increased turbidity occurs during flood events.Over 90% of samples from the four sites were found tohave pH exceeding the upper guideline value (7.8) for aquatic ecosystems. All the four sites had median pH values ranging from 8.2 to 8.4 signifying the high alkalinity of the water. The Waipara River's pH values were considerably above those of similar hill-fed rivers in Canterbury.

Ammonia toxicity is known to increase in relation to increasing pH and temperature of a water body. The guideline value for total ammonia-nitrogen is 0.9 mg/L at pH 8.0 and 20°C (ANZECC, 2000). Ammonia-nitrogen concentrations were found to be far less than the general guideline value (0.9 mg/L) in the Waipara River. Due to the high alkalinity status, ammonia concentrations were occasionally found to have reached the toxicity limit when the pH of each water sample was taken into account. Faecal coliforms in the Waipara River at all siteswere found to be in moderate to low concentrations. The Laidmores Road, Stringers Bridge and MtCass Road sites occasionally recorded faecal coliform concentrations higher than the recreationalguideline value of 200 cfu/100 ml (Meredith and Hayward,2002; Hayward et al., 2003).

Table 2 Site comparison of (1999 to 2002) monthly water quality data for Waipara River monitoring sites (two-tailed Wilcoxon Signed Rank Test) (adapted from Hayward et al. 2003).

Upstream site **Downstream site**	**Laidmore Rd** **Stringers Bdge**	**Stringers Bdge** **Mt Cass Rd**	**Mt Cass Rd** **Teviodale Bdge**
Conductivity	*** ▲	* ▲	*** ▲
Calcium	*** ▲	* ▲	*** ▲
Chloride	*** ▲	ns	*** ▲
Dissolved oxygen	* ▲	ns	** ▲
Dissoveldoxygen saturaturation	* ▲	ns	** ▲
pH	*** ▲	*** ▼	* ▲
Ammonia nitrogen	ns	ns	* ▲
Nitrate/nitrite nitrogen	** ▲	* ▼	*** ▲
Dissolved inorganic nitrogen	** ▲	* ▼	** ▲
Dissolved reactive phosphorus	* ▼	* ▲	ns

DIN/DRP ratio	*** ▲	* ▼	** ▲
Total nitrogen	ns	** ▼	*** ▲
Total phosphorus	ns	ns	ns
Faecal coliforms	ns	ns	ns
Turbidity	ns	ns	ns
Ash-free dry mass	** ▲	** ▼	** ▲
Chlorophyl *a*	*** ▲	** ▼	** ▲
% cellular N	ns	** ▼	** ▲
% cellular P	ns	* ▼	* ▲
Cellular N:P	ns	ns	ns

ns = not significant ▲ = increase in determinand concentration at downstream site

* = P < 0.05 ▼ = decrease in determinand concentration at downstream site

** = P < 0.01

*** = P < 0.005

3.3 Conclusion

The Waipara River provides a habitat for many life forms and diverse ecosystems, including for indigenous plants, birds, aquatic macro invertebrates, and fish. Indigenous and introduced grassland supports both extensive and intensive pastoral farming in the catchment. Besides the few remaining native groves, of which the Hurunui District Plan recognised a couple as significant natural areas, exotic forests, grape and olive plantations constitute the vegetation cover of the landscape. The Catchment is also known for its recreational, historical and cultural significance. The unique characteristics of the Catchment defined by its location, geology, climate and land use have exposed the river to the problems of pollution (especially periphyton growth). Hayward et al. (2003) suggested that best nutrient management practices in the catchment alone may not improve river water quality, due to the available natural sources of phosphorus discharge. Notwithstanding this, establishing the distribution pattern of N, P and sediments is a potentially significant aspect in tracing the footprints of nutrients and sediments in the landscape. Modeling the Waipara river catchment to identify the landscape sources of nutrient and sediment loading is therefore a useful approach for helping put in place a more effective and sustainable pollution control and management strategy.

Chapter 4

DESCRIPTION OF SWAT MODEL SETUP FOR THE WAIPARA CATCHMENT

4.1 Introduction

This chapter discusses the primary approach to SWAT hydrology and water quality modeling. Being a process and physically- based catchment model with a consideration for the variability in river basin physical characteristics, SWAT utilises both static and dynamic information to represent the physical processes taking place within the hydrological system. Information about static and dynamic data used in setting up and implementing the Waipara Catchment SWAT model is discussed in the chapter. The approach to visual assessment, calibration and accuracy evaluation of SWAT model outputs are also highlighted.

4.2 Data Needs and SWAT Model Setup

The ability of SWAT to integrate land management processes, plant growth, soil, slope and other environmental factors to simulate nutrients and sediment discharge, as well as hydrology in both small and large scale catchments made it a particularly more suitable tool for this study. SWAT was developed to simulate both landscape and in-stream processes with a high level of spatial resolution (Santhi et al., 2006). SWAT makes use of combined empirical and physically-based algorithms, easily accessible information and allows for simulations involving relatively long periods of time. The model is characterised by eight main constituents, including: hydrology, weather, erosion and sedimentation, soil temperature, plant growth, nutrients, agro-chemicals and land management. The primary data required for implementing the Waipara catchment SWAT model are listed in Table 3 and further discussed in subsequent sections of the chapter.

Table 3 Model input data

Data Type	Source / Date	Description
Elevation/slope	*New Zealandwide*	25 meters resolution digital elevation model (DEM)
Weather parameter	NIWA/1979 – 2013	Daily precipitation, relative humidity, solar radiation, temperature (max/min) and wind speed
	ECan/1979 – 2013	Daily precipitation
	NIWA/1971 – 2005, (MfE, 2016)	Bias corrected RCP4.5 daily precipitation & temperature (min/max)
	NIWA/2006 – 2099 (MfE, 2016)	Bias corrected RCP6.0 daily precipitation& te (min/max)
	NIWA/2006 – 2100 (MfE, 2016)	Bias corrected RCP8.5 daily precipitation & temperature (min/max)
Soil	Land resource information system portal (www.landcareresearch.co.nz/resources/data/lris)	Soil hydrologic group, soil depth, soil texture, available water capacity, bulk density, organic carbon content, saturated hydraulic conductivity, soil albedo, soil erodibility factors and rock fragments
	Digital soil map (S-Map) for New Zealand database (http://smap.landcareresearch.co.nz/home)	
Land use/cover	Landcare Research (http://lris.scinfo.org.nz/layer/304-lcdb-v30-land-cover-database-version-3/).	Land use/cover layer
Drainage	Waipara River network extracted from the River Environment Classification Canterbury (2010) data	Map layer
Flow	ECan / 2001 – 2012	Daily observed flow records at Teviotdale station
Water quality	ECan/2001 - 2006	Irregularly observed water quality records at Teviotdale station (N & P)
Management	150 kg N/h/yr FertResearch, 1998, Cameron et al. 2005, Monaghan et al. 2007.	Applied fertiliser to gazing land

4.3 Model Inputs

4.3.1 Elevation/Slope Data

A 25-m resolution digital elevation model (DEM) (Figure 3) was extracted from the New Zealand wide DEM to represent the Catchment.The catchment elevation ranges from 38 meters above sea level to 1,116 meters at the top of the hills, with an average elevation of 577 meters. The New Zealand Geodetic Datum 2000 (NZGD2000) formed the datum for elevation. Elevation and slope can have very significant impacts on Catchment hydrology and pollutant transport. The slope of the land determines the volume and timing of runoff and therefore influencing pollutant transport. The slope of the Catchment varies slightly with relatively steeper slopes within the hills and relatively flatter slopes downhill.

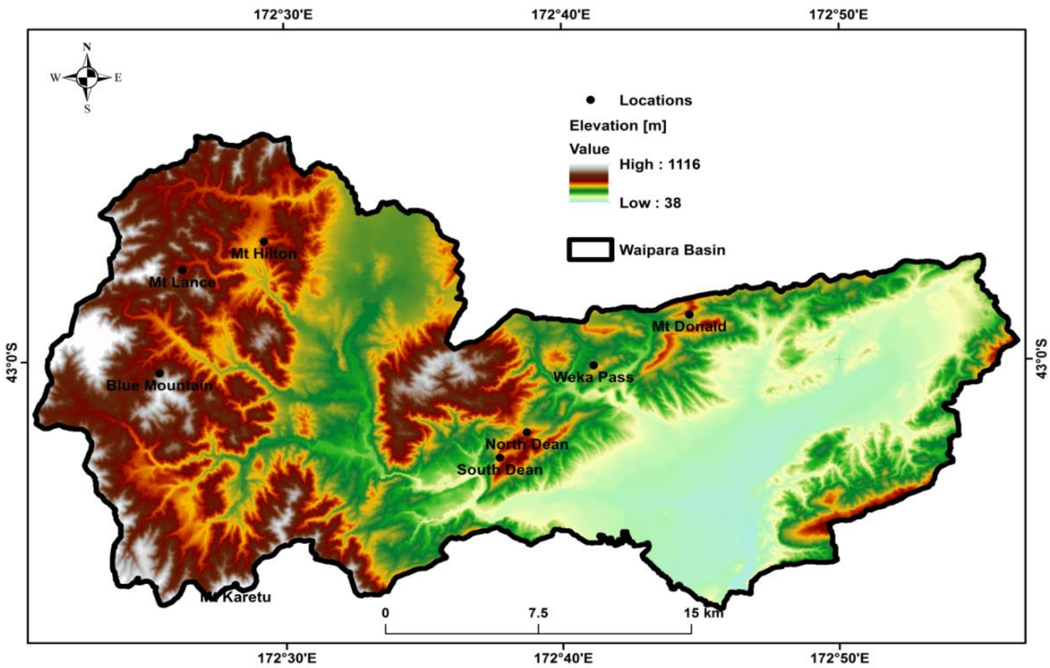


Figure 3 DEM Map showing Waipara River catchment slope distribution

4.3.2 Soil Data

Soil data are required for use in SWAT to ascertain the hydrologic characteristics of each soil group in a given sub-Catchment and hydrologic response unit. Both physical and chemical properties of the soil are involved. These include soil hydrologic group, soil depth, soil texture, available water capacity, bulk density, organic carbon content, saturated hydraulic conductivity, soil albedo, soil erodibility factors and rock fragments (Gessesse et al. 2014). The input soil layers were derived from a combination of Land Resource Information System portal (http://www.landcareresearch.co.nz/resources/data/lris) and thedigital soil map (S-Map) for New Zealand (http://smap.landcareresearch.co.nz/home). A depth of 1000 millimetres was assumed for the top soil layer. Figure 2 above showed the distribution of the Waipara River catchment soils.

4.3.3 Weather Data Input

Historical daily precipitation, relative humidity, solar radiation, temperature (max/min) and wind speed data (1979 – 2013) from the NIWA Virtual Climate Station Network (VCSN) which is a 5km grid based spatial interpolation of actual data from observation stations, were acquired and combined with the NIWA Cliflo data to make up for the years with no records as well as fill the missing weather parameter/data gaps.CliFlo is the web system that provides access to New Zealand's National Climate Database**.** In selecting the stations from which data were collected to fill-in for the years with no records for the target stations, careful consideration was given to nearby stations that fall on the same latitude. An Environment Canterbury maintained ground observation station at White Gorge with a more consistently recorded rainfall data also served in meeting the data needs.

Future climate data comprised of bias corrected daily precipitation, minimum and maximum daily temperatures; required for developing future climate change impact scenarios was also derived from NIWA’s 5km VCSN grid regional climate projection (RCP). The RCP is a product of a dynamic downscaling of 6 selected IPCC Fifth Assessment Global Climate Models (GCMs) using NIWA’s Regional Climate Model (RCM) (MfE, 2016). The 6 selected GCMs include the CAM5, GFDL, GISS, BCC, NorESM and HadGEM models. These RCPs include two stabilisation pathways (RCP4.5 and RCP6.0), and one pathway (essentially “business as usual”) with very high greenhouse gas concentrations by 2100 and beyond (RCP8.5). The data periods from the selected models utilised for this study ranged between years 1971 – 2005, 2006 – 2099 and 2006 – 2100 (for the historical, RCP4.5, RCP6.0 and RCP8.5 respectively) with respect to maximum/minimum temperatures and precipitation. Figure 4 shows the distribution of the climate stations from which data were sourced.

Differences in the periods of weather information utilised occurred due to sourcing of data from real /actual weather stations operated by NIWA. Some of the stations do not have complete weather parameters covering the desired period, especially rainfall data. Therefore, data from ECan operated stations which had complete rainfall records were employed in filling the missing data gaps. Simulated climate data from NIWA virtual climate stations which extend beyond the periods of data from real stations for the future climate data needs is also used; hence the observed differences in data periods.

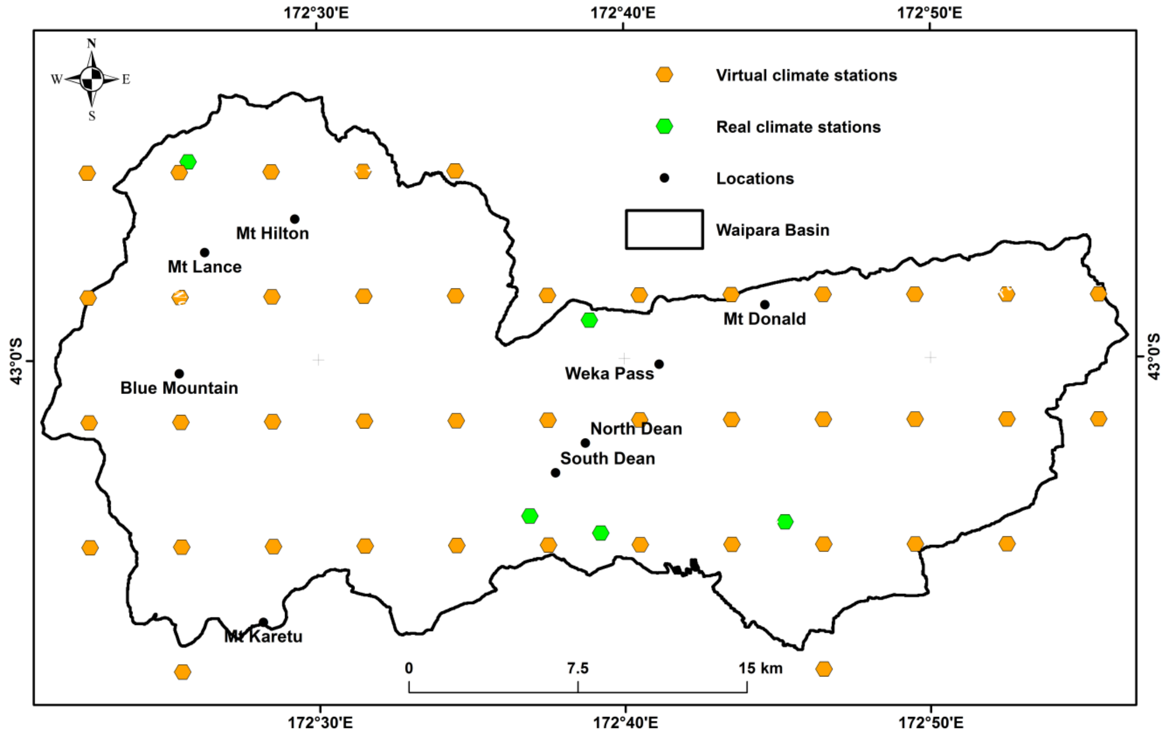


Figure 4 Distribution of climate stations

Other statistical weather parameters such as the half hour rainfall, skew coefficient for daily precipitation in month, average minimum air temperature for month etc were computed using the ArcSWAT weather generator tool (WGEN). WGEN input parameters comprising maximum and minimum air temperature and relative humidity were used for the computation, using the pcpSTAT program from the SWAT website and the R studio (software) environment. Future climate parameters such as relative humidity and wind were simulated by the WGEN.

4.3.4 Land Use Data

Land use/land cover data were sourced from the Landcare Research data portal (http://lris.scinfo.org.nz/layer/304-lcdb-v30-land-cover-database-version-3/). Reclassification of land use/land cover was carried out in ArcMap 10.3 and then input into ArcSWAT. The resulting land use/land cover classes in SWAT format include residential-med/low density, urban, transport, barren land, water bodies, grape and olives, pasture, other agricultural/crop, wetland, forest deciduous, exotic forest, gorse and broom, honey mesquite and oak (beech family). Table 4 shows land use classes in Waipara river catchment while figure 5 presents the land use map.

Table 4 SWAT land use land cover (LULC) reclassification code

ID	Code	Name	Equivalent Category/Description
1	URBN	Urban	Settlements
2	BARR	Barren land	Exposed land surfaces
3	WATR	Water bodies	Pond/lake/ stream
4	AGRR	Agricultural land	Vegetables, arable crops etc
5	GRAP	Grapes	Grapes and Olives
6	PAST	Pasture	Pastures
7	FRST	Forest	Natural/mixed vegetation/native forests
8	FRSD	Deciduous forest	Leave shading trees
9	FRSE	Exotic forest	Cultivated trees – e.g. pines
10	WETN	Wetlands	Swamps and flood zones
11	OAK	Oaks	Oak and beech family
12	GORS	Gorse & broom	Gorse and broom
13	MESQ	Mesque	Honey mesque
14	UTRN	Urban transport	Road networks

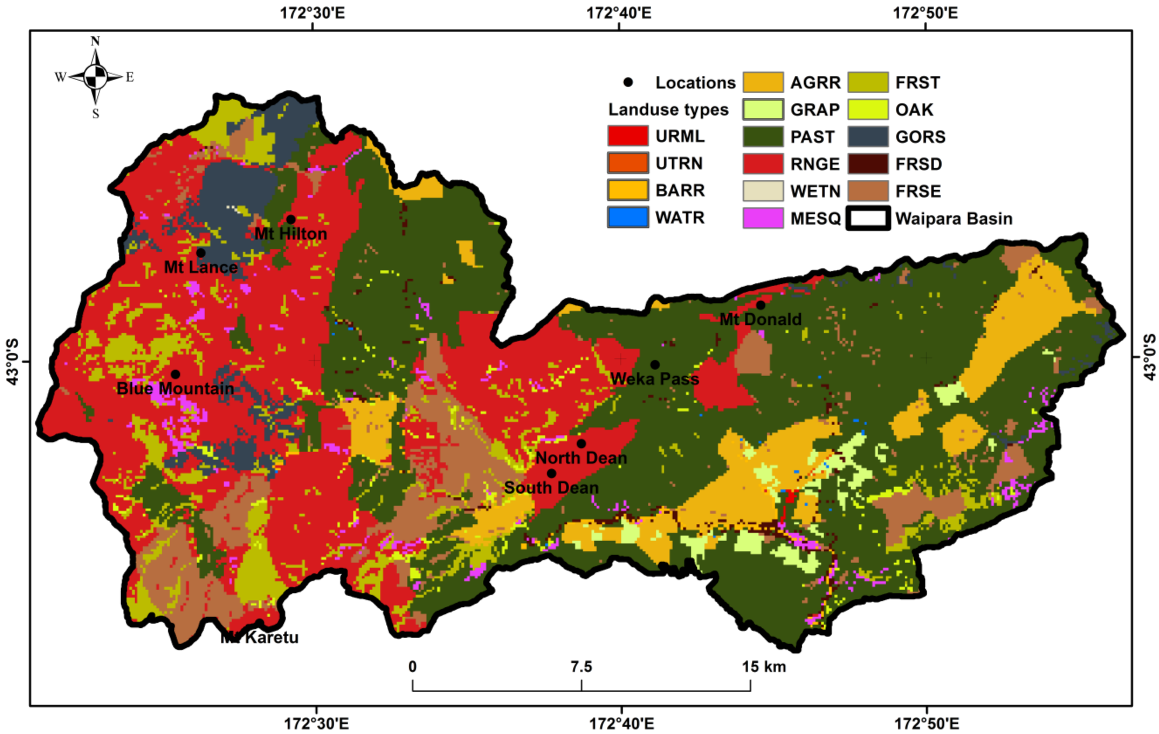


Figure 5 Waipara River catchment land use map

4.3.5 Drainage Network

The New Zealand River Environment Classification (REC) is a database that contains information describing the physical properties of all New Zealand's rivers. Each of the river segments in REC are represented based on the physical characteristics such as climate, source of flow for the river water, topography, and geology, and catchment land cover e.g. forest, pasture or urban. The Waipara River network was extracted from the River Environment Classification Canterbury (2010) data using the masking tool in ArcMap. Figure 6shows the drainage network of the Waipara River and the gauge stations.

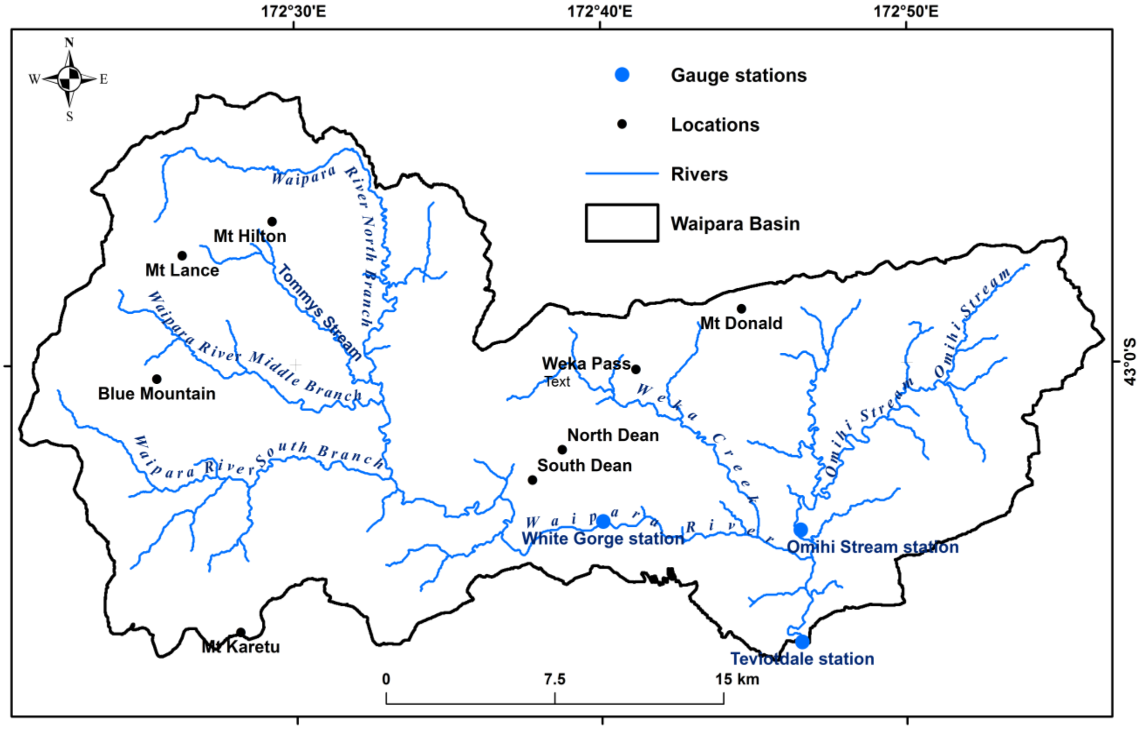


Figure 6 Waipara River drainage networks and gauge stations

4.3.6 Flow Data

There are three flow observation stations in the Waipara river catchment. They are Teviotdale, White Gorgeand the Omihi Stream station at Glen Ray (Figure6). The Teviotdale station was selected for this study because it has continously monitored flow data and also falls on the outlet of the Waipara river basin. The limited size of the catchment also makes the use of data from just a single station sufficient for the study. Daily observed flow records from 2001 to 2012 was computed into monthly (average) time-step for input in SWAT for calibration and validation.

4.4 Model Setup

The model for the Waipara River catchment was built in SWAT2012 using the ArcGIS 10.3 interface (Olivera et al., 2006). The primary procedure of setting up the model involves defining the database files, comprising of soil, land use and weather parameters. Modification and update of the default SWAT soil and land use database as well as weather station parameters, using the Waipara catchment data, were implemented following the SWAT user's manual guidelines. Based on the statistical parameters obtained from the real climate data, the weather generator in SWAT simulated the solar radiation, wind speed and the relative humidity for future climate scenarios. Figure 7 shows a graphical representation of the SWAT modeling process.

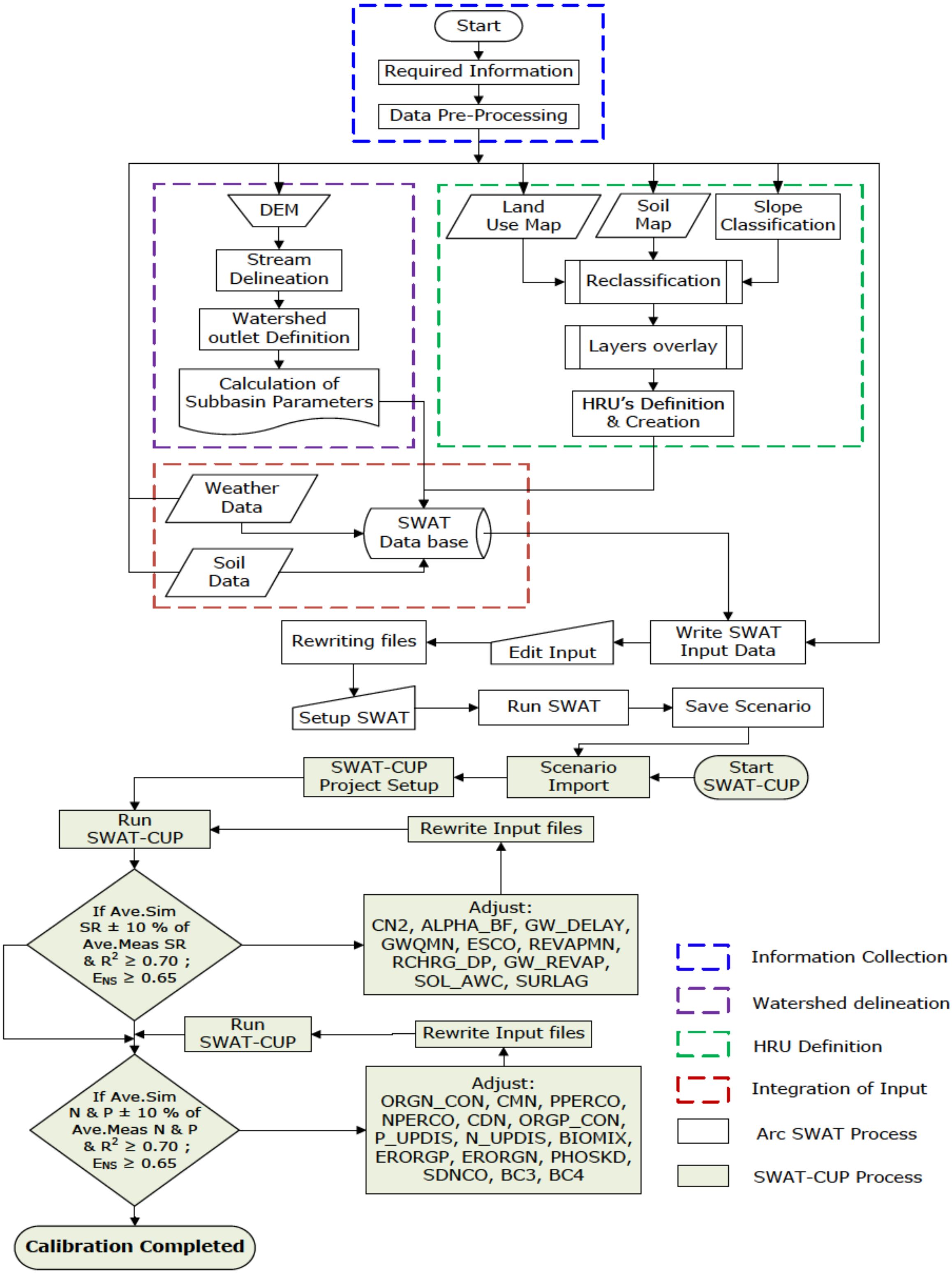


Figure 7 Soil and Water Assessment Tool Modeling Process

Having organised the required input data, the geographic information system interface – ArcSWAT (Winchell et al., 2010) was used in setting up the Waipara River catchment SWAT model. The burn-in option present in ArcSWAT was employed in integrating the digitised stream network obtained from the REC Canterbury (2010) data. The Waipara River catchment digital elevation model (DEM) was used to configure the Catchment. Catchment boundary, sub-Catchments (SWs), hydrological response units (HRUs) and slope layers were defined based on the DEM data. Discretisation of the catchment into sub-catchments connected by a stream network was performed resulting into 106 sub-catchments, using the Teviotdale gauge station as the discharge outlet. The Teviotdale gauge station was chosen as the outlet because it is the last station on the river located close to where the river discharges into the sea. Besides, at any point towards the mouth of the river other than the Teviotdale station, the stream flow interestingly seemed to go in a reverse direction during the delineation process. As a result, the total area of the catchment modeled is 702 km^2 out of the 726 km^2 totalland area.

