Framework for Assessment of Climate Impacts on New Zealand's Hydrological Systems

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EXECUTIVE SUMMARY

The objective of this research was to develop a conceptual framework for the assessment of the effects of climate change on hydrological systems in New Zealand. This research commenced with a literature review emphasizing the types of impacts that have been detected previously and methods for detecting and modelling impacts. The conceptual framework was developed and then applied to the Waimea Plains as a test catchment to assess the effect of climate change. Existing climate and hydrological data were analysed to assess possible climate change effects. Hydrological and socioeconomic models were developed and implemented to relate possible climate change to derived changes in water availability and economic productivity within the test catchment.

The conceptual framework developed as a part of this research consists of three elements:

1. Analysis of historic time series climate and hydrological monitoring data. This analysis relies principally on application of nonparametric trend analysis. Other analytical tools, including linear regression and correlation analysis, may also be utilized. Analytical results are compared with expected results from the literature and on general scientific principles. Conclusions are then based on the weight of evidence from multiple variables including –

    a. Climate –

        1) Temperature.

        2) Precipitation.

        3) Evaporation.

        4) Solar radiation and sunshine hours.

        5) Atmospheric water vapour (including relative humidity and cloud cover).

    b. Hydrological –

        1) Streamflow.

        2) Stream water quality.

        3) Groundwater levels.

        4) Groundwater quality.

2. Climate and hydrological modelling. A variety of modelling approaches are possible and available. Models are continuously being improved and updated and new ones developed. General circulatoin models (GCMs) are available for modelling standard climate change scenarios over large areas of the globe. The model results are then downscaled to apply to smaller regional areas within national boundaries like those of New Zealand. These can produce time series projections of future daily temperatures and precipitation under climate change. Traditional mechanistic models are available for modelling at regional and

catchment scale using changes in temperature and precipitation under climate change scenarios as inputs. Model outputs can then be compared with historic data and with estimates of hyrdological variables in the absence of climate change. Artificial intelligenced (AI) modelling techniques have great potential to contribute to or replace mechanistic modelling approaches.

3. Socioeconomic modelling. Socioeconomic changes may impact hydrological systems in some of the same ways that climate change does and climate change effects on hydrologic systems may produce socioeconomic effects. Therefore, there is a need for a mechanism to assess socioeconomic relationships.

Application of this conceptual framework to the Waimea Plains test catchment and results are presented in Sections 4, 5, and 6 of this report for trend analysis, climate and hydrological modelling, and socioeconomic modelling, respectively. Results were as follows:

1. Trend analysis – Trends for climate and hydrological variables were identified (some statistically significant and some not). This analysis of trends provided mixed results which, in some cases, were consistent with projected climate change but others were not. The relatively short length of many of the available databases handicaps determination of long-term trends. Reliable detection of trends requires monotonic data. Therefore, a necessary preliminary in trend analysis is review the shape of graphically plotted data to ensure this criterion is met. Measures are also necessary to ensure data quality and to maintain the regularity of data collection (i.e., prevent data gaps).

2. Climate and hydrological modelling – Two climate change emissions scenarios were modelled as a part of this project: (1) the average or A1B case; and (2) a somewhat more extreme or A2 case. These climate change results for daily temperatures and precipitation were then used with AI models to produce inputs for MODFLOW groundwater-stream interaction mechanistic modelling as well as other AI models developed to simulate Waimea River flow and groundwater levels in the Waimea Plains. Transient results for these models over a one year period incorporating occurrence of an extreme drought were consistent and indicated peak reduction in streamflow under climate change conditions for the 2058-2059 period on the order of 20 to 30%, but no substantial change in groundwater levels.

3. Socioeconomic modelling – The complexity of modelling human behaviour and social systems and the lack of appropriate socioeconomic data in New Zealand are major handicaps to this effort. The most important available data to explore socioeconomic relationships with water availability came from surveys which have been conducted in the Waimea Plains since 1999. Such data are not generally available for other catchments in New Zealand. Therefore, the socioeconomic model which was developed was relatively simplistic and in its application it was necessary to rely more on reasonable assumptions than data. The results, however, indicate that reductions in water availability by the year 2050 caused by climate change could have substantial negative economic consequences compared to 2005, particularly if economic activity increases as expected in the 45 year period, depending on the degree of decrease in water availability (with a maximum decrease modelled of 13%).

As a result of this research, the following recommendations are advanced:

1. This conceptual framework should be applied in other catchments in New Zealand.

2. Modelling results should always be considered indicative but not necessarily precise. Results, where such assessment tools are utilized, should be catalogued and tracked for future confirmatory analysis. This would allow assessment of which methods are most useful and fit for purpose.

3. Measures should be instituted to ensure the quality of climate and hydrological databases and to prevent gaps in the record. Monitoring and reporting of water use should be required.

4. Water quality variables such as major ions should be measured in surface water monitoring networks. This is not generally done at this time, but is necessary to develop appropriate data for understanding and detecting groundwater-surface water relationships in general and with respect to climate change in particular.

5. Data plots should be carefully examined to ensure the data are monotonic in nature prior to application of trend analysis methods to the data.

6. It is important to develop long-term climate, hydrological, and socioeconomic data sets for future analysis. Lack of such data at this time is a major limitation on the application of any conceptual framework for analysis.

7. Modelling methods are continually being improved and updated and new methods developed. New modelling approaches should be incorporated into this conceptual framework as they become available. In particular, AI modelling techniques have great potential to contribute to or replace mechanistic modelling approaches.

8. The state of the art of socioeconomic modelling and the availability of relevant data are relatively poor compared to climate and hydrological modelling. Therefore, there is a need for greater effort to develop meaningful models and databases to use with them. A comprehensive land use database would be particularly important. Additional research in this area is needed. Efforts in this area in other countries should be considered and, where appropriate, adopted for use in New Zealand.

1.0 INTRODUCTION

By definition, climate and hydrology are inextricably linked. Climate is defined as general or average weather conditions, including such elements as temperature, rainfall, and wind (Picket, et al., 2005) while hydrology is defined as the science of "the cycling of water in the natural environment that relates specifically with - *the continental water processes* and with - *the global water balance*" (Brutsaert, 2005). Therefore, climate deals with water in the atmosphere and its movement to land via rainfall while hydrology deals with water in any compartment of the natural environment. Additionally, elements of climate other than water itself (e.g., temperature and wind) also influence the movement of water on or within close proximity to the surface of the land through, for example, evapotranspiration.

This document reports on a one year research project conducted by the Institute for Geological and Nuclear Science Ltd. (GNS Science) under the Sustainable Land Management and Climate Change (SLMACC) portfolio funded by the Foundation for Research Science and Technology (FRST) on behalf of the Ministry of Agriculture and Forestry (MAF). The objective of this project was to develop a framework for assessing the impacts of climate change on New Zealand's hydrological system. The project consisted of the following two tasks (FRST and GNS Science, 2009):

1. Development of a conceptual framework through "review of New Zealand and international datasets, policy documents and scientific literature... with emphasis on 1) types of impacts that have been detected previously and 2) methods for detecting and modelling these impacts. Specified achievement measures were envisioned as: 1) a "workshop held with key stakeholders to identify any recent/current research in this topic area" and 2) a metadata summary of publicly available national and regional scale datasets."

2. Validation of conceptual framework by application to the Waimea Plains test catchment. To include hydrologic modelling to assess predicted "climate-induced changes in the hydrological system" and socioeconomic modelling to relate "climate-induced changes... to derived changes in economic productivity, cultural values of water, etc. within the test catchment."

It was envisioned in the project proposal that this assessment would include integration of land use and socioeconomic data. It had been planned to use the Motu Economic and Public Policy Research (Motu) land use in rural New Zealand (LURNZ) model to derive year-by-year land use maps for the test catchment which would be validated against other information. Through a linked research proposal led by Environmental Science and Research (ESR), the 1999 benchmark evaluation of Total Economic Value (TEV) of groundwater in the Waimea Plains would also be updated. A multivariate neural network model of economic drivers of water use was to be developed.

However, for two reasons it became necessary to re-scope the land use and socioeconomic components of this project: (1) the linked ESR research proposal was not funded by FRST; and (2) after further consideration Motu advised that its LURNZ model was not suitable for this purpose. With respect to the former reason, GNS reduced the scope of the socioeconomic component of the project to take reduced project resources into account. With respect to the latter reason, improving resolution of the LURNZ model to make it suitable was beyond the scope of this project. It was decided instead that, Motu would work with GNS on the development of a relevant economic model that could be integrated with the socioeconomic work being undertaken by GNS staff. Motu proposed to develop an economic model of the value of groundwater that would take urban land use, low and high intensity agriculture, and river and rainfall recharge into account and could be generalized to other locations. Motu would then apply this model to four future land use scenarios including urban expansion and rural intensification under both current groundwater recharge conditions and various climate change scenarios. However, late in the project, Motu advised that it had not developed and could not deliver this model within project deadlines (Coleman, 2010). Therefore, GNS modified the scope of the socioeconomic work GNS staff were already engaged in to address some of the elements that had been assigned to Motu. That work is discussed in Section 6.

The organization of this report was built around the above tasks. First in this report, general aspects about climate change are addressed and then related specifically to New Zealand (Section 2). Next, what is known about the potential impacts of climate change on hydrologic systems and how this information has been utilized to develop an assessment framework are discussed. This includes a metadata summary of publicly available national and regional scale datasets (Section 3).

In the remainder of this report, validation of the conceptual framework by application to the Waimea Plains test catchment will be discussed. The major portions of this presentation are: (1) analysis of climate and hydrologic data; (2) combined groundwater and surface water modelling; and (3) socioeconomic and cultural factors (Sections 4, 5, and 6, respectively).

2.0 CLIMATE CHANGE AND ITS POTENTIAL HYDROLOGIC IMPACTS

A literature review was conducted to identify the nature of climate change and its potential hydrologic impacts. Information on the nature of climate change is relevant to New Zealand as New Zealand is part of the worldwide system and information on potential or observed hydrologic impacts in other parts of the world provides us with examples of what may also occur in the New Zealand context. A large body of relevant literature was identified and obtained. The portion of that literature specifically cited in this report is listed in Section 8.

2.1 Observed Changes in Climate

2.1.1 Globally

The main “driver” of climate change is believed to be anthropogenic emissions of carbon dioxide (CO_2). Other “long-lived” greenhouse gasses (GHGs) that are also factors include methane (CH_4), nitrous oxide (N_2O), and halocarbons. Whereas CO_2 and N_2O emissions are primarily a result of emissions from the increasing use of fossil fuels since the beginning of the industrial revolution, a large portion of CH_4 emissions come from agricultural practices. The increase in concentrations of these GHGs is typified by that for CO_2, as shown in Figure 2-1. The rate of increase since 1750 is “*very likely*... unprecedented in (the) more than 10,000 years” of available data (IPCC, 2007). Figure 2-1 indicates that atmospheric levels of CO_2 have increased about 35% since the beginning of the industrial revolution.

The resultant “warming of the climate system is unequivocal,” being “evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level." Data indicating this situation are presented in Figure 2-2. With regard to temperature, the linear trend in the rate of warming over the last 100 years (1906-2005), in terms of the global average temperature, is 0.74 ^{o}C while the rate of warming over the last 50 years (1956-2005) of that period is nearly double what it was for the entire 100 year period (IPCC, 2007).

The warming trend is widespread over the globe but its magnitude varies in different locations. The temperature increase is greater for the higher latitudes of the arctic and in land regions than for ocean regions. Observed increases in sea level and decreases in the extent of snow and ice, particularly in the northern hemisphere, are consistent with the temperature warming trend (IPCC, 2007).

Other long term climate effects which have been observed include (IPCC, 2007):

1. Changes in precipitation with increases in eastern North and South America, northern Europe, and northern and central Asia and decreases in the Sahel, Mediterranean, southern Africa, and southern Asia (based on trends in data for the 1900 to 2005 period).

2. Increases in extreme weather events over the last 50 years including less frequent cold days, nights, and frosts and more frequent hot days and nights and heat waves over most land areas. There have also been increases in heavy rainfall events over most areas, an increased incidence of extreme high sea levels worldwide, and increased intensity of tropical cyclone activity in the North Atlantic since 1970 and possibly in other regions. This is consistent with what may be expected in New Zealand as a part of climate change (see further discussion in Section 2.2.2).

2.1.2 New Zealand

Assessment of New Zealand's climate and the nature of its change in response to global climate change is complicated by both the natural variability that is characteristic of climate in New Zealand and New Zealand's topography. The former diffuses the climate change signal and tends to make trend detection more difficult while the latter mitigates against uniform climate change trends for the country as a whole (Wratt, et al., 2009). The "mountain chains extending the length of New Zealand" are responsible for the latter factor. They "provide a barrier for the prevailing westerly winds" and divide the country into dramatically different climate regions" with areas to the west of the mountains being wetter while those to the east are drier" (Mackintosh, 2001). These climate zones are shown in Figure 2-3.

Interannual and decadal variability have been recognized as important factors with regard to New Zealand's climate. Natural climate variability in New Zealand is primarily a function of two major factors: (1) the El Nino Southern Oscillation (ENSO); and (2) the Interdecadal Pacific Oscillation IPO). ENSO is largely a result of abnormally warm surface ocean waters in the eastern tropical Pacific Ocean occurring simulataneously with reversing east-west surface air pressure patterns. It is believed to explain 25 to 40% of the year-to-year air temperature and precipitation variations in New Zealand. IPO is a function of movement in the South Pacific Convergence Zone.

As a part of ENSO, El Nino "events… occur irregularly" three to seven years apart for "about a year" while the La Nina phase exhibits "essentially… opposite behaviour." El Nino events are characterized by a "general pattern" of "stronger than normal southwesterly airflow, lower than average seasonal temperatures, and drier than normal conditions in the northeast of the country" while La Nina events are characterized by "more northeasterly flows, higher temperatures, and wetter than normal conditions in the north and east of the North Island." The IPO is a natural "decadal variability over parts of the Pacific Ocean." The IPO has positive and negative phases. Sea surface temperatures in the New Zealand area "tend to be lower, and westerly winds stronger" in its positive phase but climate associations with the IPO are not consistent. Phase reversals typically occur over every 20 to 30 years (Wratt, et al., 2009).

New Zealand's climate appears to generally be following the worldwide pattern with regard to climate change. Changes that have been documented include (National Climate Centre, 2008):

1. Concentrations of GHGs have increased. For example, atmospheric CO_2 has increased 17% since 1970 and the rate of its increase has accelerated.

2. There has been an overall warming trend with "nationally averaged surface temperatures hav(ing) increased by about 0.9 ^{o}C over the past 100 years."

3. There has been a trend to fewer frosts over most of the country.

4. A zonal west-east pattern in rainfall with "increases in mean and extreme daily rainfall generally" to the west on both islands and decreases in mean and extreme daily rainfall with increasing dry spell duration… generally" in the north and east (Griffiths, 2006).

5. South Island glaciers are in general retreat. Most South Island glaciers have been reduced in areal extent and volume over the last 33 years while at the same time the elevation of the accumulation zone has risen

6. An average rise in sea level of 0.16 m during the 20th century.

Analysis of New Zealand's climate record over the 1930 through 2004 period, including a detailed analysis of extreme rainfall for two periods, indicates that a substantial shift occurred during the latter years of that period. The cause of this change was attributed to strengthening of the occurrence of high pressure zones to the north of New Zealand, presumably IPO phase reversal. Reported changes are as follows:

1. "The north and east of the North Island has become 10 percent drier and five percent sunnier, with more droughts" (Salinger and Mullan, 1998; Hollis, 1998).

2. "The west and south of the South Island has become 10 percent wetter and five percent cloudier, with more damaging floods" (Salinger and Mullan, 1998; Hollis, 1998).

3. Changes in extreme rainfall have been "strongly related to changes in mean rainfall" with a similar west-east pattern of "increased rainfall extremity in the

(wetter) west, but decreased extremity and increased dry spell duration in the (drier) east" (Griffiths, 2006).

4. "Night temperatures continue to rise" (Salinger and Mullan, 1998 and Hollis, 1998).

5. "Fewer frosts are occurring nation-wide" (Salinger and Mullan, 1998; Hollis, 1998).

6. "The retreat of the west coast glaciers has halted but eastern glaciers continue to shrink" (Salinger and Mullan, 1998; Hollis, 1998).

2.2 Projected Climate Change

2.2.1 Global Models

Projecting potential changes in climate is an uncertain exercise. It requires both an understanding of how the world's interrelated natural climate systems operate and an ability to mathematically model them.

Modelling on a world scale is accomplished using general circulation models (GCMs). These are capable of producing simulations of daily temperature and precipitation. However, GCMs use relatively coarse grids on the order of several degrees on a side. For example, the ECHAM GCM has a grid of 2.8^{o} on each side (Nemesova, et al.,1999) and National Climate Centre (2008) indicates that GCMs typically have grid spacing in the range of 100 to 300 km.

A number of GCMs have been developed around the world. Mullan and Dean (2009) reported that 17 such models were obtained from the United Nation's Intergovernmental Panel on Climate Change (IPCC) and tested for suitability to the New Zealand situation using the A1B emission scenario and historic climate data (see discussion of emission scenarios below in this subsection). These models have produced a range of different projected temperature increases for the 100 year period following the 1980 to 1999 time frame (centered on 1990). For example, of these models the US gfdl_cm21 GCM projected a "middle of the road" increase of 2.53 ^{o}C while the Japanese micro32_hires GCM projected a 72% higher increase of 4.34 ^{o}C (the largest projected increase of all of the models tested). Mullan and Dean (2009) compared GCM performance to actual New Zealand weather conditions and determined that five of the 17 models tested produced results that were "noticeably worse" than the other 12. Therefore, the five "worst-performing models" were eliminated from further consideration for application to New Zealand.

The pattern of anthropogenic GHG emissions is a major controlling factor in resultant GCM outputs. However, what such emissions will be is a major point of uncertainty that is also potentially subject to political control. Since no one at this time can accurately forecast what GHG emissions will really be, the IPCC has developed a suite of long-term emissions scenarios for use with GCMs covering a range of possibilities.

The IPCC's emission scenarios encompass "four different narrative storylines... to describe the relationships between emission driving forces and their evolution." These storylines represent "different demographic, social, economic, technological, and environmental developments. Several different scenarios were developed using different modelling approaches to examine a range of outcomes." Each storyline is a family of scenarios. The A1 storyline is composed of three groups (A1B, A1F1, and A1T) while the other storylines have one group each. The IPCC produced a total of 40 emissions scenarios nested within these groups which are believed "together encompass the current range of uncertainties of future GHG emissions" (Working Group III, 2000).

Projected CO_2 emissions and resultant surface temperature increases for the four different narrative storylines and six groups during the 21st century are shown in Figures 2-4 and 2-5, respectively. The color bands in Figure 2-4 show the range of emissions over time for scenarios within each group while the color bands in Figure 2-5 show the range of temperatures predicted by the various GCMs for each scenario. In general, the A storylines assume relatively conventional economic growth and technological change while the emphasis in the B storylines is more toward environmental protection and social equity. Of the A storylines, the following should be noted (Working Group III, 2000):

1. A1B – A balanced energy scenario group producing relatively "average" emissions and temperature increases.

2. A2 – A more extreme emission scenario group with continuously increasing global population and regionally oriented economic and technological change.

3. A1F1 – A fossil fuel intensive scenario resulting in high emissions.

Under each of these three scenarios, worldwide climate is expected to continue warming. IPCC projections have been broken down by region of the world with Australia and New Zealand being lumped together as one region. Therefore, IPCC forecast climate change will be discussed in the following subsection under the heading of New Zealand.

2.2.2 New Zealand

IPCC forecasts for climate change in New Zealand were presented in ranges for both temperature and rainfall with respect to different regions of the North (western and eastern) and South (northern, western, and eastern) Islands. The broad ranges for mean temperature relative to 1990 are a warming of between 0.1 and 1.4 ^{o}C by 2030 and a warming of between 0.2 and 4.0 ^{o}C by 2080. This warming is expected to be accompanied by a 60% increase in the westerly component of annual mean wind speed by 2080 and a "tendency for increased precipitation... except in the eastern North Island and the northern South Island." Additionally, a decrease in frosts, increase in warm weather days (with temperatures over 30 ^{o}C), and in increase in the incidence of heavy rainfall events (particularly in western areas) are considered likely (Hennessy, et al., 2007).

More recent and more detailed projections of climate change impacts in New Zealand have been prepared by the National Institute of Water and Atmospheric Research (NIWA). These are summarized as follows (National Climate Centre, 2008):

1. Temperature - Increasing overall average temperatures of about 1 and 2 ^{o}C, respectively, by 2040 and 2090 "for a mid-range scenario."

2. Fewer frost days.

3. More hot days (with temperatures over 25 ^{o}C).

4. Rainfall - Decreasing rainfall for the east and north of the North Island and for coastal Canterbury and Marlborough on the South Island with increased rainfall on the west and south coast of the South Island. Different rainfall patterns with drier weather in the east and north but more rain in the west of both islands during winter and spring seasons and drier summer and autumn seasons in the west of the North Island and possibly wetter conditions in those seasons for Gisborne and Hawkes Bay. "More recent climate models simulations confirm the likelihood that heavy rainfall events will become more frequent." However, although "severe storms may become more intense… it is not yet clear… how future climate change will influence the frequency, intensity and tracking" of tropical, ex-tropical, and extra-tropical cyclones. There may be fewer but more intense storms of all of these types (Ministry for the Environment, 2008); however, it is also possible that there will be an increase in southern hemisphere storminess with increases in both peak wind speeds and extreme precipitation (Mullan, et al., 2008).

5. Rise in the average snowline. South Island glaciers are generally in retreat and there have been decreases in the areal extent and volume of glaciers as well as increases in the elevation of the accumulation zone (Hendrikx, 2009; Pelto, 2009).

6. An increase in the annual mean westerly wind component across New Zealand. There is also "strong seasonality… in projected wind changes from the models… with increased westerly flow in winter and spring and decreased westerly flow in summer and autumn."

7. Rising sea levels "likely to be similar to the global projections of sea-level rise by the IPCC Fourth Assessment, 2007." These are a "rise of at least 18-59 cm (0.18 to 0.59 m) by the 2090s from the 1990s." There could also be "A further 10-20 cm rise above current levels… if melt rates of Greenland and Antarctica were to increase linearly with the future temperature increases."

These projections were made by statistically downscaling output from GCMs to the regional New Zealand setting with a grid spacing of approximately 5 km (Wratt et al., 2009).

NIWA projections, as the mean of 12 GCMs for the A1B emissions scenario for temperature and rainfall by 50 and 100 years after 1990 (i.e., nominal time frames of 2040 and 2090, respectively), are presented in Figures 2-6 and 2-7, respectively.

2.3 Observed Worldwide Hydrologic Impacts

2.3.1 Water Quantity

Because of the high degree of natural variability in both climate change indicators (like surface atmospheric temperature) and hydrologic system parameters, attempts to document the impact of climate change on hydrologic systems are fraught with uncertainty. Limitations in spatial and temporal coverage of monitoring networks and sometimes lack of monitoring appropriate variables may also handicap efforts. As noted by Bates, et al. (2008), "There is significant natural variability – on inter-annual to decadal time-scales – in all components of the hydrological cycle, often masking long-term trends." This is critical since it is clear that the primary mechanism for observing hydrologic impacts is assessing long-term trends. Furthermore, "The observed irregular variations in hydrologic time series (such as precipitation, air temperature, streamflow, and groundwater levels) reflect a range of natural and human climate stresses" (Hanson and Dettinger, 2005 as quoted by USGS, 2009).

Natural climate variability has always been with us and impacts all parts of the hydrologic cycle including groundwater. With specific regard to New Zealand, "New Zealand's climate varies with fluctuations in the prevailing westerlies, and in the strength of the subtropical high-pressure belt. Many of these (variations) are short-lived or random. Others are linked to general variations over the southern hemisphere or Pacific Ocean. These are persistent and predictable to some degree" (Mullan, et al, 2009). They include the Antarctic Oscillation, a trend over the last 30 years towards stronger westerly winds at latitude 50^{o} south that has been attributed to a combination of global warming and stratospheric ozone depletion and the ENSO phenomena. ENSO is a two-phase pattern (El Nino and La Nina) "that affects air pressure, winds, sea temperature, and rainfall" and "follows an irregular three to seven years cycle" (Mullan, et al., 2009). ENSO is considered "the leading cause of inter-annual climate variability" and the cause of "significant climate anomalies" in New Zealand (Mullan, et al., 2002).

Only limited information has been developed with regard to whether or not climate change has impacted New Zealand hydrologic systems. However, relevant research in other parts of the world has documented various impacts. These are summarized as follows (Bates, et al., 2008) with additional notations from New Zealand sources:

1. Changes in precipitation patterns, intensity, and extremes. "Precipitation over land generally increased over the 20th century between 30 ^{o}N and 85 ^{o}N, but notable decreases have occurred in the past 30-40 years from 10 ^{o}S to 30 ^{o}N." There have been "widespread increases in heavy precipitation events... associated with increased atmospheric water vapour and consistent with observed warming." There are also indications of increased incidence of extreme events such as floods and droughts which may be attributable to climate change. Changes in patterns, intensity, and extremes of precipitation in New Zealand have been reported by Griffiths (2006). She reported zonal trends with a strong west-east pattern. This pattern was "increases in mean and extreme daily rainfall generally seen to the west of a line from Westport to Invercargill, to the west of a line from Kelburn to Waiouru to Ruakura, and at Campbell Island" and decreases in both with "increasing dry spell duration generally seen in the north and east of both islands and at Raoul Island." Where there have been increases and decreases in rainfall there would be concomitant increases and decreases in streamflow, respectively, and related impacts on groundwater.

2. Widespread melting of snow and ice. There have been decreases in the extent of sea ice, frozen ground (permafrost), and snow cover in the northern hemisphere, global melting of glaciers with an overall decrease in their mass, and delay in freeze-up at a rate of 5.8 days/century while breakup has become earlier at a rate of 6.5 days/century. There have been decreases in the areal extent and volume of glaciers on the South Island of New Zealand (Hendrikx, 2009; Pelto, 2009).

3. Increased atmospheric water vapour. “The water vapour content of the troposphere has been observed to (have) increase(d) consistent with observed warming and near-constant relative humidity.” At the same time, “Total column water vapour has increased over the global oceans by 1.2% per decade from 1988 to 2004, in a pattern consistent with changes in sea surface temperatures.” Analysis as a part of this project indicated an increasing trend in relative humidity at Nelson airport prior to 1990 but a decreasing trend thereafter (see Section 4.0).

4. Increased evaporation. Sparse data for measured pan evaporation indicates decreasing trends. However, this is only a proxy for potential evapotranspiration. It may reflect decreasing solar radiation trends previously reported over parts of Europe, Russia, and the US and may also be influenced by air pollution, aerosols, and cloud cover. Pan evaporation does not represent actual evaporation. Evapotranspiration is believed to have increased over most regions of Russia and the US. Analysis as a part of this project has indicated an increasing trend in evapotranspiration at Nelson airport (see Section 4.0).

5. Changes in soil moisture and runoff. There are only minimal historical soil moisture records (about 600 stations worldwide have been identified). Stations with the longest records (mostly within China, the former Soviet Union, and the central US) indicate a long-term increasing trend within the top 1 m during summer time.

Analysis indicates that the changes in world precipitation patterns are a result of “anthropogenic forcing” (Zhang, et al., 2007). Despite observations of general changes by latitudinal bands around the world, with increases in most latitudes and decreases in some, regional differences have been observed within bands that make it difficult to predict with any confidence what may happen in specific locations. For example, the general case for the latitudes of southern Canada and the US would be increased precipitation and, therefore, streamflow. However, the observed change in mean annual precipitation shown in Figure 2-8 is a more complex picture with substantial areas of decreased precipitation. In Vermont, where Figure 2-8 shows that precipitation is expected to increase, there is research available indicating that it has. For example, increases in precipitation of 14% and streamflow of 18% have been determined from analysis of the 72 year monitoring record (1936 to 2008) for the Winooski River Basin and its major tributaries. In addition to these increases, the mean annual level of adjacent Lake Champlain has also risen. Analysis indicates that changing land-use patterns may have played a “minor role in observed hydrologic changes” but that the dominant factor is climate change (Hackett, et al., 2009). In contrast, research has shown that for the northwest US, where Figure 2-8 shows that precipitation is expected to decrease, there has been “a shift in the character of mountain precipitation, with more winter precipitation falling as rain instead of snow, earlier snowmelt, and associated changes in river flow” (Barnett, et al., 2008). The changes in river flow are “relative increases in the spring and relative decreases in the summer months which appear to be “human-induced” and result in overall streamflow reductions (Rood, et al., 2005; Knowles, et al., 2006; Barnett, et al., 2008; Kalra, et al., 2008; Ajay, et al., 2008; Hidalgo, et al., 2009; and Luce and Holden, 2009). As indicated in Figure 2-6, NIWA predictions for the New Zealand situation also deviate from a strict latitudinal relationship.

2.3.2 Water Quality

Although the "deterioration of water quality is likely to be one of the most serious hydrological consequences of global warming" (Shiklomanov, 1999), there appears to have been less emphasis on the impact or potential impact of climate change on water quality than there has been for water quantity. Therefore, there is less information available on this topic and "documentation of actual or potential effects of climate change on water quality has been sparse" (Nordstrom, 2009). Two primary impacts are reasonable to expect and appear to have been observed to some degree: (1) increase in temperature; and (2) decrease in pH. These are, respectively, consistent with increase in atmospheric temperature and a consequence of increased atmospheric CO_2.

2.3.2.1 Temperature Related Effects

With regard to temperature, it has been reported that surface water temperatures in lakes and streams in Asia, Europe, and North America have warmed between 0.2 and 2.0 ^{o}C since the 1960s and that a smaller increase has been observed for deep water temperatures. Consequences of warming water temperatures include increased evaporative water loss, longer ice-free seasons, and earlier lake stratification "with increased thermal stability." Increased temperatures in freshwater systems may have a variety of related water quality impacts. Resulting thermal stratification in lakes has limited mixing and decreased concentrations of nutrients in shallow waters while increasing them in deeper waters for some European and East African lakes. There have also been reports of decreases in lake nutrient concentrations due to temperature-related increased biological productivity, a decrease in aluminum concentration because of the inverse solubility of that element with temperature, and increases in mercury methylation (presumably due to increased biological activity) and mercury levels with warmer water temperatures (Bates, et al., 2008).

2.3.2.2 pH Related Effects

There does not appear to be any reliable data with regard to the decrease of pH in freshwater systems in relation to climate change. However, there is some data with regard to the oceans and the same fundamental principles of carbonate system chemistry would be expected to apply. These are that increased atmospheric CO_2 levels in the atmosphere are matched by increases in the level of dissolved CO_2 in associated waters. CO_2 dissolved in water forms carbonic acid which dissociates to hydrogen and bicarbonate ions and thereby decreases pH (Drever, 1997 and Hounslow, 1995). It is believed that this has caused the pH of the oceans to decrease approximately 0.1 units from pre-industrial levels and that continuation of current CO_2 emission trends could result in further decline of mean ocean pH on the order of 0.5 units (IPCC, 2007; Orr et al., 2005; and The Royal Society, 2005). Recent information supporting this estimate includes, for example, time series data from Ocean Station Aloha about 100 km north of Oahu in the Hawaiian Islands (HOT Program, 2010). These data, covering a roughly 20 year period, show increasing ocean temperature and dissolved CO_2 levels associated with a rate of ocean acidification over the last 20 years (based on both measured and calculated in situ values) on the order of - 0.00185 pH units/year. Obviously, such slow rates challenge the accuracy and precision of pH measuring practices and equipment and, it has been pointed out, extrapolation of such rates from "very limited data" with our current understanding of the dynamics involved is uncertain (Marsh, 2008).

Increasing CO_2 and resultant decreasing pH does not directly affect alkalinity. However, as water becomes more acidic it is more likely to cause weathering of the minerals it comes into contact with and, thereby, increase dissolved concentrations of those same minerals. When the minerals are carbonate rocks, this will increase alkalinity (Driver, 1997 and Hounslow, 1995).

Increase in alkalinity related to climate change has been documented in a study of the export of alkalinity by the Mississippi River in the US. In this study, a 100 year data set was analysed. The export of alkalinity in the form of bicarbonate ion from this major watershed was found to have "increased dramatically" over the last half of the 20th century. The increase in alkalinity export was attributed to a combination of factors including: increased temperature, precipitation, stream flow, CO_2 levels, and chemical weathering (which may all be related to climate change) and changes in land use and farming practices. Sorting out these factors and determining their relative importance is the subject of future research (Raymond and Cole, 2003 and Raymond, et al., 2008).

Reportedly, "Many lakes and rivers have increased concentrations of sulphates, base cations and silica, and greater alkalinity and conductivity related to increased weathering of silicates, calcium and magnesium sulphates or carbonates" (Bates, et al., 2008).

Long-term research at the Konza Prairie site in Kansas, US, has documented the impact of increased atmospheric CO_2 levels on shallow groundwater quality in an undisturbed grassland area underlain by limestone geology. It was found there that over a 15 year period beginning in 1991 that while atmospheric CO_2 levels increased 7% associated groundwater concentrations increased about 20%. While the "forcing mechanism" for increased below ground CO_2 levels was not clear, "the annual cycle in groundwater CO_2 suggests that shallow groundwater is acting as a sink for CO_2" and the resulting water quality impacts are evident. These are cyclically increased CO_2 concentrations and resultant increases in carbonate mineral dissolution (i.e., increased chemical weathering) causing increases in alkalinity, calcium, and magnesium (Macpherson, et al., 2008).

2.4 Projected Hydrologic Impacts

2.4.1 Worldwide

Projected climate change impacts on hydrologic systems over the 21st century are similar to those which have already been observed. They include (Bates, et al., 2008):

1. Precipitation – Changes in precipitation patterns with general increases in mean atmospheric water vapour, evaporation, and precipitation. Models "suggest" general precipitation increases in tropical and high latitudes with decreases in sub-tropical latitudes. In addition to changes in mean precipitation, the incidence of extreme events is expected to become more frequent. These are likely to include more floods and longer periods of drought with low flows.

2. Snow and land ice cover – Projected to contract and decrease.

3. Sea level – Projected to continue rising at rates exceeding previous long term averages.

4. Evapotranspiration – Projected evaporative demand or potential evapotranspiration (PET) is expected to "increase almost everywhere."

5. Soil moisture – Soil moisture depends on the volume and timing of both precipitation and evapotranspiration. Projected changes for soil moisture vary by latitude with decreases in the sub-tropics, Mediterranean region, and at high latitudes and "increases in East Africa, central Asia, and some other regions with increased precipitation."

6. Runoff and stream discharge – Runoff is a function of the volume and timing of precipitation, evapotranspiration, and groundwater recharge as well as whether precipitation falls as rain or snow. Hundreds of catchment based studies focussed largely on Europe, North America, and Australasia have been conducted with varying results and a few global-scale studies have also been conducted. Runoff and streamflow generally increase in high latitudes and decrease in mid-latitudes (e.g., decreases of streamflow in the Middle East, Europe, and Central America). Changes in seasonality for locations "where much winter precipitation currently falls as snow" are a more robust finding with increased winter flow, earlier snowmelt, and decreased spring flow. Changes in lake levels "reflecting changes in seasonal distribution of river inflows, precipitation, and evaporation, in some cases integrated over many years."

7. Groundwater Recharge – Climate change is expected to affect groundwater recharge rates and shallow water table depths. However, "knowledge of current recharge and levels... is poor" and "there has been very little research on the future impact of climate change on groundwater, or groundwater-surface water interactions." Changes in precipitation (totals, rates, and frequencies) may increase or decrease rainfall recharge, while warming may increase evapotranspiration and thereby decrease it. Changes in streamflow regimes are also expected to affect groundwater, but precisely how is uncertain. Modelling studies have predicted both increases and decreases in groundwater recharge and indicate that "climate change impacts on groundwater" are likely to be "very site-specific and climate-model specific." For example, it has been projected that groundwater recharge may increase by more than 30% in parts of the Sahel, the Near East, northern China, Siberia, and the western US while it has also been projected that groundwater recharge may decrease by more than 20% in the central US Ogallala Aquifer in response to warming of 2.5 ^{o}C or greater.

8. Water Quality - "Higher water temperatures, increased precipitation intensity, and longer periods of low flows are projected to exacerbate many forms of water pollution, including sediments, nutrients, dissolved organic carbon, pathogens, pesticides, salt and thermal pollution.

2.4.2 New Zealand

Table 2-1 presents a general summary of the potential impacts of climate change which have been projected for New Zealand water resources. With regard to streamflows, these are consistent with changes from global warming estimated based on a paleoclimate scenario with mean air temperatures 1.5 ^{o}C higher than present. Projected changes in annual runoff under this scenario are as follows (Shiklomanov and Shiklomanov, 1999):

1. North Island – "9 to 40% decrease in annual runoff in the southeast, and 9-27% increase over the rest of the island (80-90% of the area)."

2. South Island – ""18-40% decrease in annual runoff in the southeast, over the rest of the island (70-75% of the area) runoff is unchanged or tends to increase by 6-40%."

3. Increase in frequency and intensity of rainfall flood events.

3.0 NEW ZEALAND CLIMATE AND HYDROLOGICAL DATABASES

3.1 Introduction

National and regional climate and hydrological databases were identified during this project. A summary of these existing databases and sources of data is provided in this section.

This information was compiled from the following sources:

1. Professional knowledge of GNS Science groundwater staff.

2. An internet search for New Zealand climate and hydrological databases.

3. Review of the "Stocktake for the Environment Domain Plan: 2010" (Statistics New Zealand, 2010).

4. A survey of each regional council in New Zealand.

GNS Science manages the National Groundwater Monitoring Program (NGMP) and the Geothermal and Groundwater (GGW) database in which groundwater data from throughout New Zealand are stored. GNS Science groundwater staff also routinely analyse groundwater level and quality data stored in the various surface water and groundwater hydrologic databases maintained by regional councils throughout New Zealand as well as other New Zealand databases related to groundwater (e.g., climate and surface water databases) along with the groundwater portion of the GGW database.

3.2 National Databases

Statistics New Zealand has compiled a "Stocktake for the environment domain plan" (Statistics New Zealand, 2010). Earlier drafts of this document were reviewed in 2009 during the first half year of this project. This document lists a large variety of environmental databases. Those 32 judged to be potentially most indicative of or relevant to climate change are listed in Table 3-1 along with summary information about the types of data monitored, when monitoring started and frequency of sampling, the nature of the monitoring network, and the source. The majority of these (20 of the 32) attempt to address the topics of land use or biological diversity. These have been placed into color-coded groups in Table 3-1 using yellow and green highlighting, respectively. Of the remaining environmental databases, there are nine (not highlighted) having direct relevance to climate change and three (blue highlighting) which are snapshots in time. Two of these, river and groundwater quality, are assessments based on data from other databases not highlighted.

With respect to climate change and freshwater hydrology in New Zealand, the most pertinent databases, because they measure variables that may directly respond to the impact of climate change on hydrologic resources, are:

1. National climate database.
2. End of season snowline.
3. River water quality.
4. Groundwater database (groundwater quality).
5. Water resources archives (river flows river and lake levels).
6. Sea levels.

These databases are all or part of the six entries (entries 1 through 6) within the bolded but not highlighted block at the top of Table 3-1 (the national climate database being found within two of the listings with the second of the two including end of season snowline). Copies of the entry pages for the above databases with relevant metadata are provided in Appendix A. This includes Tables 1.10, 1.11, 1.12, 3.15, 3.5, and 3.13 of Statistics New Zealand (2010). The locations of the 77 NIWA river water quality monitoring sites in NIWA's National River Water Quality Network (NRWQN) are shown in Figure 3-1. Streamflow data are available for each of these sites also. Data may be obtained from this system after registering with NIWA. Metadata descriptions for this database are provided in Appendix A by Table 3.15 from Statistics New Zealand (2010) and entry 14.5 from Froude (1999). Flow for a larger suite of streams and stream and lake water levels are also available online through NIWA's water resources archives. Table 3.13 of Statistics New Zealand (2010), entry 14.1 of Froude (1999), and the opening page of NIWA's Environmental Data Explorer New Zealand (EDENZ) internet site provide relevant metadata information. The locations of national groundwater monitoring programme (NGMP) monitoring wells are shown in Figure 3-2. Metadata descriptions for this database are also provided in Appendix A by Table 3.5 of Statistics New Zealand (2010) and a descriptive internal GNS "database overview." Sea level data are available from both Land Information New Zealand (LINZ) and NIWA. Internet pages for each are provided in Appendix A as well as the opening page of NIWA's EDENZ internet site.

The next three entries in Table 3-1 (entries 7 through 9) are for the GHGs implicated in causing climate change, for soil quality (which may be directly impacted by climate change and subsequently could impact water quality but is not a measure of the hydrologic system), and surface UV radiation. The situation with regard to surface UV radiation is unclear. UV radiation is a relatively small part of total solar radiation, which is one of the variables included in the national climate database. UV radiation is monitored primarily because of health concerns related to excessive exposure. There are competing factors involved with regard to the relationship between solar radiation reaching the earth's surface and climate change and there are uncertainties about the role of solar radiation at this time. Solar radiation reaching the earth's surface was generally declining until the mid-1980s (this decline has been labelled "global dimming"), but has been increasing since 1990. Since an increase in solar radiation would be expected to contribute to climate warming, the decrease in solar radiation prior to the mid-1980s may have masked some of the warming effect of

GHGs. However, it is also believed that warming from climate change will increase levels of aerosols and moisture in the atmosphere (the latter increasing cloud cover) and those changes would be expected to reduce solar radiation (Wild, et al., 2005; Bhatti, et al., 2006; and Science Daily, 2009). Therefore, solar radiation could provide negative feedback to reduce the rate of climate change; but if that were the case it appears inconsistent that solar radiation levels at the earth's surface are now increasing.

The four entries following the soil database entry in Table 3-1 (entries 10 through 13) are for one-off "snapshots" of national water quality in lakes, rivers, and groundwater and what is known of water allocation in New Zealand. However, these one-off snapshots may be updated in the future. For rivers and groundwaters, they provide assessments based on their respective ongoing national databases. For lakes, there is no longer a relevant national database. Although NIWA continues to monitor water levels at some lake sites for commercial clients, NIWA discontinued its lake water quality monitoring program (including water levels) in the 1990s as an economy measure (Schmidt, 2010). Therefore, there is no longer a national approach with regard to lakes and although the limited data NIWA is now collecting for commercial clients could be released, with the client's approval, the only ongoing data publicly available for lakes would be whatever lake monitoring is occurring at the regional level and there is no requirement that any such regional programs be nationally coordinated.

The water allocation snapshot shows that water allocation in New Zealand has substantially increased between the last snapshot in 1999 and this one in 2006. This implies greater usage; however, what is really of interest is actual water use rather than allocation and data in this regard is sparse. To begin with, data on water allocation does not count non-allocated uses. Stock watering, for example, is in this category. More importantly, actual usage is different than allocation and, because it is, precludes accurate water budget calculations without usage data. To the extent that actual usage is less than allocation, allocation provides a conservative measure of possible usage. However, limited data from seven regional councils indicates that actual water use ranges from 20 to 80 percent of allocation. This includes data from the shallow unconfined and lower confined aquifers of the Waimea Plains (see additional details of the hydrogeology of the Waimea Plains in Section 5) for three years including the 2000-2001 year. These data indicate usage approached 80% of allocation during the February to March period of that severe drought year when at the same time of the year during wetter it was closer to 20% (Aqualinc Research Ltd., 2006).

The remaining entries in Table 3-1 fall within two indirect classes: (1) data related to land use change; and (2) data related to biological diversity. These are classified as indirect because whereas they are certainly noteworthy factors with respect to water quality, they are not in a direct linkage between climate change and the hydrologic system.

Once a correlation between climate change and some component of the hydrologic system has been inferred, the influence of other possible causative factors must be considered in the next tier of the analysis. For example, changes in land use may impact water quality whether related to climate change or not. This was found to be the case by Raymond and Cole (2003) and Raymond, et al. (2008) in their study of the increase of alkalinity export from the Mississippi River basin during the 20th Century. They concluded that chemical weathering caused by the same anthropogenic CO_2 emissions involved in climate change was a primary factor producing increased alkalinity export via the Mississippi River. However, they also concluded that changes in land cover and use (specifically, changes in such agricultural practices as liming, tile drainage, fertilizer use, irrigation, tillage, crop type, rotation, and productivity) were also critical factors.

Similarly, while the biological diversity of water resources may be impacted by climate change and thereby be an indicator of it, changes in biological diversity are more likely to be a result of changes in water quantity and to some degree changes in quality produced by climate change than a step in the climate change causal linkage altering water resources. Additionally, changes in biological diversity are not always easy to conclusively document and, when they are documented, may have other causes than climate change (e.g., waste discharges or land use changes). As climate change is expected to increase flow variability in streams, and flow variability is a major factor in the biological diversity of rivers, changes in biological diversity will probably occur and monitoring for various indices of them could provide important information regarding climate change impacts.

3.3 Regional Databases

New Zealand is divided into 16 regional councils for purposes of environmental regulation under the Resource Management Act 1991 (RMA). This includes protection of surface water and groundwater quality and the monitoring of various related components of hydrologic systems. In carrying out these responsibilities, they have established and maintain networks to monitor rainfall, various meteorological variables, streamflow and quality, groundwater levels and quality, soil moisture, sea level, and other environmental variables. Of the 16 regional councils, three are district councils and one is a city council with unitary authority for environmental regulation.

As a part of this project each of the regional councils were contacted and made aware of the research being conducted. At the same time, responsible regional council hydrologic staff were interviewed to obtain information on the nature of the hydrologic monitoring programs currently in operation for which they have established relevant databases. The information obtained in this survey is summarized in Table 3-2. Table 3-2 is divided into three parts:

1. Part a – Identification of the regional council and background information including: (a) whether or not the regional council has established any policies with regard to the impact of climate change on hydrologic systems; (b) what information the regional council relies on for taking land use into consideration (a more detailed description of this aspect of the survey was documented by Zemansky, 2010); (c) whether or not the regional council requires metering and/or reporting of water use by consent holders: and, in some cases, (d) when hydrologic monitoring systems were initiated.

2. Part b – Surface water data including the numbers of gaging stations at which streamflow or spring flow is measured (there must be developed rating curves for these stations) and the numbers of stations at which water levels or stage are measured for streams (because these stations would not have rating curves, flow would not be determined for them but flow would be directly proportional to stage), lakes, or the sea and the number of stations at which stream water quality samples are taken. The number of stations in each region which are included in the national monitoring networks run by NIWA for streamflow and water quality sampling were also tabulated. During this survey, it was found that a similar

survey had recently been performed on behalf of the regional councils and a copy of tabulated results from that survey was obtained from Environment Canterbury. There is a column in Table 3-2b listing the number of streamflow gaging stations for comparison with those reported in the survey that was part of this research project. It can be seen from this comparison that there are substantial differences for some of the regions but that for others the numbers are very close, though generally not identical. Overall, there were 566 stations enumerated in the regional council tabulation of which only 515 were reported as a part of this survey. An additional 130 NIWA streamflow gaging stations exist. Regional council staff were specifically asked to make this distinction in the data they provided. The analytes involved in the stream water quality sampling program are also indicated in this part of Table 3-2.

3. Part c – The numbers of stations at which rainfall and/or other meteorological variables are monitored and the number of wells at which groundwater levels and groundwater quality samples are taken for analysis were listed. These wells would be regional council state of the environment (SOE) wells. Additionally, there are several regions having soil moisture sampling sites and two that have rainfall recharge lysimeters. As with surface waters, the number of NGMP wells for groundwater monitoring sampled in each region are listed for comparison with number of SOE wells. Although regional council staff are actually the ones sampling NGMP wells, they were specifically requested to make this distinction between SOE and NGMP wells in the data they provided. The same regional council survey that had independently reported on the distribution of regional council streamflow gaging stations also compiled numbers on rainfall measuring sites. As with streamflow gaging stations, these two independent compilations of the same information provided substantially different numbers. In this case, the order was reversed and more stations were reported as a part of this survey than had been determined from the regional council one (a total of 647 rainfall sites compared to 602).

3.4 Assessment of Databases for Purpose

National and regional council hydrologic databases have been identified and assessed for the purpose of identifying climate change impacts on hydrologic systems in New Zealand. Particular attention was directed towards those databases directly measuring components of the hydrologic system and previously identified databases of major relevance. As identified in initial GNS Science planning for this project these include:

1. Rainfall and other climate variables from the national climate database as supplemented by additional regional council databases of the same type. This includes end of season snowline data which are part of the climate change monitoring network.

2. River flow and chemistry data as supplemented by additional regional council databases of the same type. This includes river water quality and water resources archives (river flow and river and lake levels) databases maintained by NIWA.

3. The NGMP database as supplemented by additional regional council databases of the same type containing groundwater level and quality data.

4. National scale data related to land use from such sources as the land cover database.

5. Water allocation snapshot.

6. Related economic data on national water use from Statistics New Zealand.

The following summarizes the results of this assessment of available data and related issues covered in the survey of regional councils:

1. Many of the regional councils have acknowledged that climate change has potential to impact hydrologic systems within their regions. For example, the newly issued Regional Policy Statement (RPS) of the Taranaki Regional Council (TRC) contains a discussion of climate change at Section 7.2 in which it is noted that climate change may result in 20% more rainfall and a change in distribution such that large events are more frequent and more severe and, therefore, the incidence of flooding may increase. However, the TRC RPS does not go beyond a general acknowledgement of this potential with a concomitant statement to "avoid, remedy, or mitigate" adverse impacts through "the development and protection of the built environment and infrastructure in a manner that takes into account the potential effects of rising sea levels and more variable and extreme weather patterns" (TRC, 2009). The survey indicated that only two regional councils have instituted concrete policy changes to reflect concerns about the impact of climate change on water resources. One of these, Environment Waikato, has adopted a policy to limit water supply consents to a maximum of 15 years duration due to uncertainty about the future availability of water due to climate change.

2. All regional councils rely heavily on the land cover database (LCDB) system regarding regarding land use decisions within their jurisdictions (LCDB 2 is the current version). Some supplement it with additional information of various kinds (see Table 3-2a and Zemansky, 2010). While LCDB 2 provides national coverage and relevant information, it is limited by the fact that land cover information is not the same as land use.

3. While an increasing number of regional councils are requiring some form of metering and reporting of water use by consent holders (nine regional councils have partial requirements or are beginning to implement metering and reporting), two have no requirements and only five require metering and reporting of water use by all consent holders. In general, requirements for metering and reporting are relatively new and the length of associated databases short. There are also questions about the accuracy of metering and how appropriate reporting and tracking of reported data may be. To be useful, regional councils must have programs to both assure data quality and that data are kept in accessible database format. In some of the most critical areas where metering and reporting would provide necessary useful information (i.e., the Canterbury Region), implementation is just beginning and is not widespread.

4. The national climate database is a nationally significant database that serves as an essential element of any program to identify climate change impacts. It contains data from as early as 1850 from approximately 6,500 climate stations and continues to receive new data as generated from over 600 currently operating climate stations. In many ways this database is exemplary for how such databases should be operated in New Zealand. It was made freely available to the general public in 2007 and can be conveniently accessed online (http://cliflo.niwa.co.nz/). That being said, there are a number of problems with the data available within it. Due to inconsistencies in historic funding regimes and changes in agencies responsible for climate data collection in New Zealand, the amount of data available for any given location varies and may have gaps. Statistics from the Climate Database show, for example, that 37 stations have a record longer than 50 years with better than 80% data availability. This is critical since fruitful analysis of climate data requires long-term records of regularly taken data (with few if any data gaps) and such records on the order of 50 to 100 years are particularly useful (e.g., see Raymond and Cole, 2003). The record for Nelson airport, analysed in Section 4, provides an example of both data gaps and record length issues. Trend analysis was performed for rainfall and Penman potential evapotranspiration (PET) for the Nelson airport. Rainfall and Penman PET data have been collected at the Aero Club station of the Nelson airport since the 1940s. However, there are gaps of three years in the rainfall data and 18 years in the Penman PET data for that station. A new automatic weather station (AWS) was placed into operation in the 1980s, but data from it for rainfall and Penman PET are only complete and usable from 1994 onward. Regional council rainfall and meteorological stations supplement the national climate network and result in a denser database. However, these databases are generally of more limited duration (on the order of 20 years).

5. NIWA maintains national river flow and water quality databases while GNS Science maintains the national groundwater database. As with rainfall and climate data, these are supplemented by additional regional council databases of the same types but also including complete groundwater level data. Water quality information is available for 77 river stations throughout New Zealand via the NRWQN while the NGMP network has 110 wells in it. Streamflow is also available for NRWQN (and other) sites from the same system as it is necessary in proper interpretation of streamflow water quality data. A major limitation in the analysis of these datasets with regard to climate change impacts is that these individual monitoring programs follow separate design principles, which complicates comparisons. For example, the NRWQN network and most Regional Council surface water quality networks were designed to monitor land-use change impacts on water quality rather than general water quality indicators such as major ions. This limits the ability to look for changes in stream water quality that could be related to climate change (e.g., increases in alkalinity) and to explore chemical relationships between surface waters and groundwaters that might also be relevant to that question. As with climate data, inconsistencies in historic funding regimes and changes in agencies responsible for hydrologic data collection in New Zealand have impacted the amount of data available and resulted in substantial data gaps. Hydrometric data collection in New Zealand began in the early-1900s with the collection of lake level data for evaluation of

hydro-electric potential. Regular monitoring of the flow of major rivers on a national level began in the 1930s and was substantially expanded in the 1960s and 1970s. Additional stations were also run by the 20 regional Water Boards that existed by then. By 1992, when NIWA was established, the national network exceeded 500 operational water-level recorders on streams. However, this was reduced soon afterward by 20% due to a funding cut (Pearson, 1998; McBride, 1986). With regard to water quality, the NRWQN for surface water and the NGMP for groundwater were established in 1988 and 1990, respectively. Although streamflow and water quality data existed prior to that time, the length of databases available for surface water streamflow, groundwater levels, and water quality varies is often on the order of a maximum of about 20 years. In general, the number of operational stations has increased with time and, therefore, there are more stations in recent years than there were originally. The short length of these records handicaps assessment of long-term trends. There are also questions regarding data quality and data gaps. For example, a national protocol for groundwater sampling has only been in existence for less than four years (Daughney, et al., 2006) and there appear to be few if any formal programs at regional councils for data quality assurance. GNS Science review of various regional council water quality and level databases has found numerous indications of erroneous or highly unlikely data entries. Some of these could be field errors while others could be transcription errors in the office made when transferring data from field sheets into databases. Errors on the order of 0.5% are common in data entry but can be reduced through institution of appropriate practices (Rajaraman and Samet, 2005). The existence of these apparent errors in the databases does not indicate that concomitant data quality checks and reviews are taking place. There may also be unexplained data gaps. For example, both groundwater quality and level data in the databases of one regional council were found to have an unexplained gap of about two to three years in the 1999 to 2003 time frame.

6. There are only a handful of lysimeters operated by two regional councils that provide data on rainfall recharge direct to groundwater. This provides a very sparse database for such information.

The land cover database and water use information in Aqualinc Research Ltd. (2006) were discussed in Subsection 3.2. Although such information provides something when there would otherwise be nothing, neither serves as an optimum database for the purpose. Economic data on national water use will be covered in Section 6.

4.0 TEST CATCHMENT DATA COMPILATION AND ANALYSIS

4.1 Introduction

4.1.1 Background

The information search and data compilation discussed in Sections 2 and 3 were used in scoping a framework for assessment of the impacts of climate change on hydrological systems in New Zealand and for compilation and analysis of climate and hydrologic data relevant to a test catchment. The test catchment selected was the Waimea Plains in the

Tasman region. The Waimea Plains was considered a suitable test catchment primarily because of the existence of a numerical groundwater model of the catchment and the availability of data pertaining to it (e.g., climate, hydrologic, hydrogeologic, and water use data). The Waimea Plains location is within a part of New Zealand in which models indicate only minor changes are likely to occur as a result of climate change.

This section of this report addresses compilation and analysis of climate and hydrologic data for the Waimea Plains test catchment. Trend analysis was performed using the non-parametric Mann-Kendall method. Hydrological and socioeconomic modelling are then presented in Sections 5 and 6, respectively.

4.1.2 Present Tasman District Climate and Projected Climate Change Impact

NIWA prepared a report for the TDC outlining the present climate of the Tasman District and changes that were possible over the coming century as a result of anthropogenic climate change (Wratt, et al., 2008). This subsection presents a brief summary of key relevant information in that report regarding the present climate of the Tasman District and how it may be altered as a result of climate change. Unless otherwise noted, the presentation in this subsection is based on that report. Climate factors that were considered in this NIWA assessment included:

1. Temperature;
2. Rainfall;
3. Wind;
4. Evaporation;
5. Soil moisture; and
6. Sea level.

4.1.2.1 Present Tasman District Climate

The present mean annual temperature in the Waimea Plains area is about 13 ^{o}C and the median annual rainfall is approximately 1,000 mm. Cooler mean annual temperatures and greater median annual rainfall occur in surrounding areas (on the order several degrees cooler and, at higher elevations, twice as much rainfall). As elsewhere in New Zealand, there is “substantial year-to-year” variability in the climate of the Tasman District. With regard to temperature, these “fluctuations” are as much as 2 ^{o}C and “appear to be superimposed on a long-term upward trend” of around 0.73 ^{o}C between 1908 and 2006. There is also substantial variation in rainfall with annual totals ranging as much as ±40% of the long term median; however, in the case of rainfall there are no “marked long-term trends” apparent.

Natural climate variation in the Tasman District is consistent with the rest of New Zealand. As noted in Section 2.1.2, it is a function of two major factors: (1) the ENSO; and (2) the IPO. The limited available information indicates that positive IPO periods “tend to be a little drier than average” for the Waimea Plains. A positive IPO period was occurring during dry weather in 1982-1983; however, a switch to a negative IPO period occurred just prior to the

2000-2001 record drought year. Wratt, et al. (2008) notes with regard to the Tasman District that “on average summer rainfall for most of the fertile plains adjacent to Tasman Bay (e.g., Motueka and Waimea) is less than normal during El Nino periods and more than normal during La Nina periods.”

4.1.2.2 Climate Change in the Tasman District

NIWA has projected the impact of anthropogenically-induced climate change on the Tasman District by downscaling GCM results from12 GCMs for various emission scenarios. Using mean results of the 12 GCMs for the “middle of the road” A1B scenario, NIWA estimates the following possible impacts:

1. Temperature – General increasing trend for all seasons and on an annual basis.
   a. 1990-2040 period. Increase in the annual mean of 0.9 ^{o}C (between lower and upper limits of 0.2 and 2.0 ^{o}C, respectively).
   b. 1990-2090 period. Increase in the annual mean of 2.0 ^{o}C (between lower and upper limits of 0.6 and 5.0 ^{o}C, respectively).
   c. Extremes - Substantial decrease in average number of frost days and increase in days with the maximum temperature above 25 ^{o}C (an increase on the order of 20 days for either case between 1990 and 2090).
2. Precipitation – General increasing trend for all seasons, except spring, and on an annual basis. Increases or decreases are nearly equally likely for the spring season.
   a. 1990-2040 period. Increase in the annual mean of 2% (between lower and upper limits of -3 and 9%, respectively).
   b. 1990-2090 period. Increase in the annual mean of 4% (between lower and upper limits of -3 and 14%, respectively).
   c. Extremes – There is a potential for heavier extreme rainfall. This is reflected in marginal increases of depth-duration-frequency statistics for the Richmond station of 3 and 7% for the 72 hour duration two year and 100 year recurrence intervals, respectively, between 1990 and 2040 and 7 and 16% between 1990 and 2090. Additionally, drought risk (analysed in terms of potential evapotranspiration deficit) “is expected to increase” with recurrence of “the driest conditions” now happening on average once every 20 years” occurring once every 10 to 15 years or more frequently in the Waimea Plains.

It is also possible that there may be an “overall increase in the annual mean westerly component of (wind) flow across New Zealand” and that sea level will continue to rise.

It has to be noted that these interpretations are only based on projections derived from a single emission scenario and the average of 12 global climate change models. There is much variability among climate change models in particular if they are interpreted in a regional context like this. Only two possible future climate scenarios have been used in this report and this limitation has to be kept in mind while interpreting the results presented.

4.2 Monitoring Data and Trend Analysis

4.2.1 Monitoring Stations and Available Databases

Climate and hydrological monitoring stations that were identified within or close to and relevant to the Waimea Plains are listed in Table 4-1. The institute or agency in charge of the station, station name or location and identification, type of data available from the station, period of data available, and coordinates for each station are indicated in Table 4-1. In summary, the available databases were as follows:

1. Climate –
   a. NIWA – 11 historic and three currently active stations
      1) Rainfall
      2) Temperature
      3) Evapotranspiration
      4) Solar radiation
         a) Solar radiation
         b) Sunshine
      5) Atmospheric water vapour
         a) Cloud cover
         b) Relative humidity
   b. NIWA – climate change emission scenario simulations (two scenarios at four locations)
      1) Minimum daily temperature
      2) Maximum daily temperature
      3) Daily rainfall
   c. TDC – Rainfall at seven stations
2. Surface water –
   a. NIWA – No stations
   b. TDC –
      1) Streamflow – four gaging stations
      2) Stream water quality – samples taken at four stations
3. Groundwater –
   a. GNS –

1) Water level – occasionally reported in three NGMP wells
2) Water quality – samples taken from three NGMP wells

b. TDC – Water level measured in nine wells

4. Sea level – Two TDC historic but no longer active gaging stations

The locations of these monitoring sites are indicated in Figure 4-1. Additional detail with regard to the identification of groundwater level and quality monitoring wells is provided in Figure 4-2.

In addition to the monitoring sites listed in Table 4-1, there were other monitoring sites of various kinds that operated historically or for a limited purpose but are no longer in service. Those that were identified for which there are available records are listed in Table 4-2.

The two sea level gages listed in Table 4-2 were located on the coast near the mouth of the Waimea River and, therefore, close to the Waimea Plains. Because these were not open coastal locations and the periods of available data from them were relatively short, they would not necessarily provide optimum data with regard for consideration of the impact of long-term climate change. Although those gages are no longer in service, there are two sea level gages currently operating in the region at this time. One is at the Port of Nelson and the other is on the open coast at Little Kaiteriteri. The one at Little Kaiteriteri is about 30 km northwest of the mouth of the Waimea River and is operated by TDC as part of the open coast NIWA network specifically intended for long term monitoring of sea level with respect to climate change.

4.2.2 Trend Analysis

4.2.2.1 Background

Assessing the impact of climate change on hydrological systems in New Zealand requires determining if changes in climate consistent with climate change by global warming are in fact occurring and, if they are, analyzing what the impact of those changes on the associated hydrological systems is. This requires determining if there are relevant trends in the data over time. Therefore, trend analysis of time series data becomes the primary methodology utilised. For relatively slow moving long-term trends, as is the expected case with climate change, analysis of annualized data is most frequently the appropriate frequency involved.

Time series climate and hydrologic data generally can be considered to have four components: (1) “a trend or long term movement;” (2) “oscillations about the trend, of greater or less regularity;” (3) “a seasonal effect;” and (4) an irregular or random component” (Kendall, et al., 1983). Therefore, climate and hydrologic data tend to be messy. That is, they reflect variation due to the possible combination of a variety of factors (e.g., trend, intrinsic variation, seasonal variation, variation introduced in the measurement and/or sampling and analysis process, bias introduced as a function of location, and error, including data entry error) as well as missing values, outliers, and in some cases values less than detection limits (Hafley and Lewis, 1963; Legendre, 1993; Longford, 2001). The quality of data found in any database is a function of all of these factors. To the extent possible, extraneous sources of variation in the sampling, analysis, and data management process should be reduced through institution of suitable standard methods and quality assurance practices. Doing so can be expected to result in improved data interpretation (i.e., interpretation of real data and not data errors).

Trend analysis of annualized time series data may be accomplished qualitatively and quantitatively. The qualitative approach consists of visual review of a simple X-Y plot of the data (time on the X-axis and the climate variable of concern on the Y-axis). Such an approach was recently used by McKerchar, et al. (2010) as a primary method of data analysis with regard to declines in annual rainfall and annual runoff on the east coast of the South Island.

The two quantitative approaches to trend analysis are: (1) parametric linear regression; and (2) the nonparametric Mann-Kendall test. The Mann-Kendall test is widely used for trend analysis of environmental data and is implemented in Version 3.00 of the Time Trends computer program developed by NIWA (Jowett, 2009). Although linear regression will often provide similar information, the Mann-Kendall test is generally preferred in the analysis of hydrological data because it has statistical validity whether the data are normally distributed or not (Hipel, 1988; Hirsch, et al., 1991; Helsel and Hirsch, 1992 and 2002; Hipel and McLeod, 1994; Darken, 1999; Ngwenya, 2006; Tennakoon, et al., 2009). The Mann-Kendall method provides only a yes-no answer about trend at a selected level of confidence. Therefore, it is paired with the Sen's slope method for estimation of the magnitude of the rate of change of the variable of concern with time (Brauner, 1997). Both the Mann-Kendall test and linear regression are automatically implemented by the GNS spreadsheet calculator for processing water quality data, which also provides values for the rate of change; Sen's slope for the Mann-Kendall test and slope for linear regression (Daughney, 2007a and 2007b). For both methods, the trends are represented as straight lines for assumed monotonically increasing or decreasing data.

There are two types of trend "commonly considered" in the literature: monotonic and step change. However, monotonic trend is "usually... the hypothesis of interest" (Darken, 1999). Strict interpretation of monotonic trend means that Y values (the hydroclimate variable of interest) consistently increase or decrease with increasing X values (time). However, in practice as noted above, environmental data often exhibit some degree of oscillation or variation instead of a strictly consistent trend. Although both linear regression and the Mann-Kendall test are intended for application to monotonic trend data, this fact has not hindered their application to environmental data. Recent research has, however, indicated that application of these methods requires a greater degree of judgement then merely calculating results for the available monitoring data. For example, if the record incorporates oscillations and is too short (i.e., less than three cycle lengths), analysis may indicate results that are incorrect in both magnitude and direction (Chen and Grasby, 2009). There is also some support for dividing the record into several shorter linear trends in the case of a lengthy non-linear or non-monotonic record (Tome and Miranda, 2005; Shao, et al., 2010). Although the overall trend for a given time period may be in one direction, analysis of the data for segments of that time frame may show trends in opposing directions.

An example of the application of linear regression and the Mann-Kendal test with Sen's slope for trend analysis is presented in Figures 4-3, 4-4, and 4-5 for Wairoa River streamflow at the Irvines gaging station. Figure 4-3 shows an X-Y plot of the streamflow data. Both monthly mean and annual mean data provided by TDC are plotted in black with the heavier black line representing annual mean data. A red line shows the result of simple linear regression of monthly mean data. It is evident from these plots that there is at least a marginal downward trend over the 18 year period of record.

Although the results are not considered statistically significant, the downward trend is also evident in the Mann-Kendall test plots of Figures 4-4 and 4-5 for monthly and annual mean data, respectively. In contrast, if the data are divided into time period segments, other conclusions become apparent. In this case, it is evident that analysis of only the monthly data from 2005 onward indicates an increasing trend (Figure 4-6). This increasing trend is of relatively large magnitude and is statistically significant at the 95% confidence level ($p = 0.03$).

In this report, data were analysed using the Mann-Kendall test and the magnitude of any trend calculated using Sen's slope method as implemented by Version 3.00 of the Time Trends computer program. Figures 4-4, 4-5, and 4-6 are output plots from Time Trends. Other plots presented in this section (Figures 4-3 and Figures 4-7 through 4-13) were produced with Version 5.0 of the Grapher computer program and show indications of trend or correlation by use of linear regression. This was done for convenience of graphical illustration rather than statistical analysis. However, in most cases the straight lines of linear regression and Sen's slope are very similar (e.g., see slope values listed in Table 4-11).

The criterion used to consider results statistically significant is to some degree a matter of judgement. In this project, levels of significance consistent with those recommended by Newell, et al. (2007) and utilized by Griffith (2006) have been used. They are: (1) "statistically significant" for a level of significance less than or equal to 5%; and (2) "weakly significant" for a level of significance greater than 5% but less than or equal to 10%. There were few weakly significant results. Results tended to either be statistically significant at the 5% level or were not significant at the 10% level.

4.2.2.2 Climate Trend Analysis Results

Trend analysis was performed for the available NIWA and TDC climate databases listed in Subsection 4.2.1. Data were qualitatively assessed via visual examination on an X-Y plot (i.e., a scatter plot) for trend and then analysed for trend using the Mann-Kendall test. The rate of change of the trend was quantified by calculation of the Sen's slope. This was accomplished using NIWA's Time Trends programme (Jowett, 2009). When checked against other computer programmes that implement the same methods, identical results were obtained (e.g., WQStat+).

It should be noted that climate change trends are superimposed on IPO-related natural variability. Natural climate variability is over timescales on the order of several decades and, therefore, may be of similar magnitude as changes that may have resulted from "global warming." Hence shorter term (decadal) trends can be in the opposite direction of long term projected climate trends. Most of the trend analysis carried out in this section are for data sets on the order of 30 years or less long and tend to start during one phase of the IPO and finish during another. Hence we do not expect perfect consistency in the short term (decadal) trends identified in this section with long term climate projections.

The climate data analysed included rainfall, temperature, evaporation, and solar radiation data as well as data indicating the level of atmospheric water vapour (relative humidity and cloud cover). Results for these variables are summarized in Tables 4-3, 4-4, 4-5, 4-6, and 4-

7, respectively. With reference to the summary information in those tables, results were as follows:

1. Temperature

   Temperature data are available as mean daily, monthly, and annual values. Mean annual values were used to calculate trends for three currently active NIWA sites (Nelson Aero and Nelson AWS at the Nelson airport and Appleby 2 EWS). In addition, a compilation of data from multiple sites in the Nelson area is one of the stations comprising a "seven stations" temperature database that has been developed by NIWA with regard to climate change assessment in New Zealand (NIWA, 2010a). The compilation from Nelson sites included in the "seven stations" database was also analysed for trend. This compilation included various years of temperature data from two of the current monitoring sites (Nelson Aero and Appleby 2 EWS).

   Results generally indicated increasing trends (see Table 4-3). With the exception of the Appleby 2 EWS site, the rate of increase indicated by Sen's slopes ranged from about 0.01 to 0.3^{o}C/year. For the single station with the longest record (Nelson Aero), the rate of increase was about 0.02 ^{o}C/year or 1^{o}C over a 50 year period. Results for stations with the longest (Nelson Aero) and shortest (Appleby 2 EWS) records were statistically significant at the 5% level, as was the result for 1908-2008 data from the Nelson "seven stations" series compilation.

   Analysis of historic NIWA data, from NIWA's virtual climate station network (VCSN), and climate change simulations developed by NIWA at the same locations indicated similar results for three of the four locations (the TDC Nursery-Chipmill, Irvines, and Redwood locations). These were uniformly decreasing temperature trends (not significant at the 10% level) for each of the three individual periods (historic, 2030 through 2066 - nominally 2040, and 2080 through 2116 - nominally 2090) and a strong increasing trend for the data plotted as a whole over the entire 1972-2116 time frame (see Figure 4-7). In the latter case, the trend was statistically significant at the 5% level (see Figure 4-7 for an example plot of A1B emissions scenario temperature results). The values used for this trend analysis were annual means calculated from daily minimum and maximum temperatures. Note that the trends for the individual three periods are the same, as the projected time series are derived from the historic VCSN time series by scaling.

   For the TDC Nursery-Chipmill location, trends were also calculated for annual means of daily minimum and maximum temperatures from historic or emissions scenario simulation results. Analysis of these annual means generally indicated statistically significant decreasing trends for minimum temperatures and increasing trends for maximum temperatures in each of the three periods at the 5% level (historic, 2040, and 2090).

   In the case of the Livingston location, all trends were found to be increasing, although only the overall 1972-2116 period trends were statistically significant at the 5% level. In general, the trends for the overall 1972-2116 period were close to 0.02^{o}C/year or 1^{o}C in 50 years.

NIWA's VCSN values are spatially interpolated from nearby actual climate stations. This allows NIWA to estimate daily values of minimum and maximum temperature, rainfall, PET, and other climate variables (NIWA, 2010b). The Appleby 2 EWS station on the west side of the Waimea Plains commenced operation in 2001 (the first complete year of data being 2002). Comparison of temperature data indicates that maximum temperatures at the Appleby 2 EWS station are similar to those from other nearby stations (e.g., Nelson AWS at the Nelson airport) but minimum temperatures are "about" 2 ^{o}C lower. The reason for this anomaly is uncertain, but it has led NIWA to caution data users about this circumstance (Schmidt, 2010). Table 4-3 shows that the median annual minimum temperature for the period of record (2002-2009) at the Appleby 2 EWS station was 2.35 ^{o}C lower than the equivalent median annual minimum temperature for the Nelson AWS station. Hence the identified downward trend in mean and minimum temperatures for the TDC Nursery-Chipmill location (Figure 4-7) is likely to be a measurement artefact rather than "real." Similar downward trends in mean temperatures for "historic" NIWA data forming the basis of climate change simulations for both emissions scenarios were evident at the Irvines and Redwoods locations, but not the Livingston one (see Table 4-3).

2. Rainfall

Rainfall data are recorded as actual amounts over time throughout the day and available as compiled daily, monthly, and annual totals. Annual totals for three currently active NIWA stations and six of the seven TDC stations were analysed for trend. Due to the limited time in service, there were insufficient data for such trend analysis from the TDC Nursery station.

Results generally indicated decreasing, but not statistically significant, trends at the 10% level, with trend rates of around -11 mm/year (see Table 4-4). The only statistically significant trend was a decrease of about 12 mm/year for the TDC Birds station on the south end of the Waimea Plains (see Figure 4-1). An increasing trend of about 11 mm/year was indicated for data from NIWA's Appleby 2 EWS site. Small but increasing trends were also indicated for two TDC sites: (1) the Richmond office; and (2) the Trig F site in the mountains to the southeast of the Waimea Plains. These trends were not statistically significant at the 10% level. As noted above, there is an unexplained circumstance with regard to minimum daily temperature at this relatively new station.

Analysis of NIWA historic and climate change simulations for all four locations indicated, with one exception, uniformly decreasing trends on the order of 3 mm/year, but none of these were statistically significant at the 10% level (see Table 4-4). For example, when historic and emissions scenario A1B simulation results were analysed over three periods (historic, 2040, and 2090), trends for individual periods were not statistically significant but appeared to be decreasing (see blue lines in Figure 4-8). This was in contrast to the weak increasing trend indicated for the entire 1972-2016 time frame (see red line in Figure 4-8), also not statistically significant at the 10% level.

As discussed above, we do not expect decadal scale trends to be consistent with projected long term climate trends.

In summary, overall analysis of historic data indicates that rainfall in the Waimea Plains may have slowly decreased while, in contrast, NIWA simulation results indicate that rainfall may increase a small amount with climate change.

3. Evaporation

Evaporation is estimated daily from measurements (e.g., pan evaporation) or calculated from other relevant climate data (e.g., temperature, wind speed, relative humidity, and solar radiation) in several ways. Estimates of evaporation from pan data are generally considered to be higher than actual and, for that reason, when used to estimate evapotranspiration, are multiplied by a “pan coefficient” with a value less than one. A value for the pan coefficient of 0.7 is considered representative of central tendency (Brouwer and Heibloem, 1986; Allen, et al., 1998).

Evapotranspiration may also be calculated from other relevant climate data. The Food and Agricultural Organization of the United Nations (FAO) has adopted use of the Penman-Monteith equation as the standard method for doing so with regard to agricultural considerations (Allen, et al., 1998). When done for a reference grass crop, this is referred to as reference evapotranspiration (ETo) (Allen, et al., 1998). NIWA uses the Penman equation for calculating potential evapotranspiration (PET) at its climate stations.

