DIPLOMARBEIT

Titel der Diplomarbeit

Influence of groundwater levels on zero river flow:

North Branch, Ashburton River, New Zealand

Verfasserin

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angestrebter akademischer Grad

Magistra der Naturwissenschaften (Mag.rer.nat.)

Wien, 2012

Studienkennzahl lt. Studienblatt:	A 453
Studienrichtung lt. Studienblatt:	Diplomstudium Theoretische und Angewandte Geographie
Betreuer:	Prof. Dr. Thomas Glade

DECLARATION

I sincerely declare

- That work was done by me, personally
- The material has not previously been accepted in whole, or in part, for any other degree or diploma

Signature: ……………………………………….

Date: …………………………………………….

ACKNOWLEDGEMENTS

First of all, I would like to thank my supervisor Thomas Glade who initially gave me the idea of writing my thesis here in New Zealand, made contact with NIWA and supported me from a distance during my stay in Christchurch. Without Christine's hint about the scholarship (thank you SAS-team!) I would still be sitting in Vienna. Thank you also for reading these pages and the 2 hr phone call!

I'd like to thank the management team of NIWA Christchurch for providing me a desk, computer with lots of programs and data as well as the all the immense knowledge of the employees. Without all the people this whole thing would not exist: Ross, whom I met in Vienna in April 2011 to talk about my ideas; Christian who looked after me when I arrived at the campus and introduced me to all the colleagues; Graeme, my supervisor, mentor, brain (at times) and one of the most motivated scientists I've ever met! Thank you also for getting the rust off my car, Graeme. And Kerry, the Christmas-slices were delicious! In Christchurch, I was welcomed by Maurice and Eileen who made me feel welcome in their home until I found my own place. I felt really comfortable and safe on the hills even through my first earthquake experience. I still think about the beautiful lemon tree in your garden! Tim (genius, media star, legend or sometimes self-titled idiot) my office colleague – thank you for answering lots of my (sometimes stupid) questions and cheering me up on my grey, non-productive days with your talks to yourself. Graeme, Tony, Jani, Mike, Roddy, Alistar, George and Kathy shared the lunch break table with me and helped me to feel welcome. At the beginning of my stay at NIWA, Jeremy took me into the field several times, thank you for teaching me how to use the flow tracker and wow, that cable car gauging was a great adventure! Speaking of field work I want to mention Chris who supported my first field exploration at the North Ashburton River and saved me from getting swept off my feet in the swift flow. And Marty, your waders were really useful and comfortable. Thank you for the borrowing - you don't have to look for them again (at least it wasn't me then). MS showed me the variability of his job, the day on the West Coast was really interesting (and the keas almost picked the roof rack off the car). Scott, thank you for your ideas, articles and papers and for taking me to the Selwyn. Elaine and Kathy, you were great help with the variety of NIWA data. And George, I hope it was not too tough for you to edit the thesis including my endless additional ideas. Thank you so much for reading it all! I'm sure you had some great laughs with my 'not-really-english-english'. I also want to thank Myriam for reading and sharing sunny lunch breaks on the deck. I also want to thank Einar, Tiejun, Tim and Shailesh for the ping pong breaks; I hope the bin with the fish will be removed soon. Shailesh and Ruby, my friends, it was so nice of you to join me in the field on your days off - with the yummy homemade food!

How do I forget the great support from ECan! Matt organized the wells database for me and provided a lot of additional information per email. Shaun and Bryan, thank you for introducing me to well sites and leaving me well keys. Emma helped me out in the field several times and told me interesting stories about her studies. Thank you Bruce for helping me with the gaugings and especially for driving me up and down the river bed in the four wheel drive, which was really helpful (and fun)!

I also want to mention the RDR operations manager Neill who answered my weekly question if he is going to spill water down the North Branch always with, ‘Nope, not this time’.

Thank you, Don and the Ashburton River Zone Committee for giving me the opportunity to attend your meeting and present my results on April 24th 2012.

Special thanks to David and Robyn who showed me around their farm near Mayfield, presenting me border dyke irrigation, their farm land, wool shed, pet lambs, and their friendly, clever farm dogs. I’ll never forget visiting you’re neighbours milking shed, thank you for providing me this great opportunity!

Out of office I had a great ‘family’: thank you Angela, Ngarangi and Barry (and Fatty cat) for having me as a flatmate, introducing me to New Zealand groceries, teaching me ‘kiwi culture’, having nice dinners, BBQs, long talks about this and that, showing me around in Christchurch, … and just having a good time! Thank you to my friends Irene and Raphael who joined my travels around the South Island, they will always stay in my mind. Katrin, it was good to know an Austrian so ‘far away from home’. Thank you for hosting me in Wellington and giving me advice for the thesis. My new friends, Emma and Marian, I’m glad that I met you! Our coffee/lunch/dinner meetings or movie-like mountain adventures were perfect to help forget about thesis troubles.

Finally, I want to thank my family and friends back home in Austria who supported me and never forgot about me during my stay in New Zealand. I especially want to thank my parents for caring about – and looking after my flat! It was great that you all provided me with information, sweets and pumpkin seed oil from good old Austria.

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List of symbols

ADV	= Acoustic Doppler Velocimeter
ALF	= Ashburton annual low flow
°C	= degrees Celsius
cm	= centimetre
dB	= decibel
ECan	= Environment Canterbury
ETmax	= potential evapotranspiration
GPS	= global positioning system
ha	= hectares
km	= kilometre
km/h	= kilometre per hour
km^2	= square kilometre
l	= litres
l/sec	= litres per second
l/sec/km	= litres per second per kilometre of length
m	= metre
mm	= millimetre
mm/h	= millimetres per hour
m^3/sec	= cubic metres per second
m^3/sec/km^2	= cubic metres per second per square kilometre
MALF (7d)	= seven-day mean annual low flow
NIWA	= National Institute of Water and Atmospheric Research
NZST	= New Zealand Standard Time
RDR	= Rangitata Diversion Race
RMA 91	= Resource Management Act 1991
s	= second
S	= spot gauging
SCCB	= South Canterbury Catchment and Regional Water Board
SNR	= signal to noise ratio
Tmax	= maximum temperature
Tmin	= minimum temperature
yr	= year

Abstract

Many of the alluvial rivers in New Zealand are modified by water abstraction, dam construction, gravel mining and other human activities. Water demand has increased significantly since the 1980’s, mainly caused by increasing dairy farming and intensification of irrigated agriculture.

The Ashburton River North Branch is a complex system and an understanding of its operation requires knowledge of surface and groundwater flow dynamics. This is further complicated by water abstraction for irrigation and stock water.

One aim of this study is providing further clarity to the Ashburton River Zone Committee on the location, frequency and duration of drying in the North Branch in recent years. A further aim is to determine if groundwater abstractions near the river could have an effect on the low flow regime. Existing studies and data were investigated to continue former work and fill determined gaps in research by testing of formulated hypotheses.

A model was constructed for the Ashburton North Branch, to predict low flow regime durations and dry sections in recent years. Regression analyses were undertaken combining existing data with obtained measurements.

The main results show that the number of days with low flow in the last ten years was an increase compared to the previous ten year period, the overall trendline from 1983 to 2011 increases significantly. 1992 was the year with the highest number of dry days with 176. There appears to be a large number of dry days since 2001 which are not related to acknowledged droughts – this may be driven by the occurrence of lower groundwater levels. One explanation for that could be the increased amount of water takes. Nevertheless, this cannot be confirmed because there are too many uncertainties, especially concerning the complex behaviour of the groundwater system.

Zusammenfassung (German)

Viele der alluvialen Flüsse Neuseelands sind durch Wasserentnahme, Errichtung von Dämmen, Abbau von Schotter und anderen menschlichen Aktivitäten stark verändert. Der Wasserbedarf in Neuseeland ist seit den 1980er Jahren signifikant gestiegen, dies ist hauptsächlich auf die wachsende Milchindustrie und die Intensivierung der bewässerten Landwirtschaft zurückzuführen.

Der Ashburton River North Branch ist ein komplexes System. Um dessen Funktionsweise zu verstehen bedarf es an Wissen zur Oberflächen- und Grundwasserdynamik. Dies wird verkompliziert durch Wasserentnahmen für Bewässerung und Viehwirtschaft.

Ein Ziel dieser Studie ist, dem Ashburton River Zone Komitee eine Übersicht der letzen Jahre über Ort, Häufigkeit und Dauer von Trockenperioden im North Branch zur Verfügung zu stellen. Des Weiteren wird ermittelt, ob eine Entnahme von Grundwasser nahe dem Fluss das Niedrigwasserregime beeinflusst. Mit dem Testen der Hypothesen wurden bestehende Studien und Daten teilweise erweitert sowie festgestellte Lücken der Forschung gefüllt.

Es wurde ein Modell für den North Ashburton River entwickelt, um die Dauer und Verteilung von Trockenperioden und niedrigen Wasserständen im Flussbett der letzten Jahre nachzuvollziehen. Mit einer Kombination aus existierenden Daten und im Gelände erhobenen Messdaten wurden Regressionsanalysen durchgeführt.

Die wichtigsten Ergebnisse zeigen, dass die Anzahl der Tage mit Niedrigwasser in den letzen zehn Jahren höher war als in der vorigen Zehnjahres-Periode, die Trendlinie von 1983 bis 2011 steigt signifikant. Mit 176 Tagen war das Jahr 1992 das Jahr mit den meisten trockenen Tagen. Seit 2001 scheint es eine hohe Anzahl an trockenen Tagen zu geben, die nicht mit bekannten Dürren in Verbindung stehen. Dies könnte durch einen niedrigen Grundwasserspiegel verursacht sein, der sich wiederum durch einen Anstieg an Wasserentnahmen erklären lässt. Dennoch kann dieser Zusammenhang nicht bestätigt werden da es zu viele Unsicherheiten gibt, insbesondere hinsichtlich des komplexen Verhaltens des Grundwassersystems.

Thesis structure

The introduction in chapter 1 presents, in brief, modification of alluvial plain rivers due to modern environmental pressures and describes the historic situation in New Zealand. In the background several previous studies investigating human impact on hydrological systems as well as their consequences are presented. Although there have been numerous studies carried out on the Ashburton North Branch in New Zealand, some research gaps were identified. Aims of the present study are presented here.

To obtain an idea about the setting of the investigation, the study area is presented in chapter 2. A description of the increased water allocation in New Zealand demonstrates the importance of water management. The detailed description of the North Ashburton River Catchment includes its topography, lithology, hydrogeology, groundwater regime, land cover and vegetation.

Previous studies on the North Branch including a detailed excerpt of work by G. Horrell to provide the basis for the hypotheses listed at the end of chapter 3. Specific objectives to show how the hypotheses are going to be investigated are also placed here.

Methods in chapter 4 are divided into desktop work and field work and describe in detail what methods and instruments were used to achieve the results. This is followed by chapter 5, a collection of sources and resolutions of all data.

In chapter 6 results are presented. This involves research on irrigation and water use, groundwater levels and analysis of rainfall data. Regression analyses of flow recorder sites, gauging data and groundwater levels are presented to predict flow at Digbys Bridge, the number of days without flow and the length of dry sections.

Chapter 7 tests the hypotheses and attempts to find a relationship between groundwater levels and dry periods on the North Ashburton River. The accuracy of the study is also discussed here.

Chapter 8 is the conclusion to the study and it is supplemented by perspectives in chapter 9.

1. Introduction

Fertile soils and accessible surface and groundwater made most of the world's alluvial plains favoured areas for agriculture for 7000 years (Lowdermilk, 1950). Throughout history humans have managed to cultivate and use resources and therefore alluvial plains are of great cultural and economic importance. They have also served as important locations for urban development. As a consequence, alluvial plains are among the most threatened ecosystems on Earth (Tockner & Stanford, 2002). Most of these rivers have undergone hydrological and geomorphic modifications due to water abstraction, dam construction, gravel mining and other human activities. Modern environmental pressures include agricultural intensification, abstraction of surface and groundwater, river straightening and channelization and climate change (Larned et al, 2007). Those factors also impact quantity and quality of groundwater resources and the state of subsurface ecosystems (Danielopol et al, 2003).

As in the rest of the world, in New Zealand many of the alluvial rivers were modified to suit human uses. There is widespread evidence of pre-Polynesian fires in the eastern forests, and deforestation began 600-1000 years ago (Ogden, 1997). Dam construction, surface and groundwater abstraction and other human impacts began shortly after European colonization in the 19th century and continue to the present. These impacts can change or eliminate surface water – groundwater exchange (Larned et al, 2007) and therefore these rivers often have complex spatial and temporal flow patterns (Schmidt et al, 2009). Interactions between groundwater and surface water are complex and it is important to understand the ecological significance and the human impacts on those interactions (Sophocleous, 2002).

1.1. Background

As surface water and groundwater are not isolated components of the hydrologic system, development of one commonly affects the other. In his paper on the state of the research concerning interactions between groundwater and surface water, Sophocleous (2002) points out that only recently attention has been focused on exchanges between near-channel and in-channel water whereas for example the interaction between groundwater and lakes has been studied since the 1960's. Also an emerging field of study is longitudinal flow variation. These longitudinal changes include changes in the frequencies, magnitudes, durations and timing of floods, low-flows and intermittence (Sophocleous, 2002).

Globally, numerous studies have been carried out to investigate human impact on hydrologic systems. The presented examples concern the interaction between surface- and groundwater, one study broaches the issue of impacts on river morphology:

Querner et al (1997) used several physically-based models to investigate human impact on streamflow droughts in several European basins. The authors stated that human impact can be either direct, like land use change, groundwater abstractions, or indirect such as numerous activities resulting in climate change and therefore contributing to drought. As an example the complete afforestation of a small basin in The Netherlands would result in a decrease in mean flow with 10-30% more days that streamflow would be below the given threshold (Querner et al, 1997).

Human impact can additionally modify sediment transport and the delivery of water to the channel resulting in a change to streambed morphology (Gregory, 2006).

For the Arno River basin in central Italy, Billi & Rinaldi (1997) estimated that reforestation accounts for 20% of the reduction in the sediment supply while bed material exploitation accounts for the remaining 80%. The authors state that "*combination of reduced sediment supply and increased sediment transport capacity resulted in extensive streambed degradation that threatened the stability of several bridges and other structures*" (Billi & Rinaldi, 1997 p.301).

In his study Hancock (2002) highlights the importance of the hyporheic zone. This zone is located at the interface between stream surface water and groundwater and exists for most sand and gravel-bed rivers. Many human activities impact this zone either with impairing water exchange or by harming biological activity through poisoning invertebrates. As one example the author notes that "*mining, agriculture, and urbanization all may contribute silt to the hyporheic zone and lead to colmation. In general, a high level of colmation leads to decreased oxygen and nitrate concentrations* and increases in ammonification" (Hancock, 2002 p.767).

He et al (2009) investigated groundwater table fluctuation in response to the change of paddy field area due to an increase of urban area. Results show that the groundwater table on the Dogo Plain in Japan depends not only on rainfall and discharge from rivers, but also on irrigation water and evapotranspiration of the study area. The groundwater recharge occurs much more in irrigation seasons than in non-irrigation periods. As groundwater is the primary source of water, provided for municipal, industrial and agricultural uses of the area, He et al (2009) point out that this knowledge is key to enabling a sufficient water supply (He et al, 2009).

Contrary to the previous examples, work on the Selwyn River in Canterbury, New Zealand is one of the rare cases that had exactly the same research approach as the present study on the Ashburton River North Branch. Since 2003 intense studies have been carried out on the Selwyn River (Larned et al, 2007; Rupp et al, 2008; Schmidt et al, 2009; Larned et al, 2010A; Larned et al, 2010B). With the same settings as the Ashburton River, the Selwyn River also shows a complex spatial and temporal flow pattern. To understand this flow patterns, linear and logistic models were used to reconstruct a 22 year record of the Selwyn River flow across the alluvial Canterbury Plains. Using data from 38 months of flow gaugings at 18 cross sections along the river mainstream flow within the study reach was modelled as a function of flow at stage recorders located at each end of the domain. Results showed that the mean annual simulated length of dry river channel had increased by 0.6 km per year over the last two decades (Rupp et al, 2008). As a trigger Rupp et al (2008) stated that the conversion from dry land grazing to irrigated dairy farming in the Selwyn catchment was accompanied by increased water demand.

The Ashburton River North Branch located in Canterbury, New Zealand is a complex system and an understanding of its operation requires knowledge of surface and groundwater flow dynamics. This is further complicated by human impact due to water abstractions for irrigation and stock water.

Although there were numerous studies carried out on the North Branch (see chapters 3.1 and 3.2), none of them had the aim to predict length and duration of zero flow periods. Due to lack of data and the short term of this study, it was not possible to apply the same model used for the Selwyn River as described above. Therefore another model had to be built for the North Ashburton River. This and other aims of the study are described as follows:

1.2. Aims of the study

- The first aim of this study is to analyse all the existing studies and data to learn why the North Branch has gone dry for various durations and locations over the past 30 years.

- As dairy farming and farming intensification with irrigation continues to grow, there is concern that groundwater abstractions near the river could have an effect on the surface water levels (Smith, 2005).

- This study has been carried out to provide further clarity to the Ashburton River Zone Committee on the location, frequency and duration of drying in the North Branch in recent years (Hall et al, 2011).

- Due to lack of data field work is the key to the production of an Ashburton Catchment Water Management Plan by ECan.

2. Study area

Located on the South Island, with an area of 4.22 million ha, Canterbury is the largest region in New Zealand (see Figure 1). The main city is Christchurch with a population of 348,400 (S: Statistics New Zealand, 2012).

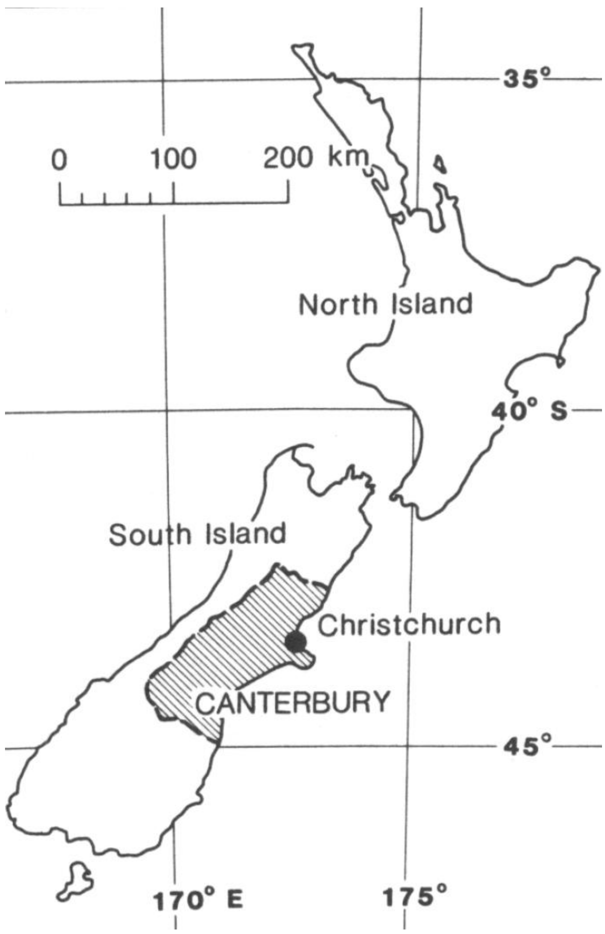


Figure 1 Location map of Canterbury (S: Ryan 1987, p. 3)

Key drivers of the economy of Canterbury are agricultural exports, with increasing importance of dairy products. Dairy cattle totals (including bobby calves) increased from 112,000 in 1990 to almost 939,000 in 2010. In the same period of time sheep totals in Canterbury decreased by 4.7 million (see Figure 2).