There is an in-built HRU overlay technique within the ArcSWAT program for automatic overlay operations. HRUs consist of unique combinations of dominant land use, soils and slope to permit simulation of spatially succinct differences in hydrological characteristics for various land uses, soils and slope groupings (Gessesse et al., 2014). The average slope of each individual HRU is calculated by the ArcSWAT interface during the model setup process. Delineation of the stream segments and sub-basin geomorphology was automatically carried out by the interface. Furthermore, the sub-basin was grouped based on dominant land use, slope and soil types, the multiple HRU option in SWAT was implemented (executing the overlay function), which resulted in discretisation of 517 HRUs for the Waipara basin.

A threshold of 400 ha unit was employed in the creation of SWs; while 18%, 15% and 10% thresholds were adopted for land use, soil and slope respectively for the HRUs. These thresholds were found to be more convenient after several trials to avoid creating too many SWs and HRUs that could significantly extend model run time (U.S. EPA, 2015). Neitsch et al. (2011) suggested that about 20%, 10% and 20%, thresholds respectively for land use, soil and slope thresholds are adequate for most applications. A simulation period of 10 years with a 4 year warm up period was adopted resulting in the total area of 702.56 km^2 of the catchment simulated by the model. Figure 8 and 9 show the Waipara catchment SWAT model hydrologic response units (HRU) and sub-basin distributions. The observed daily weather data, including precipitation, temperature (min/max), relative humidity, solar radiation and wind speed; processed for the period 1979–2013 were used to populate the model.

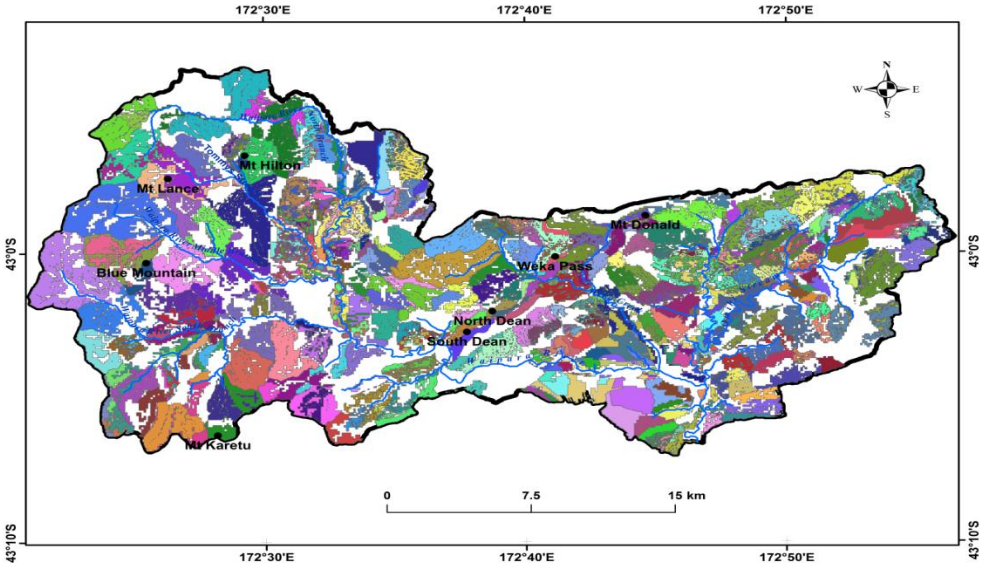


Figure 8 HRU distribution map

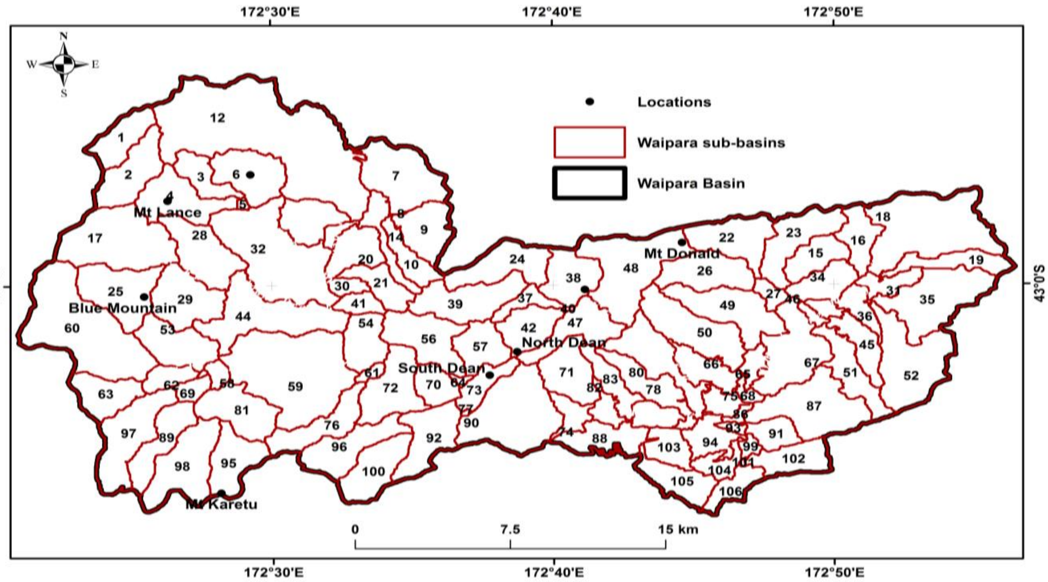


Figure 9 Waipara River catchment sub-basins

4.5 SWAT Check

The study employed the visualisation capabilities of the SWAT check module to assess the appropriateness of model output.

> "SWAT Check is a stand-alone Microsoft Windows program compatible with SWAT (versions 2005, 2009, 2011 and 2012) that performs three functions: (i) it reads selected SWAT output and alerts users of values outside the typical range; (ii) it

creates process-based figures for visualisation of the appropriateness of output values, including important outputs that are commonly ignored; and (iii) it detects and alerts users of common model application errors." (White et al., 2012).

Details of the Waipara catchment SWAT model output from SWAT Check are discussed in the subsequent chapters.

4.6 Model Calibration and Accuracy Evaluation Approach

Catchment models have over the years gained popularity in their use to support management decisions relating to water allocation, land use, climate change and pollution control etc. It has become necessary to subject these distributed Catchment models to careful calibration and uncertainty analysis. Abbaspour et al. (2007) however indicated that the usefulness of a calibrated model is limited to the purpose for which the model is built and so a single calibration and uncertainty analysis technique cannot suffice for all situations.

The model was calibrated at the catchment level employing the monitored flow and water quality information recorded at the Teviotdale station. Initial sensitivity analysis of hydrology and nutrient parameters using the Latin hypercube one-factor-at-a-time (LH-OAT) algorithm in SWAT (van Griensven et al., 2006) was implemented. This method utilises the dual benefits of global and local sensitivity analysis techniques to arrange model parameters according to their order of sensitivity (Sun and Ren, 2013).

The SWAT Calibration Uncertainty Procedure (SWAT-CUP) is employed in this study to simulate nutrients and the flow pattern of Waipara River. SWAT-CUP is a conglomerate of three programs: Generalised Likelihood Uncertainty Estimation (GLUE) (Beven and Binley, 1992); Parameter Solution (ParaSol) (van Griensven and Meixner, 2006); and Sequential Uncertainty Fitting (SUFI-2) (Abbaspour et al., 2007) linked to SWAT (Arnold et al., 1998). The SWAT-CUP program can be used in implementing SWAT model calibration, validation, sensitivity analysis (one-at-a-time, and global) and uncertainty analysis. The program connects SUFI2, GLUE, and ParaSol algorithms to SWAT. Any of these procedures can be utilised in implementing a SWAT model calibration and uncertainty analysis. The most sensitive hydrology and nutrient parameters for the Waipara SWAT model were determined by the use of the sequential uncertainty fitting program (SUFI2). Abbaspour et al. (2015) noted the existence of a close relationship between calibration and uncertainty or errors in modeling, and it is important to account for such errors and uncertainties during model calibration.

SWAT-CUP is incorporated with graphical modules that enable the visualisation of simulation outputs, uncertainty range, sensitivity graphs, Catchment layout using Bing map, and statistical reports (Abbaspour et al., 2015). SWAT-CUP also enables the parameterisation or regionalisation of SWAT model parameters according to hydrologic grouping, soil type, land use type, subbasin number and slope (Abbaspour et al., 2015).

The SWAT-CUP SUFI2 algorithm according to Abbaspour et al. (2009), strives to address every form of parameter uncertainty (e.g. uncertainty in model input, model conceptualisation, model parameters, and measured data) by recording and representing them on a given statistical scale in order to fit observed data within a common 95% prediction uncertainty (95PPU) range. By so doing, the uncertainty associated with the model output could then be measured by the 95PPU on the 2.5% and 97.5% scale of cumulative distribution by the use of the Latin Hypercube sampling technique (Arnold et al., 2012; Abbaspour et al., 2015.

The SUFI2 algorithm determines the measure of goodness of fit of model performance using a number of statistical measures. These statistical measures include: the percentage of observed data that falls within the 95PPU (*P-factor*) of the model output, estimated at the 2.5 and 97.5 percentiles of the cumulative distribution of the simulated variables; the *d-factor*, which is the ratio of the average distance between the percentiles and the standard deviation of the corresponding measured variable; *R*-factor, which is the average width of the band divided by the standard deviation of the corresponding measured variable; Nash–Sutcliffe Efficiency (NSE)(Equation 1) (Nash and Sutcliffe, 1970); the coefficient of determination (R^2) (Equation 2) and br^2 (R^2 times the slope) (van Griensven et al., 2006, Abbaspour 2015); root mean square error (RMSE) and percentage of (PBIAS). The RMSE (Equation (3) indicates a perfect match between observed and predicted values when it equals 0 (zero), with increasing RMSE values indicating an increasingly poor match. Singh et al. (2014) stated that RMSE values less than half the standard deviation of the observed (measured) data might be considered low and indicative of a good model prediction. The PBIAS (Equation 4) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts (Gupta et al. 1999). The optimal value of PBIAS is 0.0, with low magnitude values indicating an accurate model simulation (Golmohammadi et al. 2014). There are no hard and fast rules about what the values for these statistical measures should be though; Abbaspour (2015) reasoned that it is better to be high. He then went on to suggest a value of >70% as a P-factor for discharge when the R-factor approximates to 1. For this study, the NSE and R^2 statistical measures were used as objective functions and with graphs, the model performance was evaluated, as recommended by Neitsch et al., (2002). Computation of the Nash Sutcliffe Efficiency (NSE) and the coefficient of determination (R^2) are expressed in Equations 1 and 2 below.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(K_{sim,i} - K_{mnt,i})^2}{\sum_{i=1}^{n}(K_{mnt,i} - \bar{K}_{mnt,i})^2} \quad (1)$$

Where $K_{sim,i}$ is simulated flow at time *i*, $K_{mnt,i}$ is monitored flow at *i*, $\bar{K}_{mnt,i}$ is arithmetic mean of the monitored flow at time *i*, while *n* represents the number of monitored data/time series.

The NSE coefficient ranges from -00.0 to 1.0(Nash et al., 1970). When the simulated flow matches closely to the monitored flow, the NSE value approximates to 1.0 and indicates good model performance (Wang et al. 2012). Where the coefficient moves towards 0.0, it implies poor performance of the model. Van Liew et al. (2005) suggested that NSE value ranging from 0.0 to 0.36 shows poor model performance. Values ranging between 0.36 and 0.75 indicate a satisfactory model performance, and anything greater than 0.75 is rated as good. Liden and Harlin, (2000) and Henriksen et al. (2003) recommended that NSE values ranging between 0.5 and 1.0 can be classified into good, very good and excellent performance; while values from 0.0 to < 0.5 are classed as very poor and poor model outputs.

$$R^2 = \frac{\sum_{i=1}^{n}(P_{si} - \overline{P_s})(P_{mi} - \bar{P}_m)}{\sqrt{\sum_{i=1}^{n}(P_{si} - \overline{P_s})^2 \sum_{i=1}^{n}(P_{mi} - \bar{P}_m)^2}} \quad (2)$$

Where P_{si} and $P_{mi}$are simulated and monitored value for day *i* respectively. $\bar{P}_m$ and P_s represent the arithmetic means of the monitored and simulated values; n is number of observations/time series.Details of the model calibration output are discussed in the next chapter.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(\mathrm{P_i} - \mathrm{O_i})^2}{\mathrm{n}}} \quad (3)$$

$$PBIAS = \left[\frac{\sum_{i=1}^{n}(O_i - P_i)*100}{\sum_{i=1}^{n}(O_i)}\right] \quad (4)$$

where, *n* is the number of observations in the period under consideration, O_i is the *i*-th observed value, *O* is the mean observed value, P_i is the *i*-th model-predicted value and *P* is the mean model-predicted value.

Chapter 5

SWAT MODEL CALIBRATION, VALIDATION AND SIMULATION OF WAIPARA RIVER FLOW AND NUTRIENTS

5.1 Introduction

The chapter provides a discussion of the Waipara River catchment baseflow analysis, parameter sensitivity analysis, model calibration and validation. Calibrations of hydrology and nutrients were implemented separately. Simulation and estimation of catchment water budget, spatial distribution of catchment water, nutrient and sediment yields as well as nutrient yield by land use types are also implemented and discussed. The chapter is organised in two parts. Part one discusses the hydrology components and part two presents the discussions about the nutrients.

5.2 PART 1: Hydrology

Understanding hydrologic processes is an essential step towards managing the environmental health of catchments. This is because hydrology has been known to be the controlling factor for pollutant transport in Catchments. As a result, there is need for calibration and validation of any model to ensure that it is sufficiently representing the hydrologic characteristics that drive the movement of nutrients and pollutants.

Considering the difficulty in acquiring data representing the entire Catchment or river basin, hydrologists tend to group available observed data into two, based either on temporal or spatial characteristics of the catchment for calibration and validation (Engel et al., 2007). It is also recommended that in grouping the data, both wet and dry conditions should be captured for both calibration and validation periods to depict the real physical environment within which the model is to operate (Gan et al., 1997). Engel et al. (2007), however, identified a lack of adequate observed data covering long periods of time as a major constraint to capturing the wet and dry conditions. Several other studies (Van Liew and Garbrecht, 2003; Kannan et al., 2007; Biru and Kumar, 2017) proposed capturing wet conditions marked with floods events into the calibration period. Contrary to the foregoing, Reckhow (1994) argued that validation period need not have the same condition as the calibration period to give an independent evaluation of how a model performed.

The primary step to understanding the hydrological processes of the Waipara River catchment in this study was to perform a baseflow separation analysis and sensitivity analysis of SWAT model input parameters.

5.2.1 Baseflow Separation

Baseflow is water that seeps slowly over time through the ground into a stream channel. It continues to flow even after the rainfall event and therefore constitutes the source of water supply to a stream during dry weather. The baseflow separation process entails separating streamflow into two component parts, quickflow and baseflow (Thomas et al., 2015). The quickflow or surface runoff component is that part of flow or runoff that occurs during or following a rainfall event. Baseflow, on the other hand, is delayed runoff, occurring during periods of no or minimal rainfall. A good understanding of water storage systems and flowpaths is essential for modeling water and chemical movements through catchments (Fenicia et al., 2011; McMillan et al., 2011; Beven, 2012; Hrachowitz et al., 2013).

Separation of stream flow into surface runoff and baseflow is therefore the first step in hydrograph analysis, and determining baseflow discharge to streams is a very significant aspect of Catchment modeling. Baseflow recession coefficients are influential parameters that could control the recharge amount (Arnold et al., 1995; Arnold and Allen, 1999). Accurate estimation of the annual average ratio of surface flow to baseflow is capable of enhancing SWAT model calibration (Arnold et al., 1995; Arnold and Allen., 1999). As such, it is essential to apply a baseflow separation technique during a SWAT model calibration. The baseflow separation technique utilises time-series flow data to obtain the baseflow signature. Two broadly available baseflow separation approaches are the graphical technique, where baseflow thresholds intersecting the rising and recession limbs of the quick flow reaction to rainfall event are determined, and the filtering method where the entire stream hydrograph is employed to derive the baseflow hydrograph (Mishra, 2013). An automated baseflow separation program (BFLOW) developed by Arnold et al. (1995) was utilised for this study. The program employed the daily stream flow records from the Teviotdale gauge station at the basin outlet for the computations.

The BFLOW program makes use of a low-pass filter developed by Lyne and Hollick (1979). The separation technique is based on signal processing theory, which is founded on the understanding of the hydrological processes that baseflow is the low frequency part of streamflow while surface runoff is the high frequency component (Arnold et al.,1995; Partington et al., 2012). The mathematical expression of the filtering techniques for baseflow according to Eckhardt (2005), Arnold et al. (1995 and 1999) and Partington et al. (2012) are:

$$\rho_t = \beta \rho_{t-1} + (1 + \beta)/2 * (P_t - P_{t-1}) \quad (5)$$

where ρ_t is the filtered surface runoff at the t time step, P_t is the original stream flow, and β is the filter parameter. Baseflow is estimated using equation 6.

$$b_t = P_t - \rho_t \quad (6)$$

The baseflow parameters are determined when streamflow data is passed over three times, forwards, backwards, and forward again by the automated baseflow filter, resulting in each successive pass into a lower baseflow as a percentage of total flow (Arnold et. al., 1995; Partington et al., 2012). Though the automated baseflow separation program (BFLOW) has no physical interpretation, the technique corresponds well to manual separation approaches (Arnold and Allen, 1999; Partington et al., 2012).

BFLOW estimated that 45% of streamflow is contributed by baseflow. The result is useful here for the purpose of determining the best alpha baseflow parameter range for Waipara River SWAT model calibration as discussed in the next section. The estimated 45% is the average of the baseflow amount for the three passes divided by the average of the total flow amount to indicate a relative fraction. The first or second pass is usually sufficient to extract a baseflow similar to that reached by manual separation techniques (Arnold and Allen, 1999; Partington et al., 2012). The alpha factor is a recession coefficient obtained from the characteristics of the contributing aquifer to baseflow. A high alpha factor value (close to 1) indicates sharp recession, signifying quick drainage and minimal storage. A low alpha value (close to 0) on the other hand implies very slow drainage (Arnold et. al. 1995).

5.2.2 Sensitivity Analysis of Model Parameters

In order to adequately represent the spatially varying characteristics of a Catchment via model simulation, the model must have to take into account the heterogeneity in the environmental variables, such as weather parameters, topography, soils, land uses, hydrology etc. Physically based spatially distributed models like SWAT possess the capability of capturing such dynamic spatial variables but are often limited by a scarcity of requisite discontinuous spatial and continuous temporal input data. For this reason, hydrological model applications to Catchments with deficient data input often require model sensitivity analysis as part of their methodological framework. UNESCO (2005) states that 'sensitivity analysis procedures explore and quantify the impact of possible errors in input data on predicted model outputs and system performance indices'. In other words, the aim of sensitivity analysis is to determine how much effect any change in model input parameter values can have on model output values. Muleta and Nicklow (2005) therefore reasoned that in order to minimize SWAT model calibration parameters, there is a need for a systematic approach to spatial parameterisation, parameter screening, and sensitivity analysis. For this study, a sensitivity analysis was performed as a screening tool to identify the parameters requiring adjustment in the course of calibration. Using the Global Sensitivity Analysis technique built into SWAT_CUP (Abbaspour, 2015), the determination and ranking of the most sensitive parameters were achieved. Neitsch et al. (2005) provided detailed discussion of the methodology and explanation of the hydrologic parameters.

The model considered ten hydrologic parameters that were found to be sensitive to runoff. The level of sensitivity of the parameters ranges from very high (rank of 1) to small (rank of 10). Among the sensitive flow parameters, the ground water parameters were found to be more sensitive to streamflow: ALPHA_BF, ESCO, GWQMN, CN2, SOL_AWC, RCHRG_DP, REVAPMN,GW_REVAP, SURLAG and GW_DELAY.A brief description of each hydrologic parameter is listed in Table 5. Based on the sensitivity analysis, runoff tends to be more sensitive to ALPHA_BF (baseflow alpha factor, which is a measure of groundwater flow response to changes in recharge – Smedema and Rycroft, 1983) and ranked first among the model parameters. A summary of the most sensitive parameters in the Waipara River Catchment is shown in Table 5.

Table 5 Waipara River catchment SWAT model hydrologic parameterisation and sensitivity ranking

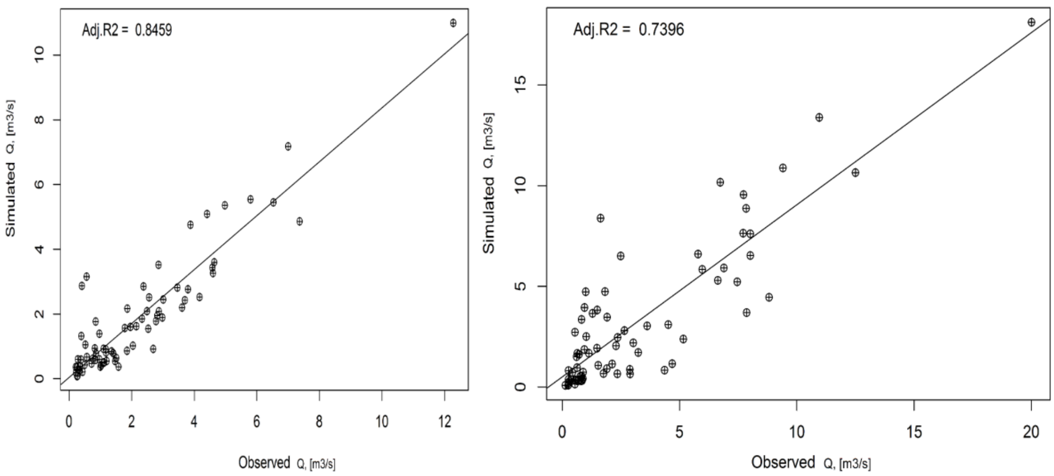
Hydrologic Parameter	Definition	Parameter Range	Fitted Value	Sensitivity Ranking
ALPHA_BF	Base-flow alpha factor (days)	0.40-0.60	0.58	1
ESCO	Soil evaporation compensation factor (dimensionless)	0.15-0.20	0.165	2
GWQMN	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	2500-3000	2750.00	3
CN2	SCS runoff curve number (dimensionless)	70.00 – 80.00	73.00	4

SOL_AWC	Available water capacity of the soil layer (mm H2O/mm soil)	0.800-0.950	0.845	5
RCHRG_DP	Deep aquifer percolation fraction (dimensionless)	0.50-0.70	0.52	6
REVAPMN	Threshold depth of water in the shallow aquifer for “revap” to occur (mm)	450-500	485.00	7
GW_REVAP	Groundwater “revap” coefficient (dimensionless)	0.02-0.15	0.085	8
SURLAG	Surface runoff lag coefficient (dimensionless)	24.00-30.00	28.20	9
GW_DELAY	Groundwater delay (days)	31.00-31.00	31.00	10

5.2.3 Calibration of Parameters Governing the Waipara River Catchment Hydrology

There are over 50 parameters in the SWAT model that require calibration for correlating simulated and observed flows. For the Waipara River SWAT model, 10 parameters were identified as sensitive (Table 5). Van Liew et al. (2007) suggested focussing on the 10 most sensitive model parameters during hydrologic calibration. For this study, the SWAT model was calibrated and validated based on monthly time steps using streamflow records of years 2001 – 2012 from Teviotdale gauge station, located at the basin outlet (Figures10, and 11). The observed data were grouped into two time periods: 2001 – 2006 and 2007 - 2012 for calibration and validation respectively (Engel et al., 2007). An automatic parameter estimation procedure in SWAT-CUP (Abbaspour, 2015), was utilised in estimating parameter values for the runoff simulations. The 10 most sensitive flow parameters were considered in the calibration processes and their values were varied iteratively within the allowable ranges until satisfactory agreement between measured and simulated streamflow was obtained. Model efficiency was significantly improved via the autocalibration processes. A total of one thousand iterations were performed to ensure a good combination of calibration parameter values that yield the best result to meet the objective functions. The Nash-Sutcliffe efficiency (NSE) and regression coefficient (R^2) (discussed in the previous chapter) were utilised in evaluating the efficiency of the model during calibration (Nash and Sutcliffe, 1970).

Model application produced a fitted water balance (calibration: NSE = 0.82, R^2= 0.85; validation: NSE = 0.73, R^2= 0.74) with RSME and PBIAS values of 0.88, -14.8 and 1.89, 1.3 respectively. The adjusted correlation coefficients (Adj. R^2) (which is a measure of the proportion of variation explained by the estimated regression line) are 0.8459 and 0.7396 (Figures10**a**and **b**) respectively for both calibration and validation periods; indicating a very strong positive relationship between the observed stream flow and the simulated. Simulation of flow for the entire period 2001 to 2012 (Figure 11) gave NSE and R^2 as 0.71 and 0.76 respectively; while the adjusted (Adj. R^2) is 0.7311. The results indicate that SWAT is an appropriate tool for water resource investigations in the Waipara River catchment, and can provide a useful tool for further eco-hydrologic research in the region (i.e. diffuse pollution impacts).