NIWA pan evaporation and/or calculated PET data were available for two stations at the Nelson airport. These were compiled into annual totals. Results of analysis of these data for trend are summarized in Table 4-5. In all cases, the indicated trend is an increasing level of evaporation. All except for Priestly-Taylor PET at the Nelson Aero station were statistically significant at the 5% level or weakly significant at the 10% level. The raw data and linear best fit lines for Penman PET data at these two stations are plotted in Figure 4-9. Unfortunately, there is a major gap of 18 years in the most recent data from the Nelson Aero station (Station #4241 with data points joined by a black line). This precludes comparison with the recent data for the Nelson AWS station (Station #4271 with data points joined by a green line). It can be seen from the linear lines of best fit (red lines for the overall data of both stations), that although the overall increasing trend for station #4241 data (1949 through 2009) is not as steep as it is for station #4271 (1994 through 2009), when the data for station #4241 are divided into two periods (1949 through 1974 and 1975 through 2009), the trend for the earlier period (blue line) is similar in magnitude to that of station #4271 overall. These trends are substantial, about 4.5 mm/year or 225 mm over 50 years. It can also be seen that despite the increasing trends indicated for the earlier period of station #4241 data and for station #4271 data, there is roughly a 15 year period for station #4241 data (1970-1985) where the trend is clearly decreasing. In this case, application of the Mann-Kendall test to data for the full period of record at station #4241 doesn’t appear appropriate because the test is intended to detect monotonic trends while it is visually evident that is not the case.

4. Solar Radiation and Sunshine Hours

Before considering analysis of surface solar radiation data for the Waimea Plains, some preamble about the potential effect of climate change on surface solar radiation levels is useful to consider. This is a complex issue that cannot be considered in isolation from other associated factors including the composition of the atmosphere. Key atmospheric composition variables include greenhouse gasses (GHGs), of which water vapour is the most important, and aerosols. "Aerosols can perturb atmospheric radiation through the direct effect of scattering and absorption of radiation, and indirectly via interaction with cloud" (Luo, 2004). When water vapour in the atmosphere becomes supersaturated, it can condense rapidly on ambient particles provided by aerosols known as cloud condensation nuclei (CCN). These are released to the atmosphere by both natural and anthropogenic sources.

Clouds play an important role in the radiant energy balance of the earth. Aerosols do also, both directly and in terms of their role in cloud formation. (VanReken, 2004; Forester, et al., 2007; Murphy, et al., 2009; Stewart, 2009).

There is a complex linkage between surface solar radiation and atmospheric water vapour content. "Water vapour is the most abundant greenhouse gas in the atmosphere" (NCDC, 2010) and inputs of water vapour by evaporation from open water surfaces (e.g., streams, lakes, and oceans) is an expected consequence of global warming. Because the warmer atmosphere can hold more water, an increase in absolute humidity would be expected to accompany global warming and in fact there are data indicating that total column water vapour has increased since 1970. There are positive and negative feedback loops associated with increased water vapour in the atmosphere and substantial scientific uncertainty about them. Higher concentrations of water vapour mean that more thermal infrared energy radiated from the earth can be absorbed, which would warm the atmosphere. However, it also means that more clouds will form from this water vapour, reflecting incoming solar radiation and thereby causing cooling. Existing data on global atmospheric water vapour levels is limited and incomplete; however, what there is "indicates generally positive trends in global water vapour" (NCDC, 2010; Trenberth, et al., 2007).

Surface solar radiation data show "A decline in solar radiation at land surface (referred to as dimming)... in many observational records up to 1990... and a widespread brightening... since the late 1980s" (Wild, et al., 2005; Trenberth, et al., 2007; Science Daily, 2009). Data from New Zealand are consistent with this global pattern (Liley, 2009). There is less clarity and more irregularity regarding the occurrence and role of aerosols in climate change. In some cases, anthropogenic aerosol concentrations may have declined as a result of air pollution control requirements while an important natural source of aerosol emissions is the occurrence of volcanic eruptions (e.g., the eruption of Mt. Pinatubo in the Philippines in 1991). As has been authoritatively stated, "aerosol effects on climate, particularly via their influence on clouds, currently represent the most uncertain forcing of climate change" (Trenberth, et al., 2007).

Solar radiation data are available as hourly, daily, monthly, and annual total values of global radiation (combined solar and diffused sky radiation impacting the earth's surface). Annual data from three currently active NIWA sites (two at the Nelson airport and Appleby 2 EWS) were analysed for trend. Results are summarized in Table 4-6. It can be seen that the available data are sparse, particularly for the Appleby 2 EWS station, and do not cover the same period for the three sites. The longest time frame of available data was for station 4241 (a 31 year period staring in 1969); however, there are seven years for which data are missing and measurements at that station were discontinued in 1999. In addition to the raw data from all three stations, three synthetic data sets were made by putting all of the data from stations 4241 and 4271 into a combined set and then dividing it into two periods (the early period from 1969 through 1989 and the late period from 1989 onward). This division was based on the apparent bifurcation of the data set evident through visual review. In making this combined data set, the two overlapping data points (for years 1998 and 1999) were filled using station 4271 data (marginally higher than the two station 4241 data points not used).

Results for the three sites indicated decreasing solar radiation trends for older data from station 4241 and newer data from the Appleby 2 EWS station; however, only the former indication was statistically significant at the 10% level. In contrast, an increasing trend was indicated for newer data from station 4247, but it was not statistically significant (at the 10% level).

As shown in Figure 4-10, the combined data for the Nelson airport indicates a non-monotonic sequence with solar radiation decreasing until 1989 and then increasing. If the combined data are analysed as a whole, the overall trend is a relatively small decreasing one (this trend is statistically significant at the 5% level). However, when the data are divided into early and late periods, the trends are decreasing for the early period (this trend is statistically significant at the 5% level) and increasing for the later period (this trend is statistically significant at the 5% level).

This bifurcation of the data and determination of trends for two sequential time periods is consistent with both the solar radiation data for Nelson and the world wide trends discussed above.

Data are also available on sunshine in the Waimea Plains area. As with solar radiation, these data are available as hourly, daily, monthly, and annual total values. Such data are only available for two NIWA sites: (1) the Nelson Aero site at the airport; and (2) the Appleby 2 EWS site. However, there are insufficient years of data for the latter site to analyse for trend. Annual data for the Nelson Aero site were analysed for trend. Results are summarized in Table 4-6. Data for the entire 1949 through 2009 period indicate a statistically significant increasing trend at the 5% level. However, if the data are bifurcated in the same manner as solar radiation data were (see Figure 4-11), a small decreasing, but not statistically significant (at the 10% level), trend is indicated for early data (1949-1989) with a substantial and statistically significant increasing trend (at the 5% level) for late data (1989 through 2009). This indicates that both total hours of annual sunshine and annual solar radiation data for this site appear to be bifurcated in a common fashion. The direction of the overall trend is different, but this is not because the general trend of the data for early and late time periods is different but rather reflects a substantially steeper slope for early time solar radiation than for sunshine.

5. Atmospheric Water Vapour

The discussion on water vapour in item four above is incorporated with regard to this item also. There are two measures of atmospheric water vapour routinely monitored at NIWA weather stations in New Zealand. These are: (1) relative humidity; and (2) cloud cover. Daily values of relative humidity at 9 am are used to calculated monthly and annual means. Such data are available from four stations in or near the Waimea Plains (including two at the Nelson airport). Data are also available for daily mean cloud cover from two stations. These were used to calculate monthly and annual means. A summary of the available data and results of trend analysis are presented in Table 4-7. Table 4-7 shows the following with regard to trend:

a) Relative humidity – Analysis indicates an increasing trend for three of the four stations when the data are analysed for the total period at each station. However, the trend is statistically significant at the 5% level in only one case (Appleby) and monitoring at that station was discontinued after 1995. Visual assessment of the scatter plot for data from the Appleby station as well as the station with the longest record (Nelson Aero) indicates that the trend may not be monotonic. If the data are divided into two periods (before and after 1990), the apparent trend for the later period becomes decreasing, which is consistent with analysis of data from the Nelson AWS station. The time frame involved may also show an inverse relationship with the trend for solar radiation.

b) Cloud cover – Analysis for the two stations with cloud cover data provides no indication of any trend at one (Appleby) but a statistically significant decreasing trend (at the 5% level) at the other (Nelson Aero).

In addition to trend, four climate variables (temperature, rainfall, PET, and solar radiation) monitored at the AWS station located at the Nelson airport were analysed for linear correlations. Results from this analysis are presented as scatter plots in Figure 4-12 and summarized in Table 4-8.

In the scatter plot on the left hand side of Figure 4-12 (part a), rainfall, PET, and solar radiation data on the y-axis are plotted in relation to temperature on the x-axis. The best indication of correlation is the positive correlation between PET and temperature. There may also be a positive correlation between solar radiation and temperature, but the solar radiation data are more widely distributed with respect to temperature than the PET data are.

In the scatter plot on the right hand side of Figure 4-12 (part b), the most evident trend of any variable with time is that PET is increasing. There also appear to be increasing trends for temperature, and solar radiation and a decreasing trend for rainfall. Trends of similar magnitude and direction were found by nonparametric analysis (Tables 4-3, 4-4, 4-5, and 4-6).

4.2.2.3 Surface and Groundwater Trend Analysis Results

Trend analysis was performed for the available GNS and TDC databases listed in Subsection 4.2.1. Streamflow and groundwater level data were qualitatively assessed via visual examination on an X-Y plot (i.e., a scatter plot) for trend and then analysed for trend using the Mann-Kendall test. The trend rate of change was quantified by calculation of the Sen's slope. This was accomplished using NIWA's Time Trends programme (Jowett, 2009). Stream and groundwater quality data were analysed using GNS's spreadsheet calculator (Daughney, 2005 and 2007). Therefore, the slope of the linear regression line of best fit was also calculated for stream and groundwater quality data.

Trend analysis results for stream flow, surface water quality, groundwater levels, and groundwater quality are summarized in Tables 4-8, 4-9, 4-10, and 4-11, respectively. With reference to the summary information in those tables, results were as follows:

1. Streamflow

   Streamflows are continuously measured by TDC at four stations: the Waimea River at the TDC Nursery location and upstream tributaries (the Belgrove and Livingston locations on the Wai-iti River and the Irvines location on the Wairoa River). Data from these stations are entered into the streamflow database as mean daily values. These were used to calculate mean monthly and annual values for trend analysis at all sites except the Waimea River at the TDC Nursery station. The longest available record of any of these stations was for the Wairoa River at Irvines. This consisted of data from 1958 through 1992 at one location and data from another location after the station was moved approximately 1 km upstream for 1992 through 2009. TDC notes that there is only "one small creek in between," which TDC does not consider substantial, and treats the data from these two stations as one (Doyle, 2010). For other streams, the period of record varied from roughly five to 20 years. For stations like the Waimea River at TDC Nursery where the record was for only a five year period, data were insufficient to perform trend analysis on an annual mean basis. With regard to Wai-iti River flow data, TDC considers data quality for both the Belgrove and Livingston locations as less than optimum due to bank profile or unstable bank conditions (Thomas, 2010).

   Results for streamflow trend analysis are presented in Table 4-8. Trends for mean annual data for all three of the upstream tributaries appear to be decreasing (using all data for the two stations on the Wai-iti River and only the later 1993-2009 data for the Wairoa River after the station was moved). Results for the Wai-iti River stations, but not the Wairoa River, were statistically significant at either the 5 or 10% level. However, when data for the 1958-2009 period from the Wairoa River at Irvines were analysed, no trend at all was indicated. In the case of mean monthly data, trends for the Wai-iti River at both Belgrove and Livingson were also decreasing and statistically significant at either the 5 or the 10% level. This was also the case for the later time Wairoa River at Irvines data after the station was moved.

In contrast, there was a statistically significant increasing trend at the 5% level for mean monthly flow of the Waimea River at the TDC Nursery station. Since data were only available for the 2005 through 2009 period in that case, data for that time frame only were also analysed for the Wairoa and Wai-iti Rivers (at Irvines and Belgrove, respectively). It was found that in both cases there were statistically significant increasing trends indicated at either the 5 or 10% level. As all data from all three rivers indicate increasing trends for the 2005 through 2009 period, the explanation for this contrasting situation with analysis of longer term data, would appear to be the time period involved.

Trend rates also varied considerably. However, the median annual increase of 1.21 m^3/sec for Wairoa River streamflow during the 2005-2009 period was similar to that for the Waimea River of 1.23 m^3/sec (the Wairoa River supplies most of the flow of the Waimea River). The trend slope for the Wai-iti River at Belgrove during the same time frame and trend slopes for both the Wai-iti and Wairoa Rivers were much smaller when complete data sets for them over longer time periods were analysed.

2. Stream Water Quality

Water quality samples are taken by TDC at four surface water sampling stations on a quarterly basis. These included stations at (the Wairoa River at Irvines and the Wai-iti River at Livingston) or near (the Wai-iti River at Pigeon Valley Road and the Waimea River at the Appleby bridge) the four stations at which flow is measured. The variables are conductivity, pH, and temperature, measured in the field during sampling, and the laboratory analysed nutrients nitrate-nitrogen (NO_3-N) and dissolved reactive phosphorus (DRP). Unadjusted raw data for all variables were analysed for trend. In addition, flow adjusted data for conductivity, and nutrients were also analysed for trend.

Results for water quality trend analysis are presented in Table 4-9. For the four streams involved they indicate the following:

a) Wairoa River at Irvines – There was an increasing trend for flow-adjusted nutrients (NO_3-N and DRP) and for unadjusted DRP at the 5% level. There were no statistically significant trends for other variables (unadjusted or flow-adjusted) at the 10% level.

b) Wai-iti River at Livingston – The only flow-adjusted trend that was significant at the 10% level was a decreasing trend for conductivity. Statistically significant increasing trends were also indicated for unadjusted pH and temperature data at the 5 and 10% level, respectively.

c) Wai-iti River at Pigeon Valley Road – There were no statistically significant trends for any variable at the 10% level.

d) Waimea River at SH60 (Appleby Bridge) – For flow adjusted data, there was an increasing trend for conductivity (at the 10% level) and a decreasing trend for DRP (at the 5% level). There was also a decreasing trend for unadjusted DRP data (at the 5% level).

The decreasing trend for conductivity and increasing trend for pH are inconsistent with what would be expected as a result of climate change (i.e., in the opposite direction in each case). But, obviously, the increase in temperature would be consistent. The increases in nutrients for the Wairoa River at Irvines and the decrease in DRP for the Waimea River at the SH60 Appleby Bridge are inconsistent with expectations for climate change and more likely to represent the kinds of land use impacts the stream water quality monitoring program was intended to detect.

3. Groundwater Levels

Groundwater levels are monitored on a monthly basis by TDC in nine wells. As indicated in Tables 4-1 and 4-10, the open interval for six of these wells is the shallow Appleby Gravel Unconfined Aquifer (AGUA). One is open across both the AGUA and the Upper Confined Aquifer (UCA) and the one is open in the Lower Confined Aquifer (LCA). The ninth is a deep well in the Redwood area to the west of the Waimea Plains. Additionally, water levels are measured in the three NGMP wells having open intervals in each of the three aquifers under the Waimea Plains (AGUA, UCA, and LCA). However, water level data for these wells is only irregularly available in the GNS database. These data are too irregular to analyse for trend.

Mean monthly groundwater level data (in mm above mean sea level datum) for the nine TDC wells were analysed for trend. Results of this analysis are summarized in Table 4-10. Table 4-10 also indicates the time frame for which data exist for each well and the amount of missing data involved. It would be expected that if climate change is impacting groundwater levels the effect would first be seen in the shallowest aquifer (the AGUA) of a multi-layer aquifer system like the Waimea Plains (Bates, et al., 2008; Taylor and Stefan, 2009; Kingston and Taylor, 2010). However, the situation is more complex than that because substantial recharge occurs both from rainfall and stream inputs. The open interval for six of the nine wells was in the AGUA. Statistically significant results at the 10% level occurred for only half of these. They were split between increasing water levels for two wells (Ferguson and McCliskies) and decreasing for one (CW2). The Ferguson well is located inland while the McCliskies well is located near the coast. Well CW2 is further from the coast than the McCliskies well. The data set for the well with the decreasing trend (CW2) is the longest of any of the six AGUA wells (the 35 year period of 1975-2010). The Sen's slope and slope of the linear regression line indicate a rate of decline in the 8 to 9 mm/year range. Of the wells with increasing trends, the length of record was longest for McCliskies (the 12 year period of 1998-2010). The Sen's slope and slope of the linear regression line for this well indicate a rate of increase of 16-17 mm/year.

Plots of the data for both wells (McCliskies and CW2) are presented as black lines in Figure 4-13. They show an annual oscillating pattern with higher groundwater levels in the winter and lower in the summer. The lowest level for both wells occurred in the summer of the severe drought that occurred during water year July 2000-June 2001. Also shown on Figure 4-13 are linear regression lines for the two complete data sets (in red) and a linear regression line for the later 12 years of CW2 data (in green). Analysis of only the later 12 years of CW2 data indicates an increasing trend (albeit one that is not statistically significant). This is also evident in the linear regression lines shown in Figure 4-13 (red line for McCliskies well and green line for CW2). Therefore, it appears that the increasing trend in the McCliskies may not really contrast with the overall decreasing trend in well CW2 and, instead, may only be a function of the time period of analysis.

Other possible factors that could influence these trends are river bank changes (due to proximity to the Waimea River) or, in the case of McCliskies well, sea level rise (due to its proximity to the coast). However, a general decline of groundwater levels in the AGUA over the longer term in combination with a short term increasing trend for McCliskies, biased at least in part by the record drought year near the beginning of the available data for it, is a reasonable interpretation of the data.

Data for the three deepest wells were also analysed for trend. These were: (1) the Rail Reserve well open across both the AGUA and UCA; (2) the Chipmill well open in the LCA; and (3) the Redwood Lane well, a deep well to the west of the Waimea Plains. Statistically significant decreasing trends at either the 5 or 10% level were indicated for all three of these wells.

4. Groundwater Quality

Water quality samples are taken from three NGMP wells in the Waimea Plains. These are implemented in each of the three aquifers involved (AGUA, UCA, and LCA). The period of record for these wells was 14 years for the well in the AGUA and 20 years each for the UCA and LCA wells. As noted above, Results for water quality trend analysis are presented in Table 4-11. The only statistically significant trend at the 10% level for data from the well monitoring the AGUA was an increasing one for sulphate. Because sulphate is a constituent of some farm chemicals, such use is a potential source of groundwater contamination in agricultural areas.

With regard to the UCA and LCA, statistically significant trends were indicated for a number of variables in each at the 5 or 10% level of significance. These trends were generally decreasing for samples from the UCA well (nine variables including pH and all major ions) and increasing for samples from the LCA well (seven variables including conductivity, calcium and magnesium, major anions, and ammonia-nitrogen). There is no readily evident reason why such changes would have any relationship to climate change and particularly in these deeper aquifers in the absence of commensurate changes for the shallow AGUA.

5.0 GROUNDWATER-SURFACE WATER INTERACTION MODELLING

5.1 Introduction

5.1.1 Waimea Plains Hydrology

Fundamental information on the hydrology of the Waimea Plains was presented in Section 4 (see Figure 4-1). The surface water system consists of the two rivers which meet downstream and to the north of Brightwater to form the Waimea River. The Waimea River then flows northward across the Waimea Plains into Waimea Inlet on the western edge of Cook Strait and into the Tasman Sea. The two tributaries forming the Waimea River are the Wairoa River, which flows northwestward out of the mountains from the southeast, and the Wai-iti River, which flows northeastward from the valley extending to the southwest of Brightwater. The Waimea Plains is underlain by a groundwater system composed of three productive aquifer layers connected to and recharged by the surface water system as well as by rainfall.

5.1.2 Types of Modelling

Two types of groundwater-surface water interaction modelling of this system were performed as a part of this project: (1) conventional mechanistic numerical modelling using the U.S. Geological Survey's (USGS) MODFLOW finite difference model; and (2) artificial intelligence (AI) modelling using various algorithms as implemented by MATLAB. AI modelling was also utilized to provide input information for MODFLOW.

A summary of the types and purposes of modelling performed is presented in Table 5-1. Water usage, rainfall recharge, and Wairoa River flow at Irvines were modelled using AI methods with results from this modelling utilized as input information for both MODFLOW and other AI modelling. AI modelling of Wairoa River flow was also used as input information for AI modelling of both Waimea River flow and the groundwater level at McCliskies well. With the above AI inputs, MODFLOW was also used to model Waimea River flow and the groundwater level at McCliskies well. The contribution of the Wai-iti River to Waimea River flow is much less than that of the Wairoa River. Mean flows for the periods of record for the Wai-iti River at Belgrove (1988-2009) and Wairoa River at Irvines (1993-2009) are 15.7 and 1.23 m^3/sec, respectively, and the Wai-iti River is frequently either dry or has flows on the order of a few tenths m^3/sec during the warm season of the year. Therefore, since it is not determinative, AI modelling of Wai-iti River flow was not conducted.

5.2 MODFLOW Modelling

5.2.1 Introduction

MODFLOW is a three-dimensional, modular, block-centered, finite-difference computer program developed by the USGS in the early-1980s to simulate groundwater flow in porous media. Since initial development, it has been upgraded and its capabilities substantially expanded (McDonald and Harbaugh, 1988). Models produced by such programs are frequently referred to as mechanistic, numerical models because in solving the mathematical equations of groundwater flow they simulate the hydrological processes associated with that flow (e.g., rainfall recharge, the hydraulics of flow through porous media, and relationships with associated surface waters) to provide quantitative results at nodes located throughout the model domain.

5.2.2 Initial Computer Modelling (Prior to 1990)

Groundwater in the Waimea Plains was first modelled by Fenemor (1988). Fenemor used a finite-difference, numerical model that had been developed by Trescott (1975) of the USGS. Trescott's model was one of the new wave of numerical models replacing the analog electrical models in use since the 1950s that had been composed of networks of resistors and capacitors. Trescott's model was the first capable of simulating three-dimensional flow (Provost, et al., 2009). Fenemor's model represented the Waimea system by three layers of 20 x 46 nodes with a uniform square grid spacing of 487 m. The grid was oriented in a southwest to northeast direction roughly parallel to the general direction of ground water flow in the Waimea Plains (see Figure 4-1). Fenemor's model established the basic configuration of the groundwater system under the Waimea Plains still in use today. His system consisted of three layers: a shallow unconfined aquifer, the Appleby gravel unconfined aquifer (AGUA); and two confined aquifers, an upper (UCA) and a lower (LCA). The AGUA ended in the Delta Zone just beyond the coast while the LCA extended beyond Rabbit Island (Fenemor, 1989).

5.2.3 GNS MODFLOW Modelling

5.2.3.1 Aquifer Representation, Properties, and Boundaries

White and Murray (1998) converted the Fenemor model to the USGS MODFLOW model in the late-1990s. By the that time, MODFLOW was becoming widely used and could be considered to be industry-standard. They implemented it using the Groundwater Modelling System (GMS) platform. This software has both pre- and postprocessor capability. In doing so, they reduced cell size to a 250 m square. The smaller cell size was used to improve performance of the model at its boundaries. Many aspects of the Fenemor model were retained, including the general areal extent of the model and the use of three layers to represent the AGUA, UCA, and LCA. Improvements in addition to reduction of cell size included extension of the model boundary seaward at the downgradient end of the first layer (AGUA) by approximately 2 km to terminate in the vicinity of Rabbit Island. The first layer was also extended a short distance to the west in the Redwoods Valley area (White, 1997 and White and Murray, 1998). MODFLOW layer grids are shown in Figures 5-1 through 5-3.

The White and Murray (1998) MODFLOW model of the Waimea Plains utilized the RIVER package to simulate the three streams. This was replaced by the STREAM package in 2000. The STREAM package is an improved way of representing streams in MODFLOW (Hong, 2000). The STREAM package "is a combination of a known flux and head-dependent flux boundary" that is more "sophisticated" than the RIVER package "because it considers the flow rate in the stream and limits the leakage between the aquifer and the stream accordingly." The STREAM package increases streamflow in gaining reaches of streams and reduces it in losing reaches. The main disadvantage of the STREAM package is that it requires much more "intensive preparation and… input parameters than the RIVER package." For example, stream configurations must normally be determined by survey instead of estimated off of such lower resolution devices as topographic maps. The model was further updated by 2008 with the addition of new data from stream surveys in the Wairoa River and Waimea River in 2005 and Wai-iti River in 2007. Figure 5-4 shows the new stream cross-section survey locations (Hong and Zemansky, 2009).

The aquifer itself and various aquifer boundary conditions (e.g., wells, drains, and streams) in a MODFLOW groundwater-stream interaction model are implemented through the cells of the grid. MODFLOW cells are block-centred. This means that nodes for calculations are located in the centre of the cell. The extent and properties of aquifer media in each layer are defined by the arrangement of the cells into a grid and assignment of hydraulic properties to each cell (e.g., transmissivity and storativity). Thicknesses and hydraulic properties for the layers in this model were consistent with those of Fenemor (1988) but were updated as appropriate from new data and through calibration (White, 1997 and Hong and Zemansky, 2009) as follows:

a) Layer 1 (AGUA) – This shallow aquifer is composed of reworked river gravels up to 15 m thick. Transmissivities of 3,600 to 19,900 m^2/day have been reported from pump tests in this aquifer. The model currently shows hydraulic conductivities in the range of 9 to 7,200 m^2/day for this aquifer. Storativities in the range of 0.044 to 0.143 were used for this aquifer. An indication of the distribution of assigned hydraulic conductivity values is given in Figure 5-5. A porosity of 0.3, no horizontal anisotropy, and a vertical anisotropy of 3 were assumed for all three aquifers.

b) Layer 2 (UCA) – This aquifer is composed of clean river gravels deposited by the old Waimea River and ranges in depth from about 18 to 32 m below ground. There are “ruptures” in the confining layer providing a hydraulic connection to the AGUA. Transmissivites of 700 to 1,300 m^2/day have been reported from pump tests in this aquifer. The model currently indicates transmissivities in the range of roughly 10 to 5,000 m^2/day. Storativities in the range of 0.001 to 0.098 were used for this aquifer. Porosity and anisotropy assumptions were the same as those for the AGUA.

c) LCA – This aquifer is composed of clean river gravels deposited within the clay-bound Hope Gravel and ranges in depth from about 30 to 50 m below ground. Transmissivites of 50 to 1,550 m^2/day have been reported from pump tests in this aquifer. The model currently indicates transmissivities in the range of roughly 10 to 1,800 m^2/day. Storativities in the range of 0.0001 to 0.0002 were used for this aquifer. Porosity and anisotropy assumptions were the same as for the AGUA.

Assigned boundaries for each layer are shown on Figures 5-1 through 5-3 and were as follows:

a. Layer 1 (AGUA) –

1) Cells containing orange circles are constant head boundary cells. Constant head boundary cells are assigned a specific head that does not change. These were placed across the downgradient end of the layer (at a head of 0.7 m), along relatively short stretches of the edge of the layer on its southeast side (where the Wairoa River leaves the mountains and enters the plains), to either side of the Wai-iti River upstream of the junction with the Wairoa River (at heads ranging from about 44 to 58 m), and in a few cells on the northwest side of the layer in the Redwood Valley area (at heads in the 4 to 5 m range).

2) Cells containing purple triangles are general head boundary (GHBs) cells. GHBs in MODFLOW are often used to simulate standing bodies of water like lakes. Cells that are designated GHBs are assigned both a head and a conductance. If the water table elevation rises above the assigned head, water flows out of the aquifer. If the water table elevation falls below the specified head, water flows into the aquifer. In both cases, the flow rate is proportional to the head difference and the conductance. GHB heads were assigned in the range of 31 to 33 m and conductance values for these cells were specified at 1,500 m2/day.

3) Yellow cells contain one or more wells. Where more than one well was located within the geographic boundaries of a cell, all wells within that cell were simulated as a single well with the combined flow of all.

4) Cells containing green circles are drains or parts of drains. Drains in MODFLOW "remove water from the aquifer at a rate proportional to the difference between the head in the aquifer and some fixed head or elevation, so long as the head in the aquifer is above that elevation, but which have no effect if head falls below that level" (McDonald and Harbaugh, 1988). Flow is also affected by the assigned conductance of the drain. Drain heads were assigned in the 0 to 2 m range and conductance values for these cells were specified at 42,709 m2/day.

5) Cells containing blue circles are streams or parts of streams. Groundwater from aquifers associated with streams may enter streams or water in streams may enter the groundwater, depending on the relative head. The rate of flow is a function of the magnitude of the differential head and streambed conductance. The streams in this model are the Wairoa and Wai-iti Rivers joining from the east and south, respectively, to form the Waimea River and the Waimea River itself. Each stream cell was assigned the values for the following variables:

   a) Top and bottom streambed elevation. A uniform streambed thickness of 1 m was used.
   b) Stream width.
   c) Stream stage.
   d) Stream slope. Slopes of either 0.002 or 0.003 were used.
   e) Mannings roughness coefficient (n). Coefficients of 0.01, 0.02, or 0.025 were used.
   f) Streambed conductance. Values in the range of about 2,000 to 800,000 m2/day were used.

6) Cells on the border of the grid with no other designation constitute no flow boundary cells.

b. Layer 2 (UCA) -

1) Yellow cells contain one or more wells in a manner similar to that of the AGUA.

2) All other cells on the border of the grid constitute no flow boundary cells.

c. Layer 3 (LCA) –

1) Cells containing orange circles are constant head boundary cells. These were placed across the downgradient end of the layer.

2) Yellow cells contain one or more wells in a manner similar to that of the AGUA and UCA.

3) All other cells on the border of the grid constitute no flow boundary cells.

5.2.3.2 Rainfall Recharge

5.2.3.2.1 Introduction

Rainfall recharge of groundwater is an important input variable for the MODFLOW model. Because of the difficulty in measuring rainfall recharge, despite its importance it is a variable that is rarely known with any precision in groundwater flow modelling and, instead, is often used as an adjustment to assist in achieving calibration. In contrast, the method which appears to be more commonly used in New Zealand is to independently estimate rainfall recharge, hold it constant, and calibrate the model by adjusting other variables (e.g., values of hydraulic conductivity) and their distribution.

A number of innovative ways have been developed in New Zealand to provide for reasonable estimates of rainfall recharge. In the original GNS MODFLOW model, rainfall recharge was calculated using the SOILMOD soil water balance model as implemented by Landcare Research for the Waimea Plains. The SOILMOD model as used was based on water holding capacity for the three main soil types of the Waimea plains. Daily rainfall and evapotranspiration (ET) data were used as inputs to this model. Rainfall was as measured at and ET was as calculated for the Nelson airport. The model assumed a single main crop of pasture and a crop rooting depth of 600 mm.

Soil water balance models have been evaluated in New Zealand by comparison with rainfall and observed recharge data sets collected from lysimeters in the Christchurch area. These evaluations have been favorable for some models based on differing conceptual mechanisms, but not others (Thorpe and Scott, 1999). More recent evaluations have shown that AI models have the ability to provide more reliable estimates of rainfall recharge than soil water balance models (White, et al., 2003 and Hong, et al., 2005).

5.2.3.2.2 Soil Types

The infiltration of rainfall into the soil column and the subsequent percolation of moisture vertically downward through the unsaturated zone to recharge the uppermost unconfined aquifer is largely controlled by the hydraulic properties of the soil. Close to the surface, ET is also an important factor resulting in some soil moisture being taken out of the soil and returned directly to the atmosphere by evaporation or indirectly through plant transpiration. Because the AGUA is so shallow (on the order of several metres below ground level) and, therefore, the overlying unsaturated zone soils in the Waimea Plains so thin, surface soil properties of concern in agricultural production are applicable throughout the soil column and there should be little change in properties over the short depths involved to groundwater.

The three soil type classifications used by Landcare Research for Waimea Plains soils were water holding capacities (WHCs) of 38, 78, and 130 mm. These units are in terms of depth of drainable water from a volume of the soil column 1 metre in height. Coarser materials will drain more readily, therefore these classifications are inversely proportional to the size of the material involved (i.e., less water will be retained after drainage) and are equivalent to soils of the soil textures listed in Table 5-1 (Ball, 1997; Fortin and Moon, 1999; and Soil Water Solutions, 1997). Most of the soils in the Waimea Plains are of the five less permeable soils series having WHCs of 130 mm and equivalent to the texture of fine sandy clay loam. The distribution of soil types within the Waimea Plains is indicated in Figure 5-6 and summarized in Table 5-2. The predominant soil type is the less permeable WHC of 130 mm (fine sandy clay loam). Those soils total about 58% of the surface area of the Waimea Plains. The coarsest soil type, highly permeable WHC of 38 mm (coarse sand), covers about half as much but most of the rest of the Waimea Plains with about 32% of the surface area. The distribution of soil coverage within the Waimea Plains by soil series is indicated in Figure 5-6.

The soil science literature is not completely consistent in its use of water moisture terms. However, it appears that WHC is very similar to and sometimes used interchangeably with the terms “profile available water,” “plant available water” (both represented by the acronym PAW), and simply “available water.” These have been defined in the literature as the difference between the moisture level of soil at field capacity (FC) and at the permanent wilting point (PWP) where: (1) FC is the soil moisture content of formerly saturated soil “after gravity drainage is complete”; and (2) PWP is the “soil moisture level when plants cannot extract water from soil” (e.g., Linsley, et al., 1982). These terms have been more specifically defined operationally as being the water retained by soil at tensions of one-third atmosphere and 15 atmospheres, respectively (Linsley, et al., 1982 and Fortin and Moon, 1999). Figure 5-7 (Figure 7 from McCauley, 2005) illustrates these concepts. At saturation, the soil holds “all the water it can.” At FC, the soil holds about half of the water it does at saturation. Soil water content at PWP depends on the plant’s ability to extract water from soil, which varies. Mathematically, PAW = FC - PWP (McCauley, 2005).

Originally, the Landcare Research soil water balance rainfall recharge model using SOILMOD was run on a daily basis for the year involved for each of the three soil groups. Recharge as a fraction of rainfall would be highest for the coarsest material (soil type 38 mm) and lowest for the finest material (soil type 130 mm). The calculated recharge for each soil group was input to the MODFLOW model by using the soil distribution map to determine the area of each soil group and using that to weight recharge according to the percentage of each soil group over the total AGUA area. This produced a composite recharge depth for uniform application at every cell in the model. In this project, rainfall recharge was estimated using both the Landcare Research soil water balance model and a new AI model to estimate rainfall recharge (see Subsection 5.3.2 for information on the development of the AI rainfall recharge model and comparison of results from it to those from SOILMOD).

5.2.3.3 SOILMOD Soil Water Balance Model

The SOILMOD model is a single-layer (lumped parameter) model based on performance of a soil moisture balance assuming no surface runoff of rainfall. The balance is conducted using the following equation:

$$S_i = S_{(i-1)} + R_i - AET_i - D_i$$

Where:	S_i	=	soil moisture at the end of week i (i = 1, 2, 3... etc.)
	Ri	=	total rainfall during week i
	AET_i	=	total actual evapotranspiration during week $_i$.
	D_i	=	total drainage to groundwater recharge on week i

The SOILMOD model reduces evapotranspiration as soil water storage declines. In the above equation AET is the most difficult of the independent parameters to quantify. The calculation of AET is based on soil field capacity, level of soil moisture, and evaporative demand on a given day. Therefore, for higher soil moistures, where S_i exceeds S_c, the critical moisture level at which AET begins to fall below PET (Thorpe and Scott, 1999):

If $S_{i-1} > S_c$ (i.e., $S_{(i-1)} > FC - U$, then

$$\frac{AET_i}{PET_i} = 1$$

while for drier soil where $S_{(i-1)} < S_c$, then

$$\frac{AET_i}{PET_i} = \frac{S_{(i-1)}}{S_c} = \frac{S_{(i-1)}}{FC - U}$$

where VC, a vegetation cover factor, is defined by:

$$VC = \frac{U.PET_i}{FC}$$

and therefore,

$$\frac{AET_i}{PET_i} = \frac{\frac{S_i}{FC}}{(1 - \frac{VC}{PET_i})}$$

Where:	FC	=	field capacity
	Sc	=	critical moisture level below which AET is less than PET
	U	=	a root factor analagous to the Penman root constant
	PET_i	=	potential evapotranspiration on day i

5.2.3.4 Operation of the MODFLOW Model

The GNS MODFLOW model of the Waimea Plains was run to perform one year transient simulations for the historic drought year of record (1 July 2000 through 30 June 2001) and for the two climate change emissions scenarios (A1B and A2) for the otherwise equivalent drought year 1 July 2058 through 30 June 2059. AI modelling was used to provide the following inputs to the MODFLOW model (see section 5.3):

1. Water usage for the Waimea Plains.

2 Rainfall recharge. Rainfall recharge was also calculated using the Landcare Research soil water balance model, but this was not used for MODFLOW modelling in this project.

3 Wairoa River flow at the Irvines location.

Output data from the MODFLOW model consisted of:

1. Waimea River flow at the TDC Nursery location.

2. Groundwater elevations for the McCliskies well.

These MODFLOW outputs are presented in Section 5.3 in comparison with equivalent AI model outputs.

5.3 AI Modelling

Data-driven AI modelling approaches are an alternative to mechanistic hydrological models. AI modelling approaches are based on machine learning algorithms that provide a “learning” capability to remember, predict, and control aspects of their virtual hydrological environment. These techniques can represent complex dynamic systems and manage uncertainty and imprecision more effectively than mechanistic hydrological models (Hong and White, 2009). The specifics of each type of AI modelling utilized are discussed in this section in the order of water usage, rainfall recharge, stream flow, and groundwater level modelling.

5.3.1 Water Usage

5.3.1.1 Introduction

Water usage is an important input variable for the both the MODFLOW model and AI modelling of Waimea River flow. As noted in Section 2.0, substantial abstraction of groundwater occurs within the Waimea Plains. Groundwater serves as a primary source of water for both agricultural irrigation and municipal drinking water in the Waimea Plains area. Groundwater abstraction in the Waimea Plains is regulated by the TDC, which places limits on usage and requires flow metering by water users. This modelling was based on no change to the current level of irrigation at 3,800 ha in the Waimea Plains.

5.3.1.2 Application of AI Modelling for Water Usage

A multi-layer perceptron (MLP) trained neural network model with an extended Kalman filtering (EKF) learning algorithm was applied for the prediction of water usage under climate change scenarios. The topology of the MLP-EKF neural network model used is shown in Figure 5-8.

The steps used in performing this modelling were as follows:

1. Daily historic metered water usage data fro the Waimea Plains were collected from TDC for the period 1 July 2003 through 30 June 2007. These data are plotted in the bottom portion of Figure 5-9. Summaries of them for various periods are presented in Table 5-3. A breakdown by water management zone for the 2005-2006 year is given in Table 5-4 as an example.

2. The MLP-EKF neural network model was developed and trained to predict daily water usage as a function of daily rainfall and maximum daily temperature using historic data for this four year period. These data are plotted in the top portion of Figure 5-9.

3. The trained MLP-EKF neural network model was then used to estimate daily water usage for the 1 July 2000 through 30 June 2001 period. This is presently the driest year on record for the Waimea Plains and is believed to be approximately a 1 in 24 year drought.

4. Daily rainfall and maximum daily temperature climate change simulation data for the Waimea Plains were provided by NIWA for two emissions scenarios (i.e., A1B and A2) for the 1 July 2058 through 30 June 2059 year. This period is equivalent in the time series to the 1 July 2000 through 30 June 2001 drought year with the only difference being 58 years of simulated climate change,. The trained MLP-EKF neural network model was run using this climate change simulation data for the 1 July 2058 through 30 June 2059 year.

5. Evaluation of the effect of the two climate change scenarios on water usage compared to the equivalent historic year prior to climate change.

The structure of the MLP-EKF neural network model was optimized by a genetic algorithm (Goldberg, 1989) with 0.65 crossover probability, 0.15 mutation probability, and 0.1 direct reproduction probability. An initial population of 300 different topologies of MLP-EKF neural network models was created and the genetic loop process to evolve the optimized MLP-EKF models was carried out for 30 generations. The optimized MLP-EKF neural network model for the prediction of water usage employs two inputs and one hidden layer with four hidden neurons which use a sigmoid transfer function. Training was carried out over 500 epochs.

The trained MLP-EKF neural network model was then applied to simulate water usage for the two selected climate change emissions scenarios (i.e., A1B and A2) using results provided by NIWA for daily rainfall and maximum daily temperature during the period of 1 July 2058 through 30 June 2059. As indicated above, that period is equivalent in the time series to the July 2000-June 2001 year historic period with the only difference being that rainfall and temperature reflect 58 years of climate change under these emissions scenarios. It was assumed in this modelling that water usage was irrigation for the same 3,800 ha historically irrigated and that the only variables of concern were changes in temperature and rainfall as a function of climate change.

5.3.1.3 Results

AI model results for water usage during the drought year of record (1 July 2000 through 30 June 2001) and for two emissions scenarios for an otherwise equivalent year after 58 years of climate change (A1B and A2 emissions scenarios for the year 1 July 2058 through 30 June 2059) are plotted in Figure 5-10. Table 5-5 presents water usage summaries for the same years in the same format used for Table 5-3 (presenting water usage data for the four years from 2003 through 2007). Historic actual water use data for the 2000-2001 year are also summarized in Table 5-5.

The general form of the plots for both rainfall and water usage appear similar. However, it is apparent that although peak rainfall events occur at the same time of the year, peak magnitudes are higher for both scenarios of the predicted climate change years. There don't appear to be very evident differences in the patterns or magnitudes of usage between the plots for historic and predicted climate change water usage.

Comparing the statistical summary of Table 5-5 to that of Table 5-3 shows that water usage during a dry year is much higher than it is for more normal years. AI model results for water usage during the dry year in Table 5-5 also compare favourably with historic data, indicating that AI model performance is satisfactory. Relative percent differences (RPDs) for modelling results compared to actual historic data were generally 2% or less and were only higher for the maximum rate category. That would be the most difficult to predict category.

5.3.1.4 Discussion of Results

Statistical summary results for climate change scenarios summarized in Table 5-5 show substantially higher levels of water usage for both scenarios in all categories except the maximum rate of usage. For example, the AI model predicts that water usage would be 18% higher for the more extreme A2 scenario than actual historic water use in 2001 during the critical dry period of 21 February through 21 April. Differences for other periods were more marginal with the mean water usage rate for the year only 5% higher for the A2 scenario than actual historic water usage. The prediction that maximum usage for the climate change scenarios would be less than for the historic year is consistent with expectations given that peak rainfall for the climate change scenarios may exceed historic data. Given that likelihood, the increased rainfall would reduce the need for water usage.

AI modelling results for daily water usage were input to the MODFLOW model and to subsequent AI modelling of Waimea River streamflow at the TDC Nursery site.

5.3.2 Rainfall Recharge

5.3.2.1 Introduction

As noted in Subsection 5.2, rainfall recharge of groundwater is a required input for MODFLOW stream-groundwater interaction modelling and was performed using two approaches: (1) a soil water budget model (SOILMOD); and (2) AI modelling. SOILMOD was discussed to some degree in Subsection 5.2. This subsection primarily addresses the AI modelling used for rainfall recharge. Some discussion of SOILMOD is also presented to facilitate understanding of the comparison between results for them.

5.3.2.2 Genetic Programming Modelling Method

The form of AI modelling utilized for prediction of rainfall recharge is known as genetic programming (GP). GP "is a method of automatic model induction based on evolutionary computational intelligence" (Hong, et al., 2005). The primary steps in GP are: (1) initialization where a population of models is created according to a set of rules; and (2) an iterative genetic loop where the parameters of models are optimized, models are evaluated against fitness criteria, poor models are discarded and new, better, models are created on the basis of 'survival-of-the-fittest' selection principles" (Hong, et al., 2005).

The GP system was previously successfully applied to evolve multivariate rainfall recharge models that can express the temporal-spatial relationship of daily rainfall recharge as functions of rainfall, potential evapotranspiration (PET), and profile available water (PAW) at daily intervals between 1 May 1999 and 30 April 2003 for each of four monitoring sites in the Canterbury Plains (Hong, et al., 2005). The GP model utilized recharge measurements from lysimeters at four sites (Christchurch Airport, Lincoln University, Winchmore, and Hororata in the north/mid Canterbury area (Figure 5-11 and Table 5-6). Table 5-6 shows total rainfall, evapotranspiration (ET), and rainfall recharge measured at four lysimeter sites in the Canterbury area for the years 1999 and 2000. The lysimeters involved are large diameter cyclinders sunk vertically into the ground. They each contain essentially undisturbed soil (White, et al., 2003).

Rainfall recharge (Figure 5-11) is commonly very low or zero in the warm part of the year. This is because evapotranspiration is commonly much higher than rainfall during that period. The lowest ratio of observed recharge to rainfall for the four sites occurred at Lincoln University, probably because of the higher PAW of the Lincoln soils which indicates finer grained and less permeable materials (Table 5-6).

Data from these sites were split into two sets: (1) a training set using data for the 1 May 1999 to 30 April 2002 period; and (2) a testing set using data for the 1 May 2002 to 30 April 2003 period. A training set is used to evolve a rainfall recharge model. A testing set is used to assess how well the evolved rainfall recharge model predicts data not used during the training phase. Measured daily values of rainfall recharge, rainfall, and potential evapotranspiration (PET) for the period of 1 May 1999 through 30 April 2003 and the PAW rating of the soil involved were available to develop and test the GP model at each of these four Canterbury Plains sites.

The best resultant rainfall recharge model evolved by GP was:

RECHARGE = RAIN * ((47.13)/(16.15+(PET*PAW)/0.5016–PET + PAW/1.014)^RAIN)

The best resultant rainfall recharge model evolved by GP had a good ability to predict rainfall recharge in both the training and testing periods. The small difference between the root mean square error (RMSE) on the training and testing sets showed that the best performing model had good capability for generalization. This GP model has been demonstrated to be capable of better performance than the soil water balance model (Hong, et al., 2005).

5.3.2.3 Modelling Waimea Plains Rainfall Recharge

Soils within the Waimea Plains have been characterized by Landcare Research into three groups based on PAW (see Subsection 5.2.3.2.2). These soils have a similar distribution to those in the Canterbury Plains. Rainfall and PET data for the three soil types (PAW values of 38, 78, and 130 mm) were then applied to the best resultant rainfall recharge model evolved by GP (see above) to generate daily rainfall recharge values for historic and simulated climate change periods at the TDC Nursery-Chipmill location. This location was a composite of the TDC Nursery monitoring site on the Waimea River south of the Appleby Highway Bridge and the Chipmill location to the northeast of it. These locations were sufficiently close that NIWA could not distinguish any difference between them in its standard simulation so they were considered a single location. The procedure was as follows:

1. Historic - daily rainfall data provided by NIWA were utilized for the 1 July 2000 through 30 June 2001 year. This year was the record drought year for the period of record for the Waimea River. Using daily minimum and maximum temperature data provided by NIWA for this location and year, PET values were calculated. The calculation was performed using Version 3.1 of the FAO ETo calculator. This program calculates ETo as a surrogate for PET using the Penman-Monteith equation (Raes, 2009). Plots of program output results from this program are shown as Figure 5-12. Values are, of course, highest during the warm period of the year. Summary statistics for historic temperature and calculated ETo values based on temperature are presented in Table 5-7.

2. Climate change simulations – the same two climate change simulations used with regard to water usage were modelled (A1B and A2 emissions scenarios for the year 1 July 2058 through 30 June 2059). Using daily minimum and maximum temperature data provided by NIWA for this simulation, location, and year, ETo values were calculated in the same manner as for historic data. A plot of program output results for the A2 emissions scenario is shown as part (b) of Figure 5-12. Results were marginally higher than for the historic year shown as part (a). Summary statistics for simulated temperature and calculated ETo values based on simulated temperature are presented in Table 5-7.

Table 5-7 and Figure 5-12 show only marginal differences in both temperature and ETo with statistical values generally increasing in the order of climate change emissions scenario A1B to A2 compared to historic data.

Three data sets of daily rainfall and ETo were fed into the best model evolved by the GP technique to produce estimates of historic rainfall recharge for the 2000-2001 drought year and for two climate change scenarios in the Waimea Plains. The two climate change cases were the A1B and A2 emissions scenarios for the 2058-2059 comparative year. SOILMOD was also used to model rainfall recharge for each of these three cases.

5.3.2.4 Rainfall Recharge Modelling Results

GP and SOILMOD model results for rainfall recharge are summarized in Table 5-8 and representative cases plotted in Figure 5-13. It can be seen that the GP rainfall recharge model predicts less rainfall recharge than the SOILMOD water balance model does for all cases in all soil types, but the difference is particularly noticeable for the two finer-grained soils (i.e., the 78 and 130 mm PAW soil types). For example, for the historic year case, the GP model predicts a recharge to rainfall ratio of 31.4% for the coarsest soil (i.e., the 38 mm PAW soil type) while the SOILMOD model predicts a ratio of 34.4% or 10% higher.

However, for the finest soil (i.e., the 130 mm PAW soil type) the GP model predicts a recharge to rainfall ratio of about 10% while the ratio predicted by SOILMOD for the same soil is 26% or more than double that of the GP model. This is also evident in the upper part of Figure 5-13 where it can be seen that the green line for SOILMOD model predicted rainfall recharge is generally higher than the red line for GP model predicted rainfall recharge and even comes close to equalling rainfall during the higher intensity rainfall events.

It can also be seen that predicted rainfall recharge declines as the grain size of soil types becomes smaller. This is graphically illustrated with GP model results for simulated data with A2 emissions scenario results for the coarsest and finest-grained soil types (i.e., the 38 mm and 130 mm PAW soil types represented by the red and green lines in Figure 5-13, respectively). Annual recharge declines dramatically from 178.5 mm for the 38 mm soil type to 56.3 mm for the 130 mm soil type under the same rainfall conditions (652.3 mm), a reduction of 68%. The equivalent rainfall recharge to rainfall ratios for these soil types would be 27.4 and 8.63%, respectively.

5.3.3 Wairoa River Flow at Irvines

5.3.3.1 Introduction

Streamflow is a major source of recharge to groundwater in the Waimea Plains. Because of its much smaller nature and the fact that the Wai-iti River is often dry during the warmest time of the year when groundwater-based irrigation is necessary, much of the streamflow difference between the Wairoa River at the Irvines gaging station in the Wairoa Gorge where it comes out of the mountains and the Waimea River at the TDC Nursery gaging station near the coastal delta in the summer season is loss to groundwater abstraction. Therefore, the prediction of the flow of the Wairoa River at Irvines in response to climate change is vital in understanding resultant groundwater-surface water dynamics in the Waimea Plains.

The dynamic neuro-fuzzy local modelling system (DNFLMS) developed by Hong and White (2009) was used to predict Wairoa River flow at Irvines as impacted by climate change.

5.3.3.2 Historic Wairoa River Flow Under Different Hydrologic Conditions

The TDC maintains flow records for the Wairoa River at Irvines. Historic flow data for four years under different hydrologic conditions are summarized in Table 5-9 and plotted in Figure 5-14. These years are as follows (all years start on 1 July and end on 30 June of the following year):

1. 1982/1983 – This was a drought year that has been classified as a 1 in 20 year drought.
2. 1991/1992 – This was a drought year that has been classified as a 1 in 10 year drought.
3. 2000/2001 – This is the driest year on record and has been classified as a 1 in 24 year drought.
4. 2004/2005 – This was an average year.

Tables 5-9 summarises observed rainfall and daily mean river flow of the Wairoa River at Irvines for three drought years and a normal year. Mean flow of the Wairoa River during the period 21 February to 21 April 2005 (average year) was approximately five and a half times higher than mean river flow for the same period in 2001 (1 in 24 drought year).

Table 5-10 provides additional dry period rainfall and flow statistics. Table 5-10 and Figure 5-14 show that the Wairoa River flow at Irvine during the average year (2004/2005) was not less than 2,000 L/s in the driest period (15 Apr-15th May 2005). However, in a severely dry year like the 2000/2001 year, the observed mean Wairoa River flow was only marginally over 1,500 L/s (21 February-21 April 2001) and was substantially below that during February through March 2001. With such low flows of the Wairoa River at Irvines, the Waimea River at the TDC Nursery gaging station south of the Appleby Highway Bridge was predicted to be dry or have only a very small flow (Hong, 2006).

5.3.3.3 Predicted Wairoa River Flow Under Climate Change

The method used in performing flow modelling for the Wairoa River at Irvines was as follows:

1. Obtain historic data sets for the Waimea Plains from TDC and calculate moving averages for the previous three days of each of the foll0wing variables:

   (a) daily Wairoa River flow at Irvines;

   (b) daily rainfall; and

   (c) maximum temperature.

2. A DNFLMS model to predict daily Wairoa River flow at Irvines was developed and trained based on the three variables listed above and their three day moving averages.

3. The trained DNFLMS model was run to estimate daily river flows for the Wairoa River at Irvine for the period 1 July 2000 through 30 June 2001 (1 in 24 year drought).

4. The trained DNFLMS model was run for two climate change emissions scenarios (A1B and A20 for the 1 July 2058 through 30 June 2058 period (equivalent with the exception of 58 years of climate change under the conditions of those emissions scenarios to the 1 in 24 year drought).

5. Analyse and evaluate the effect of the two climate change emissions scenarios on Wairoa River flow at Irvines in comparison to historic flows.

It is assumed with a dynamic model of this type that the new system can be predicted by past inputs to and outputs of the system. The ARX (Autoregressive with eXogenous) model used to represent the system is a well known linear dynamic model, while the NARX (Nonlinear ARX) model is an extension of the ARX model that represents the model as a nonlinear mapping of past inputs and outputs to future outputs. Predictive modelling of this kind can be considered a multi-input, single-output (MISO) model with n_i inputs and n_o output. This system will be approximated by a collection of coupled discrete-time DNFLMS models. The NARX model for a MISO dynamic system can be represented by:

$$y(k+1) = f\begin{pmatrix} u_1(k-n_{k_1}),....,u_1(k-n_{k_1}-n_{u_1}+1),...., \\ u_m(k-n_{k_m}),....,u_m(k--n_{k_m}-n_{u_m}+1) \end{pmatrix} \qquad (5)$$

$$k = 1,\ 2,\ \ldots\ldots,\ n$$

Here $y(k) \in Y \in R$ is the output vector, $u(k) \in U \in R^m$ is the inputs vector with *m* inputs. n and k denote the number of data samples and the discrete time samples, respectively. n_{u_m} is related to the system order. n_{k_m} represents the pure time delay between change in the inputs and the observed change in the output. $f(\cdot)$ is a nonlinear arbitrary function which can map the past inputs to future outputs.

The most important choice that has to be made is with regard to model structure parameters (n_{u_m} and n_{k_m}). For the Wairoa River at Irvines rainfall-runoff model, n_{k_m} represents the time delay between change in the inputs (rainfall) and the observed change in river flow at Irvines. A model free test proposed by He and Asada (1993) was used in this work. This method is based on the evaluation of the so-called "Lipschitz Quotients."

The "Lipschitz Quotients" method was used to find the past input variable (rainfall) for DNFLMS model construction. The results of the "Lipschitz Quotients" method are shown in Figure 5-15. It is reasonable that the DNFLMS model is first order because the slope of the curve decreases for model orders ≥ 3. The lag time between change in Wairoa River flow at Irvines and increase in rainfall is on the order of one to three days and the slope of the curve in Figure 5-15 becomes nearly flat after three days of rainfall input. Therefore, the time span over which a momentary rainfall change persists in affecting Wairoa River flow at Irvines is one to three days.

Mathematically, the multi-input, single-output (MISO) DNFLMS model for predicting Wairoa River flow at Irvines is described by:

$$\hat{River}(k) = f\begin{pmatrix} MA(3)\_Rain, Rain(k), MaxTemp(k) \\ MA(3)\_MaxTemp, MA(3)\_River \end{pmatrix}$$

where $\hat{River}(k)$ is the predicted Wairoa River flow at Irvines at time *k* and *f(.)* is a DNFLMS model. *Rain(k)* and *MA(3)_Rain* represent rainfall at time *k* and the previous three days moving average value of rainfall, respectively. Likewise, *MaxTemp(k)* and *MA(3)_Maxtemp* represent daily maximum temperature at time *k* and the previous three days moving average value for daily maximum temperature, respectively while *MA(3)_River* is the previous three days moving average value of Wairoa River flow at Irvines. The resultant DNFLMS model has five input variables and one output variable.

The number of fuzzy rules in the DNFLMS model is determined by the distance threshold value (*Dthr*). For example, the number of fuzzy rules generated will increase as the distance threshold value becomes smaller. The optimal value of the distance threshold is unknown for the specific task so it must be determined to prevent overfitting. In this work, the distance threshold value was varied in the range of 0.008–2.0 until prediction performance for the testing set was satisfactory to prevent over-fitting. An optimal distance threshold value of 0.13 was found for this work and it was observed that when the distance threshold was smaller than 0.1 the model had too many fuzzy rules and overfitting of the testing set occurred.

We repeated the experiment to determine values of measurement noise variance R and process noise covariance Q in the EKF learning algorithm for the DNFLMS. Based on a trial-and-error method to find optimal values of R and Q, R and Q were given values of 0.5 and 0.1, respectively. The initial error covariance matrix P_0 and initial parameter vector W_0 were set to 10 and 1, respectively.

The DNFLMS evolved 16 fuzzy rules during the training phase using a Gaussian fuzzy membership function. The RMSE statistic for predicted Wairoa River flow at Irvines was computed as 783 L/sec for the training set.

DNFLMS model training results for prediction of Wairoa River flow at Irvines are shown in Figure 5-16 for the historic low flow period of 1 July 2000 through 30 June 2001 (1 in 24 year drought). Observed rainfall data are plotted in the upper part of that figure. It can be seen that streamflow responds rapidly to rainfall when rainfall events follow relatively dry times and that model results closely track actual historic flow data, indicating a high level of predictive accuracy and good model performance.

The trained DNFLMS model was developed using historic data to assess possible climate change impacts on the Wairoa River flow at Irvines. The same two climate change scenarios used with regard to water usage and rainfall recharge (A1B and A2) were modelled using daily rainfall and maximum temperature values from NIWA simulations for the 1 July 2058 through 30 June 2059 year..

The trained DNFLMS model was applied to predict Wairoa River flow at Irvines for two climate change scenario data sets (A1B and A2 emission scenarios). These consisted of rainfall at time *k*, daily maximum temperature at time *k*, moving average values of the “previous” three days of rainfall (i.e., the day the average is calculated for and the preceding two days), daily maximum temperature, and flow at Irvines for the 1 July 2058 through 30 June 2059 year. Simulated rainfall and temperatures provided by NIWA for the TDC Nursery location were used as there was no significant difference between them and the values for the Irvines location, particularly for the warm season. The first three days of flow for the prediction period were initialized for this calculation using historic data. After that time, predicted flow was stored for that calculation. This year is equivalent to the 1 July 2000 through 30 June 2001 year except that rainfall and temperatures reflect 58 years of climate change under the emissions scenario of concern.

DNFLMS model results for the July 2000 through June 2001 historic year and for the July 2058 through Jun 2059 climate change year (A1B and A2 emissions scenarios) are plotted in Figure 5-17 and summarized in Table 5-11. The basic shape of the curves for each of the three historic and climate change scenario plots in Figure 5-17 are very similar. Also, the summary statistics for these historic data and climate change scenario results are very similar. For example, predicted mean flows were 1,950 and 2,093 L/sec for the two climate change scenarios (A1B and A2), respectively, during the driest part of the year (21 February through 21 Apr). These values bracket the historic mean flow for that period in 2001 of 2,061 L/sec and are only about 5% lower than and 2% higher than that historic value, respectively. The situation appears to be even closer with regard to other measures. For example, total flow predicted for the A2 emission scenario year (2058-2059) is about 0.3% higher than for the historic year (2000-2001). This is virtually the same value.

5.3.4 Waimea River Flow at TDC Nursery

5.3.4.1 Introduction and Historic Flow Data

As noted in Subsection 5.3.3, surface water is the primary direct source of recharge to the shallow unconfined aquifer underlying the Waimea Plains that supplies irrigation (during the summer season), domestic, urban, and industrial water to the region. It is also, indirectly, a source of recharge to the two deeper confined aquifers. The major rivers involved between Irvines, the upstream point on the Wairoa River, and Nursery (referred to herein as TDC Nursery), the downstream point on the Waimea River, lose a substantial amount of streamflow to groundwater, particularly in the summer and during drought conditions, and the available information indicates that this loss increases with increased groundwater abstraction (Hong, 2006). This can result in very low flow conditions in downstream sections of the Waimea River and, in the worst case, the river going dry (Hong, 2003).

Historic Wairoa River flow at Irvines and Waimea River flow at TDC Nursery data for the year 1 July 2000 through 30 June 2001 (1 in 24 year drought) are plotted in the bottom portion of Figure 5-18. Summary rainfall, water usage, and streamflow statistics for warm weather months are presented in Table 5-12. Observed Waimea Plains rainfall and water usage data for the same year are also plotted in the top and middle portions of Figure 5-18, respectively. These data show the impact of groundwater recharge to supply abstraction for irrigation during a drought year in comparison to a wet year. For example, during the 1 in 24 year drought of record (2000-2001), there was a total of 45 mm of rainfall during the critical dry period from 21 February through 21 April 2001. Additional detail of these conditions is seen in Figure 5-19 covering the first four months of 2001. Upstream and downstream flows for the Wairoa River at Irvines and Waimea River at TDC Nursery, respectively, during this period had mean values of 1,661 and 433 L/sec, respectively. This indicates a mean loss of 1,228 L/sec, which exceeded the recorded mean water usage of 715 L/sec by 72%. Additionally, as is evident in Figure 5-19, flow at the Irvines gage was less than 2,000 L/sec for much of this period.

In contrast, during the relatively wet year of 2005-2006, streamflow loss during the same period between Irvines and TDC Nursery was only a mean of 397 L/sec for water use that was somewhat less than it had been in 2000-2001. Streamflow loss during the 2000-2001 drought year had been more than three times what the loss was during the 2004-2005 wet year. Additional detail regarding rainfall, water usage, and streamflow data for relatively wet years is plotted in Figure 5-20. Figure 5-20 and Table 5-12 show that flow at Irvines was rarely below 2,000 L/sec and, on average was substantially above it (averaging 6,145 L/sec during the warm season of 2005-2006). Flow at TDC Nursery during these same wet years was similarly high in comparison to the driest part of the 2000-2001 year and was only rarely below 1,000 L/sec.

5.3.4.2 Predicted Waimea River Flow Under Climate Change

A DNFLMS was developed to predict Waimea River flow at the TDC Nursery station under A1B and A2 emissions scenario climate change conditions. The modelling procedures utilized were as follows:

1. Historical data sets for rainfall, maximum daily temperature, and streamflow for both the Wairoa River at Irvines and the Waimea River at TDC Nursery were collected from TDC and organized for modelling purposes.

2. A DNFLMS model was developed and trained to predict daily river flow at the TDC Nursery downstream gaging station on the Waimea River as a function of daily rainfall, maximum daily temperature, daily water usage, and daily Wairoa River flow at Irvines. The structure of this model is schematically shown in Figure 5-21.

3. The trained DNFLMS model was run to estimate daily Waimea River flow at the TDC Nursery gaging station for the 1 July 2000 through 30 June 2001 (1 in 24 drought year) period.

4. The trained DNFLMS model was run for two climate change scenarios (A1B and A2 emissions scenarios) for the 1 July 2058 through 30 June 2059 period. This period is equivalent to the 2000-2001 year of the historic period with the exception that rainfall and temperatures reflect 58 years of climate change under those scenarios (as simulated by NIWA).

5. Analyse and evaluate the effect of the two climate change emissions scenarios on Wairoa River flow at Irvines in comparison to the historic flows.

The DNFLMS is intended to derive multivariate inference models for predicting Waimea River flow at the TDC Nursery station as a function of daily rainfall, maximum daily temperature, daily water usage, and daily Wairoa River flow at Irvines, the upstream point. This is illustrated in Figure 5-21 where it is evident the model has those four input variables with prediction of Waimea River flow at the TDC Nursery station being the output variable.

In the Fuzzification Layer, the four input variables are fuzzified using a Gaussian fuzzy membership function. In the Fuzzy Rule System, one node per each fuzzy IF-THEN rule-based system is created. Each membership function value of each input is connected to its corresponding fuzzy local models (IF-THEN rule). Finally, each fuzzy local model generates local outputs of predicted Waimea River flow at the TDC Nursery station. Using the predictions of the individual fuzzy local models, the final prediction of the Waimea River flow at the TDC Nursery station is computed using a weighted sum of each local model.

The optimal distance threshold value used in the on-line clustering algorithm is 0.1 for this work. Based on the optimal distance threshold value of 0.1, the DNFLMS model evolved 19 fuzzy rules during the training phase using a Gaussian fuzzy membership function. We repeated this experiment to determine the values of measurement noise variance R and process noise covariance Q in the EKF learning algorithm of the DNFLMS. R and Q were given the values of 0.5 and 0.1, respectively. Initial error covariance matrix P_0 and initial parameter vector W_0 were set to 10 and 1, respectively. The RMSE statistic for river flow prediction at TDC Nursery was computed by the DNFLMS to be 284 L/sec for the training set. The training result of the DNFLMS model to predict Waimea River flow at TDC Nursery for the period 1 July 2000 through 30 June, 2001 (1 in 24 drought year) is displayed with observed river flow at TDC Nursery in Figure 5-22. It is evident from Figure 5-22 that the trained DNFLMS model has an excellent predictive capability for both wet and very dry seasons, particularly for the very dry period of 21 February through 21 April 2001. Predicted results of the DNFLMS model shown in Figure 5-22 are in very good agreement with values of observed river flow at the TDC Nursery location and represent dynamic characteristics of Waimea River flow there very well.

The trained DNFLMS model developed was then used to assess the effects of climate change on Waimea River flow at the TDC Nursery station under the same two climate change scenarios modelled for water usage, rainfall recharge, and Wairoa River flow at Irvines. The flow chart for this process is shown in Figure 5-23.

Predicted daily rainfall and maximum daily temperatures from NIWA climate change simulations were used in arriving at model values for daily water usage in the Waimea Plains and flow of the Wairoa River at Irvines under the same climate change scenarios and year. All of these were input variables to the DNFLMS model developed to predict the output flow variable for the Waimea River at the TDC Nursery station under climate change conditions. These input variables were fed into the trained DNFLMS model for the 1 July 2058 through 30 June 2059 year.

Historic Waimea River flow at the TDC Nursery location (for year 2000-2001) and DNFLMS model predicted flow for the two climate change scenarios (A1B and A2 emissions scenarios for the year 2058-2059) during the 21 February through 21 April period are shown in Figure 5-24. Historic Wairoa River flow at the Irvines location for the 2000-2001 year is also plotted.

Related mean streamflow statistics are presented in Table 5-13 for the same locations and time period for both historic data and climate change simulation predictions. It can be seen from Table 5-13 that the historic mean flow for the Wairoa River at Irvines in the 21 February through 21 April 2001 period was 2,061 L/sec in comparison with historic mean flow for the Waimea River at TDC Nursery over the same period of 433 L/sec (a loss of 1,628 L/sec or nearly 80% of flow). In contrast, for the two climate change emissions scenarios 58 years later during the critical February-April time frame, the DNZLMS models predict little change in mean Wairoa River flow at Irvines but mean Waimea River flows at TDC Nursery show substantial decreases of about 23 and 27% from 2001 flows for the A1B and A2 emissions scenarios, respectively. Table 5-13 also shows that there is marginal variation in total rainfall for the two emissions scenarios, with an unexpected 13% increase for the A1B scenario but a 11% decrease for the A2 scenario and, consistent increases in water usage after 58 years of climate change with 13 and 18% higher usage, respectively, for the A1B and A2 emissions scenarios than in the same period in 2001 prior to 58 more years of climate change.

Another way of looking at the potential impact of climate change scenarios on the hydrology of the Waimea Plains is to consider the number of days of low flows. Relevant statistics from historic flow data and for the two climate change scenarios (A1B and A2) from the DNZLMS model for the Waimea River at the TDC Nursery location are presented in Table 5-14. These indicate that climate change substantially increases the number of low flow days (primarily during the 21 February through 21 April warm weather period) in the year (defined as being less than 100 L/sec). The number of such days increases by 50% for the A1B emissions scenario and 67% for the A2 emissions scenario compared with historic data. As the flow criterion is raised the impact decreases, being only 23% higher for the A2 emissions scenario compared to historic data for streamflows less than 250 L/sec, and when a criterion of less than 1,100 L/sec is used the number of days with lower flows is nearly the same.

5.3.5 Groundwater Elevations at McCliskies Well

5.3.5.1 Introduction

Groundwater elevations at two wells located in the downgradient portion of the Waimea Plains have been historically used for calibration of the MODFLOW groundwater flow model. These are wells: (1) CW2; and (2) McCliskies (Hong, 2003). The McCliskies well is located approximately 1.2 km north and a little west of the TDC Nursery flow gaging site in the Delta area of the Waimea River. The McCliskies well has previously been selected as an indicator site for groundwater levels at the downstream end of the Waimea Plains because of its proximity to the Waimea River and because groundwater levels in it are influenced significantly by river recharge (Hong and Zemansky, 2009).

Historic groundwater elevation data for the McCliskies well are plotted in Figures 5-25 and 5-26 for both drought and more normal flow years, respectively. Those figures also show rainfall, water usage, and streamflow. Summaries of mean values for the data shown in those figures are presented in Table 5-15. Figures 5-25 and 5-26 show that rainfall is sparse during the warm season and that water usage starts, increases, and declines in relation to that season with no usage during the winter. They also show that streamflow (both for the Wairoa River at Irvines and the Waimea River at TDC Nursery) and groundwater elevations decline during the warm season with the worst case being streamflow for the Waimea River at TDC Nursery reaching zero (i.e., going dry) during February-April 2001 (1 in 24 year drought). It can be seen from Table 5-15 that groundwater elevations for the McCliskies well are roughly proportional to streamflow with average levels increasing for larger flows and decreasing for smaller ones. For the wetter 2004 through 2007 years, groundwater elevations on average exceeded 2,250 mm whereas during the 2000-2001 drought year they declined below 2,000 mm.

5.3.5.2 Predicted Groundwater Elevations at McCliskies Well Under Climate Change

A sequential modelling paradigm was used to develop an integrated DNFLMS inference model to predict groundwater elevations at the McCliskies well. The architecture of this modelling paradigm is shown in Figure 5-27. The sequential modelling paradigm was composed of two DNFLMS model parts: (1) the first DNFLMS model for predicting Waimea River flow at TDC Nursery; and (2) the second DNFLMS model for predicting groundwater levels at McCliskies well with Waimea River flow at TDC Nursery as one of four inputs. As indicated in Figures 5-21, 23, and 27, the first DNFLMS model receives four input variables (daily rainfall, daily maximum temperature, daily water usage, and daily Wairoa River flow at Irvines). The output from it is daily Waimea River flow at TDC Nursery. As shown in Figure 5-27, that output subsequently becomes one of four inputs to the second DNFLMS model for predicting the dynamic change of groundwater elevation at the McCliskies well. The other inputs are the same daily rainfall, water usage, and Wairoa River flow at Irvines used in the first DNFLMS model (daily maximum temperature is no used at this time). The main purpose of the second DNFLMS model is to evaluate the effect of climatic/hydrologic conditions and water usage on groundwater elevation at McCliskies near the Waimea River.

Results for the DNFLMS model predicting Waimea River flow at TDC Nursery as the output were described in Subsection 5.3.4. The same parameter settings for the online clustering algorithm and EKF algorithm used in that DNFLMS model were applied to this one. The same optimal distance threshold value of 0.1 was also used. Optimal values of R and Q for the EKF algorithm used in the DNFLMS were given values of 0.5 and 0.1, respectively. Initial error covariance matrix P_0 and initial parameter vector W_0 were set to 10 and 1, respectively. The DNFLMS model evolved 18 fuzzy rules during the training phase using a Gaussian fuzzy membership function.

Model training results for groundwater elevations in the McCliskies well are shown in Figure 5-28 for the 1 in 24 year drought (1 July 2000 through 30 June 2001). Rainfall, water usage, and streamflow are also plotted in that figure for the same time period. Good agreement is evident between measured and simulated groundwater levels in the McCliskies well. Historic groundwater elevation records indicate that groundwater elevations decrease during the irrigation season (between November when groundwater abstraction starts and April when it ends) and afterward recover each winter (by August). The DNFLMS model prediction shows that groundwater elevations in McCliskies well during the irrigation season track actual observations well.

The trained DNFLMS model was used to assess the effects of climate change on groundwater elevations in the McCliskies well. The same two climate change emission scenarios modelled for water usage, rainfall recharge, and streamflow were implemented for the year 1 July 2058 through 30 June 2059. This year was equivalent to the historic 1 July 2000 through 30 June 2001 drought year with the only difference being 58 years of climate change under the A1B and A2 emissions scenarios. Daily rainfall and maximum daily temperature from NIWA's climate change simulations and predicted water usage and Wairoa River flow at Irvines from other AI models were fed into the first trained DNFLMS models as inputs. The output from this model (i.e., predicted Waimea River flow at TDC Nursery), daily rainfall, and predicted water usage and Wairoa River flow at Irvines were then used as inputs to the second trained DNFLMS model to produce predicted groundwater elevations for the McCliskies well.

Results for Waimea River flow at TDC Nursery for the A1B and A2 climate change scenarios were also described in Subsection 5.3.4. Figure 5-29 presents observed historic groundwater elevations for the 2000-2001 year in comparison with predicted groundwater elevations for the two climate change scenarios for the year 2058-2059. Historic and climate change predicted mean groundwater elevations for different time periods are presented in Table 5-16. Historic and climate change predicted mean flow for the Waimea River at TDC Nursery are also shown for the same time periods.

It is apparent from Table 5-16 that predicted groundwater elevations in the McCliskies well are not likely to be substantially impacted by these climate change scenarios. Despite what could be considered substantial decreases in Waimea River flow at TDC Nursery for the two climate change scenarios in comparison with historic data, only very small changes or no changes in mean groundwater elevations were seen. For example, the predicted mean groundwater elevations for the driest part of the year (21 February through 21 April) are 1,962 and 1,964 mm for the A1B and A2 emissions scenarios, respectively. This is no change at all from the historic mean in comparison with the A1B scenario and a change of only 2 mm for the A2 scenario. The greatest change in groundwater elevation is for the full year. In that case, means of 2,303 and 2,307 mm for the A1B and A2 emissions scenarios appear to be clearly less than the mean of 2,346 mm from historic data. Although this is suggestive, the decline produced by climate change appears to be very small (i.e., less than 2%). Therefore, it appears that groundwater recharge from surface water would still be sufficient to prevent substantial decline in groundwater elevation at the McCliskies well under these climate change scenarios.

5.3.6 Comparitive MODLOW and AI Results

Both MODFLOW and the AI models developed as a part of this research project produced reasonably similar results. Most importantly, for the critical February-April period of a severe drought event, climate change could produce substantial decreases in streamflow (i.e., for the Waimea River at the TDC-Nursery location) but was not likely to do so with regard to groundwater levels in the Waimea Plains. As shown in Table 5-16, AI modelling indicates declines in streamflow of 23 and 27%, respectively, under the A1B and A2 emissions scenarios while MODFLOW indicates declines of 21 and 27%, respectively. Only minor differences were evident with regard to groundwater elevations; the largest being a mean of less than 2% lower under climate change scenarios than for historic data (see Table 5-16).

6.0 ASSESSING SOCIOECONOMIC EFFECTS

6.1 Research Objectives

The broad research objective was to utilize socioeconomic models to relate climate-induced changes in the hydrological system to derived changes in economic productivity within the Waimea Plains test catchment (Figure 6-1). For example, if changes in water availability occur due to climate change, what socioeconomic impacts might follow. Additionally, Maori cultural values of water were to be taken into account. It must also be considered that changes in socioeconomic factors may influence both water quantity and quality and that, therefore, such changes need to be factored into any determination of the cause of changes in variables measuring these. However, this latter consideration goes beyond the scope of this research.