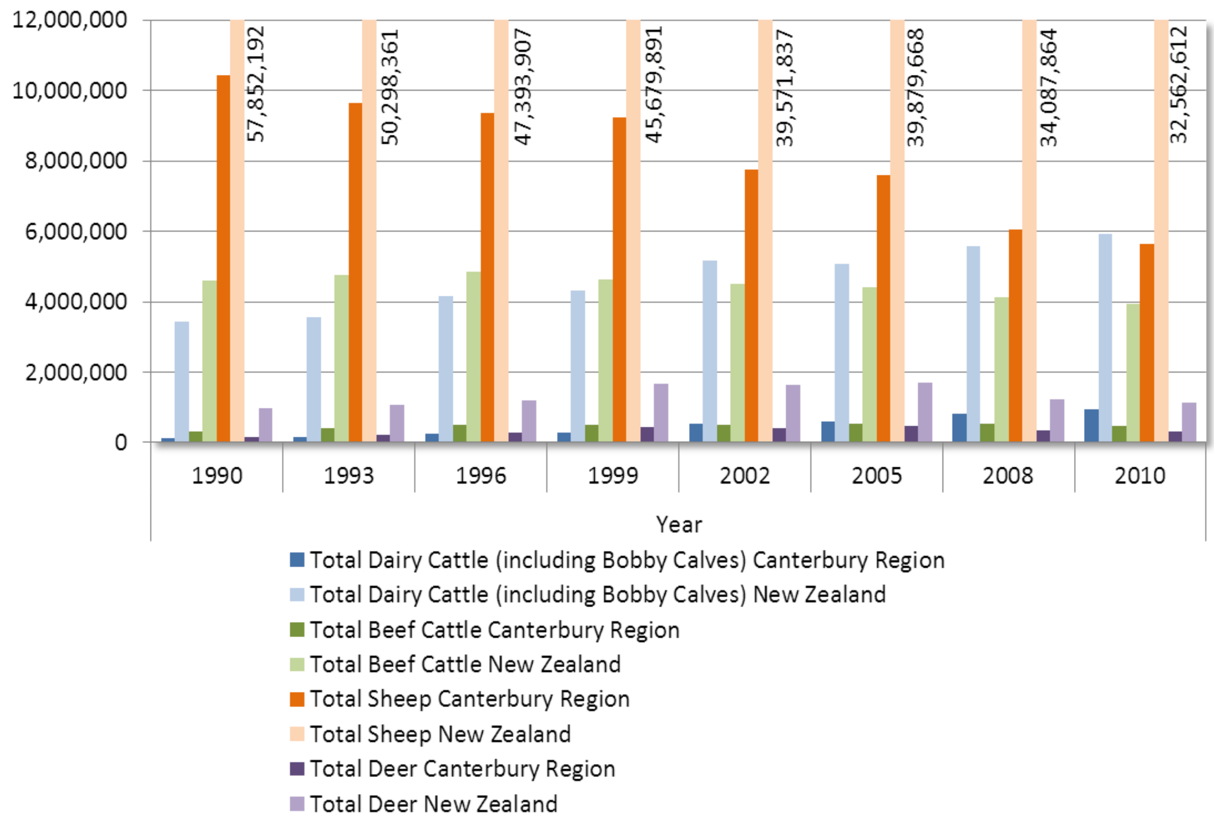


Figure 2 **Common stock of Canterbury and New Zealand 1990 – 2010 (S: Statistics New Zealand 2011)**

Land use intensification has increased economic output but has required irrigation as the area is in the rain shadow of the Southern Alps. Canterbury holds 63 % of New Zealand's irrigated land (Rajanayaka et al, 2010) and over 60 % of the water that is used for irrigation throughout New Zealand is allocated within the Canterbury Region (Miller & Veltman, 2004; Rajanayaka et al, 2010). The area has grown significantly from 150,000 ha in 1985 to 400,000 ha in 1999, and 680,000 ha in 2010 (Johnston, 2006; Rajanayaka et al, 2010). Canterbury is reaching its sustainability limits of water extraction using run-of-river offtakes and groundwater withdrawals (Johnston, 2006). Between 2006 and 2010 alone, the allocation in Canterbury increased with a difference of 25 Million m^3/week (11 %) (Rajanayaka et al, 2010).

In addition, the boost of irrigation has led to an increase in discharge to rivers and streams of irrigation bypass flow, containing additional nutrients. While the extra water may be beneficial to streams during low flow conditions in summer, the additional nutrients may promote weed growth, and cause changes in the natural ecosystems that are adapted to summer low flows (Woods & Howard-Williams, 2004). Hence water management is very important.

Aims for water allocation and management decisions in New Zealand are to provide "*water resource needs for social, economic and cultural well-being, health and safety, the potential of water resources to meet the foreseeable needs of future generations, safeguarding the life-supporting capacity of water resources, and avoiding, remedying or mitigating adverse effects of activities on water as a component of the environment*" (Memon, 1997, p. 308). Larned et al (2007) added water purification and fish production as important ecological services provided by alluvial rivers and their aquifers.

Regional Authorities are dealing with water management (e.g. by granting consents), in the area. ECan is the water manager and has been involved in

- establishing extraction volumes from rivers to provide for reliable water supplies while complying with environmental flow requirements;

- defining the sustainable supply from groundwater systems and identifying groundwater zones where allocated amounts of water have reached conservative estimates of aquifer recharge ('red zones') (Johnston, 2006).

Ashburton River

Ashburton River, one of the Canterbury braided rivers, is located in mid-Canterbury in New Zealand's South Island (see Figure 3). Since the early 1870's water has been taken from the Ashburton River and nowadays it is a highly allocated river (Horrell, 2001).

The Ashburton has two main branches; North Ashburton River and South Ashburton River. Ashburton River is similar in process, form and appearance to the other braided rivers that flow across the Canterbury Plains. This type of gravel-bedded braided river is extremely unusual and distinctive on an international scale. Many scientists have carried out studies on Canterbury braided rivers and the Ashburton itself was and continues to be the subject of intensive research (Mosley, 2001).

The estimated main stream natural mean flow at State Highway 1 is 30 m^3/sec, some 13 m^3/sec greater than the mean flow recorded over the past 15 years. The natural MALF (7d) is 400 % higher than the current low flow. With 60 % of the mean flow allocated for extraction the Ashburton River is the most highly modified river in New Zealand (Horrell, 2001).

The whole Ashburton Catchment, bordered by the Rakaia River in the North and the Hinds River to the South, drains approximately 4000 km^2. From its headwaters in the Arrowsmith Range the river is approximately 105 km long and has a mean annual flow of about 29 m^3/sec at the mouth (Horrell, 2009).

By way of a lagoon (up to 4-5 ha in area), that is bordered to both north and south by 20 m high terraces, the Ashburton flows to the Pacific Ocean. The river mouth is a dynamic system; long-shore drift displaces the mouth generally northward, commonly by 800 m (but up to 2 km) from the northern bank of the river. In a cycle of about 19 months the mouth reverts to the point where the river reaches the sea as high flows break through the bar (Mosley, 2001).

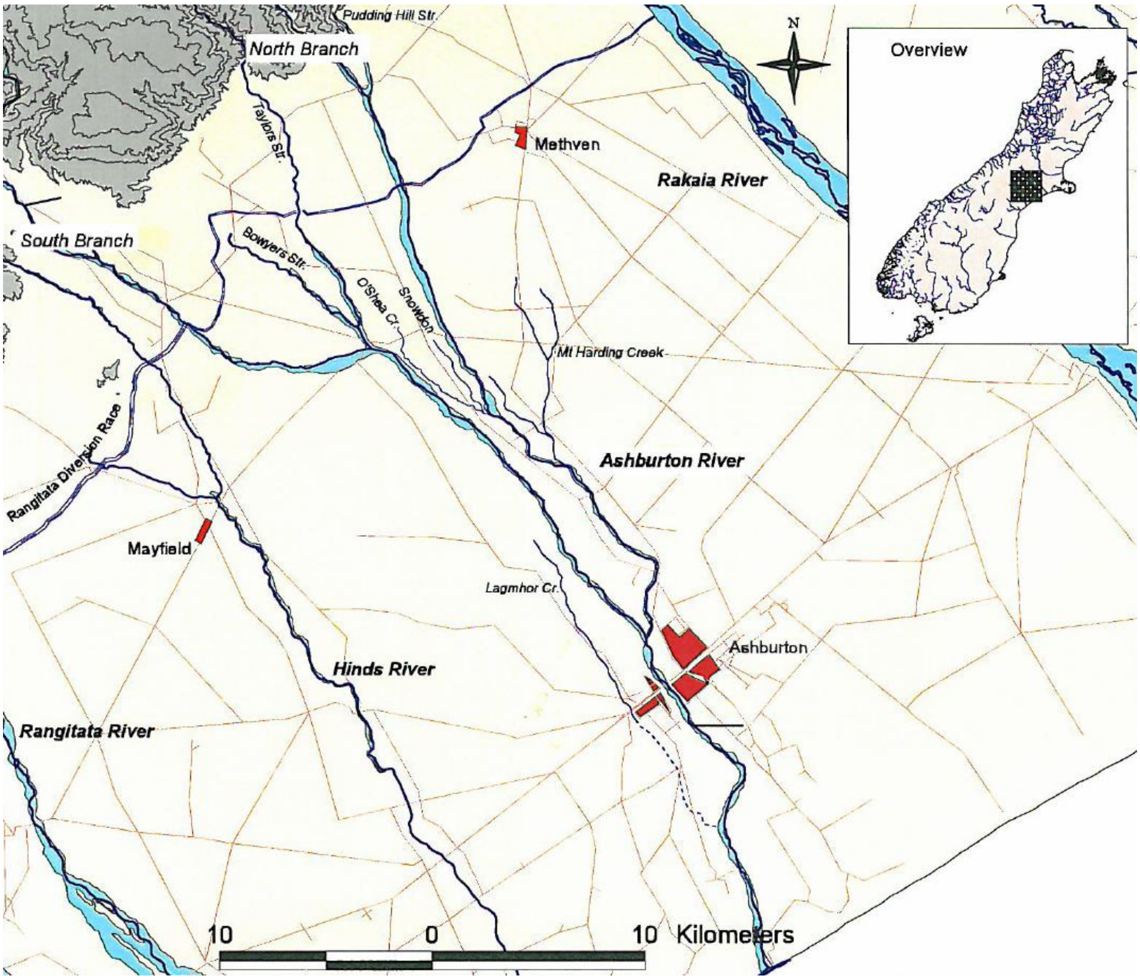


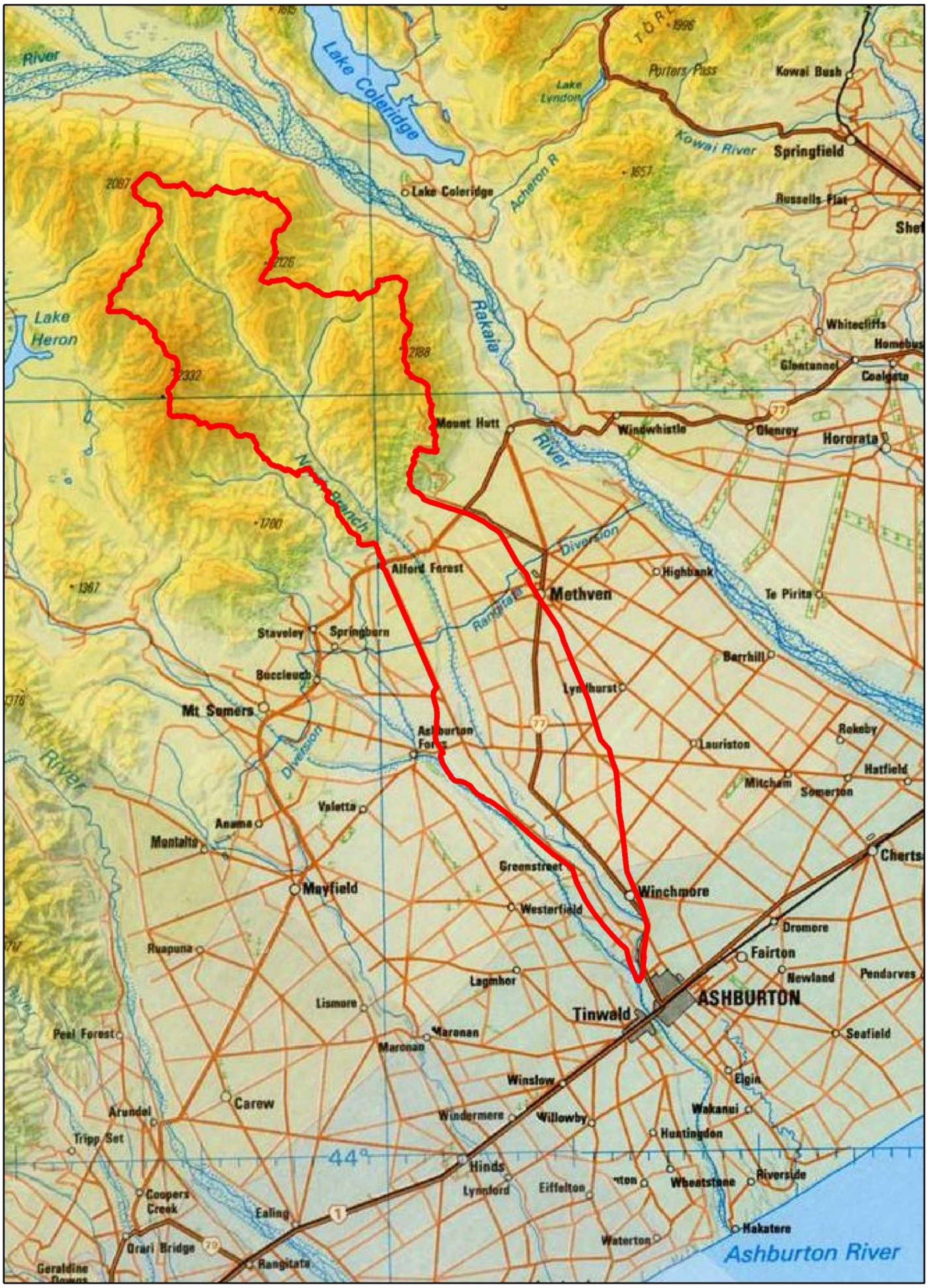
Figure 3 **Location map of the Ashburton River (S: Horrell, 2001, p 10)**

Study area in the North Ashburton Catchment

The study reaches are located 90 km south of Christchurch at five sites on the North Branch of the Ashburton River. Seven wells in the vicinity are also involved. Based on former studies (Horrell, 2001, 2004), and the flow direction of groundwater as well as the availability of wells in the region around the North Branch of the Ashburton River between the Rangitata Diversion Race (RDR) in the north west and the confluence with the South Branch in the south east was defined as field site. The North Ashburton catchment and its main features concerning topography, lithology, hydrogeology, climate and landcover are described in detail as follows:

The North Ashburton Catchment is bordered by the Rakaia River to the North and the South Branch of the Ashburton to the South (see red boundary line in Figure 4) and is approximately 515 km^2 in area above the confluence with the South Branch (Gabites, 2006). Above State Highway 72 the catchment has an area of 287 km^2. This is the major source of the catchment's water resource (Young, 1992). The catchment surface water comes from the Canterbury Foothills. The catchment consists of two topographical zones which are approximately equal in area – the mountainous upland catchment and the plains (Walsh & Scarf, 1980).

The main tributary, Pudding Hill Stream drains a catchment area of 40 km^2 and joins the North Branch on the Plains 0.5 km downstream of State Highway 72. Just above Shearers Road, the spring fed Snowdons Creek and O'Sheas Creek join the North Branch. Mt Harding Creek, also a predominately spring fed tributary, joins the North Branch about 12 km upstream of the confluence with the South Branch (Walsh & Scarf, 1980; Gabites, 2006).



Editor: Angelika Riegler 2012
Source: New Zealand Topographic Map

0 8 16 Kilometers N

Figure 4 North Ashburton River Catchment

2.1. Topography

The North Ashburton Catchment is a relatively steep catchment. It drains parts of the Taylor, Black Hill, Mt Hutt, Old Man and Alford ranges with peaks exceeding 2,100 m and ridge heights from 1,500 to 2,000 m. There, the terrain is dominated by more than 30° steep slopes and around higher peaks small, steep patches of broken rock outcrops occur. Very steep (35° or more) broken slopes or even vertical cliffs are found within the North Branch and some gorges of its tributaries (Walsh & Scarf, 1980). *The plains area which extends from the foothills for some 50 km to the sea is topographically featureless. The average gradient is 0.0085; ranging from 0.019 at the foothills to 0.005 at the coast*" (Walsh & Scarf 1980, p.7).

2.2. Lithology

The lithology of the North Ashburton Catchment is described in detail by a number of authors including Suggate (1973) and de Joux (1992). The rocks of the upper Ashburton Catchment are primarily composed of highly indurated greywacke and argillite that has been intensely folded, fractured and faulted. Deposits of Tertiary marine sediments such as siltstone, limestone and quartzose coal measures are restricted to small areas along the eastern foothills. At Mt Somers as well as in the Stour and Taylors Catchments volcanic deposits (rhyolite, andesite, Mt Somers volcanics) occur. The valley floors of the upper catchment are underlain by till deposits and glacial outwash. Eastward from the foothills, the Plains have been formed by the deposition of glacial outwash and from alluvial fans of east flowing rivers. During this time the rivers were choked with sediment which was deposited over a wide area as the river channels migrated laterally within the wider flood plains. The Ashburton River fan was not as extensive as those of the Rakaia and Rangitata Rivers. The Ashburton River contribution to fan building of the Plains was probably restricted within the neighbouring fans of those rivers. Due to this confinement the Ashburton River would apparently have experienced occasional blocking causing local ponding and deposition of clays and silts. A series of extremely cold (glacial) periods led to the erosion and deposition of greywacke and argillite gravels and silts. During warmer (interglacial) periods, erosion slowed and the rivers began to rework, sort and wash the gravels, forming channels of more permeable gravels. This process has led to the formation of alternating layers of gravel of different permeabilities in which a number of discontinuous aquifers may be found. The cycle of alternating glacial and interglacial periods was repeated at least 5 times within the evolution of this section of the Plains (Suggate, 1973; de Joux, 1992; Mosley, 2001).

2.3. Hydrogeology and groundwater

Throughout the Ashburton Catchment, known aquifers are contained entirely within the gravels of the Plains. Within the geological setting described in 2.2, aquifers are present within gravels having less fine material (deposited during interglacial periods) and may be bounded between or below relatively impermeable layers (aquitards). Basically the occurrence of groundwater is determined by the sub-surface geology and the availability of a suitable supply of water (recharge). Groundwater in the Ashburton Plains tends to be most readily available in the shallow gravels next to the rivers. In this area, the predominant source of recharge is seepage from the rivers (de Joux, 1992). Groundwater on the way to the sea may intercept the land surface as springs or creeks (Dommisse, 2006). For a schematic representation of groundwater movement through the Ashburton Plains see Figure 5 (de Joux, 1992).