(a) (**b**)

Figure 10 Scatter plots showing correlation (Adj. R2) between the observed and simulated flow for the calibration period (a) (2001 – 2006) and validation period (b) (2007 – 2012).

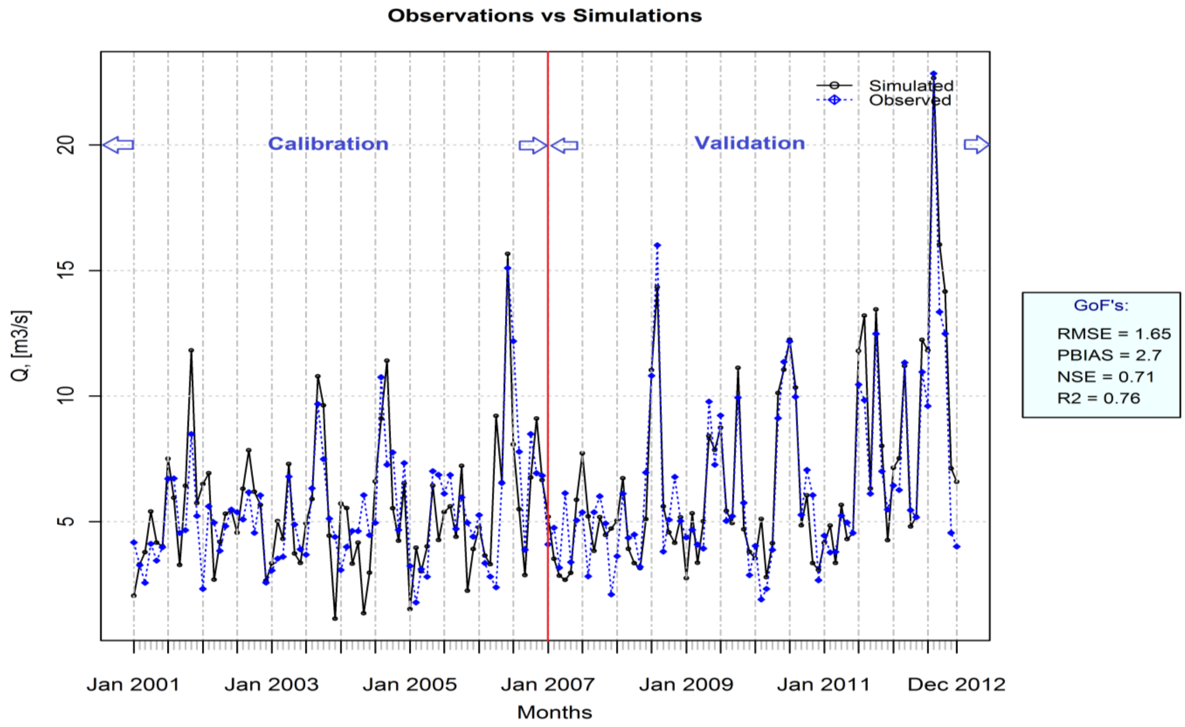


Figure 11 showing flow simulation over the entire period (2001 – 2012)

In all the cases for the model calibration and validation periods, the NSE, R^2 and the Adj. R^2 outputs are above 0.70 implying a good model performance (Wang et al., 2012).

5.2.4 Water Balance Ratios

During hydrologic calibration, the model separated the total stream flow into surface and baseflows to compute water balance ratios. The ratio of surface runoff/total flow, baseflow/total flow, streamflow/precipitation, ET/precipitation and deep recharge/precipitation are 0.40, 0.60, 0.21, 0.63 and 0.02 respectively. These ratios were based on annual basin values. Figure 12 shows the Waipara river SWAT model hydrologic budget.

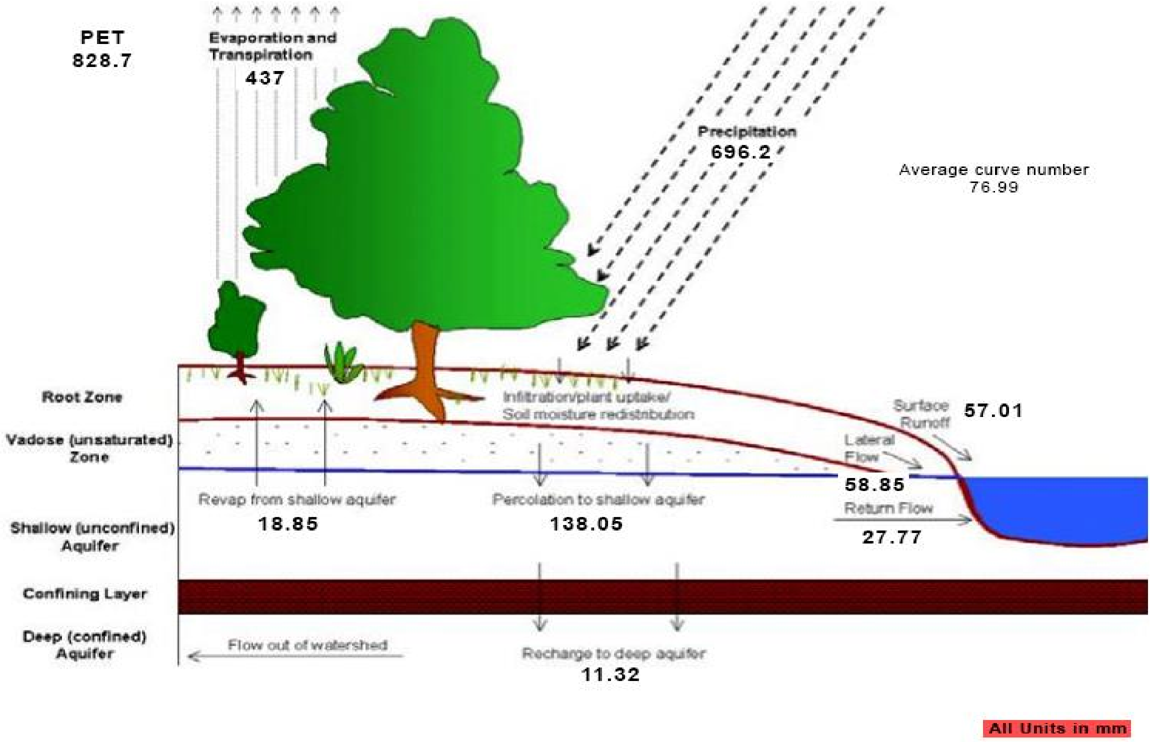


Figure 12 Hydrologic budget of the Waipara River catchment

The annual water budget estimation of the Waipara catchment is defined by the principle of conservation of mass using the formula below:

$$\Delta SW = P - (ET + latQ + surfQ + gwQ + daqQ) \quad (7)$$

Where ***ΔSW*** represents change in soil water storage (***mm***), ***P*** stands for total annual precipitation (***mm***), ***ET*** the evapotranspiration (***mm***), ***latQ*** is the lateral flow (***mm***), **surfQ** is surface runoff (***mm***), ***gwQ*** is groundwater flow (***mm***) and ***daqQ*** stands for deep aquifer recharge (**mm**).

Over the model calibration period (2001-2006), the largest of all the water components was ET, accounting for 63% of the water budget. This is followed by baseflow with 60% and surface runoff with 40%.

5.2.5 Spatial Distribution of Water Components of the Catchment

A good understanding of the temporal and spatial distribution of meteorological and hydrological attributes of water balance is fundamental for water management practice (Tadić et al., 2016). Figure 13 presents the spatial variability of rainfall, evapotranspiration, runoff and water yield in the Waipara River catchment. The spatial analysis of the hydrological characteristics of the catchment was carried out with a view to determining the significance of changes in some hydrological parameters and processes (rainfall, evapotranspiration, runoff and water yield), induced by human land use and climate change that could have direct impact on water balance, ecological, chemical, and geomorphological processes which are major concerns for water decision makers (Tadić et al. 2016).

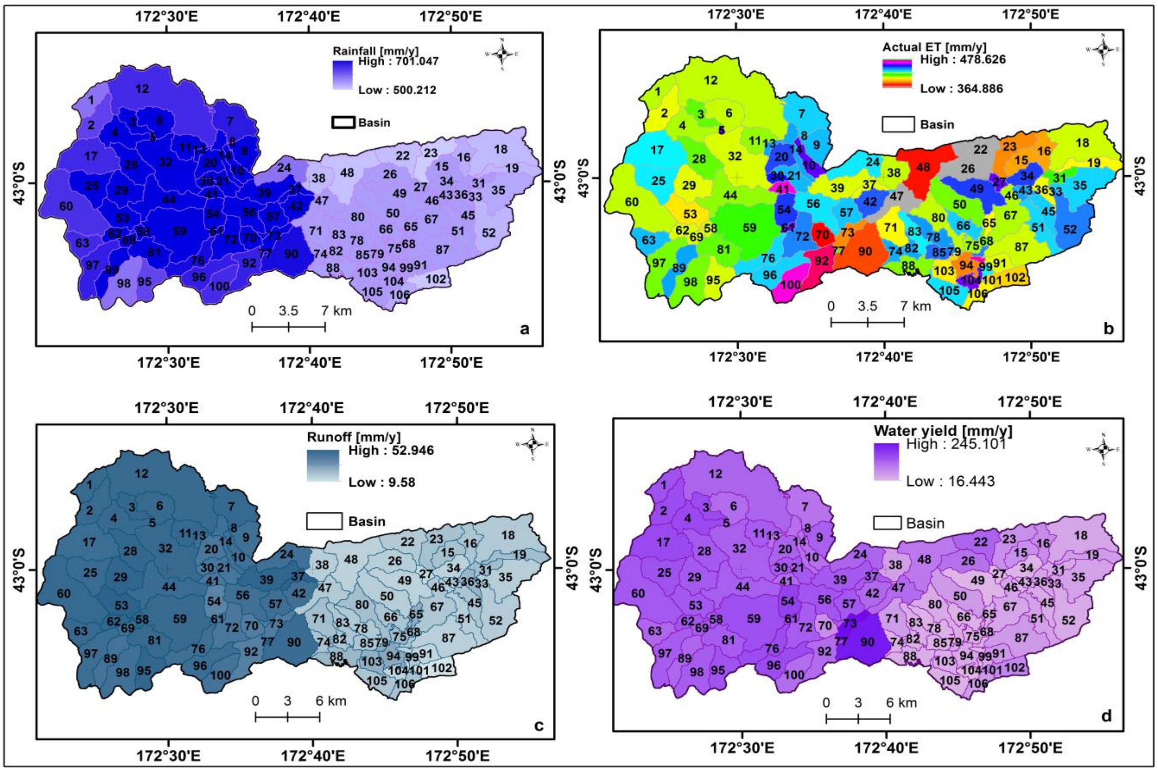


Figure 13a, b, c, d showing the water components of the Waipara River catchment

The analysis shows that in the study period and under the current climate about 49% of the catchment receives up to 701 mm of rainfall per year. Rainfall was found to be higher at the western segment of the map. This segment constitutes the leeward side of the Southern Alps and rain shadow, resulting in the rest of the catchment experiencing just above 500 mm per year (Figure 13a). Actual evapotranspiration (ET) is at its peak of about 478 mm per year infew locations within the catchment. Sub-basins 41 and 100 (Figure 13b) experienced the peak ET while the other sub basins recorded ET rates between 364 mm and 478 mm.

The spatial distribution of surface runoff within the catchment also roughly follows the same pattern with the rainfall distribution ranging between 9 mm and 53 mm per year (Figure 13c). Similarly, the water yield distribution (Figure 13d) follows the same trend as the surface runoff distribution. Sub-basins 73, 77 and 90 yielded a little above 245 mm per year while the remaining sub basins in the catchment yielded between 16mm – 245 mm/year. The SWAT model annual water yield for the catchment is therefore estimated as 154.52 mm/yr. The Waipara River catchment climate is known to vary over short distance and time Chater, 2002). The SWAT model simulation demonstrates this characteristic by revealing the spatial variability in the distribution of some of the climatic parameters that control the hydrological system. Sub basins 41, 73, 77, 90 and 100 for example showed areas of peak ET or high water yield (during modeling) period.

5.3 PART 2: Nutrients

This part of the chapter focuses on addressing research objectives one to three, which intends to analyse the spatial distribution of pollutant sources, quantify pollutant fluxes from land use types, and how current land use influences the concentrations of nitrate and phosphorus in surface water flow in the Waipara catchment. It achieves this by calibrating the Waipara catchment SWAT model for nutrients, and performing model simulations to derive landscape nutrient and sediment yields.

5.3.1 Model Calibration and Estimation of Nitrogen (N) and Phosphorus (P) Loads

Having accomplished calibration and validation of the Waipara River catchment SWAT model for flow, calibration for N and P became necessary to ensure the capability of the model in representing the behaviour of nutrient concentration/load is consistent with the stream flow pattern. Availability of good monitored water quality data over a long period therefore becomes a vital prerequisite for SWAT water quality model calibration and validation. For the Waipara River catchment, water quality data for the study period is of limited quality and quantity.

5.3.2 Limitation of Observed Water Quality Information

The available water quality data for the catchment maintained by Environment Canterbury has limitations. The data lack continuity, consistency and were collected over a short period (2001-2006) and are not coincident with the flow data collection period utilised in the hydrologic calibration and validation. This therefore makes it inadequate for validating the SWAT model for nutrients after calibration. Conventionally, SWAT requires at least one to five years of continuously monitored data for calibration and validation respectively (Srinivassan – personal communication, 2014). In order to overcome the challenges posed by the insufficiency of water quality data, the Load Estimator program (LOADEST) (Runkel et al., 2004; Rukel, 2013; Park et al., 2015) was employed in estimating mean monthly constituent loads of the water at the Teviotdale gauge station over the period 2001-2012 to match the hydrologic calibration and validation periods.

5.4 Method for Estimating Total Nitrogen and Total Phosphorus Loads

Total nitrogen (TN) and total phosphorus (TP) loads in the Waipara River were estimated using LOADEST, which employs observed streamflow information and constituent concentrations to calibrate a regression model in defining constituent loads in relation to streamflow and time (Runkel et al., 2004; Rukel, 2013; Park et al., 2015). With the use of the regression analysis, the software estimates loads over a user-defined interval. The LOADEST analysis outcomes include statistical information that helps determine the quality of model performance as well as the precision of the constituent load estimates.

Several water quality modelling studies have applied LOADEST in estimating water quality parameters including mercury, suspended sediment, total nitrogen and total phosphorus (Brigham et al., 2009; Dornblaser et al., 2009; Oh, 2011; Duan et al., 2012; Park et al., 2014; Park et al., 2015) and have established the reliability of LOADEST.

Constituent load estimation in LOADEST is based on four statistical methods: Adjusted Maximum Likelihood Estimation (AMLE), Maximum Likelihood Estimation (MLE), Linear Attribution Method (LAM), and Least Absolute Deviation (LAD). The user specifies the most suitable method depending on the quality of input data. AMLE and MLE are known to be suitable in a case of normally distributed model calibration errors (residuals) while AMLE is more desirable where the calibration data set includes censored information (data that is less or greater than a given threshold). On the contrary, where model calibration errors are not normally distributed, LAM and LAD are the most appropriate (Donato and McCoy, 2005). The Load Estimator program generates outputs such as the probability plot coefficient (Vogel, 1986), the Turnbull-Weiss likelihood ratio (Turnbull and Weiss, 1978), data for use in normal-probability plot (see Figures 19 and 22) construction and standardised residuals (see Figures 15 and 19). The model evaluation criteria for this study were based on AMLE results, since the model calibration residuals are relatively normally distributed (Figures 16 and 20).

LOADEST also provides the option for the user to select the general form of regression models from among 11 predefined/underlying regression models (Park et al., 2015), and automatically choosing the best model, based on the Akaike Information Criterion – AIC (Akaike, 1981). Automatic selection of the best regression model helps in attaining a good balance between the use of multiple predictor variables in explaining the variance in load, while suppressing the standard error in the estimated variables (Donato and McCoy, 2005). For this study, LOADEST automatically selected Model 4 (Equation 8) and Model 2 (Equation 9) as the best models based on AIC for estimation of total nitrogen (TN) and total phosphorus (TP) respectively. The selected regression models are stated as:

Model 4 (Equation 8) selected in estimating total nitrogen (TN) constituents:

$$\mathbf{Ln(Load) = a0 + a1\ LnQ + a2\ Sin(2\ \pi\ dtime) + a3\ Cos(2\ \pi\ dtime)} \qquad (8)$$

Model 2 (Equation 9) selected in estimating total phosphorus (TP) constituents:

$$\mathbf{Ln(Load) = a0 + a1\ LnQ + a2\ LnQ^{\wedge}2} \qquad (9)$$

where:

Load = constituent load [kg/d]

Q = stream flow

LnQ = Ln(Q) - center of Ln(Q)

a0 – a3 = coefficients

dtime = decimal time - center of decimal time

π = user defined period

Sources: (Rukel et al. 2004; Stenback et al. 2011; Rukel, 2013; and Park et al. 2015).

5.4.1 LOADEST Regression Analysis Evaluation

The coefficient of determination (R^2) for the best-fit regression models for predicted TN and TP loads in LOADEST do not vary significantly. The model gave very highR^2 values (82.23% and 82.03%), indicating a very good simulation of constituent loads of TN and TP respectively (Figures 14 and 18).

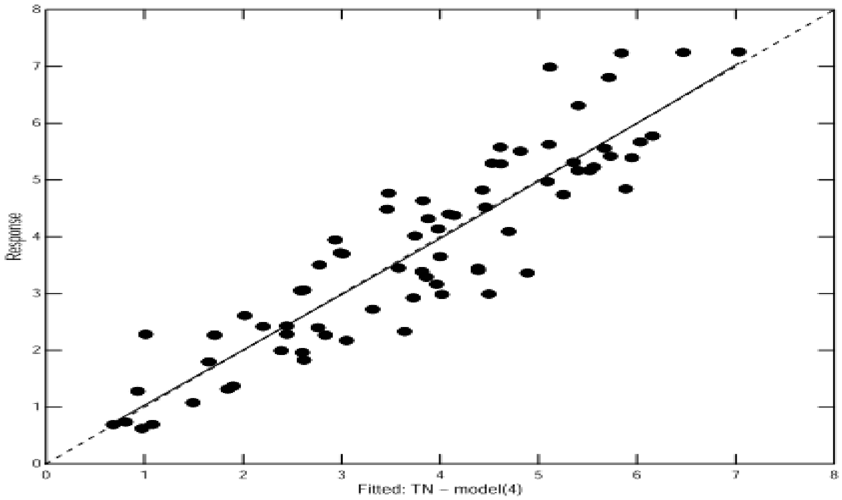


Figure 14 Correlation plot for observed and model simulation of TN in the Waipara River at Teviotdale.

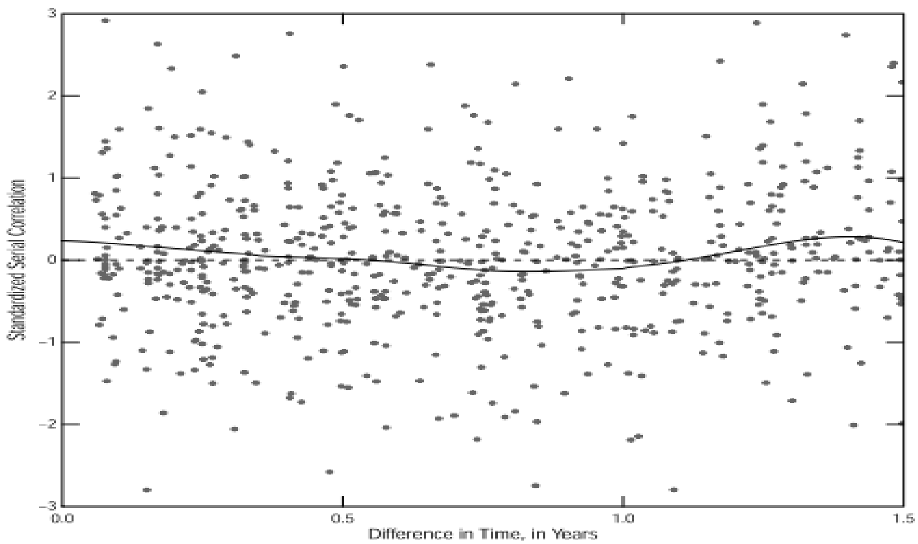


Figure 15 Standardised correlation plot for observed and model simulation of N in the Waipara River at Teviotdale.

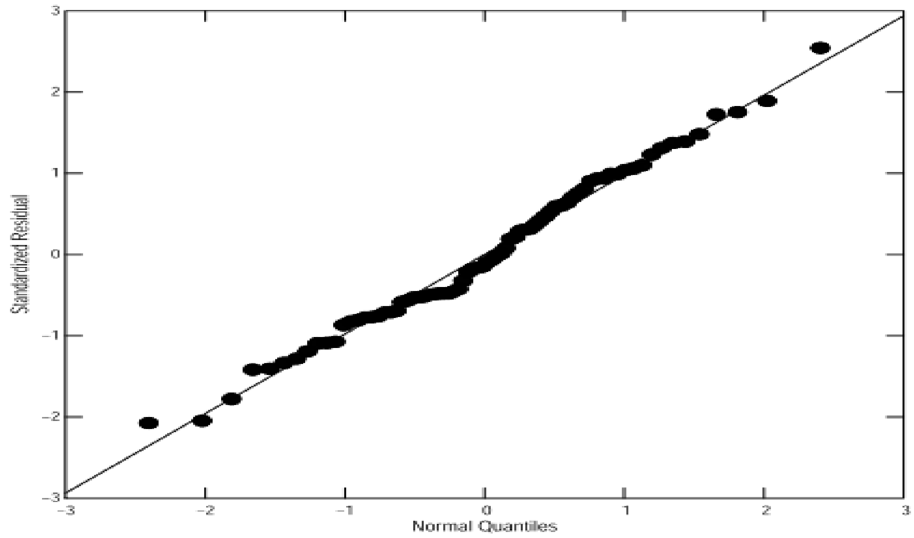


Figure 16 Residual plot of observed and model simulation for N in the Waipara River at Teviotdale.

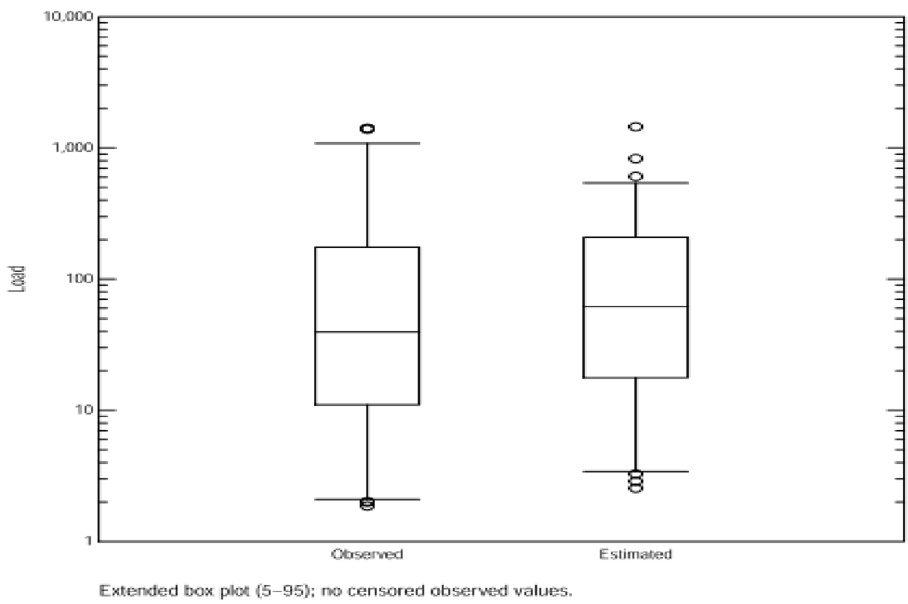


Figure 17 Extended box plots of observed and simulated data for N in the Waipara River at Teviotdale.

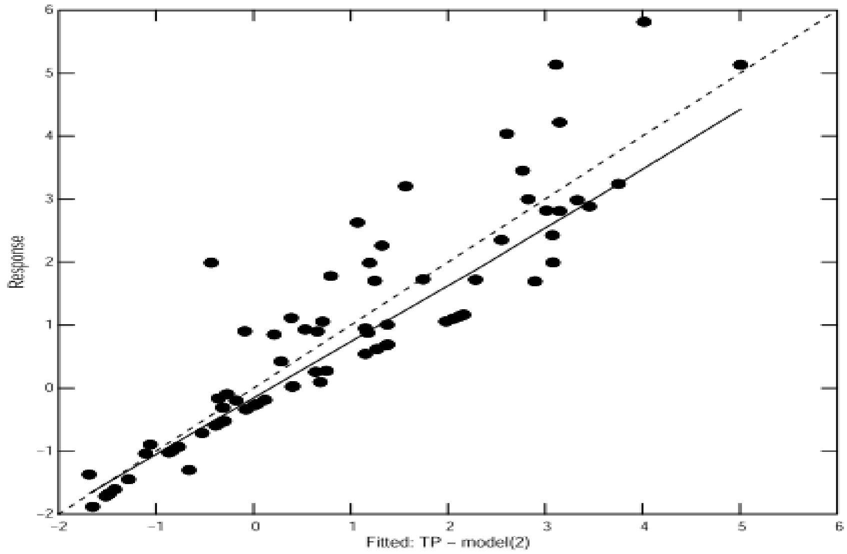


Figure 18 Correlation plot of observed and model simulation of TP in the Waipara River at Teviotdale.

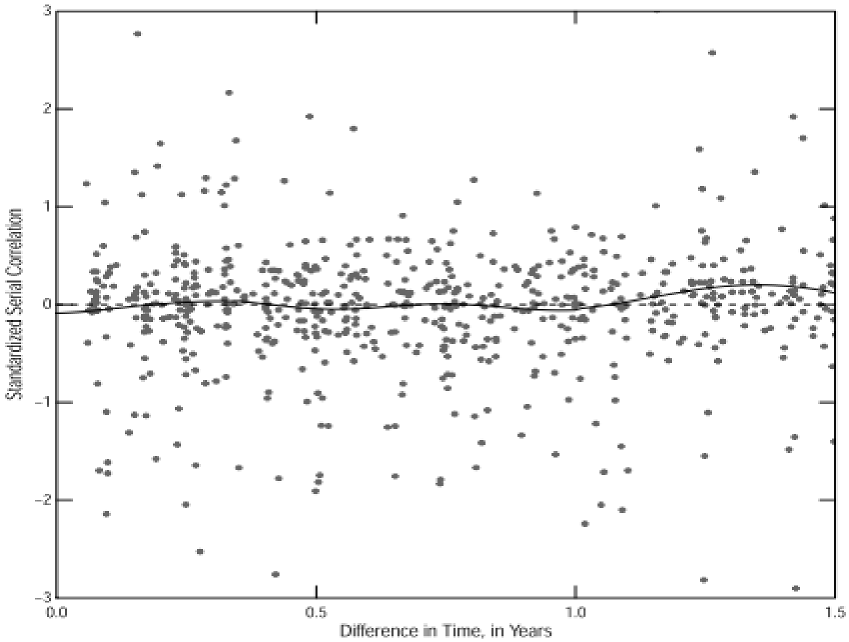


Figure 19 Standardised correlation plot for observed and model simulation of P in the Waipara River at Teviotdale.