6.2 General Background

The valuation of water resources has intrigued economists and other researchers for hundreds of years, yet to this day, a comprehensive framework for establishing the contribution of water to human welfare does not exist. This should not be seen as a failure of social science. Rather, it illustrates the complexity of the issue and the multitude of channels whereby society is interlinked with various elements of the hydrological cycle.

In a broad sense, the total economic value (TEV) of water is infinite: society could not exist without water. Evaluating marginal changes in availability is, however, a less trivial task. A change in water quantity (or quality) may affect not only agricultural, industrial and urban uses but also a range of recreational activities, existence values derived from the knowledge that the resource exists, and option values derived from making the resource available for future use. These various use and non-use benefits are often obtained from directly competing (mutually exclusive) uses of the resource – maintaining or increasing one may involve sacrifices in terms of the others. In other cases, the benefits are complementary: wetland conservation, for example, can contribute to flood protection and water quality at the same time, as well as to enhanced biodiversity and option values. Therefore, a comprehensive economic evaluation of water resources needs to consider the various functions of water and the interactions between them.

Economists have developed a range of techniques to estimate the benefits derived from natural resources. These are typically applicable to specific functions provided by the resource – a comprehensive economic assessment will thus involve the use of several techniques in combination. While a detailed review is beyond the scope of this report, we briefly list the most prominent ones.

The simplest situation arises when water is priced directly in a market: if abstraction rights are tradable, for example, irrigation can be valued by observing the prices of water rights. In cases where water is used in the production of a marketed output (as in agriculture and industry), traditional accounting or demand analysis methods can be used to establish its contribution to value. These include transactions analysis, derived demand functions, and residual value imputation (Turner, et al., 2004). Hedonic and travel cost techniques derive an implicit price for the environmental good by linking it to behaviour observed in related markets. As an example of the former, lakefront houses on average command a higher price than identical houses elsewhere. This price difference reflects people's valuation of the amenities provided by the lake. An assessment of non-use benefits on the other hand, generally requires the administration of a stated preference survey to elicit the preferences of respondents through direct questioning. Again, several techniques are available within this class of instruments including contingent valuation and choice experiments. Finally, where primary data are unavailable, benefit transfer can sometimes be used to apply the results of already existing valuation studies to the current situation. This set of techniques exhibits various levels of sophistication with increasing controls for socio-economic and methodological differences between the populations of interest and the studies, respectively. Benefit transfer is an attractive alternative to expensive primary valuation studies when data are not readily available, but similar studies have already been undertaken for valuing the resource under (slightly) different situations.

6.3 Economic Framework

As indicated in Sections 4 and 5, climate change in the 21st Century is expected to have only relatively small effects on average water availability in the Waimea Plains catchment. Although drought risk may increase, instead of a decrease in water availability climate change models indicate there may be an annual mean increase of about 2% in rainfall over the 50 year period from 1990 onward and 4% over the 100 year period to 2090. This change is within lower and upper limits of -3 to 14%, respectively, for the 100 year period, so that although a small positive change is most likely there may also be a small negative change. In contrast, trend analysis of actual rainfall data in and near the Waimea Plains indicates both increasing and decreasing rainfall trends but predominantly decreasing ones. While these trends in rainfall are generally not statistically significant at the 90% confidence level, the only one that is shows a small decreasing trend (see Table 4-4). While such changes appear to be small, they could have a substantial impact on Waimea River flow and groundwater levels under drought conditions. For example, groundwater-stream interaction modelling indicates that during a drought of record conditions similar to those of 2001, flow in the Waimea River at the TDC Nursery gaging station could decrease by an additional 23 to 27% under A1B and A2 emissions scenarios, respectively, within 50 years. A decrease of this magnitude during a time of low water availability could be critical.

The relatively small magnitude annual mean changes in rainfall and commensurate changes in streamflow predicted for the Waimea Plains under various climate change scenarios are unlikely to significantly affect all functions of water. In particular, non-use values (such as existence value) are less likely to suffer than use values. Non-use values can be a significant component of total economic value when one considers a large deterioration of the resource, but they will likely have a negligible contribution in the context of small changes to water availability. Therefore, the focus of our modelling efforts is on determining the socioeconomic effects of climate change on the following major uses of water resources in the study area: (1) water for agricultural crop irrigation; (2) water for commercial, industrial and other urban uses; and (3) in-situ water use for recreation.

Additional discussion of these uses follows:

1. Irrigation use - The value of water for irrigation can, in theory, be estimated by various methods under different circumstances. When water consents are tradeable, their market price indicates the value of the resource in agricultural production. Even when prices for water are not directly observed, a shadow price can exist wherein the value of water rights will be capitalized into agricultural land values as farmers pay a premium for land that has a water right. The amount of this premium can be determined by the present discounted value of the additional farm profit due to the water right (Grimes and Aitken, 2008). Deductive methods such as residual imputation are also often used to assign an economic value to irrigation water: in this case, net returns to water are equated to revenues minus non-water costs per land area (Young, 2005). Estimates of residual returns are sensitive to any omitted cost elements, so this method frequently leads to an overestimation of irrigation benefits. In this research, we estimate the annual TEV of water used for irrigation by looking at land values (i.e., the difference between land values with water availability and without). Although estimation of TEV is an uncertain exercise, the difference in TEV is less so.

2. Commercial, industrial and other urban use - Values for other productive uses (e.g., commercial or industrial) of water can be estimated using similar techniques as in the case of agriculture. Urban uses are valued either by observing tradeoffs made in a hypothetical market via stated preference surveys, or by the avoided costs method: calculating how much it would cost to restore water supply to its original condition using alternative technology or alternative sources.

3. In situ use - In situ values for recreation activities are often assessed using travel cost models. These are fairly sophisticated and data-intensive models based on people being prepared to incur higher travel costs in order to visit a more attractive site. By observing the tradeoffs they make in terms of recreation site quality attributes and costs, the model is able to determine willingness to pay for the various environmental attributes. Contingent valuation and contingent ranking surveys (as opposed to observed recreation data) are another potential source of information for the estimation of in-situ water values. Benefit transfer techniques are also often used in the context of non-market valuation (in the assessment of in-situ values, for example); however, they could be applied for productive (agricultural or industrial) use values as well.

Though multiple techniques are available for quantifying the benefits provided by each function of water, systematic differences exist between them. One has to be conscious of these differences when interpreting the results of valuation studies. At-source and at-site value estimates differ by the cost of delivery; values in long-run contexts can be less than those in short-run contexts because opportunities for adaptation exists over longer horizons; the relationship between flow (periodic) and stock (capitalized) values depends on the discount rate one chooses; and, lastly, benefits depend on the researcher's accounting stance, whether they are valued from a private or a social perspective (Young, 2005). Thus, seemingly similar studies sometimes value different things. As an example, urban water values estimated from a household survey are very different from those derived using the avoided cost method. The former technique is about households' subjective valuation and will therefore reflect the benefits derived from enhanced public health, fire protection and quality of life, while the latter says nothing about the value of the resource to people – it merely considers the costs of supplying it. From a policy maker's perspective, the cost of supply is a more relevant measure, so that is our focus in assessing the impact of climate change in water availability on the urban sector.

We combine survey data on the value of water to various sectors, trends relating to land use and population, and climate change projections to assign economic outcomes to the future scenarios. Our modelling approach involves several simplifying assumptions, and takes a steady state stance. By this we mean that we do not consider dynamic issues, formulations of social and private discounting, risk and uncertainty (though scenario analysis partly addresses the latter): we model an immediate and permanent, one-time drop in water availability to assess its economic effects. We also take current production technologies and socio-economic trends as given and assume that climate change has no feedback effect on any of these. In reality, society would have more flexibility in terms of the adaptation and mitigation activities it undertakes to minimize adverse impacts, leading us to overestimate the economic consequences of climate change. Given the expected magnitude of changes in water availability, however, we expect the bias introduced by these assumptions to be relatively small.

To assess climate change impacts on the recreation sector, we use an approach that is loosely based on travel cost models, but is a very crude approximation. For the surface waters of the Waimea Plains region, the approach estimates the number of recreational users visiting sites and annual costs incurred by them. The aggregate cost estimate is taken as an estimate of recreation benefits the resource provides. The simple rationale behind this is that if a person spends $10 on travelling to the Wai-iti River, the recreation experience must be worth at least $10 to this person. The survey only sampled local residents, which has the effect of biasing the recreation benefit estimates downward. At the same time, our model (unlike a real travel cost model) takes no account of alternative recreational options in the area, which leads to an upward bias in recreation benefit estimates. The crudeness of this approach is justified by the time and monetary costs of a proper travel cost analysis.

This report describes a general model of the economic and social effects of climate change on water resources (Section 6.2). This model assumes a link between climate-change effects on hydrological systems, water availability, economic measures and social measures.

The TEV framework (White, et al. 2001) is used in this report to represent economic effects of climate change on water availability. This framework includes economic values associated with the water resource for:

1. Productive sector components (agriculture, commercial/industrial and urban). Values for these components can be assessed using non-market valuation

methods based on information provided by water users through questionnaires; and

2. In situ water resource use (e.g. fishing and boating). In-situ values can be assessed from recreational use, the costs of recreational use, and contingent valuation methods.

The effects of climate change on social measures can be assessed assuming that social measures are linked to economic effects. For example broad social measures can be linked to income and specific social measures such as employment can be linked to activity of the productive sector.

The model was applied to assess the effects of climate change on economic and social measures in the Waimea Plains test catchment. Two scenarios of land use were developed for this purpose: (1) estimated land use in 2005; and (2) estimated land use in 2050. Land use was estimated in 2005 based on a survey conducted in 1999 and other information. Land use for 2050 was extrapolated from 2005 taking current trends in agricultural and urban land area into consideration.

Modelling simulations indicate that future climate change may result in reduced groundwater recharge accompanied by declines in groundwater levels and river flow in the Waimea Plains under severe drought conditions (see Section 5). The effects of this climate change are assessed in the context of the economic value of water availability in 2005 and 2050. First, the economic value of water availability in 2005 and 2050 under current climate conditions is estimated using TEV obtained from datasets developed in appendices to this report. Then the economic value of water availability in 2005 and 2050 with predicted climate change is compared with current climate values.

Economic and social modelling linked with hydrological resources requires datasets that are generally undeveloped for New Zealand. Therefore, the information needs for future assessments of the effects of climate change on economic and social measures are summarized at the end of this section.

6.4 General Model

The general model has three main components (Figure 6-2): (1) water availability; (2) economic measures; and (3) social measures. This model assumes that, between data points, economic measures (E_i) are linear functions of water availability (W_i) and social measures (S_i) are linear functions of economic measures (E_i). The nature of the relations between W_i , E_i and S_i may be non-linear. For example a shock in the form of an extreme climatic event may cause dramatic changes to social patterns where agricultural land use is at the margins of sustainability. In this application of the model it is assumed that there is linearity between data points in response to climate change but not necessarily linearity overall.

The model includes the following features:

1. Input data includes land use (Section 6.5) and relations between land use, water availability, economic measures (Appendix B), and social measures (Appendix C). The model also includes water allocation sustainability limits for hydrological features such as groundwater, rivers and springs;

2. Various checks were run on input data (i.e., land use was defined for all model cells, relations between land use and economic measures were defined for all land uses in the model, and the relation between water availability and economic measures broadly, at least, follows that described in Section 6.6.2);

3. Calculation of productive values with water availability and in situ values with water availability in the model area;

4. Calculation of TEV components and social components with current water availability using input data;

5. Calculation of TEV components and social components with alternative water availability selecting water availability as the input;

6. Comparison of calculations with current water availability to alternative water availability;

7. Comparison of water allocation with water allocation sustainability limits for hydrological features; and

8. Productive and in situ values are linked in the model (i.e., an increase in water use by production will result in a decrease in water available for in situ use).

Operationally, the model is implemented with the FORTRAN computer programming code.

Local observations are key to the development of relevant models of W_i , E_i and S_i. Model implementation described herein aims, as much as possible, to determine the nature of the relation between W_i , E_i and S_i from local observations. Data sets relevant to water economics have been collected in the Waimea Plains since 1999 (e.g., White, et al., 2001 and White, 2010). The existence of these data made development of this model possible. Relations between water availability and water economics in these data sets are linear between data points, but not necessarily linear overall.

Some data sets relevant to this project were developed during the project in a desk top exercise. Project budget limitations required that some of these data sets are little more than conceptual in nature. Two examples of this are the relation of in situ values to water availability and the relation of economic indicators to social measures. Section 6.8 presents a discussion of data needs, in general, for an assessment of W_i , E_i, and S_i and the data that were available for application in this project.

Uncertainty analysis would be very useful for assessment of the effects of climate change (Section 6.8). However, uncertainty analysis was not undertaken here because rigorous analysis of uncertainty was beyond the scope of this project. For example:

1. Field and household surveys are required to indentify errors in the relationships between in situ values and water availability;

2. Extensive analysis of Statistics New Zealand data is required to assess the relation between economic indicators, relevant to this project, to social measures.

An assessment of the uncertainty in economic values for agriculture discussed in this report can be made with an analysis of agricultural land sales. However, because there are few agricultural land sales in the Waimea Plains the accuracy of such an independent check on farmers' estimates of economic value is greatly limited (Sharp 2004).

Water availability can be steady-state or transient. Steady-state water availability means that water is equally available at all times. Typically, resource consents specify the conditions of water availability with transient conditions. An example of such conditions would be cut-backs in water allocation when river flows are low. It is assumed in this model that water availability is variable. Variability can occur for various reasons. In this case, environmental stress due to climate change could reduce water availability by requiring cut-back regimes.

Other factors that could be considered within the framework of the model include water quality and extreme weather events. Climate change effects on water quality could include: (1) an increase in nitrate concentrations in groundwater recharge due to a reduction in dilution accompanying decreases in overall groundwater recharge; and (2) an increase in nitrate concentrations in streams at low flow due to an increase of nitrate levels in groundwater discharging to those streams and a decrease in stream baseflow.

Extreme weather events (i.e., floods and droughts) may become more frequent as a result of climate change (NIWA, 2008) and this may also impact on the economics of water use. For example:

1. Surface water availability could be reduced during critical times of the year by increases in flooding causing less of the total annual flow of the stream to occur during low flow periods. This could entail extra costs in water storage to supplement surface base flow; and

2. Groundwater availability could be reduced by an increase in high rainfall events that cause increased run off instead of recharge.

Climate change effects on water quality and extreme weather events could be considered within the framework of the model. However these are not included in this report because they are outside the scope of the project contract and the full information base to assess the economic effects from such effects has not been assembled.

The following subsections include descriptions of the water availability, economic, and social measures considered in the model.

6.4.1 Water Availability

Water availability is a fundamental determinant of investment by the productive sector in land ownership and water-related infrastructure. For example:

1. Land ownership and land purchase-price decisions are influenced by water availability;

2. Water-related infrastructure such as dams and canals must have access to water prior to construction and a good ‘quality’ consent (see following);

3. Land use is constrained by water availability (e.g., development of land uses with relatively high water requirements for irrigation can be precluded by limited water availability.

Water availability (Figure 6-3), is used here as the key indicator of the state of the water resource. Therefore, the economic framework expresses values in terms of availability rather than use. This is because investment decisions are also commonly based on availability. For example, when considering a water user, it is common to request a water allocation that factors in security of supply. Security of supply is most important in drought conditions where a user typically requires more water than in average conditions. Therefore water allocation is also typically greater than water use. For example, water allocation to agricultural users in the Lower Confined Aquifer water use zone of the Waimea Plains in 2005/2006 was 70,255 m^3/week while average usage by agricultural users in this zone was only 17,806 m^3/week, about one-fourth of allocation, during the 26 week irrigation season that yea (White, 2010).

Water allocation limits are designed to protect water resources, particularly during times of stress (e.g., during summer low river flow periods). Therefore, water allocation limits may vary over time as specified by resource consents under the RMA. Quantitative information on water availability is recorded by regional councils either explicitly through such mechanisms as resource consents or implicitly through estimates of river flow, groundwater levels and models of hydrological processes.

Water availability is also fundamental with regard to in situ values such as:

1. Use values including swimming, fishing and canoeing; and

2. Non-use values including provision of environmental services (e.g., groundwater resource providing base flow to surface water), existence values (where a water resource is valued for its existence or intrinsic worth), and ecological health.

Water availability to the productive sector and for in situ uses may vary systematically over time (e.g., as determined by changes in climate). The model used here treats water availability as an independent variable that is fundamentally determined by climate (Figure 6-4) and therefore potentially impacted by climate change.

The "quality" of the consent influences investment in water-related infrastructure, land use, and land ownership. Four characteristics of consents that define its quality and may influence investment decisions include:

1. Duration. A longer-duration consent is more valuable to the holder;

2. Exclusivity. Consent holders have the ability to appropriate the benefits associated with investment;

3. Transferability. Water use may shift to higher value uses; and

4. Transformability. Consent holders may create derivative rights (e.g., leases) that may improve flexibility of water use and manage risks.

Some water use is allowed in addition to water allocation consents. For example, the RMA allows water use without consent. These are known as "permitted" uses and include individual wells for domestic purposes, stock watering, and water used for fire fighting purposes. The permitted water uses of domestic purposes and stock watering are considered in the model framework through the assessment of the economic value of water.

6.4.2 TEV Framework

The TEV framework (White, et al., 2001), Figure 6-5, used here includes:

1. Productive sector values (i.e., agriculture, commercial/industrial and urban uses); and

2. In-situ water resource use and non-use values.

Generally, productive and in situ values increase as water use increases. However the marginal value of water (i.e., the first derivative of value and water use) decreases for both productive and in situ water use as water use increases (Figure 6-6).

This framework can be used to assess trade offs of water use between the various productive uses and trade offs of water use between productive and in situ uses. For example, a reduction in water availability to the productive sector may lead to an increase in water available for in situ use. The TEV framework may be used to assess the decrease in economic values associated with a reduction in production against the increase in economic values associated with the increase of in situ use.

The TEV associated with a water supply is typically assessed as capital value. In New Zealand, the economic value of water supplies for productive purposes are significant. For example, the value of the water resource in one region (Manawatu – Wanganui) has been estimated at $2.7 billion (White and Sharp, 2002) and the annual economic value of surface water and groundwater for production in New Zealand by industry and for municipal water supply has been estimated at $34 billion/year (White, et al., 2004).

The value of water for productive sector uses, including "permitted" water uses, and in situ uses (Figure 6.4) are assessed by standard economic methods (National Research Council, 1997). The information required to quantify components of the framework are best assessed through targeted surveying in the area of study, as White, et al. (2001) did, because:

1. Economic values, such as land values and angler effort, are commonly specific to local conditions;

2. Water use requirements are commonly specific to local conditions. This is evident when it is considered that requirements for irrigation vary considerably around New Zealand with irrigation requirements minimal in some regions and crucial to agricultural sustainability in others. Therefore, water values vary considerably across the country;

3. In situ use varies substantially between regions and within regions.

However, values from national studies may be applicable to local conditions.

The following is an example of a typical approach to estimation of water values for the productive sector:

> Typically, productive sector water users are questioned about the relation between water availability and values (including land, land use, owner labor, and expenditure on labor). In this case, water availability levels of 120, 100, 80, 60, 40, and 0% of current availability were used. Table 6-1 shows one farmers estimate of how the worth of his property increases between 0% water availability and 120% water availability. The value of water allocation to this farmer is estimated as $48,780 per hectare (i.e., estimated land value with 100% water availability minus estimated land value with 0% water availability).

In this example the steep increase in estimated land value between 0 and 60% water availability reflects the high marginal value of water at relatively low water availability, as expected from Figure 6-6. However the marginal value of water decreases as water availability increases and the farmer in Table 6-1 estimates no additional economic benefit associated with water availability greater than 60% of current availability. This means that the value of the land, not estimated to increase between 60% and 120% of current water availability, becomes independent of water availability above 60% from the standpoint of this farmer. A possible reason for this may be because the existing business can stand a reduction in water availability from current availability to 60% of current availability without economic impact as crop demand is much less than current availability. The farmer in Table 6-1 also estimates that any extra allocation, in addition to the current allocation has no economic value. This is because the value of the land is not estimated to increase between 100% and 120% of current water availability.

The value of water can also be expressed on a unit basis. For example, in their 1999 survey White, et al. (2001) estimated the value of groundwater in the Waimea Plains to agriculture at $240 to $300 per allocated cubic metre.

This model is intended to represent the economic effects of water availability on productive sector values including:

1. Agriculture with production revenue, land values, water use, and employment;
2. Commercial/industrial with production, market value of firms, water use, and employment;
3. Urban with infrastructure value and operating costs.

This information is used in the application of the model to estimate the TEV of two land use scenarios (land use in 2005 and land use in 2050 per Section 6.5) with current climate (Section 6.6) and with climate change (Section 6.7). The model uses linear interpolation of data collected from targeted surveys to estimate the effects of water availability on economic measures.

Climate change effects on water quality could be included in the model by establishing the economic costs associated with changes in water quality. Some of these kinds of costs were assessed in the1999 survey of groundwater irrigators. For example, 46 irrigators in the 1999 Waimea Plains water economic survey estimated that the value of water quality is minimal to their operation. These irrigators estimated that only a minimal increase in property value of an average of approximately $4,100 compared to the average property value of approximately $772,000 would attend improvement of water quality above its current state to become "uncontaminated." Uncontaminated also meant no risk of future contamination by such things as nitrates, pesticides, salt water, and bacteria. Establishment of the economic costs associated with water quality for the productive sector and in situ uses requires targeted surveys that are outside the scope of this project. Therefore climate change effects on water quality are not included in the model.

Climate change effects on extreme weather events such as increases in the occurrence of floods and droughts as NIWA (2008) indicates is possible, could be included in the model by establishing the economic costs associated with extreme weather events and water availability. For example, a reduction in surface base flow associated with floods and droughts could be mitigated by water storage and an alternative water supply could mitigate reductions in groundwater availability resulting from floods and droughts. TDC intends to mitigate the effects of increased extreme rainfall events caused by climate change with the improvements currently planned for Richmond's stormwater drainage infrastructure (Stephenson, 2010). Establishment of the economic costs associated with water storage, alternative water supplies, and stormwater drainage infrastructure requires economic analysis that is outside the scope of this project. Therefore, climate change effects associated with extreme weather events are not included in the model.

6.4.3 Social Indicators

Generally, social indicators are broadly associated with economic indicators (Appendix D). For example, as illustrated in Figure 6-7, the wealth of a country is a key indicator of social conditions. Social indicators measure the quality of life and include objective measurements of living conditions and subjective measurements of well being. Health indicators are also broadly associated with economic indicators (Appendix D).

Social indicators available for New Zealand through Statistics New Zealand include (Appendix D): (1) the Household Labour Force Survey; (2) the Household Economic Survey; (3) the New Zealand Income Survey; (4) the Survey of Family, Income and Employment; and (5) the General Social Survey (so far completed only once in 2008). Social indicators are also reported by the Ministry of Social Development (2006, 2008).

These indicators are only a small subset of potential social indicators, such as those available for the German population which include approximately 400 indicators and more that 3,000 time series data sets (Appendix D). Collection of additional social indicators for New Zealand has been proposed (Statistics New Zealand, 2001) and the General Social Survey (Appendix D) was commenced in 2008. Therefore data on New Zealand social indicators is expected to increase over time.

The New Zealand Index of Deprivation (Salmond, et al., 2006) measured deprivation in 1991, 1996, 2001, and 2006. It is based on the national census. The 2006 index includes, in order of decreasing weight (Salmond, et al., 2007):

1. Income (people aged 18-64 receiving a means tested benefit);
2. Income (people living in households with income below an income threshold);

3. Home ownership;
4. Support (people less than 65 years old living in a single parent family);
5. Unemployment of those aged 18 – 64;
6. Qualifications of those aged 18 – 64;
7. Living space of those living below a bedroom occupancy threshold;
8. Communication (people with access to a telephone);
9. Transport (people with access to a car).

Social data for the Tasman District include:

1. NZDep2006 for approximately 199 Waimea Plains meshblocks;
2. Statistics New Zealand data (Coleman, 2010) including population, age distribution, average income, tertiary education level, number of dwellings, and occupants per dwelling.

Statistics New Zealand data are generally available for the period of the district's development since about 1961, with some indicators available since 1951.

Employment is an important social indicator. This was represented in the model because a data set on employment and economic activity had been assembled as part of water economic surveys of groundwater users in 1999 (White, et al., 2001) and for the period 2003/2004 – 2007/2008 (White, 2010).

The New Zealand 2006 Index of Deprivation (NZDep2006) is an additional useful indicator to consider in this report because:

1. The index is available for all of the New Zealand population within small population blocks as the index has been calculated within approximately 41,400 Statistics New Zealand meshblocks;
2. The index was developed from census data collected in 1991, 1996 and 2001;
3. The methodology and applications used have been published (Appendix D).

The model therefore includes NZDep2006, which incorporates income and is therefore broadly related to measurements of income on a regional scale (Appendix D). This link with the economic measure of income is developed for the model.

6.5 Estimated Waimea Plains Land Use in 2005 and 2050

Two maps of land use for the Waimea Plains were developed to represent estimated land use in 2005 and a possible scenario for land use in 2050. These maps were used to assess economic and social measures in the absence of climate change (Section 6.6) and with climate change (Section 6.7). A 250 m by 250 m grid was used to represent land uses within the Waimea Plains by these maps.

6.5.1 Estimated Land Use in 2005

Land use for the Waimea Plains in 2005 was estimated in this report (Figure 6-8 and Table 6-2). This estimate was necessary because there are no land use data documenting conditions at that time (Thomas, 2010). As noted above, this estimate was based on a survey conducted in 1999 and other information.

Estimated land use for the Waimea Plains in 2005 includes:

1. Agricultural areas with:
   a. The Waimea East Irrigation Scheme (WEIS) irrigated by surface water (yellow in Figure 6-8);
   b. Areas irrigated mostly by groundwater (red in Figure 6-8);
   c. Non-irrigated agricultural areas (light blue in Figure 6-8);
2. Richmond urban area (green in Figure 6-8). Other smaller towns such as Brightwater are not included in the model because they have a very small population relative to Richmond;
3. Non-farmed area such as river beds (dark blue in Figure 6-8).

Five types of irrigated (using either surface water or groundwater) agricultural land (Table 6-3) were considered in the model because the economics of different irrigated land uses vary considerably (White, 2010). The estimate of irrigated agricultural area is from Fenemor and Bealing (2009). They estimated the total for all agricultural land irrigated with groundwater outside of the WEIS at 2,700 ha. This includes approximately 66 ha in the Redwood Valley Scheme outside of the Waimea Plains. The 2,644 ha number in Table 6-2 is 2,700 ha minus 66 ha. The distribution of irrigated agricultural land outside of the WEIS shown in Figure 6-8 is to some degree arbitrary. The proportions of type of land use shown in Table 6-4 were estimated from a random survey of Waimea Plains farms conducted in 1999 (White, et al. 2001). The proportional distribution within the WEIS is the same as outside except that the dairy classification has been eliminated. No dairy farms currently exist within the WEIS (Fenemor, 2010).

6.5.2 Estimated Land Use in 2050

Land use for the Waimea Plains land by 2050 (Figure 6-9 and Table 6-2) was estimated assuming present trends, as identified in a survey conducted during the 2003/2004 – 2007/2008 period survey (White, 2010), continue and that the Richmond urban area grows in the future.

The survey of irrigators taking groundwater from the Lower Confined aquifer (White, 2010) indicated that the trend in agricultural land use was for high-income/hectare land uses (e.g., horticulture and market gardening) to replace low-income/hectare land uses (e.g., dairy and to a lesser extent apples). Therefore, the 2050 land use scenario assumes that the portions of irrigated land use will change in the future with high-income irrigated land uses preferentially replacing low-income irrigated land uses.

The scenario assumes that irrigated land use by dairy (outside the WEIS) will be reduced approximately 50% by 2050 and that the use of this land shifts to horticulture and market gardening. Land use for irrigated apples is assumed to increase modestly. As shown in Table 6-3, the total land irrigated in this scenario remains 3,744 ha (agricultural land outside of WEIS irrigated by groundwater of 2,644 ha and within the WEIS irrigated by surface water of 1,100 ha).

Urban Richmond land area will most probably increase in the future as the population is forecast to increase. It is estimated in Appendix E that the Richmond urban area will increase to an estimated 1,937 ha in area by 2050 (in particular, see subsection E.2.3 in Appendix E). However, existing options for town expansion (“Richmond West” and “Richmond South,” Appendix B.2.3) do not appear to provide enough land for growth to 2050. Therefore, it is assumed in this scenario that more land is required by Richmond than the “Richmond West” and “Richmond South” blocks. Such land could come from land blocks in the following areas:

1. West of Paton Road as far south as Aniseed Valley Rd;
2. West of Main Road as far south as Ranzau Road; or
3. North of Richmond outside the Waimea Plains.

The Richmond urban area in the 2050 Waimea Plains model within the Waimea Plains is estimated as 1,444 ha (Table 6-2). Use of land blocks 1 and 2 above reduce the area of the WEIS.

Estimated land use in 2050 will probably not need more water allocation than estimated land use in 2005. This is because:

1. Agricultural land use change does not result in increased water demand. For example, estimated total water use by the four major irrigated land uses in 2050 is approximately 4% less than in the 2005 land use scenario. Estimated total water use is less because the area of dairy, a land use with relatively high water use (Appendix B, Table B-2), is reduced and is replaced by horticulture and market gardening which have relatively low rates of water use (Appendix B, Table B-3 and Table B-4, respectively); and

2. Some replacement of irrigated agricultural land with urban land will probably have little impact on water demand in Waimea Plains because water use by irrigated agriculture (in the range 1,655 to 3,560 m^3/ha/year) is similar to urban water use (estimated at approximately 2,700 m^3/ha/year, Appendix E.3.2).

An alternative scenario of future land use with increased irrigation area and water storage is currently under assessment by TDC (Waimea Water Augmentation Committee, 2010). Water storage in the Wairoa River would have multiple purposes including augmentation of flows in the Waimea River.

6.6 Waimea Plains Economic and Social Indicators for Current Climate

Economic and social indicators developed in Appendices B and C, respectively, for the

Waimea Plains were applied in this section to estimated land use in 2005 and 2050 for the current climate. Economic values are expressed as 2005 dollars.

Economic values for the productive sector were assessed using data from surveys of Waimea Plains groundwater users in 1999 (White, et al., 2001) and 2003/2004 – 2007/2008 (White, 2010). These included “permitted” water uses. TEV for surface water use would probably be much the same as for groundwater use (i.e., land values and the marginal value of water are independent of irrigation water source). Furthermore, it is likely that the cost of water production, both groundwater and surface water, is very small in relation to the TEV of business operations in the Waimea Plains.

Surveys of groundwater users have established relationships between water availability and economic measures for the productive sector. The 1999 survey (White, et al., 2001) was a random survey targeted at users of groundwater and included 20% of agricultural users in the Waimea Plains, all commercial users, and the TDC (as the municipal water supplier). Surveys during the 2003/2004 – 2007/2008 period (White, 2010) targeted irrigators using the Lower Confined Aquifer (LCA) of the Waimea Plains.

In situ values, both use and non-use, were assessed from a 1999 survey of Waimea Plains householders. The objective of this survey was to identify key in situ values related to the water resource (Appendix B.4). Information from this survey was applied by estimating relations between water availability and in situ values.

A meeting with Nelson iwi (Tiakina te Taiao Ltd) discussed economic indicators important to Maori. Maori value all components of the hydrological cycle equally. Therefore productive values are equal to in situ values in the eyes of local Maori and any tradeoffs between values must be done on an “even value” basis.

Assessing tradeoffs on an even value basis means, for example, that effects of productive sector use on in situ values are treated equally at the location of effect. For example, groundwater may impact the flow of a number of springs. Some springs may have larger economic value than others in terms of in situ uses. Therefore, groundwater use would impact on economic values in some springs more than others. However all springs would be treated as being of equal value by Nelson iwi in any assessment of effects. Hence the tradeoff between productive values would be of the effects of production against in situ values ranking all springs equally.

This approach is particularly relevant to an assessment of economic and social effects of climate on local water bodies.

6.6.1 Indicators and Estimated Land Use in 2005

Economic values of the productive sector and in situ use are applied to a representation of estimated 2005 land use in the Waimea Plains (Table 6-2).

The TEV of productive sector water use is estimated at $322 million (including agriculture, commercial/industrial, and and urban). The in situ value of the resource is estimated at the much lower value of $51 million. It is not unusual that in situ values are much lower than values for productive uses (e.g., White and Sharp, 2002). Because this value does not include Maori values it can only be considered an underestimate.

The economic value of water to agriculture (Table 6-6) was calculated using estimates for irrigated land areas (Table 6-6) and multiplying them by the difference between land value with 100% and 0% water availability (Appendix B.1). It is estimated at $125 million.

Expenditure on employment related to water availability with current water availability is estimated as $66.1 million/year (Table 6-7). This figure translates to direct employment for an estimated 2,096 persons (Table 6-8) at median weekly earnings equivalent to $31,500/year in 2005. Employment in agriculture is critically dependent on the water resource, with estimated labour expenditure being less than $0.1 million/year without irrigation.

Direct employment and incomes associated with water availability affect other economic sectors as well. Total employment effect is estimated as the expenditure on labour times two (the approximate multiplier for agriculture based on Ford, et al., 2001). It is assumed to also be valid for industrial/commercial and urban water supply uses. The average income is $31,500/year. Therefore, estimated total labour directly or indirectly associated with the water resource totals is estimated at 4,192 full time equivalent (FTE) persons.

The NZDep2006 index of 977 for 2006 is taken as the index for 2005 (977, Appendix D).

6.6.2 Indicators and Estimated Land Use in 2050

The estimated TEV of water for 2050 is shown in Table 6-5 as $547 million, an increase of about 47% from $373 million in 2005 while the estimated economic value of water for agriculture for 2050 is shown in Table 6-6 as $133 million, an increase of only about 6% from 2005. The predominant increases in the value of water between 2005 and 2050 are in the productive use categories of commercial/industrial and urban and with regard to in situ surface water use.

The economic value of water to the commercial/industrial sector is estimated at $221 millions for 2050. This was arrived at assuming that the commercial/industrial sector experiences the same percentage growth in production as the agricultural sector (i.e., by multiplying the 2005 value of $160 million by the ratio of the estimated value of agricultural production in 2050 of $87.9 million to current agricultural production of $63.7 million). This is a completely arbitrary approach to estimating future value but necessary in the absence of real data on commercial/industrial production trends.

In situ values are expected to increase as the population increases. Richmond's population is estimated to increase from a level of 10,140 in 2006 to 27,600 in 2050 (Appendix E, Table C-4). Increased population brings more recreational use of associated surface water resources. However, increased demand for water by the productive sector may result in a decline in water quantity. The next section of text explores the possibility that water quantity may decline and the impact of such decline on recreational use of rivers.

Water use in 2050 is estimated at 15.1 million m^3/yr, or about 0.5 m^3/s. This is made up of:

1. Agricultural use of 9.8 million m^3/yr, estimated with the "current trend" scenario of land use;

2. Commercial/industrial use of 0.3 million m^3/yr (estimated for 2050 using current water use times the ratio of estimated agricultural production in 2050, $87.9

million, to current agricultural production, $63.7 million, exclusive of supply from TDC;

3. Urban use of 5 million m^3/yr (Appendix E, Table E-12).

Water use in 2050 is less than the current allocation (Appendix F), so on an annual basis this growth in water use can be accommodated within the existing allocation. Therefore, it is assumed that an increase in water use in the 2050 land use scenario will have no negative effect on the availability of rivers for recreation. However the seasonal water use pattern, with relatively high use in summer may exacerbate low river flows in summer. This would be expected to adversely impact summer time water-related recreation because summer is a time when that use is likely high, however there are no data regarding the relation between summer river flows and recreational use in the Waimea Plains.

The in situ vale of water is estimated at $67 million (i.e., the current value from Table 6-5 times the fractional increase between current Richmond population and estimated population in 2050).

Expenditure on employment related to water availability in 2050 is estimated as $108 million/year (Table 6-7). This figure translates to direct employment for an estimated 3,410 persons and total employment of 6,820 persons at an average income of $31,500/year (Table 6-8). For comparison purposes, these values are all expressed in terms of 2005 dollars. Although wages generally increase over time, this assumes that their real value does not.

6.7 Waimea Plains Economic and Social Indicators With Climate Change

Economic and social indicators specific to the Waimea Plains developed in Appendix B were applied in this section to estimated land uses in 2005 and 2050 with climate change. Economic values are expressed as 2005 dollars.

The effects of climate change on economic indicators were calculated as the difference between TEV with climate change and TEV with current climate.

The importance of climate change effects in the context of TEV and some social indicators associated with current climate was classified as:

1. Minor – If the change in the indicator with climate change is in the range of plus or minus 5% of the value of the indicator with current climate;

2. Moderate – If the change in the indicator with climate change is in the range of plus or minus greater than 5 to 20% of the value of the indicator with current climate;

3. Major- If the change in the indicator with climate change was outside of the range of “minor” or “moderate” for the value of the indicator with current climate.

For example the NZDep2006 index for Tasman is 977 (Appendix D). A “minor” increase in this index, as defined above, would be less than about plus or minus 49 points. That could move the index to anywhere roughly in the 928 to 1,026 range, with the higher number equivalent to the NZDep2006 index for Hawkes Bay (Appendix D). A “moderate” increase in this index would move it to somewhere in the 1,026 to 1,172 points range, with the higher number equivalent to the NZDep2006 index for Northland and Gisborne (Appendix D).

6.7.1 Climate Change Impacts on Waimea Plains Hydrology

The most significant potential impact of climate change on the Waimea Plains water resources so far identified would be the impact on groundwater and associated surface waters resulting from reductions in groundwater recharge. For climate change as projected by the A1B emissions scenario (a “middle of the road scenario), groundwater-streamflow interaction modelling (Section 5) indicates a decline of about 2% in rainfall recharge from historic data for the drought of record (1 July 2000 through 30 June 2001) to the 2058-2059 year with similar drought conditions (Table 6-9). For the A2 emissions scenario (a more extreme scenario but not the most extreme), the decline in rainfall recharge would be about 13% (Table 6-9).

Climate change can also potentially impact surface water resources. Under the same climate change scenarios run above with regard to groundwater recharge, groundwater-streamflow interaction modelling (Section 5) indicated that, under extreme drought conditions, substantial reductions in streamflow were possible compared to historic values. These are shown in Table 6-10 and amount to a reduction in flow at the TDC Nursery location of about 22 and 28%, respectively, for the A1B and A2 emissions scenarios.

Streamflow data for the Wairoa River at or near the current Irvines gaging station is available from 1958 to the present day. Hong and Zemansky (2008) estimate that it is necessary to have flow at Irvine of at least 2,822 L/s in order to ensure that flow at the Waimea River TDC Nursery gaging station does not decline below 1,100 L/s. TDC plans to use a flow of 1,100 L/s at the Waimea River TDC Nursery site as a trigger for rationing irrigation water during low flow periods. Therefore, irrigation rationing will be considered when flow at the Wairoa River Irvine gaging station falls below 2,822 L/s.

Average streamflow at the Wairoa River Irvines gaging station over the two-month low flow period during the drought of record in 2001 (indicated in Table 6-10), was less than 2,822 L/s four times between 1958 and 2010 (Figure 6-10). Considering that climate change could reduce the average flow by:

1. 95 L/s under the A1B emissions scenario (i.e., from 437 to 342 L/s) average flow at the Wairoa River Irvines gaging station may have to be maintained at 2,917 L/s to avoid rationing. Average Wairoa River streamflow at the Irvines gaging station over this two-month period was less than 2,917 L/s five times between 1958 and 2010;

2. 121 L/s under the A2 emissions scenario (i.e., 437 L/s minus 316 L/s) average flow at the Wairoa River Irvines gaging station may have to be maintained at 2,943 L/s to avoid rationing. Average Wairoa River streamflow at the Irvines gaging station over this two-month period was less than 2,943 L/s five times between 1958 and 2010.

Therefore climate change poses a risk of rationing, due to low river flow, five years in 52 or approximately one year in ten. This risk is assumed to translate to a 10% reduction in average water availability (i.e., the A1B GCM5 and the A2 GCM6 climate change emissions scenarios have a similar outcome from a water availability standpoint).

Effects on the economic value of water to productive use with climate change were estimated with the model for productive values and three values of water availability change as follows:

1. -2% consistent with the A1B GCM5 climate change scenario and possible effects on rainfall recharge to groundwater and river flow;
2. -10% consistent with the A1B GCM5 and A2 GCM6 climate change scenarios and possible effects on river flow and rainfall recharge to groundwater;
3. -13% consistent with the A2 GCM6 climate change scenario and possible effects on rainfall recharge and river flow.

6.7.2 Impact of Climate Change on Economic and Social Indicators - 2005 Land Use

Economic indicators decline due to climate change (Table 6-11) because water availability is projected to decline with climate change. For example, the modelled change in value to the productive sector is a decrease of $7.4 million with a 2% decline in water availability. In situ values are also expected to marginally decline with climate change.

It is projected that expenditure on labour (Table 6-12) and employment (Table 6-13) will decrease, most of the decrease being a result of commercial/industrial sector changes with climate change. Therefore, it is also estimated that the NZDep2006 will marginally increase with climate change from the 2005 value (Table 6-14) driven by a decrease in local income.

A small increase in this index means a small movement towards greater deprivation.

Economic effects of climate change were assessed relative to 2005 values under current climate conditions. Results are presented in Table 6-15. For example the decline in productive sector value with climate change (-$7.4 million with a 2% decline in water availability, Table 6-15) is minor (Table 6-16) in relation to the base productive value in 2005 without climate change of $322 M (Table 6-5). In contrast, a 13% decrease in water availability could reduce productive sector value by $47.8 million (Table 6-15) which would be considered a “moderate” impact (Table 6-16).

6.7.3 Impact of Climate Change on Economic and Social Indicators - 2050 Land Use

Economic indicators decline due to climate change (Table 6-11) because water availability is projected to decline with climate change. For example the modelled change in value to the productive sector is a decrease of $9.9 million with a 2% decline in water availability. In situ values are also expected to marginally decline with climate change.

Expenditure on labour (Table 6-12) and employment (Table 6-13) are both expected to decrease with climate change with most of the decrease occurring in the commercial/industrial sector.

Economic effects of climate change by 2050 are assessed relative to 2005 values with current climate in Table 6-15. For example the decline in productive sector value with climate change (-$9.9 million with a 2% decline in water availability) is minor (Table 6-16) in relation to the base value in 2005 without climate change of $321.5 million (Table 6-5). In contrast, a 13% decrease in water availability could reduce productive sector value by $69.6 million (Table 6-15) which would be considered a “major” impact (Table 6-16).

6.8 Information Needs for Optimal Assessment of Economic and Social Effects of Climate Change

As shown in this application of a demonstration model to the Waimea Plains test catchment, assessment of the economic and social effects of climate change on hydrological systems requires many different data sets. Much of the kind of data required for input into an appropriate model are not available for New Zealand catchments and regions. Therefore, this section summarises the kind of data required for future assessments of economic and social effects of climate change on the water resource.

Maps of land use are crucial to assessment of economic and social effects of climate change. These maps should include the main productive land uses associated with water resources including agriculture, commercial/industrial, and urban and be in a form suitable for digital processing. An approach that could be useful is that by Komischke and White (2006) where current, and historic, land use was summarised as GIS data sets.

Maps of future scenarios of land use are also necessary for the assessment of economic and social effects of climate change on the water resource. A detailed land use model of the sort needed for this exercise does not currently exist within New Zealand. For example, Motu’s Land Use in Rural New Zealand (LURNZ) model focuses on the four most important agricultural sectors only and is of national scale; its predictions at finer spatial scales being inaccurate (Hendy, et al., 2007). Future land use maps would also be useful for planning of water resource management. Given the heterogeneity of the New Zealand landscape, the development of regional land-use models would be needed if more accurate scenario development is desired.

A large variety of economic and water allocation and use data are required to characterise current resource use. Surveys of users are one way of obtaining such data. In fine-scale applications, such as this one, the small volume of market transactions data (on agricultural land sales, for example) is usually a limiting factor - in these cases, surveys may be more efficient in terms of generating data. Economic data required by these surveys includes values associated with the productive and in situ sectors (e.g., Appendix B). Water allocation data are available from regional councils and water use data may sometimes also be available from regional councils and water users. Currently, water use data are available for the Waimea Plains because of historic shortages and responsible regulation by TDC. Water use data are becoming increasingly available elsewhere. However, such data are not yet widely available. Of course, correct survey design and performance are important to the quality of the resulting information.

A comprehensive assessment of in-situ benefits and existence values requires surveying users and non-users of the region’s water resources in an even wider geographic area. Data requirements for such a non-market valuation study are intensive. With regard to some of the recreational benefits (e.g., fishing), environmental economists have in recent years conducted a fair number of assessments throughout New Zealand. Several of these have arrived at similar value estimates, suggesting that their results could be fairly robust. These could be used in a benefit transfer to estimate valuations in other areas.

Economic data are also required to understand how economic measures will respond to environmental stress; this information is a key requirement to assessments of economic and social effects of climate change on the water resource. These economic data can also be established by surveys of water users. The demonstration of the model in this report uses this approach. However, results from surveys lack independent verification and therefore there is substantial uncertainty with regard to relationships between economic measures and environmental stress. Cross-sectional comparisons to other similar areas experiencing different amounts of environmental stress may yield some insight into the validity of these results.

Social indicators are integral to assessments of climate change. However, time series data for social indicators in New Zealand are not typically long (Appendix D.1). More work is required on the development of catchment and regional social indicators. More work is also required on the relation between social measures and economic measures at both regional and national scales to be able to assess linkages between these two kinds of measures. Besides these uncertainties and data limitations, most social measures seem to be quite directly related to economic outcomes, and therefore focussing on the latter only may be warranted.

Uncertainty analysis would be very useful for the assessment of the economic and social effects of climate change on hydrological systems. However, uncertainty analysis was not undertaken here because rigorous analysis of uncertainty was beyond the scope of this report. Factors pertinent to the level of uncertainty with regard to this type of assessment include:

1. Assessment of the uncertainty in economic values for agriculture discussed in this report includes analysis of land sales. However, generally few agricultural land sales occur in the Waimea Plains, which means that available data are not suitable for analysis (Sharp, 2004);

2. Field and household surveys are required to indentify errors in relations between in situ values and water availability;

3. Extensive analysis of Statistics New Zealand data is required to assess the relation between economic indicators, relevant to this project to social measures.

Finally, an optimal framework for climate-induced changes in water availability would include mitigation opportunities. Constructing water storage facilities would, for example, enable society to counter to some degree the effects of increased rainfall variability. With these sorts of long-term investment decisions, however, dynamic issues become much more important, thereby substantially complicating the analysis.

7.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

7.1.1 Introduction

The objective of this research project was to develop a conceptual framework for the assessment of the effects of climate change on hydrological systems in New Zealand. This research commenced with a literature review emphasizing the types of impacts that have been detected previously and methods for detecting and modelling these impacts. The framework was then applied to the Waimea Plains as a test catchment, to assess the effect of climate change through analysis of existing climate and hydrological data and to model the effect of projected climate change. Hydrological and socioeconomic models were develoed and implemented to relate possible climate change to derived changes in water availability and economic productivity within the test catchment.

7.1.2 Potential Hydrological Impacts

7.1.2.1 Observed Changes in Climate

The main driver of climate change is believed to be anthropogenic emissions of CO_2, which have increased atmospheric CO_2 concentrations by approximately 35% since the beginning of the industrial revolution. The signature change in climate that has been observed in New Zealand and worldwide is a long-term warming trend that approaches a global average of 1^oC over the last century. Changes in precipitation patterns (both increases and decreases in different areas of the world) and increases in extreme weather events have also been documented.

Assessment of climate change and its potential effects on hydrological systems in New Zealand and worldwide is complicated by natural variability and such other factors influencing regional climate as topography. In New Zealand examples of the former are interannual variability introduced by the ENSO and decadal variability introduced by the IPO. Examples of the latter are increased rainfall on the west and south of the South Island and decreased rainfall with more frequent drought on the north and east of the North Island.

7.1.2.2 Projected Climate Change

Projecting climate change is an uncertain exercise. On a world scale, it depends on modelling using GCMs, based on our imperfect knowledge of climate systems and how they respond to perturbations as well as assumptions regarding emissions of GHGs. A spread of emissions scenarios have been established to allow us to quantify the uncertain future. The A1B scenario represents an “average” condition while the A2 scenario represents a greater level of emissions resulting in more climate change effect.

NIWA has applied regional downscaling techniques to GCM results to project climate change effects in New Zealand. These results indicate projected continued temperature rise on the order of an average of 1 and 2 ^oC over the 50 and 100 years, respectively, beyond 1990 and a continuation of current trends toward wetter and drier conditions in different parts of New Zealand.

7.1.2.3 Observed and Projected Hydrological Effects

7.1.2.3.1 Water Quantity

Detection of hydrological effects, as in the case of climate effects, is complicated by similar natural variability. Effects have been documented in other parts of the world and to some degree in New Zealand. Based on this information, projected effects include:

1. Changes in patterns, intensity, and extremes of precipitation. These changes would also imply associated changes in streamflow. Changes in annual runoff in New Zealand have been projected to be as follows –

    a. North Island - 9-40% decrease in the southeast and 9-27% increase elsewhere.

    b. South Island – 18-40% decrease in the southeast and either unchanged of 6-40% increase elsewhere.

2. Contraction in snow and ice coverage.

3. Rising sea level.

4. Increases in atmospheric water vapour.

5. Increases in evapotranspiration and evaporation.

6. Increases and decreases in soil moisture consistent with changes in precipitation patterns.

7. Changes in groundwater recharge with both increases and decreases being possible. These changes are likely to be highly site-specific.

7.1.2.3.2 Water Quality

There is very little information on observed changes in water quality. Increased surface water temperatures have been reported in some locations, the pH of the oceans appears to be decreasing, and there are reports of increased alkalinity. Potential changes in water quality related to climate change include:

1. Increased temperature.

2. Decreased pH.

3. Increased alkalinity.

4. Increased stream sediment loads.

5. Increased nutrient concentrations.

6. Increased dissolved organic carbon concentrations.

7. Increased weathering producing increased conductivity and related increased concentrations of dissolved major and minor ions and silica.

7.1.3 New Zealand Climate and Hydrological Databases

National and regional climate and hydrological databases were identified during this project. National databases included the following (with the organization maintaining the database in parens):

1. National climate database – temperature, rainfall, radiation, evaporation, cloud cover, soil moisture, and other climate variables (NIWA).
2. End of season snowline - part of the climate change database (NIWA).
3. NRWQN - river water quality (NIWA).
4. NGMP - groundwater quality (GNS Science).
5. Water resources archives – streamflows and lake levels (NIWA).
6. Sea levels – part of climate change database (NIWA).

Environmental data are collected by all 16 regional councils (including three district councils and one city council with unitary authority). Monitoring programs typically include rainfall, streamflow and stream water quality, and groundwater levels and groundwater quality. However, other parameters such as sea and lake levels, soil moisture, and groundwater recharge may also be monitored and some regional councils have systems specifically intended to monitor for seawater intrusion. There are many more regional council monitoring stations than national ones. For example, regional councils monitor surface water flow and quality for at least 515 and 782 locations compared to the 130 and 77 locations that comprise the NIWA national networks and regional councils monitor groundwater quality in 1,020 wells compared to the 110 that are included in the NGMP network.

The fitness of climate and hydrological databases in New Zealand for the purpose of assessment of climate change effects is uneven. Data quality and routine sampling intervals are important with regard to analysis and there are substantial data quality questions as well as gaps in the records. The length of records is another important factor. Although the period of available data from such national and regional databases varies, with the exception of climate variables like rainfall, few exceed 20 years. For example, on the national level, both the NRWQN and NGMP systems were established approximately 20 years ago and, at the regional level, most databases generally date from the establishment of regional councils under the RMA. Although some records may still be available with regard to historic streamflow information, it is unclear how much data collected by the earlier catchment boards in New Zealand remains available and it is apparent that some has not survived the transition into current regional council databases. Numbers of such monitoring stations have increased with time but precise numbers are difficult to pin down. Nevertheless, it is clear that there are many more stations maintained by regional councils than are part of national networks.

What is monitored also limits the potential utility some of these databases, particularly in the case of water quality. This is because only a few variables are monitored for surface water quality compared to the chemical quality of groundwater. This lack of surface water quality data severely limits both the ability to assess the effect of climate change on surface water quality and to assess any resulting surface water-groundwater relationships that might be involved.

An additional limitation on use of climate and hydrological databases in New Zealand to assess climate change effects is the lack of related socioeconomic data. If a trend in a variable is evident, this makes it difficult to separate out if it is solely a function of climate change or if other factors might also be involved (e.g., changes in land use).

7.1.4 Assessing Hydrologic Effects – Waimea Plains Test Catchment

7.1.4.1 Tasman District Climate Change Projections

The Waimea Plains was selected as a test catchment to apply a climate change effects assessment framework using available climate and hydrological data. NIWA climate change projections for this catchment indicate an increasing temperature trend similar to other parts of New Zealand (an increase in the annual mean of 0.9 ^{o}C over the 1990-2040 period and 2.0 ^{o}C over the 1990-2090 period with a decrease in the average number of frost days and an increase in days with maximum temperatures exceeding 25 ^{o}C. With regard to precipitation, the projections indicate relatively minor increases of an annual mean of 2% over the 1990-2040 period and 4% over the 1990-2090 period with both heavier extreme rainfall and a nearly doubling of drought risk.

7.1.4.2 Trend Analysis

The framework for assessment of the effect of climate change on climate and hydrological variables primarily involves trend analysis and the major tool selected for that analysis was the non-parametric Mann-Kendall test (using a level of significance less than or equal to 5% as indicating "statistically significant" and the 5-10% level as indicating "weakly significant." Correlation analysis and other statistical tools may also be applied to supplement trend analysis. The following are the climate and hydrological variables for which data were analysed and information on the results obtained:

1. Climate -

    a. Temperature – Historic actual data and NIWA climate change simulation results were analysed. Results for historic actual data generally indicated statistically significant increasing trends. Results for NIWA's climate change scenario simulations indicated decreasing trends for the three periods involved ("historic" and two future periods centered on 2040 and 2090) but overall increasing trends.

    b. Precipitation – Historic actual data and NIWA climate change simulation results were analysed. Results for historic actual data indicated decreasing but not statistically significant trends. Results for NIWA climate change scenario simulations indicated decreasing trends for all periods but an overall increasing trend, but none of these were statistically significant.

    c. Evaporation – Increasing trends were indicated for historic actual data.

d. Solar Radiation and Sunshine Hours – Trends consistent with the worldwide decreasing trend up to 1990 and increasing trend thereafter were indicated.

e. Atmospheric Water Vapour – Variable results were obtained. Analysis of relative humidity data indicates the trend may not be monotonic. Relative humidity increased prior to 1990 and decreased thereafter. The trend for cloud cover is not consistent, but may be decreasing.

2. Surface and Groundwater -

a. Streamflow – Variable trends were found depending on the river involved and time period. Trends for all Waimea River tributaries for the complete period of record may be decreasing; however, trends in recent years have been increasing.

b. Stream water quality – statistically significant flow-adjusted increasing trends were found for NO3-N and DRP for the Wairoa River at Irvines and for conductivity for the Waimea River at the Appleby Bridge while a statistically significant decreasing trend for conductivity was found for the Wai-iti River at Livingston. The increasing trend for conductivity could conceivably be related to climate change but there are also other possible factors.

c. Groundwater levels – Data show characteristic annually oscillating water levels. There is an overall statistically significant decreasing trend indicated for the well having the longest period of record in the shallowest aquifer; however, the latter part of this record (while not statistically significant) matches the statistically significant increasing trends found for two other shallow wells with much shorter records. Data for the few deeper wells (upper and lower confined aquifers) are all consistent in indicating statistically significant decreasing trends.

d. Groundwater quality – The only statistically significant trend for the NGMP well in shallowest aquifer was an increasing trend for sulfate. This is more likely to be related to agricultural operations than climate change. There were statistically significant decreasing trends for pH and all major ions for the UCA well and increasing trends for conductivity, most major ions, and ammonia-nitrogen in the LCA well. Results for these deeper wells are unlikely to be related to climate change independently of the shallow aquifer well.

7.1.5 Groundwater-Surface Water Interaction Modelling

7.1.5.1 MODFLOW Modelling

The existing finite-difference numerical model (the USGS's MODFLOW groundwater-surface water interaction model) for the Waimea Plains was utilized to model severe drought conditions for the A1B and A2 climate change emissions scenarios. The year simulated was

July 2058-June 2059. The MODFLOW model was run to perform a transient simulation for this complete year. Details of the Waimea Plains hydrology and model setup are presented in Sections 5.1 and 5.2.

7.1.5.2 AI Modelling

Artificial intelligence (AI) approaches were used both to model water usage, rainfall recharge, and Wairoa River flow at Irvines for input to the MODFLOW model and to independently simulate the same MODFLOW outputs (groundwater levels at the McCliskies well location and Waimea River flow at the TDC-Nursery location). These AI approaches are data-driven rather than mechanistic representations and are a relatively novel application that has much potential for future modelling of this kind. While there are other approaches to rainfall recharge modelling, the AI approach has been shown to be superior when relevant data are available (White, et al., 2003; Hong, et al., 2005). In this case, data from the Christchurch area with similar soils were utilized. Unfortunately, relevant data are not likely to be available in many cases. Where they are not, other models may be tried. There are mechanistic models that could be used for this purpose including the SOILMOD soil water balance model, the hydrologic evaluation of landfill performance (HELP) model, and possibly such commercially available models as MIKE SHE. The HELP model, in particular, has been used in several locations in Europe and North America to provide rainfall recharge estimates for climate change simulations (e.g., Allen, et al., 2010).

Projected temperature and rainfall accompanying climate change obtained from NIWA simulations were utilized with the AI model relationships developed to model: (1) groundwater rainfall recharge; and (2) Wairoa River flow at the Irvines location. These in turn were input to both the MODFLOW model and other AI model relationships developed to model: (1) Waimea River flow at the TDC-Nursery location; and (2) the level of groundwater at the McCliskies well.

7.1.5.3 Climate Change Model Results

Both MODFLOW and the AI models developed as a part of this research project produced reasonably similar results. Most importantly, these results indicated that during a severe drought event, climate change could produce substantial decreases in streamflow (i.e., for the Waimea River at the TDC-Nursery location) but was not likely to do so with regard to groundwater levels in the Waimea Plains. The declines in streamflow amount to 23 and 27%, respectively, under the A1B and A2 emissions scenarios for AI modelling and 21 and 27%, respectively for MODFLOW modelling. Only minor differences were evident with regard to groundwater elevations; the largest being a mean of less than 1% lower under climate change scenarios than for historic data (see Table 5-16).

7.1.6 Assessing Socioeconomic Effects – Waimea Plains Test Catchment

A model was developed that assesses the effects on economic and social measures of climate change impacts on water resources. It includes three main components:

1. Water availability
2. Economic measures;
3. Social measures.

The total economic valule (TEV) template can be used to assess economic effects. TEV includes productive and in situ uses. Productive uses include agriculture, commercial/industrial uses, and domestic water supply. In situ uses include provision of environmental services and recreation.

Social measures are not well developed in this model. This is because many of the available social indicators are unlikely to be relevant as:

1. Many social indicators are driven by wealth and so are generally independent of hydrological factors;

2. New Zealand has sufficient wealth that some social indicators (e.g., infant mortality, Figure 6-7) are most unlikely to be impacted by climate change in the next 50 years; and

3. Many social indicators are not yet well developed for New Zealand.

However the model develops two indicators related to the economy: (1) employment; and (2) the New Zealand deprivation index (NZDep).

The model was applied in a demonstration assessment to the Waimea Plains test catchment to investigate how the effects of climate change on water resources may impact economic and social measures. The model was used with two land use scenarios:

1. Estimated 2005 land use including irrigated agriculture (with four land uses common on the Waimea Plains), non-irrigated agriculture, commercial/industrial, and urban water supply; and

2. A future scenario in which land use in 2050 was estimated assuming current trends in irrigated land use continue (i.e., a reduction in the area of dairy and an increase in the area of horticulture and market gardening) and that urban growth for the Richmond township continues.

The modelling approach demonstrated for the Waimea Plains was performed in the following sequence:

1. Selected economic and social indicators associated with the two land use scenarios and current climate were estimated;

2. Relationships between economic and social indicators and water availability were estimated;

3. The change in water availability was estimated modelling of the physical water resource for selected climate change scenarios;

4. The change in economic and social indicators associated with the two representations of land use with climate change (2005 and 2050 land use) were estimated.

The economic importance of the water resource in the Waimea Plains is indicated by economic and social indicators. For example:

1. The TEV of water resources under 2005 land use in the Waimea Plains was estimated as approximately $373 million and the TEV under 2050 land use was estimated at approximately $547 million (both values in 2005 dollars). The TEV for the estimated 2050 land use was greater than estimated for 2005 land use. This is because estimated 2050 land use includes a greater value of production (both agriculture and commercial/industrial) and a greater population than for 2005 land use;

2. Employment (direct and indirect) associated with the water resource was estimated as 4,192 persons with 2005 land use and 6,820 persons with 2050 land use.

Three scenarios of future climate change impacts on water resources of the Waimea Plains were identified through hydrological modelling associated with two climate change scenarios (the A1B GCM5 climate change scenario and the A2 GCM6 climate change scenario). These were:

1. A 2% reduction in groundwater recharge leading to a reduction in groundwater availability;

2. A 10% reduction in surface water and groundwater availability caused by a reduction in surface water flow – these reductions would lead to restrictions on water users;

3. A 13% reduction in groundwater recharges leading to a reduction in groundwater availability.

Economic values reduce as water availability reduces in association with climate change by millions, to tens of millions, of dollars. For example, productive values associated with agriculture and 2005 land use in the Waimea Plains were estimated to decline by $3.1 million where water availability declined by 2% and to decline by $20.3 million where water availability declined by 13%. Economic losses are greater with 2050 land use because 2050 land use includes a greater value of production than 2005 land use.

Changes in economic and social measures, in the context of current measures for 2005 land use, with climate change are minor or moderate. For example, the changes in productive and in situ economic measures are minor with climate change for a 2% decrease in water availability (i.e., less than a 5% decrease compared with current climate) while they are moderate with climate change for a 10% or greater decrease in water availability (i.e., decreases in the range of greater than 5 to 20% compared with the current climate).

Changes in economic and social measures for estimated land use in 2050 with climate change, in comparison to current measures for land use in 2005 without climate change, were in the minor to major range. For example, changes in productive and in situ economic measures are minor (i.e., less than a 5% decrease) with a 2% decline in water availability due to climate change while changes in productive and in situ economic measures were major (i.e., decreases greater than a 20% decrease) with a 13% decline in water availability due to climate change.

7.2 Conclusions

Conclusions with regard to the objectives of this research are as follows:

1. A conceptual framework consisting of three elements has been developed from this research:

   a. Analysis of historic time series climate and hydrological monitoring data. This analysis relies principally on application of nonparametric trend analysis. Other analytical tools, including linear regression and correlation analysis, may also be utilized. Analytical results are compared with expected results from the literature and on general scientific principles. Conclusions are then based on the weight of evidence from multiple variables including:

      1) Climate –

         a) Temperature.

         b) Precipitation.

         c) Evaporation.

         d) Solar radiation and sunshine hours.

         e) Atmospheric water vapour.

      2) Hydrological –

         a) Streamflow.

         b) Stream water quality.

         c) Groundwater levels.

         d) Groundwater quality.

         5) End of season snowline and other measures of snow/ice extent.

         6) Lake level.

         7) Lake water quality.

         8) Seawater intrusion of coastal.

         9) Sea level.

   b. Climate and hydrological modelling. A variety of modelling approaches are possible and available. Models are continuously being improved and updated and new ones developed. Global climate models (GCMs) are available for modelling standard climate change scenarios over large areas of the globe. The model results are then downscaled to apply to smaller regional areas within national boundaries like those of New Zealand. These can produce time series projections of future daily temperatures and precipitation under climate change. Traditional mechanistic models are available for modelling at regional and catchment scale using changes in temperature and precipitation under climate change scenarios as inputs. Model outputs can then be compared with historic data and with estimates of hydrdological variables in the absence of climate change. Artificial intelligenced (AI) modelling techniques have great potential to contribute to or replace mechanistic modelling approaches.

c. Socioeconomic modelling. Socioeconomic changes may impact hydrological systems in some of the same ways that climate change does and climate change effects on hydrologic systems may produce socioeconomic effects. Therefore, there is a need for a mechanism to assess socioeconomic relationships.

2. Databases may have substantial quality issues including erroneous data, data gaps, and data entry errors. Care must be taken to ensure the quality of data entered into databases used for trend analysis. This includes the development and implementation of standard data quality objectives and quality control/quality assurance procedures. These are necessary for both field and laboratory procedures, but are of particular importance with regard to laboratory analysis of chemical quality. Monitoring and reporting of water use provides important information relevant to our understanding of what is occurring in the hydrologic cycle and our ability to properly regulate the system or attempt to model it.

3. Trend analysis requires a consistent database in which samples/measurements are obtained on a routine and appropriate frequency without gaps in the record.

4. Proper application of trend analysis requires that the form of the data be evaluated prior to analysis. Trend analysis is intended to detect monotonically increasing or decreasing trends. In some cases, data may not be monotonic in nature but may be divided into groups of monotonic functions that can be separately analysed.

5. Longer term data than currently exist are, in many cases, required. The period of the database being analysed is important and must be sufficient to allow determination of actual long-term trends. Climate and, to some degree, hydrological data in New Zealand may be influenced by natural variation having decadal patterns. Where they exist, the analysis period must be sufficiently long to include multiple patterns of such length.

6. This conceptual framework was applied to data from the Waimea Plains test catchment. The results present a mixed picture due in part to limited database length. Longer-term data provides some degree of support to possible climate change impact (primarily increasing temperature and evaporation, solar radiation consistent with the worldwide pattern, and possibly decreasing rainfall, streamflow, and groundwater levels). Surface and groundwater quality data provided no convincing support of any relationship to climate change; however,

the period for these data was less than 10 years for all surface water stations and only marginally greater than 10 years for groundwater wells.

7. A variety of modelling techniques are available which can be used to simulate the effect of climate change on water resources. GCMs may be used to project future temperature and rainfall conditions under climate change over broad areas of the earth's surface using established climate change emissions scenarios. These may be downscaled for application to specific regions of New Zealand under consideration. It is possible to then use such projections to model the effects of climate change on surface and groundwater resources in comparison to historic conditions. Doing so for the Waimea Plains test catchment indicates that during periods of severe drought the flow of the Waimea River at the TDC-Nursery location may be reduced by 23 to 27% below historic conditions by the middle of the 21st Century under A1B and A2 emissions scenarios, respectively. These modelling methods are available at this time. Existing modelling methods are continually being upgraded and new ones developed. They include mechanistic models like HELP and MODFLOW and data-driven AI models. Modelling results should be considered indicative but not necessarily precise and should be reviewed in the future in comparison to actual data as it becomes available.

8. Assessment of the effects of climate change on hydrological systems and the relationship of such effects with socioeconomic variables brings up highly complex issues for which existing economic, social, and land use indicators in New Zealand are not sufficient to rigorously address. Under the assumptions made in the use of the simple TEV model developed as a part of this project, decreases in water availability of 2 and 13% could result in minor to moderate economic losses (0 to 20%) for 2005 land use under climate change during severe drought conditions by 2050 compared to without climate change while for estimated 2050 land use under climate change a decrease in water availability of 13% could result in major economic losses (greater than 20%) compared to without climate change.

9. Development of a framework for assessment of the socioeconomic effects of climate change on hydrologic systems requires information on: (1) risk with regard to the potential magnitude of climate change effects on hydrologic systems and water availability; (2) the scale of those effects (e.g., catchment or regional); (3) possible future scenarios of land use and economic activity; and (4) policy responses being implemented. In addition to climate and hydrological data, it also requires substantial socioeconomic data. Data sets useful to the assessment of climate change include:

    a. Economic - Values associated with productive and in situ water uses as developed in Section 6 of this report for current water availability with estimates of uncertainty. Economic values estimated for different water availabilities, also developed in Section 6 of this report, with estimates of uncertainty, are also important to assessments of climate change. Data sets to assess local and regional economic issues are not generally available and are best developed at the local scale, or as relevant to particular hydrological features, and applied to catchment and regional scales;

b. Social - The development of social indicators, outside simple population statistics, is generally in its infancy in New Zealand (Appendix B) and much work needs to be done to assess links between social measures and economic measures. Currently, data collected by Statistics New Zealand within meshblocks is the best data available. Much work needs to be done in assessing social responses to climate change in New Zealand.

c. Land use - Maps of land use are crucial to assessment of economic and social effects of climate change. Maps of current land use, and land use trends, can be used to assess future water use and water use patterns. Information on land use in New Zealand is currently very lacking and for that reason most regional councils utilized land cover as a surrogate.

Table 7-1 indicates the large variety of data on social and economic indicators required to assess social and economic effects of climate change on water resources. The relative importance of data types is indicated by priorities for collection of data assigned based on judgment in Table 7-2. In addition, maps of land use are crucial. These indicate the main productive land uses associated with water resources including agriculture, commercial/industrial, and urban and should be in a form suitable for digital processing. Maps of future scenarios of land use are also relevant.

7.3 Recommendations

The following recommendations are based on this research:

1. This conceptual framework should be applied in other catchments in New Zealand.

2. Modelling results should always be considered indicative but not necessarily precise. Results, where such assessment tools are utilized, should be catalogued and tracked for future confirmatory analysis. This would allow assessment of which methods are most useful and fit for purpose.

3. Measures should be instituted to ensure the quality of climate and hydrological databases and to prevent gaps in the record. Monitoring and reporting of water use should be required.

4. Water quality variables such as major ions should be measured in surface water monitoring networks. This is not generally done at this time, but is necessary to develop appropriate data for understanding and detecting groundwater-surface water relationships in general and with respect to climate change in particular.

5. Data plots should be carefully examined to ensure the data are monotonic in nature prior to application of trend analysis methods to the data.

6. It is important to develop long-term climate, hydrological, and socioeconomic data sets for future analysis. Lack of such data at this time is a major limitation on the application of any conceptual framework for analysis.

7. Modelling methods are continually being improved and updated and new methods developed. New modelling approaches should be incorporated into this conceptual framework as they become available. In particular, AI modelling techniques have great potential to contribute to or replace mechanistic modelling approaches.

8. The state of the art of socioeconomic modelling and the availability of relevant data are relatively poor compared to climate and hydrological modelling. Therefore, there is a need for greater effort to develop meaningful models and databases to use with them. A comprehensive land use database would be particularly important. Additional research in this area is needed. Efforts in this area in other countries should be considered and, where appropriate, adopted for use in New Zealand.