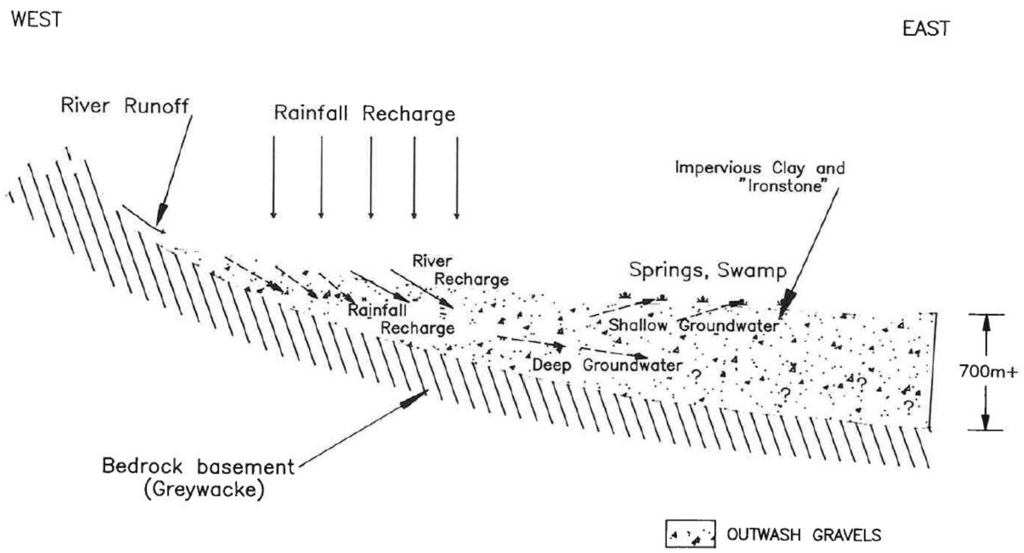


Figure 5 **Schematic groundwater movement through the Ashburton Plains (S: de Joux, 1992 p. 99)**

Shallow groundwater in the Ashburton Catchment is generally available near the main rivers. It has been heavily tapped for irrigation from Ashburton Forks to the coast. Due to lower permeability of the gravels, irrigable quantities of shallow groundwater are limited to the south of Ashburton Township. Away from the rivers gravels are less well sorted and groundwater is concentrated within narrower preferred channels or aquifers. Depths to groundwater deepen and although there is still some recharge possible from rivers, the major component of recharge is rainfall. Because of this reliance on rainfall recharge, and the lack of a large catchment to intercept and recharge, the deeper groundwaters within the upper Plains are generally have a lower yield than the groundwater from shallow bores close to the rivers The deep groundwater exists in more or less continuous layers at depths from 20 to 60 m throughout the middle and lower Ashburton Plains. Rainfall within the upper and middle Plains that does not flow into the rivers infiltrates into the thick gravel and migrates vertically and eastwards. This water becomes confined beneath layers of less permeable gravel and clays. Useable groundwater resources occur wherever this deeper groundwater intercepts layers of more permeable gravels (de Joux, 1992; Smith, 2005).

2.4. Climate

The climate of the North Ashburton Catchment is largely dominated by the migration of anticyclones separated by troughs of low pressure (Walsh & Scarf, 1980).

Four main local climate zones can be distinguished in the catchment (Ryan, 1987; Young, 1992)

a) Plains, with prevailing winds from the north east and south west. Rainfall is low and, by New Zealand standards there is a large annual temperature range.

b) Eastern foothills, where the weather is cooler and wetter, and there is a high frequency of north westerly winds.

c) Inland basins and some sheltered valleys, where rainfall is low, with a summer maximum, and diurnal and annual temperature ranges are large.

d) High country near the main divide, where the prevailing winds are north west and there is copious precipitation, winter snow and some permanent ice in the south.

In the foot hills and high country the ‘nor-wester’ is the prevailing wind from the westerly and northerly sector (Walsh & Scarf, 1980). Although they are not frequent on the Plains, the ‘nor-wester’ features largely in relation to agriculture. Evaporation on north-west days can amount to more than three times the seasonal normal resulting in a soil moisture deficit during the growing season. Irrigation is necessary in most parts on the Plains in the

North Ashburton Catchment and has become an integral part of agriculture (Ryan, 1987; Young, 1992).

2.4.1. Temperature

The warmest months are January and February, the coldest month is July. In Canterbury the mean temperature depends on the distance from the Pacific coast. Mean annual temperature near the coast ranges from 12°C in the north to 11°C in the south. Inland, the annual mean temperature decreases by 1-2°C at the western edge of the Plains, and by 3°C in the inland basins. The daily temperature range is greater at the western margin of the Plains compared with temperatures at the eastern or seaward margins. Another important factor is the degree of shelter from onshore winds (Ryan, 1987; Young, 1992).

Some very high temperatures occur as a result of the north westerlies. The highest temperatures measured in the North Ashburton Catchment are shown in Table 1: the warmest record for Winchmore was 38.5°C in February 1973; the lowest -6.3°C in July 2003. The warmest temperature measured in Ashburton was 35.9°C; the coldest -6.0°C.

Table 1 **Maximum and minimum temperatures for Winchmore and Ashburton in °C (S: NIWA 2011)**

	T max		**Tmin**	
Winchmore	08.02.1973	38.5	07.07.2003	-6.3
Ashburton	07.02.2011	35.9	21.06.2008	-6.0

2.4.1. Rainfall

Rainfall in the North Ashburton Catchment decreases from the Main Divide to the coast. The mean annual rainfall ranges from 650 mm on the Pacific coast to about 2,100 mm in the headwaters of the Mt Hutt Range (Griffiths & McSaveney, 1983).

The overall decrease from west to east is caused by the sheltering effect of the Main Divide. On the Plains there is a strong correlation between rainfall and altitude and rainfall decreases southwards (Ryan, 1987).

The decrease of rainfall from west to east is also obvious in Figure 6, where 3 records from rain gauges near the North Ashburton Catchment are plotted. Double Hill is the most western station and shows more peaks than Methven and the most eastern station, Ashburton. The highest peak of 350 mm was measured on Double Hill in August 1992. The whole data series of the three stations is plotted in Appendix IV.

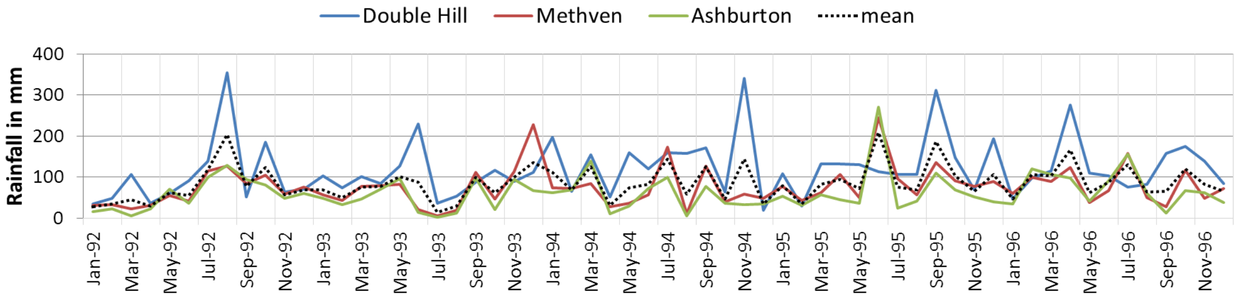


Figure 6 **Mean monthly rainfall in the North Ashburton Catchment 1992-1996 (S: NIWA 2011)**

Within the catchment rainfall is generally evenly distributed throughout the year Averaged monthly rainfall is between plus 19 and minus 25 % of the mean. June and September are the driest months and December is the wettest. There is, however, some variation in the seasonal distribution of rainfall as autumn rainfall is marginally higher than in other seasons. Due to the orographic influence near the divide maximum rainfall is in spring (Young, 1992).

2.4.2. Wind

The Canterbury 'nor-wester' is an important factor in the climate of the Ashburton Catchment. They become more frequent towards the eastern foothills, particularly in spring and summer (Ryan, 1987; Young, 1992).

Table 2 shows the maximum wind gusts for the Ashburton record for the period 2006-2011 with a maximum of 109.3 km/h on the 2nd of February 2009. In a severe wind storm in 1975, a maximum gust of 153.8 km/h was measured near Winchmore. Ryan (1987) estimated the average number of days with strong gusts in Winchmore. He states that gusts stronger than 63 km/h occur on 45.6 days of a year and gusts stronger than 96 km/h occur on 2.9 days. Comparative values for Christchurch airport are 51.5 and 2.8 days respectively.

Table 2 **Maximum wind gusts for Ashburton 2006-2011 (S: NIWA 2011)**

Date (NZST)	Speed(km/h)
02.01.2009	109.3
02.02.2011	100.1
21.12.2010	98.2
21.07.2009	96.4
01.03.2006	94.5

2.4.3. Sunshine

The Plains experience 40-45 % of possible sunshine hours. Nearing the eastern foothills this increases to around 45-50 %. Seasonal variation is small in most places, but there is a general tendency for it to be sunnier in summer in the north, and in winter in the south of the Plains (Ryan, 1987; Young, 1992). Table 3 lists the average duration of bright sunshine for four periods. In the period 1951-1980 the annual duration of bright sunshine is highest with 1,909 hours, the period 1971-2000 shows the lowest value with 1,886 hours.

Table 3 **Sunshine normals in hours for Ashburton (1941-2000) (S: NIWA 2011)**

Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1941-1970	202	168	155	144	122	117	125	147	157	183	191	193	1,904
1951-1980	198	171	149	147	126	122	126	145	155	185	188	197	1,909
1961-1990	202	172	151	153	128	122	122	143	149	180	184	199	1,906
1971-2000	198	171	160	147	132	119	123	142	147	171	181	195	1,886

2.4.4. Evaporation and water balance

The combination of high wind speeds, large saturation deficits and high sunshine hours results in high amounts of open water evaporation. Monthly evaporation is at its lowest (around 20 mm) in winter (June and July) on the Plains and generally at its highest in December or January (around 100 mm) (Ryan, 1987). About 80 % of annual evaporation occurs during the 8 months from October to April. The December-January rates are approximately 5 times those recorded in June-July (Young 1992). During the summer months, the daily evaporation is markedly variable, ranging from less than 1 mm/day to more than 8 mm/day during hot and dry ‘nor-westers’ (Walsh & Scarf, 1980).

Potential evapotranspiration and the water balance for Canterbury is discussed in detail by Ryan (1987) and Young (1992). Soil water is given up by evaporation from the surface and by plant transpiration; this loss is termed evapotranspiration. As long as it is not limited by the available soil water supply, it occurs at a maximum rate known as potential evapotranspiration (ETmax). Plants conserve moisture by reduction of transpiration when soil water is short (Ryan, 1987).

In his data analysis, Young (1992) suggests that on average the Plains annually can expect a wilting point deficit of around 250 mm. "*This is the annual deficit or shortfall between rainfall and potential evaporation. It also corresponds to the amount of irrigation needed to keep plants from wilting over a given period. […] At Ashburton there is a 50 % probability of 85 or more days of deficit per year"* (Young, 1992, p. 20).

2.5. Landcover and vegetation

The North Ashburton Catchment consists partly of dry foothills and basin floors at mid elevations and supports extensive tussock grasslands. Introduced grasses and herbs are increasing. This high producing exotic grassland makes up the majority (41.6 %) of land cover, 21 % is covered by short-rotation cropland and 13.5 % by alpine gravel and rock. Tall tussock grasslands amount to 13.2 % of the catchment.

Tussocks have a clumping growth form, with stems fanning up and outward from a central bunch. Tussock is not actually a single group of related plants but a growth habit – a particular arrangement of stems and leaves which forms a tuft of vegetation. The stems or tillers from which the leaves sprout are unusually tightly clustered. This special growth form helps grasses to survive. In the past, farmers burnt off large areas of tussock and replaced it with imported grasses, so they could graze more animals. Recent studies have highlighted the ability of snow tussock grasslands in good condition to produce high water yields from their upland catchments. Studies reported water yields of up to 80 % of measured annual rainfall, and 86 % for the snow-free six months, on unburnt snow tussock land. Tussock areas also have very low water losses through evaporation or transpiration. In some places, fog deposits water directly onto tussock leaves, adding to the water yield. Tussock grassland retains water and releases it gradually, reducing to some degree the chance of flash floods downstream (www.teara.govt.nz). Other land cover categories of the catchment (10.7 %) can be seen in Figure 7.

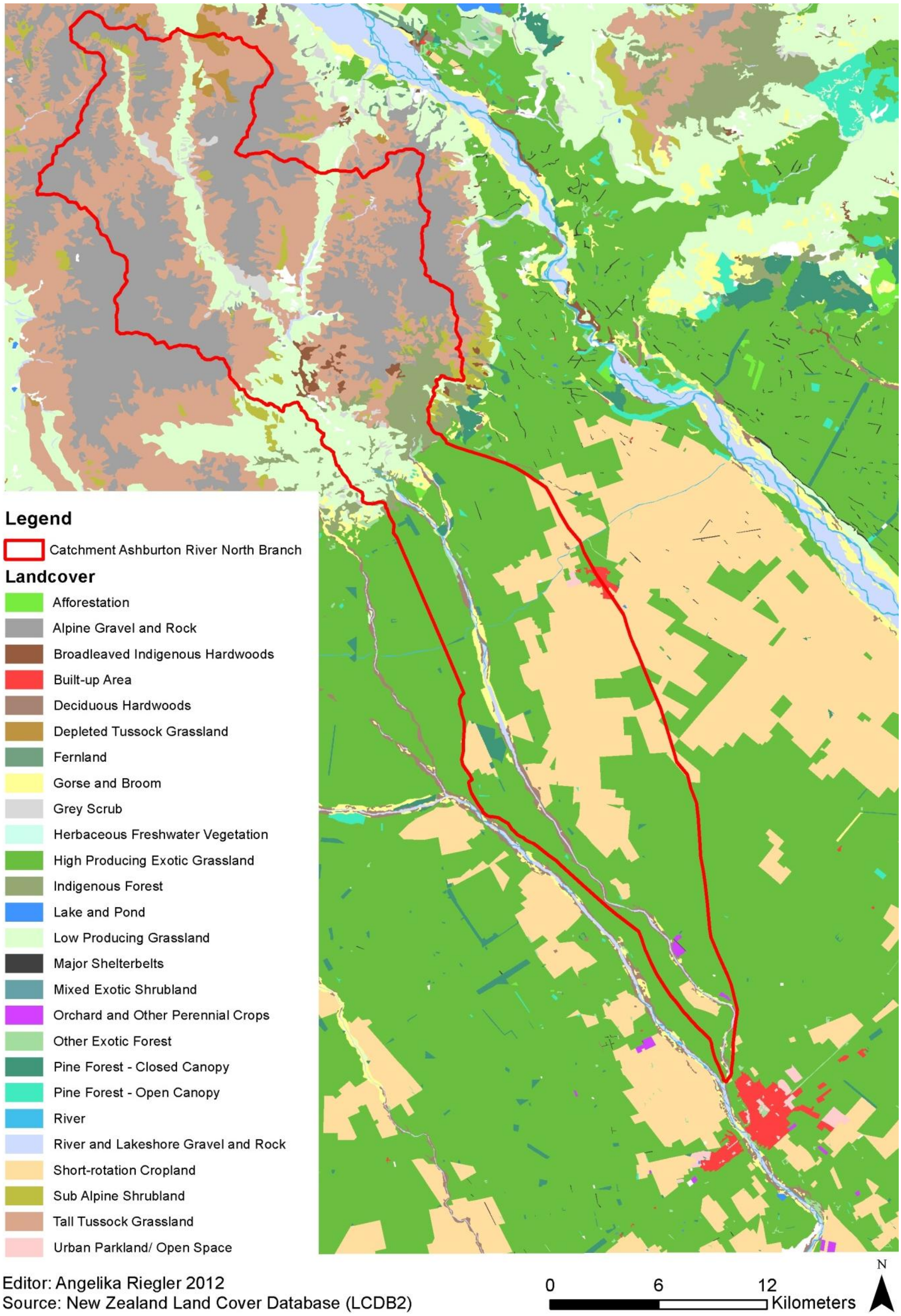


Figure 7 **North Ashburton River Catchment landcover**

3. State of research on the North Branch

After getting important information about the study area, former studies on the North Branch are presented in this chapter and represent another important basis for this investigation. Hypotheses listed in 3.3 either represent a continuation of former investigations or arose from determined gaps in research.

3.1. Significant studies on the North Branch (1980-2004)

Starting in the early 1980s, numerous studies have reported on aspects of the groundwater system within the Ashburton Catchment, the flow regime and the relationship between the North Branch and the aquifers adjacent to the river. Due to the growing importance of water to the Ashburton area, the South Canterbury Catchment and Regional Water Board (SCCB) called for a report on the water resources because it believed that conflicts for water which had arisen in the past could be expected to increase unless there was a greater knowledge and understanding of the resource. The resulting report includes detailed information about the catchment, water use, surface water resources, groundwater, and water quality of the Ashburton Catchment (Walsh & Scarf, 1980).

In 1983 the SCCB published a water management plan to resolve the conflict between continued water abstraction for agriculture and the need to maintain sufficient flow throughout the river system for fisheries protection, wildlife habitat and recreational use. The principle objectives of this water management plan were among other things: setting minimum flows for the Ashburton River, preserving where possible the natural flow pattern and quality of the river and its tributaries, establishing priorities for utilisation of the available water resources and to specify how the available water resources are to be allocated between in-stream (fisheries, wildlife and recreation) and out-of-stream (stock water, municipal water supplies, irrigation and industrial) uses (Scarf, 1983).

The stimulus for the investigation of Scott & Thorpe (1986) was the proposal to implement the Lower Rakaia Irrigation Scheme using water from the Rakaia River. The goal of the study was to obtain an overall understanding of the aquifer system between the Ashburton and the Rakaia Rivers and how this might change under the impact of future irrigation development. The authors concluded that regional drawdown of the water table caused by extensive groundwater pumping adjacent to the Ashburton River would induce recharge to the aquifers, and hence significantly reduce river flows. This effect could be marked on the low summer flow of the Ashburton River (Scott & Thorpe, 1986).

In summer/autumn of the years 1997-1999 severe droughts reactivated investigations into various options designed to provide improved flows and reliability for irrigation use. One example under study was the proposal to dam the South Ashburton which would significantly change the braided nature of the Ashburton River. The goal of an investigation by Scarf (1999) was to restore the natural low flow characteristics of the Ashburton River to enable present and future generations to enjoy the cultural, social, recreational, and other community benefits.

The scope of Mosley's (2001) report for ECan on the North and the South Branch and its emphasis is on the river downstream from the foothills. Here the water resources over the years have been exploited extensively for irrigation, stockwater, and other purposes, and there are particular issues relating to resource allocation. Mosley reported that specific yield of mean annual floods on the North Branch (at the upstream recorder Old Weir, in a gorge) are 0.62 $m^3/sec/km^2$ and the number of distinct flood events in any one year that exceed 25 m^3/sec also varies significantly. The average is 8 with a range from 3 to 15. The longest period during which there were no freshes was 176 days in 1999. Long periods of sustained low flow can occur at any time of the year, but seem to be especially characteristic of January through to August. On the North Branch at Old Weir, the average monthly 7-day low flow has varied between 9.1 m^3/sec (October) and 3.8-3.9 m^3/sec (February and March). The overall minimum monthly 7-day low flow of 1.9 m^3/sec was recorded in April 2001. Mosley concludes that flow requirements vary widely, with some characteristics and values in fact having little relationship to discharge and that there are many uncertainties which require a substantial amount of further investigation (Mosley, 2001).