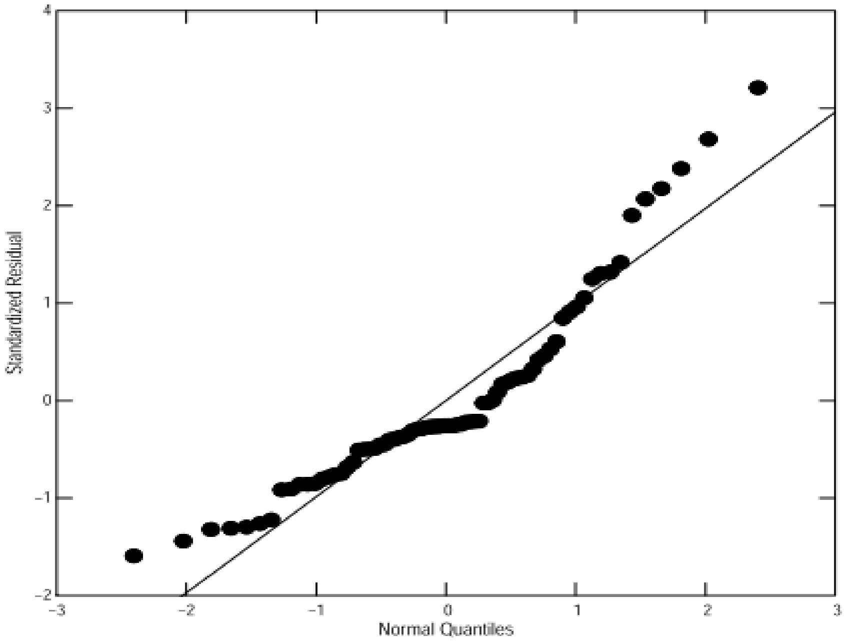


Figure 20 Residual plot of observed and model simulation for P in the Waipara River at Teviotdale.

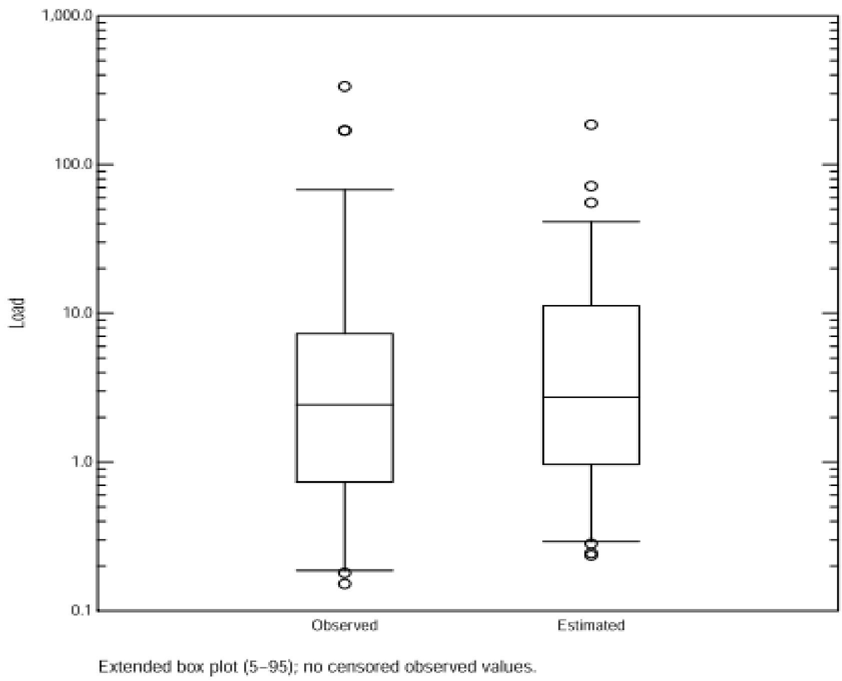


Figure 21 Extended box plots of observed and simulated data for P in the Waipara River at Teviotdale.

NSE for the TN model is 0.600 while for TP, it is 0.417. The LOADEST model performance is relatively better in estimating TN constituent loads than TP which could be as a result of the low TP concentration in the Waipara River (Donato and McCoy, 2005; Hayward et al. (2003). A common characteristic for both models is the intermittent over and underestimation of loads at various points along the regression line. The residual plots (Figures 16 and 20) and the box plots (Figures 17 and 21) show a reasonably good graphical match between observed and the estimated variables, indicative of good performance of the model in estimating the water quality data for the Waipara River.

Analysis of the model output showed better performance in estimating TP when evaluated by R^2, and poorer when the NSE is used. The main reason for the poor performance in estimating TP load correctly is that the load estimator program was not able to handle sudden changes in streamflow with the very low TP constituents during extreme high flows, resulting in poor-representation of actual loads in such events. The model however could be said to have performed relatively well for the prevailing conditions (P concentration occurring below detection limit). As such, the estimated constituent loads were utilised as input variables for the SWAT modelling.

5.4.2 Sensitivity Analysis for N and P

Observed monthly water quality information collected from Environment Canterbury for 2001 to 2006 was used in sensitivity analysis of the SWAT model nutrient parameters for both TN and TP. The model considered tennutrient parameters for sensitivity analysis from which two of them were found to be relatively sensitive with the category of sensitivity ranging from very high (rank of 1) to small (rank of 10). ERORGN.hru, CN2, ORGN_CON.hru, BC3.swq, BIOMIX.mgt, N_UPDIS.bsn, CMN.bsn, NPERCO.bsn, CDN.bsn and SDNCO.bsn were found to be sensitive to N loss.ORGP_CON.hru, PHOSKD.bsn, ERORGP.hru, PSP.bsn, PPERCO.bsn, BC4.swq, BIOMIX.mgt, P_UPDIS.bsn, CDN.bsn and SDNCO.bsn were sensitive to P loss. Appendix3shows the description of the Waipara catchment SWAT model nutrient parameters according to their sensitivity ranking, using SWAT-CUP. Organic N enrichment ratio (ERORGN) and the initial SCS runoff curve number (CN2) were the two most sensitive in simulating nitrogen loss. Organic phosphorus concentration in runoff (ORGP_CON.hru) and phosphorus soil partitioning coefficient (PHOSKD.bsn) were found to be the most sensitive parameters in the case of phosphorus simulation.

5.4.3 Calibration and Validation for Nitrogen (N) and Phosphorus (P)

The calibration of the SWAT model for N and P was set up together with the hydrology components in SWAT_CUP. The entire data period (2001 – 2012) was considered, using 2001 – 2006 for calibration period and 2007 – 2012 for the validation period. The calibration processes considered the 10 sensitive nutrient parameters (Appendix 3) and their values were varied iteratively within the allowable ranges (as in the hydrologic calibration) until satisfactory agreement between measured and simulated water quality was obtained. The autocalibration processes significantly improved model efficiency. Based on monthly time-step calibration using a similar approach adopted in hydrologic calibration, the NSE and R^2 values for both N and P were 0.77, 0.80 and 0.71, 0.72 respectively. RSME and PBIAS values for N and P model calibration are 2.63, -3.1 and 0.85, 1.8 respectively indicative of good model performance. Figures 22, 23, 24 and 25 show the nutrient model calibration and validation plots for the entire period, while Appendix 3 presents the model calibration parameters. The fitted NSE and R^2 values obtained for both calibration and validation indicate that the model application produced a plausible ranges and dynamics of nitrate and phosphorus in-stream loadings.

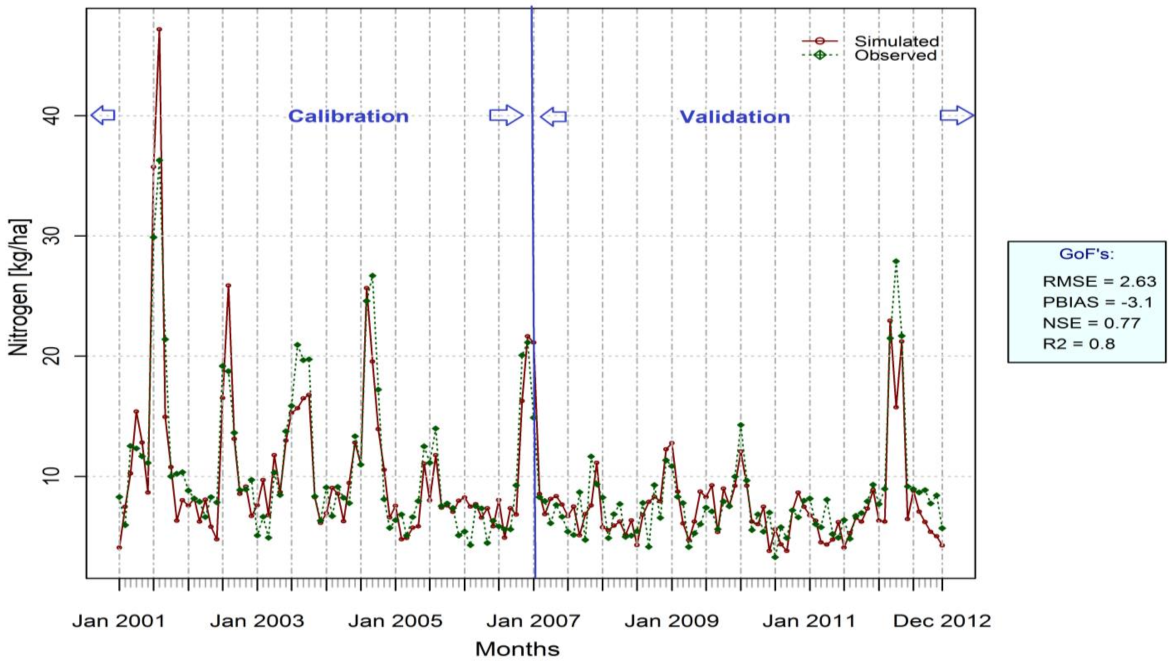


Figure 22 Calibration and validation of N for the Waipara River 2001 – 2012.

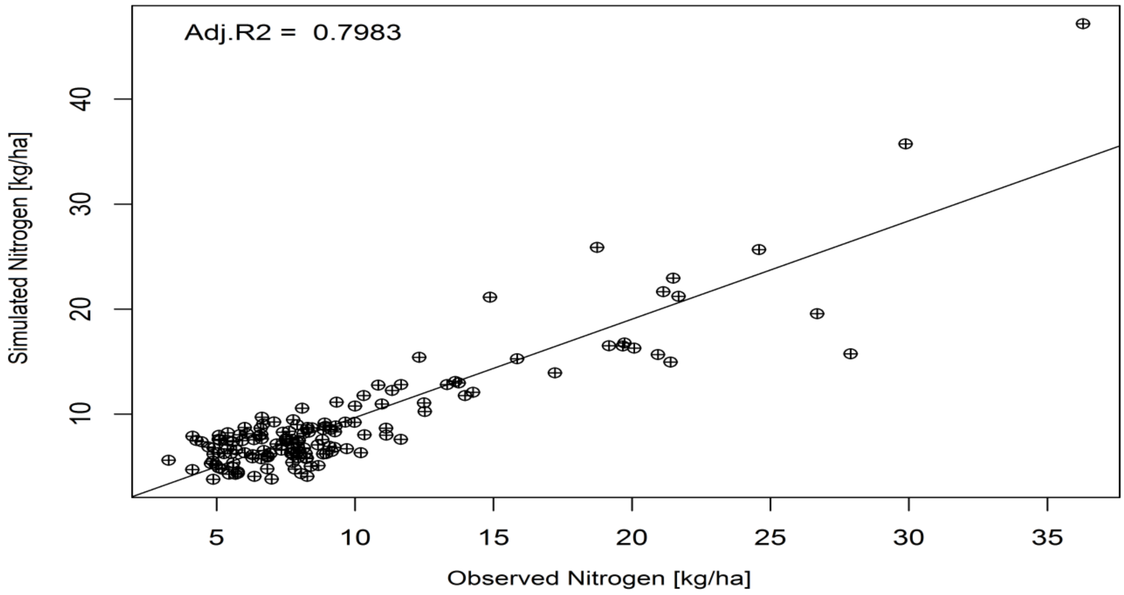


Figure 23 Scatter plot of the observed and simulated nitrogen for calibration and validation in the Waipara River 2001 – 2012.

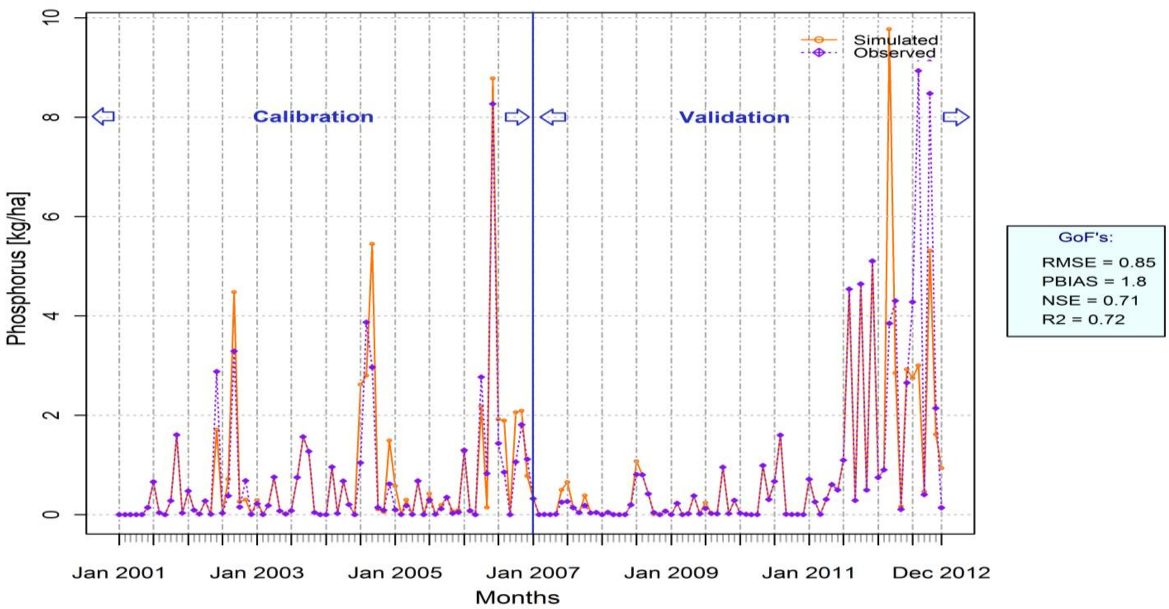


Figure 24 Calibration and validation of P in the Waipara River 2001 – 2012.

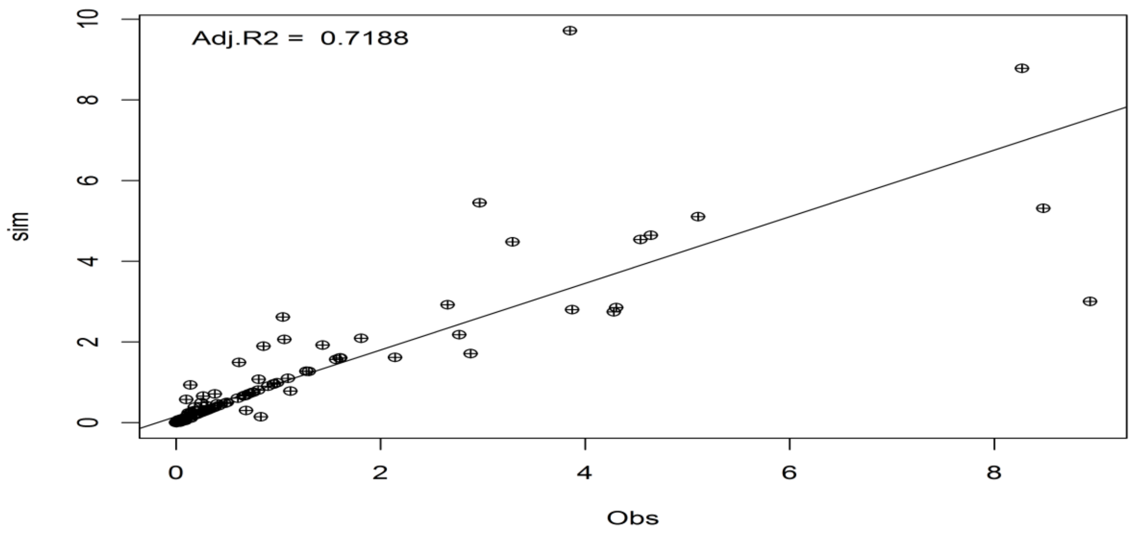


Figure 25 Scatter plot of the observed and simulated phosphorus for calibration and validation in the Waipara River 2001 – 2012.

The plots show that the model simulated N and P generally matched fairly well with the observed except in high flows. The scatter plots also show a positive correlation in strength and direction.

5.4.4 Relationship Between Nutrient Concentration and Flow

The simulation shows the highest nutrient concentrations (especially N) occurred at higher flows while the low nutrient concentrations correspond to the low flow regimes (Figures 26 and 27). This pattern results from increased run-off carrying nutrients into the stream and tributaries during high rainfall. Model simulation of phosphorus (P) concentrations is found to be generally low, consistent with the reports of Hayward et al. (2003) that P concentration in the Waipara River catchment is below detection level. Relatively high concentrations only occured during floods. This is consistent with low turbidity values and little evidence of sedimentation of the river.

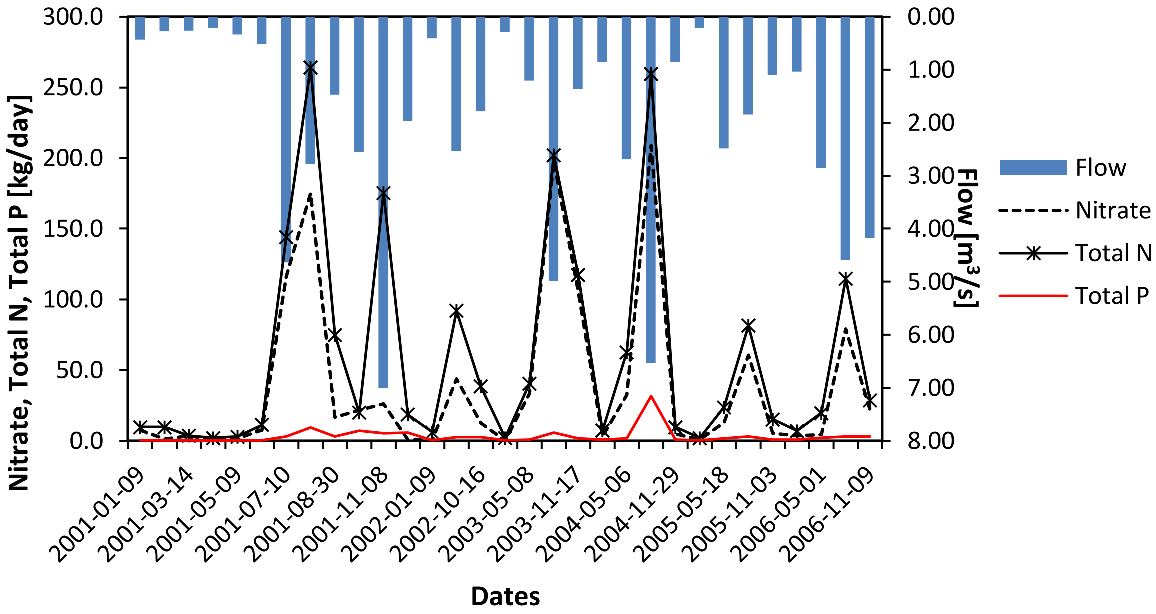


Figure 26 Calibration period: nutrient concentration and flow relationship for the Waipara River.

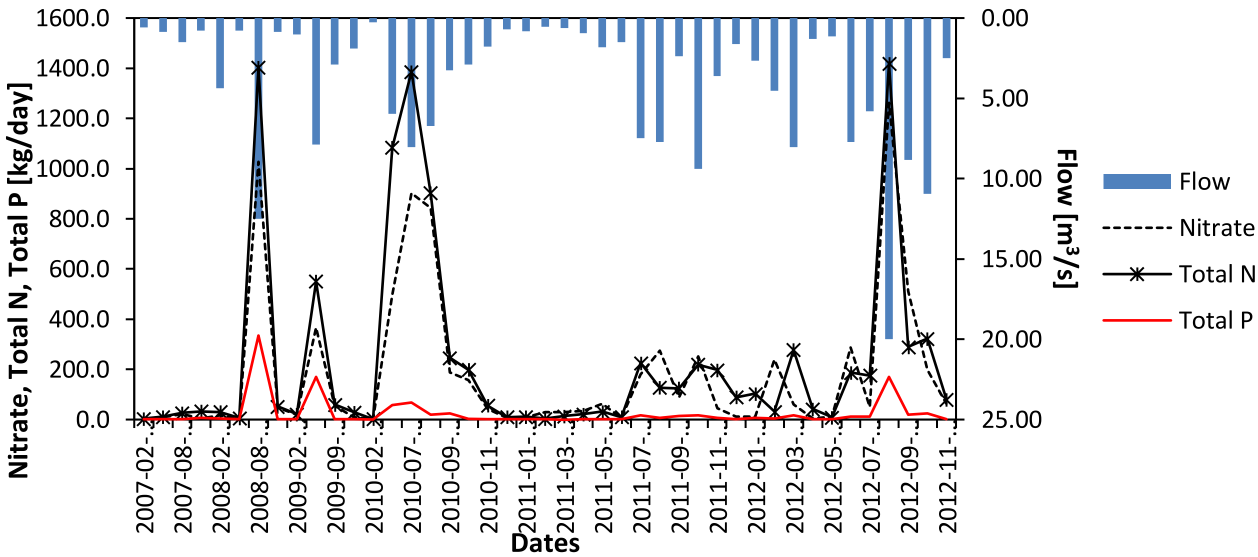


Figure 27 Validation period: nutrient concentration and flow relationship for the Waipara River.

5.4.5 SWAT Model Estimation of N and P Loads

The Waipara River SWAT model database was populated with the defined model parameters (Appendix3) and with the management operations file updated with information on type of fertiliser applied, rate and method of application, irrigation and tillage operations. For this study, the recommended minimum of 150kg/N and 25 kg/P fertiliser per hectare per year (FertResearch, 1998; Cameron et al., 2005;Monaghan et al., 2007) were applied to grazed pasture for the whole basin.The Waipara catchment historical land use (2000, 2013 and 2016) is dominated by sheep farms(22.1% -

Table7). Meanwhile sheep dominated farmlands use little or no fertilisers (field investigation). It was based on this understanding that the recommended minimum amount of 150 kg N/ha was assumed and applied to the entire grazed pasture during model simulation.

The model output (Figure 28) presents the spatial distribution of N, P and sediment. The primary focus of the study is N and P as these two are the major concerns for water quality degradation in the Waipara river catchment. Due to a lack of robust water quality data, calibration of sediment was not undertaken. Sediment yield is however reported because the Waipara catchment SWAT model simulated sediment yield corresponds to that of the existing literature (Dymond 2007; Dymond et al., 2010). This suggests that when the hydrology component of the SWAT model is well calibrated, sediment yield could possibly be accurately simulated. In addition, SWAT was primarily designed for use in ungauged river basins with no available data for calibration.

The distributions show that some sub-basins in the catchment yield as much as 25.5kg N/ha, 2.89kg P/ha and 8.4ton sed/ha per year respectively. In terms of N, this corresponds to FAR (2008), Lilburne et al. (2013), andNIWA (2013). Scott and Wong (2016) reported that median and maximum P concentrations in groundwater in North Canterbury at 30 metres depth are 0.016 and 0.77 mg/L respectively, which amounted to 0.48kg/ha and 23.1 kg/ha. The SWAT model simulated P yield in this study for the catchment (2.89kg P/ha/yr) therefore falls within their reported range (0.48kg P/ha/yr to 23.1kg P/ha/yr). Although the estimated sediment yield shown here is not based on sediment model calibration, it also falls within the range reported by Dymond (2007) and Dymond et al. (2010) *(<50 tonnes of sediment/km^2 /year = <0.5 t sed/ha/yr)* for the area. N concentration distribution in the catchment shows that some areas have up to 2.52 mg/L/N/yr (Figure 28b). From the catchment-wide perspective, the average annual basin nutrient leaching as estimated by SWAT for N03 is 4.73 kg/ha; P is 0.78 kg/ha, and sediment is 0.71 ton/ha.

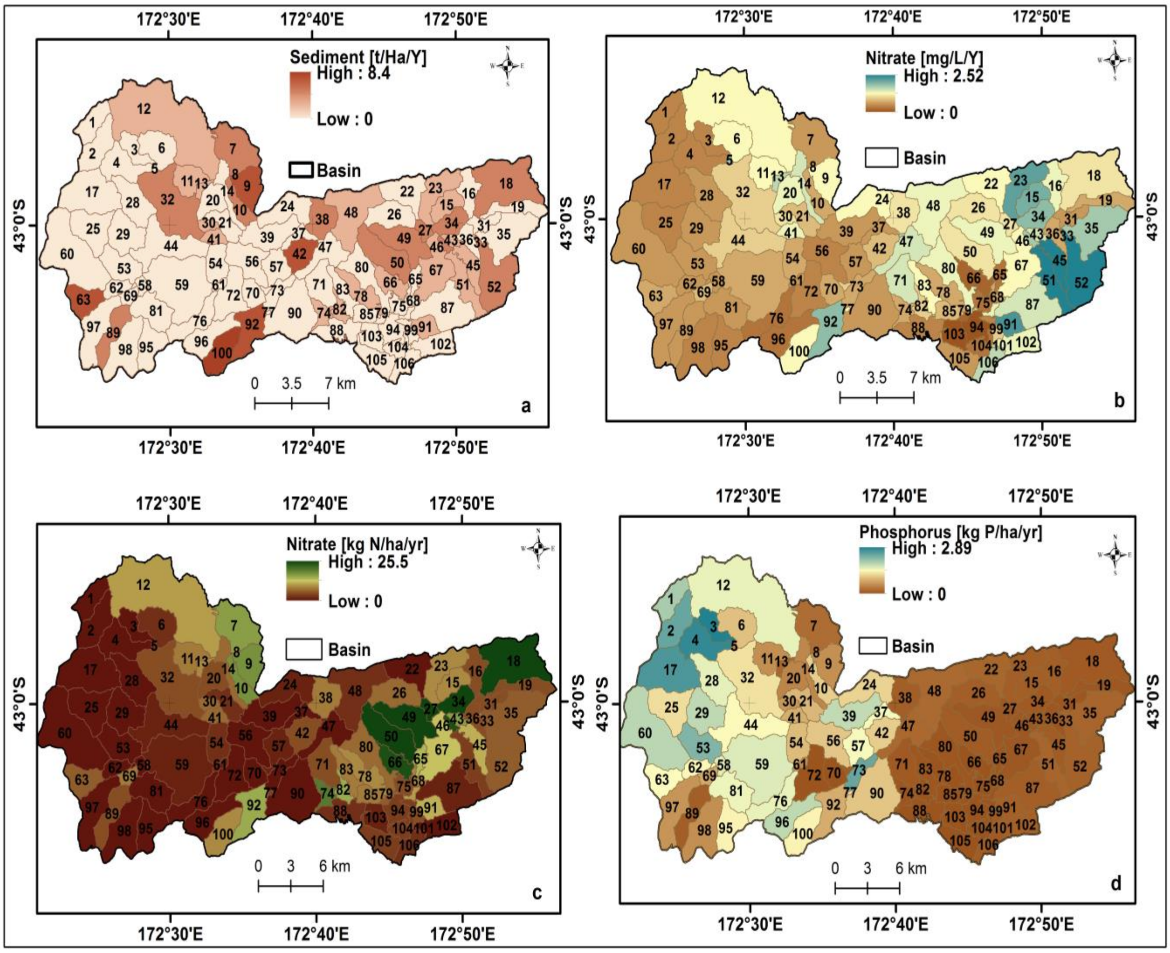


Figure 28 N, P and Sediment yield distribution in the Waipara River catchment.