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FIGURES

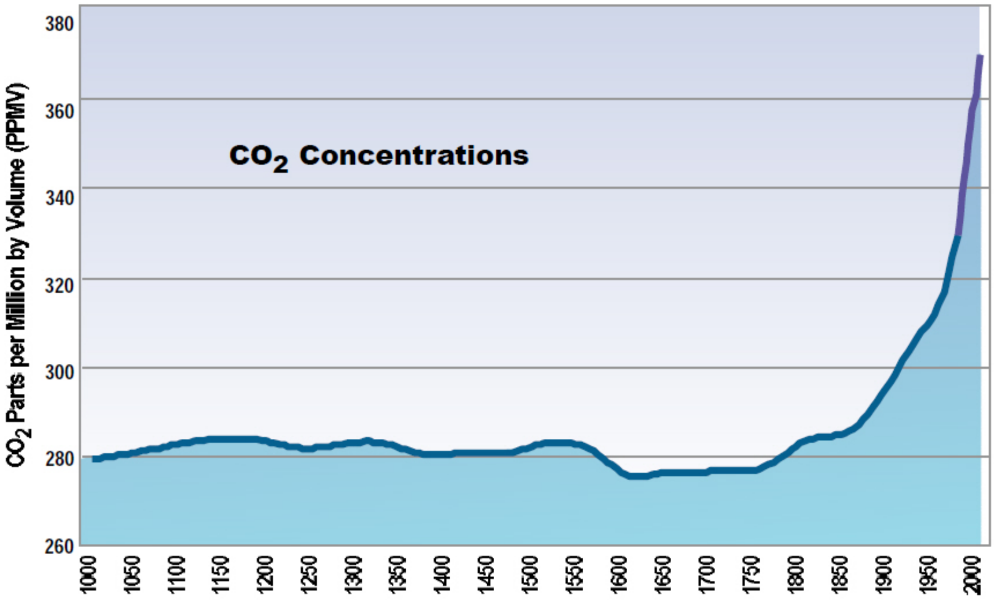


Figure 2-1: Atmospheric CO_2 Concentrations. (From National Assessment Synthesis Team, 2000)

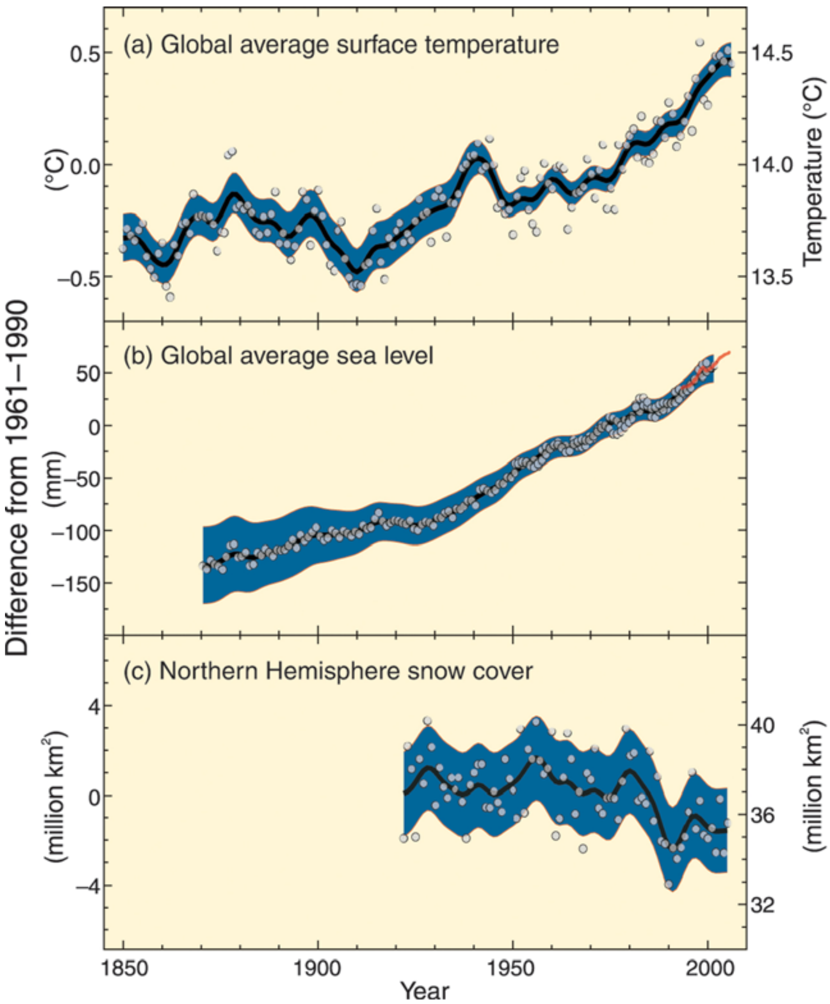


Figure 2-2: Observed Changes from Warming Climate. (From IPCC, 2007)

Figure 2-3: New Zealand's Climate Zones. (From Mackintosh, 2001)

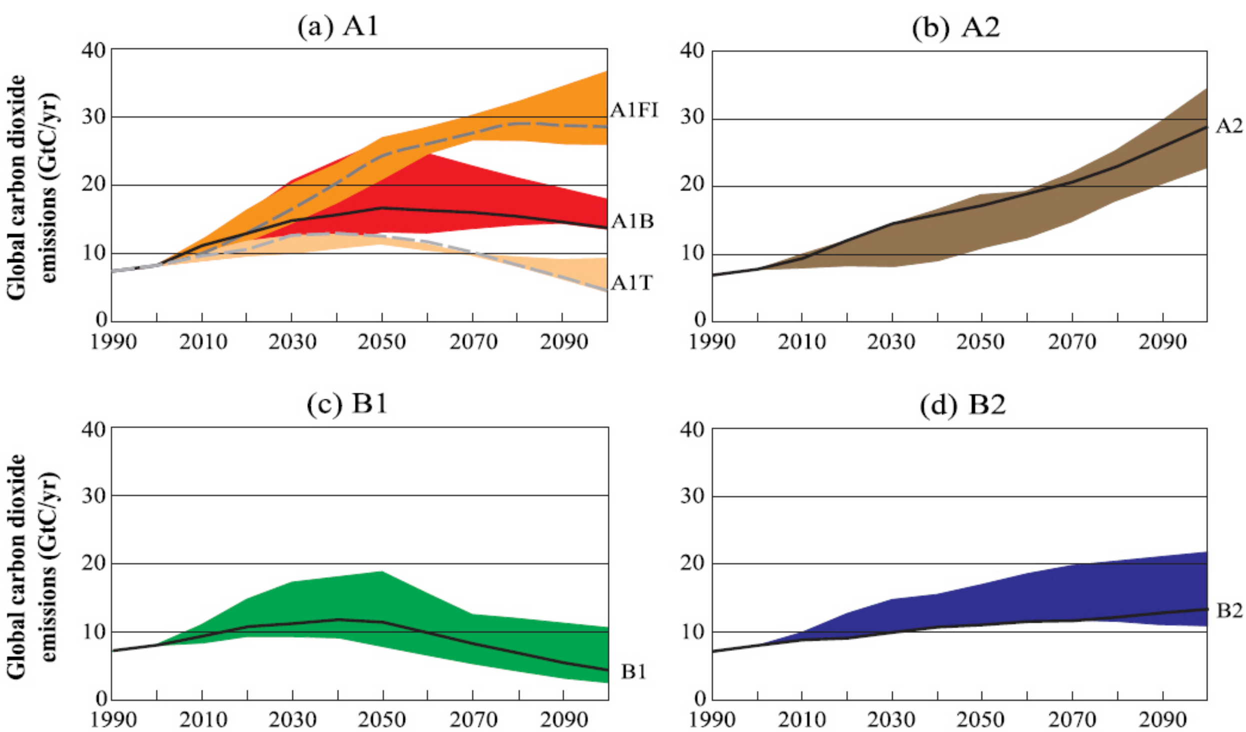


Figure 2-4: CO_2 Emissions Under Four IPCC Storylines. (Figure 3 from Working Group III, 2000)

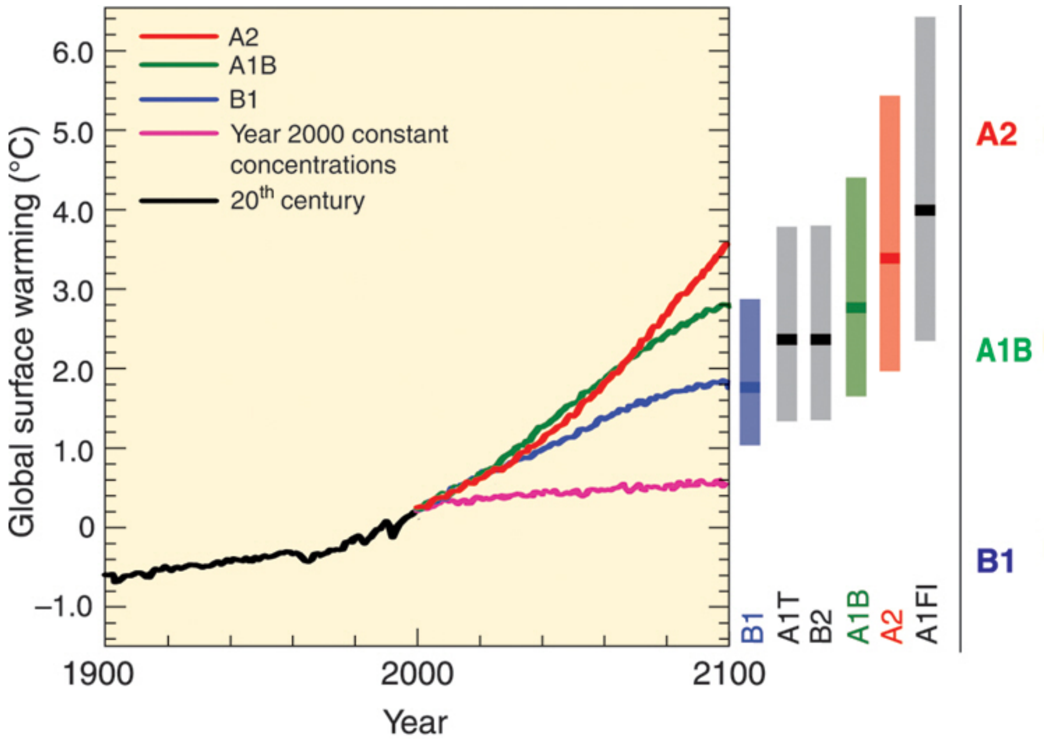


Figure 2-5: Global Warming Under Various Emissions Scenarios. (Figure 3.2 from IPCC, 2007)

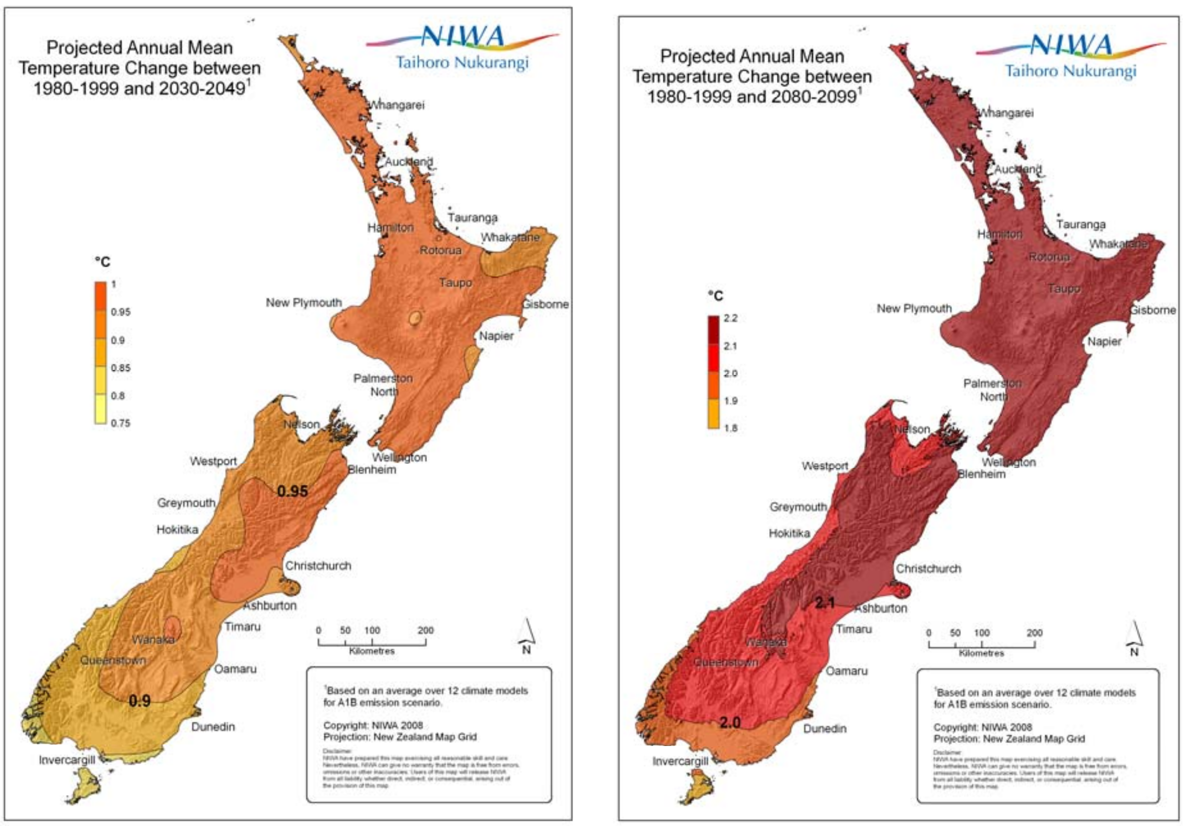


Figure 2-6: Projected New Zealand Temperature Increase Under Climate Change. (From Figure 3 of Wratt and Mullan, 2008)

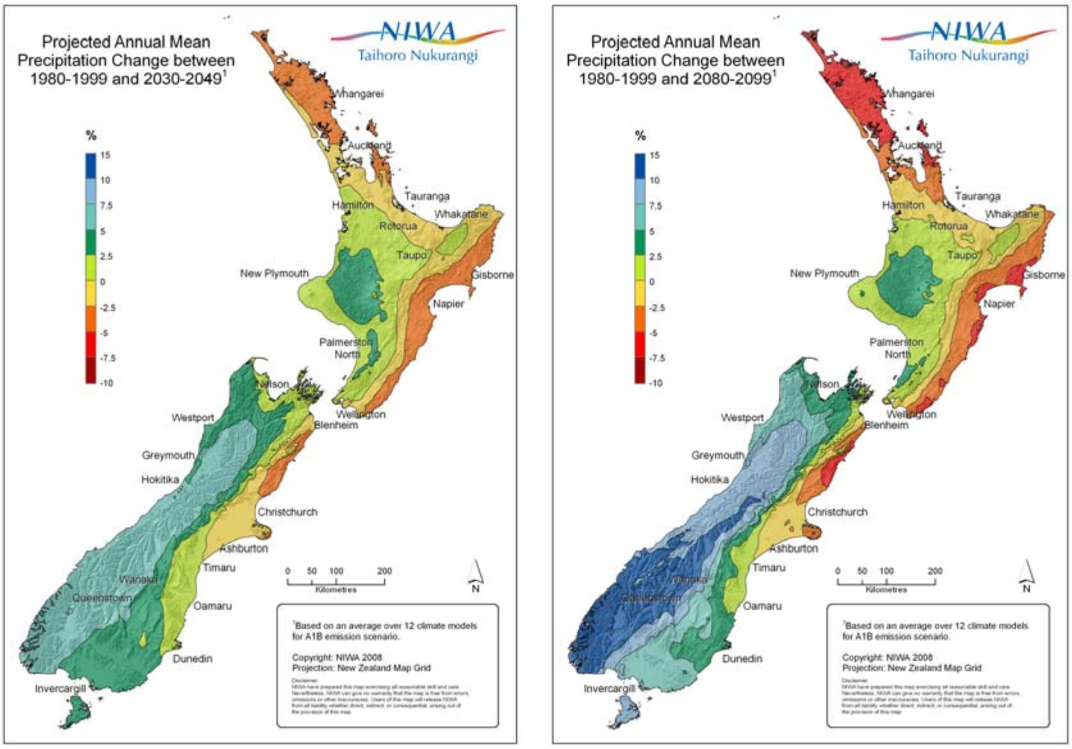


Figure 2-7: Projected New Zealand Precipitation Change under Climate Change (From Figure 4 of Wratt and Mullan, 2008)

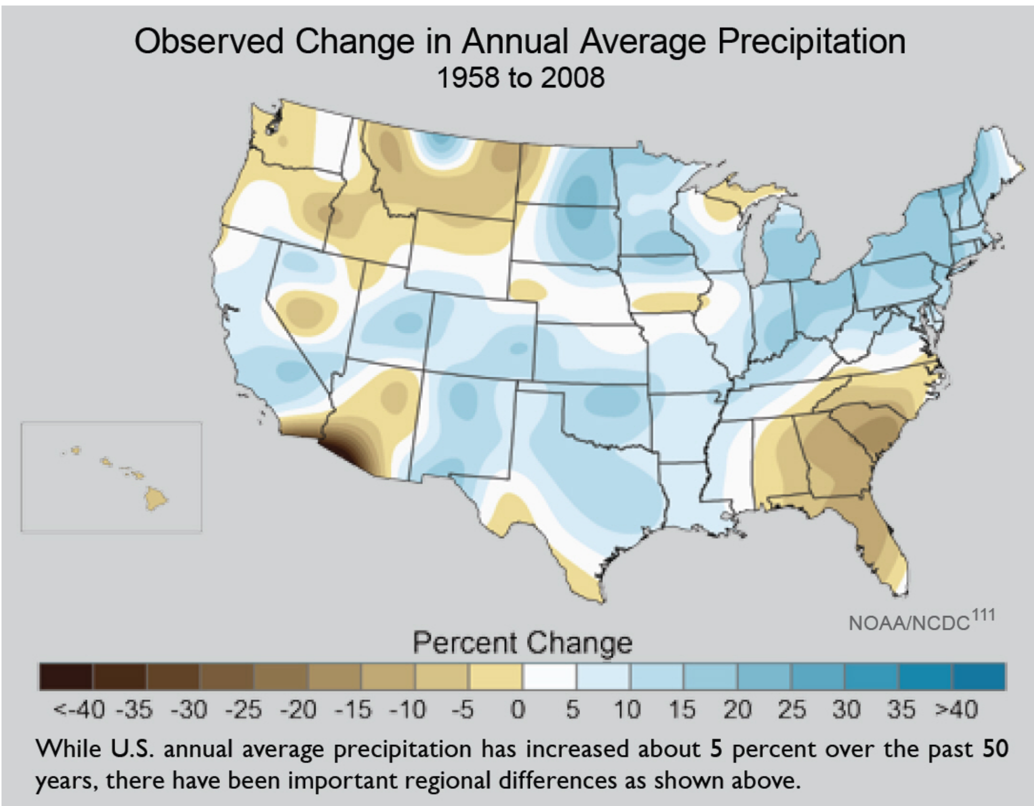


Figure 2-8: Observed Change in Mean Annual Precipitation Across the US. (From Karl, et al., 2009)

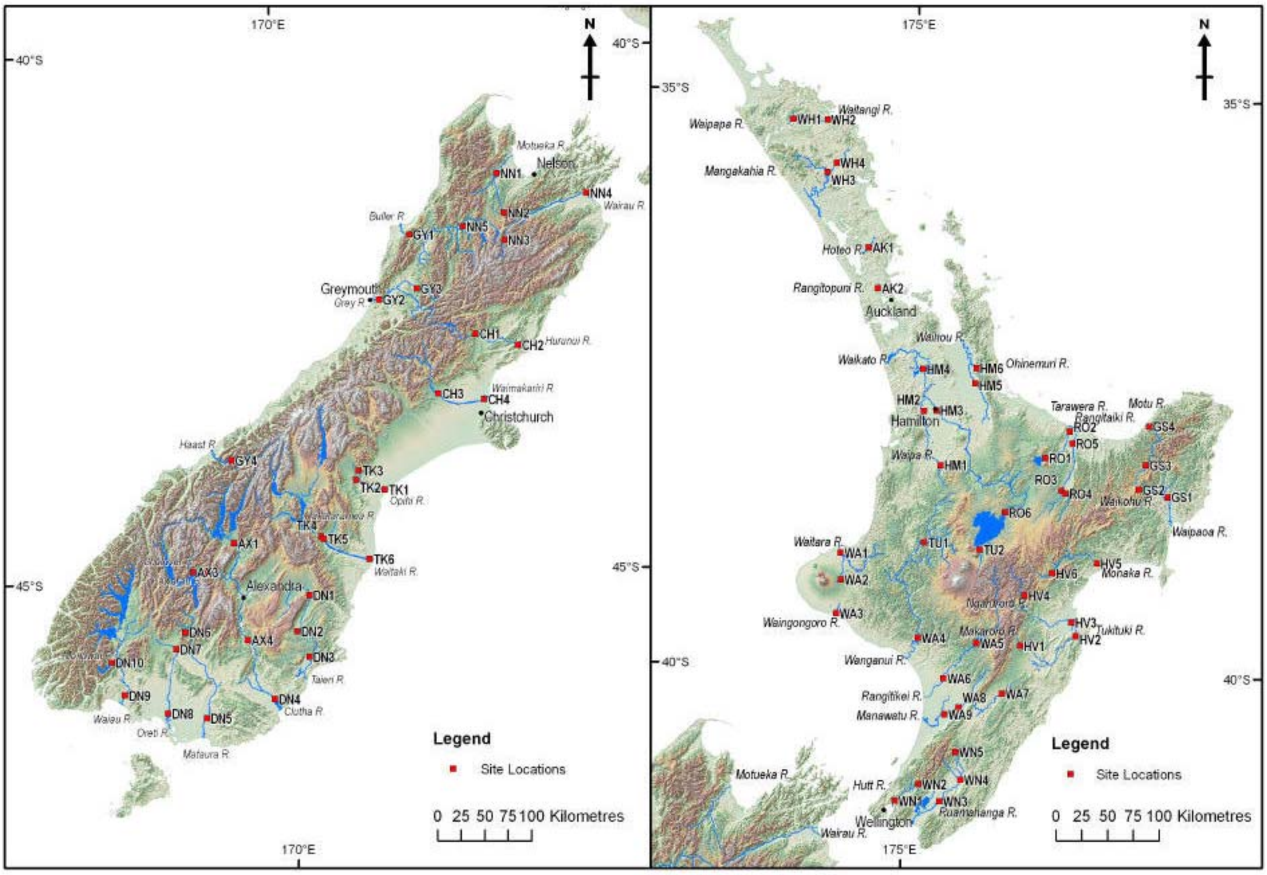


Figure 3-1: NIWA NRWQN Stations (NIWA, 2010)

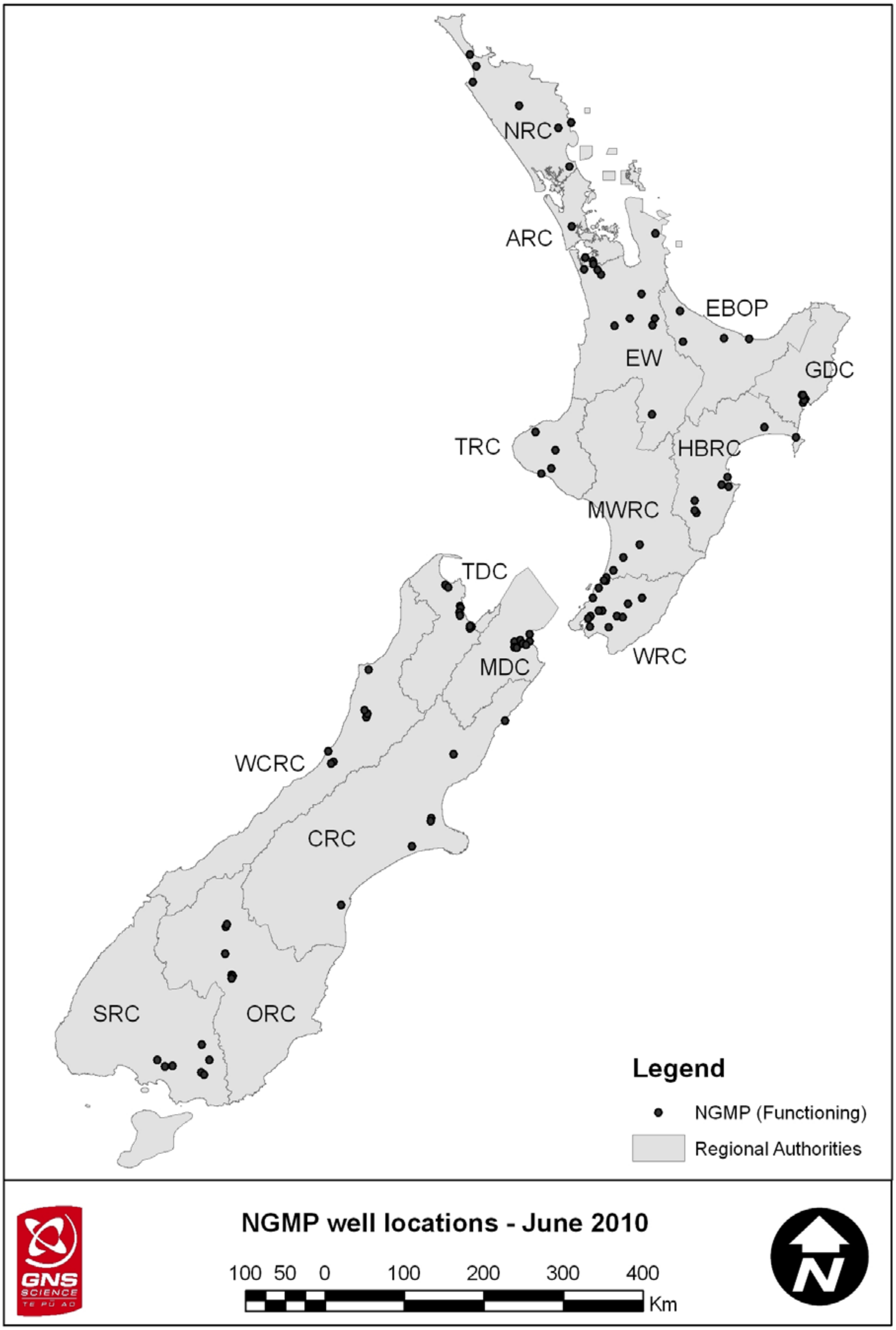


Figure 3-2: NGMP Well Locations

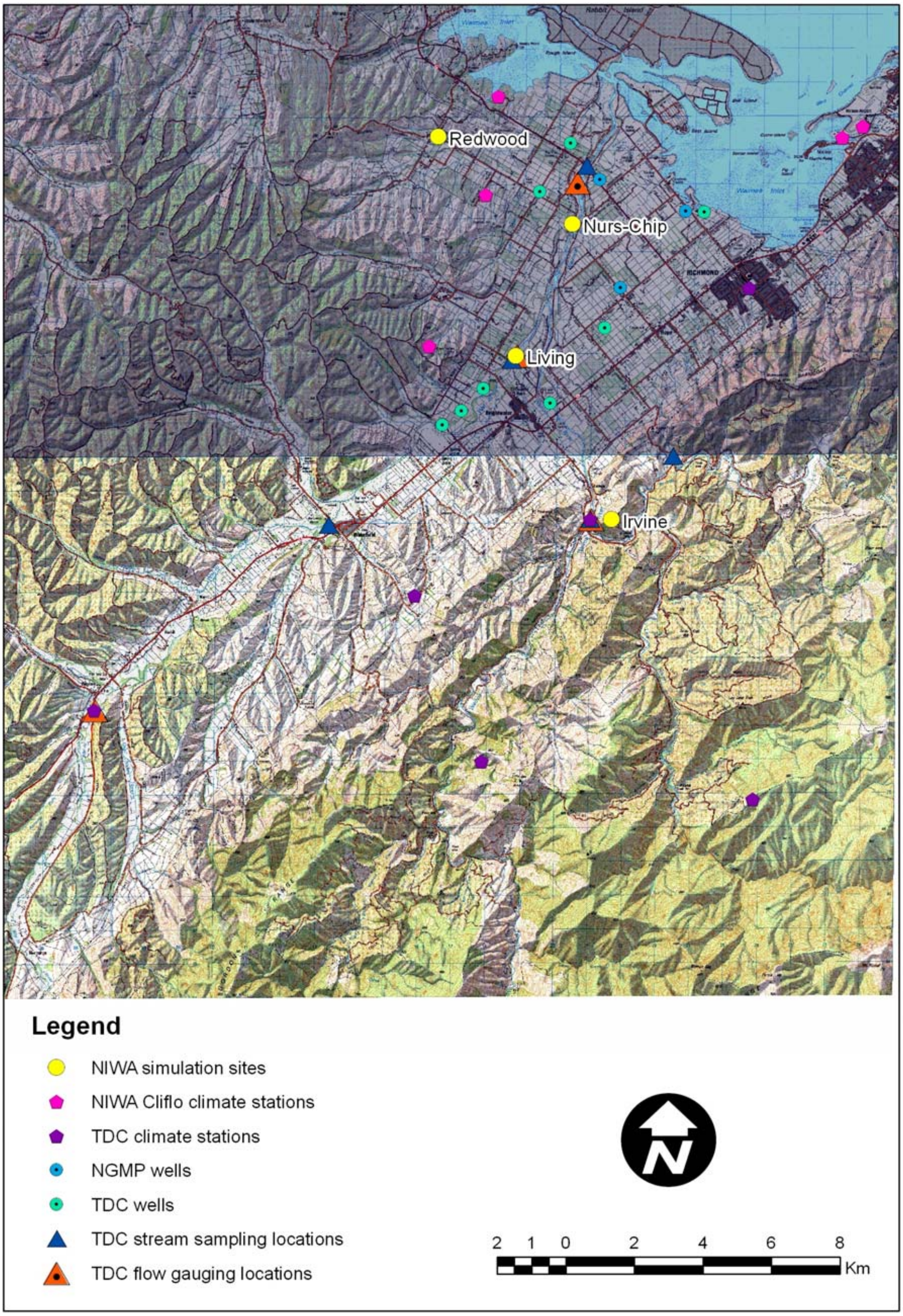


Figure 4-1: Hydrologic Monitoring Sites in the Vicinity of the Waimea Plains

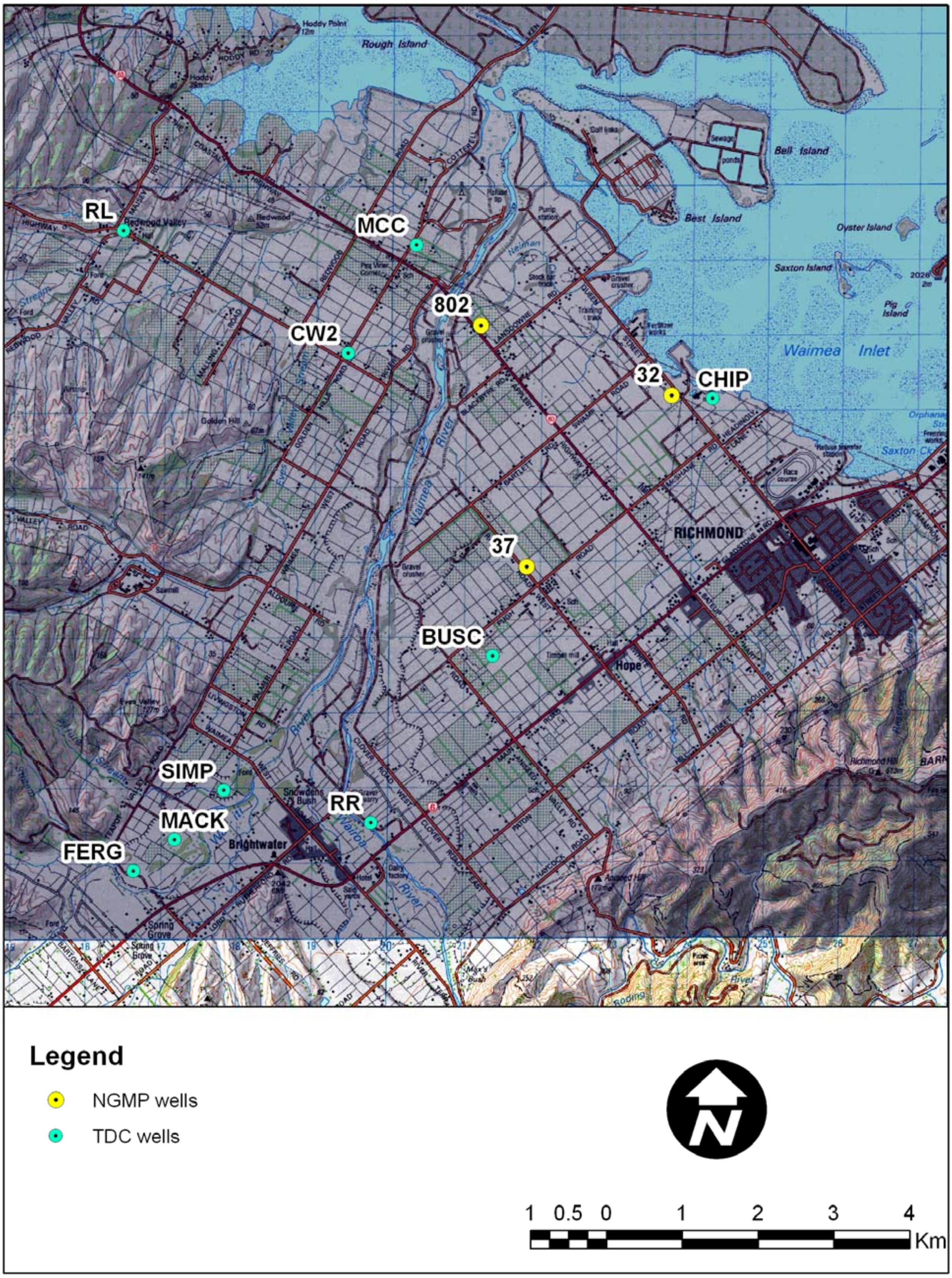


Figure 4-2: Waimea Plains GNS and TDC Groundwater Monitoring Wells

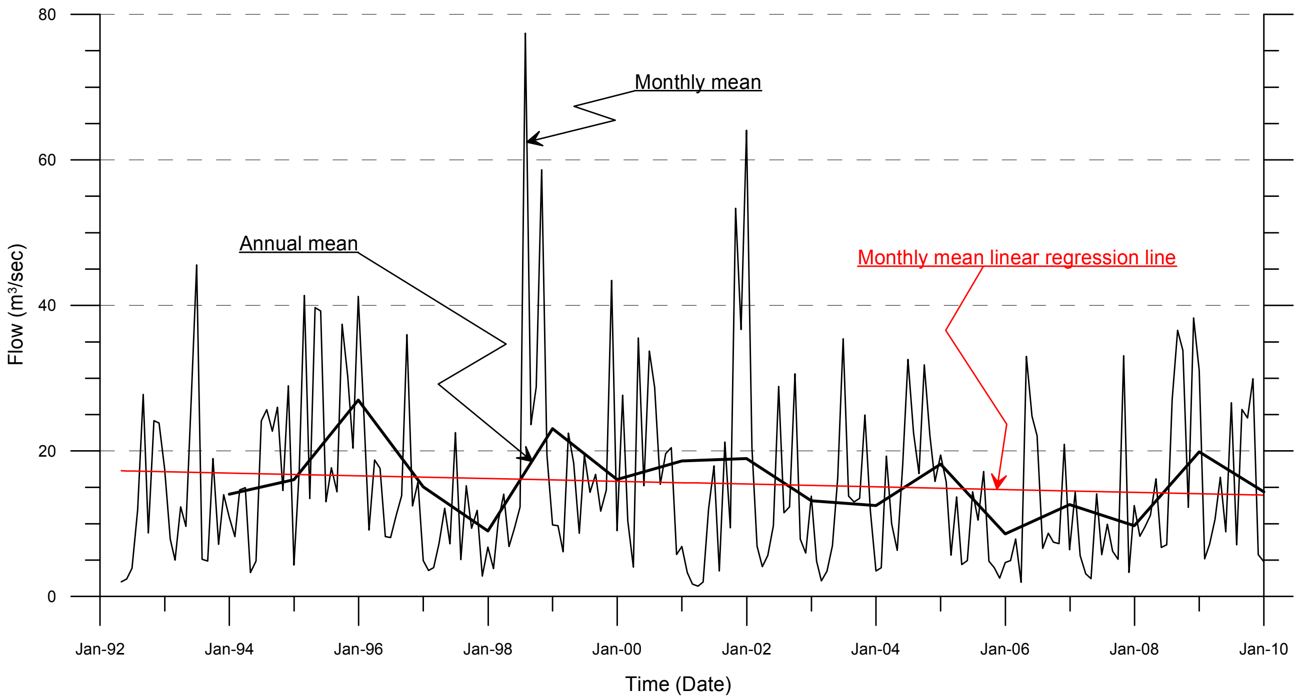


Figure 4-3: Wairoa River Streamflow at Irvines (Line Plot)

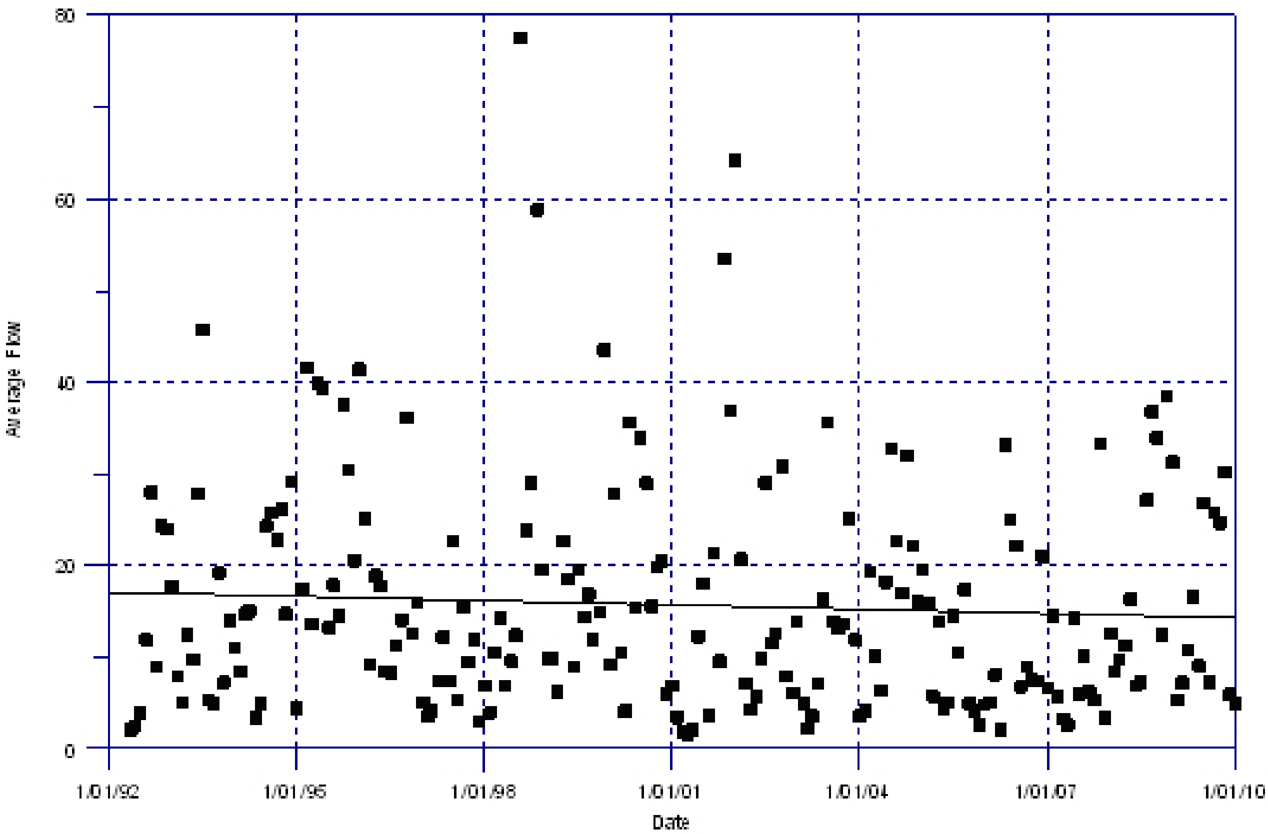


Figure 4-4: Wairoa River Streamflow at Irvines and Sen's Slope (1992-2009 Monthly Data)

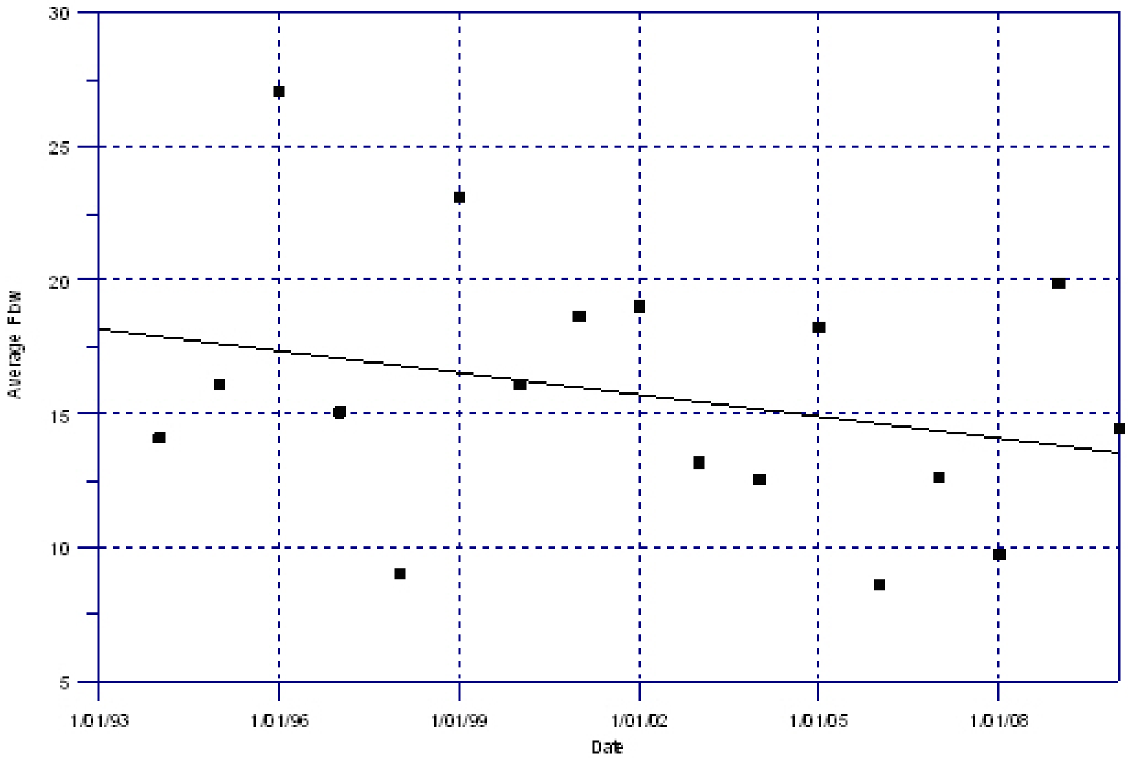


Figure 4-5: Wairoa River Streamflow at Irvines and Sen's Slope (1993-2009 Annual Data)

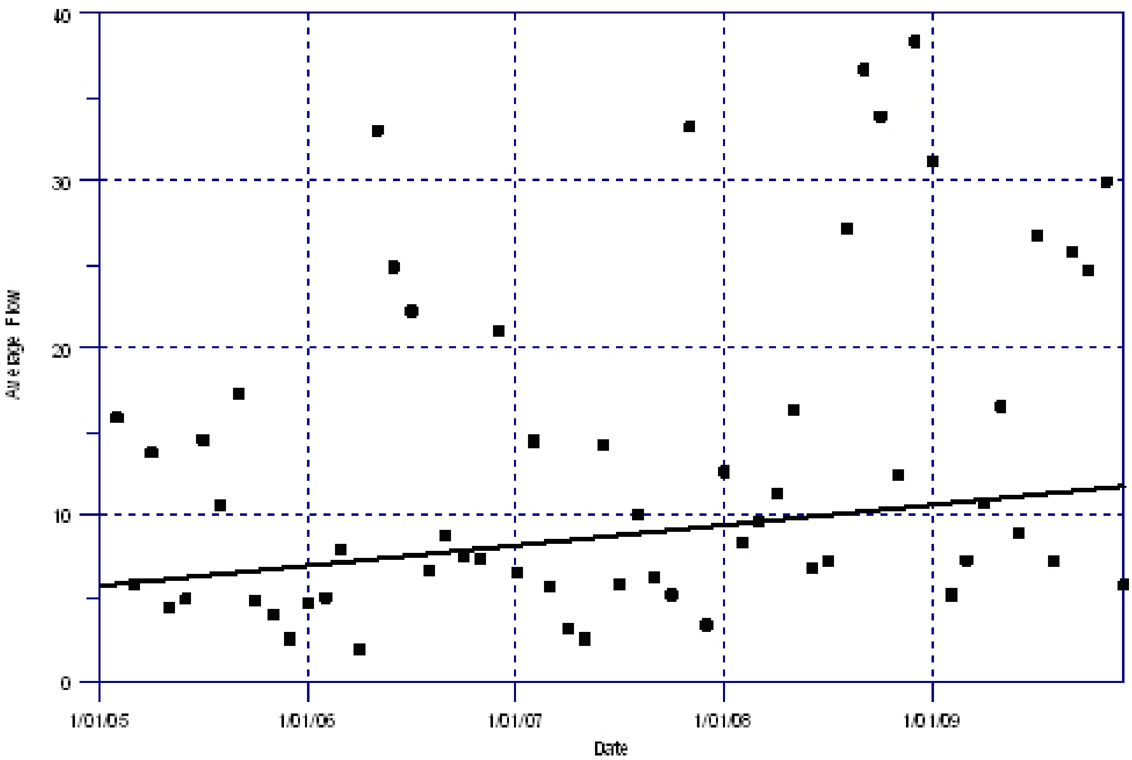


Figure 4-6: Wairoa River Streamflow at Irvines and Sen's Slope (2005-2009 Monthly Data)

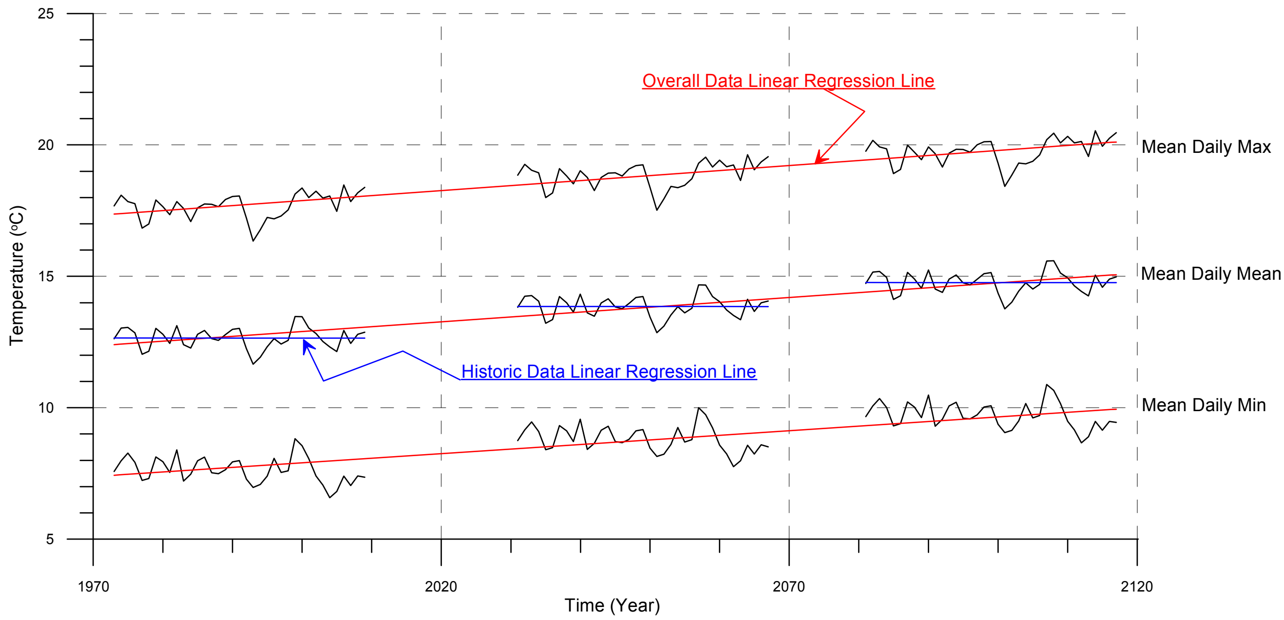


Figure 4-7: NIWA A1B Simulation Temperature Trend Analysis (TDC Nursery-Chipmill)

*Note: Plot of annual mean daily min and mean values questionable due to inclusion of Appleby 2 EWS station data (see Section 4.2.2.2)

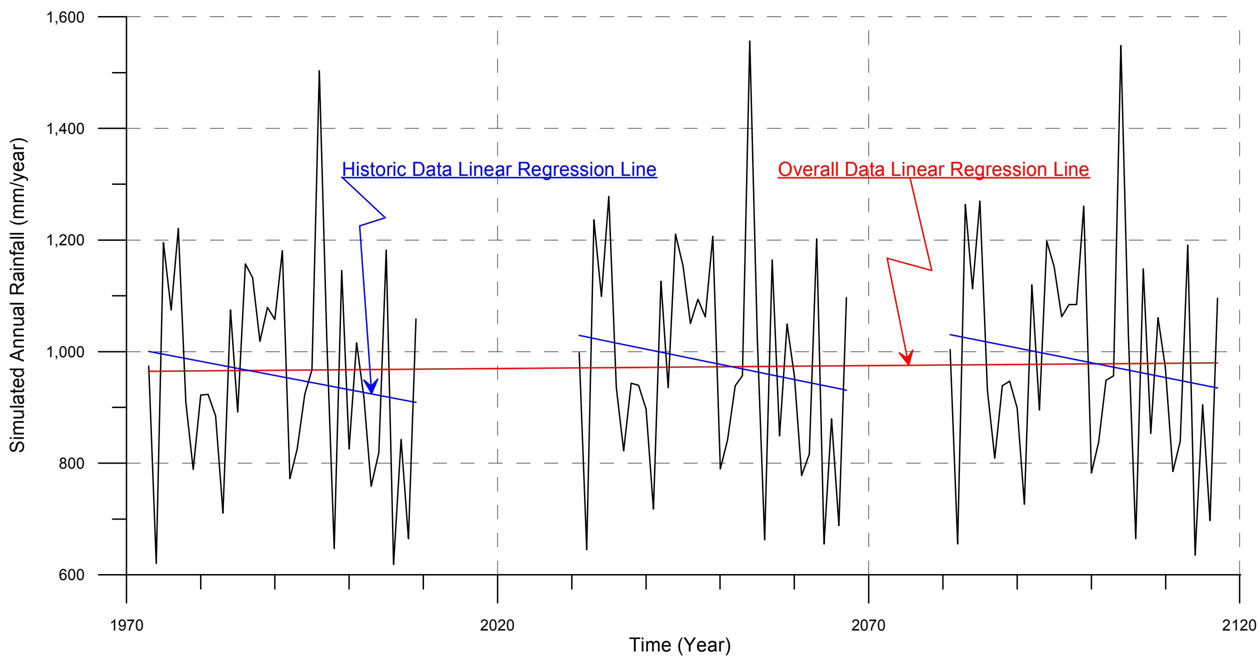


Figure 4-8: NIWA A1B Simulation Rainfall Trend Analysis (TDC Nursery-Chipmill)

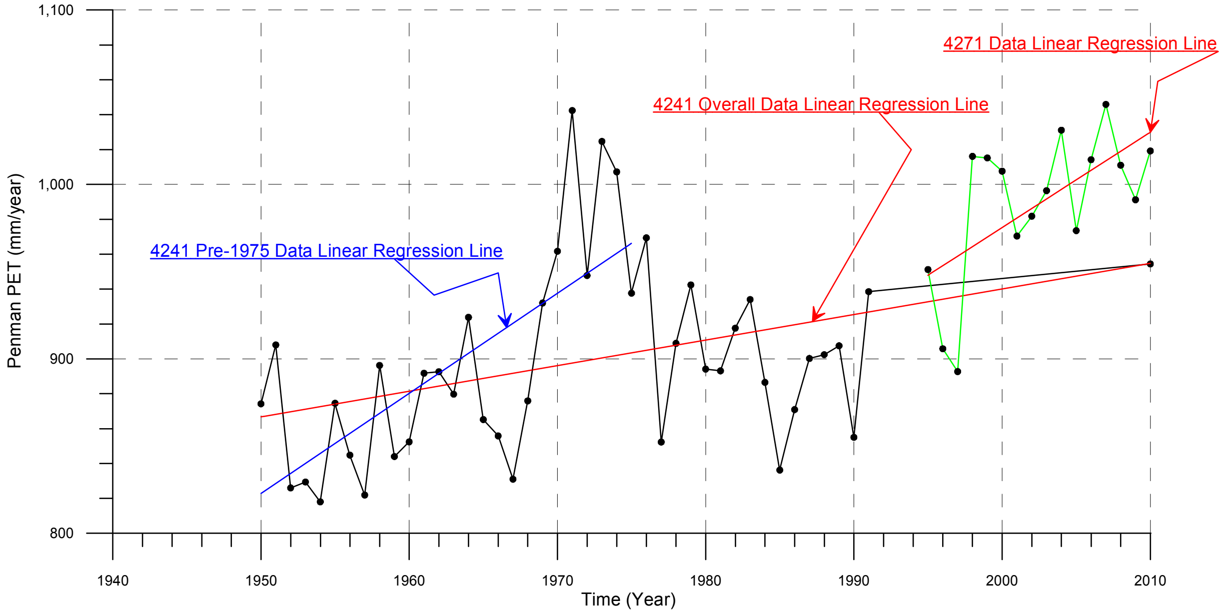


Figure 4-9: Penman PET Trend for Nelson Airport (4241 and 4271) Data

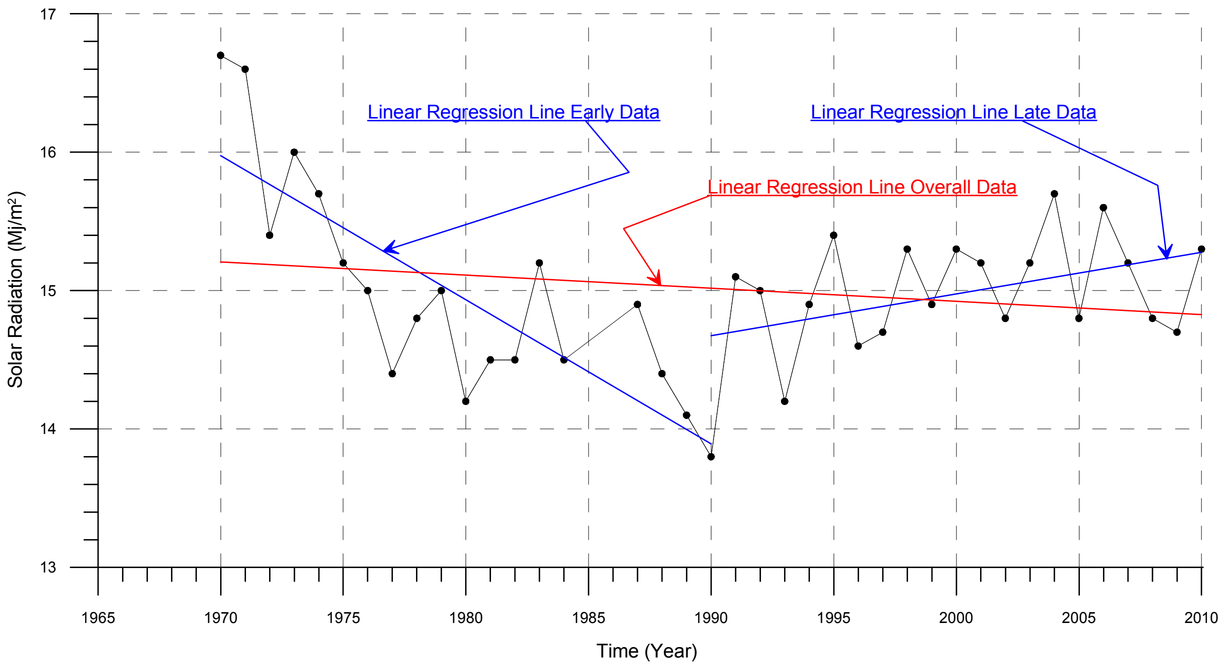


Figure 4-10: Solar Radiation Trend for Combined Nelson Airport (4241 and 4271) Data

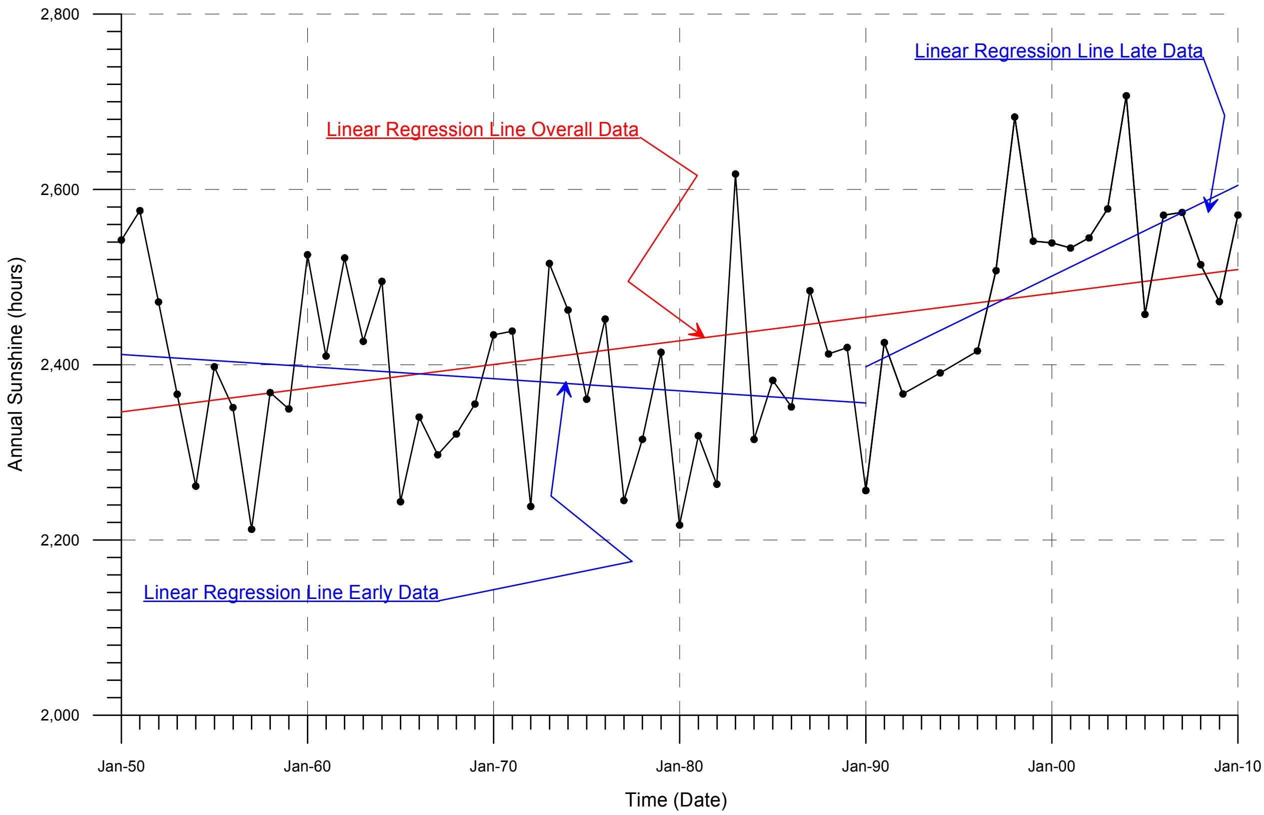


Figure 4-11: Annual Sunshine Trend for Nelson Aero (4241) Data

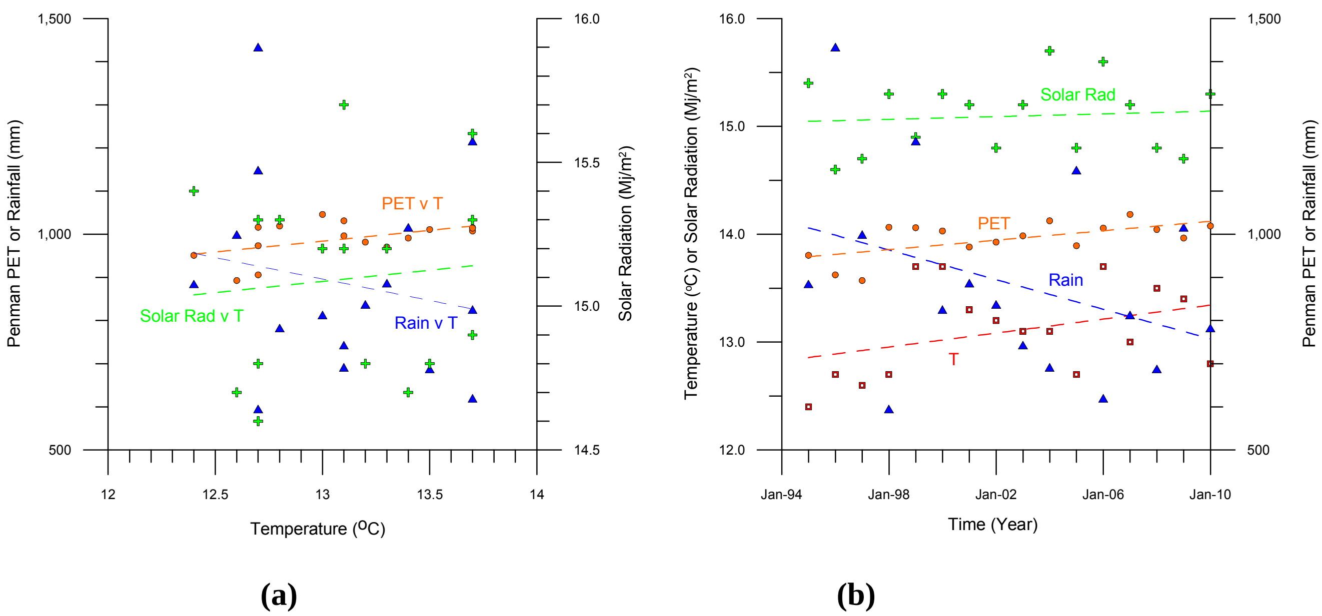


Figure 4-12: Climate Variable Linear Correlation Scatter plots

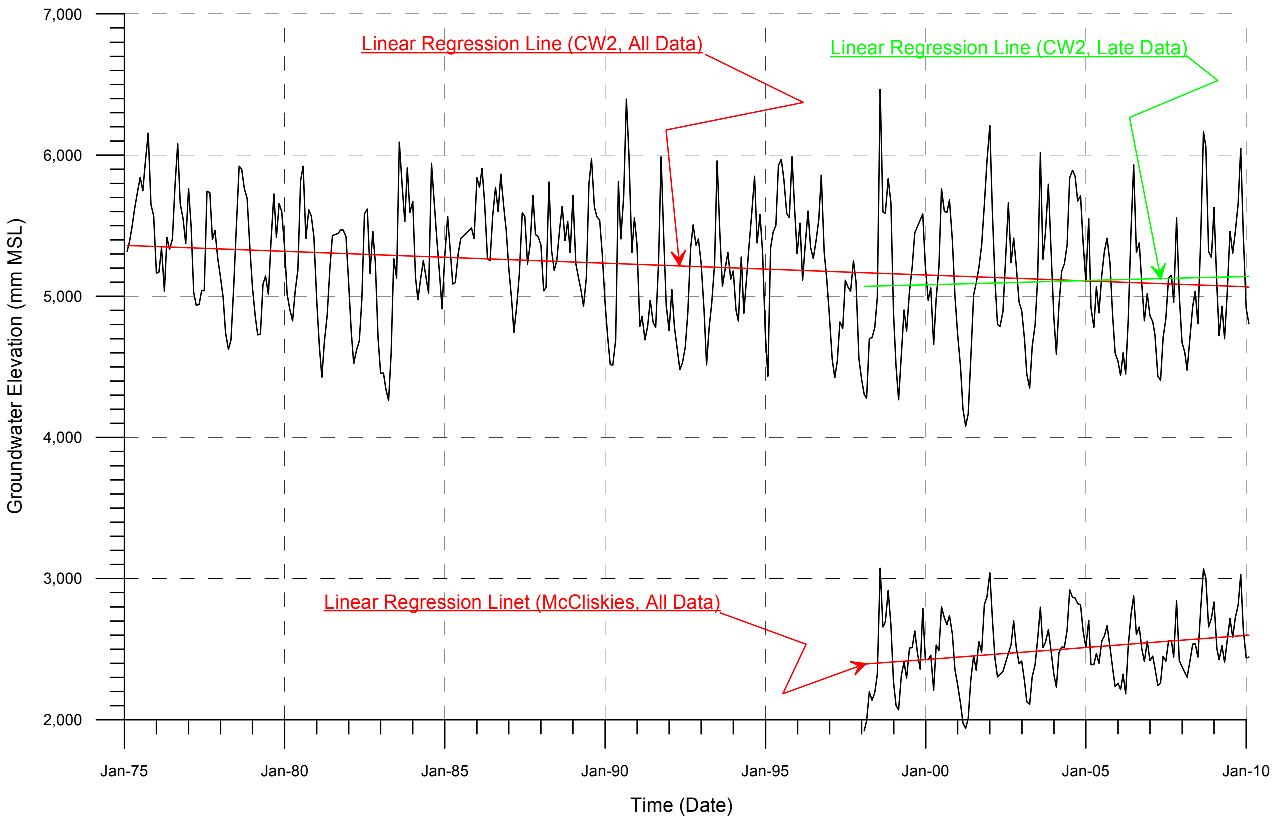


Figure 4-13: AGUA Groundwater Level Trends

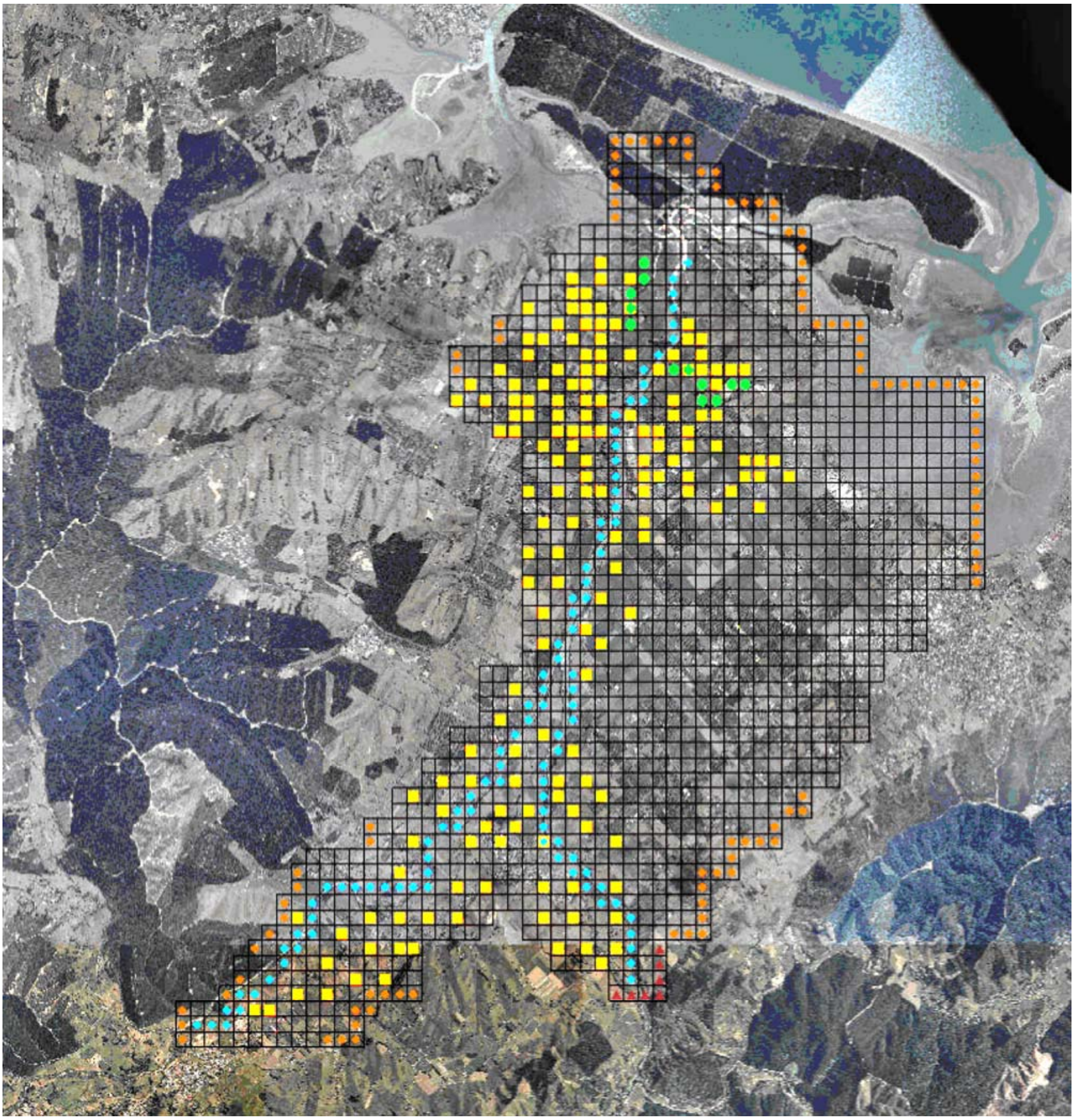


Figure 5-1: Layer 1 MODFLOW Model Grid Superimposed on Aerial Photo (North Up)

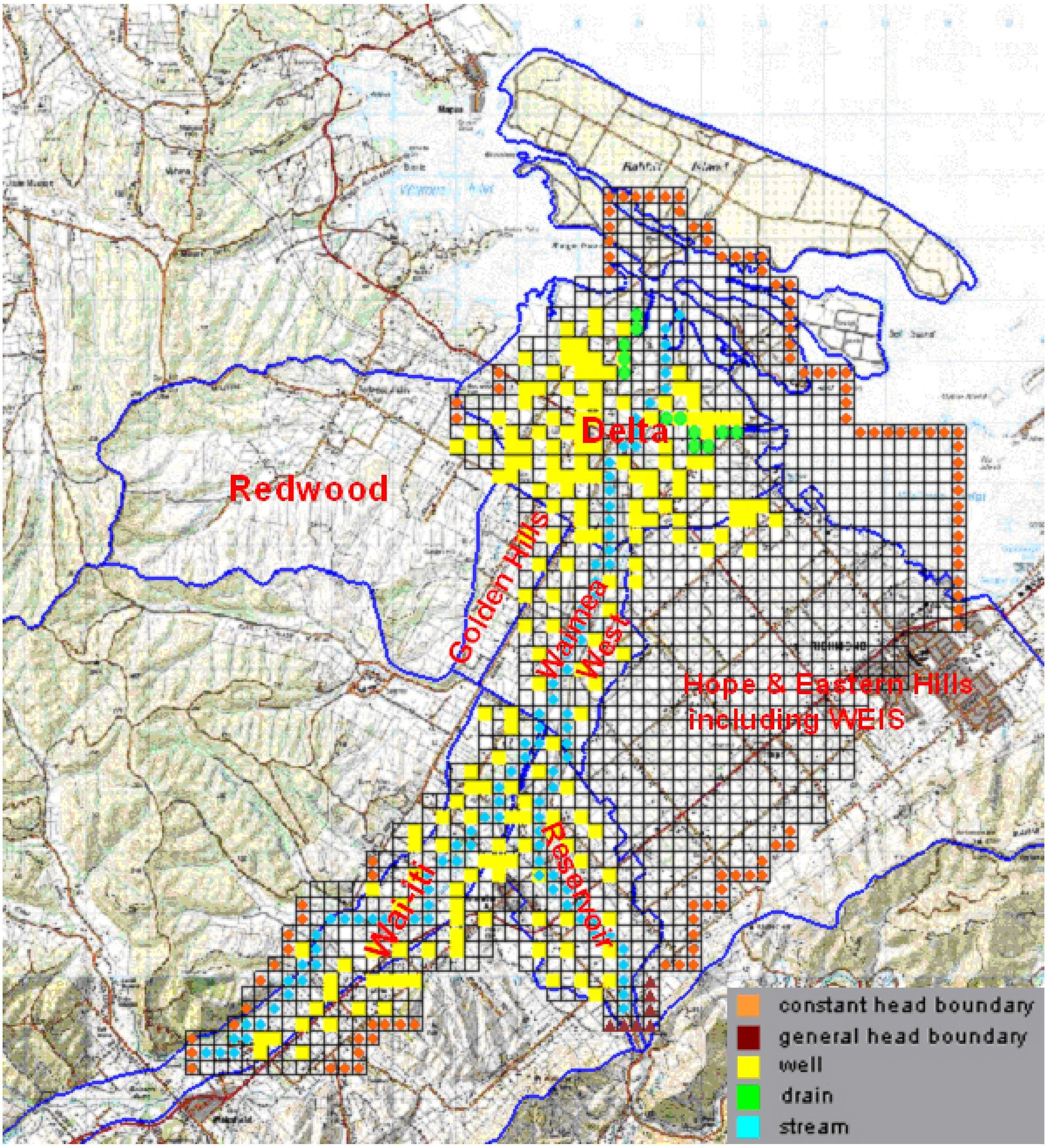
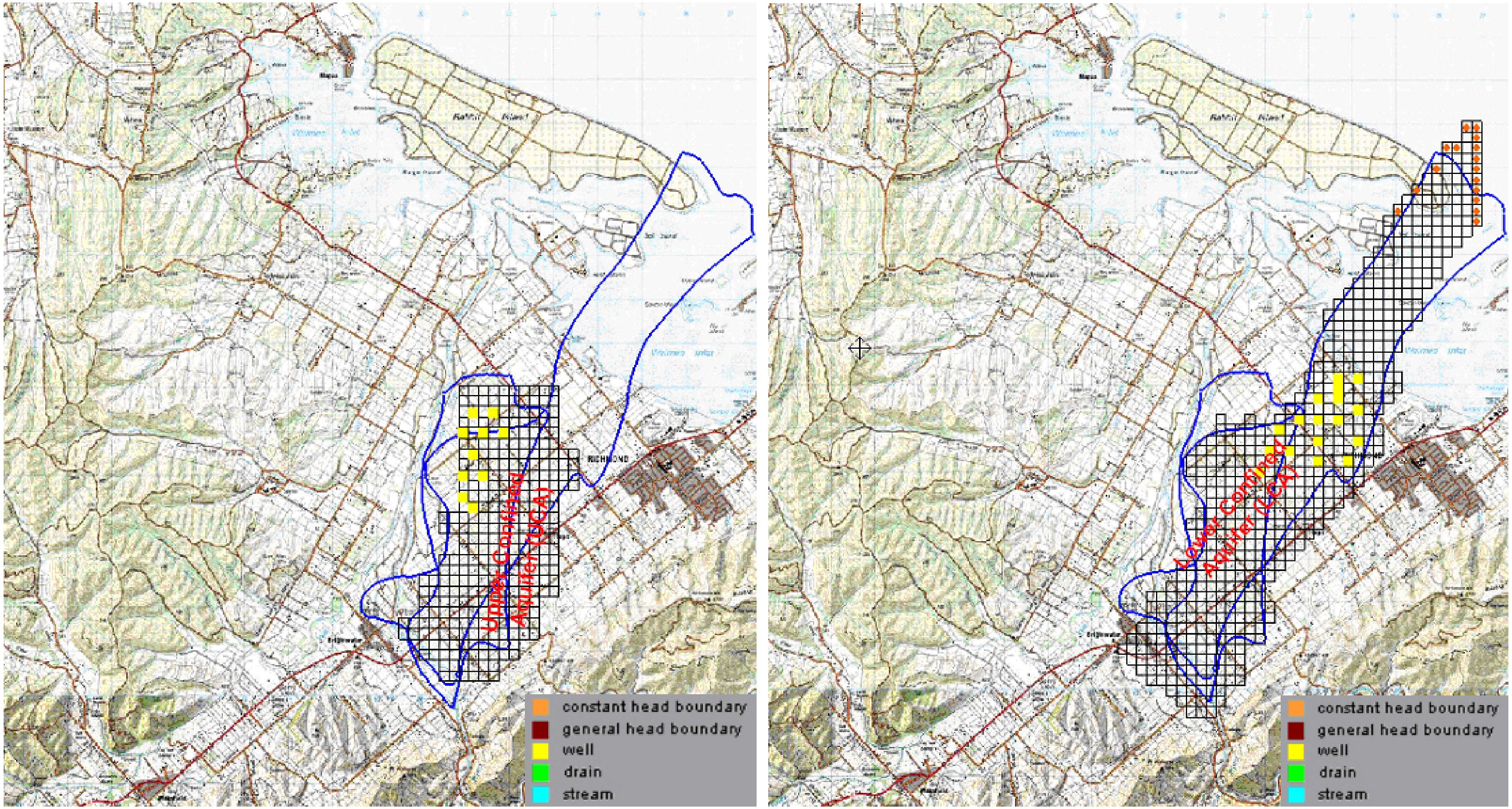


Figure 5-2: Layer 1 (AGUA) MODFLOW Model Grid Superimposed on Topographic Map (North Up)



(a) Layer 2 (UCA) **(b) Layer 3 (LCA)**

Figure 5-3: Layers 2 and 3 MODFLOW Model Grid Superimposed on Topographic Map (North Up)