Horrell (2001) attempted to establish what the natural flow regime would be without abstractions to determine whether the North Branch of the Ashburton River would go dry under natural conditions. He derived daily time series of natural flows using linear regression from primary flow recorder stations or groundwater levels. As Horrell's studies are an important basis for investigated hypotheses, these results are discussed in detail.

3.1.1. The North Branch flow regime

Horrell (2001) stated that the historical mean flow record developed for the Old Weir site showed considerable fluctuations but there was no trend of abnormally reduced flows in the last 20 years. However flows in the lower reaches of the North Branch were much lower than they have been historically. The North Branch only went dry in 1890, 1931 or 1932 and 1945 but never stopped flowing until the late 1960's. Observations at Digbys Bridge show there is no flow for many months at a time. Natural changes do not appear to account for this change. By comparing the natural flows at Digbys Bridge to the consented total abstraction, Horrell (2001) reports that it was evident that the large amount taken from the river was the major reason why the river goes dry. Also, contributing to the zero flows are losses due to water uptake by willows and the reduced groundwater resource to the east. The last action of a series which finally caused the North Branch to go dry was the increase of frequency of the Greenstreet take of 1200 l/sec from O'Shea Creek since 1980 (Horrell, 2001).

Within this study the number of days where the North Branch is dry in the vicinity of Digbys Bridge were predicted back to 1982 together with an investigation as to whether the dry sections increased over the 10 last years (see hypothesis a in 3.3).

3.1.2. Losses and gains during summer low flow conditions

"*Losses from the North Branch to the surrounding groundwater systems and gains to the South Branch are important for the understanding of Ashburton River water resource*" (Horrell, 2001, p. 21). In the summer of 1999/2000, Horrell (2001) calculated losses and gains by comparing two runs of concurrent gaugings down the main Ashburton River and its major tributaries. Looking at the North Branch in Figure 8, the total losses between the gorge and the confluence with the South Branch were estimated to be 0.7 m^3/sec. This loss recharges the groundwater system to the east of the North Branch and contributes to gains in the South Branch (Horrell, 2001).

The North Branch gains from the gorge (gain rate 356 l/sec/km). The first significant loss of 1.3 m^3/sec is from the Methven Auxillary downstream to Fleming Road. The losses to Thompsons Track Road are insignificant. From there to Shearers Road there remains a loss (645 l/sec), but from Shearers Road to Ollivers Road there is a gain mainly from

Mt Harding Creek inflow. From Ollivers Road to Digbys Bridge there are major losses from the channel (1.3 m^3/sec).

The gain (rate 182 l/sec/km) from Digbys Bridge to the confluence with the South Branch could be sourced from upstream losses re-entering the stream. Assuming upstream losses continue at the same rate as identified in the summer of 1999/2000, Horrell (2001) estimated the losses to the east (below Ollivers Road) to be of the order of 2 m^3/sec. The highly modified flows suggest this groundwater resource would not receive these inflows continuously (in the summer of 1999/2000 it was only 1.3 m^3/sec). This may explain the periods of zero flow in the lower reaches (especially at Digbys Bridge) on the North Branch (Horrell, 2001).

In Horrell (2004) it is stated that the key to understanding the loss and gain rates throughout the North Branch reach is knowledge of the state of groundwater systems at the time of the flow measurements. This information was not available at the relevant locations to model losses and gains over the full reach. He concluded that a lack of detailed knowledge of the groundwater system at the time of the field investigation detracts from the analysis.

Based on information in Horrell (2001), seven wells were added in the current investigation to measure the groundwater level. At the same time measurements of losses and gains of the North Branch in summer 2011/2012 are taken into account in hypothesis b (see chapter 3.3).

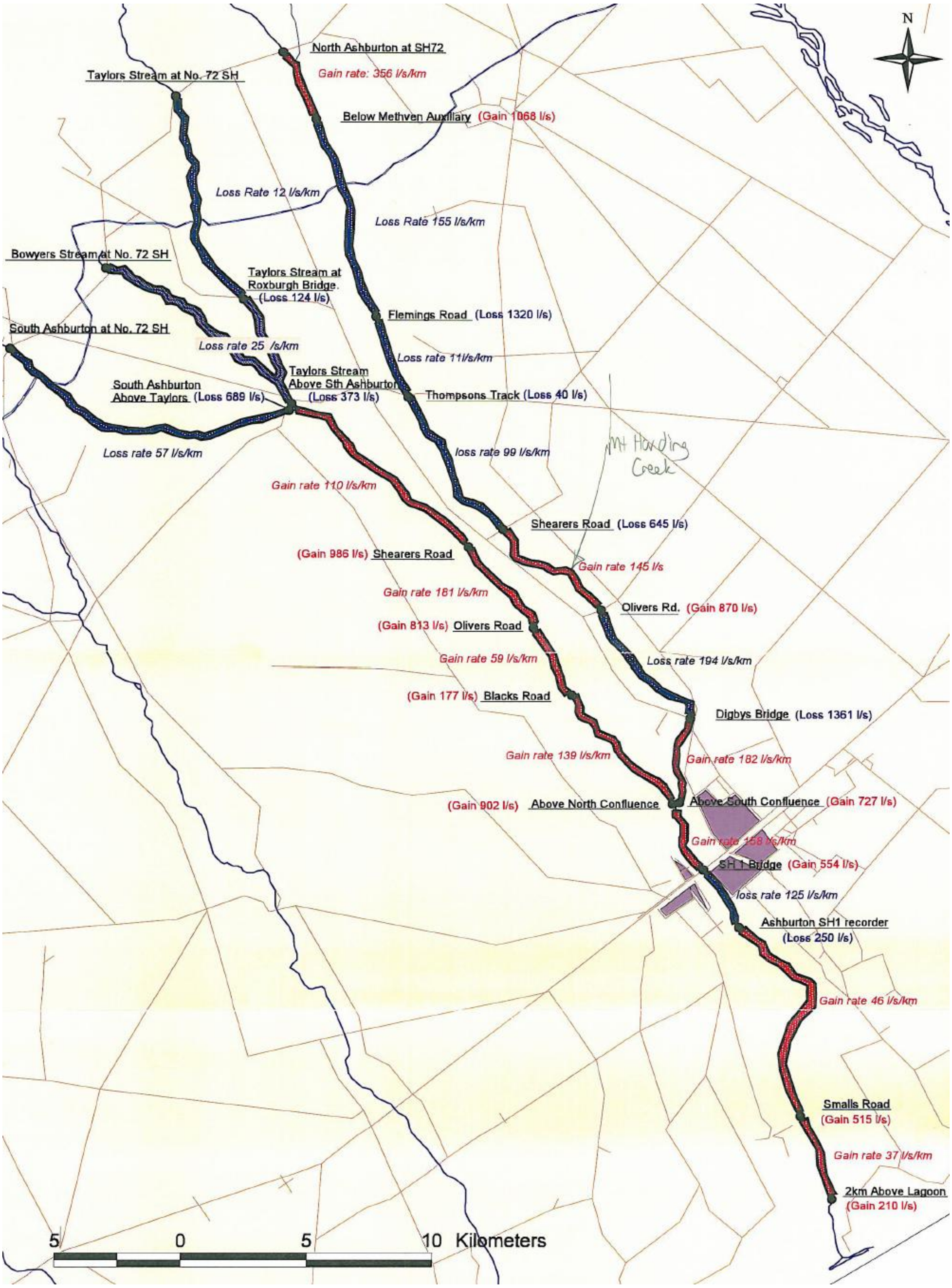


Figure 8 Flow losses and gains in the main tributaries (S: Horrell, 2001, p. 24)

3.2. Significant studies on the North Branch (2005-2010)

In June 2005 a groundwater level survey was undertaken within a designated area on the eastern side of the North Ashburton River. The purpose of the project was to collect water level data from nominated wells to construct a piezometric contour map of the area (see Figure 9). Additionally, a river flow gauging survey was undertaken along the reach of the North Branch to enable an assessment of the groundwater/surface water interaction between the river and the surrounding groundwater system. Smith (2005) reported that the depth to standing water in areas close to rivers is generally less than 5 m, about 10 m at the coast, 60 m at Chertsey and further inland, near Lauriston and Lyndhurst, depth to water exceeds 100 m. In the vicinity of rivers, the natural seasonal variation is less than a metre but in areas of deeper groundwater it can be as much as 12 m. According to Smith (2005), the piezometric contours show that groundwater generally flows eastwards and northwards from the North Ashburton River towards Winchmore. At the time of this investigation, the North Branch was running dry between Mt Harding Creek and Site 9. Due to technical difficulties, the data from this survey was unavailable for further analysis (Smith, 2005).

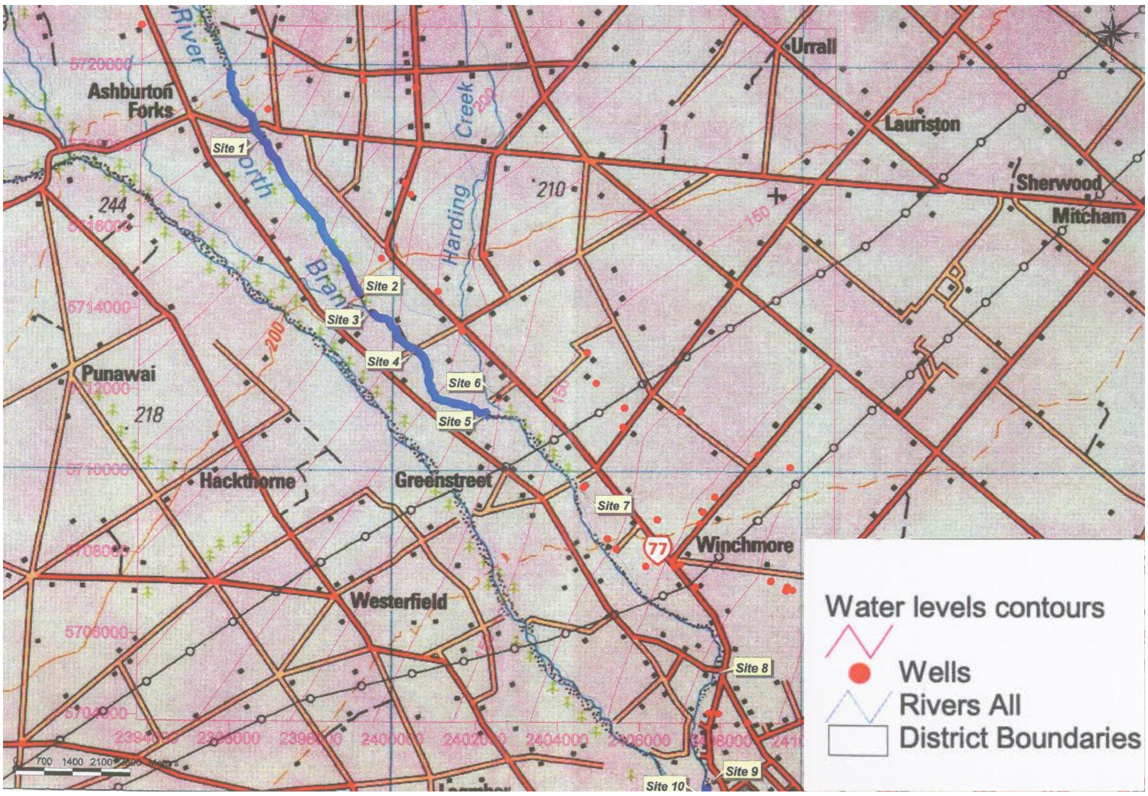


Figure 9 **Modified piezometric contour map constructed using water level data (S: Smith 2005, p. 2)**

The fact that the dataset of Smith (2005) is not available is unfortunate. Consequently an investigation concerning the relationship between the groundwater system and the river flow in the North Branch was carried out using data gained in summer 2011/12 (see hypothesis c in chapter 3.3).

Gabites (2006) prepared an ECan report on the Seven-day Mean Annual Low Flow (MALF (7d)) and mean flow values for the North and South Ashburton River Catchments. To establish MALF (7d) for each year of record, the lowest flow averaged over seven consecutive days had to be found. At the Old Weir recorder, the North Ashburton normalised MALF (7d) was estimated at 3.08 m^3/sec over a total of 30 years. The measured mean flow at this site was 8.41 m^3/sec (Gabites, 2006).

Thorley et al (2010) published an ECan report with the purpose of advancing the technical understanding of the groundwater system to inform resource management decisions in the Rakaia-Ashburton Plains area. The report recommends resource management strategies for managing the risk of irrigation development in the vicinity and has been written in the context of applications to take groundwater for irrigation over the current allocation limit.

3.3. Hypotheses

Based on former studies the following hypotheses are investigated:

a) Low flow regime durations and dry sections in the North Ashburton at Digbys Bridge are increasing with the increase in groundwater abstraction in the vicinity over the last 10 years.

b) Flow losses on the North Ashburton between all gauging sites from the Old Weir recorder site to the confluence with the South Branch are higher at higher flows throughout the reach

c) The North Ashburton outflow at Digbys Bridge is directly related to the inflow at Old Weir at high river flow, no matter what the groundwater levels are, and conversely when Old Weir flows are low, the flow at Digbys Bridge is closely related to groundwater levels and Old Weir flows.

3.4. Specific objectives

The hypotheses were investigated in detail as follows:

Hypothesis a)

To predict the dry periods at Digbys Bridge back to 1982, multiple linear regression analysis were applied using flow records from the Old Weir site and the groundwater level of one well in the vicinity. The annual number of dry days and the long term mean were plotted to be comparable with other analysis. An attempt was also made to predict the length of the dry reaches.

In another approach, flow records from Ashburton River North Branch and the Selwyn River, which has a similar foothill catchment, were tested for long term trends. The months January to April were selected as they are typically the lowest flow months.

Long term means of groundwater levels, the 90 days annual low flow at the Old Weir recorder as well as available allocation totals were also used to investigate this hypothesis.

Hypothesis b)

Nine spot gauging runs at five river cross sections on the North Branch between Thompsons Track Road and the confluence with the South Branch were performed in summer 2011/12 and completed with data records using the upstream flow at Old Weir to calculate losses and gains throughout the reach.

Hypothesis c)

Observations from the gauging runs in the summer 2011/12 were plotted together with the flow at Old Weir and groundwater levels in the vicinity to determine the relationship between them. The predicted flow at Digbys Bridge was also used for this investigation.

4. Method

The methods applied in this thesis can be divided into desktop work and field work. The desktop work was mainly carried out in an office at the campus of the National Institute for Water and Atmospheric Research (NIWA) in Christchurch, Canterbury. The data in the field was gained weekly to fortnightly from the end of November 2011 to February 2012.

4.1. Desktop work

Information, data and pictures concerning irrigation and water use in the Ashburton catchment was collected from various sources: a literature research was carried out and a farmer in the Mayfield Hinds irrigation scheme was visited and interviewed.

After collecting information about the North Branch, including reading technical reports, one of the first tasks was visiting the groundwater section of ECan in Christchurch and learning about the contents of their 'Wells database' and how to use the data (see chapter 5.2).

4.1.1. Interpolation of selected wells

To obtain a set of wells in the vicinity of the North Branch of the Ashburton River from the 'Wells database' Microsoft Access 2010 software was used. After the wells were selected by their location, record length, depth and status, the accessible ones were put into a database. This database was imported into ArcGIS (version 10 by the time of writing) and connected to a map of the vicinity of the North Branch. After a layer of the field site was drawn by hand, the function 'make an XY event layer' was used to produce a layer of the wells within the field site. Later, maps were produced showing age and use of the wells and well depth to get an understanding of the study area. The most important criterion for well selection was the length of records. Unfortunately the length of the records differed from well to well and some time series had gaps (see data availability in Figure 23). With the help of NIWA TIDEDA Version 4 groundwater levels were interpolated to get consistent data series for every single well. TIDEDA is software for processing time-dependent data, especially river flow data. The program captures records from a keyboard or data import (e.g. Excel sheets). See detailed workflow in Appendix II.

4.1.2. Regression analyses

The availability of flow and groundwater level data along the North Ashburton River is poor, especially in the drying reaches of interest, so a method was required to estimate the flow for those reaches. There is one recorder measuring natural river flows upstream at the Old Weir in a gorge. Across the plains there are only sparse spot gaugings at river crossings down to Digbys Bridge obtained in historic investigations.

In his study, Scarf (1972) introduced standard correlation techniques. He used long term recording sites as primary sites and 12 to 15 gaugings from secondary sites to establish the average annual flow of the secondary site. In his report about the Ashburton River low flow regime Horrell (2001) describes deriving daily time series of natural flows using linear regression analysis from the primary flow recorder and also some multi linear regression analyses including groundwater levels. Also, Gabites (2006) used regression analyses in her study. Using the equation and the available data of the South Ashburton annual low flows (ALF), an extra 8 years of ALF's were synthesised and averaged with the data from the North Ashburton. Regression analyses were also used to predict incremental effects of spatial or temporal changes in flow regimes and to estimate river flow (Rupp et al, 2008; Schmidt et al, 2009; Larned et al, 2010A; Larned et al, 2010B). In the present investigation regression analyses were applied using data from various sources. The regressor variable (x) may have to be easily controlled and accurately measured. The method of regression analysis assumes that this variable is measured essentially without error (Heyworth & Sealy, 1980). The program used was Microsoft Excel. In a first step, commands *Data / Data analysis / Regression* were selected. In the opened regression window, the input y-range (independent variable) and the x-range (dependent variable) were selected.

Output tables were produced for linear and multiple regression analyses using well records, gauging data and the recorded flow data from the North Branch. The output table in Figure 10 shows an example for a regression analysis using a dataset from Digbys Bridge as independent variable (y) and the dependent variables Old Weir flow (x_1) and groundwater level in well number K36/0051 (x_2). The result shows if the groundwater level and the flow data are dependent. Regression outputs made using Excel show that the R square, adjusted R square, Standard Error (…) and also the formula

$$y = b+a_1x_1+a_2x_2+...a_nx_n$$

could be derived from the output table as:

$$y\ (m^3/sec) = -7.66335 + 0.949885 * \text{Old Weir}\ (m^3/sec) - 0.81646 * K360051\ (m)$$

In this example the result is

$$\text{Predicted flow at Digbys Bridge}\ (m^3/sec) = -7.66335 + 0.949885 * \text{Old Weir}\ (m^3/sec) - -0.81646 * K360051(m)$$

SUMMARY OUTPUT									
Regression Statistics									
Multiple R	0.955673804								
R Square	0.91331242								
Adjusted R Square	0.907120449								
Standard Error	0.60047652								
Observations	31								
ANOVA									
	df	*SS*	*MS*	*F*	*Significance F*				
Regression	2	106.3683869	53.18419	147.4995	1.35331E-15				
Residual	28	10.09601742	0.360572						
Total	30	116.4644043							
	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*	
Intercept	-7.663345751	1.051190453	-7.29016	6.16E-08	-9.816611783	-5.510079718	-9.816611783	-5.510079718	
Old Weir Flow (m^3/s)	0.949885105	0.059071462	16.08027	1.13E-15	0.828882701	1.070887508	0.828882701	1.070887508	
K36051	-0.816455154	0.161702489	-5.04912	2.42E-05	-1.147687687	-0.48522262	-1.147687687	-0.48522262	

Figure 10 Regression analysis output

The most important parts of the regression analysis output table provided in Excel are

- overall regression accuracy: *R Square* and *Adjusted R Square*. E.g. in this example 91 % of the variance are explained, so the flow at Digbys Bridge is dependent on groundwater level in K 36/0051 and the upstream flow at the Old Weir site. Thereby adjusted R square is more reliable because it takes into account the sample size and should especially be taken into account at multiple regressions.