5.4.6 Nutrient and Sediment Yield by Land Use Land Cover

The Waipara SWAT model simulation of nitrogen and sediment distribution according to land use/cover (2012) type and extent in the catchment showed that pasture land made up 69.82% of the catchment and generated 57.02 kg N/yr and 69.4 t sed/yr (Table 6). Grape vines occupied 9.51% of the area and discharged 5.15kg N/yr and 0.45 t sed/yr while gorse and broom occupied about 3.19% and yielded 33.85 kg N/yr and 114.64 t sed/yr. Land under native forests constitutes 3.05% of the catchment and generated a total of 24.30kg N/yr and 11.20 t sed/yr. Exotic forest land (pines) occupied 51.60km^2 (7.56%) of the catchment and produced about 0.82kg N/yr, while lands under cropping occupied 39.85 km^2 (5.84%) and yielded a total of 7.54kg N/yr and 1.12 t sed/yr. Barren lands or exposed surfaces such as roads, excavations and rocky grounds made up 0.007% of the catchment and generated 3.52 t sed/yr. The NO_3 yield in surface runoff according to land use coverage showed pasture, gorse and broom, and native forest yielded 1.74 kg/yr, 0.98 kg/yr 0.89 kg/yr respectively, followed by grapes, barren land, exotic forest, crop lands and deciduous forest.

Table 6 Waipara catchment land use and cover modeled nutrient and sediment yield

LULC	**Area /km^2 (%)**	**N kg/h/yr**	**P kg/h/yr**	**NO_3 kg/h/yr**	**Sediment ton/h/yr**
Pasture (PAST)	476.32 (69.82)	57.02	22.01	1.74	69.40
Grapes (GRAP)	64.88 (9.51)	5.15	1.02	0.35	0.45
Gorse & broom (GORS)	21.73(3.19)	33.85	8.76	0.98	114.64
Native forest (FRST)	20.79(3.05)	24.30	4.18	0.89	11.20
Exotic forest (FRSE)	51.60 (7.56)	0.82	0.21	0.25	0.10
Forest deciduous (FRSD)	7.020.24 (1.03)	0.00	0.13	0.06	0.01
Barren land (BRR)	0.05 (0.007)	0.00	0.09	0.32	3.52
Crop lands (AGRR)	39.85(5.84)	7.54	1.32	0.15	1.12

5.5 Conclusion

Water budgets present an avenue for assessing sufficiency and sustainability of supply of water. The measure of natural inflow and outflow of water within a geographic region such as a river catchment describes the water budget/balance (Healy et al., 2007). A good understanding of water budgets and basic hydrologic mechanisms such as ET, rainfall, surface runoff, and water yield creates an effective platform for a sustainable water resource use as well as environmental planning and management. Considering the significance of the spatial distribution of water resources to economic development especially farming, Pangborn and Woodford (2011) noted that besides very few areas of heavy soils and limited areas in the rain shadows around the foothills, irrigation has been the only water management technique that can make dairying economically practicable under the Canterbury conditions, if increasing dairy farming in the catchment is desired.

Alterations in water budgets over time and space can provide a means of determining the impacts of man's activities and change in climate on water resources. Human activities have been known to affect the hydrologic cycle in a variety of ways. Human induced changes to the land for agricultural purposes, such as construction of drainage and irrigation systems are capable of modifying rates of runoff, infiltration, evaporation as well as evapotranspiration (Healy et al., 2007). Modeling the flow, analysing the water budget and the hydrologic processes of the Waipara River catchment therefore provide a means to better understand and appreciate the implications of land use and climate change for water resources (especially the surface flow) of the region.

Two hydrological and water quality models (SWAT and LOADEST) have been integrated to accomplish calibration and validation processes for modeling N and P loads in the catchment. Whereas the SWAT model's performance depends on good time series water quality data, the limitations with the available observed water quality information for the Waipara River catchment suggests a poor performance of SWAT in estimating pollutant loads. The Load Estimator Program was therefore employed in estimating the river water constituent loads for the desired period and the data used in SWAT for calibration and model parameter estimation. For both SWAT and LOADEST, the goodness of fit evaluation criteria was statistically acceptable.

SWAT model output for the catchment is found to be consistent with previous works with respect to nitrogen, phosphorus and sediment yields. The model performance in estimating P is however found to be poorer than with N. This can clearly be seen from model calibration and validation, which is also consistent with an earlier observation that P concentration is below detection limit in the Waipara River (Hayward et al., 2003). Modeled average basin output for N, P and sediments seem to be low; nonetheless, the distributions showed that the majority of the sub-basins (source areas) are quite low on N, P and sediment yields, thereby creating a diminishing effect on the basin-wide average values. Nutrient and sediment loading of land use/cover type by area coverage per year is also presented to indicate which land cover type that has more significant impact in nitrate and sediment yield in the catchment. This result suggests the need for taking both critical source area and basin-wide approaches to the implementation of catchment pollution control management strategies.

Chapter 6

EVALUATING THE LONG TERM EFFECTS OF CURRENT LAND USE TRENDS ON CATCHMENT WATER QUALITY

6.1 Introduction

This part of the study focuses on analysing the trends in land use change and their implication for water quality and quantity in the Waipara River catchment, contributing to objective four. The years 2000, 2013 and 2016 constitute the observation periods of land use/cover data, for which satellite images were obtained. Section 6.2 of the chapter provides a general background to land use change detection based on current trends. Discussion of the methods adopted for land use change analysis and future scenario development is presented in sections 6.3 and 6.4, while section 6.5 lays out the results and discussion of land use change projections. Sections 6.6 and 6.7 examine the nutrient and sediment yield and implications for water quality for the projected periods. Estimation and analysis of dairy land use water demand, with a conclusion follows in sections 6.8 and 6.9.

6.2 Background to Land Use Change Detection

Detecting a change in land use entails the determination and categorisation of the complex relationships that exist between man and the physical environment (Verburg et al., 2004). Changes in land use patterns resulting from developments within Catchments have been known to impact on biodiversity and aquatic ecosystems (Turner et al., 2001). Increased surface runoff, pollutants loading to surface and groundwater systems as well as a drop in groundwater levels are some known negative effects of land use change on biodiversity and aquatic ecosystems (Turner et al., 2001). A critical analysis of the structure of land use and the trends in land use change in a Catchment is therefore a very significant step towards appropriate planning and management of land and water resources. Identifying changes and potential changes of the Earth's surface features increases understanding which is important for better resource management and better decision making (Lu et al., 2004; Seif and Mokarram, 2012).

The analytical process that aims to detect change*s* over time and space of the land cover or land use is a measure that observes the differences in the state of the land at different times (Singh, 1989). Thus, the thematic change information so derived can bring about a better understanding and recognition of the underlying processes necessary for restoring land cover and management of land use change impacts (Ahmad, 2012). Change detection therefore entails the use of multi-temporal remote sensing data to quantify the impacts of historical events on the earth surface, and thus aids in the determination of the implications of alterations in land use and land cover characteristics of the remotely sensed data (Zoran, 2006; Ahmad, 2012, and Seif and Mokarram, 2012). Analysis and derivation of land cover maps for representing earth surface features and the analysis of the transformations in land cover structure over time are primary conditions for change detection.

6.3 Method for Land Use Change Analysis and Future Scenario Development

6.3.1 Data Collection

Three Landsat image data sets, captured on 25 November 2000, 25 September 2013 and 15 December 2016 were used. The first image was captured from the sensor Landsat Enhanced Thematic Mapper (ETM), while the other two were from the Landsat 8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS), respectively. The US Geological Survey (USGS) database provided the source of the information.

The image obtained from the Landsat ETM sensor comprises of eight spectral bands with a spatial resolution of 30m. It is characterised by a 30 meters x 30 meters Instantaneous Field Of View (IFOV) in bands 1-5 and 7. Bands 6 and 8 are 60 meters x 60 meters, and 15 meters by 15 meters IFOV respectively. The images from Landsat 8 are of nine spectral bands. Bands 1–7 and 9 have spatial resolution of 30m x 30m, while band 8 (panchromatic) is of 15m x 15m spatial resolution. All 9 bands from both Landsat ETM and OLI_TIRS sensors are found in the optical and infrared regions of the electromagnetic spectrum. The 30m resolution was maintained for the three images for the purpose of further analysis with cellular automata (CA). A cellular automaton (CA) is a computational model comprising of a group of cells structured in grids (in a spatial arrangement), in such a way that individual cells change state based on time, following predefined principles involving the states of neighbouring cells (Aburasa et al., 2016).

6.3.2 Data Pre-Processing

Radiometric correction was carried out on the three satellite images of the Waipara River catchment for the years 2000, 2013 and 2016. The top of the atmosphere (TOA) process was employed in converting digital numbers (DNs) to reflectance values to enable comparison of the images as they were captured on different dates. Following Vázquez-Quintero et al. (2016), equation (10) was used in the radiometric conversion process for the Landsat ETM and OLI_TIRS sensors.

$$\rho_\lambda^* = \frac{\rho^\lambda}{Sin\,\theta_{SE}} \tag{10}$$

Where ρ^λ is the TOA planetary reflectance, with correction for solar angle and θ_{SE} is the local sun elevation angle.

The image from Landsat 8 was utilised in normalising the reflectance of the images from 2000. The normalisation process enables making modifications on the histogram and thereby improving the brightness values of the images, taking the image from 2013 as a reference. The approach helped in reducing the spectral differences in the land use covers (Vázquez-Quintero et al., 2016).

6.3.3 Land Use Classification

The supervised land use classification approach was carried out by the use of the maximum likelihood technique. The approach, according to Vázquez-Quintero et al. (2016), entails the use of training areas as polygons and decision rules of maximum likelihood (see equation 11), in image classification.

$$g_k(x) = \ln\, p(C_k) - \frac{1}{2}\ln\left|\sum{}_k\right| - \frac{1}{2}(x - y_k)^t \sum{}_k^{-1}(x - y_k) \tag{11}$$

Where: C_k = land cover class k; x = spectral signature vector of a image pixel; $p(C_k)$ = probability that the correct class is C_k; $|\Sigma_k|$ = determinant of the covariance matrix of the data in class C_k; $\Sigma^{-1}{}_k$ = inverse of the covariance matrix; y_k = spectral signature vector of class k.

The classified land use map for year 2000 was derived from the Landsat ETM sensor image, while the land use maps of 2013 and 2016 were derived from the images from the Landsat OLI_TIRS sensor; all having spatial resolution of 30m. The land uses classified in all images for the Waipara catchment were: Forest, Scrub, Vineyards, Sheep farms, Beef farms, Sheep and Beef farms, and Beef or Dairy farms. It is necessary to note that on the satellite images, the spectral signatures of beef land use appeared the same as that of dairy land use in certain parts of the catchment. Further investigations through field visits revealed the presence of similar high quality grass/herbage and mixed land uses (beef and dairy). It was due to this realisation that such areas were classified as beef/dairy (following the pattern of the catchment land use data obtained from AsureQality in 2013).

6.3.4 Spectral Separability

The structure of each land use played a very significant role in accomplishing the classification. The reflectance of plant cover in the infrared region has been known to be closely associated with water absorption capacity. The structure of the vegetation as well as the aerial space among the foliage is responsible for energy dispersion (Eastman et al., 2005; Mitsova et al., 2011, Vázquez-Quintero et al., 2016). The Jeffrey-Matusita (JM) Distance (J_{xy}), (Equation 12), which estimates the separability of a pair of probability distributions (Richards and Jia, 2006), was adopted in the determination of the spectral separability. The approach is found useful for Maximum Likelihood Classifications result evaluation. JM Distance is stated thus:

$$J_{xy} = 2(1 - e^{-B}) \quad (12)$$

$$B = \frac{1}{8}(x-y)^t \left(\frac{\sum x - \sum y}{2} \right)^{-1} (x-y) + \ln \left(\frac{\left| \frac{\sum x + \sum y}{2} \right|}{\left| \sum x \right|^{\frac{1}{2}} \cdot \left| \sum y \right|^{\frac{1}{2}}} \right) \quad (13)$$

Where: *x* = first spectral signature vector; y = second spectral signature vector; Σ*x* = covariance matrix of sample *x*; Σ*y* = covariance matrix of sample *y*.

The JM Distance is asymptotic to 2 when signatures are completely different, and tends to 0 when signatures are identical.

6.3.5 Accuracy Assessment

The classification accuracy assessment was done using the Kappa coefficient (Equation 14) by making use of 200 control points from the false colour compositions and Google Earth images of years 2000, 2013 and 2016. It is common practice to employ the Kappa coefficient and the error matrix in validating the correctness of thematic maps derived from the classification process. Verification of a given category of classifications can therefore be achieved using field or referenced data (Vázquez-Quintero et al., 2016).

$$Kappa = \frac{N \sum^k X_{ii} \cdot \sum^k (X_{i+} \times X_{+i})}{N^2 - \sum^k (X_{i+} \times X_{+i})} \quad (14)$$

Where: Kappa = Kappa index, k = number of matrix files, X_{ii} = observation number on row i and column *i* (along the diagonal), X_{i+} and X_{+i} = total marginal for row i and column i, respectively, N = total number of observations.

6.4 Predicting Land Use Change in the Waipara Catchment Using Markov Chains

In determining the changes in Waipara catchment land use, the Markov Chains (MC) technique was used. The MC technique uses a stochastic modeling approach, based on a transition probability matrix to describe the probability of a change from one land use form to another (Vázquez-Quintero et al., 2016; Cabral and Zamyatin, 2009; Glenn et al., 1992). The probability that a land use type in the image (pixels) at a given time t_0 would change to another form of land use in time t_1 is described by the transition probability. A probability transition matrix was therefore derived from the observed changes in land use in the images from one date to another; and by crossing between the images and setting a proportional error to predict the future land use for the catchment (Vázquez-Quintero et al., 2016). The transition probability is expressed as:

$$\sum_{i=1}^{m} p_{ij} = 1 i = 1,2,\dots m \tag{15}$$

$$P = (P_{ij}) = \begin{matrix} P11 & P12 & \dots & P1m \\ P21 & P22 & \dots & P2m \\ \dots & \dots & \dots & \dots \\ Pm1 & Pm2 & \dots & Pmm \end{matrix} \tag{16}$$

Where: P_{ij} = the probability of transition from one land use to another, m = the type of land use of the area studied, P_{ij} values range from 0–1.

Applying the Markov and Cellular Automata (MCA) together makes it possible to simulate the land area portrayed by pixels in the image. Individual pixels can however take on a value ranging from a finite set of states and can be influenced by a transition function (TF). The TF utilises the measured values as arguments and the values of the adjoining pixels as a function of time. The determination of the transition function for the Waipara River catchment was based on the variation between years 2000 and 2013. Employing the TF for the periods 2000 and 2013 in MCA, it was possible to model the future land use/cover for the years 2020, 2025 and 2030. By implication, the probability transition matrix generated from the observed variations between 2000 and 2013, as well as the probability transition maps of 2013 with each scenario enabling the production of the future land use maps. Using the transition probability maps in an interactive process in MCA, the inherent suitability for individual pixels to transform from a particular land use form to another was established. A 5 x 5 filter (Figure 29) was then used to assign suitability weights to pixels that are far from the analysed pixel. The probability of changes was found to remain constant in the analyses for the years 2000 and 2013, and based on that, projections for years 2020, 2025 and 2030 were made. The analyses showed the shorter term projections to be more realistic. As a result, the simulation was run for the years 2020, 2025 and 2030.

0	**0**	**1**	**0**	**0**
0	**1**	**1**	**1**	**0**
1	**1**	**1**	**1**	**1**
0	**1**	**1**	**1**	**0**
0	**0**	**1**	**0**	**0**

Figure 29 (5 x 5) filter configuration used in Markov and Cellular Automata (MCA).

6.4.1 Model Validation

The result of the Markov simulation for year 2013 land use, together with the reference map derived from the supervised classification process for year 2016 were used in validating the model prediction. By comparison of the catchment land use of 2016 generated by the supervised classification processes against the simulated MCA model, validation of land use change was possible. To establish the probability of land use change, a transition matrix (probability that a land use type in the image – pixels - at a given time would change to another form of land use - equation 16) was generated and was critically analysed for the determination of the future state of land use.

6.4.2 Cellular Automata (CA)

Cellular Automata analysis was performed using the MCA module in IdrisiSelva. CA model simulation assumes space and time as discrete variables while interactions assigned are treated as local variables (Benenson and Torrens, 2004). The analysis of the MC output is used in CA to predict future land use. The supervised classification results for years 2000, 2013 and 2016 were used for the prediction.

6.5 Results and Discussion

6.5.1 Spectral Separability

Appendix4 presents the JM distance outputs for the analysed land use types in the Waipara River catchment for the years 2000, 2013 and 2016. Considering the analysed bands of the Landsat sensors, band 4 of sensor ETM and band 5 of sensor OLI_TIRS present the highest spectral separability values for the land use classes: Forest vs Scrub, Forest vs Sheep farms, Forest vs Beef farms, Forest vs Sheep and Beef farms, Forest vs Beef/Dairy farms and Forest vs Vineyards (JM = 1.70, 1.68, 1.66, 1.66, 1.63, 1.53). The high separability values indicate that there is a clear distinction between the aforementioned land use types on the satellite images. Also, values of spectral separability for the classes Scrub vs Sheep farms, Scrub vs Beef farms, Scrub vs Sheep and Beef farms, Scrub vs Beef/Dairy farms and Scrub vs Vineyards are acceptable, even though JM distances are low (JM = 1.12, 1.17, 1.13, 1.05, 1.02). The implication of this is that there is confusion between the spectral signatures of Scrub and the considered farmlands. This confusion is more significant between Sheep farms vs Sheep and Beef farms, and Beef farms vs Beef/Dairy farms (JM = 0.77, 0.52) respectively. Despite the fact that 0.77 and 0.52 constitute the highest JM distances for the paired land use types, they are less than 1.0 indicating high levels of confusion or no difference between the land use types on the image. The analysis has also shown that the infrared band (band 5 in Landsat ETM; band 5 in Landsat OLI_TIRS) is crucial in the differentiation of the land use categories under study.

6.5.2 Land Use Classification 2000, 2013 and 2016

Seven main agricultural land use categories, constituting the most dominant land use activities with the potential of impacting on nutrient yields in the Waipara River catchment were identified (Figure 30). The pasture dominated land in the Waipara river catchment supports the pastoral farming system including: sheep farms, beef farms, sheep & beef farms, and beef or dairy farms. In order to determine the rate and pattern of change in these individual land uses, image classification process did not lump these pasture based land use categories simply as pasture but identified them as they were (Tab 6-8), which was helpful in implementing further analyses.

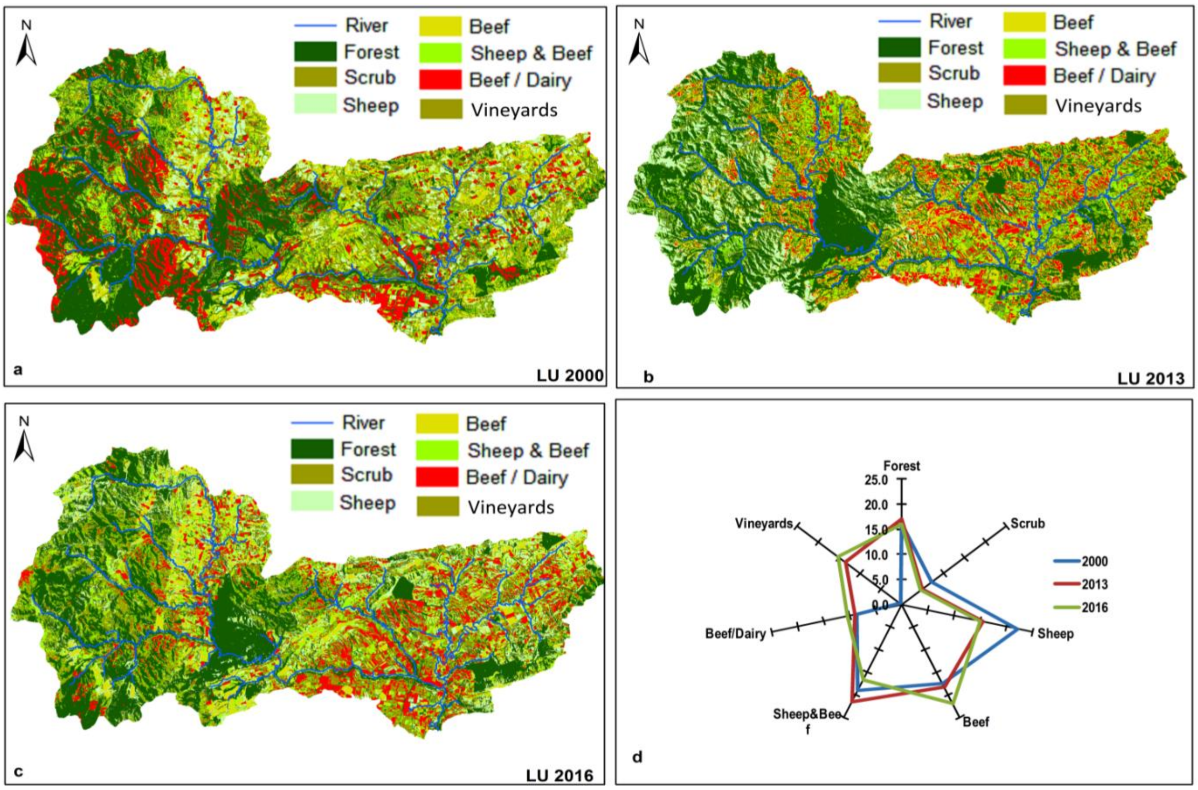


Figure 30 Waipara catchment land use classes and distribution 2000 (a); 2013(b); 2016(c) (%) and changes over time (d).

Table 7 presents the classification accuracy of the seven land use categories in the Waipara catchment. The ratio between the number of correctly classified pixels and the reference total pixels for particular LULC class is called the producer's accuracy. The producer's accuracy (PA) informs the image analyst of the number of pixels correctly classified in a particular category as a percentage of the total number of pixels actually belonging to that category in the image. Producer's accuracy measures errors of omission. The ratio between the number of correctly classified pixels and the classified totals pixels of particular LULC class is the user's accuracy - because users are concerned about what percentage of the classes has been correctly classified. The user's accuracy (UA) is computed using the number of correctly classified pixels to the total number of pixels assigned to a particular category. It takes errors of commission into account by telling the consumer that, for all areas identified as category X, a certain percentage are actually correct. Overall accuracy is calculated by dividing the correctly classified pixels (sum of the values in the main diagonal) by the total number of pixels checked.

Table 7 Land use classification accuracy for Waipara River catchment

Classes	Classification Accuracy			
	Producer Accuracy (%)	User Accuracy (%)	Overall Accuracy (%)	Kappa
Year 2000				
Forest	93.05	92.91	71.70	0.64
Scrub	77.50	81.65		
Sheep farms	66.73	63.78		
Beef farms	58.12	58.86		
Sheep & Beef farms	53.35	48.41		
Beef/Dairy	64.08	67.32		
Vineyards	70.12	68.90		
Year 2013				
Forest	94.58	94.83	76.50	0.70
Scrub	78.41	82.28		
Sheep farms	72.32	69.63		
Beef farms	65.34	66.03		
Sheep & Beef farms	63.88	60.47		
Beef/Dairy	65.84	67.32		
Vineyards	71.02	69.82		
Year 2016				
Forest	93.84	94.83	80.43	0.76
Scrub	82.77	85.79		
Sheep farms	73.80	75.22		
Beef farms	75.79	72.69		
Sheep & Beef farms	70.53	67.43		
Beef/Dairy	77.98	78.82		
Vineyards	76.80	74.67		

These also presented the largest errors for the year 2000. The estimated overall accuracy, based on the error matrix, was 71.70% with a Kappa index of 0.64 indicating a high degree of reliability of the image classification approach (Ghimire et al., 2010).

The land use classification for the year 2016 showed the highest precision, with less error in the spectral characterisation of the classes, and registering an overall accuracy of 80.43%, with a Kappa index of 0.76. For the year 2013, overall accuracy was 76.50% with a Kappa index of 0.70 (Table 7). The overall accuracy attained for the maps obtained from the 2016 image resulted from the attained individual precisions for each of the different classes. Together, the classes gave producer accuracy within the range of 70.53% – 93.84% and user accuracy within the range of 67.43% – 94.83% indicative of how well a pixel (land use type) classified on the satellite image corresponds to that land use category on the ground (Story and Congalton, 1986). The Kappa coefficient is recommended as a standard measure for determining the accuracy or reliability of all multi-valued image classification issues (Ben-David, 2008). The high Kappa index and accuracy values obtained for the image classification show that the classified land use maps for this study adequately represent the actual land use categories in the Waipara catchment.

A detailed examination of the structure and distribution of land use types on the three images for the catchment revealed that beef/dairy land represents one of the least spatially distributed land use. Forest and scrub lands together occupied a little over 23.3% of the total area (Table 8).

Table 8 Areas (ha), percentages and changes of land use for the years 2000, 2013 and 2016 in the Waipara River catchment.