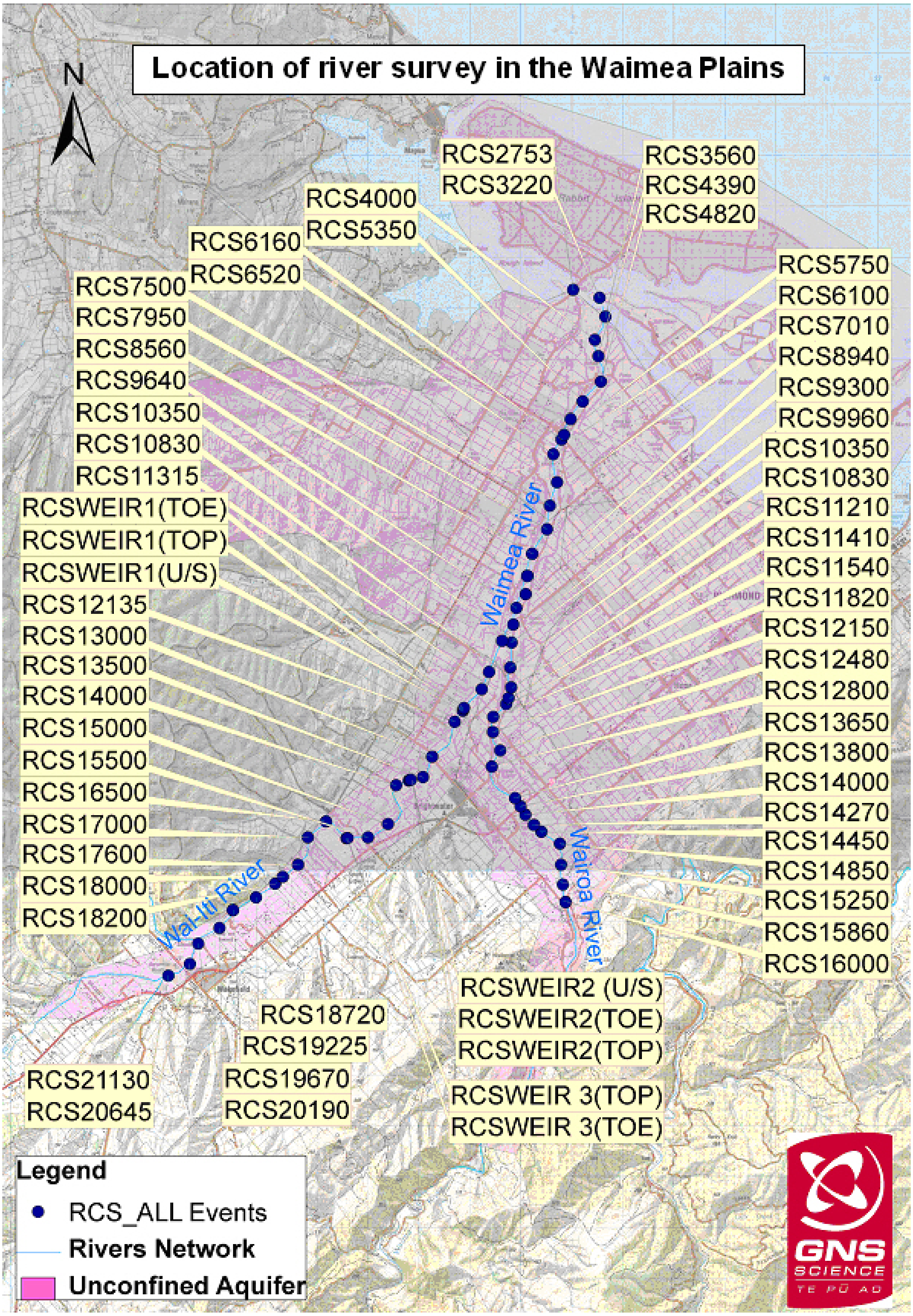


Figure 5-4: New Stream Cross-Section Survey Locations for MODFLOW Model

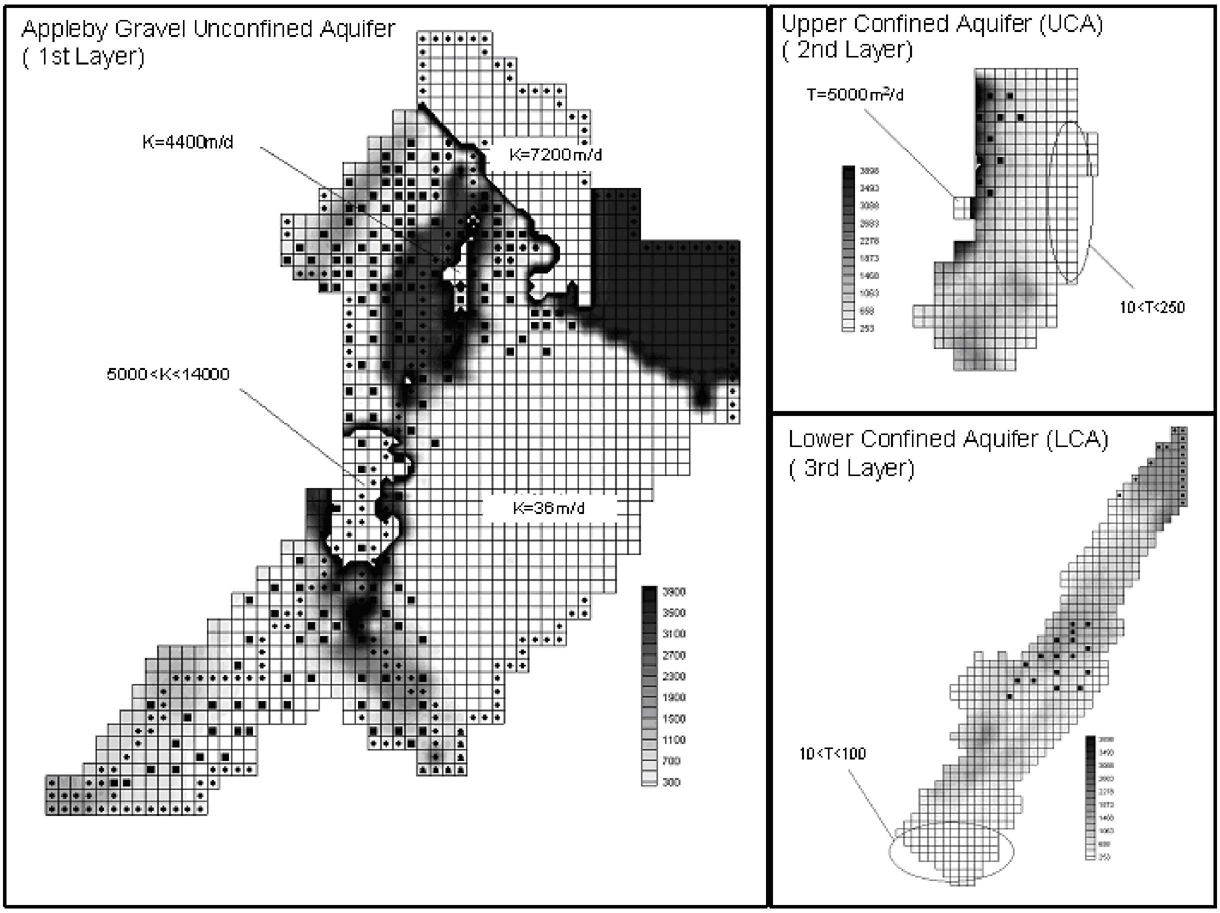


Figure 5-5: Spatial Distribution of Hydraulic Conductivity Values by Layer

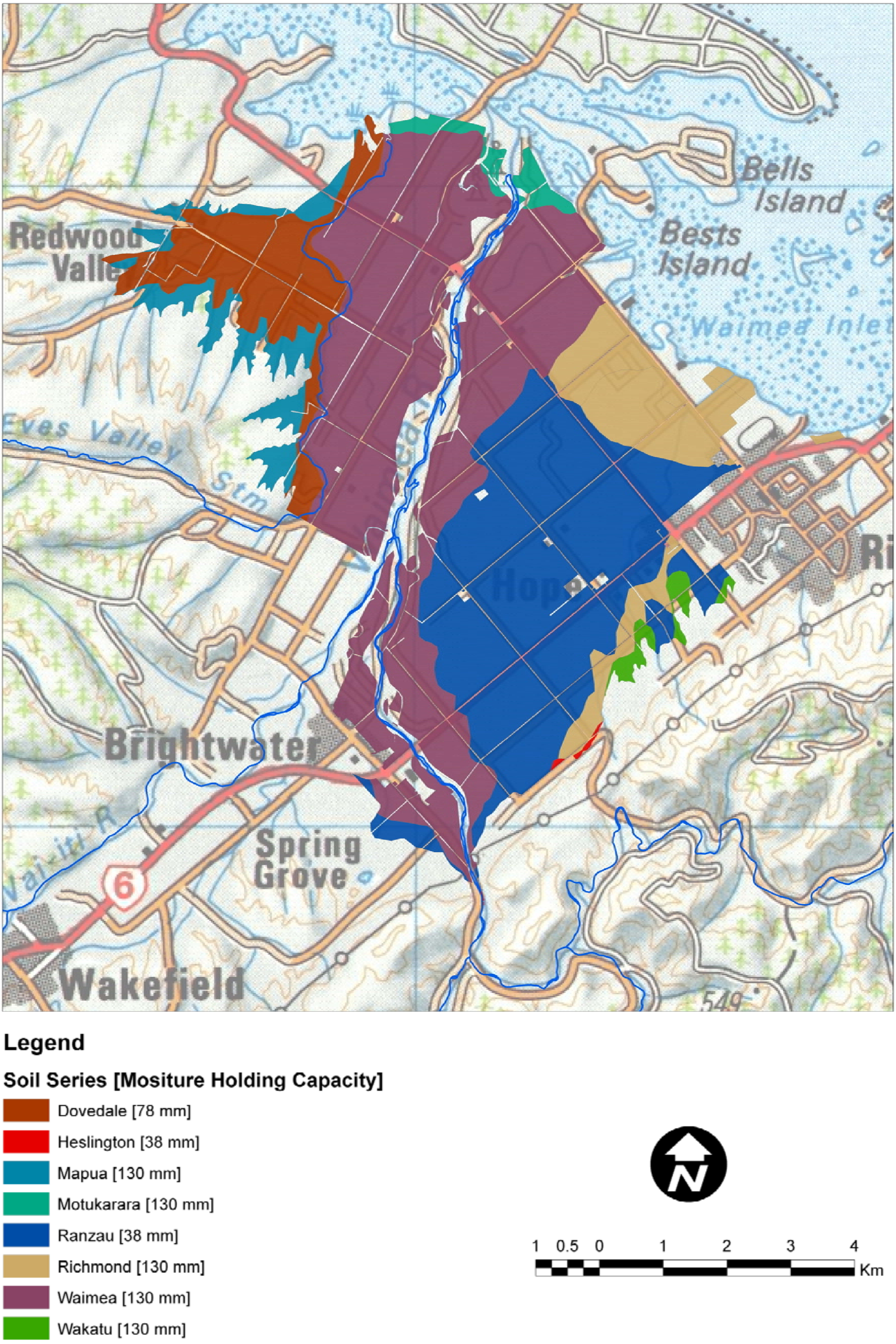


Figure 5-6: Soil Series Distribution Within the Waimea Plains

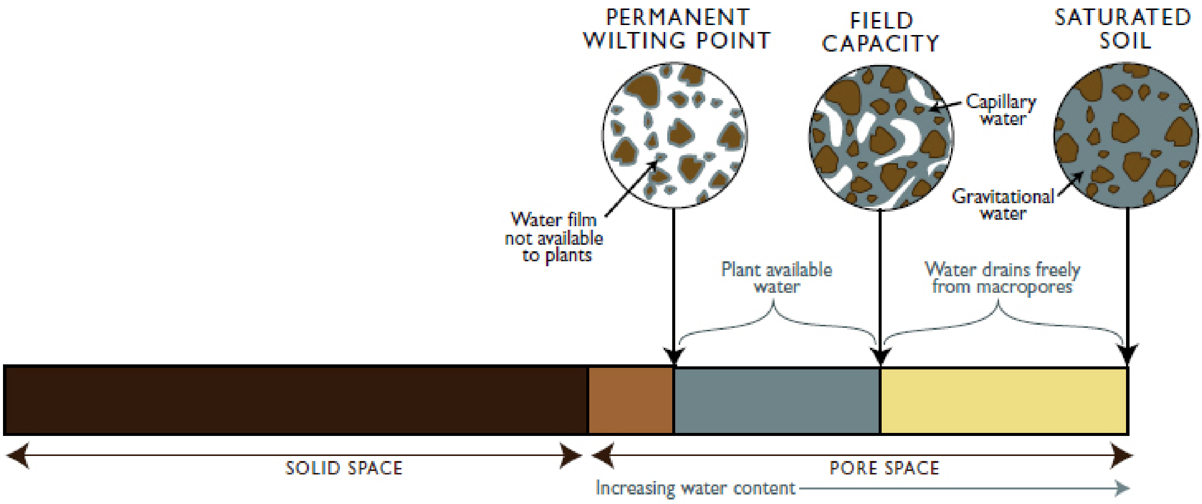


Figure 5-7: Soil Water Holding Terminology (Figure 7 from McCauley, 2005)

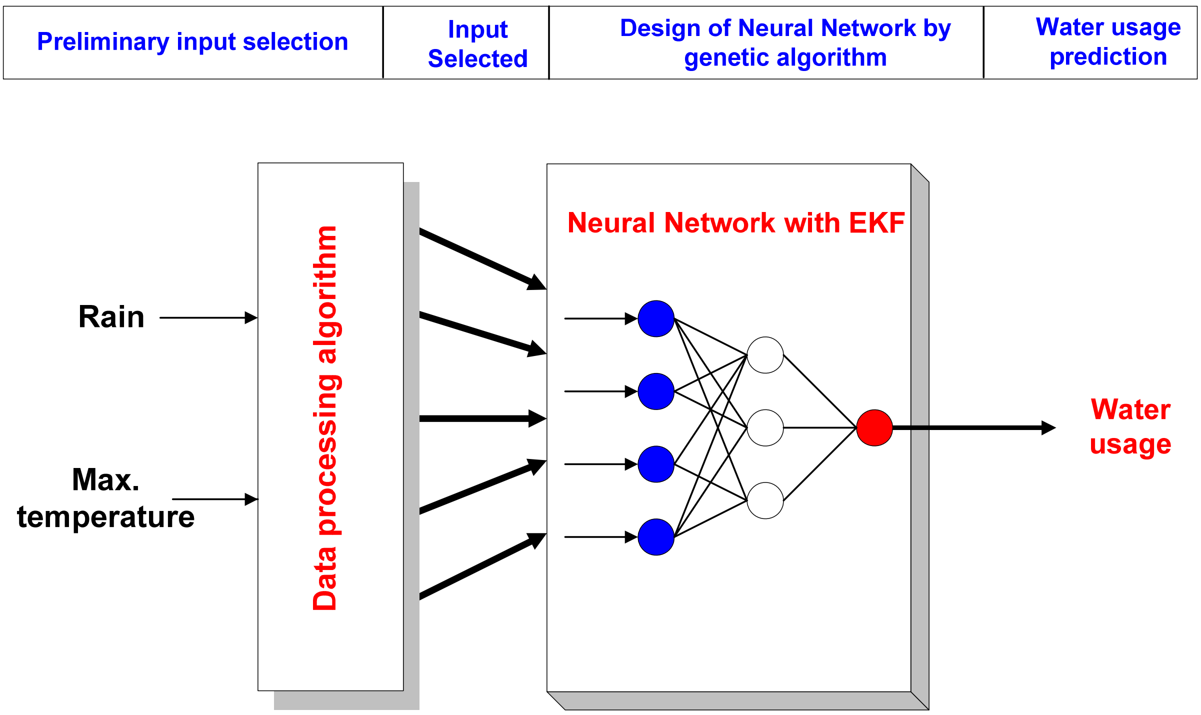


Figure 5-8: MLP-EKF Model Structure to Predict Water Usage

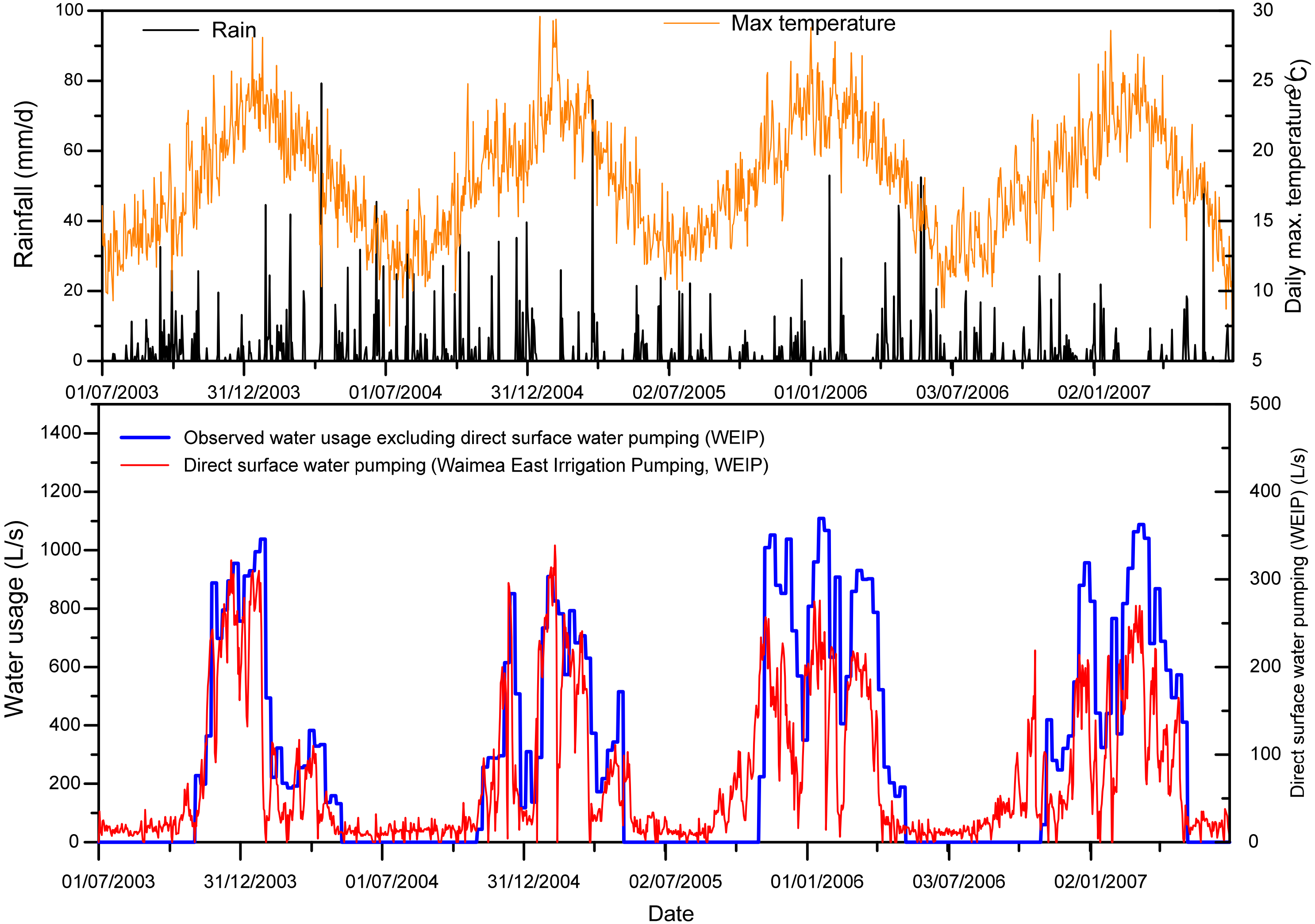


Figure 5-9: Historic Water Usage Data (1 Jul 03 – 30 Jun 07)

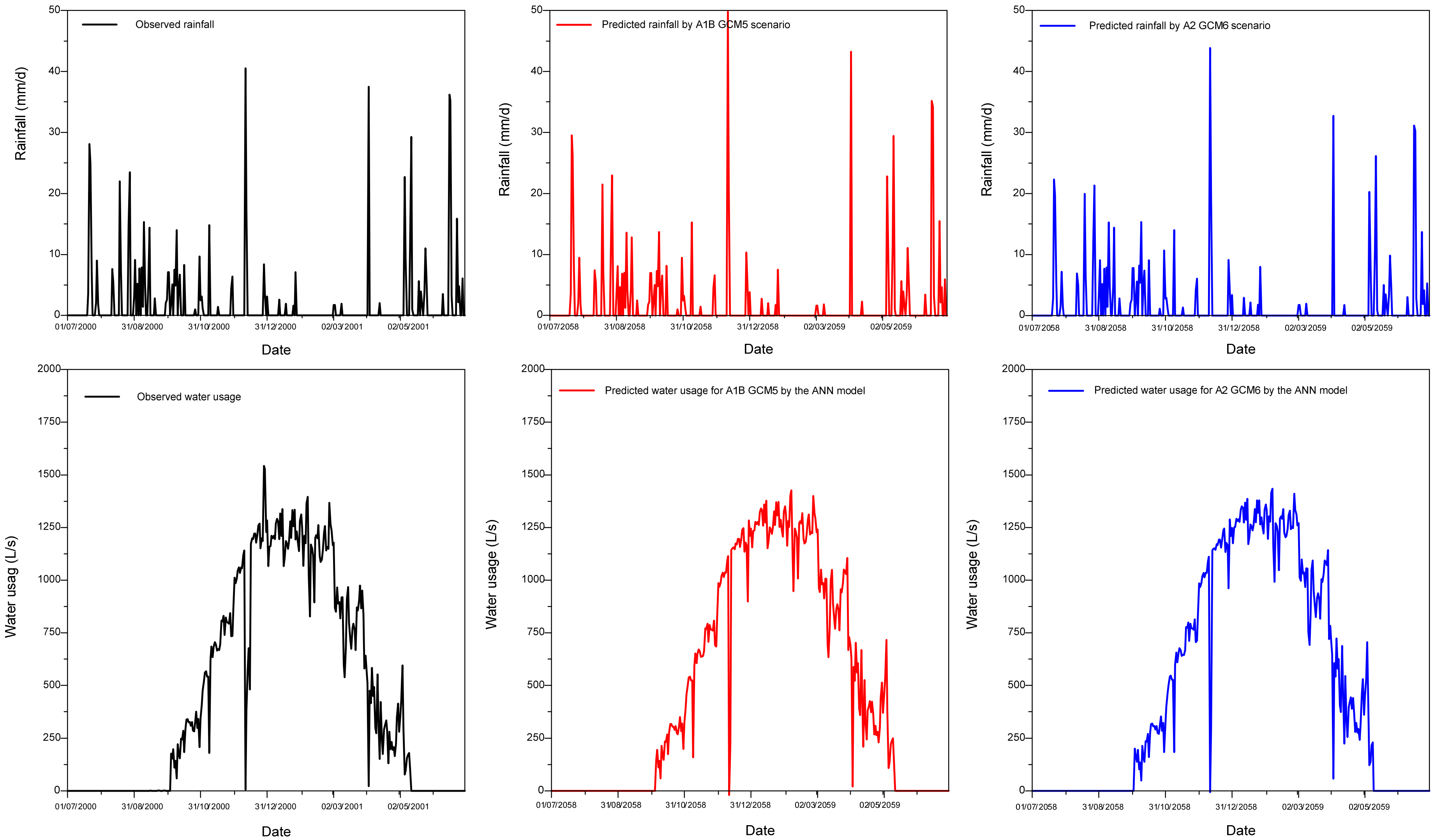


Figure 5-10: Historic and Modelled Rainfall and Water Usage (00-01 and 58-59)

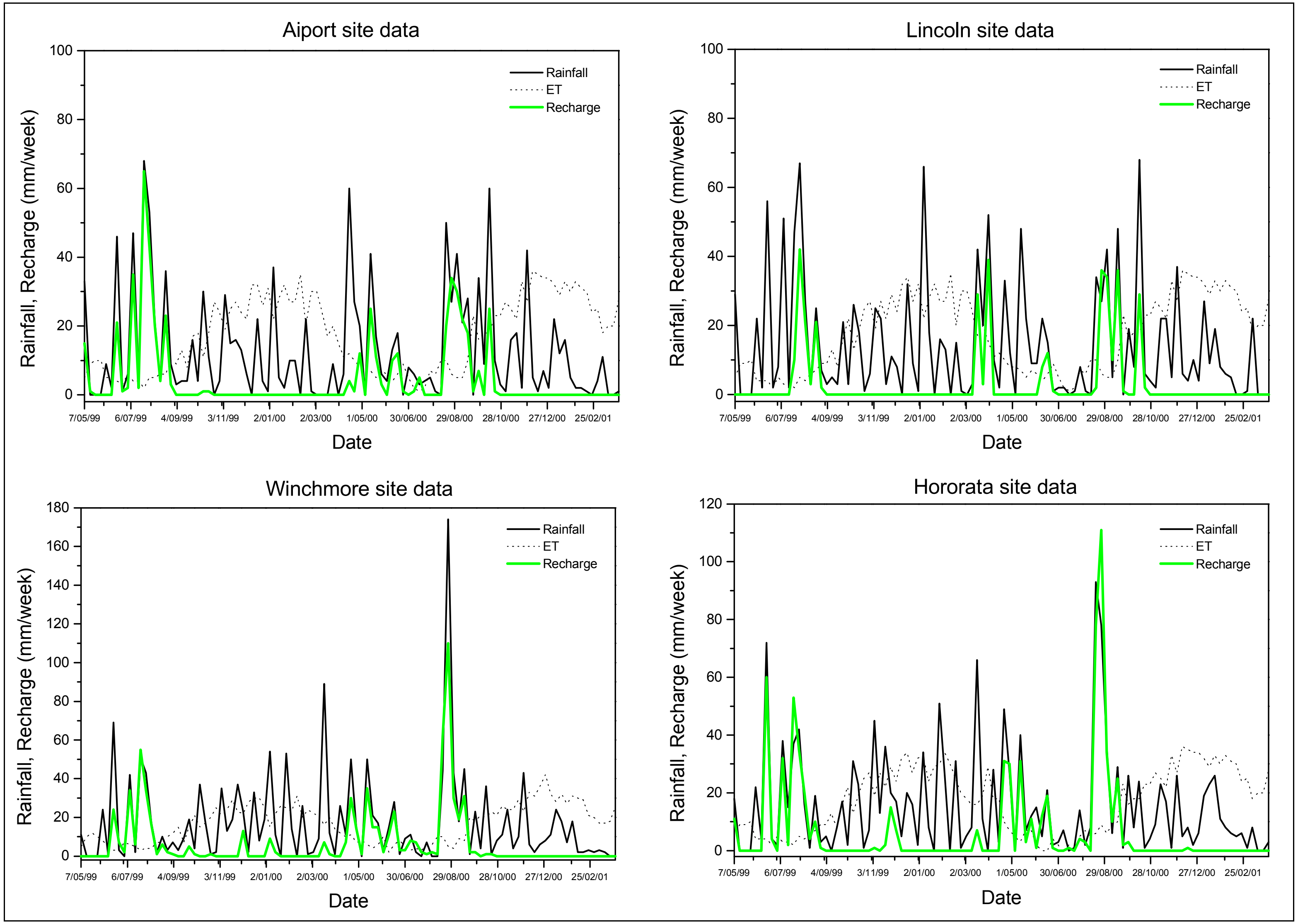
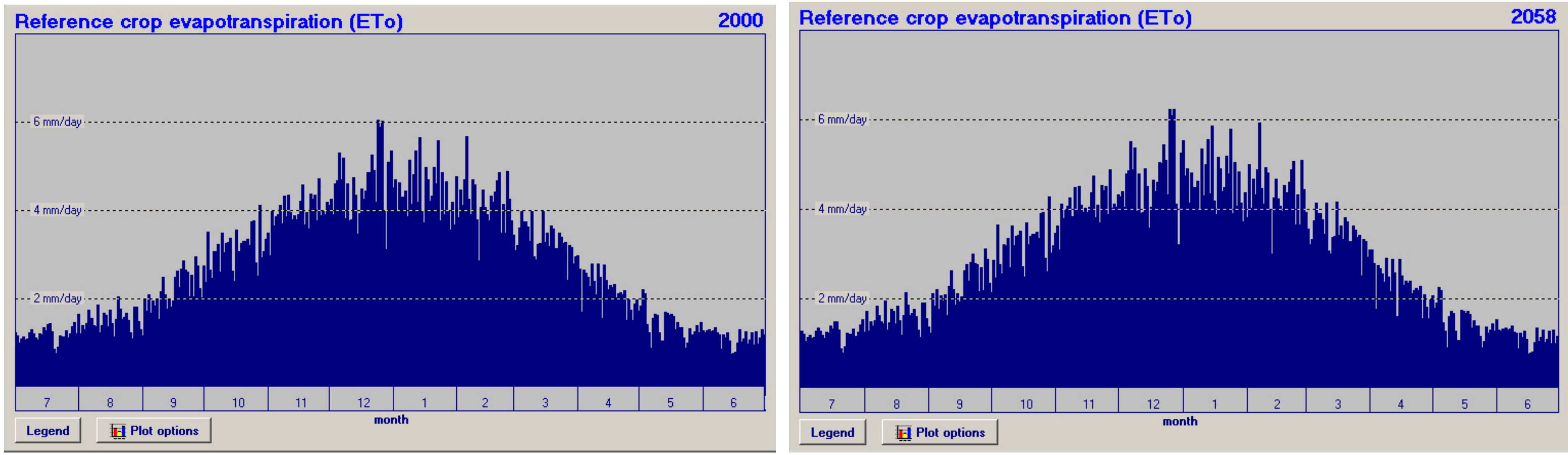


Figure 5-11: Rainfall and Rainfall Recharge Measurements at Four Sites (99-01)



(a) Year 2000 – 2001 **(b) Year 2058 - 2059**

Figure 5-12: Reference Evapotranspiration (ETo)

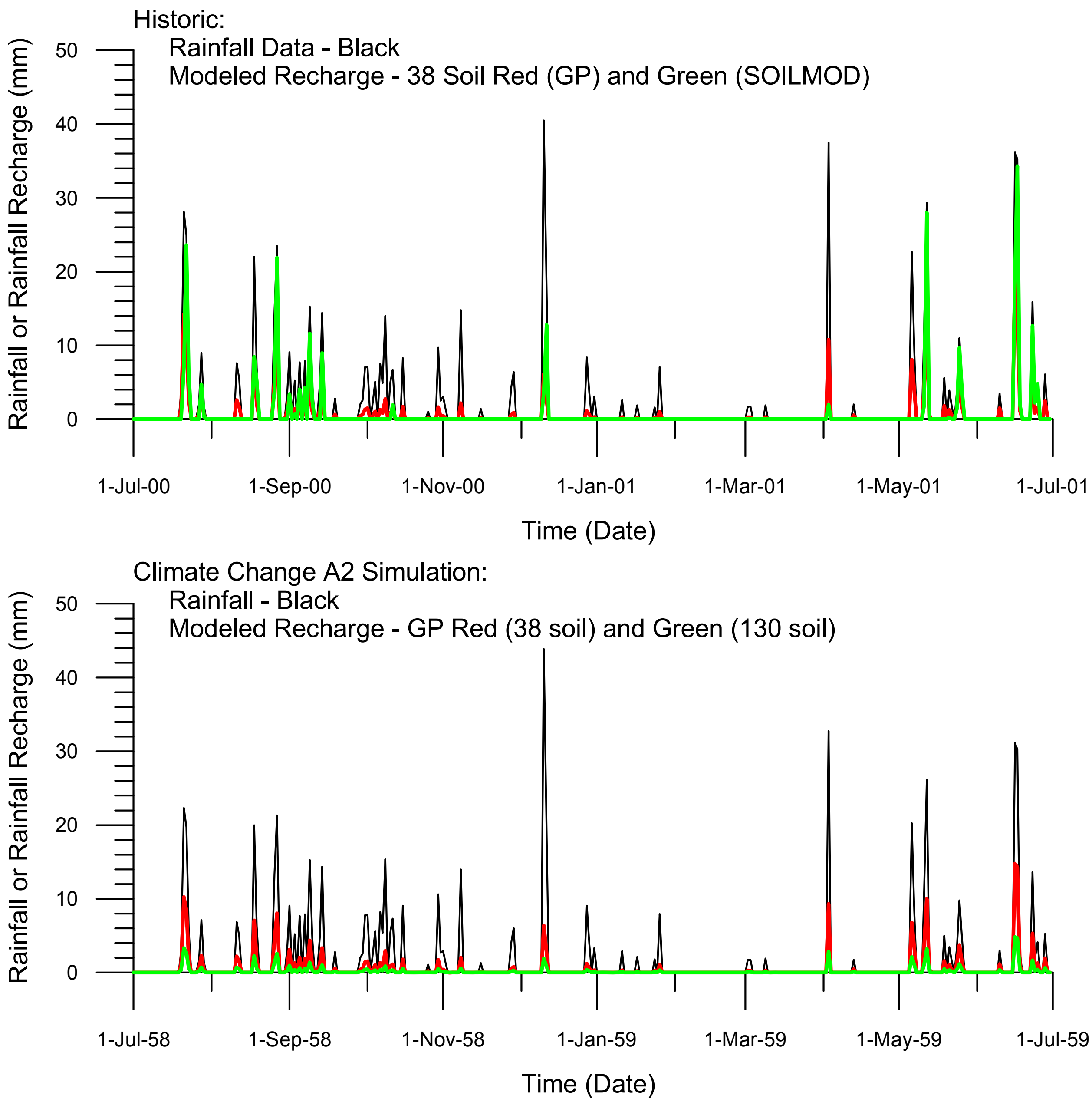


Figure 5-13: Rainfall Recharge Model Results (00-01 and 58-59)

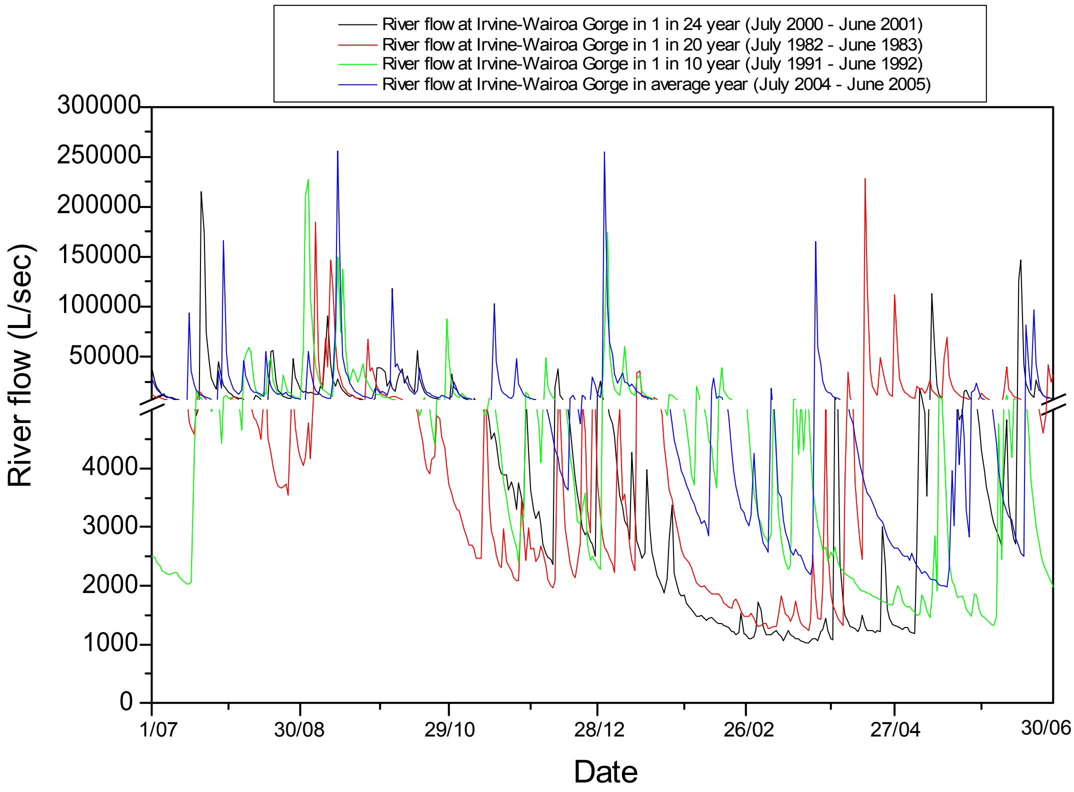


Figure 5-14: Historic Wairoa River Flow at Irvines (82-83, 91-92, 00-01, and 04-05)

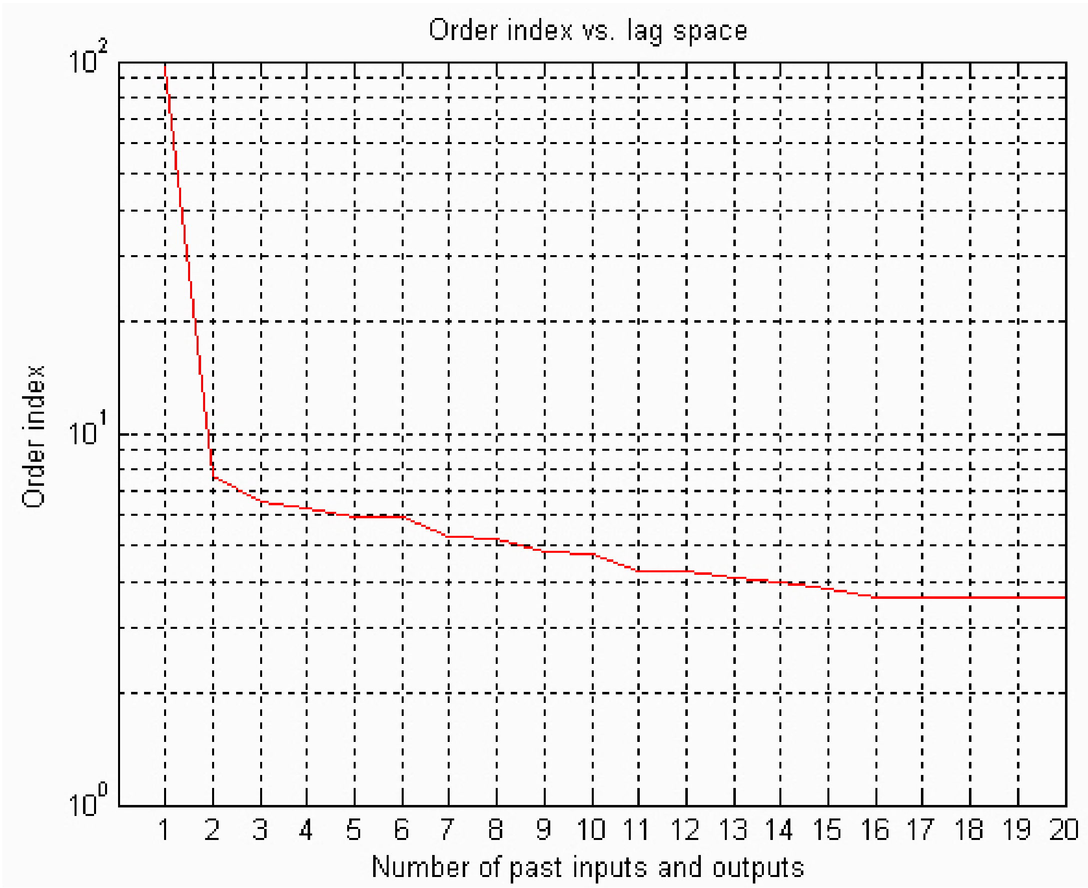


Figure 5-15: “Lipschitz Quotient” Method for Lag Time

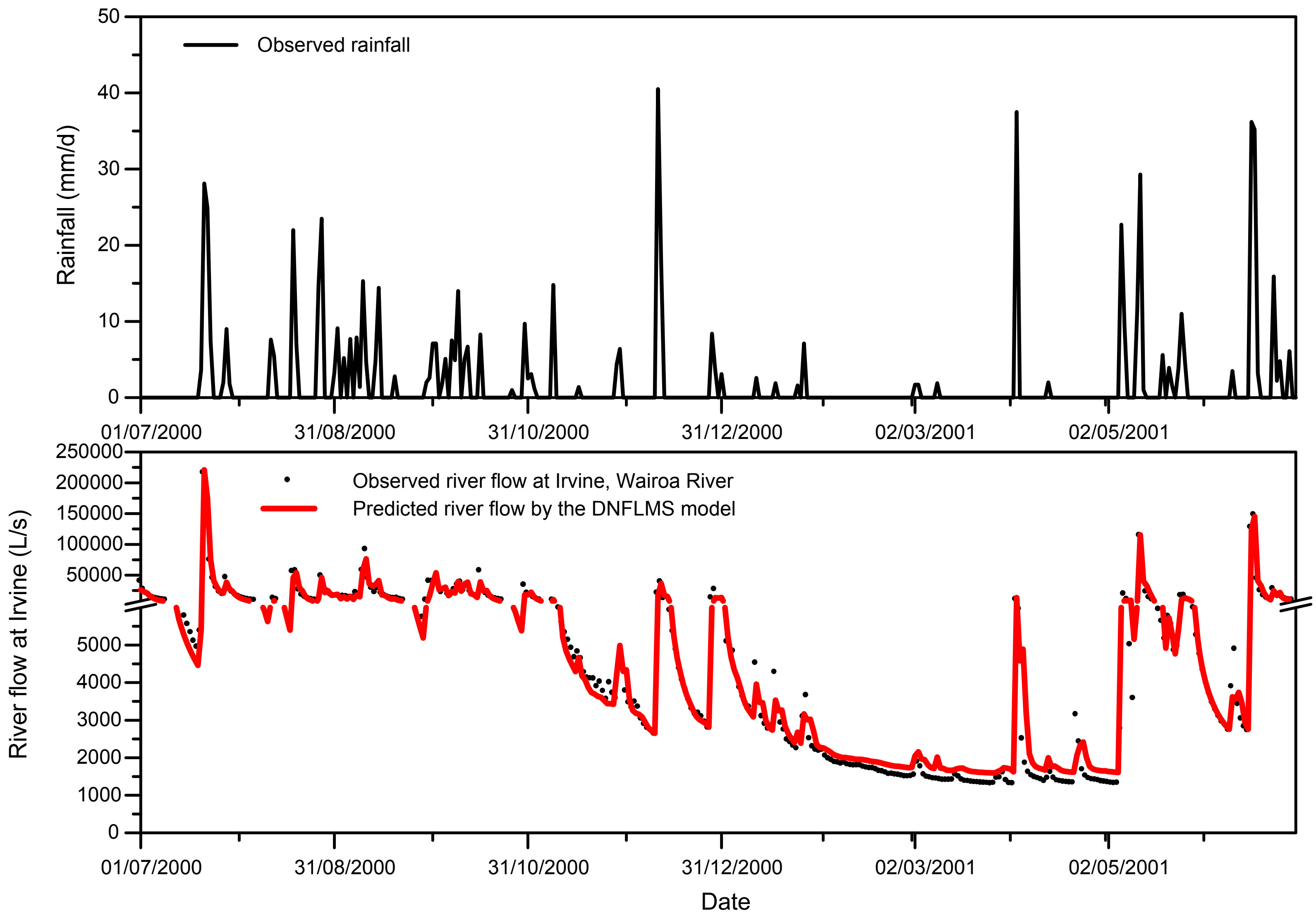


Figure 5-16: Wairoa River Flow at Irvines (00-01) DNFLMS Model Training Results

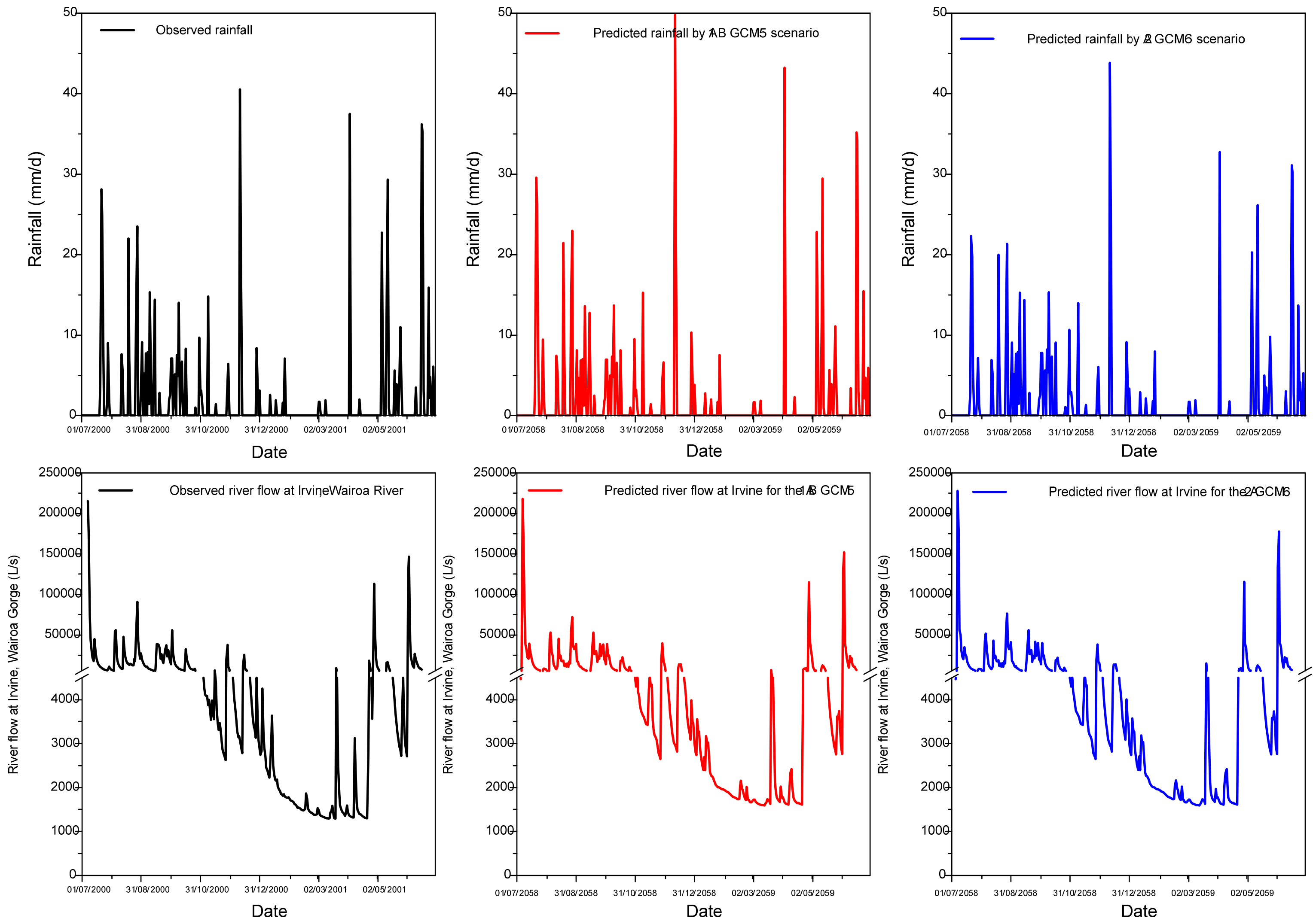


Figure 5-17: Wairoa River Flow at Irvines (00-01 and 58-59) Predicted by DNFLMS Model

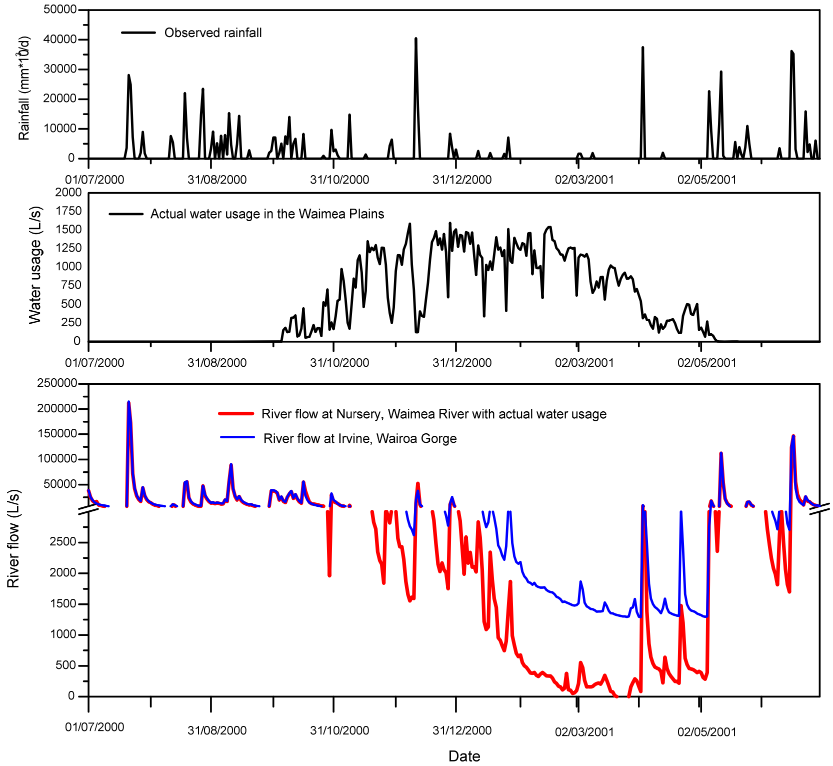


Figure 5-18: Historic Rainfall, Water Usage, and Streamflow (Irvines and TDC Nursery, 00-01)

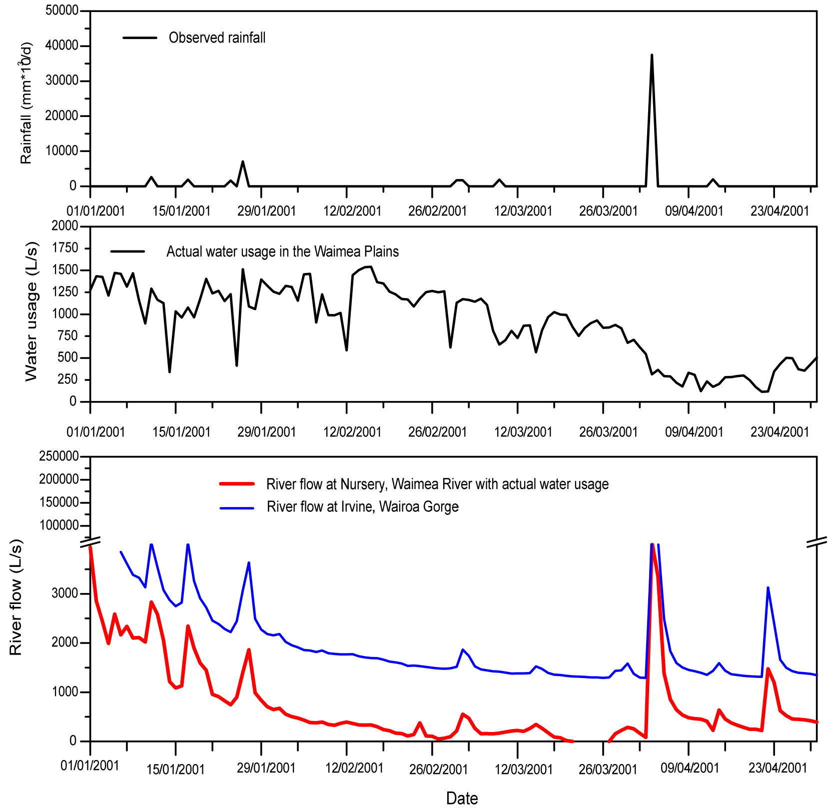


Figure 5-19: Historic Rainfall, Water Usage, and Streamflow (Irvines and TDC Nursery, Feb-Apr 01)

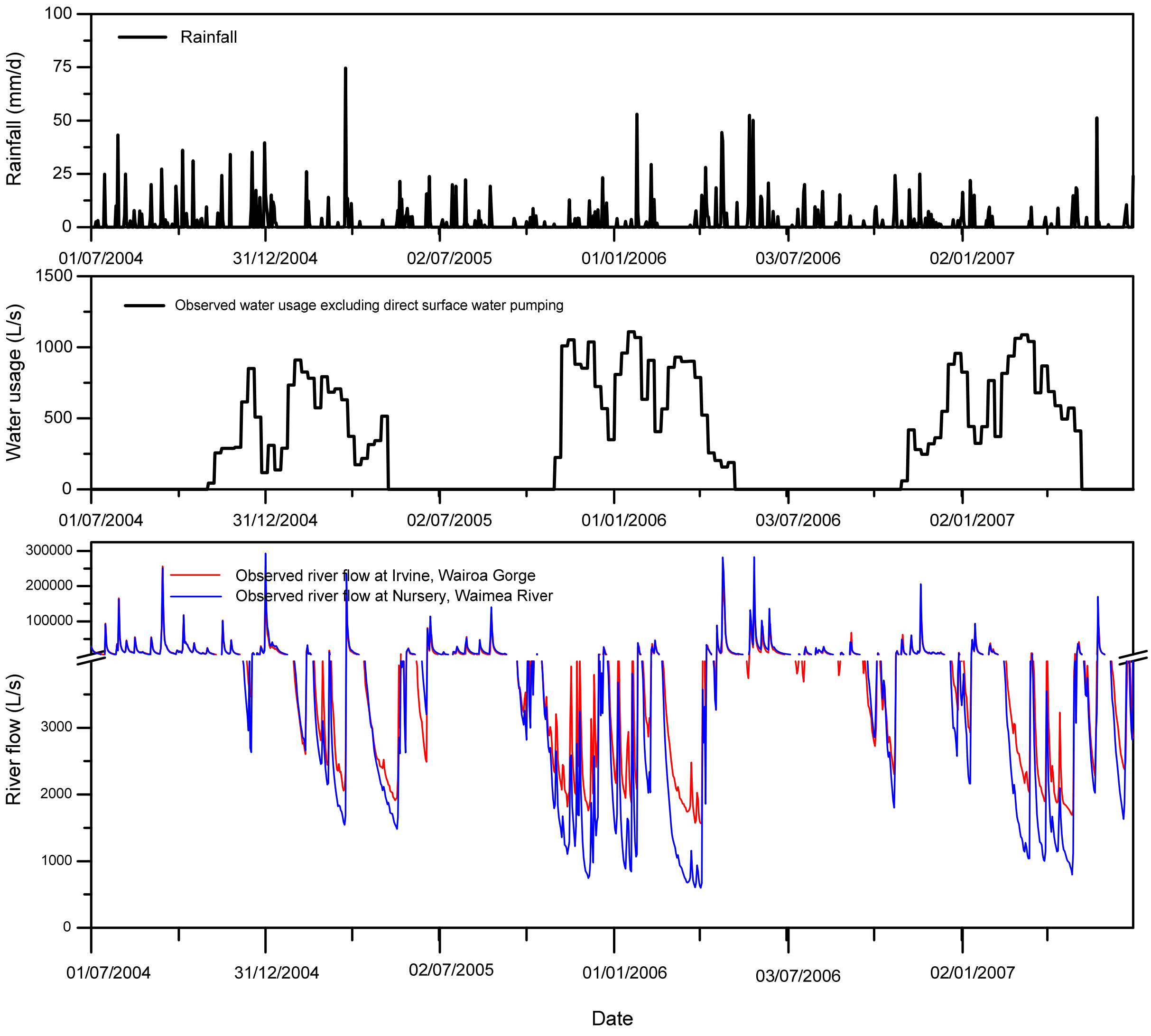


Figure 5-20: Historic Rainfall, Water Usage, and Streamflow (Irvines and TDC Nursery, 04-07)

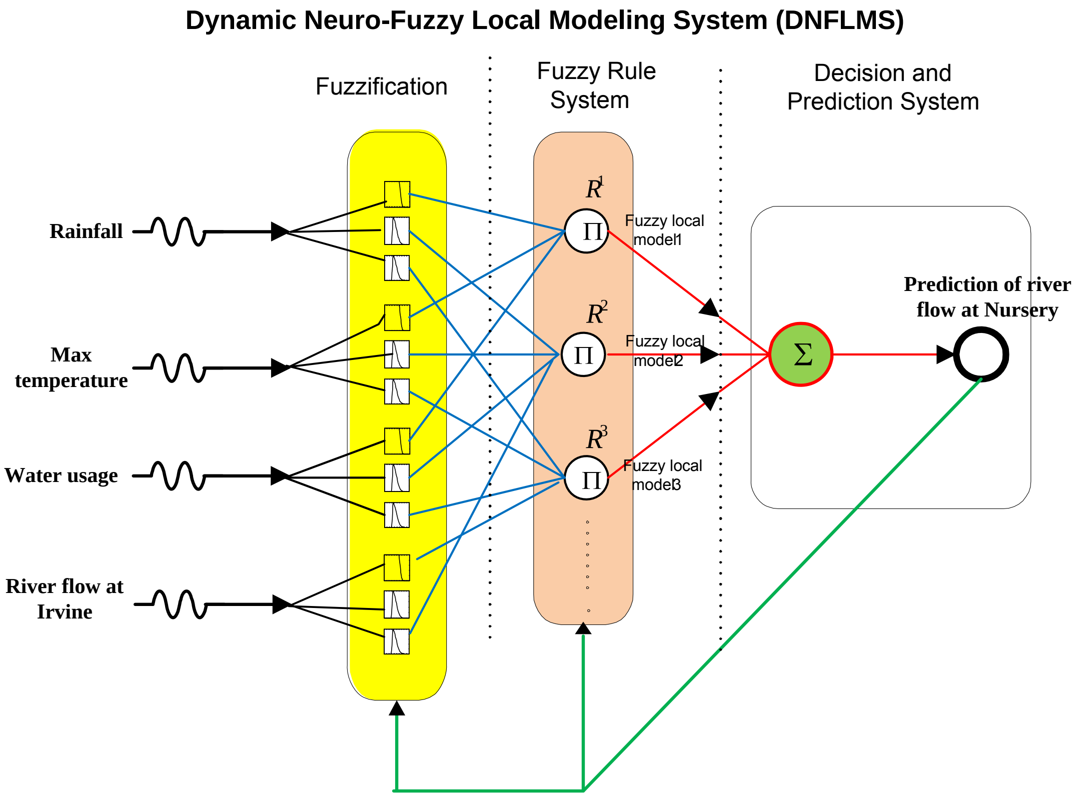


Figure 5-21: Structure of DNZLMS Model to Predict Waimea River at TDC Nursery

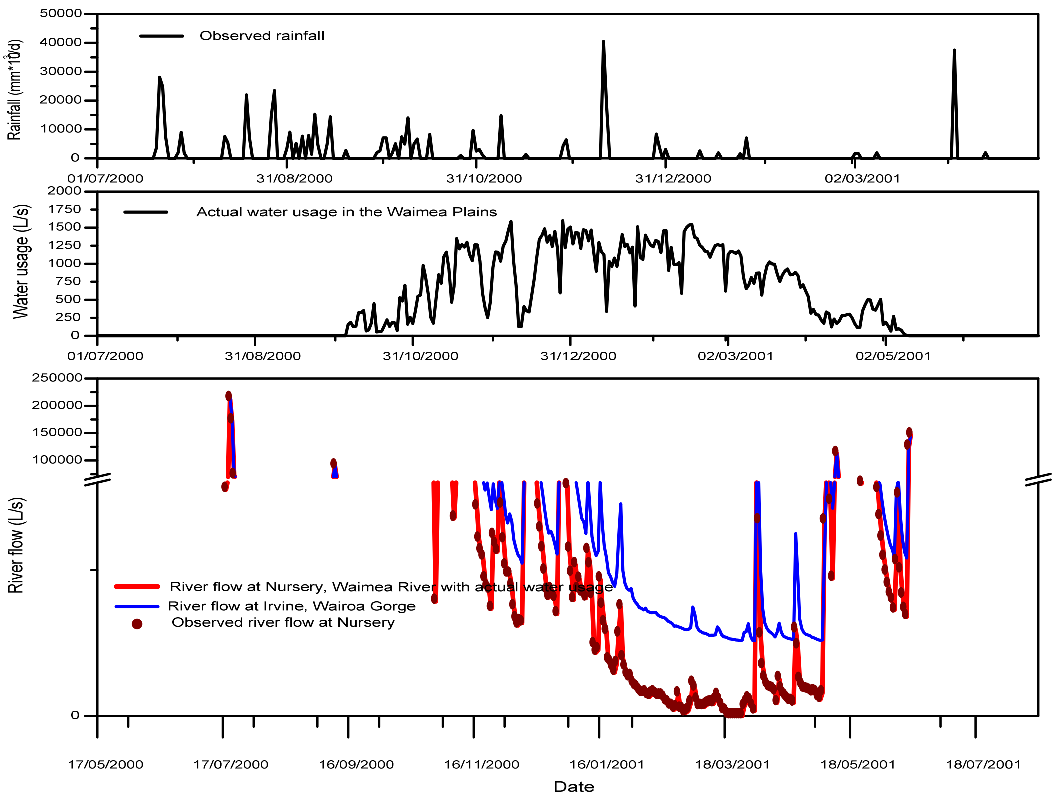


Figure 5-22: Waimea River Flow at TDC Nursery (00-01) DNFLMS Model Training Results

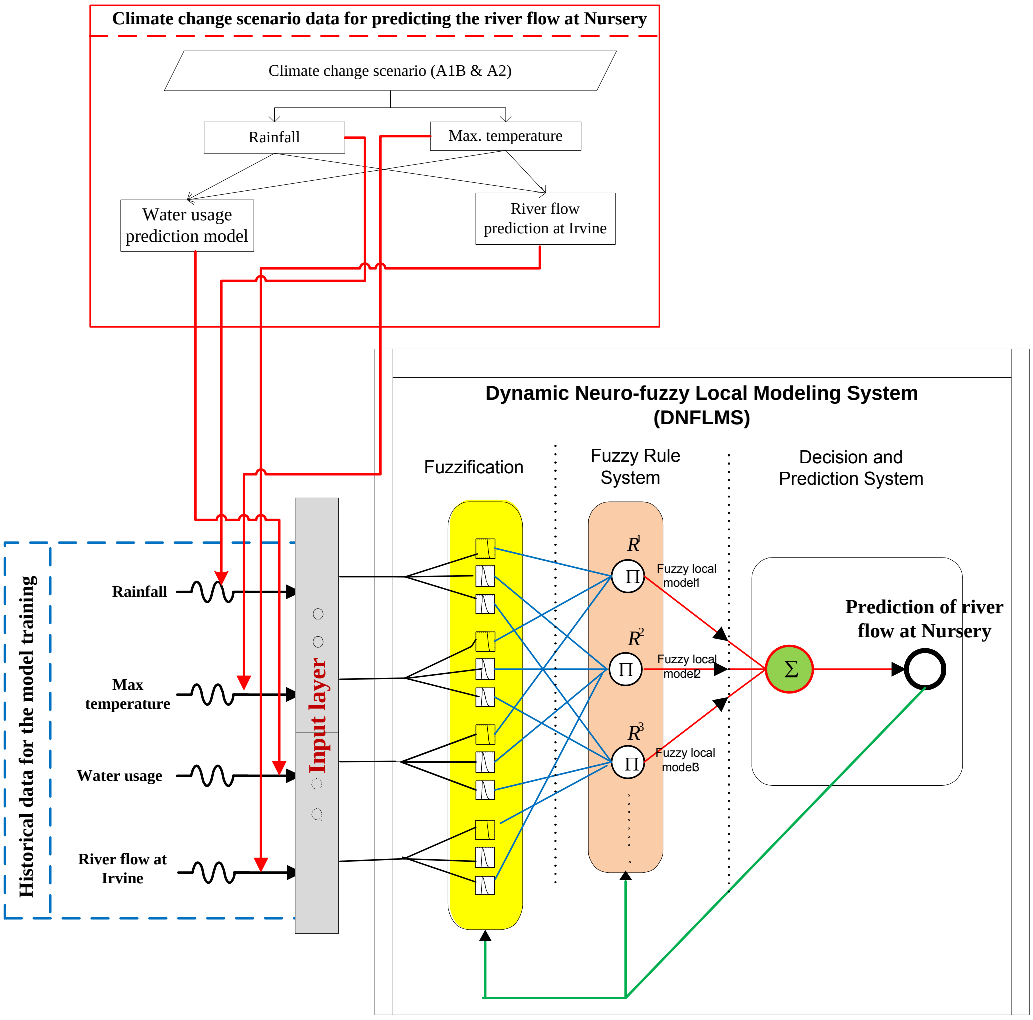


Figure 5-23: Structure of DNFLMS Model to Predict Waimea River Flow at TDC Nursery

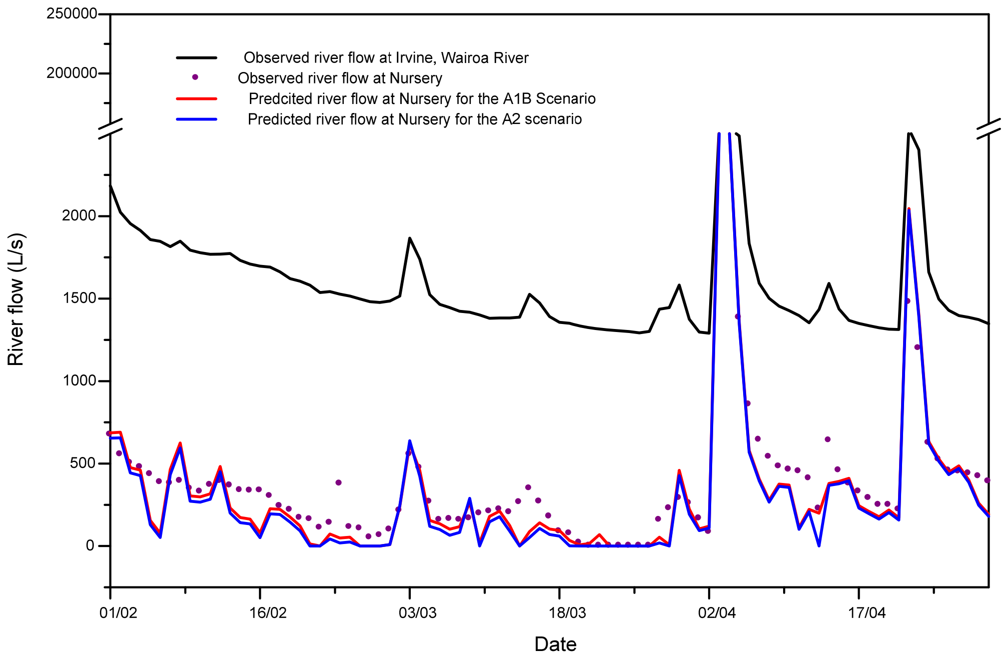


Figure 5-24: Predicted Waimea River Flow at TDC Nursery under Climate Change

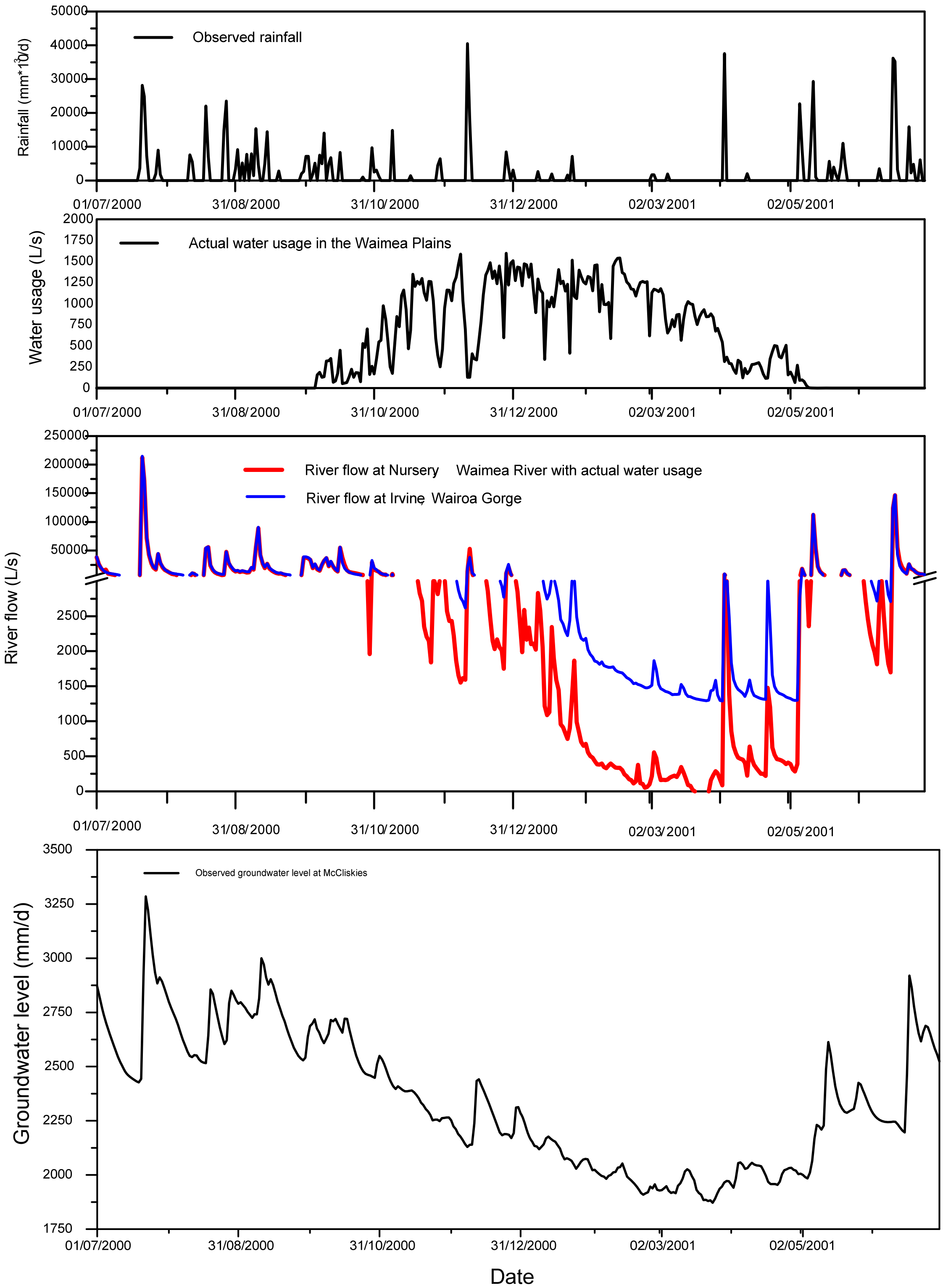


Figure 5-25: Historic Groundwater Levels at McCliskies Well (2000-2001)

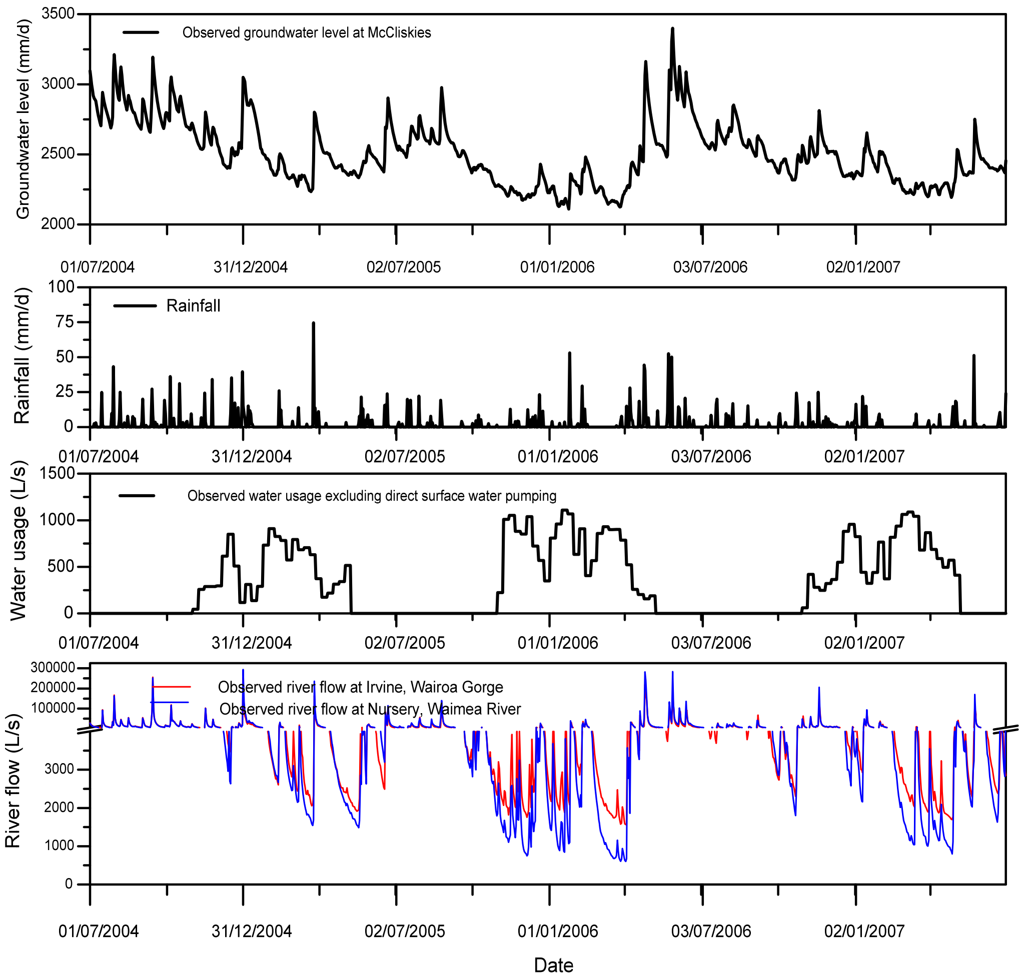


Figure 5-26: Historic Groundwater Levels at McCliskies Well (2004-2007)

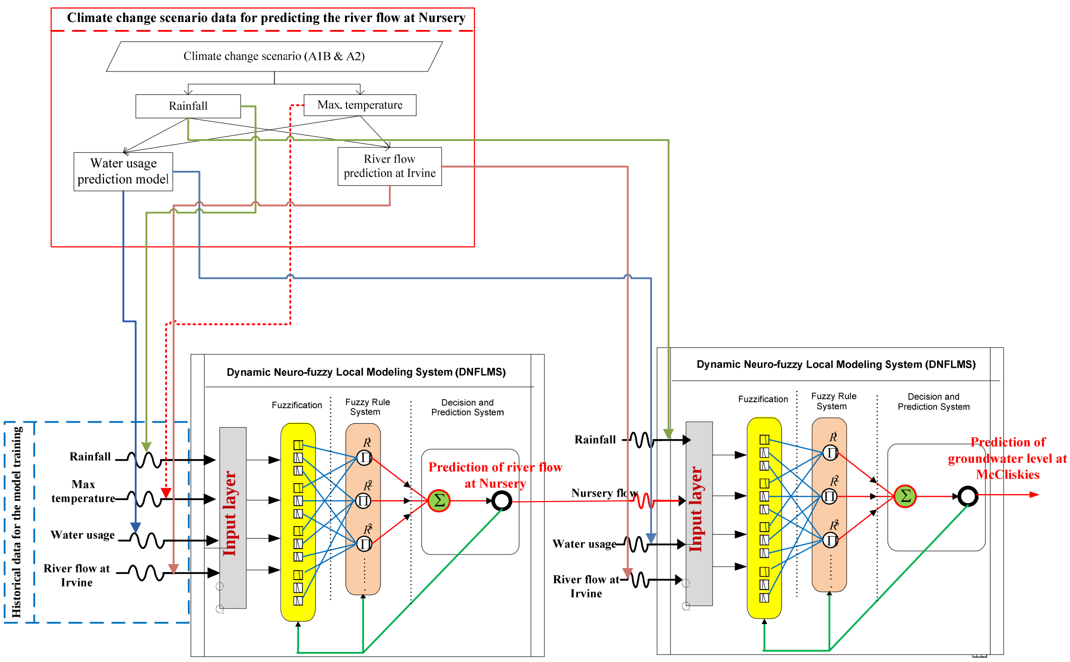


Figure 5-27: Structure of DNZLMS Model for Predicting Groundwater Level at McCliskies Well under Climate Change