- probability that the regression output is not random. The smaller *Significance F* the greater probability that the output is not by chance. In our example there is a 1.35 % probability that the output was random chance

- standard error measures the variability of actual y values from the predicted y values and is the same as standard deviation.

4.1.3. Field study data

After each day of gaining data at the North Branch, the programme FlowTracker v2.20 was used to transfer data from the handheld instrument to the computer. This data was plotted automatically and checked for errors. If necessary the dataset could be edited with NIWA TDGauge. Water depths and section widths had to be plausible. The correction factor for the starting and ending edge (where the depth was 0) was 0.6 and had to be entered during the gauging. The value 0.6 means, in this section the flow is estimated to be 60 % of the mean flow of the first measured vertical. If the river had more than one braid at one site, the values of each braid were added together and listed in an Excel database. After gauging sites went dry, the extent of dry sections was mapped. Thus the GIS coordinates of interesting sites (flow disappearing/flow reappearing) were collected in the riverbed. The coordinates (in meters) were entered into an ArcGIS file, using the Projected Coordinate System 'GD 1949 New Zealand Map Grid'. To import the layer into a map, it was projected into 'NZGD 2000 New Zealand Transverse Mercator'. In a next step the dry sections, flowing section as well as changes to the previous run were drawn as lines. The length of the sections was measured automatically within the program and plotted on the map.

4.2. Field work

Field work was carried out on the North Branch of the Ashburton River. It was gauged regularly from November 25th 2011 at five sites using a SonTek Flow Tracker. The sites were selected based on the availability of some historical discharge data and easy access e.g. road or bridge. These sites are (from North to South in Figure 11, pictures in Appendix III):

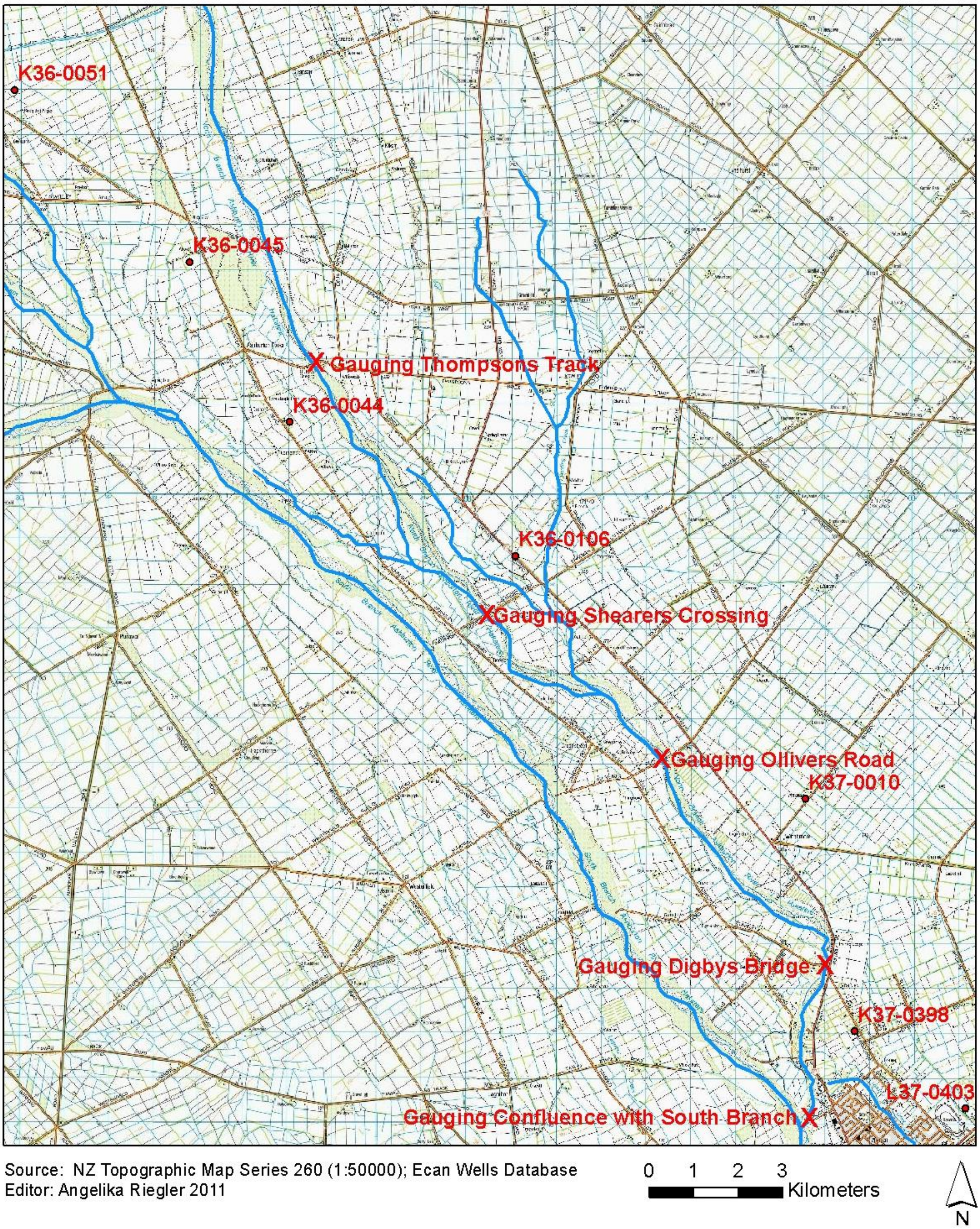
- Thompsons Track Road
- Shearers Road
- Ollivers Road
- Digbys Bridge

- North Branch near Melrose Road (confluence with South Branch)

Before a gauging could be started it was important to find a suitable site (see chapter 4.2.1) near access into the riverbed. As the North Branch of the Ashburton is a braided river, either a single, main braid-section in the vicinity had to be found, or all braids required separate gauging and the discharges of each braid had to be summed. The selected sections were retained during the length of study.

When the gauging sites at Shearers Road and Digbys Bridge went dry, the length of the dry sections had to be measured by collecting coordinates (e.g. E2399422/N5713931) with a handheld GPS. The first run was done by walking upstream from Shearers Road to see where the flow disappeared. As it was assumed that the flow at Ollivers Road was coming from Mt Harding Creek, just walking downstream to see where the flow was disappearing was necessary. While walking with the GPS the elevation of the riverbed was recorded, and the information written in a notebook. In the office the coordinates were put onto a map (see also chapter 6.2). The spots where the water was emerging or disappearing were noted to calculate the extent of dryness in the office. For the next weeks four wheel drive vehicles were supplied by NIWA and ECan to drive up the riverbed from the confluence of the South Branch to Thompsons Track Road to map dry/flowing sections and verify the assumptions made earlier.

A water level meter was used to measure the depth to water at the seven selected wells in the area. ECan provided the keys for those wells secured with a lock. Information about the selected wells is provided in Appendix I.



Source: NZ Topographic Map Series 260 (1:50000); Ecan Wells Database
Editor: Angelika Riegler 2011

Figure 11 Gauging sites on the North Branch and measured wells in the vicinity

4.2.1. SonTek Flow Tracker

To measure the Ashburton River discharge, the Flow Tracker (Figure 12), a handheld instrument was used. Measurement is based on an Acoustic Doppler Velocimeter (ADV). "*The Doppler principle says that if a source of sound is moving relative to the receiver, the frequency of the sound at the receiver is shifted from the transmit frequency. The Flow Tracker uses the Doppler shift by measuring the change in frequency of sound that is reflected off particles in the water*" (SonTek Flow Tracker User's manual, 2009, p.31).

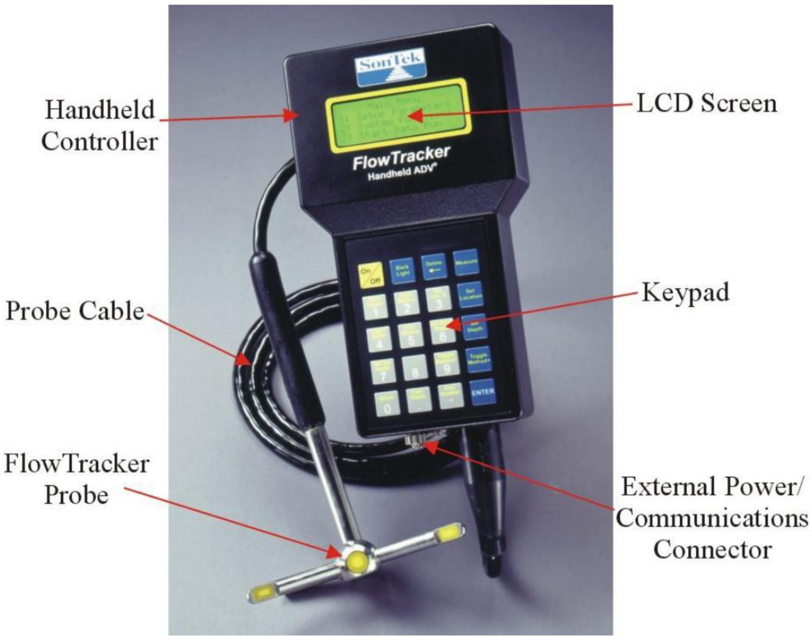


Figure 12 Flow Tracker with 2D Probe (S: User's manual, 2009, p.1)

The Flow Tracker probe for a bistatic Doppler current meter is shown in Figure 13. It is fixed on a wading rod. "*Bistatic means separate acoustic transducers are used for transmitter and receiver. The receivers are mounted to focus at a fixed distance (10 cm) from the probe. The beam intersection determines the location of the sampling volume*" (SonTek Flow Tracker User's manual, 2009, p.31).

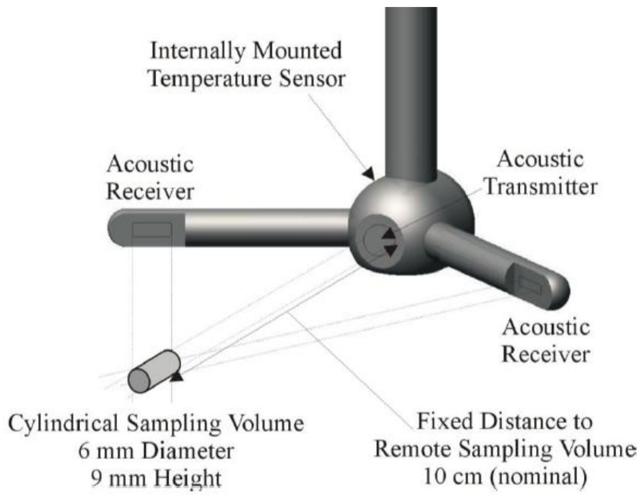


Figure 13 **Flow Tracker 2D side looking probe and sampling volume (S: User's manual, 2009, p.31)**

Measuring river discharge with the Flow Tracker requires wading across the river while taking measurements of velocity and water depth at several locations. The total discharge can then be evaluated by combining velocity measurements with depth/width information.

To gauge a river, it is important to select moderately uniform bottom conditions that can be waded safely (generally not more than 1 m deep). A tape is fixed across the river perpendicular to the riverbanks. At one edge of the water (usually the left bank) the measurement is started. At each river cross section, location and water depth is entered and the Flow Tracker measures the velocity at one depth (normally 0.6 of depth) for 40 seconds. As shown in Figure 14, the probe's X-axis must be maintained perpendicular to the measuring tape at each of the measuring locations (typically 20 per gauging).

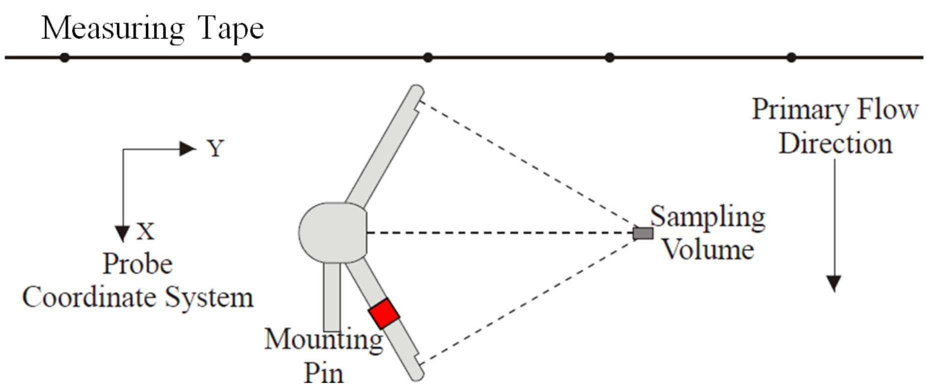


Figure 14 **Flow Tracker probe orientation relative to stream flow (S: User's manual, 2009, p.3 modified)**

Velocity data is recorded once per second for the entire averaging time (approximately 40 seconds), and then averaged to evaluate the mean velocity. Based on section width, depth, and mean velocity, the discharge for a section is calculated. The total discharge is the sum of all sections and edge discharge values.

Figure 15 First gaging run on 25th November 2011

4.2.2. Water level meter

The water level meter is used as an instrument to measure the depth to water in the seven selected wells of this study. On the end of a measuring tape a sensor is installed (see Figure 16). On meeting the water surface, the sensor sends an auditory signal and the depth can be read on the measuring tape.

Figure 16 Water level meter (S: www.bestservices.co.in)

5. Data

This chapter gives a description of available information and data gained from the field. Source, form and resolution are defined in detail.

5.1. Irrigation, water use and abstraction

Information and data concerning irrigation in Canterbury were taken from Lewthwaite, (1983) and Smith (2005). The history of the RDR as well as data about the community irrigation schemes are taken from the homepage of the RDR (www.rdrml.co.nz) information is additionally based on Cant & Evans (1983). Technical information about different systems were mainly collected from the homepage of the manufacturer Reinke (www.reinke.com), research was also based on Edkins (2006) and online (www.teara.govt.nz). Additionally very helpful input was collected and pictures were taken during a visit to David and Robyn Neeson's farm in Mayfield.

A dataset containing annual abstraction rates from the North Branch and its tributaries in litres per second was made available by ECan.

5.2. Well data

Well data for elementary analysis was taken from the 'Wells database' operated by ECan. Water levels from seven selected wells were later collected as part of the field study.

The 'Wells database' contains well data gained from two sources: reports of recently drilled wells and field visits to (old) wells by council staff. Each of the approximately 10,000 wells in the database has a unique well number. "*The well numbering system is based on the NZMS 260 series topographical map number and a sequential number separated by a forward slash e.g. M35/1234*" (Wilson & Ettema, 2010, p.6).

The 'Wells database' holds information regarding: construction of the well, the well owner, files associated with the well, water level and water quality data associated with the well, and the owners intended use of the well (Wilson & Ettema, 2010).

Important information for selecting wells for field work included

- well number
- grid reference
- well depth
- well diameter
- water level data (metres from the measuring point of a particular well)

To gain this information, files from the ‘Wells database’ were transferred and edited within a Microsoft Access database. Key details were also logged as

- comments.

Important information such as well deepening or dry wells and other relevant information could be gained by phoning the owner to obtain details.

For locating the well for field work it was important to extract the following from the database

- contact details (address, phone number) of the well owner
- location description and sketches
- photos

Groundwater levels were measured as part of the field work from November 2011 to February 2012. Date, time and water level was recorded for seven shallow wells (see locations in Figure 11):

- K36/0044 (well depth 4.84 m)
- K36/0045 (well depth 11.5 m)
- K36/0051 (well depth 8.61 m)
- K36/0106 (well depth 17.98 m)
- K37/0010 (well depth 28.65 m)
- K37/0398 (well depth 7.90 m)
- L37/0403 (well depth 37.79 m)

5.3. River flow data

River flow data were obtained in three different forms – as real time data, archive data, and data gained by gauging.

Real time data is available from the recorder operated by ECan on the North Ashburton River at the Old Weir Site. The most useful record for this study was the flow in cubic metres per second. This data is published on the ECan homepage (ECan.govt.nz) along with other information listed below

- Site name
- Date (NZST)
- Stage m (water level)
- Flow m^3/sec
- Change mm/h (water level)
- 7 day peak stage (metres)
- 7 day peak flow (m^3/sec)
- 7 day peak date

The homepage was visited regularly to check the flow upstream of the study reach to help decide when an appropriate flow for field work was occurring.

The North Ashburton at Old Weir site has been recorded continuously since May 1982. This data was accessible from the NIWA desktop archiving and processing software TIDEDA. As mentioned earlier, the program captures records from a recorder directly by telemetry. The majority of the automatic recording instruments are operated by ECan and NIWA in the Canterbury region. "*Once entered into the system, data are stored in a binary format designed to facilitate checking, correcting and analysis*." (Thompson, 2000, p.1-1)

TIDEDA river flow data can be used in different resolutions, according to the analysis; data may be tabled hourly or daily/monthly averaged.

The data set gained from a river flow measurement or gauging included

- Mean SNR (dB)
- Mean temperature (°C)
- Total width
- Total area
- Mean depth
- Mean velocity
- Total discharge

Unfortunately, for the main site of interest, Digbys Bridge, no data record was available. Spot gaugings from several dates and sources were used for the analysis and are listed in Table 4.

Table 4 Available gaugings for Digbys Bridge

Date	Source of Information	Date	Source of Information
18/11/1985	ECan	14/06/2005	ECan
02/03/1995	ECan	27/07/2007	ECan
03/03/1995	ECan	11/10/2011	ECan
01/04/1995	ECan	12/10/2011	ECan
20/01/1999	ECan	14/10/2011	ECan
29/01/1999	ECan	25/11/2011	Gauging A. Riegler
05/02/1999	ECan	02/12/2011	Gauging A. Riegler
11/02/1999	ECan	13/12/2011	Gauging A. Riegler
25/02/1999	ECan	23/12/2011	Gauging A. Riegler
09/03/1999	ECan	05/01/2012	Gauging A. Riegler
23/03/1999	ECan	12/01/2012	Gauging A. Riegler
26/03/1999	ECan	19/01/2012	Gauging A. Riegler
23/06/1999	ECan	25/01/2012	Gauging A. Riegler
25/06/1999	ECan	01/02/2012	Gauging A. Riegler
30/06/1999	ECan	08/02/2012	Gauging A. Riegler
21/12/1999	ECan	14/02/2012	Gauging A. Riegler
29/02/2000	ECan	21/02/2012	Gauging A. Riegler

5.4. Climate data

The source of the climate data used in this study is CliFlo which is the web system that provides access to New Zealand's National Climate Database. The climate database holds data from about 6,500 climate stations which have been operating for various periods since observations made in the year 1850. The database continues to receive data from over 600 stations that are currently operating (cliflo-niwa.niwa.co.nz).

The output file includes information about the stations, namely:

- Name
- Agent Number
- Network Number
- Latitude
- Longitude
- Height (m)
- Position Precision
- Observing Authority

CliFlo contains raw data and depending upon the end use, it is possible to get ten minute, hourly and daily frequencies as well as monthly or annual normals and statistics. Information is available for

- Combined Observations (e.g. monthly and annual statistics combined in one table)
- Wind
- Precipitation
- Temperature and Humidity
- Sunshine & Radiation

- Weather
- Pressure
- Clouds
- Evaporation / Soil moisture

5.5. Maps and GIS data

Topographical maps of the Ashburton field site were available through MapToaster (Version 5.0.240). This is computer software installed on every NIWA desktop.