Land Use	**Area in (ha) and Percentage (%)**						**Change in (ha)**		
	2000		**2013**		**2016**		**2013 - 2000**	**2013 - 2016**	**2000 - 2016**
	Area	**%**	**Area**	**%**	**Area**	**%**			
Forest	11380.3	16.2	12001.0	17.1	11187.5	15.9	+620.7	-813.4	-192.7
Scrub	4988.2	7.1	3372.3	4.8	3161.5	4.5	-1615.9	-210.8	-1826.6
Sheep farms	15525.9	22.1	10941.8	15.6	10538.4	15.0	-4584.1	-403.4	-4987.5
Beef farms	12360.1	17.6	12912.9	18.4	15456.3	22.0	+552.8	+2543.3	+3096.1
Sheep &Beef	13469.3	19.2	15200.3	21.6	11820.5	16.8	+1731.0	-3379.8	-1648.8
Beef/Dairy	6102.8	8.7	6350.5	9.0	7343.4	10.5	+247.8	+992.9	+1240.6
Vineyards	245.9	0.35	9484.5	13.5	10749.1	15.3	+9238.6	+1264.6	+10503.2

Considering the natural potential of the region in terms of economic activities as well as nutrient yielding capabilities (due to fertiliser/animal manure), forest, scrub, vineyards, sheep farms, beef farms, sheep and beef farms, and beef/dairy were together the most significant land use types in the Waipara River catchment.

6.5.3 Land Use and Land Cover Change (2000–2016)

Having derived the land uses for the catchment through the supervised classification method, analysis of the pattern of change in land use was carried out. Table 8 above presents the surface change pattern in each land use class. From 2000 to 2013, forest land increased by 620.7 ha, but decreased by 813.4 ha from 2013 to 2016 and had an overall decrease of 192.7 ha from 2000 to 2016. Scrub land decreased by 1615.9 ha between 2000 and 2013, decreased by 210.8 ha from 2013 to 2016, with a total reduction in area of 1826.6 ha from 2000 to 2016. Sheep farms lost 4584.1 ha, 403.4 ha and 4987.5 ha between 2000 to 2013, 2013 to 2016 and 2000 to 2016 periods respectively. Beef farms however gained by 552.8 ha, 2543.3 ha and 3096.1 ha respectively over the three periods. Sheep and Beef farms increased by 1731.0 ha in 2000 to 2013, decreased by 3379.8 ha from 2013 to 2016; with an overall decrease of 1648.8 ha between year 2000 and 2016. Beef/Dairy land use on the other hand witnessed a positive change over the three periods. It increased between 2000 and 2013 by 247.8 ha; 2013 to 2016 by 992.9 ha and by 1240.6 ha in total from year 2000 to 2016. Similarly, vineyards in the catchment witnessed a positive change over the three periods. It grew by 9238.6 ha from 2000 to 2013; 1264.6 ha between 2013 and 2016, with an overall growth of 10503.2 ha from 2000 to 2016. The implication of the observed changes in land use activities in the Waipara catchment is the consequent impacts on future nutrient and sediment yields (Table 11). Increasing trends means more nutrient and sediment export to the environment and consequently impacting negatively on water quality. In effect, the observed trends should raise an alarm among environmental managers, planners and policy makers to initiate a re-evaluation of the existing policy instruments and tools guiding the catchment land use.

6.5.4 Validation of Land Use Change Projection

Model validation was undertaken by comparing Markov Chain simulated land use areas with the most recent (2016) land use areas. The results (Table 9) show that forest, beef farms, sheep and beef farms, and beef/dairy land uses show relative errors below 4%.

Table 9 Comparison of land use in 2016 generated by supervised classification processes against the simulated MCA model for the Waipara River catchment.

Land use	**Observed 2016**		**Simulated 2016**		**Prediction error**	
	Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Forest	11187.5	15.9	11240.9	16.0	-53.4	-0.5
Scrub	3161.5	4.5	2669.7	3.8	491.8	15.6
Sheep farms	10538.4	15.0	9976.3	14.2	562.1	5.3
Beef farms	15456.3	22.0	16650.6	23.7	-1194.3	-7.7
Sheep & Beef farms	11820.5	16.8	12084.0	17.2	-263.5	-2.2
Beef/Dairy	7343.4	10.5	7657.9	10.9	-314.5	-4.3
Vineyards	10749.1	15.3	9976.3	14.2	772.8	7.2

Forest land presented the best agreement in which the actual area is 11,187.5 ha, and the MCA simulated area is 11,240.9 ha. The overall simulation accuracy of MCA in year 2016 was 80.43% with a Kappa index of 0.76, indicative of an acceptable level of precision. Based on these results, it was assumed that the MCA model can be utilised in predicting the spatial distribution of future land use for the catchment.

6.5.5 Land Use Change Projection

The Markov Chain model was used to forecast future land use change for the years 2020, 2025 and 2030. Figure 31 a, b, c and d shows the spatial distribution of land use types in the Waipara catchment for the future, based on the 2016 classification.

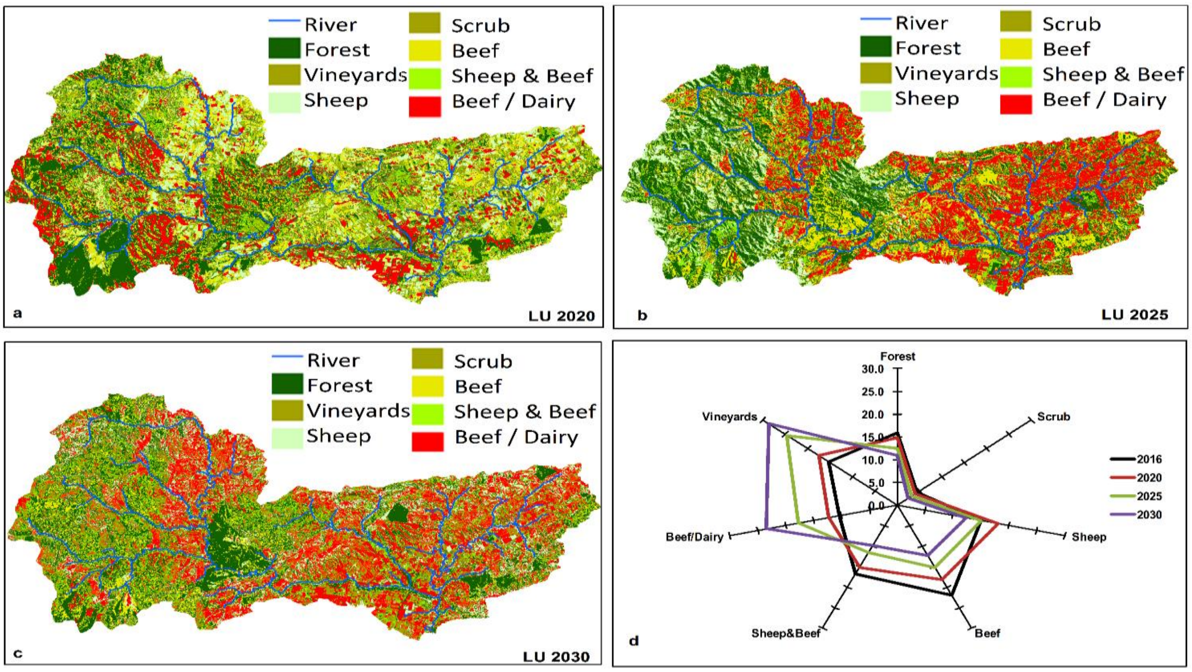


Figure 31 Waipara Catchment Projected Land Use: 2020(a); 2025(b); 2030(c) and percentage change over time (d).

The results (Table 10) indicate that forest land will decrease by 1.1%, 3.5% and 5.0% for the years 2020, 2025 and 2030 respectively from its initial 15.9% coverage of the catchment in 2016. Scrub land will decrease by 0.4% in 2020, 1.2% in 2025 and by 2.0% in 2030; while sheep farms will increase by 3.1% and 0.1% in 2020 and 2025 respectively, and then drop in coverage by 2.7% in 2030.

Table 10 Percentage land use changes for three forecast periods for Waipara River catchment using Markov Chain based on 2000 – 2016 trends.

Land use	2016	2020		2025		2030	
	Area (%)	Area (%)	Variation (%)	Area (%)	Variation (%)	Area (%)	Variation (%)
Forest	15.9	14.8	-1.1	12.4	-3.5	10.9	-5.0
Scrub	4.5	4.1	-0.4	3.3	-1.2	2.5	-2.0
Sheep	15.0	18.1	3.1	15.1	0.1	12.3	-2.7
Beef	22.0	18.1	-3.9	15.3	-6.7	12.3	-9.7
Sheep & Beef	16.8	15.2	-1.7	11.6	-5.2	9.8	-7.0
Beef/Dairy	10.5	12.2	1.8	17.7	7.3	23.5	13.0
Vineyards	15.3	17.5	2.2	24.6	9.3	28.75	13.5

Beef farms are expected to decrease in the catchment by 3.9% in 2020, 6.7% in 2025 and by 9.7% in 2030. Similarly, sheep and beef will decrease by 1.7% in 2020, 5.2% in 2025 and in 2030 by 7.0%. Beef/dairy land use on the other hand is expected to be on the increase by 1.8% in 2020, 7.3% in 2025 and 13.0% in 2030. In the same manner, vineyard coverage in the catchment is expected to increase by 2.2%, 9.3%, and 13.5% respectively for the 2020, 2025 and 2030 periods based on the current trend analysis.

6.6 Nutrient and Sediment Yield

Land Use Change analysis was performed using satellite images of years 2000, 2013 and 2016 to establish trends (%) in land use change. The Land Use data for 2013 (obtained from AsureQuality Limited, Palmerston North New Zealand) for the catchment was employed for the image analysis/interpretation and formed the reference year for the analyses, which also corresponds to the upper limit of the SWAT model calibration and validation period (2001-2012). The percentage trend of change for various land uses (sheep, beef, sheep and beef, beef/dairy and scrub) as shown in Figure 31 c and d was further used to project changes in land use for years 2020, 2025 and 2030 (Figure 32 a, b, c and d) based on the projected year 2016 (Figure 31 c) land use data for the catchment. By implication and in all scenarios, the upper limit of 2001 – 2012/2013 remains the baseline year for land use change. The Spider Chart (Figure 32 d) shows the percentage coverage of each land use in the catchment for the various years.

The projected land use maps for 2020, 2025 and 2030 then formed inputs for the SWAT model run. Applying the minimum 150kg N/ha per year (Cameron et al., 2005) to grazed pasture in the SWAT run, N and P as well as sediment yields were obtained. Table 11shows N, P and sediment yields in surface runoff in the catchment for the reference/base year (2001-2012/2013) and the projected years (2020, 2025 and 2030), together with the percentage changes - with reference to the base year. The values however represent the average basin yield per hectare per year.

Table 11 Projected Waipara River Catchment Average Nutrient and Sediment yield in surface water per hectare: 2020 – 2030.

Elements load in Surface Runoff	**(2001-2012)/2013**	**2020**	**2025**	**2030**
N Yield in Surface Runoff kg/ha/yr	4.73	4.90 (3.6 %)	5.58 (17.4 %)	6.39 (29.7 %)
P Yield in Surface Runoff kg/ha/yr	0.78	0.80 (2.5 %)	0.83 (6.3 %)	0.86 (9.4 %)
Sediment Yield in Surface Runoff kg/ha/yr	0.71	0.76 (7.0 %)	0.83 (15.9 %)	0.89 (21.4 %)

The analyses show that N yield in surface water will increase by 3.6% in 2020, by 17.4% and 29.7% in 2025 and 2030 respectively in the Waipara catchment. Phosphorus (P) yield is estimated to increase by 2.5%, 6.3% and 9.4% respectively for years 2020, 2025 and 2030. Sediment yield is also predicted to increase by 7.0%, 15.9 % and 21.4% in 2020, 2025 and 2030 respectively.

6.7 Implications of Nutrients and Sediment Yield for Water Quality

In the same way fertiliser application to crop lands enables plant growth, nutrient enrichment of water bodies supports the development of lower plant communities and other micro organisms in the water (Minnesota Pollution Control Agency – MPCA, 2008). Given the observed increasing trends in nutrient yields in the Waipara catchment, the river water may become vulnerable to eutrophication under this scenario. Although nutrient supply to streams or lakes is essential to sustain the health of the aquatic ecosystem, over enrichment could lead to increased aquatic plant populations especially algal growth and potentially (cyanobacteria) that may be detrimental (Ministry of Primary Industries – MPI, 2018). Increased growth and decomposition of algae blooms could decrease dissolved oxygen in water and can cause breathing problems to fish and other life forms in the Waipara River (MPCA, 2008; US EPA, 2017, MPI, 2018). Certain species of algae (blue-green) can affect the water with toxins that are hazardous to human and animal health when ingested (MPI, 2018). Reduction in the quality of river, stream or lake water could create several detrimental effects. MPCA (2008) reported a proliferation of less desirable fish (e.g. carp and bullhead) in lakes for angling due to pollution. Excessive algal blooms could create foul odour in water bodies and thereby decrease the aesthetics of the water. Decomposition of dead algae and under water plant species reduces available oxygen in water thereby starving other living organisms of oxygen and killing them (MPCA, 2008, MPI, 2018). Consequently, the utility of the water body for fishing, recreation and tourism may be lost. There have been health warnings of the dangers of benthic cyanobacteria discovered in parts of the Waipara River by the Hurunui District Council (HDC, 2013). About 14% of the riverbed near Stringers Bridge was once said to have been affected by the potentially toxic algae, Phormidium. A recent report (HDC, 2017) confirmed that the danger had been averted as Phormidium is no longer present in the Waipara River. However, the increasing trend in future N, P and sediment yield in surface water in the Waipara catchment under this land use change scenario shows that the chances of reoccurrence of the toxic algae should not be ruled out.

Perhaps economic pressures may be driving a desire for more dairy in the catchment in future, which is likely to be affected by the availability of water supply. The next section evaluates the possibilities of the Waipara catchment water supply capability in sustaining an increase in dairying.

6.8 Water Demand for Dairy Farming

An inadequate and unreliable source of water supply for dairy pasture irrigation, animal consumption and cleaning will limit the possibility of increasing dairy farming in the Waipara catchment. MAF (2011) also made a similar assertion about the Canterbury Plains' inability to fully utilise the potential irrigable land areas due to insufficient available water resources. This section therefore attempts to estimate the water demand for the projected increasing dairy land use.

The study adopted 5,950m^3/ha/year of water use for irrigation (at 80% and >50% rate of irrigation efficiency and plant available water) (Aqualinc, 2015) for the computation. Also, 140 and 70 liters per cow per day water for consumption and cleaning respectively (MPI 2017); 3.47 cows per hectare stocking rate (New Zealand Dairy Statistics, 2015-16), 7,343.4-hectare dairy land area for year 2016 (Table 12) and 108,559,571.2m^3 water yield for Waipara catchment in 2016 (SWAT model water yield) were used in estimating water demand for dairy farms for the base year (2016). Projections were then made into years 2020, 2025 and 2030 (Table 12). It is assumed that under all climate change scenarios, the catchment water yield capacity may not change significantly for 2020, 2025 and 2030 as these periods fall within the same climate change period 2016 - 2050. This assumption is consistent with the reports of Cubasch et al. (2013), and Moss et al. (2010) which indicate that summer months will witness some increases in mean precipitation under RCP 6.0 conditions. A potential increase in precipitation is also feasible in spring under RCP 4.5 conditions over the period 2016 to 2050.

Table 12 Projected dairy water demand for Waipara River catchment: 2020 – 2030.

Year	Irrigation water use/ m^3/ha/yr	Water consumption/l/cow/day	Water for cleaning/l/cow/day	WaiparaCatchment dairy land area/ha	Stocking rate/ha	Total irrigation water/m^3 = (irrigation water use x dairy land area)	Total number of cows = (stocking rate x dairy land area)	Rate of land use change/%	WaiparaCatchment wateryield/m^3	Total water consumption & cleaning /m^3/yr =((consumption + cleaning) x total number of cows x365)	Total dairy water demand/m^3= ((irrigation water + consumption & cleaningwater)(% land use change)	Catchment water balance/ m^3= (Catchment water yield - Total dairy water demand)
2016	**5,950**	**140**	**70**	**7343.4**	**3.47**	**43,693,230**	**25482**	**-**	**108559571.2**	**1953195.3**	**63225183**	**45334388.2**
2020	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**1.8**	**-**	**-**	**113805329.4**	**-50245758.2**
2025	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**2.3**	**-**	**-**	**145417920.9**	**-36858349.7**
2030	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**3.0**	**-**	**-**	**189675549**	**-81115977.8**

The results indicate that demand for dairy water use in the area would approximately double for this scenario, from the current level of 63.2 million cubic meters in 2016 to 113.8 million cubic meters in 2020, 145.4 million cubic meters by 2025 and 189.7 million cubic meters in 2030. The rise in the demand for water in the catchment is influenced by dairy pastures irrigation, consumption and cleaning needs (considering the rate of dairy land use change). There are, however, other land use activities within the catchment that require the use of water that are not considered in this analysis. The study also recognises the implications of climate change as well as other possible factors that may influence the baseline conditions (2016 conditions - eg. dairy land area, number of cows, water yield) upon which the projections were based. Looking at the water balance values (column 13 of Table 12) however, the catchment will be grossly in water deficit, confirming NZIER (2014) and Morgan et al. (2002).

To match up water demand for the projected increase in dairy land use as well as other activities, importation of water from external sources is necessary. The planned Hurunui Water Project (HWP) is designed to deliver water to the Waipara catchment through pipes from the Hurunui River catchment. The current design flows in the pipes are 3 m^3/s (approx. 87,091,200m^3/yr) coming into the Waipara catchment via the Omihi, and 1 m^3/s (approx. 29,030400m^3/yr) into the Upper Waipara – these are indicative until uptake is confirmed (Robb, C. -Personal comm. 2017). The total deliverable water supply from the HWP is about 116,121,600m^3/yr which is barely sufficient to meet the demand for year 2020. In year 2025 and 2030, other measures would be required to meet the demand.

6.9 Conclusion

Modeling the spatio-temporal dynamics of land use for the Waipara catchment represents an alternative for monitoring/ management of ecosystems. The satellite images classified depicted high levels of accuracy as supported by the Kappa index, in relation to ground reference data. The positive and negative changes witnessed in land use area in the catchment could be attributed to both national and global economic policies and forces of demand and supply for land use products. The initial increase in forest land cover could possibly be as a result of the earlier increased carbon pricing which made forestry very lucrative (EBEX21, 2011). Decrease in scrub land area in the catchment could be due to the growing viticulture practices (cultivation of grapes/vineyards) in the area (Cooper, 2008). The drop in sheep farm land area could be as a result of the withdrawal of government subsidy for sheep farming in late 1980s (Stringleman and Peden, 2013) as the dairy industry overshadowed it. The increasing viticulture which is an economic driver particularly in the Waipara catchment could as well be responsible for the decrease in sheep farmlands. The positive gain in beef farm areas over the early periods (2000 to 2016) could be because of increasing domestic as well as international demand for beef, resulting from recent *bilateral, plurilateral and multilateral trade negotiations with other countries* that improved export earnings from New Zealand beef (Beef and Lamb NZ, 2015; 2016). The combined sheep and beef farm lands however experienced a decline after an initial increment possibly because of the drastic decrease in sheep numbers, giving rise to increase in beef land use. In a similar vein, the increasing price *(*Beef and Lamb NZ, 2018) for New Zealand dairy products could possibly explain the positive change witnessed in dairy land use in the area.

Even though dairy is one of the land use activities occupying the smallest area of the catchment, it presents the biggest current threat to water quality, given its steady growth rate and the general belief that dairy land use is among the worse environmental polluting activities in New Zealand (Perrie, 2007; Hughey et al., 2008; McDowell and Wilcock, 2008). The land uses of the catchment projected for 2020, 2025 and 2030 also followed the same pattern when compared to the period 2000, 2013 and 2016. The general increasing trend in pollutant yield for the predicted land uses for the periods together pose a great concern for water quality. The realities of the predictions are however predicated upon the prevailing socio-economic and the political circumstances of the times.

Chapter 7

CLIMATE CHANGE IMPACTS ON WATER RESOURCE

7.1 Introduction

In the previous chapter, analysis of future land use change and nutrient yield in the Waipara River catchment was undertaken, and the consequent impacts on water resources were established. This chapter focuses on assessing the implications of climate change for water resource availability and quality to meet objective five of the thesis. The chapter overviews climate change in section 7.2. Section 7.3 presents a discussion of the methods adopted in assessing the effect of future climate change on water resources in Waipara River catchment. Discussion of the climate change scenario and impacts on water resources are presented in section 7.4. Section 7.5 examines the implications of climate change for nutrient yield under four different land use scenariosfollowed by the concluding remarks in section 7.6.

In analysing the trend in climate change, the entire climate change period 2016 to 2099 is considered, but in estimating the impact of climate change on water quality and quantity, 2016 to 2050 climate scenario is used. The reason for this is that the future state of the Waipara catchment land use could only be predicted (with some degree of certainty) up to year 2030 which falls within the climate change period 2016 to 2050.

7.2 Overview of Climate Change

Water is a fundamental resource for life and for agriculture development which is one of the principal sectors that drives New Zealand's economy. Like many countries, the water resources of New Zealand are unequally distributed across the country (Collins et al*.,* 2012). In the Waipara catchment, the mountains create greater variability in the climatic conditions than in most other parts of New Zealand, characterised by low rainfall and high range of temperatures, making it one of the country's driest regions (Wilson, 2015). Under such dry conditions, future climate change could have great negative consequences for water resource availability, as climatic variability drives fluctuations in the abundance and quality of water resources. Knowing how future climate will affect water availability in a drier environment should be of great assistance to water users and water managers.

Worldwide, it is recognised that the climate is changing both globally and regionally. These changes are the consequences of increasing greenhouse gas concentrations in the atmosphere (Ministry for the Environment (MfE), 2016a). Since the 1950s, atmospheric carbon dioxide levels have been rising. This increase may result in significant changes to both global and local climatic elements such as temperature and precipitation, thereby impacting usable water resources (Yu et al., 2002).

In the Canterbury Region, according to a report on climate change projections for New Zealand (MfE, 2016a), temperatures could be 0.7˚C to 1.0˚C warmer by 2040 and 0.7˚C to 3.0˚C warmer by 2090. A decrease in rainfall of about 12% is anticipated in Christchurch and about 10% in Hanmer for winter by 2090 is likely (MfE, 2016b). The report indicates that global warming will clearly affect water resources in the future. If the prevailing climatic conditions continue in the same direction, the effect of rising temperature on water resource availability will become a concerned issue.

A common approach to estimating global warming is to apply a general circulation model (GCM) that seeks to forecast the effect of rising atmospheric carbon concentration on climatic elements. GCM results are generally at a very coarse scale, ranging between 100 – 200km and so do not effectively represent variability in local topography which influences climatic processes (e.g. rainfall pattern and temperature) at local/regional levels. It therefore cannot be used directly for climate impact analyses at high levels of accuracy, especially in terrestrial environments (McMillan, et al., 2010). Thus, to assess the potential effects of future climate change on water resources at a local scale, it is recommended that predictions from GCMs be downscaled to spatial scales appropriate for the physical processes taking place in the hydrological cycle at the local levels. To do so, a regional climate model (RCM) has to be used. The scale of the RCM is more appropriate to regional/local climates and so can represent them better in directly simulating any climatic process of interest (Durman et al., 2001).

Several approaches have been employed in investigating impacts of climate change on water resources. For example, Burn (1994) studied the effects of climate change on timing of spring runoff events using a non-parametric statistical test in west-central Canada. Mansell (1997) investigated how trends in rainfall and flood risks are affected by climate change in western Scotland employing graphical and statistical techniques. Fowler (1999) adopted a climate change scenarios approach to analyse potential impacts of climate change on water resources in Auckland Region of New Zealand. In addition, Fowler (1999) employed a daily water balance model to assess the effects of change in seasons on soil moisture level and catchment water yield. A popular technique is to use simulated primary weather parameters (temperature and precipitation) from a GCM for the current and doubled atmospheric CO_2 levels and use the mean monthly or annual variations to change the historical weather records by a fixed amount, which then becomes input data for hydrologic models (e.g. Gleick, 1989; Mearns et al., 1990; Kjellstrom et al., 2016). This method may however underestimate the inherent variability in daily weather conditions in the future climate (Yu et al., 2002).

In the present study, NIWA's Regional Climate Model (RCM) future climate data series (temperature and precipitation) generated at a daily time scale for the Waipara catchment were used in calibrating and validating the SWAT model. An evaluation of the impact of future climate change on the water balance component of the Waipara River catchment hydrology was implemented. The Waipara River catchment SWAT model was then used to simulate the implications of future climate change prediction on surface and groundwater resources. This was done in order to quantify the impact of climate change on surface flow for the catchment, and also how climate change affects nitrogen (N) and phosphorus (P) yield as set out in objective five of this study.

7.3 Methods

In order to evaluate the effect of future climate change on water resources, the future climate data were first generated for the catchment from NIWA's Regional Climate Model (RCM) output/data for New Zealand. Table 13 shows the periods of RCM simulations from 2006 to 2100. The RCM (30 km grid scale) outputs were bias corrected and dynamically downscaled to 0.05° latitude - longitude boxes against observed gridded data from the virtual climate station network (VCSN) (Sood, 2014; Tait et al. 2016). Dynamical downscaling is a process of deriving local climate information (at the 5 kilometre grid-scale - VCSN) from larger-scale model or observational data. These future climate data were simulated considering the Representative Concentration Pathways (RCPs): RCP4.5, RCP6.0, and RCP8.5 from the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (IPCC, 2013a, 2013b) for New Zealand.

Table 13 Periods of the regional climate model (RCM) simulations, for each of the six CMIP5 models and pathways.

Model names (Rank) Institute (Country)	**Historical**	**RCP4.5**	**RCP6.0**	**RCP8.5**
HadGEM2-ES (2) MOHC (UK)	1971–2005	2006–2100	2006–2099	2006–2100
CESM1-CAM5 (1)	1971–2005	2006–2100	2006–2100	2006–2100

NSF-DOE-NCAR (USA)				
GISS-E2-R (14) NASA-GISS (USA)	1971–2005	2006–2100	2006–2100	2006–2100
BCC-CSM1.1 (17) BCC (China)	1971–2005	2006–2100	2006–2099	2006–2100
Average data	**1971-2005**	**2006-2100**	**2006-2099**	**2006-2100**

Source: Adapted from Ministry for the Environment (2016).

The RCPs are climate change scenarios describing four (RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5) possible scenarios in future greenhouse gas (GHG) emissions and concentrations in the atmosphere engendered by anthropogenic activities. RCP 2.6 presupposes that global annual GHG emissions and CO_2concentrationswill reach the highest point in 2010–2020, and then decline significantly.Emissions under RCP 4.5 will reach a climax by the year 2040 and then drop down thereafter. With regards to RCP 6.0, GHG emissions will reach a peak around 2080, and then start declining. Under RCP 8.5conditions, greenhouse gas emissions will increase throughout the 21st century (Meinshausen et al., 2011). The four representative pathways have been identified in describing different possible future climates, depending on the amount of greenhouse gases released into the atmosphere. The RCPs are named based on the possible range of radiative forcing amounts in the year 2100 in relation to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m^2, respectively) (Moss et al, 2008; Weyant et al., 2009).