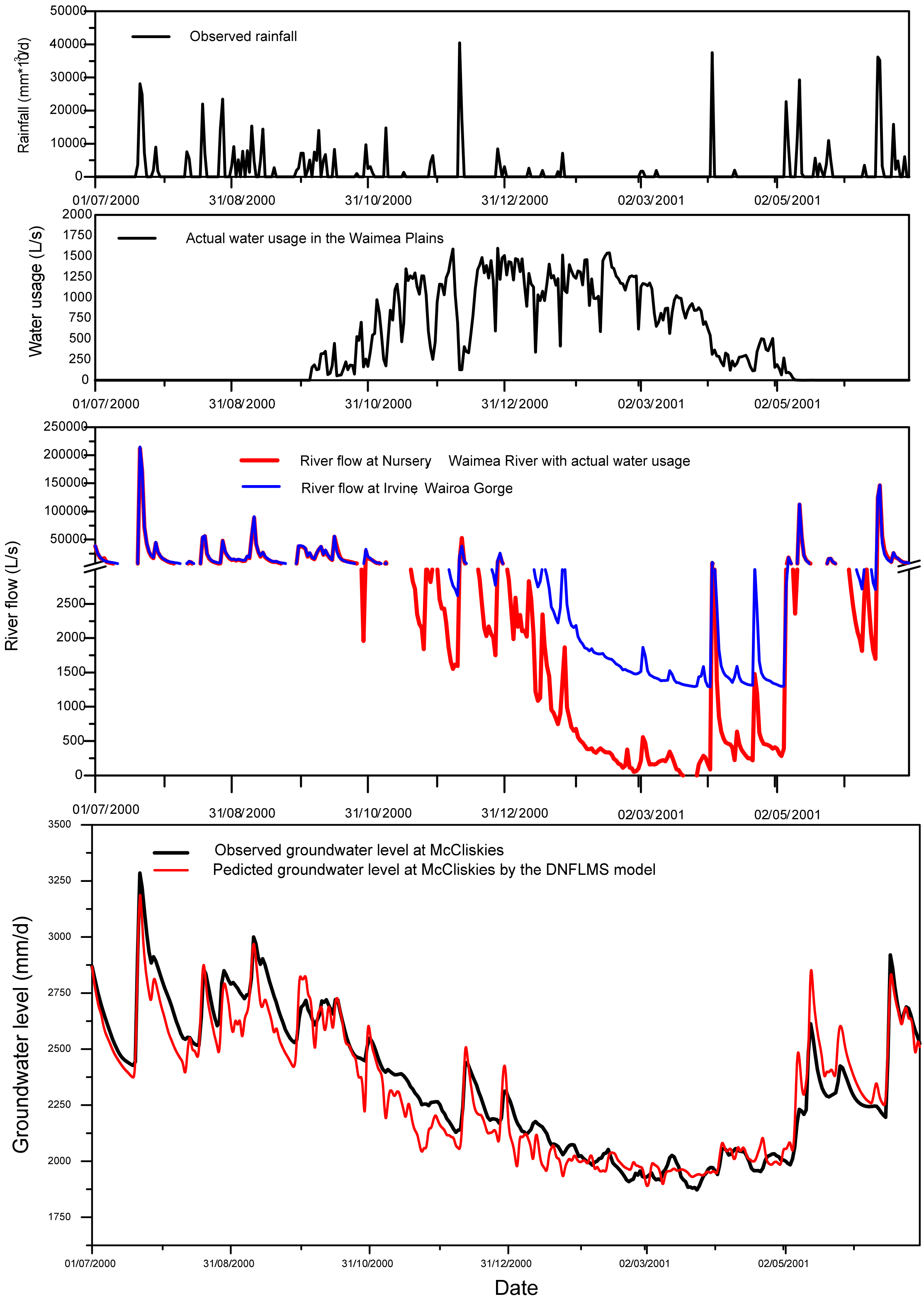


Figure 5-28: DNFLMS Model Groundwater Elevation Training Results

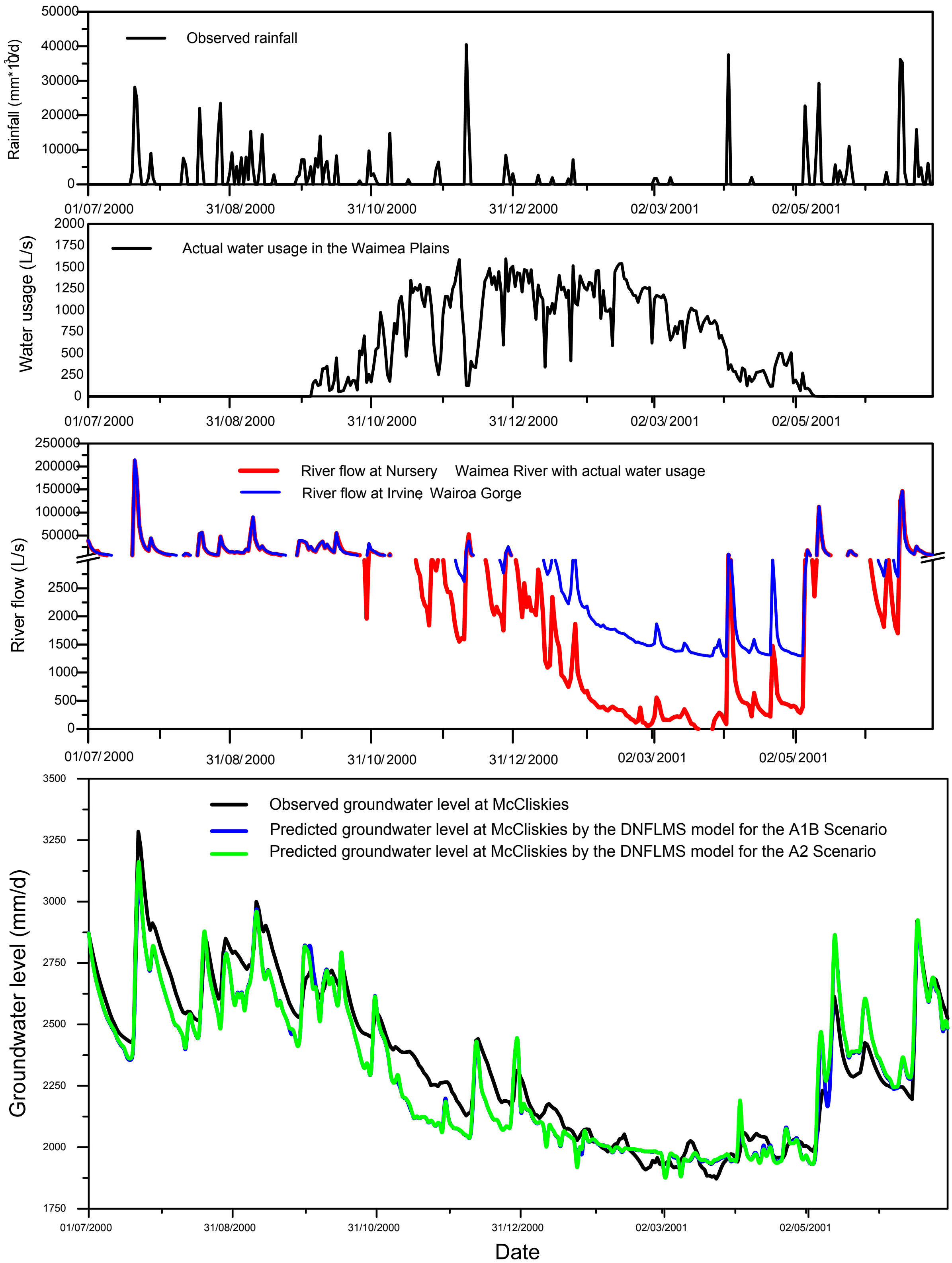


Figure 5-29: DNFLMS Model Groundwater Elevation Climate Change Predictions

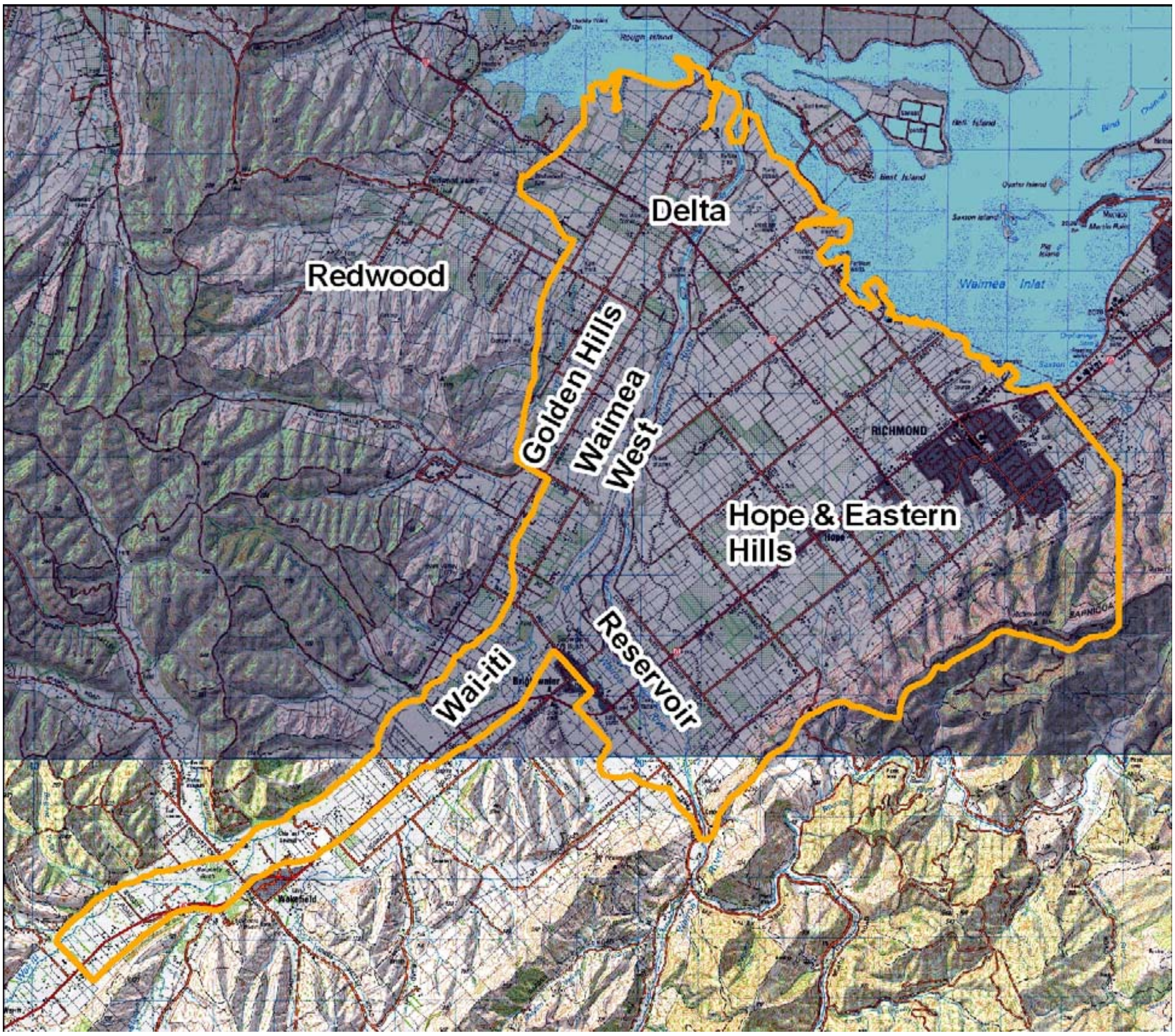


Figure 6-1: Waimea Plains with TDC water management zone boundaries indicated

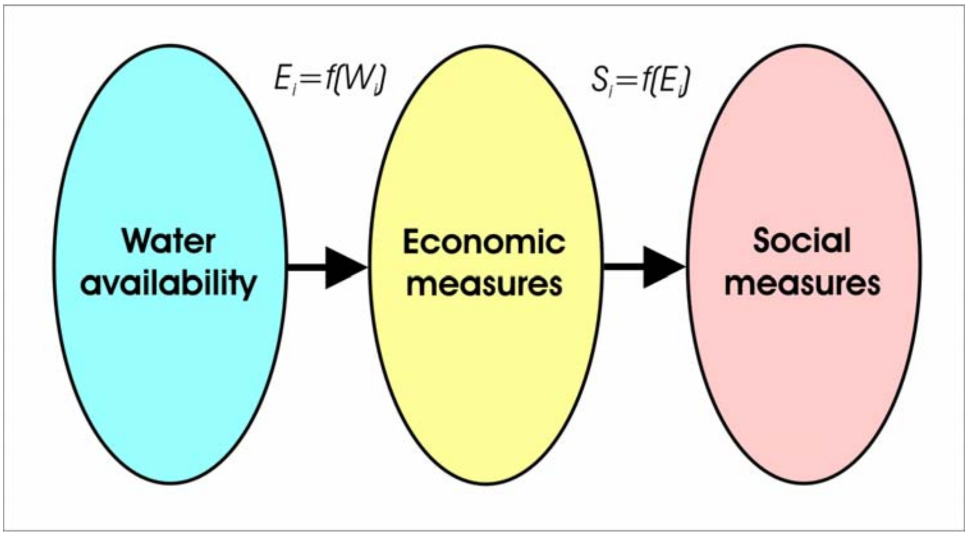


Figure 6-2: Three main elements of the socioeconomic model

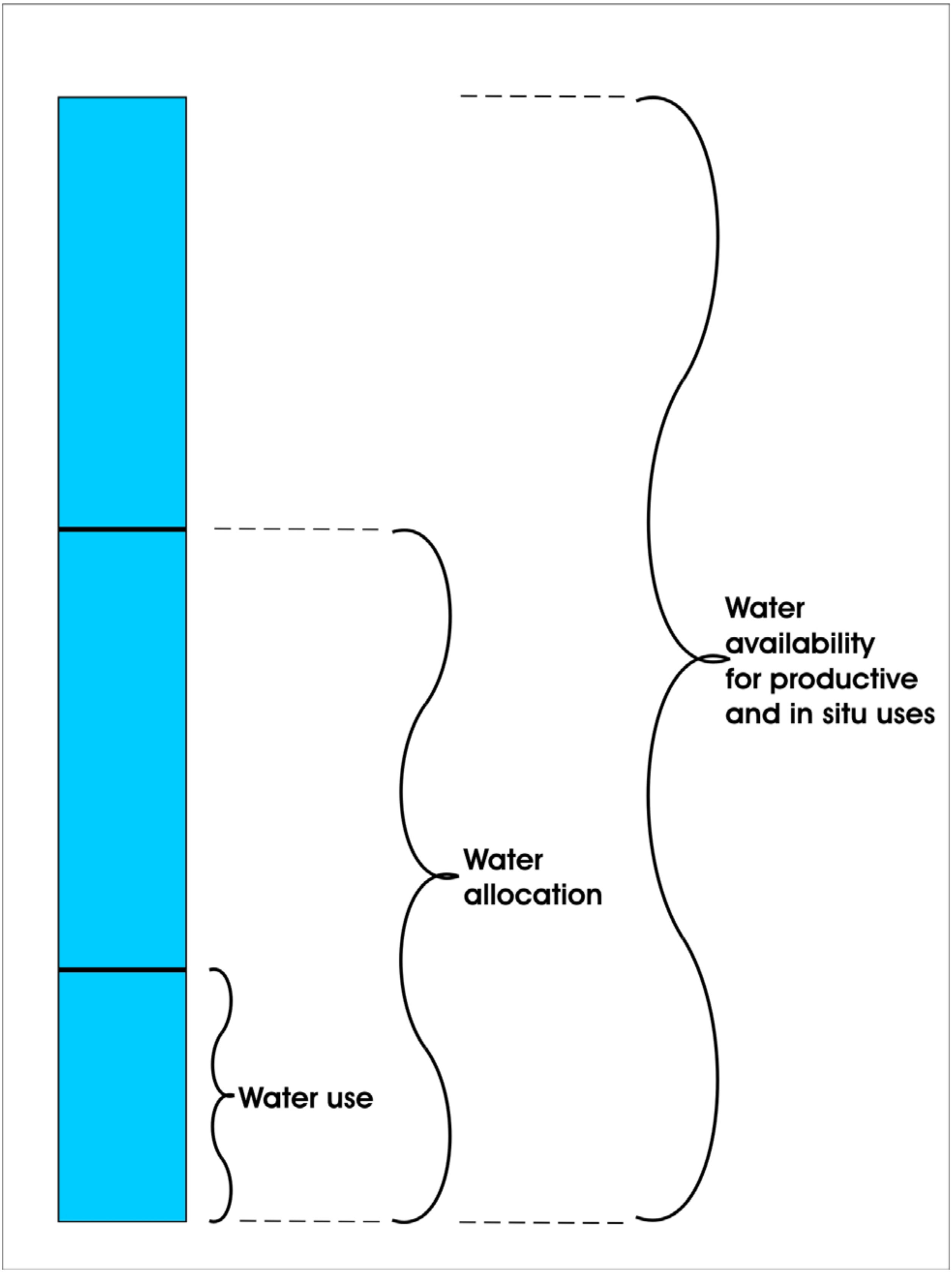


Figure 6-3: Relative nature of water use, allocation, and availability

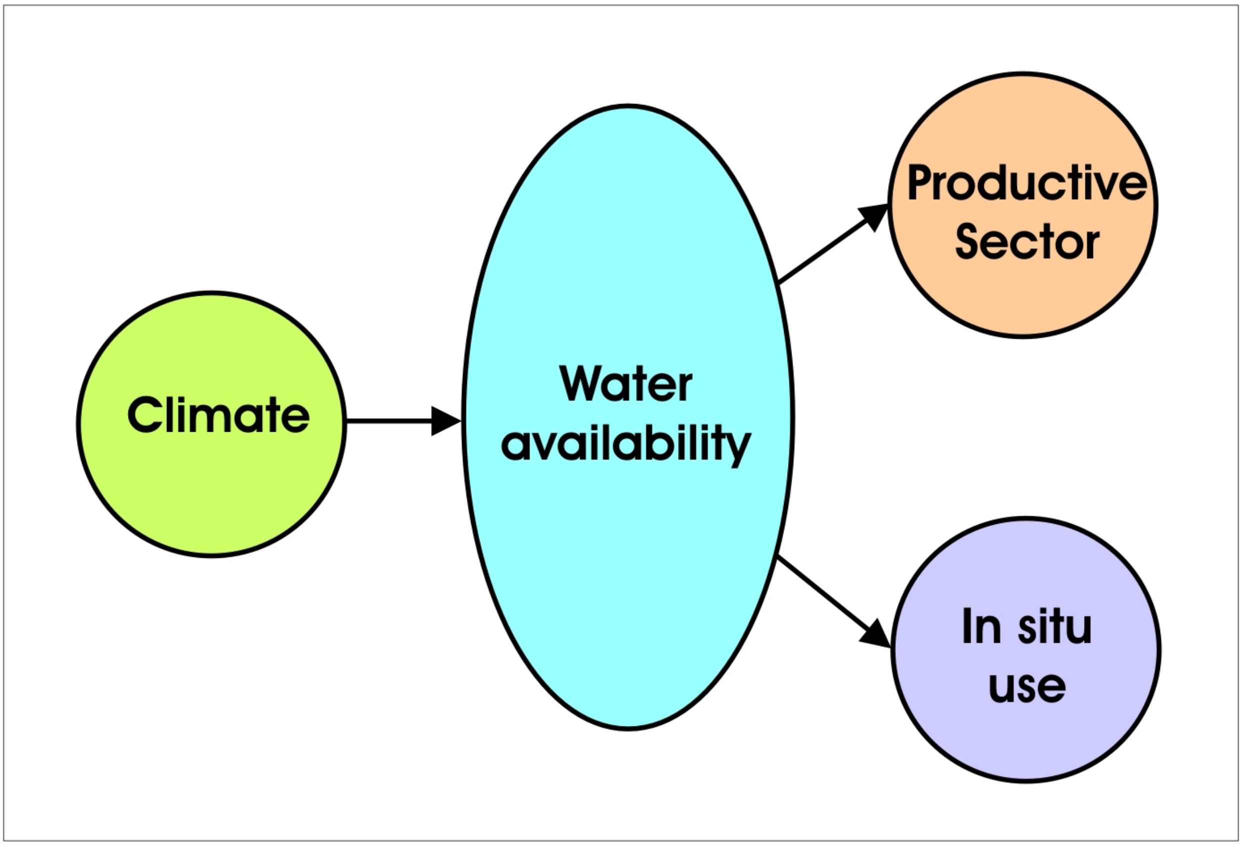


Figure 6-4: General water availability model relationships

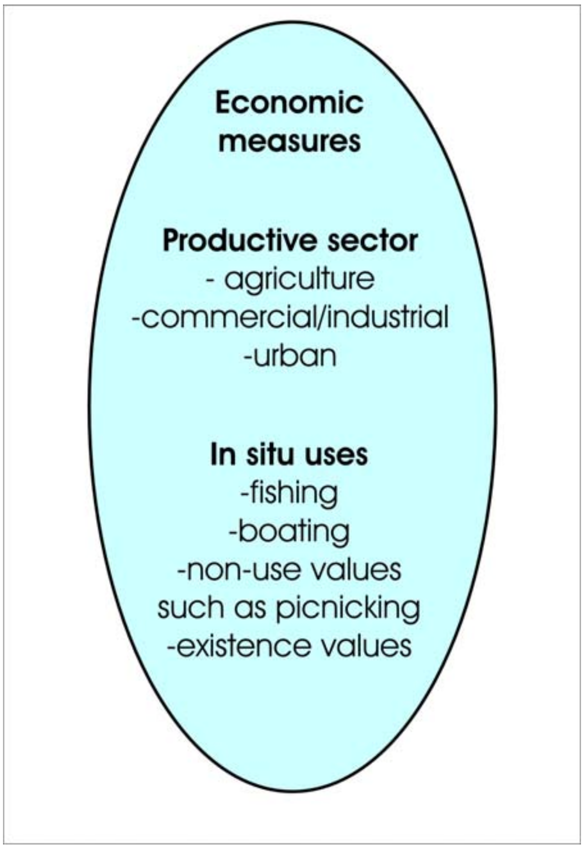


Figure 6-5: Total economic value model of the water resource

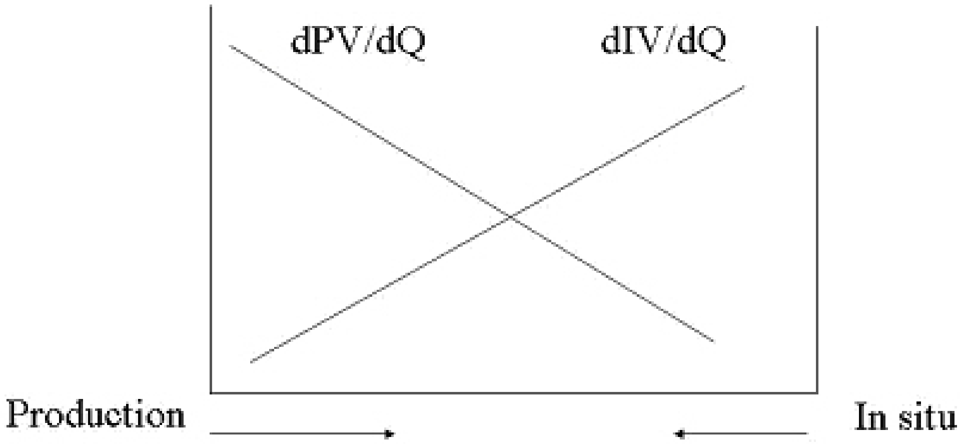


Figure 6-6: Relation between productive values (PV), in situ values (IV) (Sharp, 2000)

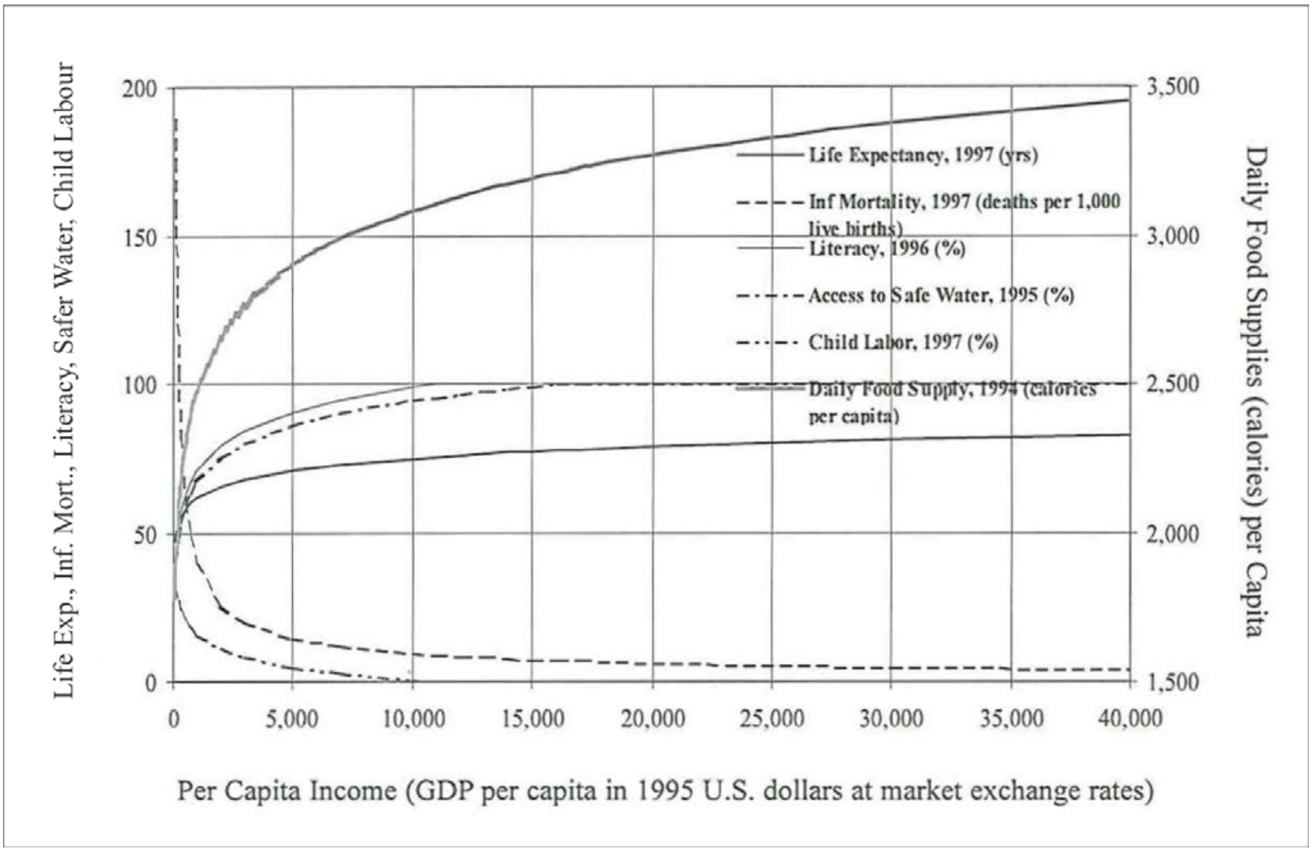


Figure 6-7: Social indicators and wealth (Goklany, 2002)

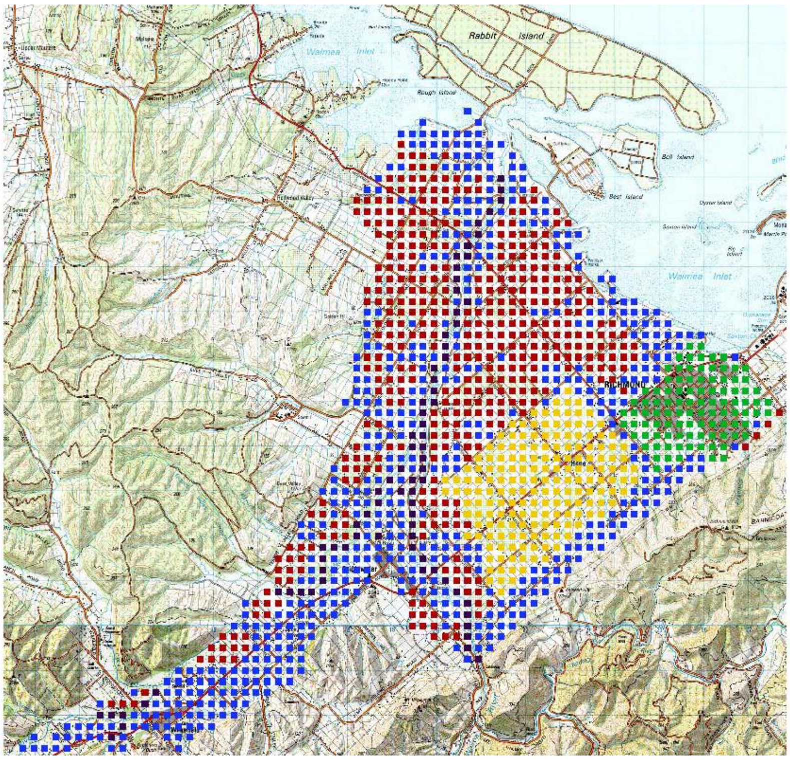


Figure 6-8: Estimated Waimea Plains land use in 2005
Red - agricultural land irrigated by groundwater
Yellow - Waimea East Irrigation Scheme (WEIS) irrigated by surface water
Green - Richmond township
Light blue - non-irrigated agricultural land
Dark blue - river beds.

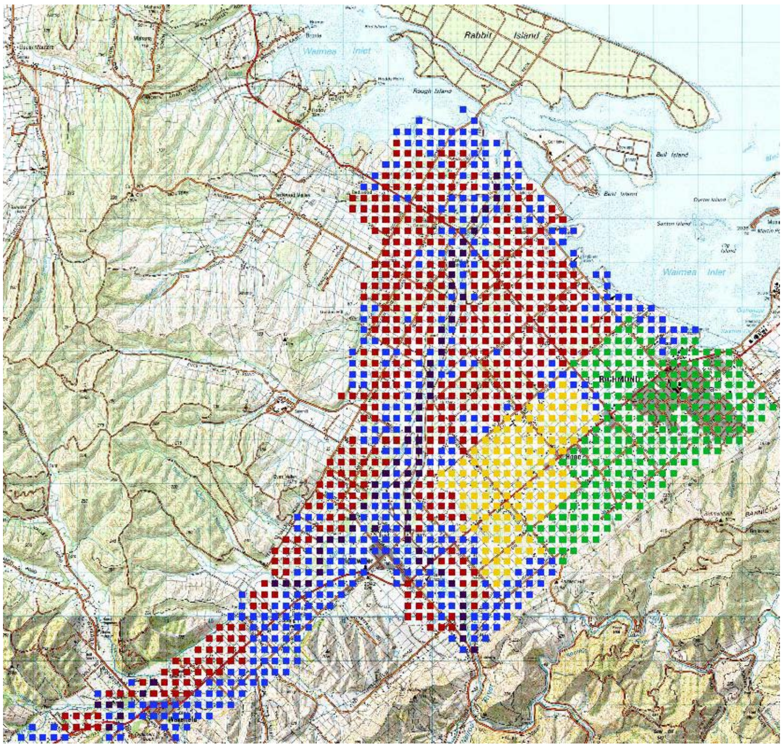


Figure 6-9: Estimated Waimea Plains land use in 2050
Color code same as for Figure 6-8

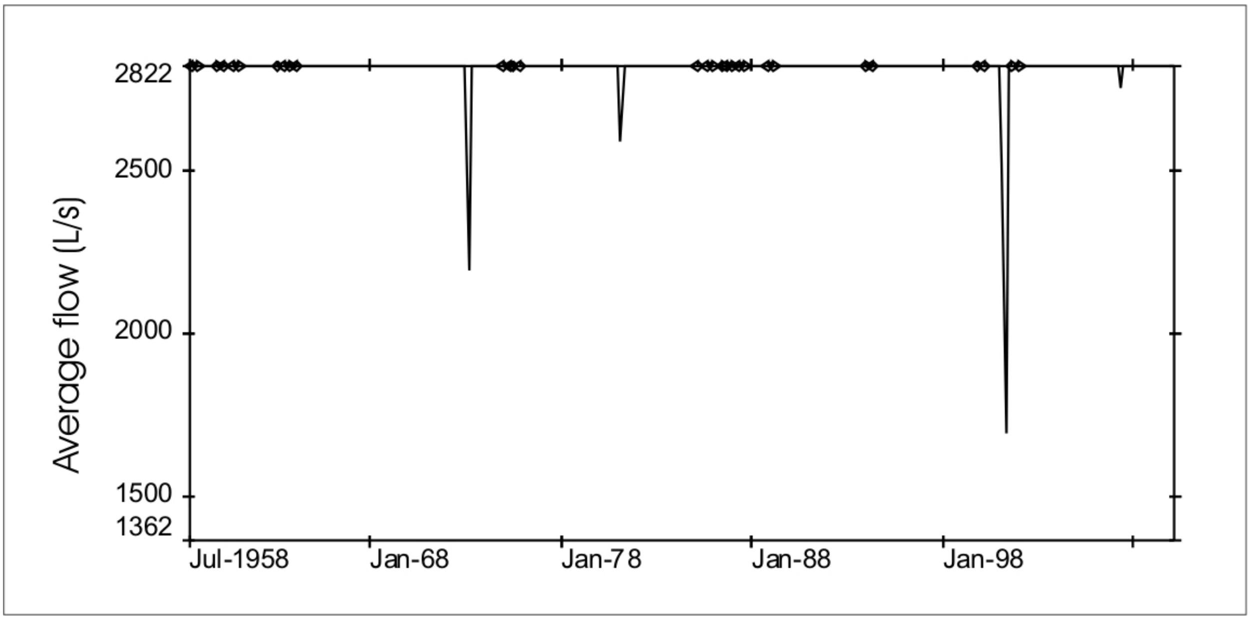


Figure 6-10: Two-Month Mean Wairoa River Flow at Irvines Less Than 2,822 L/s

TABLES

Table 2-1: Potential Impacts of Climate Change on New Zealand Water Resources[1]

Resource	Potential Impact	Present Sensitivity to Climate
Rivers	River flows likely to, on average, increase in the west and decrease in the east of New Zealand More intense precipitation events would increase flooding (by 2070 this could be from no change, up to a fourfold increase in the frequency of heavy rainfall events) Less water for irrigation in northern and eastern areas Increased problems with water quality	Strong seasonal, interannual aqnd interdacadanal fluctuations
Lakes	Lake levels likely to increase, on average, in western and central parts of New Zealand, and possibly to decrease in some eastern areas Higher temperatures and changes in rainfall, particularly in areas such as the Rotorua Lakes, could result in a range of effects, including: * Increased eutrophication * Altering of lake margin habitats by rainfall changes * Negative impacts on aquatic macrophytes * Decrease in range of trout * Increased ranges of pest species	Seasonal and interannual fluctuations
Wetlands	Coastal and inland wetlands would be adversely affected by increases in temperature, increases/decreases in rainfall, and sea level rise	Many already under threat
Groundwater	Little change to groundwater recharge is expected in eastern New Zealand, but increased demand for water is likely Some localized aquifers in northern and eastern regions could experience reduced recharge. For example, small coastal aquifers in Northland would be under threat from reduced rainfall	Seasonal fluctuations; but at present, generally stable over the longer term
Water Quality	Reduced rainfall and increased temperatures could have significant impacts on the quality of surface water resources in northern and eastern New Zealand Lower stream flows or lake levels would increase nutrient loading and lead to increased eutrophication	Most sensitive during summer months and in drier years

1. Extracted from Table 4.2 of Mullan, et al. (2008).

Table 3-1: Databases Potentially Relevant to Climate Change and Hydrologic Impacts (2010 Environmental Stocktake)[1]

No.	Database	Type of Data	Data Years[2]	Source[3]	Frequency	Stations
1	National climate database (data available via http://cliflo.niwa.co.nz)	Direct climate variables (rainfall, temperature, wind speed and direction, sunshine, radiation, pressure, cloud type/coverage, evaporation, soil moisture, etc.)	1852 (few stations and sporadic) onward	NIWA	Sub-hourly, hourly, daily, monthly	Large national network
2	Climate change routine monitoring networks	Sea level, stream flow and water quality, end of season snowline, sea surface temperature, cloud imagery, ocean physical and biological data, ocean colour, atmospheric radiance, biological diversity of streams and lakes, climate, solar radiation, and ocean waves	1860 (few stations and sporadic) onward	NIWA	Daily, monthly, or annually	Large national networks
3	River water quality aka as National Rivers Water Quality Network (NRWQN) (data available via https://secure.niwa.co.nz/wqis/index.do)	Water quality (DO, pH, conductivity, temperature, clarity and turbidity, colour, nutrients, total and E. coli bacteria started 2005, macroinvertebrates, benthic algae, BOD_5 discontinued 2002, major ions 1989 only). Streamflow data are also available for each site.	1989 onward	NIWA	Monthly	77 stations nationwide
4	Groundwater and geothermal (GGW) database including national groundwater monitoring program (NGMP) (data available via http://ggw.gns.cri.nz/ggwdata/)	Groundwater quality data (pH, conductivity, temperature, major ions, fluoride, nutrients [including ammonia and nitrate nitrogen and dissolve reactive phosphorus, and silica routinely, pesticides, Fe, Mg, trace metals, bacteria, and other variables irregularly)	1990 onward	GNS	Quarterly	110 nationwide
5	Water resources archives (data available via http://edenz.niwa.co.nz/)	River flows and river and lake levels	1905 (few stations) onward	NIWA	Quarterly or semiannually	160 stations for flow and level (plus >140 for commercial clients), 77 stations for water quality nationwide
6	Sea levels (data available via http://edenz.niwa.co.nz/)	Sea level	1971 onward, most commenced 1994	NIWA	Electronic at 1 or 5 min intervals	21 nationwide
7	Greenhouse gas (GHG) concentrations database	Greenhouse gasses (CO_2, CH_4, CO, N_2O, O_2, O_3. For the first three carbon compounds, three isotopes are measured)	1970 onward for CO_2	NIWA	Depends on gas (minutes, weekly, less frequently)	Baring Head (Wellington)
8	Soil Database	Soil analysis (pH, Olsen P, major cations, SO4, sometimes total C and organic S.	1952 onward	Ag Research Ltd	Annually	Winchmore in Canterbury and Whatawhata in Waikato
9	Surface radiation measurements	UV irradiance	1950 onward	NIWA	Daily measurements	70 nationwide
10	Snapshot of lake water quality in NZ	Lake trophic level index (N, P, algae, clarity, submerged plants)	2003-2006	MfE	One-off (may be updated)	150 nationwide
11	State and trends in river water quality	Water quality (variables in river water quality database)	1989-2007	MfE	One-off (may be updated)	77 nationwide
12	Snapshot of groundwater quality in NZ	14 year medians and trends for groundwater quality	1995-2008	MfE	One-off (may be updated)	110 NGMP wells and 819 georeferenced regional council SOE wells nationwide
13	Snapshot of water allocation in NZ		2006	MfE	One-off (may be updated)	Nationwide
14	National land use and land-use change mapping.	Spatial map of satellite data	1990, 2008	MfE	Irregular. Planned for 2012	Entire country
15	Permanent sample plot database	Data on growth and yield of planted forests	1921 onward	Scion	Quarterly	Large national network
16	Farm monitoring programme	Survey of farm units (production and status)	2000 onward	MAF	Annually	~250 operator units nationwide
17	National exotic forest description	Survey of forest plantations >40 hectares	2000 onward	MAF	Annually	All forests >1,000 ha (>40 ha biannually)
18	Land cover database	National database of land cover (LCDB-1 and 2)	1996-97 and 2001-02	Terralink Int.	Irregular. Planned for 2006-2008 satellite imagery.	Entire country
19	Agriculture production surveys/censuses	Survey of farmers and foresters	Early-1900s onward	MAF	Annually	~30,000 (~80,000 on five year intervals)
20	EcoSat	Satellite imagery of basic land cover	2004 (one off)	Landcare	One-off	Entire country
21	Soil and Land Management Database	Soil type and order, land use, and management history	Data collected 2002-2006	Plant and Food Research	Ad-hoc	>800 stations nationwide

No.	Database	Type of Data	Data Years[2]	Source[3]	Frequency	Stations
22	River environment classification	Ecosystem-based spatial framework for river management	2004 (one off)	NIWA	One-off	All rivers nationwide
23	Freshwater organisms	Temporal and spatial variability of freshwater biota (including algae, macrophytes, invertebrates, and fish)	1960s onward	NIWA		
24	BioWeb assets project	Records of species observations	1800s (limited) onward	DOC	Ongoing	Entire country
25	Biodiversity data inventory	Integrated biodiversity database including threatened species (compilation of all available biodiversity data)	2007 onward	DOC	Ongoing	Entire country
26	NZ freshwater fish database	Geospatial freshwater fish database	1960s onward	NIWA	Variable	Entire country
27	Aqautic plants database	Geospatial aquatic plant species database	1978 onward	NIWA	Updated continuallly	113 lakes and 988 water bodies nationwide
28	National vegetation survey databank	Geospatial national vegetation database	1950s onward	Landcare	Ad hoc	~77,000 vegetation survey plots
29	Plant - Allan herbarium collection database	Geospatial flora database	1928 onward	Landcare	Ad hoc	Collection with nationwide coverage
30	NZ fungi herbarium	Geospatial fungi database	1940s onward	Landcare	Ad hoc	Collection with nationwide coverage
31	NZ arthropod collection	Geospatial terrestrial invertebrate database	1920 onward	Landcare	Ad hoc	Collection with nationwide coverage
32	National nematode collection of NZ	Geospatial nematode database	1904 onward	Landcare	Ad hoc	Collection with nationwide coverage
33	International collection of microorganisms from plants	Geospatial database of NZ microoranisms	Ad hoc	Landcare	Ad hoc	Collection with nationwide coverage

1. *Statistics New Zealand. 2010. Stocktake for the environment domain plan: 2010. Statistics New Zealand, Wellington, 161 pages. Highlighting: (1) None - Active hydrologic databases; (2) Blue - Snapshots; (3) Yellow - Land use; and (4) Green - Biological diversity.*
2. *Data years beginning with first available data. Initial stations may be a very limited portion of stations for which there are later data.*
3. *Sources:*
    a. *MfE - Ministry for the Environment*
    b. *NIWA - National Institute for Water and Atmospheric Research*
    c. *GNS - Institute of Geological and Nuclear Sciences Ltd.*
    d. *MAF - Ministry of Agriculture and Forestry*
    e. *DOC - Department of Conservation*
    f. *Landcare - Landcare Research*

Table 3-2a: Regional Council Hydrologically-Related Databases (Related Information)[1]

	#	Name	Type[2]	Climate Change Policy	Land Use Info[3]	Meter/Reporting of Water Use		Initial Data[4]
North Island								
	1	Auckland	RC	No.	LCDB 1 & 2, NZLRI, and Agribase. ARC also holds a range of other land use and built environment information (e.g., from consents).	Required for all consents.	Yes	-
	2	Bay of Plenty	RC	No.	LCDB 1 & 2, AgriBase, land use for Lake Rotorua catchment from 2003 aerial photography and some other areas (e.g., Whakatane).	No.	No	Late-1980s.
	3	Gisborne	DC	No.	LCDB 1 & 2, aerial photos	Required for all consents.[5]	Yes	-
	4	Hawke's Bay	RC	No.	LCDB 1 & 2, direct field surveys by students on 5 year cycle, info from other Council databases.	Required for all new consents >2,500 m^3/week.[6]	Partial	~20 years ago for SW and 15 for GW. Current program state for about 5 years.
	5	Manawatu-Wanganui	RC	Horizons adopted practices with regard to issuance of SW consents.	Horizon's Landuse/Landuse Capability Layer (Clark and Roygard, 2008) synthesized from Agribase, LCDB 2, and Horizon's dairy discharge consents.	Required for all consents. Telemetry required for most significant consents.	Yes	-
	6	Northland	RC	No.	LCDB 1 & 2 and onlilne aerial photography (Koordinates.com).	Required for GW consents >200 m^3/day. SW on case-by-case basis.	Partial	-
	7	Taranaki	RC	Yes. Climate change is considered in Section 6.2 of proposed Regional Policy Statement of Feb 09.	LCDB 1 & 2 and aerial photo coverage (re-shot every 5 years). Also, old land use capability classification system on 1:10,000 maps. TRC commissions Landcare Research to random check database every 5 years.	Required for all consents.	Yes	-
	8	Waikato	RC	Policy to limit consents to 15 years because of climate change uncertainty.	LCDB 1 & 2, AgriBase, aerial photographs, and limited ground truthing.	Required for all consents >15 m^3/day.	Partial	Typically mid-1980s except Waikato R. since late-1930s.
	9	Wellington	RC	No.	LCDB 1 & 2, AgriBase	Metering required. Reporting required only for "large" consents. Data stored in consent files and not readily available in a database.	Partial	-
	Total North Island						4	
South Island								
	10	Canterbury	RC	Policy document on website.	LCDB 1 & 2 and AgriBase.	Generally none. New program being implemented.[8]	Starting	-
	11	Marlborough	DC	No.	LCDB 1 & 2. Staff makes some field checks (primarily of vitaculture).	Required on about 87% of current consents. Current reporting response rate is poor.	Partial	Rainfall-1905, SW flow-1960s, SW WQ-1998 (SW long-term monitoring site adjustments made for consistency in 2005), GW WL-late-1970s/early-1980s, GW WQ-1987
	12	Nelson	CC	No.	LCDB 1 & 2	Required on some new consents. Normally ask for reporting of monthly summaries.	Partial	-
	13	Otago	RC	No.	LCDB 1 & 2, REC (landcover), and limited staff observations.	Required for all consents with annual reporting.	Yes	-
	14	Southland	RC	Considering potential for sea level rise of 35 cm by 2050 and change in rainfall distribution.	LCDB 1 & 2	Required on most consents with variable reporting provisions. Areas under pressure required to report via daily telemetry. Dairy monitor monthly, report annually.	Partial	SW flow started late-1070s, SW WQ late-1990s, GW after 2000.
	15	Tasman	DC	NIWA study in progress. Consider-ing in water supply modelling.	LCDB 1 & 2 and soil maps.	Required in some designated water zones (e.g., Waimea) with reporting in summer only.	Partial	-
	16	West Coast	RC	No	LCDB 1 & 2	No.	No	-
	Total South Island						1	

1. Compiled from interviews of regional/district/city council environmental staff September-November 2009.
2. "Type" council means regional council (RC) or district council (DC) and city council (CC) with unitary governmental functions.
3. "LCDB" means land cover database. LCDB 1 and 2 were based on satellite imagery from 1996/1997 and 2001/2002, respectively. An update based on 2006-2008 satellite imagery is in progress as LCDB 3.
4. "Initial Data" indicates start of climate and "SW" (surface water) or "GW" (groundwater) databases for various councils. Some data may be archived from catchment boards that preceded councils; however, most council hydrologic data-bases date from the late-1980s or early-1990s when councils were established under the Resource Management Act. In general, the scope of environmental monitoring programs has increased and protocols improved since inception. In some cases there are substantial gaps in the record. For example, the there are no data for most of the 1999-2002 period in the Environment Bay of Plenty programs groundwater level and quality monitoring database.
5. Report biweekly for GW, monthly for SW (Oct-Apr).
6. Generally record weekly, report monthly.
7. Required for all takes >750 m3/day or where sum of all SW takes >15% of mean annual low flow (MALF).
8. None for most of existing 7,000 - 8,000 SW and GW consents. Recently required metering in ~100 mostly SW consents, but generally only reporting when requested. Recentaly called in ~660 GW consents for one zone to be reissued with hourly metering and annual reporting required.

SW- NIWA and most regional programs monitor flow and stream water levels continuously using automatic equipment (transducers and data loggers, some with telemetry) and take monthly water quality samples.
GW- NGMP and most regional programs monitor water levels and sample quarterly. Some sample annually. Many regional programs also have transducers and data loggers regarding water levels at 15' intervals.
Biological monitoring - Macroinvertebrates and microbiology.
Metering - At discretion of regional programs. MfEhas proposed a NES to require metering of actual water use by consents.
15 and 5 minutes auto monitoring gages (rainfall and/or streamflow and/or GW level).

Table 3-2b: Regional Council Hydrologically-Related Databases (Number of Surface Water Gages/Stations)[1]

#	Name	Type[2]	Council[3] Stream Flow Survey	Council[3] Stream Flow From ECAN	Council[3] Stream WL	Council[3] Lake WL	Council[3] Sea Level	Council[3] Spring Flow	Council[3] WQ	Council[3] Major Ions	NIWA Flow	NIWA WQ
North Island												
1	Auckland	RC	32.	38.	-	0.	0.	0.	32.	No	4.	2.
2	Bay of Plenty[4]	RC	33.	19.	22.	12.	9.	0.	14.	No	7.	6.
3	Gisborne	DC	5.	39.	10.	0.	0.	0.	13.	Yes	5.	3.
4	Hawke's Bay[5]	RC	32.	47.	21.	0.	0.	0.	69.	Partial	9.	6.
5	Manawatu-Wanganui[6]	RC	58.	63.	60.	0.	0.	0.	65.	Yes	18.	7.
6	Northland	RC	36.	33.	-	0.	0.	0.	30.	No	6.	4.
7	Taranaki[7]	RC	16.	18.	4.	0.	0.	0.	11.	No	7.	3.
8	Waikato[8]	RC	44.	46.	12.	2.	5.	0.	110.	Infrequently	12.	8.
9	Wellington	RC	49.	40.	1.	0.	0.	0.	56.	No	7.	5.
Total North Island		-	305.	343.	130.	14.	14.	0.	400.	4.	75.	44.
South Island												
10	Canterbury[9]	RC	89.	87.	111.	0.	0.	0.	135.	No	8.	10.
11	Marlborough	DC	17.	18.	19.	0.	0.	5.	23.	No	6.	2.
12	Nelson	CC	8.	Not Reported	0.	0.	0.	0.	27.	Yes	0.	0.
13	Otago[10]	RC	35.	48.	9.	1.	0.	0.	53.	No	14.	8.
14	Southland[11]	RC	22.	21.	46.	0.	0.	0.	71.	No	1.	6.
15	Tasman	DC	36.	37.	2.	0.	2.	2.	36.	No	5.	3.
16	West Coast[12]	RC	3.	12.	1.	1.	0.	0.	37.	No	21.	4.
Total South Island		-	210.	223.	188.	2.	2.	7.	382.	1.	55.	33.
Total New Zealand		-	515.	566.	318.	16.	16.	7.	782.	5.	130.	77.

1. *Compiled from interviews of regional/district/city council environmental staff September-November 2009.*
2. *"Type" council means regional council (RC) or district council (DC) and city council (CC) with unitary governmental functions.*
3. *From "Survey" means performed by GNS. "From ECAN" means provided by Leftly (2009). "WL" indicates water level only (i.e., there is no rating curve to cross over stream stage to flow). "WQ" indicates water quality sampling. Major ions were only measured by the NIWA program for the initial year (1989). Most councils follow the NIWA lead on this. However, a few include analysis for major ions or other analytes. Those are indicated by light yellow highlighting.*
4. *These SW sites are sampled monthly. Additionally 36 SW sites sampled monthly every third year. Some field variables monitored in lakes (e.g., temperature, dissolved oxygen, and turbidity.*
5. *Hawke's Bay Regional Council analyses surface water samples for a partial list of major ions (i.e., alkalinity, calcium, and magnesium).*
6. *In addition to streamflow, NIWA has 18 SW stream stage (WL) sites. In addition to routine State of the Environment (SOE) monitoring, Manawatu-Wanganui Regional Council receives SW quality data from 36 instream discharge monitoring sites.*
7. *These are continuously logged flow gaging sites. Two of the flow gaging sites are shared with NIWA but the regional council has separate sensors, dataloggers, and rating curves. There are some additional flow gaging sites that are not continuously logged and 12 sites where SW temperature is received via telemetry (plus another 10 manually downloaded).*
8. *Arsenic, boron, and lithium are monitored in samples from Waikato River stations. Major ions are analysed for at 110 surface water sites once every five years.*
9. *Regional council also monitors 18 high country and 6 coastal lakes.*
10. *WQ sites vary. 53 were monitored in 2009.*
11. *Additionally, at 11 stream stations temperature is measured, at five stream conductivity is measured, and at two stream dissolved oxygen is measured. There is on lake WQ station. On the coast there are four WL and 13 WQ stations.*
12. *SW quality is generally monitored summer, autumn, and winter and primarily for nutrients. Lake Brunner is the only lake monitored. Samples are taken at four stations within the lake, in six tributary streams flowing into it, and at its outlet quarterly.*

Table 3-2c: Regional Council Hydrologically-Related Databases (Climate, Groundwater, and Soil Moisture)

#	Name	Type[2]	Climate[3]			GW[3]			Soil Moisture	GW Recharge Lysimeter[5]
			Rainfall		Met					
			Survey	From ECAN		WL	WQ	NGMP[4]		
North Island										
1	Auckland	RC	36.	44.	18.	83.	24.	6.	2.	0.
2	Bay of Plenty (EBOP)	RC	57.	32.	8.	77.	62.	4.	0.	2.
3	Gisborne	DC	34.	48.	5.	90.	75.	6.	0.	0.
4	Hawke's Bay[6]	RC	62.	78.	8.	73.	35.	8.	6.	0.
5	Manawatu-Wanganui[7]	RC	52.	62.	16.	153.	28.	3.	10.	0.
6	Northland	RC	80.	30.	1.	82.	29.	7.	0.	0.
7	Taranaki	RC	25.	25.	5.	10.	0.	5.	8.	0.
8	Waikato[9]	RC	24.	24.	6.	150.	110.	10.	8.	0.
9	Wellington	RC	50.	50.	8.	147.	71.	15.	7.	0.
Total North Island			420.	393.	75.	865.	434.	64.	41.	2.
South Island										
10	Canterbury	RC	72.	71.	2.	505.	460.	6.	0.	5.
11	Marlborough[10]	DC	19.	24.	3.	31.	15.	8.	0.	0.
12	Nelson[11]	CC	9.	Not Reported	3.	0.	0.	0.	0.	0.
13	Otago[12]	RC	45.	24.	3.	148.	69.	7.	3.	0.
14	Southland[13]	RC	26.	26.	-	126.	36.	7.	10.	0.
15	Tasman	DC	45.	45.	2.	37.	6.	10.	0.	0.
16	West Coast	RC	11.	19.	0.	28.	0.	8.	0.	0.
Total South Island			227.	209.	13.	875.	586.	46.	13.	5.
Total New Zealand			647.	602.	88.	1,740.	1,020.	110.	54.	7.

1. *Compiled from interviews of regional/district/city council environmental staff September-November 2009.*
2. *"Type" council means regional council (RC) or district council (DC) and city council (CC) with unitary governmental functions.*
3. *From "Survey" means performed by GNS. "From ECAN" means provided by Leftly (2009). "Met" means station at which other meteorologic variables in addition to rainfall are monitored (e.g., wind direction and speed). "GW" means groundwater, "WL" means groundwater level, "WQ" means samples taken for water quality, and "NGMP" means National Groundwater Monitoring Programme (NGMP).*
4. *Active status NGMP wells as of June 2010. Four wells were taken out of service during the 2009-2010 fiscal year (two in EBOP, one in Horizon's, and one in Taranaki) and three replacements put into service (one each in Northland, Southland, and Tasman). In addition to 110 active wells, there are 80 inactive wells for which there are some data availble, and one NGMP well at Kaitoke sampled only for tritium. GNS also has 819 georeferenced State of the Environment (SOE) wells identified by Regional Councils in its GGW database.*
5. *"GW Recharge Lysimeter" means specially designed and installed soil columns for direct sampling of groundwater recharge. Work is in progress to install two additoinal co-located lysimeters in the Bay of Plenty Region.*
6. *Hawkes Bay Regional Council (HBRC) has access to a total of 154 open and 101 closed raingages. Of the open ones, data from 59 are telemetered daily to the HBRC offices. Climate stations normally monitor rainfall, soil temperature and moisture, humidity, air temperature, and wind speed and direction. At two stations potentiao evapotranspiration solar radiation are also monitored. HBRC has access to data from 23 open climate stations and manages eight of which it fully owns four.*
7. *Otherwise known as Horizons. WL in 13 wells measured automatically at 15 minute intervals. For 140 wells it is measured manually on a monthly basis.*
8. *There are 31 automatic rain gages in this network. In addition, Met Service operates eight Met stations in the Northland region and NIWA operates two. The Northland region also has an unofficial station at Dargaville.*
9. *Environment Waikato currently has 150 wells in this network, but no core State of the Environment network. The total number and actual locations used in a given year may vary.*
10. *All SOE and NGMP wells are sampled quarterly. Additionally, 14 wells are sampled each spring for bacteria (feacal coliforms and E. Coli.), five of seven coastal sentinel wells are sampled each summer (one is sampled for bacteria earlier and another is an NGMP well).*
11. *Only two of the three Met stations also include rainfall.*
12. *There are three evapotranspiration sites and three new shallow coastal wells for measuring WL sites in south Dunedin to monitor GW response to sea sea level changes.*
13. *At some GW WQ sites samples are also analysed for organo-nitrates and arsenic. At five sites GW WL, rainfall, and soil moisture are all measured. At an additional 14 wells, groundwater is sampled for nitrate only and at an additional five locations soil temperature is monitored. is monitored.*

Table 4-1: Waimea Plains Climate and Hydrology Monitoring Sites[1,2]

Source	Station Name	Aquifer	Station	Well ID	Type	Period In Service		NZMG	
						From	To	Easting	Northing
NIWA	Nelson aero	-	4241	-	Climate	1941	2010	2528914	5989728
NIWA	Appleby 2 EWS	-	21937	-	Climate	2001	2010	2517926	5987719
NIWA	Nelson AWS	-	4271	-	Climate	1981	2010	2528327	5989396
NIWA	TDC Nursery-Chipmill	-	Simulation	-	T and Rain	1972	2116	2520452	5986857
NIWA	Redwood	-	Simulation	-	T and Rain	1972	2116	2516541	5989419
NIWA	Livingston Road	-	Simulation	-	T and Rain	1972	2116	2518800	5983000
NIWA	Irvines	-	Simulation	-	T and Rain	1972	2116	2520970	5978200
TDC	Belgrove (Wai-iti R.)	-	157517	-	Rain	1993	2010	2506500	5972600
TDC	TDC Nursery (Waimea R.)	-	157523	-	Rain	2006	2010	2520573	5983289
TDC	Irvines (Wairoa R.)	-	157521	-	Rain	1993	2010	2521600	5978200
TDC	TDC Richmond Office	-	-	-	Rain	1995	2010	2525602	5984983
TDC	Birds	-	134036	-	Rain	1982	2010	2515842	5975974
TDC	Little Ben		134001	-	Rain	1983	2010	2517800	5971100
TDC	Trig F		134236	-	Rain	1990	2010	2525700	5970000
TDC	Belgrove (Wai-iti R.)	-	57517	-	SW flow	1987	2010	2506500	5972600
TDC	Livingston (Wai-iti R.)	-	57520	-	SW flow	1987	2010	2518800	5983000
TDC	Irvines (Wairoa R.)	-	57521	-	SW flow	1993	2010	2521600	5978200
TDC	TDC Nursery (Waimea R.)	-	57523	-	SW flow	2005	2010	2520573	5988085
TDC	Livingston (Wai-iti R.)	-	57520	-	SW quality	1999	2010	2518800	5983000
TDC	Irvines (Wairoa R.)	-	57521	-	SW quality	1999	2010	2520958	5978179
TDC	Appleby (Waimea R.)	-	-	-	SW quality	2000	2010	2520873	5988556
TDC	Pigeon valley road (Wai-iti R.)	-	-	-	SW quality	2000	2005	2513350	5978026
GNS	Near Buschls 2 (Waimea)	UCA	WWD37	37	GW quality	1990	2010	2521850	5984980
GNS	Near Chipmill (Waimea)	LCA	WWD32	32	GW quality	1990	2010	2523760	5987240
GNS	Near TDC Nursery (Waimea)	AGUA	WWD802	802	GW quality	1996	2010	2521250	5988160
TDC	Redwood Lane[3]	Deep	1330108	RL	GW level	2002	2010	2516541	5989419
TDC	Simpson (Wai-iti R.)	AGUA	1330127	SIMP	GW level	2001	2010	2517861	5982024
TDC	MacKenzie (Wai-iti R.)	AGUA	1330128	MACK	GW level	2001	2010	2517213	5981376
TDC	Ferguson (Wai-iti R.)	AGUA	1330129	FERG	GW level	2001	2010	2516666	5980960
TDC	McCliskies (Waimea)	AGUA	1331069	MCC	GW level	1998	2010	2520398	5989229
TDC	CW2 (Waimea)	AGUA	1331098	CW2	GW level	1975	2010	2519500	5987800
TDC	Rail Reserve (Waimea)[4]	AGUA-UCA	1331105	RR	GW level	1975	2010	2519800	5981600
TDC	Chipmill (Waimea)	LCA	1331119	CHIP	GW level	1977	2010	2524300	5987200
TDC	Buschls 2 (Waimea)	AGUA	1331238	BUSC	GW level	1996	2010	2521400	5983800

1. *Data provided by National Institute for Water and Atmospheric Research (NIWA), Institute of Geological and Nuclear Science (GNS), and Tasman District Council (TDC).*
2. *With the exception of surface water quality, beginning year for data is for first full year of monitoring. Coordinates as New Zealand Map Grid (NZMG). "Type" of data as indicated. "T and Rain" means daily minimum and maximum temperatures and daily rain. "Simulation" means climate change simulation results including historic data for 1972-2009 and model results for A1B and A2 climate change emission scenarios for the 2030-2066 and 2080-2116 periods.*
3. *This well has a screen depth of 60 to 500 m and penetrates deep confined Moutere gravels.*
4. *This well is in a stream recharge transition zone to both the AGUA and UCA.*

Table 4-2: Waimea Plains Former Climate and Hydrology Monitoring Sites[1,2]

Source	Station Name	Station ID	Type	Period In Service		Coordinates	
				From	To	Long	Lat
NIWA	Moutere hill	4260	Climate	1960	1986	173.075	-41.359
NIWA	Appleby	4239	Climate	1932	1996	173.099	-41.293
NIWA	Appleby EWS	12755	Climate	1996	2000	173.099	-41.293
NIWA	Nelson waterworks	4278	Climate	1907	1915	173.300	-41.300
NIWA	Wairoa gorge #3	4294	Climate	1967	1981	173.087	-41.459
NIWA	Wairoa gorge	4290	Climate	1948	1961	173.083	-41.483
NIWA	Nelson	4244	Climate	1989	1951	173.295	-41.275
NIWA	Nelson atawai	4246	Climate	1932	1944	173.333	-41.233
						NZMG	
						Easting	Northing
GNS	-	WWD508	GW quality	1998	1998	2518130	5983180
GNS	-	WWD285	GW quality	1998	1998	2519740	5989610
GNS	-	WWD59	GW quality	1998	1999	2522010	5988220
GNS	-	WWD524	GW quality	1998	1998	2521570	5987420
TDC	Mapua Wharf	57300	Sea level	1986	1994	2518400	5994400
TDC	Shags Roost	57500	Sea level	1981	1999	2525600	5989900

1. *Data provided by National Institute for Water and Atmospheric Research (NIWA), Institute of Geological and Nuclear Science (GNS), and Tasman District Council (TDC).*
2. *With the exception of surface water quality, beginning year for data is for first full year of monitoring.*

Table 4-3: Temperature Trend Analysis Summary[1]

Station Site	Station ID	Emission Scenario	Data Date Range	# Data Points	Missing Data Years	Median (°C)	Trend	Sen's Slope (°C/year)	P Value	Data Source	Temp Used[2]
TDC Nursery-Chipmill Simulation Results	20301	Historic	1972-2008	37	-	12.63	DECR	-0.00180	0.72	NIWA	Mean
			1972-2008	37	-	7.53	DECR	-0.01870	0.02	NIWA	Min
			1972-2008	37	-	17.75	INCR	0.01520	0.03	NIWA	Max
		A1B	2030-2066	37	-	13.84	DECR	-0.00220	0.72	NIWA	Mean
			2080-2116	37	-	14.75	DECR	-0.00200	0.70	NIWA	Mean
			1972-2116	111	-	13.84	INCR	0.01809	0.00	NIWA	Mean
			2030-2066	37	-	8.70	DECR	-0.01820	0.02	NIWA	Min
			2080-2116	37	-	9.61	DECR	-0.01840	0.01	NIWA	Min
			1972-2116	111	-	8.71	INCR	0.01630	0.00	NIWA	Min
			2030-2066	37	-	18.94	INCR	0.01510	0.03	NIWA	Max
			2080-2116	37	-	19.84	INCR	0.01520	0.03	NIWA	Max
			1972-2116	111	-	18.85	INCR	0.01906	0.00	NIWA	Max
		A2	2030-2066	37	-	13.90	DECR	-0.00220	0.74	NIWA	Mean
			2080-2116	37	-	14.96	DECR	-0.00200	0.70	NIWA	Mean
			1972-2016	111	-	13.90	INCR	0.01980	0.00	NIWA	Mean
Irvines Simulation Results	20302	Historic	1972-2008	37	-	12.52	DECR	-0.00180	0.74	NIWA	Mean
		A1B	2030-2066	37	-	13.71	DECR	-0.00230	0.74	NIWA	Mean
			2080-2116	37	-	14.60	DECR	-0.00170	0.76	NIWA	Mean
			1972-2116	111	-	13.67	INCR	0.01780	0.00	NIWA	Mean
		A2	2030-2066	37	-	13.76	DECR	-0.00230	0.76	NIWA	Mean
			2080-2116	37	-	14.80	DECR	-0.00170	0.76	NIWA	Mean
			1972-2116	111	-	13.76	INCR	0.01950	0.00	NIWA	Mean
Livingston Simulation Results	20303	Historic	1972-2008	37	-	11.98	INCR	0.00390	0.56	NIWA	Mean
		A1B	2030-2066	37	-	13.16	INCR	0.00330	0.52	NIWA	Mean
			2080-2116	37	-	14.08	INCR	0.00410	0.54	NIWA	Mean
			1972-2116	111	-	13.14	INCR	0.01830	0.00	NIWA	Mean
		A2	2030-2066	37	-	13.20	INCR	0.00330	0.52	NIWA	Mean
			2080-2116	37	-	14.26	INCR	0.00400	0.52	NIWA	Mean
			1972-2116	111	-	13.20	INCR	0.02010	0.00	NIWA	Mean
Redwood Simulation Results	20275	Historic	1972-2008	37	-	12.52	DECR	-0.00530	0.29	NIWA	Mean
		A1B	2030-2066	37	-	13.73	DECR	-0.00450	0.38	NIWA	Mean
			2080-2116	37	-	14.62	DECR	-0.00480	0.34	NIWA	Mean
			1972-2116	111	-	13.69	INCR	0.01760	0.00	NIWA	Mean
		A2	2030-2066	37	-	13.78	DECR	-0.00450	0.38	NIWA	Mean
			2080-2116	37	-	14.82	DECR	-0.00480	0.34	NIWA	Mean
			1972-2116	111	-	13.76	INCR	0.01920	0.00	NIWA	Mean
Nelson Aero	4241	Historic	1944-2009	63	3	12.30	INCR	0.02000	0.00	NIWA	Mean
Nelson AWS	4271	Historic	1994-2009	16	0	13.10	INCR	0.03000	0.28	NIWA	Mean
Nelson AWS	4271	Historic	1994-2009	16	0	17.80	INCR	0.05000	0.36	NIWA	Max
Nelson AWS	4271	Historic	1994-2009	16	0	8.50	DECR	-0.03000	0.55	NIWA	Min
Appleby 2 EWS	21937	Historic	2002-2009	8	0	12.15	INCR	0.12000	0.02	NIWA	Mean
Appleby 2 EWS	21937	Historic	2002-2009	8	0	18.15	INCR	0.10000	0.11	NIWA	Max
Appleby 2 EWS	21937	Historic	2002-2009	8	0	6.15	INCR	0.16000	0.00	NIWA	Min
Nelson 7 Station Series	-	Historic	1863-1880	18	0	12.30	INCR	0.02560	0.19	NIWA	Mean
			1908-2008	101	0	12.56	INCR	0.00920	0.00	NIWA	Mean

1. *NIWA simulation results provided by Schmidt (2010). NIWA historic data for three currently active stations obtained via Cliflo (available at http://cliflo.niwa.co.nz/). Nelson station data for NIWA's "7 Station" series temperature data from NIWA internet site (available at:www.niwa.co.nz). Bold cell indicates statistically significant at the 95% confidence level (p≤0.05).*
2. *Tempreratures used for most analysis were mean (Mean) annual temperatures calculated from mean daily temperatures. For simulations, mean daily temperatures were calculated as mean of daily minimum (Min) and maximum (Max) temperatures. Trends were also run on mean annual minimum and mean annual maximum temperatures for TDC Nursery-Chipmill historic and A1B emission scenario values.*

Table 4-4: Rainfall Trend Analysis Summary

Station Site	Station ID	Emission Scenario	Data Date Range	# Data Points	Median (mm)	Trend	Sen's Slope (mm/year)	P Value	Data Source
Nelson Aero	4241	Historic	1941-2009	64	923	DECR	-0.72	0.510	NIWA
Nelson AWS	4271	Historic	1993-2009	17	838	DECR	-14.02	0.127	NIWA
Appleby 2 EWS	21937	Historic	2002-2009	8	845	INCR	10.73	0.360	NIWA
Belgrove (Wai-iti R.)	157517	Historic	1993-2009	17	1,152	DECR	-17.97	0.170	TDC
TDC Nursery (Waimea R.)[2]	157523	Historic	2006-2009	4	922	NA	NA	NA	TDC
Irvines (Wairoa R.)	157521	Historic	1993-2009	17	1,024	DECR	-12.67	0.200	TDC
TDC Richmond Office	-	Historic	1996-2009	14	910	INCR	0.06	0.956	TDC
Birds	134036	Historic	1983-2008	26	1,099	DECR	-12.37	0.040	TDC
Little Ben (Wairoa R.)	134001	Historic	1983-2008	26	1,212	DECR	-7.83	0.130	TDC
Trig F	134236	Historic	1990-2009	20	1,505	INCR	0.09	1.000	TDC
TDC Nursery-Chipmill Simulation Results	20301	Historic	1972-2008	37	924	DECR	-3.44	0.300	NIWA
		A1B	2030-2066	37	956	DECR	-3.55	0.280	NIWA
			2080-2116	37	957	DECR	-3.53	0.380	NIWA
			1972-2116	111	956	INCR	0.03	0.963	NIWA
		A2	2030-2066	37	904	DECR	-3.51	0.300	NIWA
			2080-2116	37	974	DECR	-3.63	0.260	NIWA
Irvine Simulation Results	20302	Historic	1972-2008	37	1,024	DECR	-3.10	0.367	NIWA
		A1B	2030-2066	37	1,068	DECR	-3.10	0.266	NIWA
			2080-2116	37	1,071	DECR	-3.22	0.327	NIWA
		A2	2030-2066	37	994	DECR	-3.16	0.381	NIWA
			2080-2116	37	1,073	DECR	-3.24	0.367	NIWA
Livingston Simulation Results	20303	Historic	1972-2008	37	1,099	DECR	-2.62	0.456	NIWA
		A1B	2030-2066	37	1,150	DECR	-3.70	0.278	NIWA
			2080-2116	37	1,164	DECR	-3.39	0.353	NIWA
		A2	2030-2066	37	1,090	DECR	-3.19	0.340	NIWA
			2080-2116	37	1,170	DECR	-3.35	0.381	NIWA
Redwood Simulation Results	20275	Historic	1972-2008	38	936	DECR	-3.25	0.291	NIWA
		A1B	2030-2066	37	974	DECR	-3.27	0.314	NIWA
			2080-2116	37	979	DECR	-3.28	0.381	NIWA
		A2	2030-2066	37	918	DECR	-3.10	0.302	NIWA
			2080-2116	37	985	DECR	-3.35	0.302	NIWA

1. *NIWA simulation results provided by Schmidt (2010). NIWA historic data for three currently active stations obtained via Cliflo (available at http://cliflo.niwa.co.nz/). TDC data provided by Doyle (2010). All rainfall data analysed as total annual rainfall in mm/year. Bold cell indicates statistically significant at the 95% confidence level (p≤0.05).*
2. *Insufficient data points for trend analysis (NA).*

Table 4-5: Evaporation Trend Analysis Summary[1]

Station Site	Station ID	Type Measurement	Data Date Range	Analysis	Results	Notes
Nelson Aero	4241	Raised Pan	1987-2009	# of observations	16	7 years omitted due to missing data
				Median (mm/year)	1,309	
				Trend	**INCR**	
				Sen Slope (mm/year)	6.972	
				P value	0.053	
Nelson Aero	4241	Penman PET	1949-2009	# of observations	43	18 year omitted due to missing data (1991-2008)
				Median (mm/year)	893	
				Trend	**INCR**	
				Sen Slope (mm/year)	1.517	
				P value	0.007	
Nelson Aero	4241	Priestley-Taylor PET	1949-2009	# of observations	56	5 years omitted due to missing data (1992, 1994-1997)
				Median (mm/year)	768	
				Trend	INCR	
				Sen Slope (mm/year)	0.327	
				P value	0.170	
Nelson Aero	4241	Penman Open Water	1949-2009	# of observations	43	18 year omitted due to missing data (1991-2008)
				Median (mm/year)	858	
				Trend	**INCR**	
				Sen Slope (mm/year)	2.752	
				P value	0.001	
Nelson AWS	4271	Penman PET	1994-2009	# of observations	16	-
				Median (mm/year)	1,002	
				Trend	**INCR**	
				Sen Slope (mm/year)	4.479	
				P value	0.065	

1. *Data obtained from NIWA Cliflo internet site (available at: http://cliflo.niwa.co.nz/). Bold cell indicates statistically significant at the 95% confidence level (p≤0.05). Bold cell and yellow shading indicates weakly significant at 90% but less than 95% confidence level (p≤0.10 and >0.05).*

Table 4-6: Solar Radiation Trend Analysis Summary[1]

Station Site	Station ID	Data Date Range	Analysis	Results
Solar Radiation:				
Nelson Aero	4241	1969-1999	# of observations	24
			Missing years	7
			Median (Mj/m^2)	14.9
			Trend	DECR
			Sen Slope (Mj/m^2 per year)	-0.070
			P value	0.000
Nelson AWS	4271	1992-2009	# of observations	17
			Missing years	1
			Median (Mj/m^2)	15.2
			Trend	INCR
			Sen Slope (Mj/m^2 per year)	0.010
			P value	0.480
Combined Nelson Airport Early	4241 & 4271	1969-1989	# of observations	19
			Missing years	2
			Median (Mj/m^2)	14.9
			Trend	DECR
			Sen Slope (Mj/m^2 per year)	-0.100
			P value	0.000
Combined Nelson Airport Later	4241 & 4271	1989-2009	# of observations	21
			Missing years	0
			Median (Mj/m^2)	15.0
			Trend	INCR
			Sen Slope (Mj/m^2 per year)	0.021
			P value	0.224
Combined Nelson Airport All	4241 & 4271	1969-2009	# of observations	39
			Missing years	2
			Median (Mj/m^2)	15.0
			Trend	DECR
			Sen Slope (Mj/m^2 per year)	-0.003
			P value	0.689
Appleby 2 EWS	21937	2002-2009	# of observations	8
			Missing years	0
			Median (Mj/m^2)	15.35
			Trend	DECR
			Sen Slope (Mj/m^2 per year)	-0.090
			P value	0.550
Sunshine Hours				
Nelson Aero	4241	1949-2009	# of observations	59
			Missing years	2
			Median (Hours/year)	2,420
			Trend	INCR
			Sen Slope (Hours/year)	2.960

Station Site	Station ID	Data Date Range	Analysis	Results
			P value	0.000
Nelson Aero	4241	1949-1989	# of observations	41
			Missing years	0
			Median (Hours/year)	2,368
			Trend	DECR
			Sen Slope (Hours/year)	-1.530
			P value	0.310
Nelson Aero	4241	1990-2009	# of observations	19
			Missing years	2
			Median (Hours/year)	2,533
			Trend	INCR
			Sen Slope (Hours/year)	9.200
			P value	0.010

1. *Data obtained from NIWA Cliflo internet site (available at: http://cliflo.niwa.co.nz). Bold cell indicates statistically significant at the 95% confidence level (p≤0.05).*

Table 4-7: Water Vapour Trend Analysis Summary[1]

Var	Station Site	Station ID	Data Date Range	Analysis	Results
Relative Humidity (%):					
	Appleby	4239	1972-1995	# of observations	23
				Missing years	1
				Median (%)	79.6
				Trend	**INCR**
				Remarks	Late DECR
				Sen Slope (% per year)	0.167
				P value	0.030
	Nelson Aero	4241	1962-2009	# of observations	48
				Missing years	0
				Median (%)	80.9
				Trend	INCR
				Remarks	Late DECR
				Sen Slope (% per year)	0.016
				P value	0.505
	Nelson AWS	4271	1983-2009	# of observations	18
				Missing years	9
				Median (%)	79.2
				Trend	DECR
				Sen Slope (% per year)	-0.085
				P value	0.495
	Appleby 2 EWS	21937	2002-2009	# of observations	8
				Missing years	0
				Median (%)	78.0
				Trend	**INCR**
				Sen Slope (% per year)	0.486
				P value	0.043
Cloud Cover (oktas units):					
	Appleby	4239	1940-1995	# of observations	56
				Missing years	0
				Median (oktas units)	4.3
				Trend	NONE
				Sen Slope (oktas units/year)	0.000
				P value	0.921
	Nelson Aero	4241	1962-2007	# of observations	42
				Missing years	6
				Median (oktas units)	4.25
				Trend	**DECR**
				Sen Slope (oktas units/year)	-0.017
				P value	0.000

1. *Data obtained from NIWA Cliflo internet site (available at: http://cliflo.niwa.co.nz). Bold cell indicates statistically significant at the 95% confidence level (p≤0.05).*

Table 4-8: Nelson Airport Climate Correlations/Trends[1]

Variable	Equation of Linear Best Fit[2]	Coefficient of Determination (r^2)	Plot[3]	
			Color Code	Symbol
Penman PET v T	y = 50.2 x + 331	0.25	Orange	Circle
Rain v T	y = - 99.2 x + 2186	0.03	Blue	Triangle
Solar Radiation v T	y = 50.2 x + 331	0.25	Green	+
Temperature v Time	y = 8.85E-5 x + 9.78	0.13	Red	Square
Penman PET v Time	y = 0.0150 x + 428	0.37	Orange	Circle
Rain v Time	y = - 0.0470 x + 2645	0.13	Blue	Triangle
Solar Radiation v Time	y = 1.73E-5 + 14.4	0.01	Green	+