"*MapToaster Topo/NZ is New Zealand's only topographical mapping package, with all the rich detail of the paper maps, 1:50,000 though 1:2 million scale maps, integrated aerial photography included as standard and easy-to-use software*" (www.integrated-mapping.com).

The source of MapToaster is 'Land Information New Zealand' and the maps are also known as 'New Zealand Topographic Map Series 260'. Detailed sections of the Ashburton vicinity were selected in the scale 1:50,000 in MapToaster and transferred into ArcGIS for further analysis.

Data Layers (river system) for ArcGIS were provided by NIWA, spatial reference for every well is listed in ECan's Wells Database.

6. Results

6.1. Irrigation and water use

To irrigate all suitable land in Canterbury could require up to 3 billion cubic metres of water per year. In total there is more than that flowing in groundwater alone: in addition Canterbury's rivers send around 25 billion cubic metres to sea every year. By developing all sources – groundwater, water direct from rivers and with the construction of water storages – it will prove feasible to irrigate a large proportion of the suitable soils (Lewthwaite, 1983).

The abstraction and use of groundwater resources is managed by ECan, in accordance with the Resource Management Act 1991 (RMA 91) which requires a permit to be obtained prior to the drilling of a bore and a resource consent for the abstraction of groundwater. "*Bylaws also require the driller to take records of the underground strata and supply that information to the Council*" (Smith, 2005, p.16).

6.1.1. Irrigation schemes

The popularity of the first schemes built by government in Central Otago and the problems of intermittent drought on the Canterbury Plains prompted a demand for similar schemes there. In 1935, the new government, eager to create employment (worldwide depression) in all sectors of the economy, responded positively to petitions for irrigation. Work began on the Rangitata Diversion Race (RDR) which was to supply water for irrigation from September to April and generate electricity at Highbank power station during the remainder of the year. (Cant & Evans, 1983)

The RDR, colored in black in Figure 17, is 67 km long extending from the main intake on the Rangitata River at Klondyke to a discharge at Highbank on the Rakaia River. The race can carry a flow of approximately 30 m^3/sec. The RDR provides water for 3 community irrigation schemes:

- Mayfield Hinds: contract area 32,000 ha; scheme allocation 16.5 m^3/sec
- Valetta: contract area 7,300 ha; scheme allocation 4.4 m^3/sec
- Ashburton Lyndhurst: contract area 25,000 ha; scheme allocation 13.0 m^3/sec

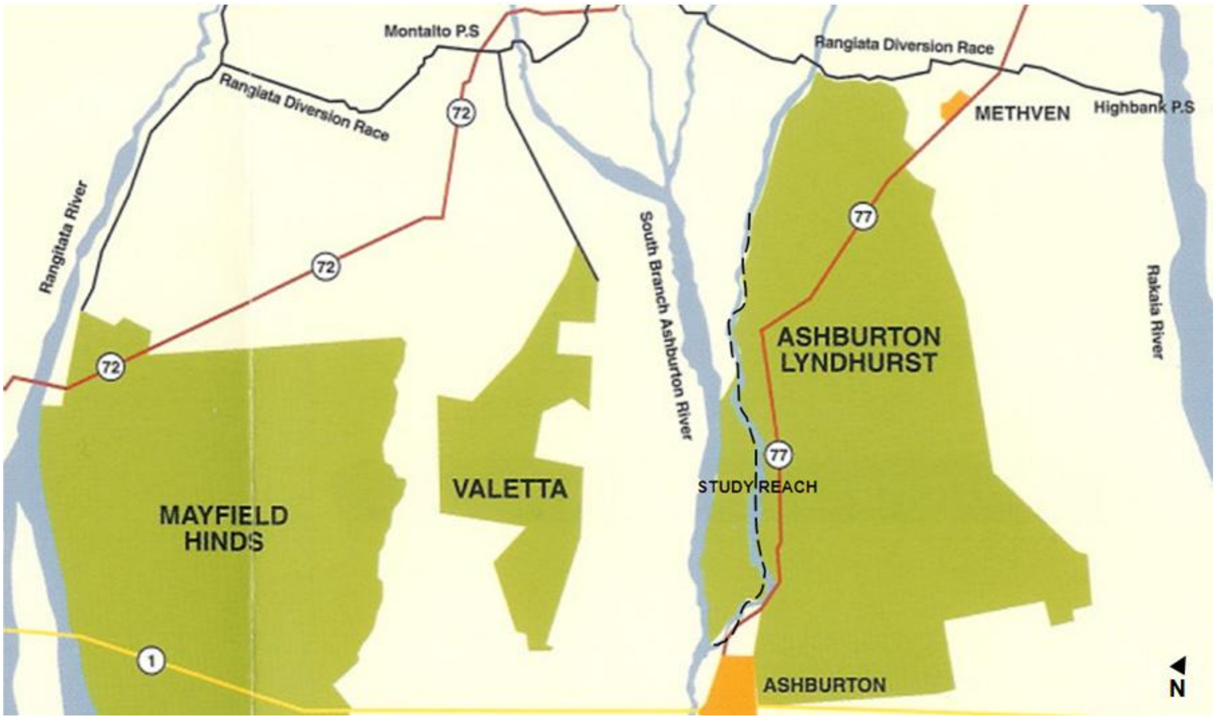


Figure 17 **Location diagram of the Rangitata Diversion Race and irrigation schemes (S: www.rdrml.co.nz, modified)**

Within the community irrigation schemes, two main types of irrigation are applied: sprinkler/spray irrigation or border dyke irrigation. In a border dyke irrigation system water is diverted from the main water race (here: RDR) into smaller ones on farms (see intake in the left picture in Figure 18). There a temporary dam must be created at the outlet to each 'border' so the water spills through onto pasture (right picture in Figure 18). A farmer e.g. gets water for 5 days every fortnight and manages to irrigate every single paddock with opening and closing the gates in the small water races.

Figure 18 **Border dyke irrigation (left: intake at the farm, right: dams for spilling the paddocks)**

Since the early 2000s most of the irrigated land in Canterbury use different kinds of sprinkler and spray systems. One type of spray irrigators are centre pivot systems, shown in Figure 19 which pump water from underground aquifers along rotating arms that travel in a circle across the paddock. The rate of rotation can be altered, and different parts of the arm can be set to apply differing volumes of water. A 500 m long centre pivot arm can irrigate about 79 ha in one rotation (www.teara.govt.nz). Another spray system is the lateral move system, which travels (e.g. engine driven) straight across square and rectangular fields with and can irrigate nearly 100 % of these fields (www.reinke.com).

Figure 19 Lateral move irrigation system

In contrast to border dyke systems, most of spray irrigation systems need water storage e.g. pumping from ground or ponds on the farm. If the farmer has no consent for pumping groundwater and e.g. gets water for 5 days every fortnight from the RDR he will fill up his storage pond and pump the water to the irrigator when required (Neeson, 2012). In recent years more and more farmers fill in borders and adapt their paddocks for spray irrigation systems because these systems have higher application efficiency than border dyke systems (Edkins, 2006, Neeson, 2012, www.teara.govt.nz).

6.1.2. Abstractions from the North Branch

Within the North Ashburton Catchment, water for irrigation is not only delivered by the RDR but also abstracted from the groundwater and surface water from the tributaries.

Table 5 shows that abstraction from the North Branch and its tributaries in litres per second totals 7,431.7. Groundwater takes are only relevant during the summer months and are limited to the North Branch and O'Shea Creek. Surface water takes effect all tributaries as well as the North Branch and total 6,410.7 l/sec of which the North Branch accounts for the biggest share (2,752.1 l/sec in summer + 540 l/sec in winter). Surface water takes in winter only occur from the North Branch. Abstractions for stockwater takes are included in the surface water takes. In contrast to surface water takes for irrigation, which are only relevant in summer, stockwater is abstracted all year round.

Table 5 **Annual abstractions of the North Ashburton River and its tributaries in l/sec (S: ECan 2012)**

Source	**North Branch**	**Pudding Hill**	**O'Shea**	**Mt Harding**	**Total**
Groundwater total	329.00	-	152.00	-	**481.00**
Surfacewater total	3,292.10	537.00	1,385.00	1,736.60	**6,950.70**
thereof Stockwater	*1,217.00*	*509.00*	-	*566.00*	*2,292.00*
Grand total	**3,621.10**	**537.00**	**1,537.00**	**1,736.60**	**7,431.70**
Average abstraction	**3,131.70**	**537.00**	**1,080.67**	**1,387.63**	**6,137.00**

The grand total in Table 5 shows the consented abstraction: e.g. farmer A has a consent to take 500 l/sec on even days and farmer B has a consent to take 500 l/sec on odd days. So the average rate is 500 l/sec from (500+500)/2 and the total consented instantaneous rate on paper is 1000 l/sec. Or farmer C takes 450 l/sec twice a week and farmer D takes 320 l/sec every second day. So for this example the average rate is (450/7(x2))+ (320/2)= 288.5 and the instantaneous grand total, paper consented rate is 770 l/sec.

6.2. Groundwater levels and river bed elevation

The distance from the Old Weir recorder to the gauging sites is shown in Table 6. The Old Weir recorder is 19.8 km upstream of the top gauging site (Thompsons Track Road) and 42.4 km upstream of the bottom gauging site (Confluence with the South Branch). Digbys Bridge, the main location of interest is 38.7 km distant from the recorder.

Table 6 Distance from gauging sites to Old Weir recorder

Site	Distance to Top (m)
Old Weir recorder	0
Thompson Track Road	19,760
Shearers Road	26,709
Ollivers Road	32,256
Digbys Bridge	38,697
Confluence with South Branch	42,419

The elevation of the study area is shown in Figure 20; the most upstream gauging site at Thompsons Track Road is at 233 m. The elevation decreases downstream to 186 m at Shearers Road, 158 m at Ollivers Road, 131 m at Digbys Bridge and 109 m at the confluence with the South Branch.

To understand the influence of groundwater levels on zero river flow it is important to analyse the location and elevation of measured wells. Most of the wells are at considerably lower elevations as displayed in Figure 20, well K36/0051 at 331 m (about 4.2 km to the north west of well K36/0044) is omitted.

Well K36/0045 varied 3.33 m in water level (Figure 21) during the time of the study and the mean depth to water was 6.5 m. Therefore the groundwater level in the north west of the river fluctuated between 268.75 m and 272.08 m. K36/0044 was observed to be directly affected by irrigation and varied 0.54 m going up during the irrigation season. K36/0106 in the north east of the river varied 0.71 m, the mean depth to water was 9.4 m. Therefore the groundwater level for this area is estimated to be around 175.9 m. The elevation of the river bed to the north of the well is 199 m, some 24 m higher. K37/0010 south east of K36/0106 dropped 1.14 m during the field study; the mean depth to water was 22.9 m. The estimated groundwater level in this area varies between 123.5 m and

124.7 m whereas the riverbed is at 157 m. K37/0398, north of Ashburton township, fluctuated 1.58 m; the mean depth to water was 3.29 m. The estimated groundwater level for this area varies between 110.6 m and 112.2 m. The elevation of the riverbed of the North Branch north of this location is about 126 m, 15 m above the groundwater. L37/0403 in the north east of the town fluctuated 1.22 m; the mean depth to water was 11.51 m giving a groundwater level between 84.9 m and 83.63 m.

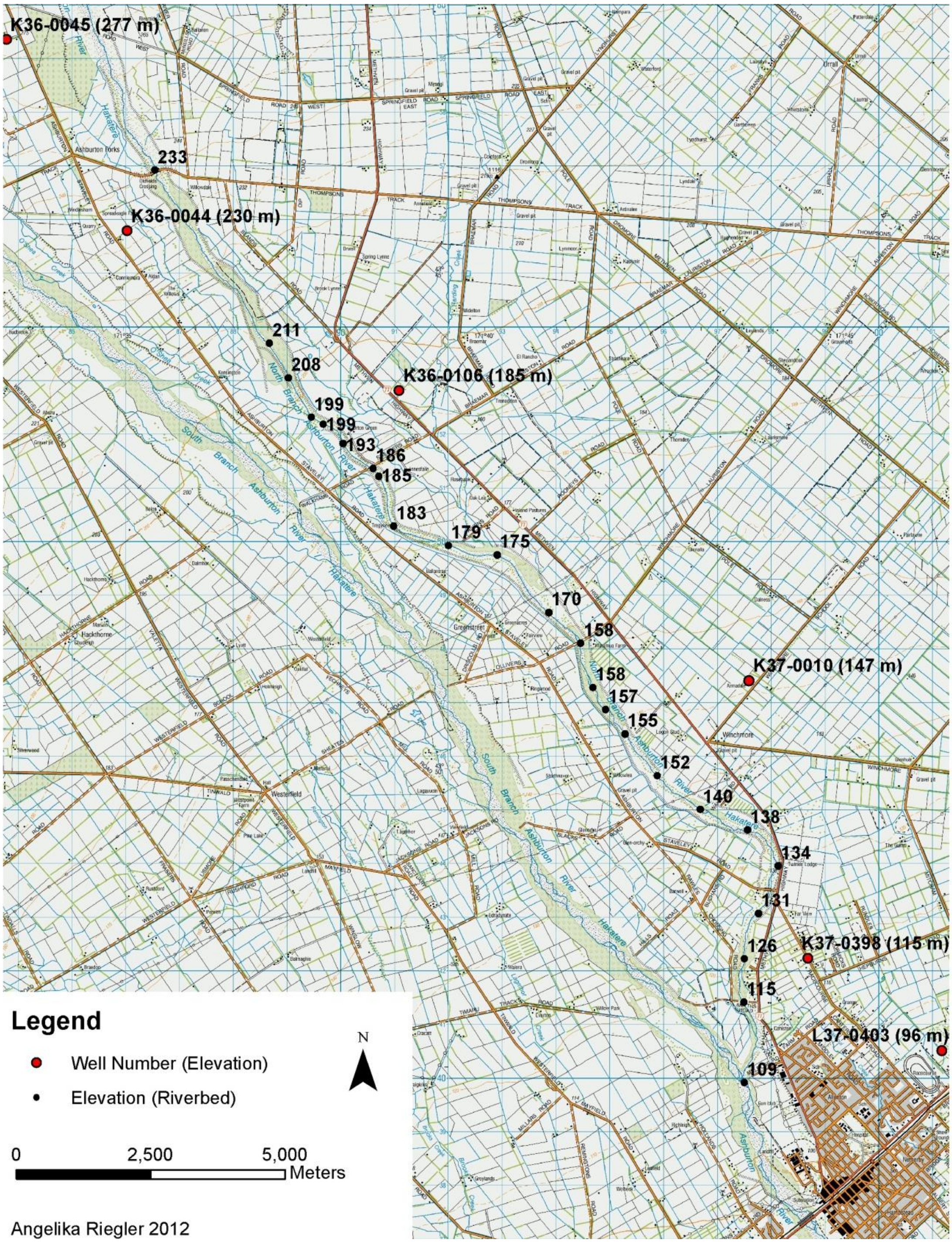


Figure 20 **River and well elevations of the study area**

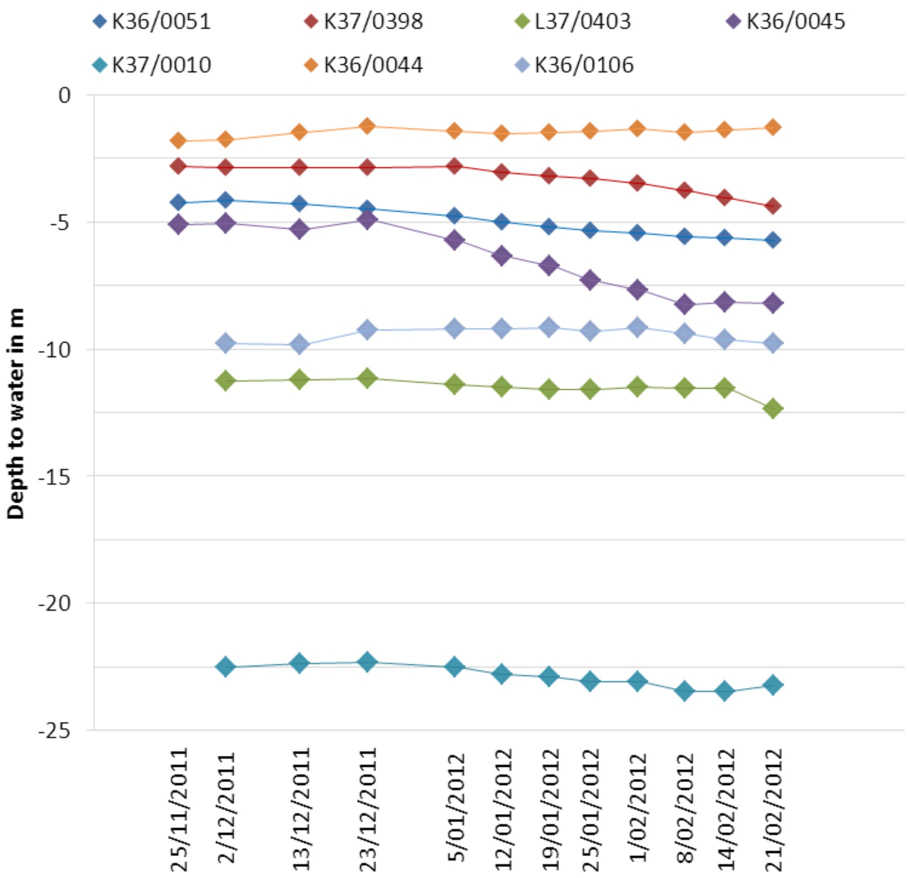


Figure 21 **Groundwater levels during field work**

The availability of recorded river flow and groundwater data along the North Ashburton River is poor. There is one flow recorder site at the Old Weir (data record started on May 7th 1982) and some sparse flow gauging information about Digbys Bridge from case studies completed by ECan.

Groundwater levels from well records of the area were made available through the ECan Wells database; however these records are not spatially extensive. Consequently for the analysis, existing data was combined with the measurements made from November 2011 to February 2012.

Upstream river flow records and groundwater level measurements at the only available wells were compared using regression to the residual flows measured in the downstream reaches.

The sketch in Figure 22 shows the study area: long term data records were available for the Old Weir recorder and the wells and ten concurrent flow measurements were available for five sites.

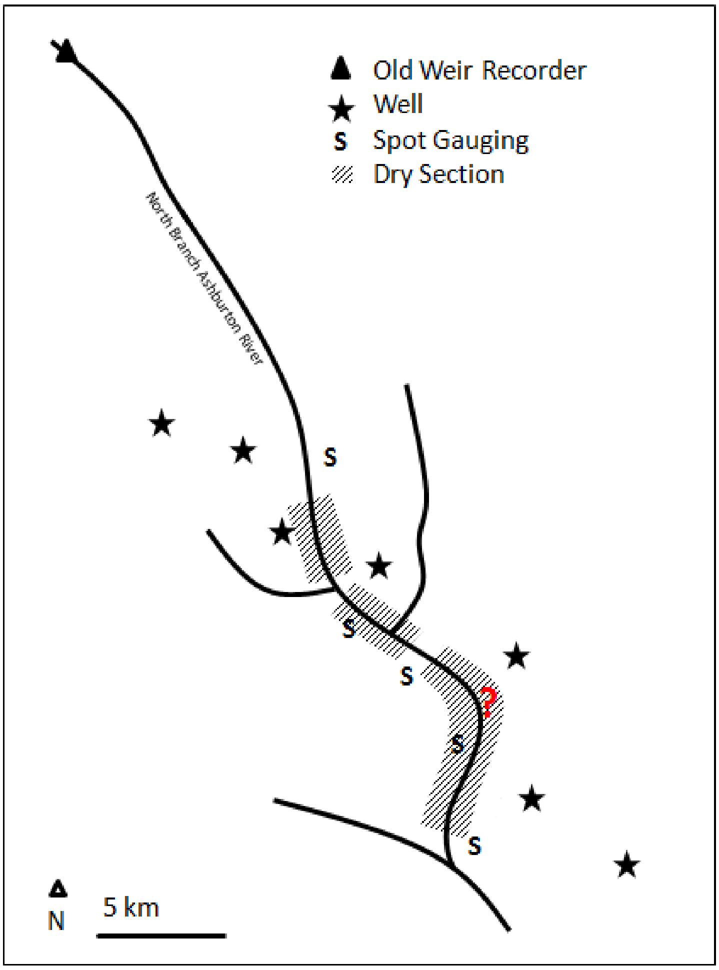


Figure 22 **Sketch of the model area**

Different colours in Figure 23 show the data history of the measured groundwater wells. The line on the bottom is the Old Weir flow recorder.