The conceptualisation of the four RCPs is in accordance with certain socio-economic suppositions or models (*Ward et al., 2012*). RCP4.5 and RCP6.0 constitute two atmospheric carbon concentration stabilisation pathways while RCP 8.5 is basically 'business as usual' with very high carbon concentrations by the year 2100 and beyond.

The four best GCMs have been selected for dynamic downscaling. These four models were selected from among the AR5 models, based on their overall ranking (1=best) on 63 models' validation metrics over the historical period as derived by Mullan et al. (2013a, 2013b). The validation of their local 'climate sensitivity' was based on raw global climate model air temperature changes for each RCP (MfE, 2016a). Table 14presents an overall ranking of the selected models and their local 'climate sensitivity' based on raw global climate model air temperature changes (in degrees Celsius), for each considered RCP.The models ranked at 1, 2, 14, 17 were selected because of how well they represent the 'current' climate (Mullan et al, 2013a, 2013b).

Table 14 Overall ranking of the selected models and their local 'climate sensitivity' based on raw global climate model air temperature changes (in degrees Celsius).

Model Name	Ranking	Warming Signal		
		RCP4.5	RCP6.0	RCP8.5
CESM1-CAM 5	1	2.01	2.38	3.41
HadGEM2-ES	2	1.91	2.52	3.52
GISS-E2-R	14	0.99	1.62	2.36
BCC-CSM1.1	17	0.95	1.36	2.40
Ensemble-average warming		1.465	1.97	2.92

Source: Adapted from Ministry for the Environment (2016).

In order to carry out the assessment of climatic impact, the mean bias at each grid point between VCSN observations and the model(NIWA'sRCM) simulation was calculated over the baseline period 1986 – 2005, and then subtracted from the time series (past and future) model data to enable further adjustment for temperature and precipitation data. The period 1986 to 2005 was used as the baseline because New Zealand land-average temperatures increase, in degrees, relative to 1986—2005 conditions for the three future emissions scenarios (RCP 4.5, RCP 6.0 and RCP 8.5). The assumption is that the model climatology would be similar to the VCSN observations as climate impact models utilise the RCM daily data, although with some differences in year-to-year variability (MfE, 2016a).

Dynamic downscaling was applied to temperature and precipitation projections from the four best models. The historical data with the three considered RCPs generated from the four models were averaged to produce one-time series dataset which was used in assessing climate change impact on water resources in the Waipara catchment. These data were introduced into the calibrated and validated SWAT model for the catchment to assess climate change impact on water resources.

7.4 Discussion of Climate Change Scenario and Impacts on Water Resources

Trends in changes in projected temperature are found to increase with time and RCP linked with the strength of their radiative forcing (MfE, 2016a). Generally, the summer seasons of the periods under study (2016–2050 and 2065–2099) indicated the largest warming with winter and spring showing the least.The analyses showed that the extent of increase in temperature between 2016 and 2050 (relative to the historical period 1971–2005 (Table 13), based on NIWA's RCM output for 1986-2005) ranges approximately between +0.6°C and +1.0°C, while warming in atmospheric temperature in the period 2065–2099 will approximate +1.2°C to +3.3°C (see Figures 32 and 33).In terms of the radiative forcing of the three RCPs during the projected period 2016 – 2050, mean seasonal temperature warming under RCP 4.5 for summer, autumn, winter and spring are 0.8°C, 0.8°C, 1.0°C and 0.7°C respectively (Figure 32). Mean annual atmospheric temperature is estimated to be <1.0°C for the catchment.

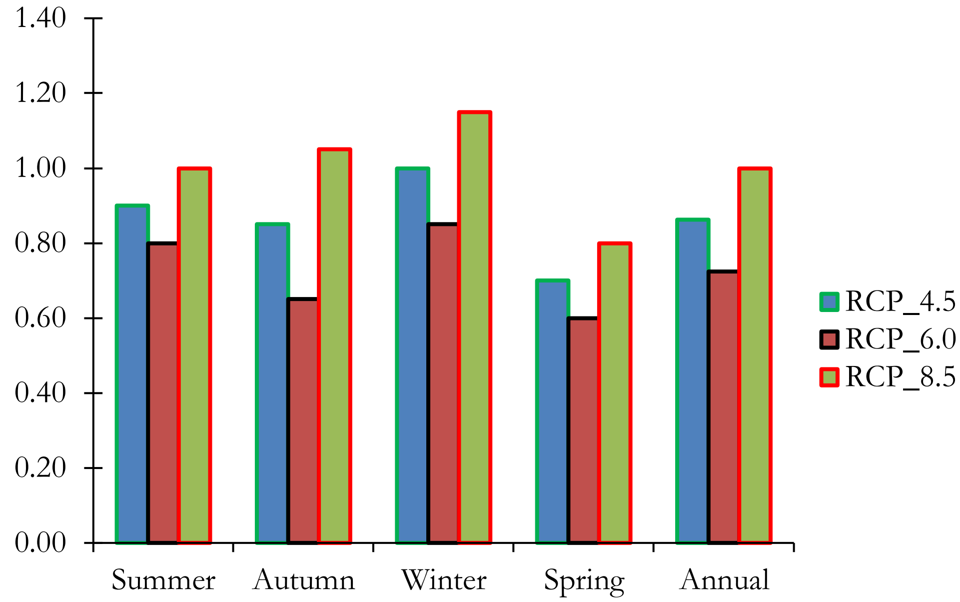


Figure 32 Projected changes in seasonal and annual mean temperature (°C) between 1971–2005 and 2016–2050, in the Waipara catchment

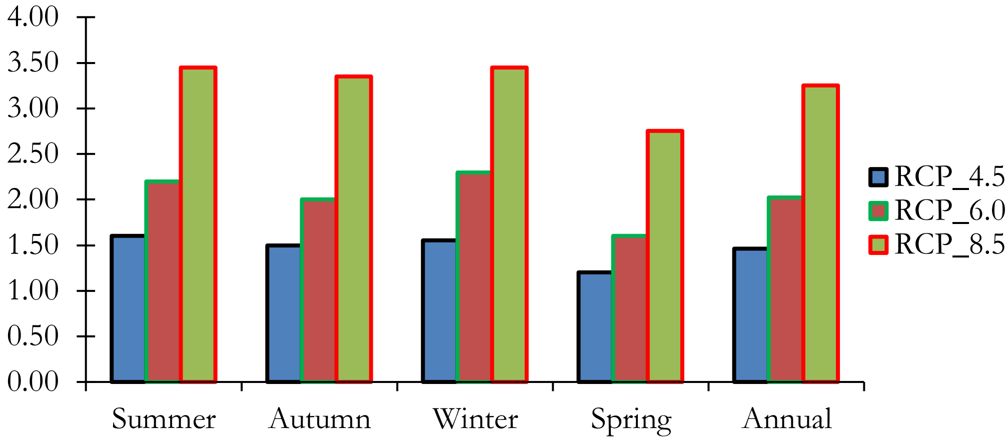


Figure 33 Projected changes in seasonal and annual mean temperature (°C) between 1971–2005 and 2065–2099, in the Waipara catchment.

The analyses also show systematic seasonal and annual changes in precipitation over the same time periods in the catchment. Figure 34 revealed that large reductions in precipitation are expected during winter (under RCP 8.5) by 2050. Summer months would witness some increases in mean precipitation under RCP 6.0 conditions, even at an annual scale. An increase in precipitation is also feasible in spring under RCP 4.5 conditions (that is when BMPs are vigorously pursued to control further greenhouse gas emissions) (Cubasch et al. 2013; Moss et al. 2010).

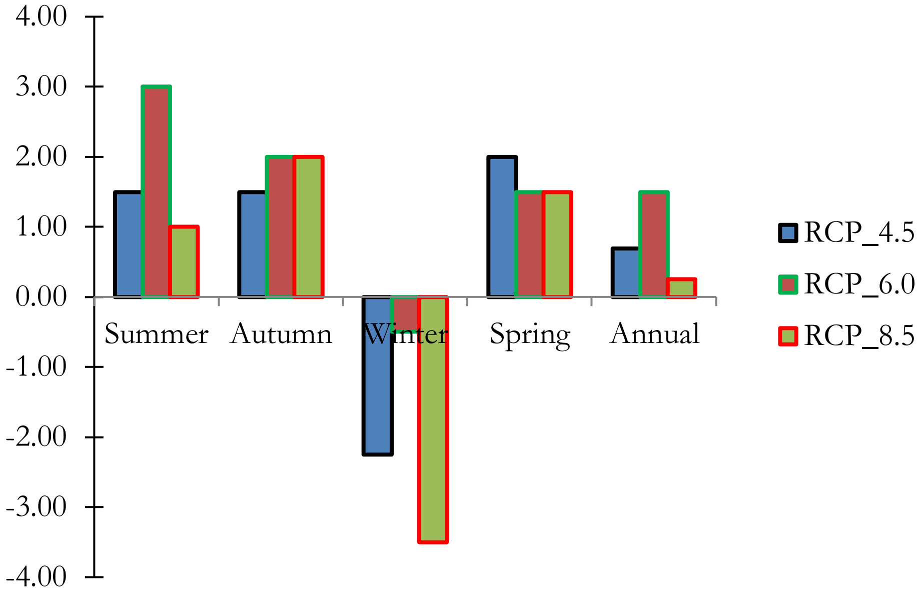


Figure 34 Projected percentage changes in seasonal and annual precipitation between 1971–2005 and 2016–2050, in the Waipara catchment.

In the longer term (2099) however, an increase in mean precipitation is projected to occur in summer under RCP 8.5 conditions and also with some slight increases in autumn and spring under the three RCP conditions. Precipitation in the winter months is however expected to decrease over the catchment (Figure 35).

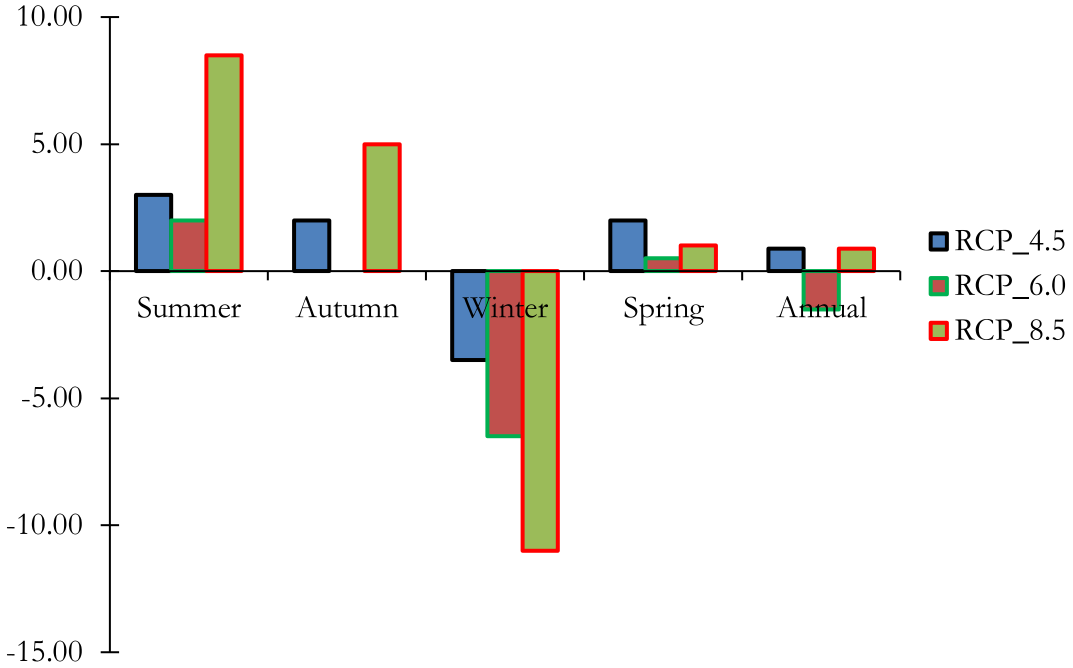


Figure 35 Percentage changes in seasonal and annual precipitation between 1971–2005 and 2065–2099, in the Waipara catchment.

In the foregoing, an analysis of the climate over the entire periods 1971 – 2099 was undertaken. To analyse the trend in climate change however, the climate change period from 2016 to 2099 wass considered. To analyse the impacts of climate change on water quality and quantity, the 2016 – 2050 climate scenario is considered. The reason for this is that determination or prediction of the state of the Waipara River catchment land use was only possible (with some degree of certainty) up to year 2030 which falls within the period 2016 - 2050.

7.4.1 Surface Flow

Using the 2030 catchment land use map generated by MCA as input, the SWAT model output showed that a decrease in surface flow is expected over winter within the study period (2039–2050). Some slight increases are expected in summer, autumn and spring. The projection also shows that variability is related to the strength of the radiative forcing, similar to the observed changes in climatic parameters, with the highest percentage change being associated with the highest RCP (Figure 36).

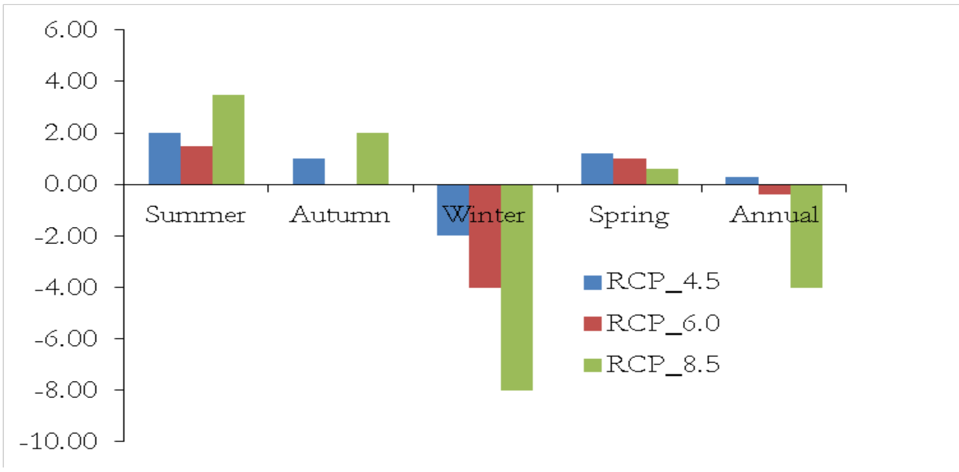


Figure 36 Projected percentage changes in seasonal and annual mean surface flow between 2001–2012 and 2039–2050, in the Waipara catchment.

7.4.2 Groundwater

In winter months, given the worst case scenario of highest atmospheric CO2concentrations (RCP8.5), groundwater levels will reduce by about 4%, while the reduction will be about 1.6% and 0.5% respectively for RCP 6.0 and RCP 4.5 (see Figure 37). An increase in groundwater level of about 2.5% in spring is expected under RCP 4.5. The summer months are also expected to experience an increase of about 1.7% in groundwater level under RCP 8.5 during the period 2039 – 2050.

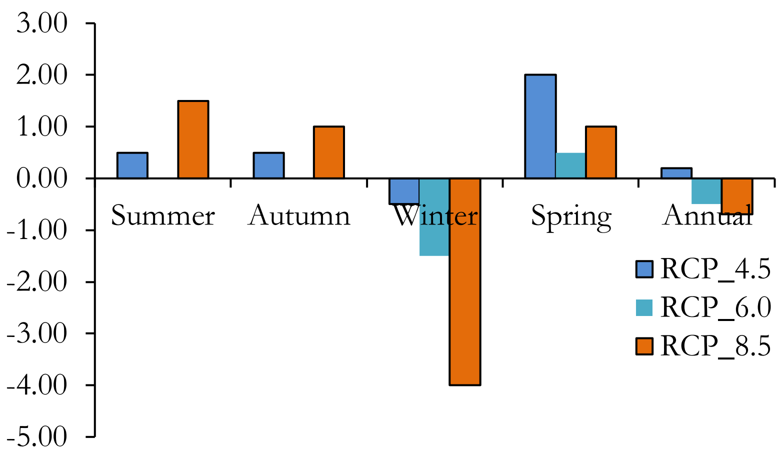


Figure 37 Projected percentage changes in seasonal and annual mean groundwater recharge between 2001–2012 and 2039–2050, in the Waipara catchment.

7.5 Implications of Climate Change for Nutrient Yield Under Different Land Use Scenario

This section addresses the potential impacts of climate change on nutrient (N and P) yield in the Waipara catchment under several land use change scenarios. Climate change is known to be linked to land use change which could either worsen (Molina-Navarro et al., 2014) or reduce (Fan and Shibata, 2015; Jin et al., 2015) the discharge and availability of nutrients in the environment. The effects of land use change on water quality are associated with hydrological processes including evapotranspiration, surface runoff, groundwater recharge and erosion processes (Nunes et al., 2013; Molina-Navarro et al., 2014; Fan and Shibata, 2015; Heo et al., 2015). El-Khoury et al. (2015), Jin et al. (2015) and Serpa et al. (2017) suggested that investigations regarding future water quality should consider the interelationships existing between land use and climate change impacts.

The problem of water pollution by agricultural activities is also known to increase with the intensity of rainfall events, due to an increase in surface runoff, erosion, mobilisation and export of agrochemicals to aquatic ecosystems (Rodrigo et al., 2016; Lefrancq et al., 2014). Alterations in rainfall pattern or regimes associated with change in climatic conditions can potentially affect the processes controlling the fate and movement of nutrients, herbicides and pesticides in an agriculturally dominated catchment (USEPA 2016; Ficklin et al., 2013).

The vulnerability of the Waipara catchment to climate change, resulting in a decrease in annual rainfall and a rise in average annual temperatures has been established in this chapter. The previous chapter presented analyses of current trends in land use change and nutrients (N and P) yield. An analysis of climate change impact on nutrient yield under potentially varying land use change conditions in the catchment is presented here. Four possible land use change scenarioswerecreated which include land use change scenario1 (LU_Scen1 = sheep & beef to forest). This refers to changing all sheep and beef farms to forests. Land use change scenario2 (LU_Scen2 = beef & dairy to forest) involves converting beef and dairy land to forests. Land use change scenario3 (LU_Scen3 = beef & dairy to vineyards) implies replacing all beef and dairy lands of the catchment with vineyards. Land use change scenario4 (LU_Scen4 = sheep &beef to vineyards) entails converting all sheep and beef lands to vineyards. The percentage coverage of each of the landuse categories is presented in table 10.

The development of the climate change scenario is based on the mean outputs of the two selected GCMs (CESM1-CAM5 and HadGEM2-ES) driven by the two atmospheric carbon concentration stabilisation pathways - RCP 4.5 and RCP 6.0 (Kovats et al., 2014; Serpa et al., 2017). The two GCMs were chosen for the climate change and land use change scenario analyses because they are the best ranked (first and second) among the four selectedGCMs that well represented the New Zealand future climate.The same storylines as for the climate change scenario were followed in developing the land use change scenarios with RCP 4.5 and RCP 6.0 (i.e focusing on environmental conservation and economic development) (IPCC 2013a, 2013b, 2018).The simulated future climate data (temperature and precipitation) of the two RCPs were employed in the Waipara catchment SWAT model. Additionally, reclassification of the land use data to reflect the different scenario configurations was carried out to allow for the evaluation of the land use change impacts on nutrient yield.

7.5.1 Land Use Change Impacts on N, P Yield Under RCP 4.5, RCP 6.0

The impact of land use change on nutrient yield in the Waipara catchment is found to be influenced by the two climatic conditions (RCP 4.5 and RCP 6.0). We assumed that New Zealand's level/stage of emission discharge/management and implementation are far beyond the RCP 8.5 condition - which is "business as usual" (without caution). New Zealand is committed to transparent and accurate annual reporting on the national greenhouse gas inventory as a developed country Party to the UNFCCC. New Zealand's gross greenhouse gases emissions in 2015 were 80.2 million tonnes of carbon dioxide equivalent (Mt CO2-e). This comprises emissions from the energy (including transport), agriculture, industrial processes and product use, and waste sectors. New Zealand is probably at RCP 6.0/4.5 scenario levels, and so RCP 8.5 scenario analysis was not undertaken. In total, the impact of New Zealand's policies and measures were estimated to reduce gross emissions by 6.2 Mt CO2-e between 1990 and 2015 and by 41.8 Mt CO2-e from 2016–30 (MfE, 2017). In figure 38, the error bars show that the percentage change in annual nitrogen (N) yield from all four land use change scenarios exhibited great reductions under climate change scenario RCP 4.5.

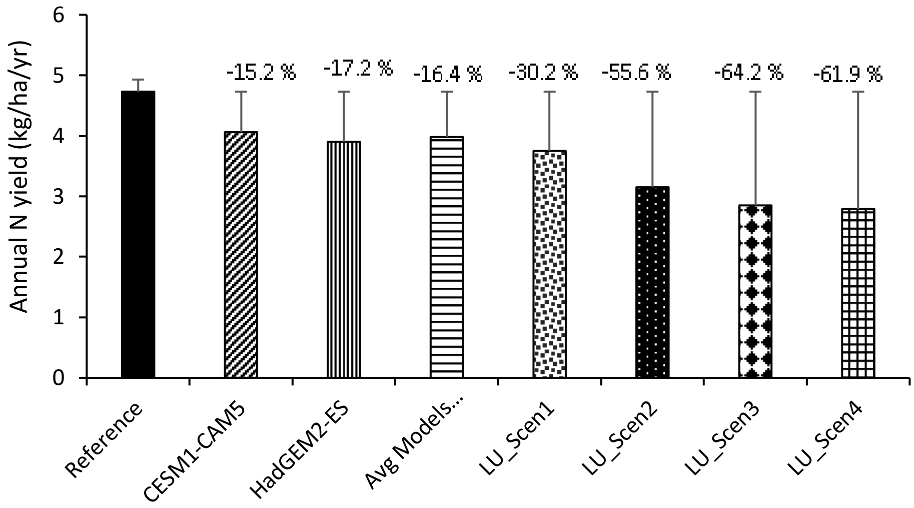


Figure 38 Percentage of Nitrogen variation under different land use scenarios applying climate scenario RCP 4.5.

The analysis shows that by changing all sheep and beef farms to forests (LU Scen1) in the catchment under climate change scenario RCP 4.5 conditions, annual N export will decrease by 30.2%. Converting beef and dairy land to forests (LU_Scen2); beef and dairy to vineyards (LU_Scen3); and, sheep and beef farms to vineyards (LU_Scen4), nitrogen yield will reduce by 55.6%, 64.2% and 61.9% respectively. The variation in the degree of impact from all four land use change scenarios on nitrogen yield could probably be explained by either the size of each land use cover of the catchment, level of agrochemical demand of each land use, and or other physical characteristics. Most grassland in the catchment, especially dairy land, receives nitrogen inputs through fertiliser application and animal droppings which are probably not taken up completely but leach out to contaminate water resources. These findings are in agreement with the reports of Mehdi et al. (2015a) and Serpa et al. (2017) which state that changing from cultivation of crops that rely heavily on agrochemicals can create positive impacts on water quality. Considering RCP 6.0, the percentage of annual nitrogen export under different land use change scenarios (Figure 39) also decreased but not as much as that of RCP 4.5.

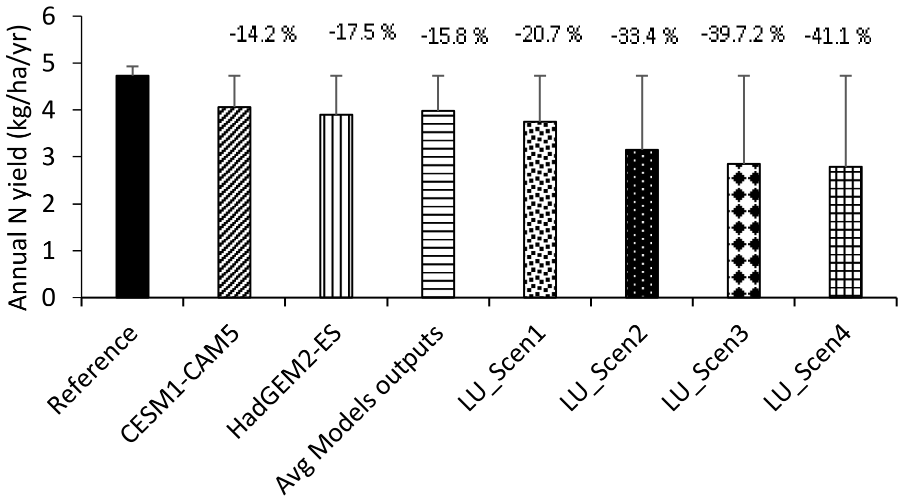


Figure 39 Percentage of Nitrogen variation under different land use scenarios applying climate scenario RCP 6.0.

The rate of reduction in annual N yield under the two climate scenarios could probably be associated with the variability in the amount of annual precipitation and temperature under the two climatic conditions. Climate can have a direct impact on water export by regulating catchment water yield/flow (Mengsitu et al., 2013), and thereby affecting the rate of export of soluble nutrients. This potentially explains the reason for the reduced rate in the impacts changes in land use made on N yield reduction under RCP 6.0 compared to RCP 4.5. This result corresponds with the findings of Wagena et al. (2018) which show that climate change, in the form of increased precipitation, can increase winter or spring flow substantially, leading to an increase in the export of soluble nutrients and sediments. On the contrary, reduction in summer flow as a result of increasing summer temperatures and greater evapotranspiration will affect export of dissolved nutrients and sediment. This implies that because there is a lesser amount of (annual) precipitation under RCP 6.0 to enable high runoff rate that can potentially demobilise and export nutrients, the effect any of the land use change scenarios could have on reducing contaminant export is also reduced. Similarly, phosphorus (P) export to surface water in the Waipara catchment is also influenced by change in climatic conditions under the various land use change scenarios. The analysis (Figure 40) reveals that under RCP 4.5 conditions, the four land use change scenarios decreased P export by 45%, 47%, 51% and 52% respectively.

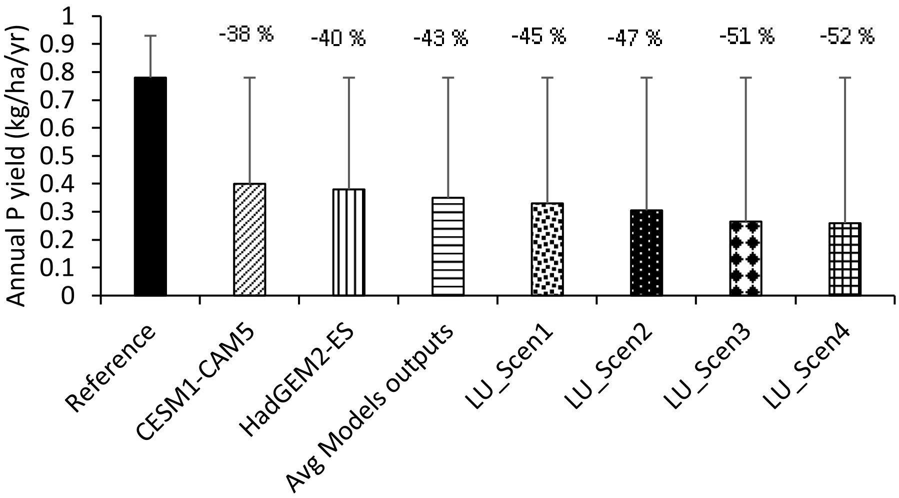


Figure 40 Percentage of Phosphorus variation under different land use scenarios applying climate scenario RCP 4.5.