1. *Weather station 4271 at Nelson airport. Usable data for this analysis is 1994-2009. Linear line of best fit and coefficient of determination from version 5 of Grapher computer program.*
2. *Variable v Temperature means correlation for variable (Penman PET, rain, or solar radiation) with tempera ture (T). In linear best fit equation, x is temperature and y is the variable. Variable v Time is a time series plot of the variables temperature, Penman PET, Rain, and Solar Radiation. In linear best fit equation, x is time and y is the variable.*
3. *Color code and symbol used in plots of data points and linear best fit lines in Figure 4-11.*

Table 4-9: Streamflow Trend Analysis Summary[1]

Location		Station ID	Data Date Range	Analysis	Results	
Stream	Station				Monthly	Annual
Wairoa R	Irvines	-	1958-2009	# of observations	-	52
				Median (m^3/sec)	-	15.90
				Trend	-	N
				Sen's Slope (m^3/sec per year)	-	0
				P Value	-	0.920
Wairoa R	Irvines	-	1958-1991	# of observations	-	34
				Median (m^3/sec)	-	16.58
				Trend	-	INCR
				Sen's Slope (m^3/sec per year)	-	0.1
				P Value	-	0.15
Wairoa R	Irvines	57521	1993-2009	# of observations	213	17
				Median (m^3/sec)	12.31	15.06
				Trend	DECR	DECR
				Sen's Slope (m^3/sec per year)	-0.152	-0.270
				P Value	0.215	0.390
Wairoa R	Irvines	57521	2005-2009	# of observations	60	NA
				Median (m^3/sec)	8.80	NA
				Trend	INCR	NA
				Sen's Slope (m^3/sec per year)	1.210	NA
				P Value	0.030	NA
Wai-iti R	Belgrove	57517	1987-2009	# of observations	262	23
				Median (m^3/sec)	0.83	1.05
				Trend	DECR	DECR
				Sen's Slope (m^3/sec per year)	-0.013	-0.024
				P Value	0.033	0.030
Wai-iti R	Belgrove	52517	2005-2009	# of observations	58	NA
				Median (m^3/sec)	0.50	NA
				Trend	INCR	NA
				Sen's Slope (m^3/sec per year)	0.050	NA
				P Value	0.090	NA
Wai-iti R	Livingston	57520	1987-2009	# of observations	277	23
				Median (m^3/sec)	2.28	3.3
				Trend	DECR	DECR
				Sen's Slope (m^3/sec per year)	-0.050	-0.062
				P Value	0.011	0.080
Waimea R	TDC Nursery	57523	2005-2009	# of observations	60	NA
				Median (m^3/sec)	8.63	NA
				Trend	INCR	NA
				Sen's Slope (m^3/sec per year)	1.228	NA
				P Value	0.048	NA

1. *All data for TDC gaging stations. Data provided by Doyle (2010). "NA" indicates not analysed due to insufficient data for trend analysis. Bold cell indicates statistically significant at the 95% confidence level (p≤0.05). Bold cell and yellow shading indicates weakly significant at 90% but less than 95% confidence level (p≤0.10 and >0.05).*

Table 4-10: Stream Water Quality Trend Analysis Summary[1]

Location		Station ID	Data Date Range	Analysis	Cond uS/cm	pH units	Temp °C	NO_3-N mg/L	DRP mg/L
Stream	**Station**								
Wairoa R	Irvines	57521	1999-2004	# of observations	46	45	49	28	28
				Unadjusted Median	121.5	7.7	12	0.069	0.005
				Unadjusted Trend	INCR	INCR	NA	DECR	INCR
				Sen Slope (units/year)	1.8869	0.0110	0.0000	-0.0010	0.0005
				P value	0.1181	0.4406	0.9725	0.8586	0.0185
				# of observations	45	NA	NA	28	28
				Flow Adjusted Median	121.9	NA	NA	0.055	0.0047
				Flow Adjusted Trend	DECR	NA	NA	INCR	INCR
				Sen Slope	-0.1895	NA	NA	0.0120	0.0005
				P value	0.7767	NA	NA	0.0231	0.0345
Wai-iti R	Livingston	57520	1999-2005	# of observations	26	29	30	28	28
				Unadjusted Median	110	7.2	14.15	0.725	0.007
				Unadjusted Trend	DECR	INCR	INCR	INCR	DECR
				Sen Slope (units/year)	-2.9800	0.1700	0.7900	0.0100	-0.0002
				P value	0.1900	0.0000	0.0800	0.8000	0.5500
				# of observations	26	NA	NA	28	28
				Flow Adjusted Median	85.2	NA	NA	0.46	0.007
				Flow Adjusted Trend	DECR	NA	NA	INCR	INCR
				Sen Slope	-3.4400	NA	NA	0.0300	0.0001
				P value	0.0800	NA	NA	0.8000	0.7800
Wai-iti R	Pigeon Valley Rd	-	2000-2005	# of observations	16	19	21	17	17
				Unadjusted Median	99	7.3	15.7	0.49	0.008
				Unadjusted Trend	DECR	INCR	DECR	INCR	INCR

Location		Station ID	Data Date Range	Analysis	Cond uS/cm	pH units	Temp °C	NO_3-N mg/L	DRP mg/L
Stream	Station								
				Sen Slope (units/year)	-1.0200	0.0500	-0.1300	0.0100	0.0000
				P value	0.3900	0.2000	0.8300	0.8400	0.7700
				# of observations	15	NA	NA	16	16
				Flow Adjusted Median	100.3	NA	NA	0.32	0.008
				Flow Adjusted Trend	DECR	NA	NA	INCR	DECR
				Sen Slope	-1.1400	NA	NA	0.0066	-0.0001
				P value	0.1100	NA	NA	0.9600	0.6200
Waimea R	SH60 Appleby	-	2000-2009	# of observations	34	33	36	37	37
				Unadjusted Median	128	7.51	13.65	0.32	0.005
				Unadjusted Trend	INCR	INCR	DECR	INCR	**DECR**
				Sen Slope (units/year)	0.2600	0.0050	-0.1000	0.0100	-0.0004
				P value	0.8600	0.7600	0.8400	0.3500	0.0005
				# of observations	25	NA	NA	25	25
				Flow Adjusted Median	127.3	NA	NA	0.39	0.0038
				Flow Adjusted Trend	**INCR**	NA	NA	INCR	**DECR**
				Sen Slope	1.6900	NA	NA	0.0036	-0.0004
				P value	0.0800	NA	NA	0.8300	0.0077

1. *All data for TDC gaging stations. Data provided by Doyle (2010). "NA" indicates not analysed. Standard chemical abbreviations used for analytes. Bold cell indicates statistically significant at the 95% confidence level (p≤0.05). Bold cell and yellow shading indictes weakly significant at 90% but less than 95% confidence level (p≤0.10 and >0.05).*

Table 4-11: Groundwater Level Trend Analysis Summary[1]

Well Name Aquifer	Well ID	Data Date Range	Analysis	Monthly Results	Missing Data
Redwood Lane Deep	1330108	2002-2009	# of observations	92	2 months
			Median (mm)	26,711	
			Trend	DECR	
			Sen Slope (mm/year)	-43	
			P value	0.0000	
Simpson AGUA	1330127	2001-2010	# of observations	98	5 months
			Median (mm)	24,450	
			Trend	INCR	
			Sen Slope (mm/year)	12	
			P value	0.3600	
McKenzies AGUA	1330128	2001-2009	# of observations	94	7 months
			Median (mm)	29,304	
			Trend	DECR	
			Sen Slope (mm/year)	-2	
			P value	0.8300	
Ferguson AGUA	1330129	2001-2010	# of observations	102	
			Median (mm)	33,684	
			Trend	INCR	
			Sen Slope (mm/year)	9	
			P value	0.0900	
McCliskies AGUA	1331069	1998-2010	# of observations	143	2 months
			Median (mm)	2,492	
			Trend	INCR	
			Sen Slope (mm/year)	17	
			P value	0.0030	
CW2 AGUA	1331098	1975-2010	# of observations	414	7 months
			Median (mm)	5,232	
			Trend	DECR	
			Sen Slope (mm/year)	-9	
			P value	0.0000	
CW2 AGUA	1331098	1998-2010	# of observations	143	2 months
			Median (mm)	5,058	
			Trend	INCR	
			Sen Slope (mm/year)	6	
			P value	0.6500	

Well Name Aquifer	Well ID	Data Date Range	Analysis	Monthly Results	Missing Data
Rail Reserve AGUA-UCA	1331105	1975-2010	# of observations	412	4 months
			Median (mm)	19,297	
			Trend	**DECR**	
			Sen Slope (mm/year)	-10	
			P value	0.0600	
Chipmill LCA	1331119	1977-2010	# of observations	379	18 months
			Median (mm)	2,304	
			Trend	**DECR**	
			Sen Slope (mm/year)	-31	
			P value	0.0000	
Buschls AGUA	1331238	1995-2009	# of observations	154	16 months
			Median (mm)	17,036	
			Trend	DECR	
			Sen Slope (mm/year)	-4	
			P value	0.9100	

1. *All data for TDC gaging stations. Data provided by Doyle (2010). Bold cell indicates statistically significant at the 95% confidence level (p≤0.05). Bold cell and yellow shading indicates weakly significant at 90% but less than 95% confidence level (p≤0.10 and >0.05).*

Table 4-12: Groundwater Quality Trend Analysis Summary[1]

NGMP Well ID	Analysis	Cond uS/cm	DO mg/L	pH units	Temp °C	Ca mg/L	Fe mg/L	Mg mg/L
WWD37	# of results	42	20	29	43	52	52	52
UCA	Median	435	8.22	7.46	14.7	9.5	0.0008	47.5
Inland	Trend	DECR	N	DECR	N	DECR	N	DECR
	Sen's Slope (units/year)	-6.9600	-	-0.0591	-	-0.1543	-	-0.9192
	Lin Reg Slope (units/year)	-1.3400	-	-0.0480	-	-0.1620	-	-0.9360
	P value	0.0016	0.9928	0.0633	0.3900	0.0000	0.1465	0.0000
WWD32	# of results	41	18	28	38	51	51	51
LCA	Median	360	6.2	7.47	14.5	19.2	0.0002	28
Near Coast	Trend	INCR	N	N	N	INCR	N	INCR
	Sen's Slope (units/year)	2.39	-	-	-	0.0741	-	0.320
	Lin Reg Slope (units/year)	2.36	-	-	-	0.0800	-	0.316
	P value	0.0000	0.9093	0.2436	0.1950	0.0001	0.3379	0.0000
WWD802	# of results	42	23	35	45	40	40	40
AGUA	Median	200	7.1	7.13	14.6	16.8	0.0009	11.15
Near Coast	Trend	N	N	N	N	N	N	N
	Sen's Slope (units/year)	-	-	-	-	-	-	-
	Lin Reg Slope (units/year)	-	-	-	-	-	-	-
	P value	0.2010	1.0000	0.8650	0.2950	0.5061	0.3886	0.3217
NGMP Well ID	Analysis	Mn mg/L	K mg/L	Na mg/L	HCO_3 mg/L	Br mg/L	Cl mg/L	F mg/L
WWD37	# of results	48	53	53	53	34	53	35
UCA	Median	0.0005	0.81	10.5	147	0.0150	16.8	0.04
Inland	Trend	N	DECR	DECR	DECR	N	DECR	N
	Sen's Slope (units/year)	-	-0.0080	-0.0881	-2.5500	-	-0.1270	-
	Lin Reg Slope (units/year)	-	-0.0100	-0.9190	-2.6700	-	-0.1770	-
	P value	1.0000	0.0046	0.0000	0.0000	1.0000	0.0000	0.3930
WWD32	# of results	47	52	52	50	38	52	37
LCA	Median	4.91E-07	0.635	9.9	108.5	0.046565	16.8	0.029
Near Coast	Trend	N	N	N	INCR	N	INCR	N
	Sen's Slope (units/year)	-	-	-	0.680	-	0.119	-
	Lin Reg Slope (units/year)	-	-	-	0.723	-	0.157	-
	P value	1.0000	0.5590	0.1460	0.0000	1.0000	0.0000	0.8342
WWD802	# of results	40	40	40	40	39	40	39
AGUA	Median	0.008	0.585	7.85	86.5	0.0206	12.9	0.03
Near Coast	Trend	N	N	N	N	N	N	N
	Sen's Slope (units/year)	-	-	-	-	-	-	-
	Lin Reg Slope (units/year)	-	-	-	-	-	-	-
	P value	1.0000	0.4912	0.1950	0.3269	1.0000	0.8066	0.8655

NGMP Well ID	Analysis	Cond uS/cm	DO mg/L	pH units	Temp °C	Ca mg/L	Fe mg/L	Mg mg/L
NGMP Well ID	Analysis	SO4 mg/L	SiO_2 mg/L	NH_3-N mg/L	NO_2-N mg/L	NO_3-N mg/L	DRP mg/L	MRT Years
WWD37	# of results	53	52	41	7	53	16	1
UCA	Median	33.8	36	0.0075	0.0060	18.3000	0.0378	48
Inland	Trend	DECR	N	N	N	DECR	N	NA
	Sen's Slope (units/year)	-0.1050	-	-	-	-0.4622	-	NA
	Lin Reg Slope (units/year)	-0.0810	-	-	-	-0.4020	-	
	P value	0.0028	0.4971	0.1775	0.7508	0.0000	0.7187	NA
WWD32	# of results	52	51	41	7	52	19	1
LCA	Median	23.05	28.8	0.0046	0.0030	13.0500	0.0056	38
Near Coast	Trend	INCR	N	INCR	N	N	N	NA
	Sen's Slope (units/year)	0.572	-	0.000	-	-	-	NA
	Lin Reg Slope (units/year)	0.569	-	-0.001	-	-	-	NA
	P value	0.0000	0.2763	0.0231	0.7038	0.4027	1.0000	NA
WWD802	# of results	40	40	40	0	40	18	1
AGUA	Median	9.1	15.55	<0.02	ND	2.25	0.0056	45
Near Coast	Trend	INCR	N	N	N	N	N	NA
	Sen's Slope (units/year)	0.2883	-	-	-	-	-	NA
	Lin Reg Slope (units/year)	0.2922	-	-	-	-	-	-
	P value	0.0845	0.7350	1.0000	ND	0.4484	1.0000	NA

1. *Data provided by GNS from NGMP database. Standard chemical abbreviations used for analytes. "NA" means not applicable. Bold cell indicates statistically significant at the 95% confidence level (p≤0.05). Bold cell and yellow shading indicates weakly significant at 90% but less than 95% confidence level (p≤0.10 and >0.05). Age dating results for one sample in years mean residence time (MRT). For analytes with statistically significant trends, both Sen's slope and linear regression (Lin Reg) line slope are listed for comparison. Where no statistically significant trend was found, trend is labelled as "N" and so slope is listed.*

Table 5-1: Groundwater-Stream Interaction Modelling

Modelling Classification		Type AI Modelling
Artificial Intelligence (AI) Modelling		
	Water usage	Multi-layer perceptron-trained artificial neural network (ANN) trained with extended Kalman filtering learning algorithm (MLP-EKF)
	Rainfall recharge	Genetic programming (GP)
	River flow (Wairoa River at Irvines)	Dynamic neuro-fuzzy local modelling system (DNFLMS)
	River flow (Waimea River at TDC Nursery)	DNFLMS
	Groundwater level at McCliskies well	DNFLMS
MODFLOW Modelling		
	River flow (Waimea River at TDC Nursery)	-
	Groundwater level at McCliskies well	-

Table 5-2: Waimea Plains Soils[1]

WHC mm	Soil Series	Soil Texture	Soil Series Area Ha	Soil WHC Area Ha	Fraction of Total %
	Heslington		5.74		
38.	Ranzau	Coarse sand	1,649.32	1,655.06	31.7
78.	Dovedale	Fine loamy sand	525.52	525.52	10.1
	Mapua		251.95		
	Motukarara		86.29		
	Richmond		500.86		
	Waimea		2,136.95		
130.	Wakatu	Fine sandy clay loam	55.68	3,031.73	58.2
-	Total	-	5,212.31	5,212.31	100.

1. *Compiled from data obtained from Landcare Research. Areas calculated from relevant GNS GIS database file*

Table 5-3: Summary of Waimea Plains Historic Water Usage Data (exclusive of Waimea east pumping)[1]

Statistic	Day-Month	Water Usage Flow (L/sec) Year			
		2003-2004	2004-2005	2005-2006	2006-2007
Mean Rate (critical dry period)	21 Feb - 21 Apr	265	505	669	830
Maximum Rate	1 Jul 03 - 30 Jun	1,038	910	1,109	1,088
Total[2]	1 Jul 03 - 30 Jun	92,837	88,071	132,050	115,483
Mean Rate (warm period)	1 Jan - 30 Apr	450	512	700	704
Mean Rate (annual)	1 Jul 03 - 30 Jun	254	241	362	316
Rainfall (warm period) in mm[3]	1 Jan - 30 Apr	204	440	240	315

1. *Source: Tasman District Council. Usage is exclusive of the surface water pumping for irrigation in the Waimea east area.*
2. *Total means sum of daily usage rates.*
3. *Tasman District Council monitoring data.*

2000	Jan-Apr	345
2001		95
2003		290
2004		204
2005		440
2006		240
2007		315

Table 5-4: Breakdown of Waimea Plains Historic Water Usage Data 2005-2006 Year (exclusive of Waimea east pumping)[1]

Water Management Zone	Water Usage Flow (L/sec)				
	Mean Rate Critical Dry Period 21 Feb - 21 Apr 06	Maximum Rate 1 Jul 05 - 30 Jun 06	Total[2] 1 Jul 05 - 30 Jun 06	Mean Rate Warm Period 1 Jan - 30 Apr 06	Mean Rate Annual 1 Jul 05 - 30 Jun 06
Delta	189	312	38,816	195	106
Golden Hill	25	47	4,533	26	12
Hope	12	24	2,540	13	7
LCA	95	152	18,710	100	51
Reservoir	193	302	35,088	195	96
UCA	38	77	7,592	41	21
Wai-iti	45	92	10,025	52	27
Waimea west	71	118	13,282	71	36
Wai-iti Dam Service	7	13	1,466	7	4
All Above Zones[3]	669	1,109	132,050	700	362
Waimea east pumping	127	276	30,598	133	84

1. *Source: Tasman District Council. Usage is exclusive of the surface water pumping for irrigation in the Waimea east area.*
2. *Total means sum of daily usage rates.*
3. *Sum of zone numbers may not equal total in "All Above Zones" row due to rounding.*

Table 5-5: Historic and Modeled Water Usage

Statistic	Day-Month	Water Usage Flow (L/sec)					Change (%)[4]	
		1 July 2000 - 30 June 2001			1 July 2058 - 30 June 2059		1 July 2058 - 30 June 2059	
		Historic[1]	Model Training	RPD (%)[2]	A1B GCM5	A2 GCM6	A1B GCM5	A2 GCM6
Mean Rate (critical dry period)	21 Feb - 21 Apr	715	716	-0.1	810	844	13.29	18.04
Maximum Rate	1 Jul 03 - 30 Jun	1,598	1,543	3.5	1,426	1,435	-10.76	-10.20
Total[3]	1 Jul 03 - 30 Jun	171,924	168,486	2.0	177,688	181,018	3.35	5.29
Mean Rate (warm period)	1 Jan - 30 Apr	900	883	1.9	964	990	7.11	10.00
Mean Rate (annual)	1 Jul 03 - 30 Jun	471	462	1.9	487	496	3.40	5.31
Rainfall (warm period) in mm	1 Jan - 30 Apr	95	-	-	68	68	-27.68	-27.68

1. *Source: Tasman District Council. Usage is exclusive of the surface water pumping for irrigation in the Waimea east area.*
2. *Relative percent difference between historic data and AI model training results for year 2000-2001.*
3. *Total means sum of daily usage rates.*
4. *Simulated/modeled change in water usage and rainfall compared to historic data as a function of climate change.*

Table 5-6: Summary of Rainfall Recharge Data at Four Lysimeter Sites in the Christchurch Area (1999-2000)[1]

Site	PAW mm	Calendar Year						Average Recharge[2] %
		1999			2000			
		Rainfall mm	PET mm	Rainfall Recharge mm	Rainfall mm	PET mm	Rainfall Recharge mm	
Christchurch Airport	45.	684.	888.	230.	686.	931.	225.	33
Lincoln University	170.	622.	904.	116.	646.	777.	220.	26
Winchmore	95.	729.	864.	200.	936.	713.	410.	36
Hororata	75.	907.	-	254.	908.	-	396.	36

1. *Summary of rainfall, potential evapotranspiration (PET), and lysimeter measured rainfall recharge for national network sites from NIWA archives.*
2. *Observed rainfall recharge divided by observed rainfall.*

Table 5-7: Waimea Plains Historic/Simulated Tmax and Calculated ETo Values[1]

Statistic	ETo (mm)			Maximum Daily Temperature (^oC)		
	Historic 2000-2001	Simulated		Historic 2000-2001	Simulated	
		A1B Scenario 2058-2059	A2 Scenario 2058-2059		A1B Scenario 2058-2059	A2 Scenario 2058-2059
Minimum	0.7	0.7	0.7	10.7	11.9	11.6
Median	2.7	2.8	2.8	18.3	19.4	19.3
Mean	2.7	2.8	2.9	18.3	19.5	19.5
Maximum	6.0	6.2	6.2	28.6	29.9	30.4
Stdev	1.34	1.38	1.39	-	-	-
Sum	1,002.2	1,038.5	1,043.8	-	-	-
	21 Feb-21 Apr 01	21 Feb-21 Apr 59	21 Feb-21 Apr 59	21 Feb-21 Apr 01	21 Feb-21 Apr 59	21 Feb-21 Apr 59
Minimum	1.5	1.6	1.6	16.8	18.0	18.2
Median	3.2	3.2	3.3	21.9	23.0	23.5
Maximum	4.9	5.0	5.1	28.5	29.8	30.3
Sum	186.2	192.7	195.7	-	-	-

1. *Reference evapotranspiration calculated from historic or NIWA simulated temperatures under climate change using Version 3.1 of FAO ETo program (Raes, 2009).*

Table 5-8: Rainfall Recharge Model Results[1]

Scenario	Time Frame	Total Rainfall (RF) mm	Soil Type PAW mm	GP Model		SOILMOD Model	
				Total Recharge (Rechg) mm	Rechg / RF Ratio %	Total Recharge (Rechg) mm	Rechg / RF Ratio %
Historic	1 Jul 00 - 30 Jun 01	693.6	38.	217.9	31.4	238.2	34.4
			78.	112.8	16.3	200.2	28.9
			130.	69.3	9.99	180.3	26.0
A1B GCM5	1 Jul 58 - 30 Jun 59	707.1	38.	197.5	27.9	240.5	34.0
			78.	101.6	14.4	184.0	26.0
			130.	62.3	8.81	105.3	14.9
A2 GCM6	1 Jul 58 - 30 Jun 59	652.3	38.	178.5	27.4	192.3	29.5
			78.	91.8	14.1	148.1	22.7
			130.	56.3	8.63	93.6	14.3

1. "GP" means genetric programming AI model. Scenarios are: (1) historic data; and (2) NIWA climate change simulations for the A1B and A2 emissions scenarios using the #5 and #6 GCM output, respectively.

Table 5-9: Historic Wairoa River Flow at Irvines Data[1]

Statistic	Period	1991-1992 year (1 in 10 dry year)		1982-1983 year (1 in 20 dry year)		2000-2001 year (1 in 24 dry year)		2004-2005 year (average year)	
		Rain (mm/d)	Flow (L/s)	Rain (mm/d)	Flow (L/s)	Rain (mm/d)	Flow (L/s)	Rain (mm/d)	Flow (L/s)
Mean	21 Feb - 21 Apr	1.	3,473.	3.	10,348.	1.	1,661.	2.	9,134.
Maximum	1 Jul - 30 Jun	43.	227,506.	73.	228,360.	41.	215,152.	75.	256,046.
Total	1 Jul - 30 Jun	774.	4,503,137.	658.	3,886,650.	694.	4,118,222.	914.	5,678,317.
Mean	1 Jan -30 Apr	2.	8,821.	2.	9,840.	0.	2,118.	2.	10,656.
Mean	1 Jul - 30 Jun	2.	12,344.	2.	10,682.	2.	11,389.	3.	15,637.

1. Tasman District Council data. Annual "Total" is the sum of all daily flow rates, not the total amount of water.

Table 5-10: Historic Wairoa River Dry Period Flow at Irvines Data[1]

Type Year	Period	Total Rainfall mm	Observed Flow L/sec
1 in 20 Drought Year	February-March 1983	37.	1,756.
1 in 24 Drought Year	February-March 2001	8.	1,285.
Average Year	15 April-15 May 2005	4.	2,633.
Average Year	February-April 2005	184.	7,980.

1. Tasman District Council data. Annual "Total" is the sum of all daily flow rates, not the total amount of water.

Table 5-11: Predicted Wairoa River Flow at Irvines Under Climate Change[1]

Statistic		Period	Historic Year 2000-2001		A1B Scenario 2058-2059		A2 Scenario 2058-2059	
Flow	**Rainfall**		**Rain (mm)**	**Flow (L/sec)**	**Rain (mm)**	**Flow (L/sec)**	**Rain (mm)**	**Flow (L/sec)**
Mean	Total	21 Feb - 21 Apr	44.8	2,061.	50.7	1,950.	39.8	2,093.
Mean	Total	1 Jan -30 Apr	58.0	2,327.	64.7	2,272.	54.7	2,344.
Mean	Total	1 Jul - 30 Jun	693.6	11,369.	707.1	11,239.	652.3	11,438.
Maximum	-	1 Jul - 30 Jun	-	220,875.	-	217,854.	-	227,925.
Total	-	1 Jul - 30 Jun	-	4,126,464.	-	4,068,029.	-	4,140,259.

1. Predicted by DNFLMS model for historic year and for equivalent year after 58 years of A1B (GCM5) and A2 (GCM6) climate change emissions scenarios.

Table 5-12: Mean River Flows and Losses[1]

Item and Location	Units	1 Feb -30 Mar Year 1982-1983	21 Feb-21 Apr Year 2000-2001	15 Apr-15 May Year 2004-2005	21 Feb-21 Apr Year 2005-2006	21 Feb-21 Apr Year 2006-2007
Wairoa River Flow at Irvines (Upstream)	L/sec	1,756.	1,661.	2,633.	6,145.	2,738.
Waimea River Flow at TDC Nursery (Downstream)	L/sec	746.	433.	2,375.	5,747.	1,808.
Upstream-Downstream Flow Loss	L/sec	-1,010.	-1,228.	- 258.	- 397.	- 930.
Waimea Plains Total Rainfall (mm)	mm	37.	45.	132.	98.	30.
Waimea Plains Mean Water Usage (L/sec)	L/sec	ND.	715.	501.	669.	822.

1. TDC data.

Table 5-13: Historic and Climate Change DNFLMS Model Predicted Stream Flows[1]

Period	**Mean Wairoa River Flow at Irvines (L/sec)**		
	Observed Historic	**A1B Scenario**	**A2 Scenario**
	2000 - 2001 Year	**2058 - 2059 Year**	**2058 - 2059 Year**
21 Feb - 21 Apr	2,061.	1,950.	2,093.
1 Jan - 30 Apr	2,327.	2,272.	2,344.
1 Jul - 30 Jun	11,369.	11,239.	11,438.
	Mean Waimea River Flow at TDC Nursery (L/sec)		
	Observed Historic	A1B Scenario	A2 Scenario
Period	2000 - 2001 Year	2058 - 2059 Year	2058 - 2059 Year
21 Feb - 21 Apr	433.	335.	318.
1 Jan - 30 Apr	777.	780.	765.
1 Jul - 30 Jun	10,522.	10,452.	10,472.
	Mean Loss of Streamflow (Irvines - TDC Nursery in L/sec)		
	Observed Historic	A1B Scenario	A2 Scenario
Period	2000 - 2001 Year	2058 - 2059 Year	2058 - 2059 Year
21 Feb - 21 Apr	-1,628.	-1,615.	-1,775.
1 Jan - 30 Apr	-1,550.	-1,492.	-1,579.
1 Jul - 30 Jun	- 847.	- 787.	- 966.
Variable	Waimea Plains (21 Feb - 21 Apr)		
Total Rainfall (mm)	45.	51.	40.
Mean Water Usage (L/sec)	715.	810.	844.

1. *Observed historic flow data from TDC. Predicted climate change streamflows from DNFLMS model. Negative numbers indicate loss of flow between Irvines and TDC Nursery.*

Table 5-14: Historic and Predicted Low Flow Days for Waimea River at TDC Nursery Station[1]

Case	Year	Number of Days River Flow Less Than			
		100 L/sec	**250 L/sec**	**600 L/sec**	**1,100 L/sec**
Historical Data	Jul 2000 - Jun 2001	18	44	82	96
A1B Emissions Scenario	Jul 2058 - Jun 2059	27	52	86	98
A2 Emssions Scenario	Jul 2058 - Jun 2059	30	54	88	98

1. Historic data from TDC. Predicted data using DNFLMS model.

Table 5-15: Historic Groundwater Level Data for McCliskies Well[1]

Time Period	Mean Groundwater Level at McCliskies Well (mm)			
	2000-2001	**2004-2005**	**2005-2006**	**2006-2007**
21 February - 30 April	1,962.	2,421.	2,260.	2,258.
1 January - 30 April	2,012.	2,491.	2,308.	2,331.
1 July - 30 June	2,346.	2,621.	2,459.	2,446.
	Mean Waimea River Flow at TDC Nursery Station (L/sec)			
21 February - 30 April	433.	11,234.	5,596.	1,834.
1 January - 30 April	782.	12,996.	12,886.	5,680.
1 July - 30 June	10,524.	16,238.	13,853.	8,845.

1. TDC data.

Table 5-16: Predicted Groundwater Elevations at McCliskies Well and Waimea River Flow at TDC-Nursery[1]

	Mean Groundwater Elevations at McCliskies Well				
		DNFLMS		**MODFLOW**	
	Historic Year	**A1B Scenario**	**A2 Scenario**	**A1B Scenario**	**A2 Scenario**
Time Period	**2000-2001 mm**	**2058-2059 mm**	**2058-2059 mm**	**2058-2059 mm**	**2058-2059 mm**
21 February - 21 April	1,962.	1,962.	1,964.	1,964.	1,963.
1 January - 30 April	2,012.	1,999.	2,000.	2,013.	2,008.
1 July - 30 June	2,346.	2,303.	2,307.	2,336.	2,337.
	Mean Waimea River Flow at TDC Nursery				
		DNFLMS		MODFLOW	
Time Period	Historic Year 2000-2001 L/sec	A1B Scenario 2058-2059 L/sec	A2 Scenario 2058-2059 L/sec	A1B Scenario 2058-2059 L/sec	A2 Scenario 2058-2059 L/sec
21 February - 21 April	433.	335.	318.	342.	316.
1 January - 30 April	777.	780.	765.	778.	754.
1 July - 30 June	10,522.	10,452.	10,472.	9,941.	9,714.

1. Historic data from TDC. Climate change results from DNFLMS or MODFLOW model as indicated.

Table 6-1: Example of effect of water availability on estimated land value and value of allocation[1]

Water Availability (% of current allocation)	Land Value (Millions of $)	Estimated Land Value ($/ha)	Estimated Value of Allocation ($/ha)
0	1.1	53,659	0
40	1.7	82,927	29,268
60	2.1	102,439	48,780
80	2.1	102,439	48,780
100	2.1	102,439	48,780
120	2.1	102,439	48,780

1. *White (2010).*

Table 6-2: Estimated Land use classes In Waimea Plains model[1]

Land use class	Area (ha)	
	2005	2050
Agriculture - Waimea East Irrigation Scheme (WEIS)	1,100.	819.
Agriculture – mostly irrigated from groundwater	2,644.	2,925.
Agriculture - non-irrigated	3,294.	2,462.
Urban (Richmond)	613.	1,444.
River beds	475.	475.
Total	8,126.	8,125.

1. *White (2010).*

Table 6-3: Estimated land uses for irrigated agricultural

Land use	Area (ha)	
	2005	2050
Apples – irrigated	919.	950.
Dairy – irrigated	1,425.	712.
Horticulture – irrigated	475.	931.
Market gardening – irrigated	381.	663.
Other irrigated	431.	375.
Unproductive (part of irrigated properties)	113.	113.
Total	3,744.	3,744.

1. Combined irrigation either by using surface water or groundwater.

Table 6-4: Estimated proportion of land use by type (2005)

Land use	Proportional Land Use Outside WEIS (%)	Proportional Land Use Inside WEIS (%)
Apples	13	28
Cropping	4	9
Dairy	54	0
Deer	1	2
Dryland	1	2
Horticulture	10	22
Lifestyle	1	2
Market garden	7	15
Sheep	7	15
Unproductive	2	4
Total	100	99

Table 6-5: TEV of Waimea Plains Water Resources

Sector	Economic Value Rounded to Nearest $\$10^6$	
	2005 Land Use	2050 Land Use
Productive:		
Agriculture	124	133
Commercial/industrial	160	221
Urban	38	99
Subtotal	322	453
In situ		
Groundwater	27	27
Surface water	25	67
Subtotal	51	94
TEV	373	547

Table 6-6: Estimated Economic Value of Water Resources to Agricultural Land Uses

Land Use	Land area (ha)		Economic Value Rounded to Nearest $\$10^6$	
	2005	2050	2005	2050
Apples - irrigated	919.	950.	35.	41.
Dairy – irrigated	1,425.	712.	48.	24.
Horticulture – irrigated	475.	931.	18.	37.
Market Garden – irrigated	381.	663.	8.	16.
Other irrigated	431.	375.	15.	15.
Unproductive part of irrigated land	113.	113.	<0.1	<0.1
Unirrigated land	3,294.	2,463.	1.	1.
Total	7,038.	7,038.	125.	133.

Table 6-7: Expenditure on Employment in the Productive Sector

Water Availability (%)	Agriculture Expenditure (Millions of $)	Comm./Ind. Expenditure (Millions of $)	Urban Expenditure (Millions of $)	Total Expenditure (Millions of $)
2005				
0.0	0.	23.2	0.0	23.2
100.0	45.1	44.0	0.2	89.3
Expenditure Attributed to Water Supply	45.1	20.8	0.2	66.1
2050				
0.0	0.	32.1	0.	32.1
100.0	78.5	60.9	0.4	139.8
Expenditure Attributed to Water Supply	78.5	28.8	0.4	107.7

Table 6-8: Labour Associated With Waimea Plains Land Use

Category	Labour Cost $/FTE	Agricultural FTEs	Commercial/Industrial FTEs	Urban FTEs	Total FTEs
2005 Land Use					
Direct Labour	31,500	1,432	660	4	2,096
Indirect Labour	31,500	1,432	660	4	2,096
Total Labour	-	2,864	1,320	8	4,192
2050 Land Use					
Direct Labour	31,500	2,492	914	4	3,410
Indirect Labour	31,500	2,492	914	4	3,410
Total Labour	-	4,984	1,828	8	6,820

Table 6-9: Potential Impact of Climate Change on Rainfall Recharge During An Extreme Drought Year

Rainfall Recharge (July 2000-June 2001)	Soil Type			% Change[1]
	38	78	130	
Historic	217.9	112.8	69.3	N/A
Climate change scenario A1B (GCM5)	219.6	109.2	67.0	-2
Climate change scenario A2 (GCM6)	189.4	97.5	59.8	-13

1. *Percent change in recharge for the Waimea Plains based on weighted area of soil type.*

Table 6-10: Potential Impact of Climate Change Scenarios on Streamflow at TDC Nursery

Period	Mean Flow L/Sec	Flow Change %
Historic (21 February-21 April 2001)	437	N/A
A1B Emissions Scenario (21 February-21 April 2059)	342	-22
A2 Emissions Scenario (21 February-21 April 2059)	316	-28

Table 6-11: Effects of Climate Change on Economic Value of Water

Change in Water Availability %	Change in Economic Value of Water ($10^6)						
	Productive Uses				In Situ Uses		
	Agriculture	Comm/Ind	Urban	Total	Groundwater	Surface water	Total
Estimated 2005 Land Use							
-2	-3.1	-3.5	-0.8	-7.4	-0.3	-0.3	-0.6
-10	-15.3	-17.4	-3.8	-36.5	-1.7	-1.7	-3.4
-13	-20.3	-22.6	-4.9	-47.8	-2.2	-2.2	-4.4
Estimated 2050 Land Use							
-2	-3.1	-4.8	-2	-9.9	-0.9	-0.9	-1.8
-10	-19.6	-24.1	-9.9	-53.6	-4.3	-4.3	-8.6
-13	-25.5	-31.3	-12.8	-69.6	-5.6	-5.6	-11.2

Table 6-12: Change in Expenditure on Direct Labour With Climate Change

Change in Water Availability %	Millions of Dollars			
	Agriculture	Commercial/Industrial	Urban	Total
2005 Land Use				
-2	-0.1	-0.47	0	-0.57
-10	-0.6	-2.4	0	-3
-13	-0.8	-3.1	0	-3.9
2050 Land Use				
-2	-0.1	-0.7	0	-0.8
-10	-0.6	-3.3	0	-3.9
-13	-0.8	-4.2	0	-5

Table 6-13: Change in Employment With Climate Change

Change in Water Availability %	Labour Cost $/FTE	Agricultural FTEs	Comm./Ind. FTEs	Urban FTEs	Total FTEs
2005 Land Use					
-2	31500	-6	-30	0	-36
-10	31500	-38	-152	0	-190
-13	31500	-50	-196	0	-246
2050 Land Use					
-2	31500	-6	-44	0	-50
-10	31500	-38	-210	0	-248
-13	31500	-50	-266	0	-316

Table 6-14: Change in NZDep2006 With Climate Change for Estimated 2005 Land Use[1]

Change in Water Availability %	Change in NZDep2006
-2	0
-10	1
-13	1

1. Change from a value of 977 for Tasman in 2006 (Appendix E).

Table 6-15: Economic Indicators of Climate Change

Change in Water Availability %	Millions of Dollars			
	Total Productive Use[1] Base of $321.5 x 10^6$	Total In Situ Use[1] Base of $51.3 x 10^6$	Direct and Indirect Labor Expenditure[2] Base of $512 x 10^6$	NZDep2006 Base of 977
2005 Land Use With Climate Change Compared to 2005 Land Use Without				
-2	-7.4	-0.6	-1.1	0
-10	-36.5	-3.4	-6.0	1
-13	-47.8	-4.4	-7.8	1
2050 Land Use With Climate Change Compared to 2005 Land Use Without				
-2	-9.9	-1.8	-1.6	
-10	-53.6	-8.6	-7.8	
-13	-69.6	-11.2	-10.0	

1. *From Table 6-5.*
2. *From Appendix E. Assumes a mulitplier of 2 for agriculture and commercial/industrial.*

Table 6-16: Change in Economic Indicators

Change in Water Availability %	Total Productive	Total In Situ	Direct Labour Expenditures	NZDep2006
2005 Land Use With Climate Change Compared to Without				
-2	Minor	Minor	Minor	Minor
-10	Moderate	Moderate	Minor	Minor
-13	Moderate	Moderate	Minor	Minor
2050 Land Use With Climate Change Compared to 2005 Land Use Without				
-2	Minor	Minor	Minor	
-10	Moderate	Moderate	Minor	
-13	Major	Major	Minor	

APPENDICES

APPENDIX A: DATABASE METADATA INFORMATION

Statistics New Zealand
TATAURANGA AOTEAROA

Stocktake for the Environment Domain Plan: 2010

newzealand.govt.nz

Reproduction of material

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Table 1.10

Sea levels

Topic	1. Climate change 4. Marine environment
Information type	Database of direct measurements (Geo-referenced sea level data)
Data custodian	National Institute of Water and Atmospheric Research (NIWA)
Information source	Sea-level data from 21 sites operated by various agencies including NIWA, regional councils, ports, Antarctica New Zealand, and the National Tidal Centre (Australia)
Information source type	Sea level at all sites; some sites also measure barometric pressure and sea temperature
Frequency	Sea level measured at 1- or 5-minute intervals. Daily updates including storm surges, long waves, and tsunami are uploaded to the NIWA website. Data quality-assured when funding permits. Last quality-assured data was processed up to and including 2006.
Reference period	Earliest gauge site was set up in 1971 (Moturiki Island), but most sites commenced in 1994 or later.
Objectives (what the purpose is)	Measure temporal and spatial variability in sea level, storm surge, tsunami, and tides around the open coast of New Zealand and at Scott Base.
Data collected (key variables, outputs)	Data collected from 21 representative stations including Chatham Islands and Scott Base (Antarctica) Coverage: New Zealand Key output variables: sea levels, barometric pressure, sea temperature
Data access	Daily web site updates (free access) QA datasets up to 2006 for NIWA gauges freely available at: http://edenz.niwa.co.nz
Further information	www.niwa.co.nz

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Table 1.11

National Climate Database

(A nationally significant database)

Topic	1. Climate change
Information type	Database of direct measurements
Data custodian	National Institute of Water and Atmospheric Research (NIWA)
Information source	NA
Information source type	NA
Frequency	Sub-hourly, hourly, daily, and monthly
Reference period	1852–ongoing
Objectives (what the purpose is)	To understand regional climate and variability; climate change studies, climate hazards, risks, and extremes
Data collected (key variables, outputs)	Data collected from voluntary and co-operative observation networks of weather and climate elements throughout New Zealand and the South Pacific. Networks include manual observations and by electronic sensing of climate. Coverage: see above Key output variables including weather and climate elements: rainfall, temperature, dew point, wind speed and direction, sunshine, radiation, barometric pressure, cloud type and amount, significant weather phenomenon, earth temperature, evaporation, snow, soil moisture, upper air observations of temperature, winds and dew point, ship observations of sea-state
Data access	Data is available by registration through a web-based service.
Further information	http://cliflo.niwa.co.nz/

Table 1.12

Environmental information relevant to monitoring climate change and its impacts

Topic	1. Climate change
Information type	Database/dataset of direct measurements including modelled information (routine monitoring, satellite remote sensing, surveys)
Data custodian	National Institute of Water and Atmospheric Research (NIWA)
Information source	NA
Information source type	NA
Frequency	Daily or monthly depending on data type and whether automatic station or manually read (automatic quality assurance (QA) only); annually with QA
Reference period	1860 (few stations) to present (ongoing)
Objectives (what the purpose is)	Measure temporal and spatial variability in New Zealand's air and water environment
Data collected (key variables, outputs)	Sea level (various open-coast sites) River flows (Tideda database) Water quality (> ten variables) End of season snowline Sea surface temperatures (satellite) Cloud imagery (satellite) Ocean physical and biological data from ship transects Ocean colour (satellite) Multi-wavelength atmospheric radiance data from satellites Biological and biodiversity data from rivers, streams, lakes, coasts Climate (rain, temperature, radiation, sunshine, earth temperature, pressure, wind, evaporation, soil moisture) Solar radiation Ocean waves
Data access	Some freely available on web
Further information	http://cliflo.niwa.co.nz/ National Climate Centre: http://www.niwa.co.nz/ncc National Water Resources Centre: http://www.niwa.co.nz/ncwr

Table 3.15

River water quality

Topic	3. Freshwater 9. Ecosystems and biodiversity
Information type	Dataset/database of direct measurements (monthly survey)
Data custodian	National Institute of Water and Atmospheric Research (NIWA)
Information source	NA
Info source type	NA
Frequency	Monthly sampling
Reference period	January 1989 to present (monthly)
Objectives (purpose)	Measure temporal and spatial variability in the water quality of New Zealand freshwaters (rivers) (state and trends)
Data collected (key variables, outputs)	Nutrients. 5 forms: total phosphorus (TP) and dissolved reactive phosphorus (DRP), total nitrogen (TN), oxidised nitrogen (NOx = nitrate-N plus nitrite-N) and ammoniacal nitrogen (Am-N) Major cations (Na, K, Ca, Mg) and anions (bicarbonate, chloride, sulphate) were analysed monthly for 1989 only. Conductivity measurement (in the laboratory) continues as an index of total ionic content. Dissolved oxygen is measured in the field as percent saturation, and then converted to parts per million (ppm) by calculation taking into account pressure and altitude corrections as required. Water temperature is measured in the field at the same time as dissolved oxygen. Visual clarity is measured in the field as the visual range of a black disc target. Turbidity is measured by nephelometry in the laboratory, as a backup to field visibility measurement. Biochemical oxygen demand after five days (BOD5) analysis ceased for all but three sites (AK2, RO2, WA9) as at August 2002. Faecal indicator bacteria testing (total coliforms and E. coli) commenced February 2005. Benthic algae (periphyton) are assessed in the field (monthly) on a visual abundance scale. Benthic macroinvertebrates are collected annually (by Surber sampler) – and analysed to provide an index of overall river ecological 'health'. Coverage: most of New Zealand – 77 representative stations on rivers draining about half of the New Zealand land area
Data access	Via NIWA website using the Water Quality Information System (WQIS) once a signed End User Licensing Agreement (EULA) form is on file
Further information	See National River Water Quality Network (NRWQN) publications, particularly: Smith, D. G.; McBride, G. B. (1990): New Zealand's national water quality monitoring network - Design and first year's operation. *Water Resources Bulletin 26:* 767-775. Smith, D. G.; Maasdam, R. (1994): New Zealand's National River Water Quality Network 1. Design and physico-chemical characterisation. *New Zealand Journal of Marine and Freshwater Research 28:* 19-25.

Table 3.5

Groundwater and Geothermal (GGW) Database

(A nationally significant database)[4]

Topic	3. Freshwater
Information type	Dataset/database of direct measurements
·Data custodian	Institute of Geological and Nuclear Sciences (GNS)
Information source	NA
Information source type	NA
Frequency	Quarterly or on an ad hoc basis
Reference period	1990 to present
Objectives (what the purpose is)	To store low frequency water quality and related datasets from groundwater, geothermal and volcano related projects.

Table continued next page

[4] Nationally significant databases and collections are identified by the Foundation for Research, Science and Technology (FRST) as being of significant national importance. For more information refer to: http://natsigdc.landcareresearch.co.nz/natsigdc_home.html

Table 3.5 (continued)

Data collected (key variables, outputs)	A collection of hydrological, geochemical (sampling and chemistry), geological and geophysical data collected from over 500 sites within New Zealand for groundwater research purposes. The 112 sites comprising the National Groundwater Monitoring Programme are sampled quarterly.
Data access	Access via password-protected internet site
Further information	www.gns.cri.nz

Table 3.13

Water Resources Archive

(A nationally significant collection and database)

Topic	3. Freshwater
Information type	Database/dataset of direct measurements including modelled information
Data custodian	National Institute of Water and Atmospheric Research (NIWA)
Information source	NA
Information source type	NA
Frequency	3–6 monthly for quality assured (QA'd) data (some real-time data available on NIWA website, but not QA'd)
Reference period	1905 (few stations) to present (ongoing) (water resource) and 1979 to present (water quality)
Objectives (what the purpose is)	Measure temporal and spatial variability in New Zealand's freshwater resources and define flood hazard and drought risk.
Data collected (key variables, outputs)	Coverage: most of New Zealand. 160 stations (plus > 140 externally owned data feeds that might be available following client consent); also 77 sites of water quality data. Key variables: River flows and river and lake levels in a Tideda database, water quality data in relational database.
Data access	Publicly-funded data are freely available on the web. edenz.niwa.co.nz (water resource) wqis.niwa.co.nz (water quality)
Further information	National Water Resources Centre: http://www.niwa.co.nz/ncwr

Database Title	**7.1 National Climate Database**
Keywords Type1. Type 11.	*Climate. Rainfall, temperature, sunshine, radiation, wind, meteorological phenomena.*
Abstract	*This database stores a variety of climate information from climate stations around New Zealand as well as the Pacific and Antarctica. Different climate stations report different parameters, with many just reporting rainfall. (Approximately 3/5 of climate stations are closed and no longer reporting. There are many reasons for closure including increasing automation and increasing focus on weather forecasting versus long term science.*
Geographical Coverage	New Zealand (primarily). Also sites in Antarctica and the Pacific Islands.
Dataset start date.	Some records began in 1860's, some in the 1930's, and most in the 1960's. Computerization began in the mid 1960's.
Dataset end date.	Current.
Status/currency.	In progress.
Maintenance.	Nationally significant database funded through PGSF
Update frequency.	Ongoing.

Technical Evaluation	
Parameters- what is measured	Different parameters are measured at different sites. The suite of measured parameters are: • cloud system • earth temperature • evaporation rate • ice accretion on ships • number of lightning bolts • direction and speed of highest wind gust • maximum, minimum and grass minimum extreme temperatures • msl and station level pressure and change • global, diffuse and direction radiation • precipitation amount and state of ground

	• rain rates, amounts and duration • duration of bright sunshine • direction and speed of wind near surface • air temperature / humidity measurements There are also observations of a variety of weather phenomena.
Parameters- what is calculated	Totals, means and extremes for local month and year • total rainfall - mm • wet days - number of days with more than 1mm rain • mean air temperature - Celsius • mean daily maximum air temperature - Celsius • mean daily minimum air temperature - Celsius • mean daily grass minimum temperature - Celsius • extreme maximum air temperature - Celsius • extreme minimum air temperature - Celsius • extreme grass minimum air temperature - Celsius • total sunshine- hours • mean 5cm earth temperature Celsius • mean 10cm earth temperature - Celsius • mean 20cm earth temperature - Celsius • mean 30cm earth temperature - Celsius • mean 100cm earth temperature - Celsius • mean daily wind run - km • mean vapour pressure - hPa • mean daily global radiation - MJ / sq m • highest daily wind run - km • total evaporation for sunken pan - mm • total evaporation for raised pan - mm • number of days of occurrence: thunder • number of days of occurrence: ground frost • number of days of occurrence: screen frost • number of days of occurrence: gale • number of days of occurrence: fog • number of days of occurrence: hail • number of days of occurrence: lightning • number of days of occurrence: snow • number of days of occurrence: snow lying • mean MSL pressure at 9am - hPa • number of days of wind gusts >= 33 knots • number of days of wind gusts >= 51 knots • mean wind speed - m / sec • total Penman potential evapotranspiration - mm • total Priestly - Taylor potential evapotranspiration- mm • total Penman open water evaporation - mm • Penman saturation deficit - hPa • rain days - number of days with 0.1mm or more of rain • maximum 1-day rainfall - mm • mean cloud amount - eighths • lowest maximum air temperature - Celsius • highest minimum air temperature - Celsius • highest speed of wind gust - m / sec • wind - gust - direction of highest wind gust - degrees • mean 50cm earth temperature - Celsius

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	• mean daily direct radiation - MJ / sq m • mean daily diffuse radiation - MJ / sq m • maximum 10-minute rainfall - mm • maximum 20-minute rainfall - mm • maximum 30-minute rainfall - mm • maximum 1-hour rainfall - mm • maximum 2-hour rainfall - mm • maximum 6-hour rainfall - mm • maximum 12-hour rainfall - mm • maximum 24-hour rainfall - mm • maximum 48-hour rainfall - mm • maximum 72-hour rainfall - mm • days of wind gust >= 24 knots - day • standard deviation of daily mean temperature - Celsius • lowest daily mean temperature - Celsius • highest daily mean temperature - Celsius • mean 9am relative humidity - percent • mean 9am temperature - Celsius. Normalised monthly and annual statistics for 30 year period
Methods used to measure parameters	Data comes from NIWA automated and manual climate stations and Meteorological Service electronic data.
Secondary sources of data	N/A
Scale of use	Most data is collected hourly or daily. Some is collected at 10 minute intervals.
Number of records	There are 2,312 open climate stations which are still reporting and 3,761 closed stations that are no longer reporting.
GIS compatibility.	The climate stations are located using latitude and longitude grid references.
Available formats for users.	The data is on an Oracle database. NIWA is working on developing web access. Reports are prepared on request.
Access constraints.	Those who want to extract data from the database need to be set up as online users. There is a variable charge for external users who access data by this means. Some staff handle requests for data and prepare reports; a charge is made. A manual and helpdesk are provided for online users.
Measurement Accuracy	Accuracy for various elements are dependent on the accuracy of the instruments being used. Some elements such as cloud amount are visually estimated.
Completeness of dataset	Some stations have perfect data sets. Others have gaps because of broken or faulty instruments, observer sickness or lost records. For any station a gap might be short or long, and gaps might be rare or frequent. Stations may sometimes reopen at the same site creating a gap. For many stations there are earlier records on paper, not yet stored in the database.

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Positional accuracy	Each station has its position located on a map, latitude and longitude determined in degrees and minutes, then these are stored as degrees to three decimal places. Early stations had positions based on old maps. Many of the later New Zealand stations also have grid references based on NZMS260.
Database steward	NIWA
Database custodian	NIWA
Database custodian contact person	Allan Penney
Database custodian Contact Address Phone Fax Email	NIWA, P.O. Box 14 901, Kilbirnie, Wellington + 64 4 386 0341 + 64 4 386 0341 + 64 4 386 0574 + 64 4 386 0574 a.penney@niwa.cri.nz
References	• NIWA NZ Climate digest (produced monthly) • Penney, A.C. 1999. Climate database (CLIDB) user's manual. Fourth edition (revised). NIWA Technical Report 59. • The Climate Update - a monthly summary of New Zealand's climate to assist management of climate-sensitive industries and environments. NIWA.
Date metadata record prepared.	October 1999
Author of metadata record.	Victoria Froude

Management Evaluation	
Original purpose.	The database was primarily established for scientific research purposes. It was also intended that it would assist with weather forecasting.
Relationships with classification systems.	N/A
Relationships with other databases	The data from the database links to the Water Resource Archive also managed by NIWA.
Known relationships with proposed EPIP indicators.	Not known.
Who uses this database?	There are approximately 100 registered users. These include

	NIWA staff, other Crown Research Institutes, ESR, Universities, consultancies, BRANZ, Agriculture NZ, power companies. There are also many occasional requests.
Public awareness of the database	There is a large NIWA web site. NIWA's National Climate Centre web page (www.niwa.cri.nz/ncc) provides access to a number of products such as "The Climate Update" every month, and details of a subscription service called "CLIMATE NOW" can be found under OTHER CLIMATE LINKS on that web page.
Database strengths.	• the database is a powerful one using Oracle; • the database has ISO 9002 certification; • data extends back to 1860's; • interactive web access is being developed.
Database limitations.	• Approximately 50% of the data is only on paper forms. This older data is being entered slowly into the electronic database as funds become available; • it is often difficult to identify specific climate information for a specific time. This is because individual sites only record some data; some stations can be for a short term only; and some long term stations can be closed for various reasons; • the analyses of long term trends in the data can be complicated because of the changing situations with climate stations (when they are open / closed; instrumentation changes, and changing environmental conditions around the station (e.g. increase or removal of shading and shelter).

What are the Current and Emerging Uses of the Database for:	
Assisting with determining historic state/baseline.	The database is primarily one of (recent) past climate. There are some difficulties with interpreting past data as, for example,. climate site conditions can change due to change in shading and shelter provided by vegetation and buildings.
Assisting with determining current state/baseline.	The database provides current climate (as opposed to weather) information.
Assisting with modeling possible future outcomes.	Intend to develop this.

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Risk assessment.	Used to assess / identify climate risk, e.g. drought.
Monitoring site selection and sample design.	N/A
Aggregating and reporting data locally, regionally or nationally.	Users determine how they want their data presented. As data is stored by station rather than region, or other administrative unit, it can be difficult to aggregate data because representative stations need to be selected.

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Database Title	**14.1 Water Resources Archive**
Keywords Type1. Type 11.	*Freshwater; water quality; water quantity.*
Abstract	*The Water Resources Archive is a national repository for freshwater time series data. It consists of two national networks and databases for water quality and water quantity. Types of data stored are:* • *river and lake water levels* • *river flows* • *river suspended sediment concentrations;* • *rainfall intensities* • *river water quality parameters(temperature dissolved oxygen, conductivity and pH)* *The management of the archive, including checking incoming data and distributing data to users, is covered by quality assurance (ISO 9002). Time series data is held from more than 1500 river and lake locations throughout New Zealand.* *Within the Water Resources Archive the National Water Quality Network contributes to the Water Quality Database. The National Hydrometric Network contributes to the Hydrometric Database.*
Geographical Coverage	New Zealand(mainland)
Dataset start date.	1905(water quantity). 1989(water quality)
Dataset end date.	Current
Status/currency.	In progress
Update frequency.	See contributing databases.
Maintenance.	Data are provided principally through a PGSF programme. Other providers include regional councils and the hydro electric sector.

Technical Evaluation	
Parameters- what is	See contributing databases

measured	
Parameters- what is calculated	See contributing databases
Methods used to measure parameters	See contributing databases
Secondary sources of data	See contributing databases
Scale of use.	See contributing databases
Number of records	>3 billion data values
GIS compatibility.	See contributing databases
Available formats for users.	CD Rom. In future the Water Resources Archive will be accessible by Internet, with connections to other important national databases such as New Zealand Land Resources Inventory. See contributing databases.
Access constraints.	See contributing databases
Measurement Accuracy	*To be completed by database manager.*
Completeness of dataset	*To be completed by database manager.*
Positional accuracy	*To be completed by database manager.*
Database steward	NIWA
Database custodian	NIWA
Database custodian contact person	1. Charles Pearson (water quantity) 2. Graham Bryers (water quality)
Database custodian Contact Address Phone Fax Email	1. P.O. Box 8602 Christchurch 2 +64 3 348 8987 +64 3 348 8987 +64 3 348 5548 +64 3 348 5548 c.pearson@niwa.cri.nz 2. P.O. Box 11-115 Hamilton +64 7 856 7026 +64 7 856 7026 +64 7 856 0151 +64 7 856 0151 g.bryers@niwa.cri.nz
References	
Date metadata record prepared.	October 1999

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Author of metadata record.	Victoria Froude

Management Evaluation	
Original purpose.	• To provide a basis for developing knowledge on freshwater resources and providing a basis for decision-making. • To identify trends in the condition of New Zealand freshwater bodies.
Relationships with classification systems.	See contributing databases
Relationships with other databases	Related databases include: • National Climate Database. The connection between these two databases allows the seamless transfer of data between the two systems • National Groundwater Database (IGNS) • Regional and District Council Water Resources Databases • Digital Elevation Models-to establish channel networks • Land Resource Inventory (to identify approximate evaporation) • Land Cover Database These databases are used in various ways to refine models on water quantity, water quality and land use.
Known relationships with proposed EPIP indicators.	N/A
Who uses this database?	The Water Resources Archive has a wide range of end-users including: • PGSF research programmes (more than 25 research programmes use the data, resulting in more than 30 scientific papers per year • industry including the hydro electric, agriculture, forestry and horticulture sectors • central government (MfE, DoC, Civil Defence) • local authorities (e.g. used by regional councils to determine low flow allocations) • international programmes (e.g. UNESCO, World Meteorological Organisation, International Association of Hydrological Sciences, International Panel on Climate Change, Land Ocean Interactions in the Coastal Zone)

Public awareness of the database	They have been some popular articles in Water and Atmosphere as well as several public talks. The hydrological community knows about the database.
Database strengths.	• There is continuity of data over time. • Data gaps are eliminated or minimized (e.g. damaged recorders are replaced as soon as possible). • There are many end users and uses for the baseline data. • The archive is easily accessible. • It is the only database that comprehensively stores New Zealand's freshwater data. There are reciprocal arrangements for sharing water resources data with 10 regional councils.
Database limitations.	• There is limited funding for the archive. This means that although the archive itself is managed there is little funding to interpret the data in the archive. • The Tideda software used for the archive is not a proprietary product (i.e. it is produced by NIWA). Regional councils use different products. There is not yet an effective way to communicate between these different types of software. • The original construction of the databases limits opportunities for future change. • Some monitoring sites are funded at least in part by non- government funders. When these funders no longer wish to contribute funding it can be difficult to keep the monitoring programmes for those sites going.

What are the Current and Emerging Uses of the Database for:	
Assisting with determining historic state/baseline.	The Archive contains historical records, especially for water quantity (hydrometric database). This data was used extensively in the analysis of the Opua Dam collapse.
Assisting with determining current state/baseline.	The data is used extensively for determining current condition of water bodies. The water quantity data is real-time data.
Assisting with modeling possible future outcomes.	The data is used extensively for determining current condition of waterbodies. The water quantity data is real-time data.
Risk assessment.	The data is used extensively for identifying hazards such as

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	floods and droughts.
Monitoring site selection and sample design.	The water quality network can be used for selecting sites for monitoring. The national hydrometric network was assembled on an ad hoc basis that was determined by user needs.
Aggregating and reporting data locally, regionally or nationally.	Annual reports and four quarterly reports are prepared for each database. There is also an annual report for each recording location. Data can be reported in regional council units.

Database Title	14.5 National River Water Quality Network
Keywords Type1. Type 11.	*Freshwater, water quality, rivers*
Abstract	*The National River Water Quality Network includes 77 sites distributed throughout the North Island (44 sites) and South Island (33 sites). The network was established in early 1989 using an agreed to design. At each site river flow, physical and chemical attributes and nuisance periphyton cover are measured either monthly or four weekly. The sites were selected to reflect both "baseline" conditions (32 upstream sites) and "impact" conditions (45 downstream sites).* *The field work is carried out by NIWA's 14 regional hydrometric field teams. The laboratory analyses are carried out at the NIWA Hamilton laboratory.*
Geographical Coverage	New Zealand North and South Islands
Dataset start date.	1989
Dataset end date.	Current
Status/currency.	In progress
Update frequency.	Monthly with each new data set
Maintenance.	PGSF funded database (part of Water Resources Archive)

Technical Evaluation	
Parameters- what is measured	• River flow • dissolved oxygen % saturation • river temperature • River visual clarity • PH • Conductivity • Turbidity • biochemical oxygen demand • absorption coefficient at 340 and 440 nm • oxidised N • ammoniacal N • total N

	• dissolved reactive P • total P
Parameters- what is calculated	Trends in the above parameters adjusted to recognise natural seasonal variation and flow dependence in some parameters.
Methods used to measure parameters	Field teams visited the sites once per month. At each site sampling was at the same time of day to remove diurnal variation. Field measurements included the first four items listed in parameters measured. Samples were collected for laboratory analyses of the remaining parameters measured. Every effort was made to ensure that field and laboratory sampling and measurement was consistent.
Secondary sources of data	N/A
Scale of use.	N/A
Number of records	10 years of monthly data (120 records) for 77 sites.
GIS compatibility.	Yes (point data)
Available formats for users.	The raw data is in Excel tables. Annual reports Published papers
Access constraints.	The data is freely available.
Measurement Accuracy	*To be completed by database manager.*
Completeness of dataset	*To be completed by database manager.*
Positional accuracy	*To be completed by database manager.*
Database steward	NIWA
Database custodian	NIWA
Database custodian contact person	Graham Bryers
Database custodian Contact Address Phone Fax Email	P.O. Box 11 115 Hillcrest Hamilton +64 7 856 7026 +64 7 856 7026 +64 7 856 0151 +64 7 856 0151 g.bryers@niwa.cri.nz
References	Smith, D.G.; Maasadam, R. 1994 New Zealand's national river quality network. 1 Design and physico-chemical characterization. *New Zealand Journal of Marine and Freshwater Research: Vol. 28: 19-35..* Smith, D.G.; McBride, G.B.; Bryers, G.G.; Wisse, J.; Mink,

2

	D.F.J. 1996. Rends in New Zealand's national river water quality network. *New Zealand Journal of Marine and Freshwater Research: Vol. 30: 285-500.* Smith, D.G.; McBride, G.B.; Bryers, G.G.; Davies-Colley, R.J.; Quinn, J.M.; Vant, W.N. 1989. A national water quality network for New Zealand. *DSIR Water Quality Centre Consultancy Report 8016/2.*
Date metadata record prepared.	October 1999
Author of metadata record.	Victoria Froude

Management Evaluation	
Original purpose.	To detect significant trends in water quality. To develop better understanding of the nature of water resources and thereby assist their management
Relationships with classification systems.	N/A
Relationships with other databases	Part of the National Water Resources Archive.
Known relationships with proposed EPIP indicators.	N/A
Who uses this database?	• NIWA - for research purposes and to assess the trends shown in the data. • Regional councils - to assist them in their water management responsibilities. • Industry - for resource consent applications. • International purposes (see Water Resources Archive)
Public awareness of the database	There is good awareness among regional council staff. Otherwise awareness is generally low.
Database strengths.	• The database contains a complete dataset. • There is rigorous quality control on the collection, measurement and analysis of data. • The data is readily available. • The data has been collected using consistent methods.
Database limitations.	• The database does not include microbiological,

	pesticides, organics and heavy metal data. • As funding for the database has remained constant there has been a reduction in funding available to analyse the data collected.

What are the Current and Emerging Uses of the Database for:	
Assisting with determining historic state/baseline.	The database will, over time, provide a historic baseline. This will allow comparison because there have been no changes in methods.
Assisting with determining current state/baseline.	The database provides a current baseline for a number of water quality parameters.
Assisting with modeling possible future outcomes.	The database is being used for trends analysis. It has been used for the hearings of some water conservation orders e.g. Mohaka, Motu and Wanganui.
Risk assessment.	The database is being used to develop models to predict the effects of land-use changes on river water quality (especially nutrient levels and water clarity).
Monitoring site selection and sample design.	The monitoring network has been carefully designed to cover a range of land uses and both control and impact sites.
Aggregating and reporting data locally, regionally or nationally.	Data can be reported at different levels. At this stage the focus has been on national trends analysis.

1. 0 The Geothermal-Groundwater (GGW) database overview

The GGW database has been developed by GNS Science and is designed to store geothermal and groundwater related data. The design and terminology of the GGW database are based on the Australian National Groundwater Data Transfer Standard (National Groundwater Committee Working Group on National Groundwater Data Standards, 1999), adapted for New Zealand conditions (Wood et al., 1999). The types of information that can be stored in GGW include: site location details, site owner names and contact details, surrounding land use, well construction, analytical methods and uncertainties, sampling and analytical results, and project details.

1.1 Terminology

Important terminology used in the GGW database and relevant to import of the regional authority SOE data includes:

Feature: A natural or constructed structure that allows some type of measurement to be made. A feature might be a well, bore, spring, seep, etc. A feature must have a specified location.

Feature identifier: A unique number assigned by the GGW database to each feature. This is a method of labelling sites that may have multiple names (e.g., as per site naming conventions that use the site owner's name) or, ensure that the same number assigned to two (or more) different features by two (or more) different regional authorities cannot exist. The GGW feature identifier should always be quoted in reports and documents where data for that site have been used, to ensure that the correct site can be identified later.

Event: A discrete episode of data collection from a feature.

Sample: The object for which properties are observed, measured or interpreted, e.g. water samples, rock samples.

Parameter: A specific property that has been measured, observed or interpreted during, or associated with, a sample collected during an event. A parameter is made up of several components including:

Parameter number – a unique identification number for each parameter (akin to a feature identification number for each feature).

Property – the characteristic that was measured, observed or interpreted, e.g. water level, pH, calcium concentration, electrical conductivity, etc. Chemistry properties are generically formatted within GGW as organic/inorganic–type/units–form–fraction, e.g. Inorganic–Iron mg/l–all forms as Fe–filterable.

Equipment – type of equipment used to measure the property.

Method – analysis method used to derive the property.

Detection limit of the method/equipment.

Result: the actual numeric value or qualitative descriptor of the measured parameter from a particular sample collected from a particular feature during a particular event. For example, if the parameter property is "Inorganic–Iron mg/l–all forms as Fe–

filterable", the result might be 0.51.

Analysis: An analysis is defined within GGW by event (a combination of Feature, project and sampling date), analysis type (field or laboratory) and event type (discrete, regular, duplicate, etc.).

Project: an amalgamation of all the features, events, samples, parameters, results, etc. collected for a particular coherent purpose.

1.2 Overview of database structure

The GGW database structure has been built to host georeferenced features, linked to projects. The design of the GGW database ensures unequivocal attribution, ownership traceability and retrieval of data. It also supports through table relationships activities such as summarising, querying, automated reporting. The data structure following the linkage: Project→ Feature→ Event→ Sample→Sample Analysis→ Parameter→ Result optimises storage volumes by disabling blank result to be held. It also prevent blank result to be counted when data summary are being run.

Sea Level Data

http://www.linz.govt.nz/hydro/tidal-info/gauges/index.aspx

LINZ has established a network of sea level monitoring sites at 18 locations around New Zealand and Antarctica.

The first site was established in March 2007 and the network was completed in July 2010.

Sea level data downloads

Sea level data (tide gauge readings) for each of the 18 sites is available for download.

With the exception of the Antarctic site, the primary purpose of the network is to upgrade and improve New Zealand's response to tsunami hazards. However, the data generated can also be used for other purposes.

To view plots of the sea level data and for more information on the use of sea level data in a tsunami detection system, visit the GeoNet website.

See below for details on sea level data that is also available from LINZ on behalf of other organisations, and from other sources.

Other sea level data available from LINZ

LINZ also obtains sea level data from port companies, regional councils and the National Institute of Water & Atmospheric Research Ltd (NIWA). This data is retained by LINZ and can be made available on request subject to the approval of the supplier of the data.

Requests for this sea level data can be made using our contact form (category type = "Nautical information").

Other sources of sea level data

Information about NIWA's sea level stations and data access can be found at NIWA - Sea levels and long waves and Environmental Data Explorer - Sea level monitoring stations.

The University of Hawaii Sea Level Center (UHSLC) also holds sea level data for a number of New Zealand sites. To find New Zealand data, click on the "Country" column to sort by country then scroll down to New Zealand.

Taihoro Nukurangi

National Institute of Water & Atmospheric Research

Sea Levels

This system combines daily sea-level data from NIWA, regional councils, port companies, Antarctica NZ, Bureau of Meteorology and territorial authorities.

- Anawhata
- Charleston
- Dog Island
- Green Island
- Jackson Bay
- Kaikoura
- Kaingaroa
- Kapiti Island
- Kawhia
- Little Kaiteriteri
- Lyttelton
- Marsden Point
- Moturiki Island
- Pouto Point
- Port Taranaki
- Raglan
- Scott Base
- Sumner Head
- Tararu
- Timaru
- Whitianga Wharf

This added-value service (updated daily) uses sea-level data streams from NIWA; regional councils (Northland Regional Council, Environment Waikato, Environment Canterbury); territorial authorities (Tasman District Council); port companies (Port Taranaki, Primeport-Timaru, Port Lyttelton); Antarctica NZ; and Bureau of Meteorology (Australia).

http://www.niwa.co.nz/our-services/online-services/sea-levels

Contact NIWA

Free phone within New Zealand
0800 RING NIWA
0800 746 464 0800 746 464

Environmental Data Explorer New Zealand

(http://edenz.niwa.co.nz/)

This web site provides access to near real-time and archive data from NIWA's extensive automated monitoring network. There are two ways that you can browse through the data:

Look at a type of data
(click on the data you are interested in)

Look at a part of the country
(click on the part of the country that you are interested in)

About this site

EDENz provides visitors with access to data from a range of stations monitored by NIWA. This site was created to display data from River Flow and Rainfall sites funded through the Foundation of Research, Science & Technology (FRST) Public Good Science and Technology (PGS&T) Nationally Significant Database program.

More recently it has been extended to include data relating to various Sea Level, Air Quality and Climate stations. While some Climate related data is shown on this site, NIWA's core Climate database is accessible from the Climate Database.

There are two types of data shown on this site. The first is near real-time data which has been transferred using a national telemetry network and is unaudited. This data is provisional and cannot be downloaded. The second type of data is archive data which has been reviewed and/or had quality assurance procedures applied. It is now possible to download the archive datasets from sites which are part of the Nationally Significant Database program. Other archive datasets are also available for download where the site owner has provided permission.

Nationally Significant Database: Water Resources and Climate

The goal of this programme is to provide comprehensive and accessible data as a basis for improved knowledge on New Zealand's climate and freshwater resources.

The programme collects, stores, and disseminates data from national monitoring networks, and comprises two core nationally significant databases:

- the Climate Database and
- the Water Resources Archive.

The data include air temperature, barometric pressure, wind direction, rainfall, lake and river water levels, river flows and sediment loads, and river water quality variables.

A key aspect of the archiving programme is application of stringent quality control procedures ensuring national consistency and providing assurance that data can be confidently used for scientific and planning purposes.

The databases are accessed by other PGS&T research programmes and by a wide spectrum of users, and contributes to the sustainable management of air and freshwater resources and ecosystems, flood control, and education.

The databases are augmented by over $1m of funding from the hydro-electricity industry and by data provided by regional councils.

FRST contract: C01X0029.
Programme coordinator: Dr Charles Pearson (email Charles).

Browser compliance

Considerable effort has been expended to ensure that this site is compliant with appropriate web standards. We have tested the site and found it to work reliably with the recent versions of Firefox and Internet Explorer.

2

If you are not using a standards-compliant browser or have JavaScript turned off the site may appear "funny" or may not function as expected. We recommend Firefox, available for free here.

Map display problems

A few users have reported that the pop-up "balloons" on the maps appear in the wrong place. This is usually due to old web browsers that cannot handle every detail of our modern maps. For best results, you may like to upgrade (for free) to the faster and more secure latest version of Firefox.

Terms of use

Use of this website is subject to our terms and conditions of use.

APPENDIX B: ECONOMIC FACTORS AND EMPLOYMENT IN THE WAIMEA PLAINS

Appendix B.1: Agriculture

Economic factors and employment related to water use by agriculture are summarised in this Appendix for the irrigated agricultural uses apples, dairy, horticulture, market gardening, and other (Appendix Tables B-1 through B-5, respectively). The factors were assembled from observed data and presented in tables with references to the source of the data.

One objective was to estimate values for the year 2005. Therefore data for the period 2003/2004 – 2005/2006, from the 2003/2004-2007/2008 water economics survey (White, 2010), were preferred where suitable. Other data from the 2003/2004-2007/2008 water economics survey were used if more suitable. Data sources are listed in each table. For example “2004-2005” refers to data from the 2003/2004-2005/2006 survey and “2005” refers to the 2004/2005 survey year. Generally, typical water use was calculated as the median and time-average estimates were calculated for the average (e.g., production and land area). Land price estimates consider availability of some “permitted” water uses (see Section 6.2.1) such as domestic use and stock water. For example, land prices were estimated with a change in water availability for all uses.

Targeted data for the full range of “other” land uses (Appendix Table B-5) was not completed in the 2003/2004-2007/2008 survey. Water economic indicators for other irrigated land uses were assumed as the same for cropping. Water economic indicators for cropping were taken from one small farm that produced lucerne in 2005. Land price was taken as that for dairy land use.

Water economic factors for non-irrigated agriculture (Appendix Table B-6) were estimated by Fenemor (2010). These include:

1. Stocking rates 12 – 15 SU (stock units) per hectare. One ewe is 1 SU and a beef cow is 5.5 SU);
2. Water needs by stock as follows -
    a. Sheep, 3 – 4.5 L/head/day;
    b. Cattle, 30 - 45 L/head/day.
3. Gross dryland sheep and beef returns approximately $1,000/ha.

Economic indicators were estimated as follows:

1. Average land value per ha at zero water availability of $22,300. This was based on reduction in land values of $300/ha with no water for stock watering (White and Sharp 2002);
2. Average land value per ha at 100% water availability of $56,100. This was based on the estimated value of dairy land without irrigation in 2005 (Appendix Table B - 2);

3. Water use at zero water availability of 0 m^3/ha/year and at 100% water availability of 50 m^3/ha/yr (assuming 3 beef cows/ha and 45 l/day/head);

4. Production at zero water availability of 0$/ha and at 100% water availability of $1,000/ha (Fenemor, 2010).

Appendix B.2: Commercial

These data were based on the 1999 survey by White, et al. (2001) of 13 commercial users of groundwater in the Waimea Plains by businesses not on and on TDC reticulated water supply. Production by these commercial users included wood, juice, meat, hops, gravel, concrete, wine, and fruit.