Work for Horrell (2001) took place in the late 1990’s and includes some ECan spot gauging data for Digbys Bridge. Apart from that study, some single gauging runs from ECan and this study’s gaugings, no more information was available for this site.

After a logical review, four data lines had to be deleted due to inconsistency. The complete dataset as well as those discarded data are listed in Appendix V.

Unfortunately there is also a large time gap for four out of seven wells from the early 1980s up to 2000/2001. After a review in 2010 (red line in Figure 23), ECan decided to close more wells– or change from 15 minute interval (continuous line) to monthly (dashed line) readings, so there are increased gaps after 2010.

Continuous well data was required from 1982 to November 2011 for this study. Within the field study the wells were read concurrently each day of gauging along with the daily flow values for the Old Weir recorder.

Figure 23 **Data availability of groundwater and flow data in the Ashburton North Branch field site**

6.3. Analysing rainfall data

Three long-term climate stations measuring annual rainfalls were used to compare these values with mean flow at the Old Weir site. Long time records were available for Ashburton Council, Methven and Lake Coleridge Homestead (see Figure 24). The last station is north of the catchment border but as there was no long term record available within the upper catchment, the Lake Coleridge Homestead was selected to represent the upper North Ashburton Catchment.

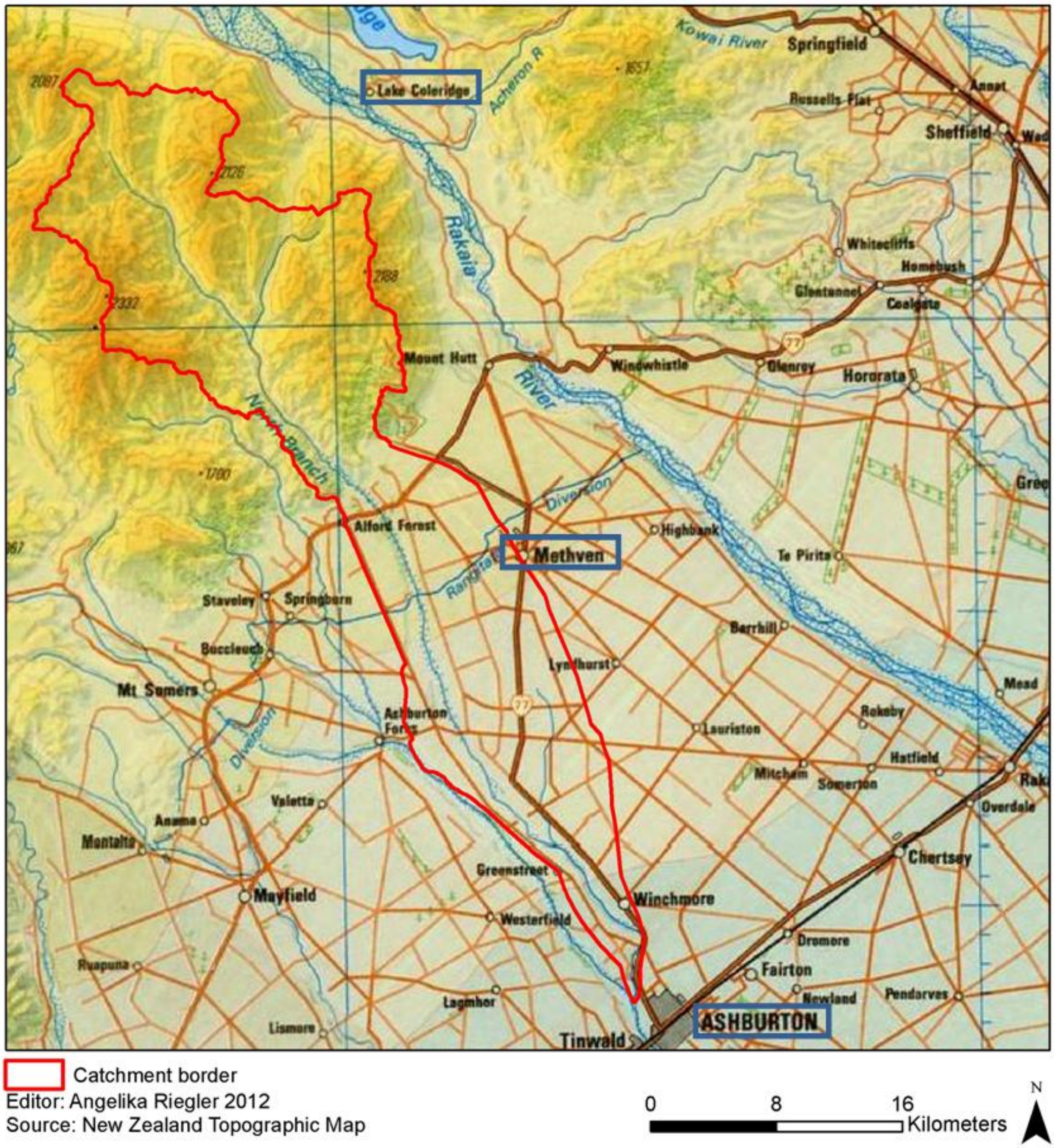


Figure 24 **Location of the climate stations (framed blue)**

Annual rainfall totals from the climate stations and the mean annual flow in the North Branch were plotted from 1982 to 2010 to establish that less rainfall was not occurring and that rainfall and reduced runoff are not the reason for the decreasing flow in the lower North Branch observed in recent years. As similar river flows have occurred in the last 30 years.

Figure 25 shows that the linear trend line of the mean flow is markedly decreasing whereas the rainfall totals of the Ashburton Council and Lake Coleridge homestead are increasing. Only Methven shows slightly decreasing rainfall totals.

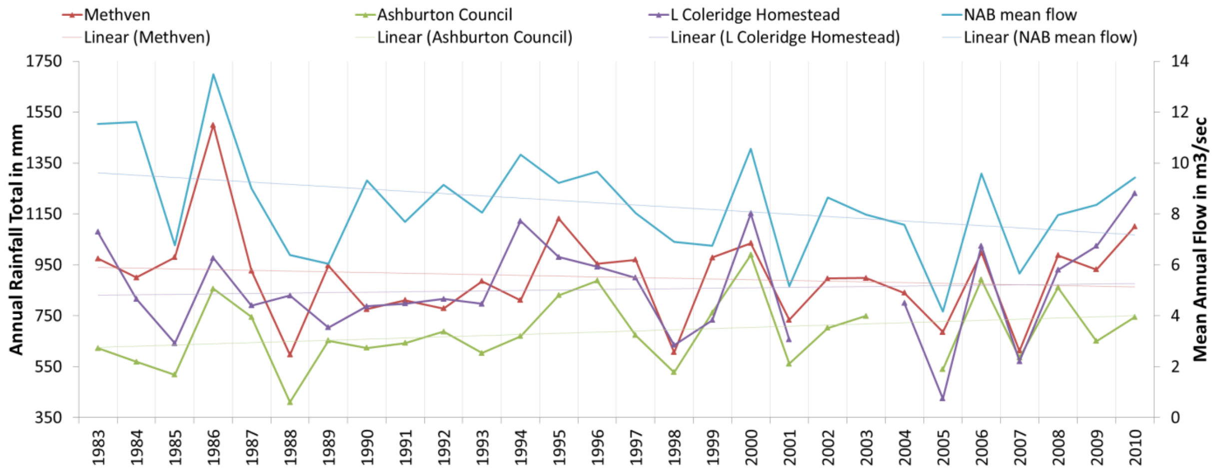


Figure 25 **Annual rainfall totals and mean flow of the Ashburton River North Branch 1982-2010**

6.4. Predicting dry periods at Digbys Bridge

Applying the multilinear regression analysis to earlier data (19 observations from 1985 to 2007), the best adjusted R squared value was 0.79 (using well number K36/0051). Therefore, it was appropriate to combine datasets from previous ECan studies with those of this study to obtain a robust regression model. Results from multiple linear regression analyses to predict flow at Digbys Bridge using 29 to 31 observations including flow at Old Weir and each observation well are listed in Table 7. Well K36/0051 with Old Weir flow has the best result with 91 % of the variance explained and a standard error of 600 l/sec.

Table 7 **Regression using wells and flow at Old Weir**

Well Number	Regression equation (y=b+a1x1+a2x2)	Adjusted R Square	Standard Error (m^3/sec)	Number of Values
K360051	y=-7.66335+0.949885*Old Weir-0.81646*K360051	0.91	0.60	31
K360106	y=-5.00177+0.751475*Old Weir-0.27679*K360106	0.80	0.83	30
L370403	y=-1.39608+0.772821*Old Weir+0.111529*L370403	0.80	0.83	30
K370398	y=-1.50287+0.732562*Old Weir+0.213581*K370398	0.83	0.82	31
K370010	y=-1.31638+0.776312*Old Weir+0.056767*K370010	0.79	0.84	30
K360044	y=-2.58320+0.621523*Old Weir-0.38579*K360044	0.75	0.69	29
K360045	y=-1.55719+0.619998*Old Weir+0.067903*K360045	0.75	0.69	29

Three wells, with the highest adjusted R squared, were then plotted for the part of the irrigation season when the North Branch was going dry at Digbys Bridge.

Figure 26 shows the number of days when the flow of the North Branch at Old Weir was less than 5 m^3/sec. This threshold was chosen by comparing the North Branch flow with Digbys Bridge drying, using only flows of 4.7 m^3/sec or less.

The number of days of low flow in the last ten years was an increase compared to the previous ten year period of 1992 to 2001. In the nine year period from 1983 to 1991, the long term mean of 68 days was slightly higher than in the following ten year period (63 days) but still considerably lower than the ten year period from 2002 to 2011 (83 days).

Mean irrigation season groundwater levels in K36/0051 and K36/0045 dropped dramatically in 1981/82 and 2008/09, the long term trend for both wells show a decline.

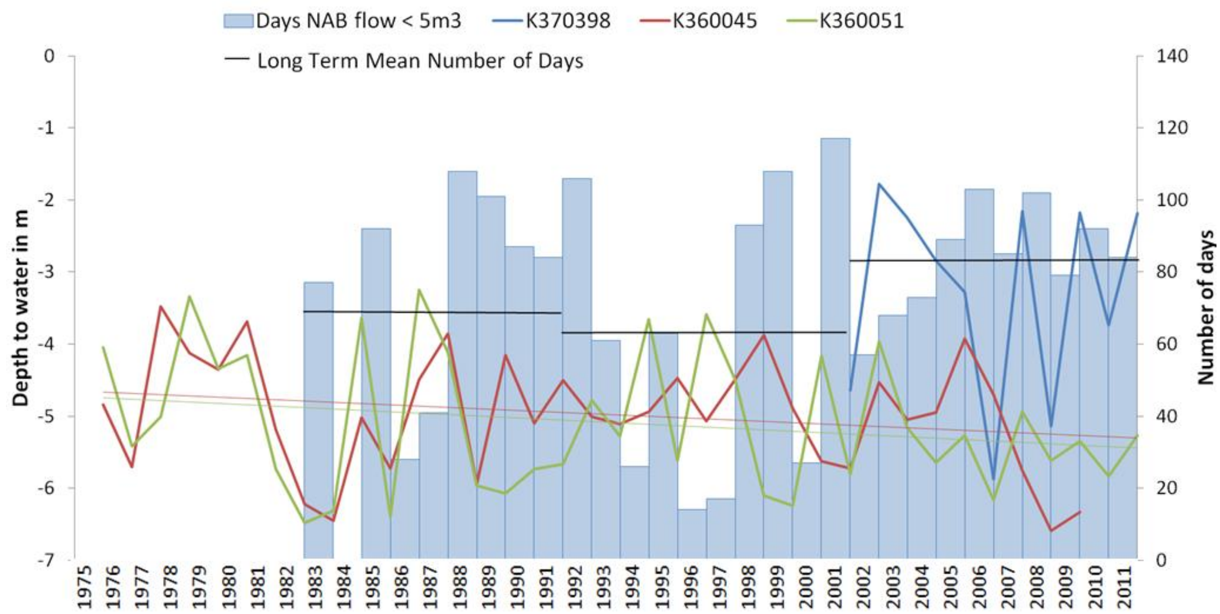


Figure 26 **Number of days with <5 m^3 flow at the North Ashburton Old Weir recorder and mean depth to water in 3 selected wells during irrigated months Jan-April**

Comparing the adjusted R squared values and taking into account the information in Figure 26, following model was created to predict the daily flow at Digbys Bridge (y):

$$y\ (m^3/sec) = -7.66335 + 0.949885 * \text{daily flow at Old Weir}\ (m^3/sec) - 0.81646 * \text{daily level in K360051}\ (m)$$

After applying the model to the whole dataset (containing daily values from May 7th 1982, to November 17th 2011 for the North Branch at Old Weir site and groundwater levels at K36/0051), all predicted daily flow results ≤ 0 were assumed as 'dry'. The whole dataset is shown in Figure 27 where dry sections are those where the predicted flow line falls below the 0-line.

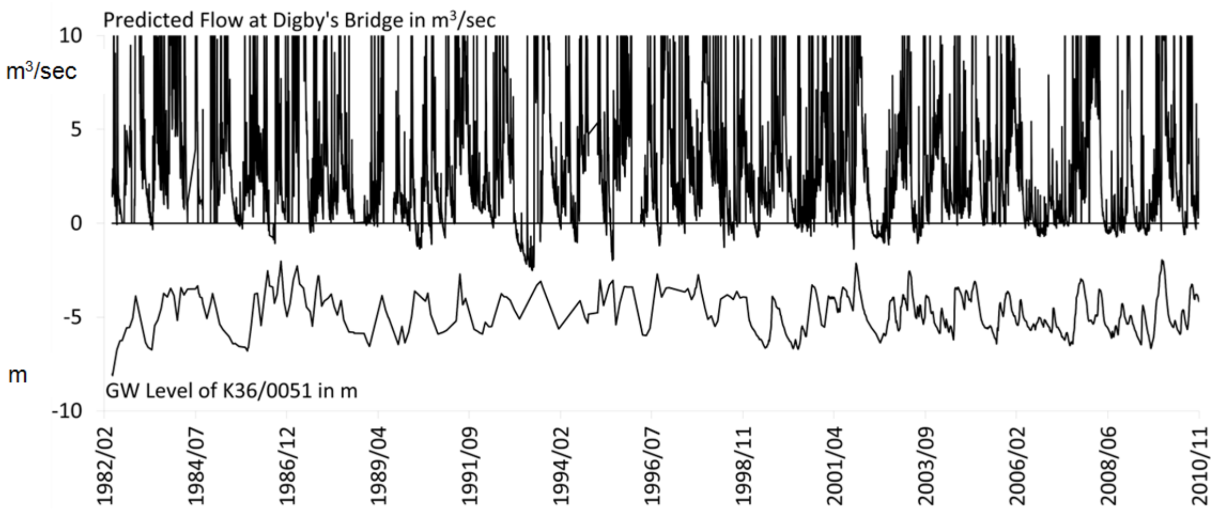


Figure 27 **Predicted flow and dry periods at Digbys Bridge**

Between 1982 and 1989 there are only two established periods of drying. The most significant dry period was at the end of 1989 corresponding with the 1988/89 drought in Canterbury (Horrell, 2012).

Between 2001 and 2010 the frequency of falls below the 0-line is markedly higher than in years before, which means that the river was dry more often. This pattern is also evident in Figure 32 and Table 8 where the 1992 is the year with the highest number of dry days (176). In 2001 there were 157 days of no flow at Digbys Bridge, followed by 2007 with 138 days. There appears to be a large number of days dry since 2001 which are not related to acknowledged droughts, this may be driven by occurrence of lower groundwater levels.

Table 8 **Number of dry days per year (top 6 values and 1985)**

Year	Number of days	Information (Horrell, 2012)
1992	176	was a drought year more commonly associated with a hydro power crises in New Zealand
2001	157	the autumn of 2001 was a severe drought
2007	138	not regarded as a drought
2005	119	was a winter with very low rainfall recharge for the groundwater system of Canterbury
1989	93	is associated with the 1988/89 severe drought
2008	92	was not regarded as a notable drought
1985	*23*	*the most severe draught in South Canterbury*

For 1984 the model result is zero days without flow; 2003 and 2011 also show less than 10 days without flow.

The mean number of days with zero flow in the longterm period 1983 to 1991 was 25 days; in the period 1992 to 2001 it was significantly higher with a mean of 64 days. In the period from 2002 to 2011, mainly due to a very low number of dry days in 2003 and 2011, the mean decreased slightly to 54 days.

The overall trendline from 1983 to 2011 increases significantly.

6.5. Predicting extent of dry reaches

Measurements of the length of dry reaches in the North Branch were available on four occasions; three more were interpolated. Initially, regressions involving Old Weir flow, and existing groundwater well information as independent variables were used to find the best regression fit (highest adjusted R squared) with length of dry reach.

The equation with the best fitted well was then applied to the long term (from 1982) Old Weir flow record and groundwater well record to predict the dry sections at Digbys Bridge back to 1982.

Available data was then used to predict the length of the dry river reaches. Table 9 shows that the length of the dry reaches on the North Branch has increased significantly during this study from the first observation on January 5th 2012 to the last measurement on February 14th 2012.

Table 9 Measured dry sections in m (*interpolated values)

Date	Section Length in m	Increase on previous date in m
5/01/2012	5,600*	
12/01/2012	7,550*	1,950
19/01/2012	9,480*	1,930
25/01/2012	10,721	1,241
1/02/2012	13,367	2,646
8/02/2012	14,976	1,609
14/02/2012	16,057	1,081

The weekly extent of dry reaches is displayed in colour in Figure 28: the grey line represent the dry sections on January 25th, the red line shows the increased dry reach from January 25th to February 1st, the orange line the additional dry reach from February 1st to 8th, and the yellow line a further increase from February 8th to 14th until the rain in the following week increased river flow. The grey values are the sum of dry section length measured on January 25th and all colour extensions represent the condition on February 14th. The largest increase was from January 25th to February 1st with a 2.6 km increase in dry reach length. Altogether, the North Branch on February 14th 2012 between Thompsons Track Road (top left corner in Figure 28) and the confluence with the South

Branch (bottom right corner of the map) was more dry (16,057 m) than flowing (6,790 m).