Given the RCP 6.0 climate parameters, the impact of land use change scenarios on P yield runs very closely to that of RCP 4.5 conditions. Figure 41 shows that when all sheep and beef farms, and beef and dairy lands are converted to forest lands (LU_ Scen1 and LU_Scen2), P export decreases by 40% and 46% respectively. However, when these land use types are converted to vineyards (LU_Scen3 and LU_Scen4), P yield reduces by 49% and 50% respectively.

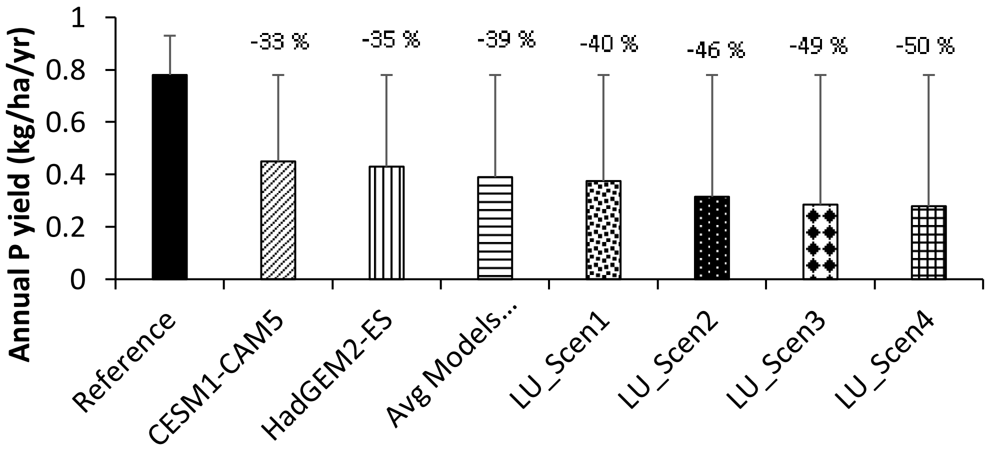


Figure 41 Percentage of Phosphorus variation under different land use scenarios applying climate scenario RCP 6.0.

Similar to the case of N, the influence of climatic change on P reduction under various land use change scenarios is conspicuous. The results show that under RCP 4.5, with relatively higher annual precipitation, a possible increase in surface runoff would enhance erosion and transport of sediment. Sediments are the preferential pathways for phosphorus export (Molina-Navarro et al., 2014). Converting grazing lands to forests under such climatic condition would therefore cause a decrease in rate of erosion and sediment yield; cosequently reducing export of P. Serpa et al. (2015; 2017) made a similar observation that TP export decreases proportionately to decrease in sediment export.

RCP 6.0 predictions of drier conditions would not support high rates of surface runoff, erosion and transport of sediments. As a result, land use change impact on P export is found to be less than the RCP 4.5 scenario. The observed effects of land use change in reducing P export could be attributed to the fact that perennial crops such as grapevines, unlike grasses, have greater ability to store phosphorus in their stems, bark and roots to support growth at their stages of high P demand (Skinner and Mathews, 1989; Martins et al., 2012). As a result of converting grasslands to vineyards/perennial crops, the rate of P export to water bodies is thereby inhibited.

7.6 Conclusion

This chapter explored potential future climate change scenarios and the implications for water resources in the Waipara catchment. The future climate data from NIWA's Regional Climate Model (RCM) output for New Zealand were generated for the catchment. Analyses of the data (temperature and precipitation) showed notable changes. Increasing trends in temperature overlong-term periods were projected to occur across seasons and in keeping with the strength of the radiative forcing (RCPs).

A decrease in mean precipitation is also projected to have a substantial effect on the catchment with increasing forcing (RCP) and according to variation in seasons. The winter season was predicted to have reduced rainfall while rainfall in summer is projected to increase slightly over the catchment under the three RCPs. Little change in annual precipitation occurs under the various RCPs with RCP 4.5 and 8.5 showing very small positive change. Furthermore, the time-series temperature and precipitation data generated for the future climatic conditions for the catchment were used as inputs to the Waipara catchment SWAT model to investigate changes in surface and groundwater resources. The model output showed that great reduction in surface flow can be expected in winter. Slight increases are expected in summer, autumn and spring. The variability is also found to be related to the strength of the radiative forcing with the highest percentage change being associated with the highest RCP.

Observable changes in groundwater resources exhibit a similar pattern with the greatest reduction found during winter and decreases with the increasing strength of the RCP. Slight increases in groundwater resources were also projected for summer, autumn and spring. The results of the scenarios suggest that as the winter season is predicted to experience reduction in rainfall, greater evaporation and evapotranspiration among other things are expected, leading to a negative change in groundwater reserves. Indeed, the projected warming of the atmospheric temperature as well as variability in precipitation for the periods under study pose a great concern for water resources availability in the Waipara River catchment.

In addition, four land use change scenarios under two climatic conditions were analysed to assess their impacts on total nitrogen and total phosphorus export. In all four scenarios, changing from predominantly sheep and beef, beef and dairy farming to forestry and viticulture (vineyards) had notable impacts in decreasing N and P yield to the environment. The findings of this study therefore suggests that N and P load reduction in the Waipara catchment is strongly associated with the type of land use, its extent and the climatic conditions (Mehdi et al., 2015b; Serpa et al., 2017). The current New Zealand Government plans to plant one billion trees over 10 years (between 2018 and 2027), and the Ministry of Primary Industries is taking a lead to achieve the goals. The main purpose of the plan is for diversifying national income, investing in the future, improving land productivity, and tackling environmental issues such as erosion. Other benefits include reducing the effects of climate change, improving water quality, moderating river flows, providing important habitats for a range of native species, enhancing natural landscapes, and to create jobs. The results of this study therefore also indicated that the Government policy proposal, when implemented, could significantly reduce water pollution problems in agricultural dominated catchments. The findings of the study could therefore be of significant importance in charting a course or drawing a road map for the implementation of the 1 billion tree planting proposal within this catchment.

Chapter 8

CONCLUSIONS AND RECOMMENDATIONS

8.1 Introduction

The primary aim of this thesis was to identify a useable modeling approach for the assessment of the impact of land use and climate change on water quality and quantity in the Waipara River catchment, New Zealand. The degradation of water quality is perceived as the largest and most threatening environmental issue in New Zealand (Hughey et al., 2011), as it is continuously being aggravated by land use activities, particularly intensive pastoral land use (Davies-Colley, 2013; Parliamentary Commissioner for the Environment, 2013). The general increase in awareness about the cause of the problem has formed the basis upon which all stakeholders (e.g. the pastoral industry, environmental research community, resource managers/planners, policy makers and the general public) are striving to improve the quality of the environment (Gluckman, 2017). It is, however, a difficult task to controlpollution from diffuse sources such as from pastoral land use (Davies-Colley, 2013). It is even harder where detrimental land use and climate change are at play and interlinked. Gluckman, (2017) suggestedthat the decline in water quality is expected to continue as intensification and expansion continues in pastoral land uses, especially dairying. Five main objectives were outlined to address the aim of the research.

8.2 Summary of Findings in Relation to the Research Objectives

This research has employed the Soil and Water Assessment Tool (SWAT) and remote sensing techniques to address the research objectives. This study has shown which land use activities contribute to water quality and quantity problems of the catchment and has also identified the trends in land use and climate change implications for water resources. A framework of land use change patterns and future scenarios has also been developed to guide land use change policy decisions that could deliver improved environmental outcomes.

The study has critically assessed and identified the spatial distribution of pollution sources in the catchment through modeling and mapping to achieve the first objective. It was found that some areas are contributing more nitrogen (N), phosphorus (P) and sediments than others. The distributions show that some sub-basins in the catchment yield as much as 25.5kg N/ha, 2.89kg P/ha and 8.4tonnes sediment/ha per year respectively. Similarly, the catchment hydrologic component is found to be unevenly distributed. For instance, the western part of the catchment receives more rainfall than other parts. Other hydrologic parameters/processes such as evapotranspiration (ET) and surface runoff are unevenly distributed. These analyses and findings were covered in chapter five.

In order to achieve objective two, nutrient/pollutant fluxes from the various land use types were analysed and quantified using the SWAT model. The analyses (presented in chapter five) indicate that pastoral land use, vineyards, gorse and broom, and native forests occupied the largest areas of the catchment. The four land use categories also constitute the largest contributors in terms of N, P and sediment yield in the catchment.

Remote sensing techniques were also utilised to analyse the rate of land use change and projected the probable state of land use coverage into the near future (year 2030), assuming the existing trends continue. The land use change analyses indicate that while the majority of the land use types in the catchment will decrease in area coverage, beef/dairy and vineyards are expected to expand. Beef/dairy land use will grow by 1.8% in 2020, 7.3% in 2025 and 13.0% in 2030 while vineyards are expected to increase by 2.2%, 9.3%, and 13.5% for the 2020, 2025 and 2030.

Further analyses were carried out to determine the rate or trend of pollutant yields from both present and future land use coverage in the catchment to meet the third objective. These were presented in chapter six, and show that the rate of N, P, and sediment yields in the catchment will increase progressively in the future.

The sustainability of the projected expansion in land use types, especially dairy land use, in relation to the availability of water to drive the growing dairy sector, was also assessed. Sourcing water externally from outside the catchment (e.g. via the Hurunui Water Project) offered a window of opportunity for keeping up with the possible increase in water demand for the increasing dairy sector of the catchment since dairying cannot thrive without water.

Research objectives four and five were designed to establish the relationship between future land use change and pollution discharge on surface flow as well as estimate the impacts of climate change on surface flow and water quality. Current trends in atmospheric temperature warming, and also by analysis of how various land use change scenarios could help in reducing nutrients (N and P) yield under different climate scenarios is covered in chapter seven. It was found that systematic seasonal and annual changes in temperature and precipitation over the catchment are expected under the three Representative Concentration Pathways (RCP 4.5, 6.0, 8.0). Substantial reductions in rainfall especially during winter seasons are expected while summer is expected to experience slight increases in rainfall. Irregularities in rainfall and temperature patterns are expected to cause fluctuations in surface flow, and likewise in groundwater levels over summer, autumn, winter and spring, as well as on annual basis.

The impact of land use change on nutrient yield in the Waipara catchment is found to be influenced mainly by two climate change conditions (RCP 4.5 and RCP 6.0). All four land use change scenarios (sheep and beef to forest; beef and dairy to forest; beef and dairy to vineyards; sheep and beef to vineyards) exhibited notablereductions in nitrogen (N) and phosphorus (P) yields under climate change scenarios RCP 4.5 and 6.0.

SWAT has been used worldwide for the study of both large and small catchment hydrology and land use impact applications. However, little research has been carried out using SWAT in examining the impact of land use on water quality in this part of the world. The few New Zealand based SWAT applications are limited in scope to river catchment hydrology and nutrients/contaminants simulations (Ekanayake and Davie, 2005; Cao et al., 2009; Morcom, 2013; LERNZ, 2015; Me et al. 2015; 2017). While the application of SWAT in New Zealand is not new, its use in assessing the combined land use and climate change impacts on water resources in the current study is. Employing GCMs and SWAT in this thesis to simulate the impacts of future climate scenarios and land use change scenarios is the first such study in New Zealand.

8.3 Implications of the Study

The results of this research showed that the projected land use changes, especially an increase in beef/dairy land, will increase nitrate and sediment loadings to the Waipara River in the future. This implies that as land conversions from other uses to beef/dairy farm increase, leading to increase use of nitrogen fertilisers and high nitrate runoff from land, the consequence will be a further degradation of water quality.

The implications of the predicted impacts of climate change on water resources are that:

- The Waipara River flow pattern may change according to the changes in rainfall patterns.
- Low flows will be experienced during winter while summer will experience some high flows.
- This may result in prolonged low flows as well, thereby leading to high nutrient concentrations in the river.

- Groundwater availability may also be negatively affected as a result of decreased rainfall and change in rainfall patterns over the seasons.

The study also found that conversion from predominantly a grazing based land use economy to forestry and viticulture could be of great advantage for improving water quality with respect to decreasing N and P export. This may, however, reduce water quantity and increase acidity when certain types of forests e.g. pines, are planted (GREENPLAN, 2007; Nisbet and Evans, 2014; Carter, 2018). Choosing the right types of trees for planting is necessary.

The integrated approach adopted by the thesis shows the significance of using SWAT in monitoring spatio-temporal changes in land use and climate change that could have great impacts on water quality. The quantitative information provided by the study thus constitutes a premise for evaluating institutional responses and the sustainability in the existing tools for managing land use and climate change impacts as well as the available water resources. It is therefore essential for the authorities responsible for land and water resources management to direct policy instruments towards the trends and the consequences of land use change.

The results of this study could aid in identifying potential policy measures that may guide land use decision making. The scenario analyses have shown the degree of impact a change from the current grazing dominated activity to forestry and viticulture may have in reducing nutrient contamination of the catchment surface water resources. Following the research outcomes, a suggestion for the formulation of policies that may encourage land use changes capable of enhancing water quality as well as socio-economic development is made. Such policy instruments may include, among others:

- Monetary incentives and support for land conversion from grazing to forestry and viticulture
- Tax holidays for existing vineyard and forest growers
- Increased monitoring of grazing activities and enforcement of existing laws

While the Waipara catchment does have its own unique characteristics, it faces similar issues to many east coast New Zealand river catchments. Various regional councils are striving to restore the degraded quality of the water bodies within their domains. The results of the integrated land use and climate change scenarios of this study can be extrapolated to considerations for these other catchments.

8.4 Contribution to Knowledge

The results of this study indicated that when the SWAT model is well calibrated, it can produce reasonably good hydrologic simulations with respect to future land use and climate change impacts, which can be of great use to water and environmental managers, and also policy and decision makers.

For the first time in New Zealand, SWAT has been applied with GCMs to demonstrate the implication of climate change for water quality and quantity. The use of SWAT to evaluate climate change effects via different land use scenarios in this part of the world is novel. Another novel contribution of this study is the use of SWAT in assessing the atmospheric CO_2 concentration pathways (RCP4.5, 6.0, 8.0) which could be invaluable for developing climate and land use change adaptation strategies for water resources management in New Zealand.

Another major contribution of the study is how future land use choices will affect the catchment water quality. The study has found that converting from predominantly pastoral farming systems to forestry and viticulture could result in great reductions in N and P yield under different climate change scenarios. This in essence will improve the catchment water quality and could therefore serve as an adaptation strategy to the impacts of climate change on water quality when appropriate measures are put in place. The study has also made available useful information about the amount of water required in meeting the water demand for a potential increase in dairy land use in the catchment, which is of great concern to the regional council.

The spatial distribution of pollutant sources (nitrogen, phosphorus and sediments) in the catchment has also been revealed by this study. The results suggest the need for taking both critical source area and basin-wide approaches to the implementation of catchment pollution control management strategies. This information can therefore aid policy makers in prioritising agri-environmental policy resources and guide the focus of pollution abatement measures in the Waipara River catchment. The current study has added to the procedures for determining the best model to use in the assessment of land use and climate change impacts (outlined in chapter 2). This approach could serve as a guide to others in choosing the most appropriate model in similar case studies. The SWAT model and the methodology/approach used in the study can help to identify the “best” or optimum configurations (land use pattern) for catchments aiming to lower their nutrient levels.

8.5 Limitations of the Study

Notwithstanding the potential usefulness of the Waipara catchment SWAT model and the research outputs as tools for evaluating alternative land and water management policy, this research has suggested several limitations.

Although SWAT can generate high quality outputs to guide management decision making, it requires a higher level of technical skills to understand and interpret the outputs. Setting up a working model takes time and requires knowledge of several SWAT sub-models. For this study, time and financial constraints as well as the scope could not allow for undertaking the study of other SWAT sub models/extensions for use in carrying out certain modeling functions or tasks that could enhance model performance and output. Another limitation of the research is in the area of input data quality. The lack of long periods of observed water quality data greatly reduced the model performance during calibration.

Due to time constraints, it was not possible to collect information such as socio-economic data that could be used to build the model for simulation and analysis of socio economic drivers that underlie land use change in the catchment. Capturing the socio-economic information in conjunction with spatial data could better improve the model and the modeling outcomes. Considering time constraints, the study was limited to the analysis of landuse change impacts on annual nutrient (N and P) yield under different climate change scenarios without taking into account the seasonal variabilties.

8.6 Future Research Directions

The application of SWAT to the Waipara catchment has successfully provided useful information to aid future management of the water resource. In the process, several future research directions were highlighted. The research has quantified the water demand for dairy operations. To better manage the overall water requirements for the catchment, the water demand of other land use types needs to be quantified. Other in-catchment sources of water supply need to be identified e.g. wastewater recovery. The research employed the SWAT model and remote sensing in the study of the Waipara River catchment. Further studies using different model(s) in order to compare the results with the SWAT outputs is necessary.

It has been known that P concentrations in the Waipara River catchment are below detection levels and in this research, the model did not perform very well in simulating P during calibration. Improving the ability of SWAT to effectively simulate the low concentration of P in the catchment could be worthwhile.

Studies on the use of nitrogen/phosphorus inhibiting technologies by farmers to determine pollutant flux and land use change relationship impacts on water quality in the catchment could be undertaken. As highlighted above, the current research has demonstrated the usefulness of SWAT in analysing the impacts of land use change under climate change scenarios on water quality without considering socio-economic and government policy as drivers of land use change. Likewise, seasonal variability in percentage nutrient yield due to landuse change under climate change scenarios was not examined. Future research could investigate such factors.

Economic decisions (as in the above) on the use of land lie in the hands of the individual owners and are probably influenced by market forces. Further research into how land use change behaviours can affect the outcomes of the change scenarios in this study is also necessary. The study has shown a pattern in the Waipara River catchment land use that could help reduce water quality degradation. It is an accepted fact that climate change and water pollution are two major global as well as New Zealand specific issues. The question now is whether farmers and land owners will be willing to change from their current land use activities. There would be a need to investigate farmers' perceptions of land use change as an adaptation strategy for climate change impact on water quality.

Everyone depends on high quality freshwater. Adopting an approach or tool for defining and resolving water quality and water resource issues in order to achieve a balance between economicaspirations and environmental bottom-lines is critical. Managing land use to achieve limits presents a great challenge globally as well as in New Zealand. Computer modeling provides a reliable and cost-effective way to investigate causes and potential solutions to water quality problems. The importance of modeling in trying to address water pollution and degradation cannot be over emphasised, as the results of studies such as this can inform long-term decision making and ultimately improve water quality. This research has highlighted the issues relating to catchment water quality degradation and demonstrated a useful modeling approach towards solving the problem in this Waipara River catchment case study.

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Appendixes

Appendix 1 A selection of hydrological models in this chapter

Model	Type	Spatial Scale	Simulation Process and Variables	Reference
Hydrologiska Byråns Vattenbalansavdelning (HBV)	Lumped conceptual model (also known as grey-box models)	Catchment	Surface and underground flows	Bergström, 1976, 1992
Stanford Catchment Model (SWM)	Lumped conceptual	Catchment	Surface and underground flows	Crawford and Linsley, 1966
Sacramento	Lumped conceptual	Catchment	Surface and underground flows	Burnash et al., 1973, Burnash, 1995.
MIKE-SHE	Distributed physically based	Catchment	Surface and underground flows, interception, evapotranspiration, in-stream flows, water quality.	Abbott et al., 1986a,b
Institute of Hydrology Distributed Model (IHDM)	Distributed physically based	Catchment	Hydrology/flood forecast	Beven et al., 1987
Thales	Distributed physically based	Catchment	Hydrology, sediment	Grayson et al., 1992a,b; Adams et al., 2008
TOPMODEL	Conceptual distributed	Catchment	Hydrology, water quality	Beven and Kirkby, 1979

Model	Type	Spatial Scale	Simulation Process and Variables	Reference
Soil and Water Assessment Tool (SWAT)	Distributed physically based	Basin	Hydrology, plant growth, sediments, nutrients, pesticides.	Arnold et al., 2012
Artificial Neural Network (ANN)	Empirical (black-box)	Catchment	Hydrology	Riad et al., 2004, Ghumman et al., 2011
Unit hydrograph (UH)	Empirical (black-box)	Catchment	Surface hydrology	Sherman, 1932, Ramírez, 2000
XAJ	Distributed physically based conceptual	Catchment	Hydrology/flood forecast	Zhao et al., 1980
Mix runoff generation (MIX)	Distributed physically based conceptual	Catchment	Hydrology/flood forecast	Bao and Wang, 1997
Northern Shannxi (NS)	Distributed physically based conceptual	Catchment	Hydrology/flood forecast	Zhao et al., 1983
WATBAL	Distributed physically based	Catchment	Rainfall runoff modeling system	Knudsen et al., 1986
Nedbor Afstromnings Model (NAM)	Lumped conceptual	Catchment	Rainfall runoff modeling system	Nielsen and Hansen, 1973

Appendix 2 General characteristics of the three classes of models

Empirical model	Conceptual model	Physically based model
Rely on data metric/black box Based only on the facts contained in available observed statistics and involves mathematical equations. It has little or no regard for the characteristics and physical processes of the hydrological system Accurate forecasting, but weak on explanation Information generated cannot be extended/applicable to different Catchments of similar characteristics E.g., ANN, Unit hydrograph Credible within the limits of a specific territory	Parametric or grey box model Uses interconnected reservoirs and semi empirical equations to represent the hydrologic system/physical processes Generates model parameters in laboratory settings/from observed data and involves calibration. Uncomplicated and can be executed in a given programming language without difficulty. It requires huge amount of observed river flow and climatic records E.g., SWM, XAJ, Sacramento model Calibration requires the determination of a curve that fits a specified set of points making it hard for deducing the physical relationships	Mechanistic or white box model Built upon the concept of variability in geographic space, Assessment of attributes of geographic locations Uses existing information about structure and attributes of geographic location/Catchment Not easy to understand, and demands high level expert/numerical skills/knowledge. Problem of inconsistency in defining effects of allied interacting processes involving varying scales in a heterogeneous landscape E.g., IHDM, SWAT Applicable in diverse contexts

Source: Devi et al. (2015)

Appendix 3 Waipara catchment SWAT model nutrient parameters and sensitivity ranking

Parameter	Definition	Range	Fitted Value	Sensitivity Ranking	
				N	P
ORGP_CON.hru	Organic phosphorus concentration in runoff, after urban BMP is applied (0-50 ppm)	0.001-0.020	0.0181		1
PHOSKD.bsn	Phosphorus soil partitioning coefficient (10m^3/Mg)	20.00-30.00	21.00		2
ERORGP.hru	Phosphorus enrichment ratio for loading with sediment	0.01-0.30	0.1550		3
PSP.bsn	Phosphorus availability index	0.00-0.01	0.009		4
ERORGN.hru	Organic N enrichment ratio for loading with sediment	4.00-5.00	4.50	1	
CN2	Initial SCS runoff curve number (dimensionless) for moisture condition II	70.00 – 80.00	73.00	2	
ORGN_CON.hru	Organic nitrogen concentration in runoff, after urban BMP is applied (0-100 ppm)	0.001-0.020	0.0105	3	
BC3.swq	Rate constant for hydrolysis of organic N to NH_4 in the reach at 20^oC (day)	0.30-0.40	0.33	4	

Parameter	Definition	Range	Fitted Value	Sensitivity Ranking	
				N	P
PPERCO.bsn	Phosphorus percolation coefficient in soil layer ($10m^3/Mg$)	17.00-17.50	17.15		5
BC4.swq	Rate constant for mineralization of organic P to dissolved P in the reach at 20°C (day^{-1})	0.60-0.70	0.69		6
BIOMIX.mgt	Biological mixing efficiency	0.02-1.00	0.51	5	7
N_UPDIS.bsn	Nitrogen uptake distribution parameter	10.00-20.00	11.00	6	
CMN.bsn	Rate factor for humus mineralization of active organic N	0.0001-0.0010	0.00073	7	
NPERCO.bsn	N percolation coefficient	0.002-0.020	0.0074	8	
P_UPDIS.bsn	Phosphorus uptake distribution parameter	95.00-100.00	99.50		8
CDN.bsn	Denitrification exponential rate coefficient	0.01-0.10	0.073	9	9
SDNCO.bsn	Denitrification threshold water content	0.02-1.00	0.1180	10	10

Appendix 4 JM distance for the land use classes in the Waipara River catchment.

Landsat ETM	Landsat OLI_TIRS	Band Name	FRS vs SCB	FRS vs SHP	FRS vs BEF	FRS vs SNB	FRS vs BND	FRS vs VNY	SCB vs SHP	SCB vs BEF	SCB vs SNB	SCB vs BND	SCB vs VNY	SHP vs BEF	SHP vs SNB	SHP vs BND	SHP vs VNY	BEF vs SNB	BEF vs BND	BEF vs VNY	SNB vs BND	SNB vs VNY	VNY vs BND
Band 1	Band 2	Blue	1.23	1.32	1.43	1.40	1.35	1.21	1.10	1.09	1.11	1.02	0.98	0.73	0.73	0.76	0.72	0.50	0.35	0.40	0.33	0.28	0.20
Band 2	Band 3	Green	1.27	1.22	1.18	1.21	1.12	1.20	0.97	1.02	0.89	1.03	1.02	0.67	0.70	0.67	0.58	0.48	0.29	0.32	0.26	0.22	0.17
Band 3	Band 4	Red	1.14	1.12	1.16	1.11	1.10	1.10	1.01	0.88	0.82	0.92	0.98	0.71	0.69	0.70	0.68	0.32	0.23	0.21	0.19	0.17	0.15
Band 4	Band 5	NIR	1.50	1.48	1.46	1.36	1.33	1.43	0.96	1.02	0.97	0.95	0.97	0.66	0.71	0.78	0.76	0.48	0.39	0.30	0.37	0.29	0.23
Band 5	Band 6	SWIR1	1.70	1.68	1.66	1.66	1.63	1.53	1.12	1.17	1.13	1.05	1.02	0.76	0.77	0.88	0.70	0.56	0.52	0.48	0.41	0.36	0.32
Band 7	Band 7	SWIR2	1.68	1.43	1.34	1.26	1.22	1.18	1.02	0.97	0.87	0.85	0.81	0.65	0.58	0.67	0.68	0.38	0.45	0.40	0.38	0.29	0.22