Results of this survey aggregated for the 13 businesses are presented in Appendix Table B-7 and include:

1. A production index which expresses the change in production across all products with the change in water availability;

2. Market value, the estimated value of the firms with the change in water availability;

3. Estimated water use with the change in water availability, assumed as prorated by the production index

4. Expenditure on labour as estimated by the firms.

Estimates of market value and direct employment in 2005 were made aiming to have values comparable to estimates of land values for agriculture. Market value and employment in 2005 were estimated from the 1999 survey by adjustment using the consumer price index (CPI) from Reserve Bank of New Zealand (2010). The annual average of the four-quarter CPIs was 834 for 1999 and 967 for 2005. Therefore estimates from the 1999 survey were adjusted by 1.16 (Appendix Table B-7).

Appendix B.3: Urban

The economic value of the Richmond water supply was approximately $38 million in 2005. This was calculated by:

Assessment of the net cost of alternative options for Richmond water supply of $33 million in 1999 (White, et al., 2001). The survey was completed in 1999 by TDC;

Adjustment of this figure by the CPI (Reserve Bank of New Zealand, 2010) between 1999 and 2005 (the ratio of 1.16 noted above).

Water use per person in Richmond was estimated as (Appendix E):

1. 100 m^3/person/year in 1996 and prior years;

2. 149 m^3/person/year in 2001; and

3. 177 m^3/person/year in 2006.

As noted in Appendix E there is some evidence that per capita consumption is increasing over time. Estimated use per hectare also appears to be increasing over time (Appendix Table B-8).

The economic value of Richmond municipal water supply (Appendix Table B-9) was estimated assuming:

1. Water use equals water availability;

2. Water value is approximately \$21.2 /m^3 (i.e. the estimated value in 2005 of \$38 million divided by the estimated water use in 2006 of 1.79 million m^3);

3. Values in 2050 (as 2005 dollars) are approximately 2.6 times values in 2005 based on the estimated increase in population.

Appendix B.4: In Situ Values

In situ values of the Waimea Plains water resource estimated in this appendix are based on surveys of Waimea Plains residents in 1999 (White, et al. 2001). Use values estimated herein are those associated with surface water only. Non-use values estimated here are those associated with the maintenance of environmental services. Non-use values do not include existence values as these were not assessed in the survey.

Appendix B.4.1: Use of Surface water

A survey of Richmond households in 1999 included questions about the recreational use of the surface water features in the Waimea Plains indicated in Appendix Figure B-1. This was a random survey of 398 of the approximately 6,300 households on the Waimea Plains (White et al., 2001). A total of 180 of the survey questionnaires were returned for detailed evaluation.

Results of this survey are summarized in Appendix Table B-10. The Wairoa-Waimea River feature is the most used for recreation and swimming during summer months is the most common activity.

Actual resident trout angler days for the whole Waimea catchment were: 1,780 ± 340 for the 1994-95 fishing season; 240 ± 80 for the 2001-02 fishing season; and 390 ± 150 for the 2007-08 fishing season (Deans, 2010). Fishing for trout and some estuarine species is undertaken, mainly in the lower Waimea River. However the fishing effort has declined over the past 15 years due to the frequency of low or nil flows in the river (Unwin, 2009).

The Waimea River, and its berms, are also used for gamebird hunting during the winter season; being particularly favoured by pheasant hunters for the limited three weekend season each year. Hunters come from around the whole region to hunt this major publicly administered area (Deans, 2010).

Little use is made of Pearl and Neiman creeks for any form of recreation and no respondent in the survey reported hunting. However, Deans (2010) found that some whitebait fishing and gamebird hunting occurred in the lower reaches of these creeks in season (spring and late autumn/winter, respectively).

The “travel cost” method is commonly used to estimate the value of recreation. The value of recreation related to surface water was estimated in Appendix Table B-10 as follows:

1. Estimates were made of costs/day for different recreational activities;

2. Estimates of costs/year for all respondents in the survey (i.e., person-days/year times the cost of each trip);

3. Estimates of costs/year for all Waimea Plains households (TAH) based on 35 times the costs for those respondents surveyed (respondent households were 1/35th of all households).

4. Estimates of costs/year for all TAH adjusted to 2005 using the CPI (i.e., multiplying by a factor of 1.16).

5. Estimates of the capitalized total economic value (in $Millions) to all households made using annual cost discounted at 5%.

Appendix B.4.2: Non – use values

A survey of householders in the Waimea Plains indicated a mean willingness-to-pay for environmental services provided by the groundwater resource of at least approximately $183/year per household (White et al., 2001). Environmental services provided by the groundwater resource that were mentioned in the survey included: prevention of sea water intrusion to groundwater; maintenance of flow in the Waimea River preventing algal growth; and maintenance of flow in spring-fed Pearl and Neiman creeks).

A similar study of the residents of Christchurch (Kerr et al., 2003) indicated a mean willingness to pay for the protection of the local groundwater supply of approximately $800/year per household. These values indicate that people value the groundwater resource for the environmental benefits (i.e., in situ values) it delivers.

The in situ value of Waimea Plains groundwater resources for provision of environmental services was estimated as at least $1.15 million/yr (i.e., at least $183/yr per household times approximately 6,300 households on the Waimea Plains). The equivalent capitalized value is $26.7 million (i.e., the annual cost discounted at 5% including an adjustment (1.16) for the CPI index (Reserve Bank of New Zealand 2010) between 1999 and 2005.

In situ values of the surface water resource were considered to some degree in the Waimea Plains household survey. For example, maintenance of spring flow and maintenance of surface water base flow in the Waimea River were part of the Waimea Plains householder survey. Therefore, to the degree that such in situ groundwater environmental values as maintenance of base flow are involved, a targeted survey of in situ values associated with surface water may overlap with in situ values for the groundwater system.

In situ values such as existence values and ecological health were not explicitly assessed in this household survey and it is possible that these two values were considered by respondents. Therefore, these two values are included in the estimate of minimum willingness-to-pay to maintain environmental services provided by the groundwater resource.

Appendix B.4.3: In situ values and water availability

The relationship between in situ values and water availability in Appendix Table B-11 depends largely on assumptions because collection of data on this relationship was beyond the scope of this project. The following assumptions were made:

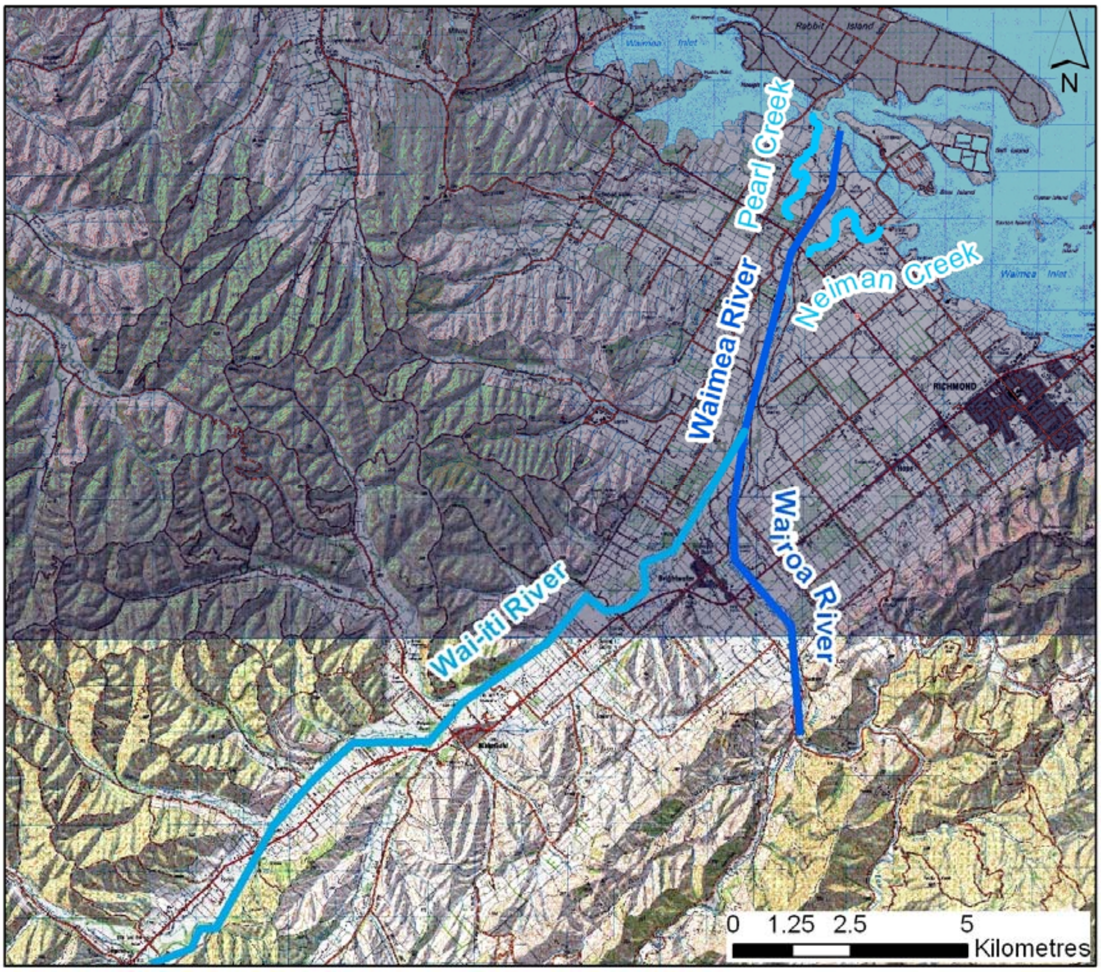
1. In situ values increase as water becomes more available;

2. The change in situ water values decreases as water availability increases (i.e., Figure 6.6). For example, the change of the in situ value for groundwater was estimated as –

   a. $7.5 million between 0 and 20% water availability; and
   b. $6.3 million between 20 and 40% water availability.

3. The magnitude of the decrease of in situ values with water availability is arbitrary.

In situ values in 2050 are equal to the 2005 values (Appendix Table B-12) multiplied by 2.6, the estimated increase in population between 2005 and 2050.



Appendix Figure B-1: Surface water features assessed for recreational use in 1999.

Appendix Table B-1: Economic indicators for water availability to agriculture for apples use[1]

Water Availability (% of current allocation)	Apple Area (Fraction of current Allocation)	Production TCE (Fraction of current Allocation)	Production (TCE/ha)	Revenue ($/TCE)	Land Price ($/ha)	Water Use (m^3/ha/yr)	Employment Spend ($/ha)
0.	0.00	0.00	0.	0.	65,100.	3,560	0.
40.	0.41	0.41	1,800.	19.45	79,300.	3,560	12,000.
60.	0.83	0.83	1,800.	19.45	82,200.	3,560	12,000.
80.	1.00	1.00	1,800.	19.45	86,300.	3,560	11,000.
100.	1.00	1.00	1,800.	19.45	102,600.	3,560	12,000.
120.	1.00	1.00	1,800.	19.45	102,600.	3,560	11,000.
Time Frame	2004-2006	2004-2006	2004-2006	2004-2006	Average 2005	Median 2004-2008	2004-2006

1. *Data from White (2010).*

Appendix Table B-2: Economic indicators for water availability to agriculture for dairy use[1]

Water Availability (% of current allocation)	Dairy Area (Fraction of current Allocation)	Milk Solids (Fraction of current Allocation)	Milk Solids (kg/ha)	Revenue ($/kg)	Land Price ($/ha)	Water Use (m^3/ha/yr)	Employment Spend ($/ha)
0.	0.00	0.00	0.	0.	22,300.	0.	0.
40.	0.25	0.25	1,542.	4.32	33,800.	2,700.	3,700.
60.	0.42	0.42	1,542.	4.32	45,700.	2,700.	3,000.
80.	0.98	0.98	1,542.	4.32	51,500.	2,700.	2,000.
100.	1.00	1.00	1,542.	4.32	56,100.	2,700.	2,200.
120.	1.00	1.00	1,542.	4.32	56,500.	2,700.	1,800.
Time Frame	2004-2006	2004-2006	2004-2006	2004-2006	Average 2005	Median 2004-2008	2004-2006

1. *Data from White (2010).*

Appendix Table B-3: Economic indicators for water availability to agriculture for horticulture use

Water Availability (% of current allocation)	Horticulture Area (Fraction of current Allocation)	Production (Fraction of current Allocation)	Revenue ($/ha)	Land Price ($/ha)	Water Use (m³/ha/yr)	Employment Spend ($/ha)
0.	0.00	0.00	0.	65,100.	0.	0.
40.	0.24	0.24	30,800.	79,300.	2,149.	32,000.
60.	0.41	0.41	30,800.	82,200.	2,149.	36,000.
80.	0.48	0.48	30,800.	86,300.	2,149.	39,000.
100.	1.00	1.00	30,800.	102,600.	2,149.	39,000.
120.	1.00	0.96	30,800.	102,600.	2,149.	39,000.
Time Frame	2004-2006	2004-2006	2004-2006	Use Data for Apples	Median 2004-2008	2004-2006 Prorated

1. Data from White (2010).

Appendix Table B-4: Economic indicators for water availability to agriculture for market gardening use[1]

Water Availability (% of current allocation)	Market Garden Area (Fraction of current Allocation)	Production (Fraction of current Allocation)	Production ($)	Revenue ($/ha)	Land Price ($/ha)	Water Use (m³/ha/yr)	Employment Spend ($/ha)
0.	0.00	0.00	0.	0.	147,100.	0.	0.
40.	0.47	0.47	165,393.	16,400.	156,800.	1,655.	22,000.
60.	0.75	0.75	263,925.	16,400.	166,700.	1,655.	30,000.
80.	0.76	0.76	267,444.	16,400.	166,700.	1,655.	31,000.
100.	1.00	1.00	351,900.	16,400.	166,700.	1,655.	31,000.
120.	1.09	1.09	383,571.	16,400.	166,700.	1,655.	31,000.
Time Frame	2005-2007	2005-2007	2005-2007	2005-2007	Average 2005	Median 2004-2008	2005-2007

1. Data from White (2010).

Appendix Table B-5: Economic indicators for other irrigated land uses[1]

Water Availability (% of current allocation)	Area (Fraction of current Allocation)	Production	Revenue ($/ha)	Land Price ($/ha)	Water Use (m^3/ha/yr)	Employment Spend ($/ha)
0.	0	0	0.	22,300.	0.	0.
40.	0	0	0.	33,800.	0.	0.
60.	0	0	0.	45,700.	0.	0.
80.	1	1	2,400.	51,500.	1,200.	1,300.
100.	1	1	2,400.	56,100.	1,200.	1,300.
120.	1	1	2,400.	56,500.	1,200.	1,300.
Time Frame	2005, one farm	2005, one farm	2005, one farm	2005, average	2005, one farm	2005, one farm

1. *Data from White (2010). Targetted data collection for the full range of other land uses was not completed in the 2004–2008 survey. Water economic indicators for other irrigated land uses are assumed as the same for cropping. Water economic indicators for cropping are taken form one small farm that produced lucerne in 2005. Land price is taken as that for dairy land use.*

Appendix Table B-6: Economic indicators for non-irrigated agriculture land use[1]

Water Availability (% of current allocation)	Area (Fraction of current Allocation)	Production (Fraction of current Allocation)	Revenue ($/ha)	Land Price ($/ha)	Water Use (m^3/ha/yr)	Employment Spend ($/ha)
0.	1	0.00	0.	22,000.	0.	0.
40.	1	0.40	400.	22,120.	50.	300.
60.	1	0.60	600.	22,180.	50.	300.
80.	1	0.80	800.	22,240.	50.	300.
100.	1	1.00	1,000.	22,300.	50.	300.
120.	NA	1.20	1,200.	22,300.	50.	300.
Time Frame	Estimate	Estimate	Estimate	See above	Estimate	Estimate

1. *Data from White (2010). Economic indicators were estimated as follows:*
a. *Average land value at 0 water availability of $ 22,300 (based on reduction in land values of $300 with no water for stock watering from White and Sharp, 2002);*
b. *Average land value at 100% water availability of $22,300 (based on estimated value of dairy land without irrigation in 2005 from Table C-2);*
c. *Water use at 0 water availability of 0 m3/ha/yr;*
d *Water use at 100% water availability of 50 m3/ha/yr (assuming 3 beef cows/ha and 45 L/day/head);*
e. *Production at 0 water availability of $0/ha;*
f. *Production at 100% water **availability** of $1,000/ha (Fenemor 2010).*

Appendix Table B-7: Economic indicators for water availability to commercial/industrial users[1,2]

Water Availability (% of current allocation)	Production Index	Market Value Millions of $	Water Use (m^3/ha/yr)	Employment Spend ($/ha)
0.	0.45	440.6	770,000.	23.2
40.	0.61	456.2	1,040,000.	24.2
60.	0.81	517.6	1,380,000.	34.3
80.	0.98	565.4	1,670,000.	39.3
100.	1.00	600.2	1,700,000.	44.0
120.	1.02	602.5	1,730,000.	44.2
Time Frame	1999	1999	1999	1999

1. *Data from White (2010).*
2. *Adjusted to estimate 2005 values.*

Appendix Table B-8: Estimated Richmond water use on an urban land area basis[1]

Year	Estimated Urban Area ha	Estimated Water Use Million m^3/yr	Water Use (m^3/ha)
1950	84.74	0.2	2360
1960	140.11	0.35	2498
1970	149.17	0.57	3821
1980	247.01	0.68	2753
1990	274.01	0.78	2847
2000	456.19	1.58	3463

[1] Estimated for the nearest year

Appendix Table B-9: Estimated economic value of Richmond municipal water supply.

Water Availability % of Current Use	2005 Value $Millions	2050 Value $Millions
0	0.00	0.00
20	7.60	19.80
40	15.20	39.52
60	22.80	59.30
80	30.40	79.00
100	38.00	98.80
120	45.60	118.60

Appendix Table B-10: Estimates of recreational use surface water features by survey respondents

Activity	Daily	Wairoa-Waimea River		Wai-iti River		Pearl and Neiman Creeks	
	Cost ($)	person-days/year	$/Year	person-days/year	$/Year	person-days/year	$/Year
Picnicking	10	356	3,560	22	220	25	250
Walking	10	530	5,300	99	990	4	40
Bird watching	10	2	20	0	0	2	20
Fishing	20	60	1,200	2	40	0	0
Canoeing	10	51	510	0	0	0	0
Swimming	10	1,221	12,210	122	1,220	0	0
Power boating	50	8	400	0	0	0	0
Hunting	10	18	180	3	30	6	60
Jogging	10	51	510	13	130	0	0
Ex Pet	10	180	1,800	40	400	0	0
Working	10	6	60	6	60	0	0
4WD	20	9	180	0	0	0	0
Geology	10	2	20	0	0	0	0
Painting	10	4	40	0	0	6	60
Horseriding	10	19	190	27	270	0	0
Biking	10	6	60	0	0	0	0
Scouts	10	0	0	30	300	0	0
Total for Respondents	-	2,523	26,240	364	3,660	43	430
Total All Households (TAH)	-	-	918,400	-	128,100	-	15,050
TAH Adjusted to 2005	-	-	1,065,344	-	148,596	-	17,458
Capitalized Value All Households	-		$Millions		$Millions		$Millions
All Households	-		21.3		3.0		0.3

Appendix Table B-11: Estimated in situ values as a function of water availability (2005)

Water Availability % of current allocation	In Situ Value Groundwater ($Millions)	In Situ Value Surface Water ($Millions)
0	100.0	100.0
40	66.8	61.5
60	44.5	41.0
80	33.4	30.8
100	26.7	24.6
120	22.3	20.5

APPENDIX C: SOCIAL INDICATORS IN THE WAIMEA PLAINS

This appendix summarizes some social indicators (NZDep2006, Appendix B; and employment) and estimates of their relationship with water availability.

The NZDep2006 index for meshblocks including the Waimea Plains is summarised in Appendix Table C-1. The average of the NZDep2006 for the Tasman District is less than 1,000 (implying that social deprivation in the District is less than the national average). The average of the NZDep2006 for the rural Waimea Plains is less than urban Waimea Plains (implying that social deprivation in rural areas is less than in urban areas). However, because the standard deviation is greater than the difference, it is assumed that the difference in NZDep2006 between rural and urban Waimea Plains is not significant. Therefore, the NZDep2006 is assumed the same for all of the Waimea Plains.

Despite the fact that there was only weak correlation between the regional average NZDep2006 and weekly income (a coefficient of determination of 0.314), some relation between the two was evident in Appendix D. Therefore, the relation between average NZDep2006 for the Waimea Plains $NZDep2006_{WP}$ and estimated 2005 weekly income (WI2005), which was estimated as the 2006 weekly income corrected by the CPI of about 3% between 2005 and 2006, used was:

$$NZDep2006_{WP} = -0.28\ (WI2005) + 1173$$

The relationship between $NZDep2006_{WP}$ and water availability (Appendix Table E-2) was estimated for 2005 assuming labour supply was constant but that income changed with water availability. Direct employment commercial and agricultural income was estimated for 2005 land use and these estimates then translated into the NZDep2006 including pro-rating them to the NZDep2006 value of 977 for the Tasman Region in 2006 for 100% water availability (Appendix D).

The difference in $NZDep2006_{WP}$ estimates between 100% water availability and 0% water availability was estimated as 22 (i.e. 1025 – 1005). This change in $NZDep2006_{WP}$ is about the same as the current difference of NZDep2006 between the Tasman and Taranaki regions of 977 and 999, respectively (Appendix D).

The number of Waimea Plains households was estimated as 7,700 in 2006. The annual income for these households was also estimated as a total of $512 million with Statistics New Zealand data including taking into account wage and salary as a proportion of household income (78% in 2006), annual South Island household income relevant to the Waimea Plains ($73,952/year in 2008), and average individual income ($36,400/year in 2008). This income is associated with an estimated labour effort of 12,320 FTE.

Information on employment and expenditure on employment was collected during the 1999 and 2004–2004 Waimea Plains water economic surveys. Data on employment was summarised for agriculture and the commercial/industrial sector (Appendix B). Employment indirectly related to water use was estimated by the use of multipliers. The multiplier for employment, related to agriculture, was estimated as 1.94 times direct employment by agriculture (Ford, et al., 2001). Therefore total employment (direct plus indirect) related to water use by agriculture is approximately twice that estimated in the surveys.

For example, the estimated expenditure on labour per hectare was expressed as full-time equivalents (FTE) on a 100 ha dairy farm (Appendix Table C-3). This assumes one FTE is the equivalent of approximately $31,500/yr for 2005 (i.e., median weekly earnings of $605/week from the estimate of median weekly earnings in 2006 of $624/week for the Tasman/Nelson region adjusted to 2005 by use of the CPI). Total employment was estimated as 8.2 FTE for this farm, including 4.1 FTE of indirect employment.

Appendix Table C-1: NZDep2006 for meshblocks including the Waimea Plains

Area	NZDep2006	
	Mean	Standard Deviation
Tasman District	969	53
Waimea Plains	944	50
Waimea Plains - urban	948	53
Waimea Plains - rural	931	32

Appendix Table C-2: Estimated NZDep2006 and water availability.

Water Availability % of Current	Direct Employment ($Millions)			Waimea Plains Income $Millions	Income Index	Estimated 2005 Weekly Income $	Estimated NZDep2006
	Commercial	Agricultural	Total				
0	23.2	0.0	23.2	446.1	0.87	527	998
40	24.2	39.9	64.1	487.0	0.95	575	986
60	34.3	43.9	78.2	501.1	0.98	594	981
80	39.3	43.9	83.2	506.1	0.99	600	979
100	44.0	45.1	89.1	512.0	1.00	606	977

Appendix Table C-3: Employment dairy land use.

Water Availability % of Current Allocation	Employment Spend $/ha	Dairy Land Area ha	Estimate Direct Employment (FTE)	Estimated Indirect Employment (FTE)	Estimated Total Employment (FTE)
0	0	0	0	0	0
40	0	0	0	0	0
60	0	0	0	0	0
80	1,300	100	4.1	4.1	8.2
100	1,300	100	4.1	4.1	8.2
120	1,300	100	4.1	4.1	8.2

APPENDIX D: NATIONAL SYSTEMS OF SOCIAL INDICATORS

This appendix identifies some of the social indicators available through Statistics New Zealand surveys and an index (The New Zealand Index of Deprivation) that is a useful summary of social conditions. Health conditions are related to social and economic conditions indicators. Therefore this appendix also summarises research on the relation between health and socioeconomic indicators.

This appendix shows that social indicators available for New Zealand are a subset of potential social indicators, such as those available for the German population. Information on the German system is provided to put the nature of the New Zealand system into context. Some social indicators indentified in the German system are available through Statistics New Zealand but do not appear to be identified directly by Statistics New Zealand as social indicators.

APPENDIX D.1: New Zealand Social Indicators

Statistics New Zealand (www.stats.govt.nz) records social data in groupings including: education and training; health; people and communities; population; and work, income and spending. Statistics New Zealand has the responsibility of running the following population census and social surveys:

1. Household Labour Force Survey (HLFS), available from 1986 including data on people employed, unemployed, or not in the labour force -

    a. the jobless; those without a job and (presumably) wanting a job.
    b. total actual hours worked.
    c. household composition.
    d. underemployment.

2. Household Economic Survey (HES), available from 1998 including -

    a. average annual household income.
    b. household expenditure on housing costs.
    c. household material standard of living.
    d. personal demographics.
    e. household demographics.

3. New Zealand Income Survey (NZIS), available from 1998 including wage and income measures.

4. Survey of Family, Income and Employment (SoFIE), available from 2002/2003 including –

    a. family type.
    b. household type for individuals.
    c. labour force involvement.
    d. number of labour force involvement.
    e. weekly employee earnings total duration of labour force involvement.

5. General Social Survey (NZGSS), available for 2008 only (first year conducted) including -

   a. overall life satisfaction.
   b. Health.
   c. knowledge and skills.
   d. paid work.
   e. economic standard of living.
   f. Housing.
   g. physical environment.
   h. safety and security.
   i. support across households.
   j. social connectedness.
   k. leisure and recreation.
   l. culture and identity.
   m. human rights.

Other social indicators relevant to the potential effects of climate change on society include:

1. The New Zealand Index of Deprivation (NZDep); and

2. Health indicators.

The NZDep is performed at five year intervals starting in 1991 and is based on information from the national census. The 2006 index included, in order of decreasing weight (Salmond, et al., 2006 and 2007):

1. Income (i.e., people aged 18-64 receiving a means tested benefit);

2. Income (i.e., people living in households with income below an income threshold);

3. Home ownership;

4. Support (i.e., people less than 65 years old living in a single parent family);

5. Unemployment of those aged 18 – 64;

6. Qualifications of those aged 18 – 64;

7. Living space of those living below a bedroom occupancy threshold;

8. Communication (i.e., people with access to a telephone);

9. Transport (i.e., people with access to a car).

The index is calculated within approximately 41,400 meshblocks. “Meshblocks” are geographical units defined by Statistics New Zealand containing a median of approximately 87 people in 2006 (Salmond, et al. 2007). Two indices were calculated for the NZDep in 2006 (NZDep2006):

1. The NZDep2006 continuous score, scaled to a mean of 1000 index points and a standard deviation of 100 index points with low scores representing the least deprived areas and high scores representing the most deprived areas.

2. NZDep2006 ordinal scale ranging from 1 to 10 with low scores representing the least deprived areas and high scores representing the most deprived areas. The ordinal scale is derived from the continuous score.

The NZDep2006 continuous score is averaged for each region of the country in two ways (Appendix Table D-1): (1) as an average by meshblock; and (2) as a weighted average by meshblock population. Generally the NZDep is inversely related to a measure of average regional wealth (Appendix Table D-1, Appendix Figure D-1) where greater average wealth generally means less deprivation. For example:

1. The four regions with the highest regional GDP/capita in 2001 were less deprived than average in 2006 (i.e., a NZDep less than 1000);

2. The four regions with the lowest regional GDP/capita in 2001 were more deprived than average in 2006 (i.e., a NZDep greater than 1000).

Weekly regional income for those employed (Appendix Table D-1, Statistics New Zealand 2009c) is somewhat related to the regional average NZDep2006 (Appendix Figure D-2). The correlation between NZDep2006 and weekly income is poor (R^2 = 0.3143), but it does appear that there is some relation between the two variables. It is noteworthy that 10 of the 16 regions were plotted in Appendix Figure D-2. This is because Statistics New Zealand (2009c) aggregates regional income for six regions (footnote to Appendix Table B.1); data for these regions were not plotted in Appendix Figure D-2). A relation between weekly regional income and the NZDep2006 regional average is not surprising as income is part of the NZDep2006.

Other New Zealand social indicators (e.g., health, knowledge and skills, civil rights, cultural identity and recreation) are summarised for the general population (Ministry for Social Development and Employment, 2006) and for children and young people (Ministry for Social Development, 2008).

Good health is related to social, cultural and economic factors (National Advisory Committee on Health and Disability, 1998). The National Advisory Committee on Health and Disability (1998) also found “there are persisting health inequalities as a result of socioeconomic factors in New Zealand” and that “people in the lowest socioeconomic groups consistently have the poorest health.” For example, New Zealand males, between 1975- 1977 and 1985-1987, in the lowest social class had age-standardised mortality rates about two times the rates for males in the highest social class.

Statistics on health indicators recorded by District Health Boards (not analysed in this report) are available through the Ministry of Health (Lewis, 2010) and include:

1. Hospital surgical activity, www.moh.govt.nz/moh.nsf/indexmh/dataandstatistics-subjects-surgvolsmar10;

2. Fetal and infant deaths, www.moh.govt.nz/moh.nsf/indexmh/fetal-infant-deaths-2006;

3. Mortality and demographic data - www.moh.govt.nz/moh.nsf/indexmh/mortality-demographic-data-2007;

4. Suicide facts - www.moh.govt.nz/moh.nsf/indexmh/suicide-facts-deaths-2007-dec09.

National Advisory Committee on Health and Disability (1998) notes that "there is good evidence that (the) level of individual or family income affects individual health." They propose a general relationship between health and family income where:

1. Relatively large improvements in health are associated with modest improvements in family income at low incomes; and

2. Relatively small, or no, improvements in health are associated with modest improvements in family income at high incomes.

Social and economic inequalities are also related to health measures in New Zealand. As Ministry of Health (2000) found, "the Dep96 deprivation index appears to have the strongest association with health outcomes (including morbidity and risk factors such as smoking) of all the socioeconomic indicators examined."

Health is also related to ethnicity, with Maori health worse than the health of persons of European extract across many measures. For example "life expectancy at birth for non-Maori exceeded that of Maori by 8.6 years for males and by 7.9 years for females in 2005–07" (Statistics New Zealand, 2009). Relatively poor Maori health is possibly related to relatively low Maori income levels. For example median annual personal income for Maori was $20,900 and median annual personal income for persons of European extract was $25,400 in the 2006 census (www.stats.govt.nz).

There is a clear relationship between average per capita income and measures of health in developing countries; however, in developed countries improvements in health are not strongly related to rates of economic development and increasing per capita incomes. Wilkinson and Pickett (2009), for example, make a strong case that health and social measures in developed countries are related to inequality.

APPENDIX D.2: German Social Indicators

The German system provides a good example of a national system of social indicators (www.gesis.org/en/services/data/social-indicators/the-german-system-of-social-indicators). It includes approximately 400 indicators and more that 3,000 time-series data sets.

The German system includes the following indicators:

1. Population:

    a. Number of residents, births, children, immigrants, marriages and divorces;
    b. Growth rate; and
    c. Percentage of people living in cities/small towns;

2. Socioeconomic status and subjective class identification:

a. Income sources;
b. Number of people or percentage of population in employment and self-employment;
c. Subjective class identification;

3. Labour market and working conditions:

a. Size of working age population;
b. Work conditions;
c. Working time;
d. Unemployment;
e. Job satisfaction;

4. Income and income distribution:

a. Income;
b. Poverty rate;
c. Share of net income of the poorest percentage of population;
d. Satisfaction with income;
e. Concern about economic situation;
f. Importance of income.

5. Consumption and supply:

a. Per capita consumption;
b. Energy consumption;
c. Number of households with phones, freezer, dishwasher, video recorder, computer;
d. Level of short-term security provided by property;
e. Monthly savings;
f. Welfare expenditures;
g. Food, clothing and housing expenditures;
h. Taxes and social insurance payments,
i. Satisfaction with living standard or with the supply of goods and services.

6. Transportation:

a. Distances travelled;
b. Distances travelled per transportation mode;
c. Specific travel purposes (job, education, etc.);
d. Time needed to travel to work;
e. Households that own a car;
f. Access to public transport system;
g. Transportation risks, deaths and casualties in traffic accidents (by mode of transportation);
h. Expenditures of transportation;
i. Emissions and noise pollution;
j. Energy consumption;
k. Surface area covered by transportation system.

7. Housing:

   a. Housing units per household;
   b. Unoccupied units;
   c. Rooms and residential space per person;
   d. Housing without standard amenities;
   e. Noise pollution;
   f. Rent;
   g. Housing ownership;
   h. Satisfaction with housing condition.

8. Health:

   a. Life expectancy;
   b. Mortality rate, accident, drugs and disease death rates;
   c. Sick leave, sick rate, hospital stays;
   d. Permanent disability and illness;
   e. Regular medication;
   f. Subjective evaluation of personal health;
   g. Percentage of population that is very concerned about health;
   h. Satisfaction with health;
   i. Health insurance;
   j. Number of physicians, dentists, hospital beds;
   k. Health care expenditures as a percentage of the GDP;
   l. Early cancer diagnoses examinations;
   m. Work and traffic accidents;
   n. Alcohol and cigarette consumption;
   o. Percentage of overweight people and smokers.

9. Education:

   a. Children in school, kindergarten and child care;
   b. School attendances by school type;
   c. School leavers;
   d. University students;
   e. Adult education centres;
   f. Participation in extended vocational training/continuing education;
   g. Foreign language skills;
   h. Computer skills;
   i. Deficient literacy in maths, reading or science;
   j. College or university degree;
   k. Unemployment rates for people without vocational training;
   l. Unemployment rates for people with university degree;
   m. Education expenditures and funding;
   n. Satisfaction with educational attainment.

10. Participation:

    a. Voter turnout at elections;
    b. Participation in political parties, citizen’s action groups or local politics;
    c. Companies with work council;
    d. Religious affiliations and attendance of services;
    e. Members of associations/clubs;
    f. Voluntary workers;
    g. Satisfaction with possible political participation, the church or democratic institutions.

11. Environment:

    a. Land use;
    b. Emissions;
    c. Environmental protection;
    d. Damaged forests;
    e. Drinking water;
    f. Complaints about access to park and woodlands and the destruction of the countryside;
    g. Concerns about air and water pollution and climate change;
    h. Household waste and recycling;
    i. Expenditures on environmental protection as a percentage of the GDP;
    j. Environmental crimes.

12. Public safety and crime:

    a. Crime rate and risk of victimisation (by crime);
    b. Public safety;
    c. Fear of crime and expectation of victimisation (by crime);
    d. Police density;
    e. Percentage of public service employees that work in public safety and administration of justice;
    f. Expenditures for public safety and administration of justice as a percentage of the GNP (Gross National Product);
    g. Solved crime cases;
    h. Indictment and conviction rates;
    i. Imprisonment rate;
    j. Reoffender rate;
    k. Crime suspects rate;
    l. Female/male rate of suspects and foreign/German rate of male suspects;
    m. Convict rate;
    n. Female/male rate of convicts and foreign/German rate of male convicts.

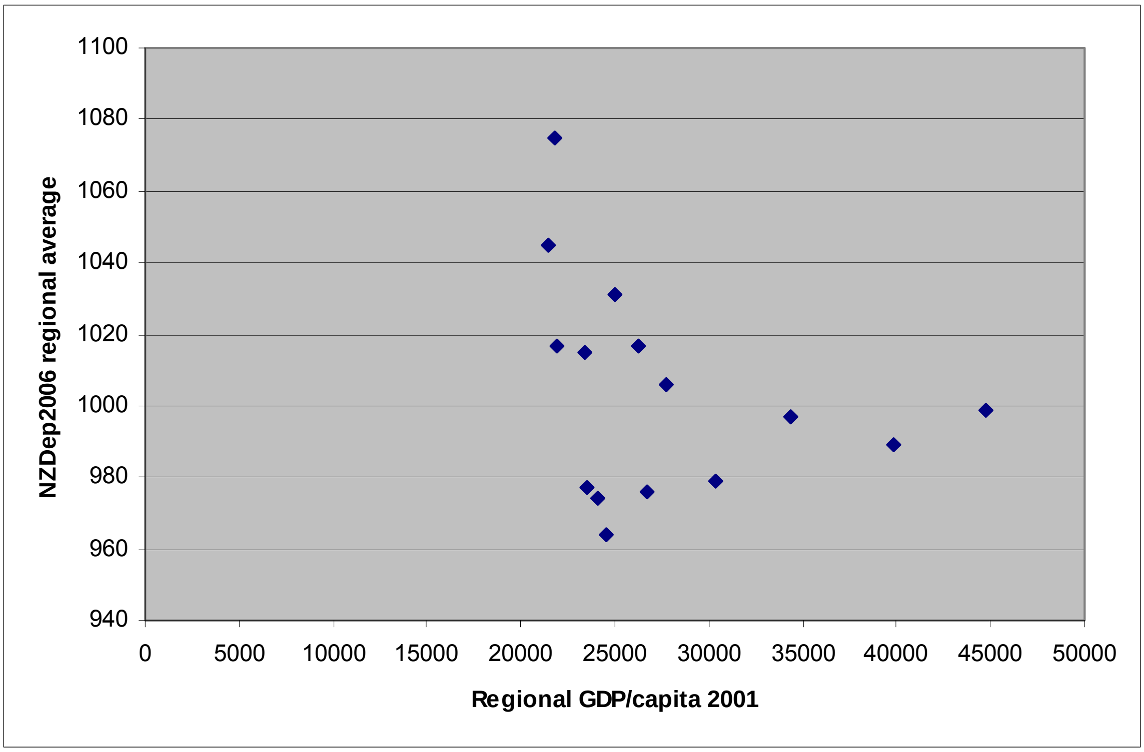
13. Leisure and media consumption:

    a. Amount of free time;
    b. Visits to theatres, museums, concerts, sporting events;
    c. Sporting activities and sport clubs;

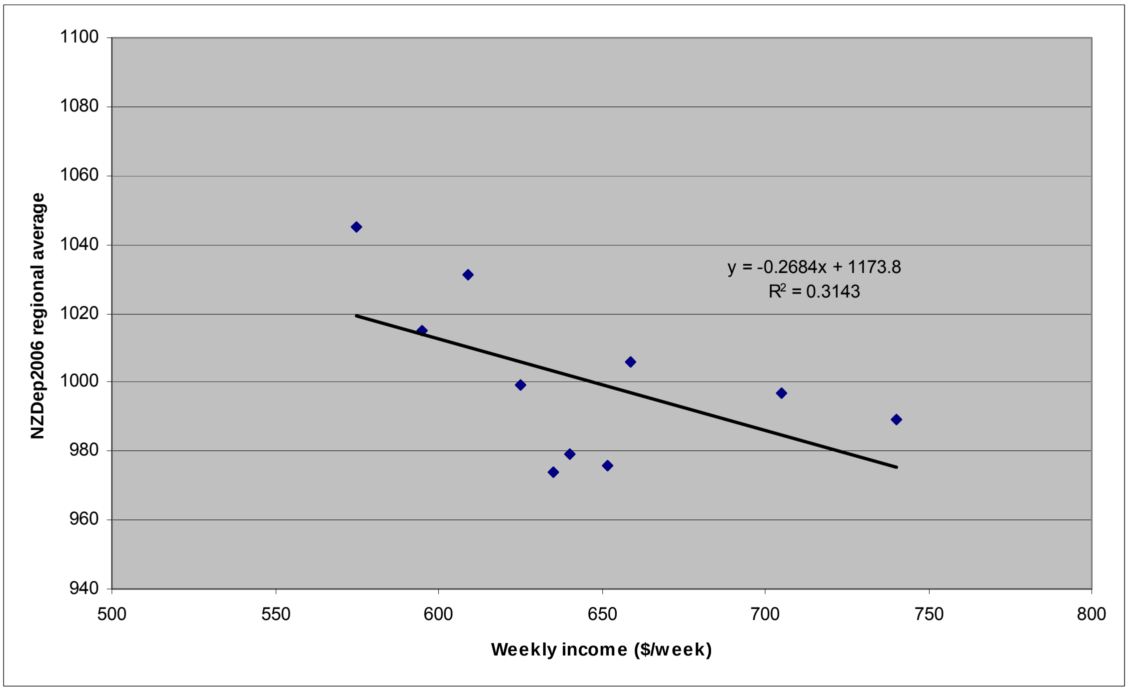
d. Gardening or family-orientated leisure time occupation;
e. Holiday trips (long and short term) and destinations;
f. Percentage of disposable income which is spent on leisure, entertainment and culture;
g. Leisure time expenditures by goods;
h. Subjective assessment of leisure time;
i. Usage of and attachment to media (newspapers, TV, radio, books).

14. Global welfare measures:

- Social wealth and welfare
- Per capita GDP
- Human development index (HDI)
- Social security benefits;
- Subjective well being;
- Suicide rate.



Appendix Figure D-1: NZDep2006 regional average and regional GDP (2001).



Appendix Figure D-2: NZDep2006 regional average and regional weekly income (2006)

Appendix Table D-1: Regional wealth, earnings and NZDEP2006

Regional Council	GDP/Capita 2001	Employed Median Weekly Earnings $/Week (2006)	NZDep2006	
			Regional Average	Weighted Regional Average
Taranaki	$44,798	625	999	1,000
Wellington	$39,869	740	989	984
Auckland	$34,318	705	997	999
Southland	$30,317	640	979	977
Waikato	$27,724	659	1,006	1,003
Canterbury	$26,744	652	976	975
Hawke's Bay	$26,275	614	1,017	1,021
Bay of Plenty	$25,027	609	1,031	1,019
Marlborough	$24,570	624	964	965
Otago	$24,079	635	974	976
Tasman / Nelson	$23,519	624	977	976
Manawatu-Wanganui	$23,415	595	1,015	1,015
West Coast	$21,907	624	1,017	1,006
Gisborne	$21,748	614	1,075	1,077
Northland	$21,515	575	1,045	1,042

[1] Regional Gross Domestic Product (2001), Statistics New Zealand (2007), divided by regional population (2001), Statistics New Zealand (2009a). The 2001 year is used for these calculations as it is a population census year and it is the latest year of published Regional Gross Domestic Product calculations.

[2] Income for those in paid employment is aggregated (Statistics New Zealand 2009c) for: Hawkes Bay and Gisborne; and for Tasman, Nelson, Marlborough and West Coast.

APPENDIX E: RICHMOND URBAN AREA.

The following historic trends in the Richmond urban area were assessed:

1. Population;
2. Land area;
3. Water supply
4. Waste water treatment
5. Storm water

Future demand for water, waste water treatment, and storm water services in the Richmond urban area were estimated from projections of historic trends. Capital and operating costs for water, waste water treatment, and storm water in the future were estimated from historic costs and from TDC Asset Management Plans covering the period 2009-2019.

Appendix E.1: Population

Appendix E.1.1: Historic Population

Tasman District's population has grown since 1951 (Appendix Table E-1). The population grew at about 1.7% (compounded) per annum from 1951 to 2006.

Richmond's population has also grown, historically since 1951. Historic estimates of Richmond population include (Millar, 1968):

1. 1885 - population considerably under 1,000 people;
2. 1914 - 1,200 people; and
3. 1968 - 5,019 people.

Data on Richmond's population during the 1951-2006 period are presented in Appendix Table E-1 and plotted in Figure E-1. With this increase in population has come an increase in the number of dwellings, but a decline in the number of occupants/dwelling. The rate of growth of the Richmond population was about 3% (compounded) per annum. Population growth was relatively rapid (approximately 4% compounded) between 1951 and 1976 and after 1991. Population growth in the period 1976 to 1991 was slower (about 2% compounded).

Appendix E.1.2: Future Population

It has been estimated that New Zealand's future population ("Series 4 projection") will peak at around 4.64 million around 2044 and then decline to 4.24 million by 2101 (Figure E-2) [Statistics New Zealand, 2000].

The population of the Tasman District will probably continue to grow, at least while the New Zealand population as a whole grows. For example Statistics New Zealand (2008), as shown in Appendix Table E-2, estimates the Tasman District population will grow from around 45,800 in 2006 to 53,900 in 2031. This is an annual growth rate of approximately 0.7% (compounded).

The population of Richmond will probably continue to grow, at least while the general New Zealand population grows and the population of Richmond will probably grow at a greater rate than that of the Tasman District as a whole. This is probable because the historic growth rate of Richmond population (3% compounded per annum 1951 to 2006) is greater than the growth rate of Tasman District population (0.7% compounded per annum 1951 to 2006).

Future Richmond population was estimated as follows (Appendix Table E-2):

1. Estimated Richmond population of 10,140 in 2006 (Appendix Table E.2);

2. 3% compounding from 2006 to 2040 to match historic growth rates for 1951- to 2006, rounded to the nearest hundred;

3. 0% growth for 2040-2100 period suggesting that the decline in New Zealand population in the period will not be fully represented in Richmond population.

Appendix E.2: Richmond Land Area

Appendix E.2.1: Historic Boundaries

The boundaries of Richmond township in 1950 approximately followed the boundaries of sections 25, 26, 65 and 66 of the 1842 survey of Barnicoat and Thompson for the New Zealand Company (Sutton, 1992). The land area of Richmond increased between 1950 to 2010, reflecting the increase in population (Appendix Table E-2 and Appendix Figure E-3).

Appendix E.2.2: Future Richmond development options

Three options for potential future Richmond development are under consideration by TDC (Appendix Figure E-4):

1. Richmond West, currently before the Environment Court (Field, 2010);

2. Richmond East, including land within the Nelson City Council boundary; and

3. Richmond South.

Tasman District Council is planning to assess options for provision of services to these areas (Arnold, 2010).

Approximate land areas for these future development options, calculated from the map in Appendix Figure E-4, are summarised in Appendix Table E-3. Population and dwellings for these areas are estimated based on:

1. Population of 10,578 in 2001 (Appendix Table E-1);

2. 3,954 dwellings in 2001 (Appendix Table E-1);r

3. Occupants/dwelling 2.7 in 2001 (Appendix Table E-1);

4. Richmond land area 456.19 ha in 2000; and

5. Population/hectare approximately 23.

Assuming 2.7 occupants/dwelling, the estimated population for all three of these land areas would be 11,200. Therefore, the existing Richmond town area combined with the three development options contains sufficient land area to provide for a Richmond population of around 22,600 (i.e., approximately the population growth estimated for Richmond to the 2030-2035 period, see Appendix Table E-2).

However the population is ageing and the number of people per household is declining over time (Appendix Table E-1). Therefore, the population that could be provided for in the Richmond area development options is estimated based on 2.0 occupants/dwelling for future housing, or 17 persons/ha. This makes the estimated population for these three development areas 8,200. In that event, the existing Richmond town area and the three development options would only provide sufficient land area for a population of around 19,600 which would be exceeded prior to 2030

Appendix E.2.3: Future Richmond land area

Richmond land area in the future was estimated as follows (Appendix Table E-2):

1. Current 2010 land area of 1,018 ha and estimated 2010 population of 11,400;

2. Population growth to 2020 at 20 persons/ha (i.e., 2.3 persons/house); and

3. Population growth after 2020 at 17 persons/ha (i.e., 2 persons/house).

This gives an estimated future land area for Richmond. Note that, with these assumptions, approximately 487 ha of development area options will have been utilized by 2030; therefore Richmond will need more land beyond that if growth is to continue after 2030.

Appendix E.3: Water Supply

Appendix E.3.1: History

Richmond's water supply came from wells and roof-tanks in the early years of development (Millar, 1968). Construction of a water supply system including a dam in the Higgs Valley commenced about 1885 (Sutton, 1992). Water was supplied from the Roding River by 1940 (Sutton, 1992) and by the 1970s groundwater was being taken from bores in Queen Street and Appleby (TDC, 2009).

Richmond's current water supply (TDC, 2009) comes from three sources:

1. The Roding River;

2. Wells located in Queen Street;

3. A well at Appleby.

TDC (2009) has this comment on urban water availability for Richmond with the current water supply system:

Overall the Council has sufficient water allocation for Richmond, however, with projected growth, the water rationing that occurs during droughts and the increasing competition for water in the district, it is becoming more difficult to source the water.

Appendix E.3.2: Historic water use

Historic water use for Richmond presented in Appendix Table E-4 was calculated from TDC water meter readings (Stephenson, 2010). Data from the Cargill and Appleby recorders was utilized. The Cargill water meter was faulty between June 2006 and August 2007. Therefore, water use for Cargill in calendar year 2006 and calendar 2007 was estimated from the historic record. This water use for Richmond shows a growth of about 6% per annum, compounded, between 1997 and 2007.

Paired water use and population data for Richmond are available for three years. These are presented in Appendix Table E-5. Estimated per capita water use over this 10 year period is also shown and appears to have increased strongly. Using population data and assuming annual per capita water use of 100 m^3, historic water use prior to 1996 was estimated starting with year 1951 (Appendix Table E-6).

On an area basis, water demand in 2000 for Richmond was estimated as approximately 2,700 m^3/ha/year (i.e., water use of 1,237,300 m^3/year divided by land area approximately 456 ha, Appendix Tables E-4 and E-2, respectively).

Appendix E.3.3: Future water demand

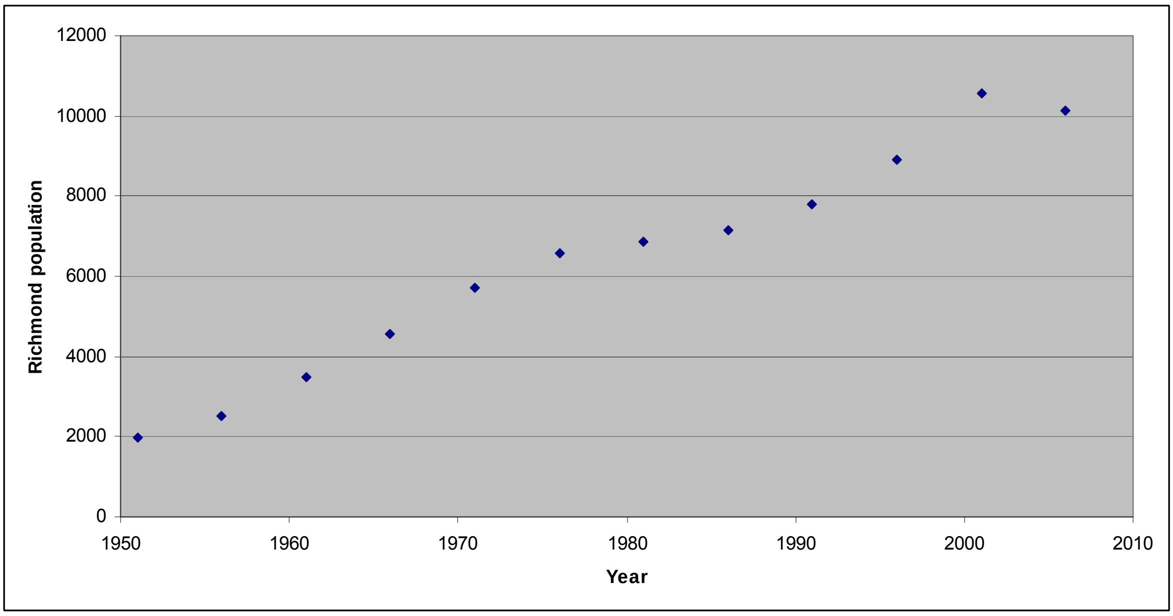
Future population growth for Richmond will result in a growth in water demand. Future water demand was estimated as future population times per capita annual water use in 2006 rounded up of 180 m^3/person/year. These estimates indicate future demand could increase by a factor of two to three over water use in 2006 by the end of this century (Appendix Table E-7).

Projected new capital expenditure (i.e., capital expenditure for new works) for the Richmond water supply totals approximately $51 million for the period 2009/2010 to 2028/2029, or approximately $2.6 million/year (TDC, 2009). Some of the higher cost items include:

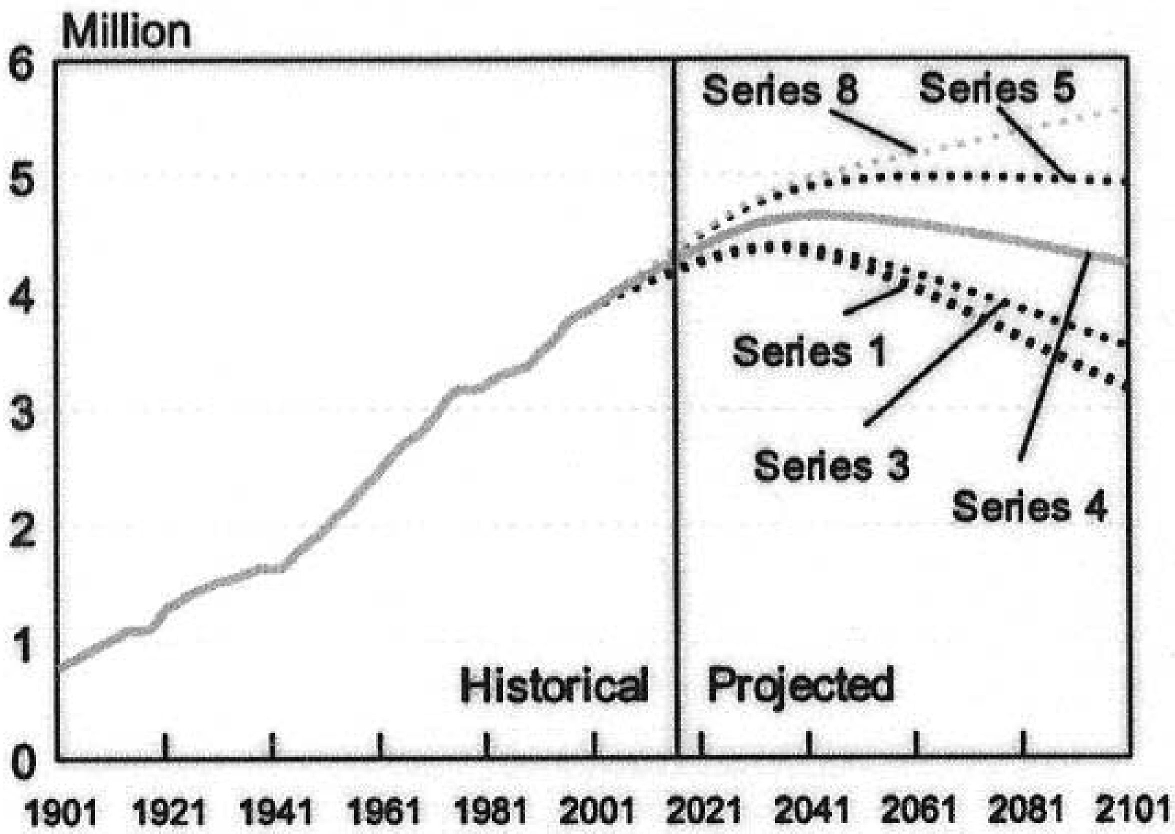
1. Pipe renewals;
2. Meter renewals;
3. A new groundwater source;
4. A new treatment plant.

Projected capital expenditure for renewals (i.e., works on existing assets) for the Richmond water supply totals approximately $25 million in the period 2009/2010 to 2028/2029, or approximately $1.2 million/year (TDC, 2009). Some of the higher cost items include:

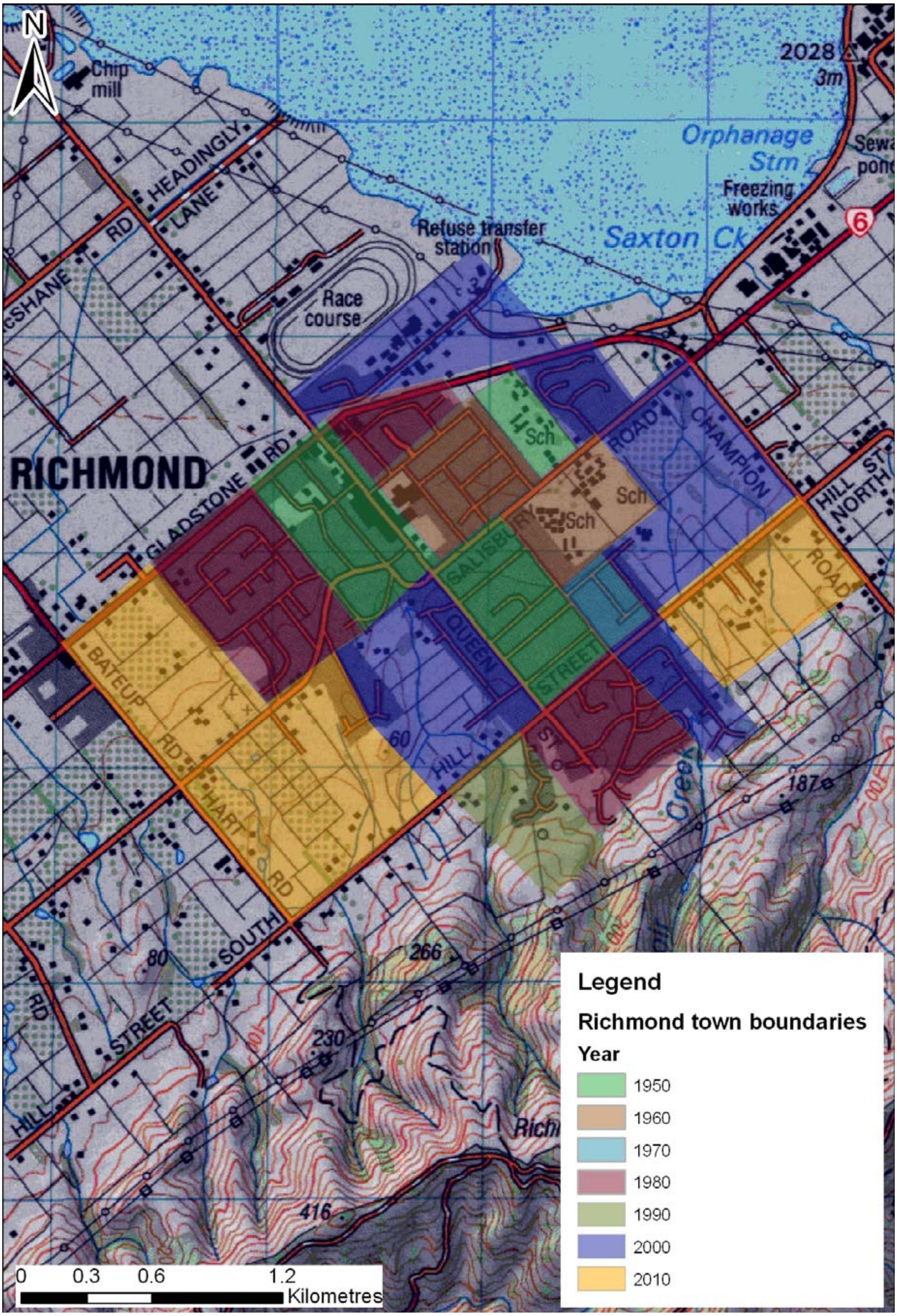
1. Pipe renewals;
2. Water meter renewals and valve replacements.



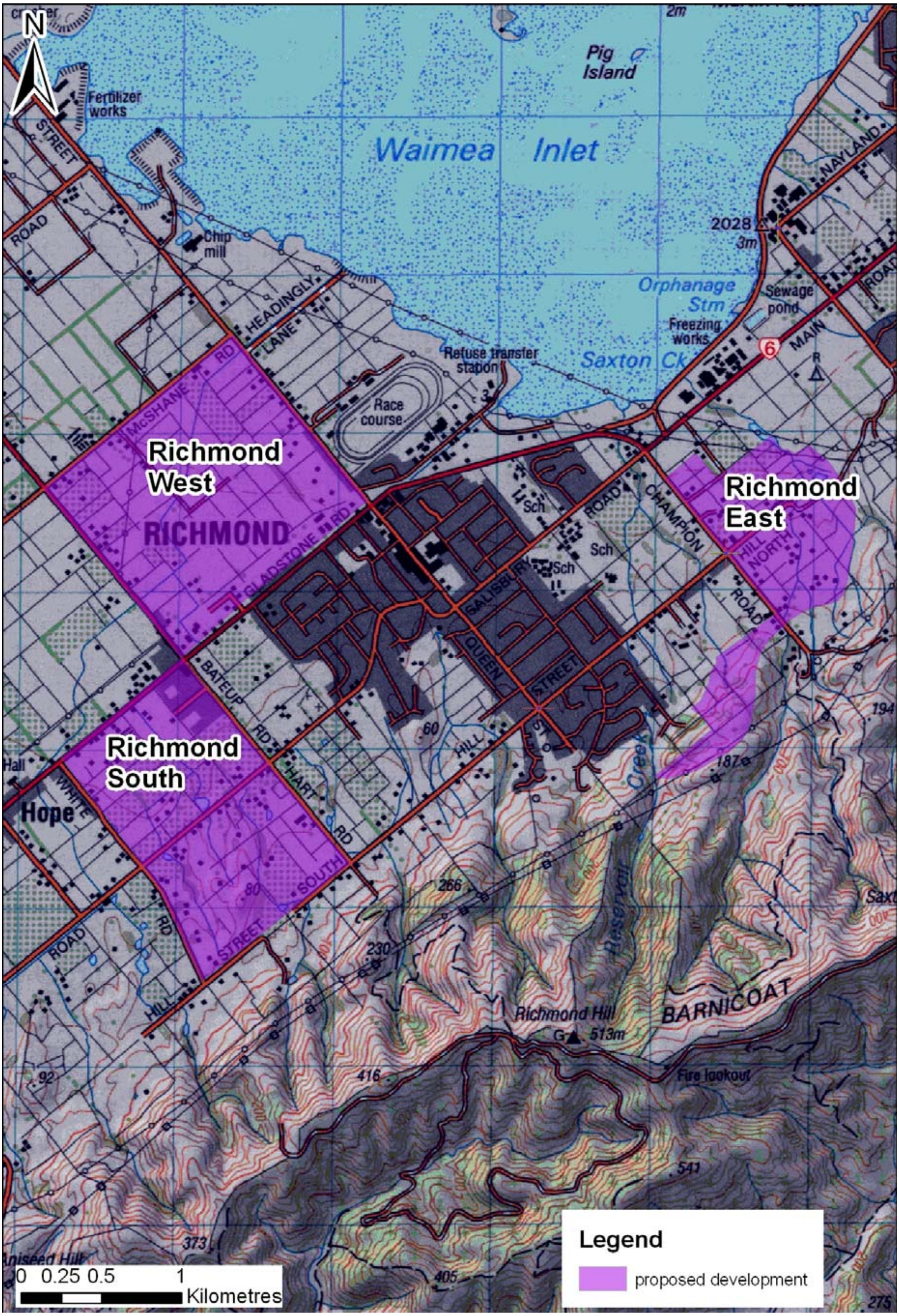
Appendix Figure E-1: Richmond population (1951-2006)



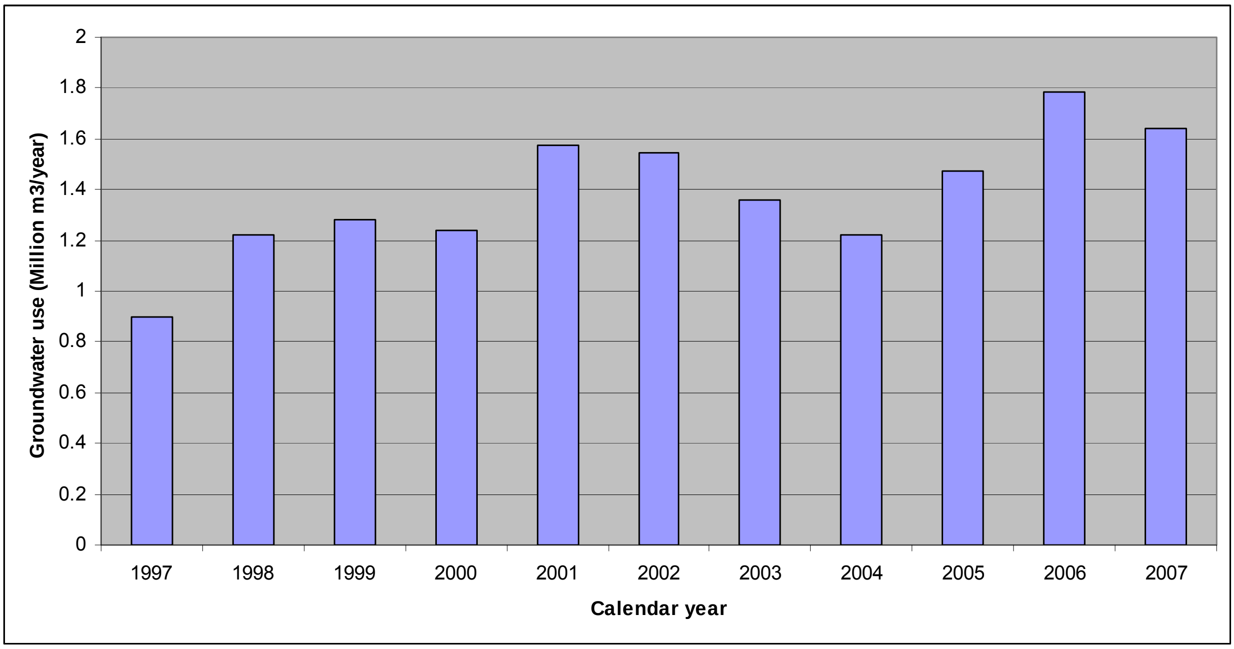
Appendix Figure E-2: Estimated New Zealand population (1901–2101) [Statistics New Zealand]



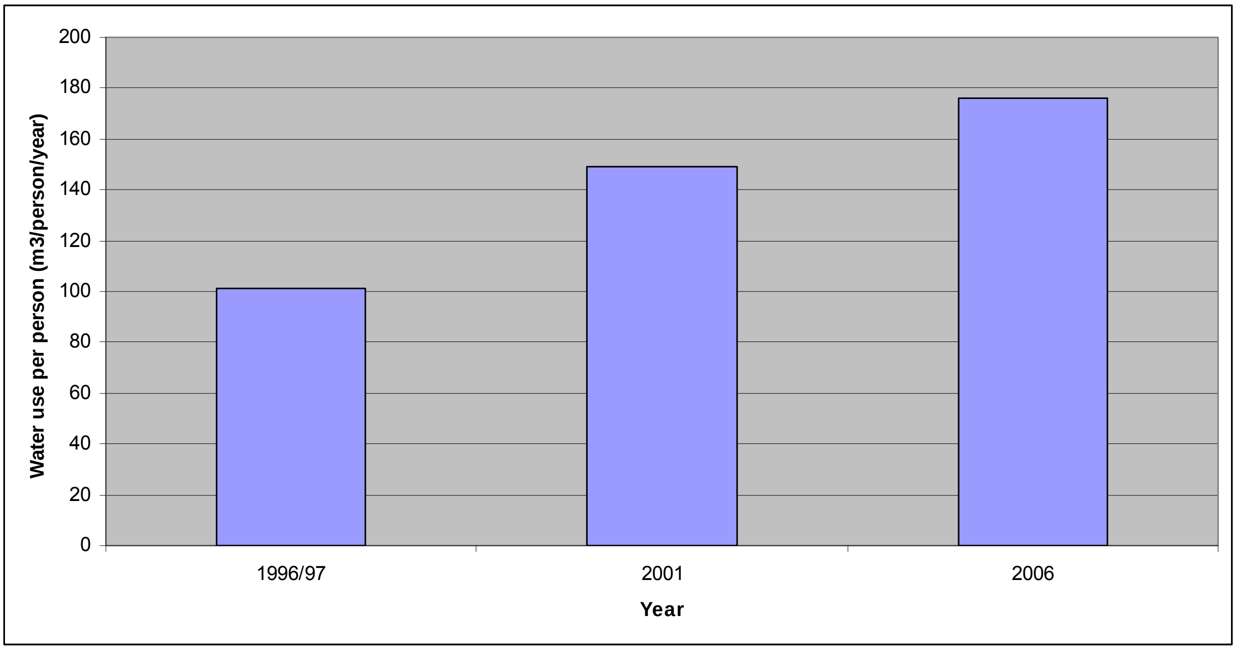
Appendix Figure E-3: Development of Richmond urban area boundaries 1950-2010



Appendix Figure E-4: Proposed Richmond development (Richmond West, East. and South)



Appendix Figure E-5: Total groundwater use by Richmond (1997-2007)



Appendix Figure E-6: Per capita groundwater use in Richmond (1996/97, 2001, and 2006)

Appendix Table E-1: Tasman Region Population and Richmond Population and Dwellings[1]

	Population		Estimated Richmond Dwellings	
Year	Tasman Region	Richmond	Number Dwellings	Occupants/Dwelling
1951	17,340	1,973	535	3.7
1956	19,547	2,515	699	3.6
1961	17,585	3,482	916	3.8
1966	21,462	4,574	1,187	3.9
1971	21,532	5,707	1,571	3.6
1976	23,238	6,587	1,936	3.4
1981	23,727	6,849	2,211	3.1
1986	25,170	7,155	2,412	3.0
1991	34,131	7,809	2,868	2.7
1996	37,968	8,895	3,336	2.7
2001	41,352	10,578	3,954	2.7
2006	44,625	10,140	4,419	2.3

1. *Population and dwellings for the "Richmond East" and "Richmond West" census districts. Since Richmond is currently growing beyond the boundaries of these census districts, these population figures may underestimate the actual Richmond population in later years. Statistics NZ data.*

Appendix Table E-2: Estimated historic and future population and urban land area[1]

	Population[1]		Richmond Land Area (ha)[2]
Year	Tasman District	Richmond	
1950	-	-	85
1960	-	-	140
1970	-	-	149
1980	-	-	247
1990	-	-	274
2000	-	-	456
2006	-	10,140	-
2010	47,400	11,400	1,018
2015	-	13,200	1,108
2020	-	15,300	1,213
2021	50,900	-	-
2025	-	17,700	1,354
2030	53,900	20,500	1,519
2035	-	23,800	1,713
2040	-	27,600	1,937
2050	-	27,600	1,937
2060	-	27,600	1,937
2070	-	27,600	1,937
2080	-	27,600	1,937
2090	-	27,600	1,937
2100	-	27,600	1,937

1. *Statistics NZ (2008) with Tasman District population compounded at 0.07%/year. Future Richmond population estimated as stated in text.*
2. *Historic land area estimated by Field (2010).*

Appendix Table E-3: Richmond development options and areas

Development option	Development Option Area (ha)	Population--2.7 person/house[1]	Population--2 person/house[1]	Dwellings[1]
Richmond West	205.88	4,700.	3,500.	1,800.
Richmond East	108.46	2,500.	1,800.	900.
Richmond South	172.48	4,000.	2,900.	1,500.
Total	486.82	11,200.	8,200.	4,200.

[1] *Rounded to the nearest hundred.*

Appendix Table E-4: Richmond Water Usage (1997–2007)

Year	Cargill meter water use (m^3)	Appleby meter water use (m^3)[1]	Richmond total (m^3)
1997	663,603.	234,341.	897,944.
1998	985,719.	235,041.	1,220,760.
1999	1,041,896.	236,956.	1,278,852.
2000	1,009,151.	228,149.	1,237,300.
2001	1,344,082.	233,678.	1,577,760.
2002	1,308,900.	233,705.	1,542,605.
2003	1,184,151.	176,912.	1,361,063.
2004	1,028,737.	191,914.	1,220,651.
2005	1,265,719.	210,136.	1,475,855.
2006	1,565,499.	220,092.	1,785,591.
2007	1,423,366.	220,092.	1,643,458.

1. *There were no data for years 2006 and 2007 for the Appleby meter water use. Therefore, these totals were estimated as the average for the 1997–2005 period.*

Appendix Table E-5: Water use by Richmond 1996/97, 2001 and 2006.

Year	Population	Water Use (m^3)	Per Capita Water Use (m^3/person/year)
1996/1997[1]	8,895.	897,944.	101
2001	10,578.	1,577,760.	149
2006	10,140.	1,785,591.	176

[1] *Population data for 1996 and water use data for 1997.*

Appendix Table E-6: Estimated Richmond Water Use 1951-2006.

Year	Total Population	Estimated Richmond Water Use[1] (Million m^3/year)
1951	1,973.	0.20
1956	2,515.	0.25
1961	3,482.	0.35
1966	4,574.	0.46
1971	5,707.	0.57
1976	6,587.	0.66
1981	6,849.	0.68
1986	7,155.	0.72
1991	7,809.	0.78
1996	8,895.	0.90
2001	10,578.	1.58
2006	10,140.	1.79

1. *Observed water use from Appendix Table C-4 for 1996, 2001, and 2006, otherwise estimated as 100 m^3/person/year.*

Appendix Table E-7: Estimated Future Richmond Water Demand

Year	Estimated Richmond Population	Estimated Richmond Water Demand (Million m^3/year)
2010	11,400	2.1
2015	13,200	2.4
2020	15,300	2.8
2025	17,700	3.2
2030	20,500	3.7
2035	23,800	4.3
2040	27,600	5.
2050	27,600	5.
2060	27,600	5.
2070	27,600	5.
2080	27,600	5.
2090	27,600	5.
2100	27,600	5.

APPENDIX F: GENERAL WATER AVAILABILITY FOR THE WAIMEA PLAINS

Current water availability to the productive sector of the Waimea Plains is estimated as current allocation limits (Appendix Table F-1) for surface water and groundwater.

Water allocation limits for Waimea Plains water use zones (Figures 6-1 and 6-8) were set by Tasman District Council (1991) and are summarized in Appendix Table F-1.

Water allocation to the WEIS is equivalent to approximately 8,100 m^3/ha/yr (i.e., 565 L/s allocation for irrigation over an estimated 26 week irrigation season (Tyson, 2010).

Current water availability to in situ uses is not the subject of limits set by Tasman District Council. Therefore water availability is estimated as the difference between flow and allocation. As average values, these are summarised in Appendix Table F-2. Note that in situ flows available for use will vary considerably over the seasons with low availability in summer when flows are low and irrigation takes high.

Appendix Table F-1: Tasman District Council (1991) Water Allocation Limits

Water Management Zone	Allocation Limit (L/s)	Allocation Limit (m^3/s)	Source
Wai-iti River	200	0.20	Groundwater
Reservoir	826	0.83	Groundwater
Waimea West	178	0.18	Groundwater
Golden Hills	113	0.11	Groundwater
Waimea River Delta	1,000	1.00	Groundwater
Upper Confined Aquifer (UCA)	144	0.14	Groundwater
Lower Confined Aquifer (LCA)	203	0.20	Groundwater
Hope Aquifers and Eastern Hills[1]	97	0.10	Groundwater
Waimea East Irrigation Scheme (WEIS)[2]	565	0.57	Surface water
Total	3,300	3.29	

1. *TDC (2009a).*
2. *Allocation equivalent to weekly allocation, Tyson (2010).*

Appendix Table F-2: Estimated Average Water Availability for In Situ Use

Water body	Average Flow m^3/s	Allocation[3] m^3/s	In Situ Water Availability m^3/s
Groundwater[1]	1.51	1.4	0.1
Surface water[2]	202.	0.6	15.8

1. *Estimates of groundwater flow in winter conditions taken from Fenemor (1988) for the Appleby gravel unconfined aquifer (AGUA), upper confined aquifer (UCA), and Lower Confined Aquifer (LCA).*
2. *Taken as average flow in the Wairoa/Waimea River (16.2 m^3/s at site 57521 between 1957 and 2010) and the Wai-iti River (3.8 m^3/s at site 57520 between 1986 and 2010).*
3. *This allocation assums a 26 week irrigation season (i.e., equivalent annual allocation about one half of the values in Table A-1).*

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