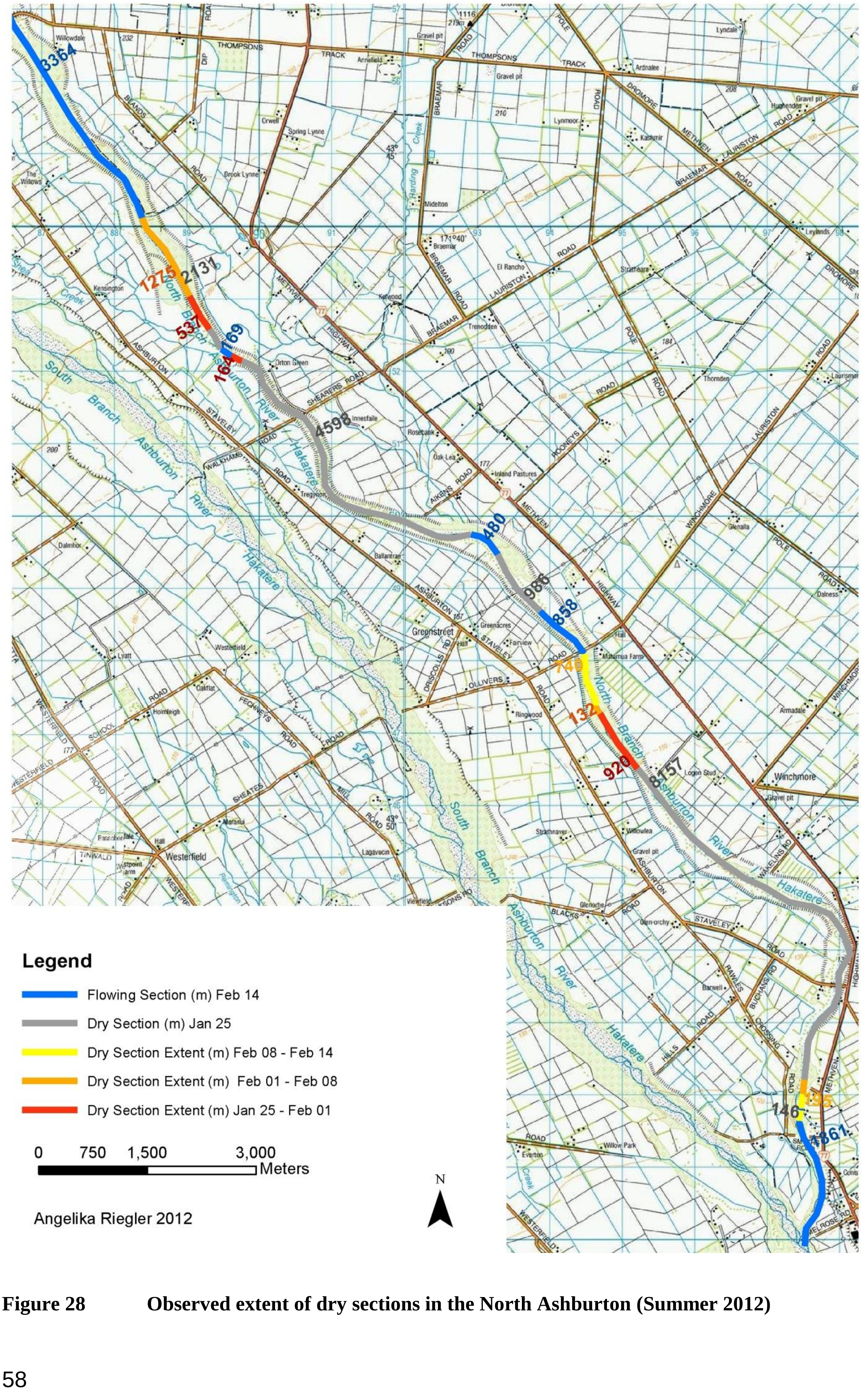


Figure 28 **Observed extent of dry sections in the North Ashburton (Summer 2012)**

Water was always flowing from Thompsons Track Road downstream for 3,364 m (Figure 29).

Figure 29 Flow at Thompsons Track Road (left: 25th Nov 2011 and right: 5th Jan 2012)

The bordering dry section to Thompsons Track Road measured on January 25th was 537 m long and extended for another 1,275 m in the following week. From February 8th to 14th there was no change in the length of the dry section.

1,600 m upstream of Shearers Road crossing, O'Shea Creek joins the North Branch from the true right bank (Figure 30) and was flowing for 170 m before it went dry and stayed dry for another 4,600 m where Mt Harding Creek flows into the North Branch.

Flow on the true left was observed for 480 m downstream, mostly under the willows.

Figure 30 O'Shea joins North Branch (left) and dries up after 170 m (right)

The following dry reach didn't change over this study and was 986 m long, and reappeared about 850 m upstream of Ollivers Road crossing.

Then, the longest extent of the dry section was 920 m from January 25th to February 01st and just slightly increased the next week (132 m) but had another big dry from February 8th to 14th with an increase of 740 m.

The dry section from there, on both sides of Digbys Bridge (Figure 31), reached 8,157 m downstream until some small creeks joined the North Branch from the true left near Rawles Crossing.

The flow there was not permanent and dried up for 200 m from February 1st to 8th. For 1,861 m there was always flow down to the confluence with the South Branch.

Figure 31 **Dry riverbed at Digbys Bridge on January 5th 2012 (left: upstream, right: downstream)**

To predict the extent of the dry sections in the vicinity of Digbys Bridge back to 1982, the length of the dry reach measurements from 2012 were applied in a regression analysis using a dataset of flow at Old Weir and groundwater levels in K36/0051. The dataset is shown in Table 10.

Table 10 **Dataset used for predicting the length of dry sections**

Date	Section Length (m)	Old Weir Flow (m^3/sec)	K360051 (m)
25/11/2011	0	10.24	-4.25
02/12/2011	0	7.37	-4.15
05/01/2012	5,600	4.25	-4.79
12/01/2012	7,550	3.85	-5,00
19/01/2012	9,480	3.36	-5.19
25/01/2012	10,721	3.29	-5.33
01/02/2012	13,367	3.15	-5.46
08/02/2012	14,976	2.83	-5.57
14/02/2012	16,057	3.12	-5.65

The adjusted R squared was 0.98. The regression equation to predict the dry sections (y) was:

$$y\ (m) = -49{,}416.81931 + 157.7935169 * Old\ Weir\ (m^3/sec) - 11{,}367.26636 * K360051\ (m)$$

After reviewing the results it became clear that the raw data measured to develop the model equation is not of sufficient range to predict dry reach lengths back to 1982. Values ranged from negative up to 28,000 m and showed strongly decreasing lengths in dryness from 1982 to 2011. The dataset collected covers only a small range of groundwater levels in the well, varying between -4.25 and -5.65 m, whereas in the whole dataset the levels can also drop from -2 down to -8 m. The same situation was experienced with river flow from 10.24 to 2.83 m^3/sec.

6.6. Summary

The North Ashburton River is a highly allocated river, mainly due to abstraction for irrigation and stock water. Within the catchment water is taken from groundwater and surface water. The annual abstraction of the North Branch and its tributaries totals 7,431.7 l/sec.

To understand the influence of groundwater levels on zero river flow the elevation of study wells was measured. The elevation of the river decreases from 233 m at Thompsons Track Road downstream to 109 m at the confluence with the South Branch but most of the wells are at considerably lower elevations.

Analysis of rainfall data proved that a decrease in rainfall was not occurring and so rainfall and reduced runoff are not the reasons for decreasing flow in the lower North Branch observed in recent years.

Existing data for the analyses were combined with the measurements gained in this field study from November 2011 to February 2012. The number of days with less than 5 m^3/sec flow in the North Branch in the last 10 years increased compared to the previous ten year period.

The most significant dry period was at the end of 1989 and 1992 is the year with the highest number of dry days (176). In 2001 there were 157 days of no flow at Digbys Bridge, followed by 2007 with 138 days. The overall trend line from 1982 to 2011 increases considerably.

The length of the dry sections on the North Branch has increased significantly from the first observation on January 5th 2012 to the last on February 14th 2012. Altogether the reach of the North Branch on February 14th 2012 between Thompsons Track Road and the confluence with the South Branch was 16,057 m dry and 6,790 m flowing.

To predict the extent of the dry sections in the vicinity of Digbys Bridge back to 1982, dry section length measurements from 2012 were applied using a regression with a dataset containing flow at Old Weir and groundwater levels but after reviewing the results it became clear that the model is not sufficiently robust to give useful results.

7. Discussion

7.1. Testing of hypotheses

a) *Low flow regime durations and dry sections in the North Ashburton at Digbys Bridge are increasing with the increase of groundwater abstraction in the vicinity in the last 10 years.*

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During the last ten years (2001 – 2010) the frequency of river dryness at Digbys Bridge was estimated to be markedly higher than in the periods from 1981 to 1990 and 1991 to 2000 (see Figure 32) and large numbers of days dry for individual years that are not related to known drought years (Table 8).

As the Selwyn River is a similar foothills catchment to the Ashburton River and provides a longer flow record, it was used to test for trends (Figure 33). The months January to April were selected as they are the typical lowest flow months and because the North Ashburton went dry at Digbys Bridge for the first time in January 2011/2012.

To normalise these two flow records the number of days per January to April period below 60 % of mean flow were calculated and compared. The highest 10 year average number of days less than 60 % of the mean flow occurred in the last 10 years for both sites with a mean of 101 days at the Selwyn River Whitecliffs recorder and 86.5 days at the Ashburton North Branch Old Weir recorder.

The period 1965 to 1980 at the Selwyn River averaged about 80 days of flow less than 60 % and after an increase to 96 days in the period 1981 to 1990 it dropped to 82 days in the period 1991 to 2000. Although the average number of days less than 60 % mean flow was highest in the period 2001 to 2010 it is, however, a trend that is not conclusive.

Figure 32, Figure 33 and Figure 34 were all plotted with the same long term periods to show relationships between the groundwater level and the number of low flow/dry reaches in the North Branch.

A summary of the results of the North Branch is shown in Table 11. The long term mean dry days at Digbys Bridge from 1983 to 1990 is comparatively low with 27 days, at the same time the number of days less than 60 % mean flow at the North Branch was around 67 days. Mean groundwater levels in K36/0045 averaged at -5.26 m. In the period from 1991 to 2000 the mean number of dry days at Digbys Bridge increased to 49 whereas the number of days less than 60 % mean flow at the North Branch dropped to 60 days.

This could indicate that upstream of Digbys Bridge more surface water was taken in this period than the period 1983 to 1990, as groundwater levels increased to -4.9 m. In the period from 2001 to 2010, the number of days less than 60 % mean flow at the North Branch (87) as well as mean number of dry days at Digbys Bridge (69) increased, at the same time the groundwater level dropped to -5.66 m.

Table 11 Summary of 10 yr trends

10 yr mean...	**1981-1990**	**1991-2000**	**2001-2010**
... number of days dry at Digbys Bridge	27	49	69
... mean number of days<60 % North Branch	67	60	87
... mean water level in K36/0045	-5.26	-4.90	-5.66

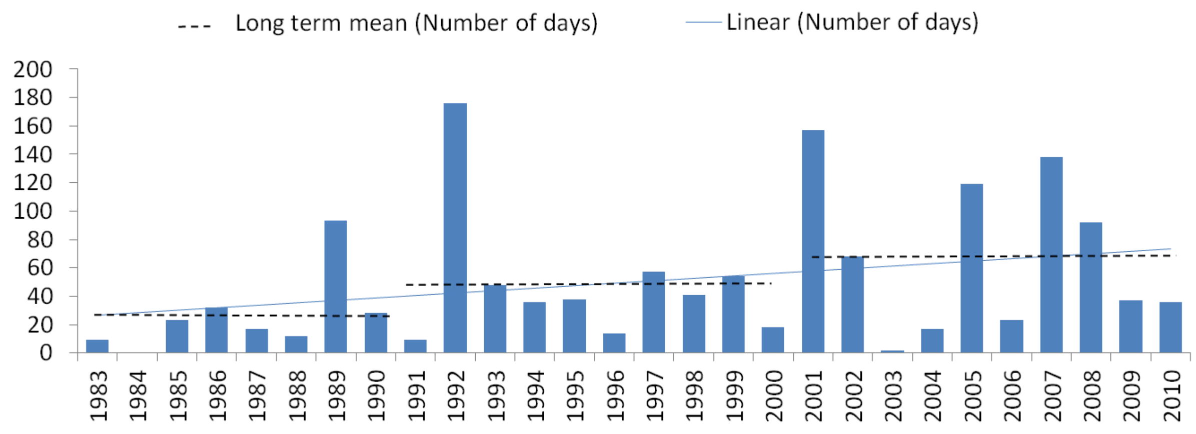

Figure 32 **Number of dry days at Digbys Bridge**

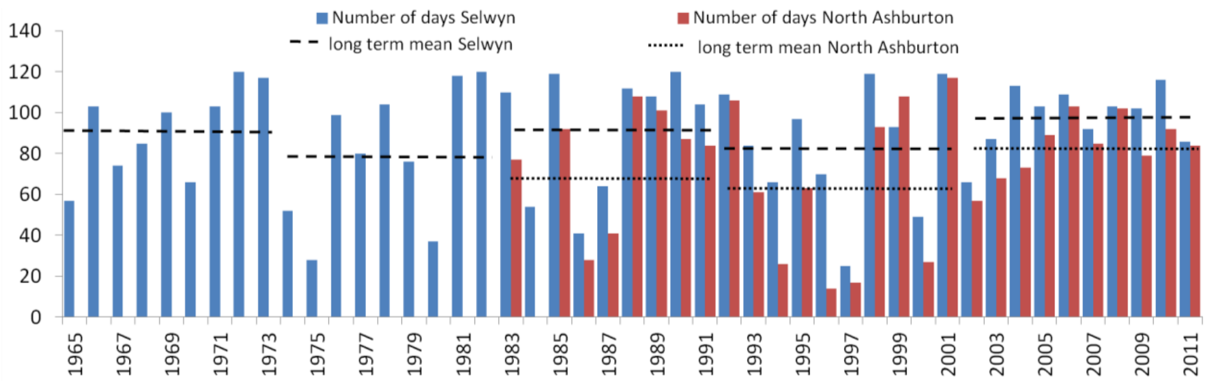

Figure 33 **Number of days with 60 % or less mean flow at the Selwyn River (<1.9m³/sec) and North Ashburton River (<5m³/sec) January – April**

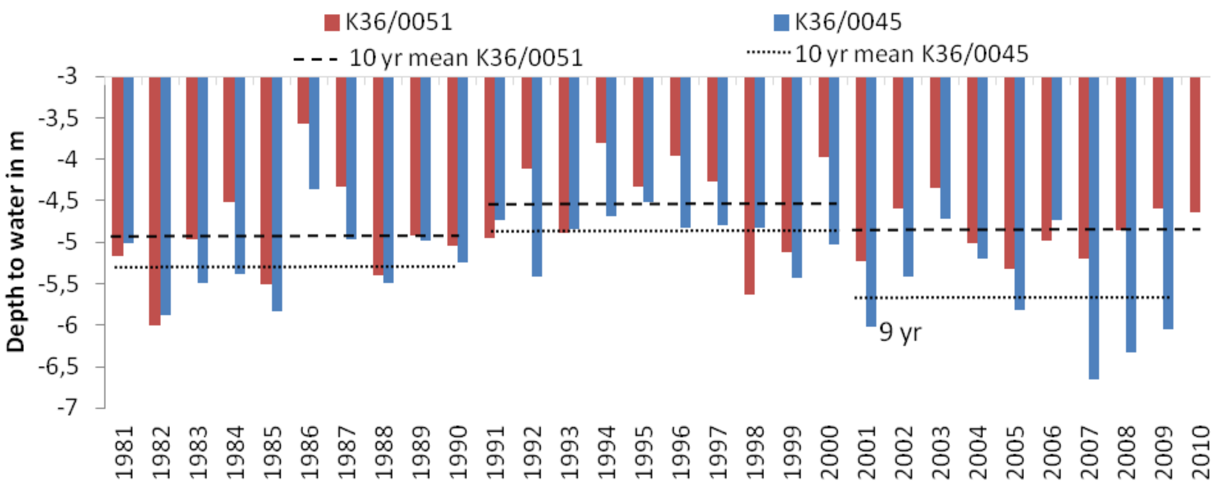

Figure 34 **Mean annual groundwater level in K36/0045 and K36/0051**

One explanation of the high number of dry days in the last 10 years is the natural decrease in runoff measured at Old Weir coupled with a natural drop of groundwater levels and/or intensification in groundwater abstraction.

Comparing all this available information, represented in Figure 32, Figure 33 and Figure 34 with the increasing annual allocation in Figure 35, it appears that the intensification of irrigated agriculture sourced from groundwater is the main driver of an increase in the number of days of low flow/dry days at Digbys Bridge.

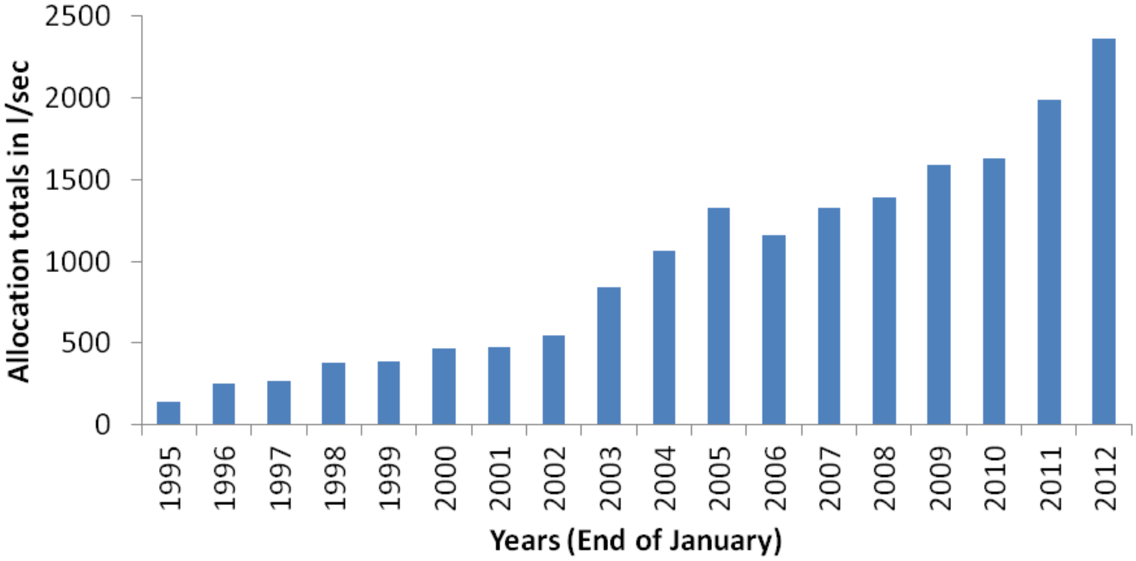

Figure 35 **Allocation totals for the Ashburton River groundwater zone (wells screened less than 40 m) (S: Smith, ECan 2011)**

Figure 35 is based upon relatively shallow wells in the whole Ashburton catchment - only those which are pumping from 40 m deep or less. The significant increase in allocation since 1995 may explain the noticeable decline in groundwater levels and reduced flow in the Ashburton River North Branch.

In Figure 36 the number of dry days is compared with 90 days annual low flow at the Old Weir recorder and the groundwater level in well K36/0051. Looking at 1985 and 2007 show that in both years groundwater levels had a low stage and the 90 days ALF was around 3,000 l/secec. However the number of dry days at Digbys Bridge in 2007 is notable higher. One explanation for that could be the increased amount of surface water and groundwater takes.

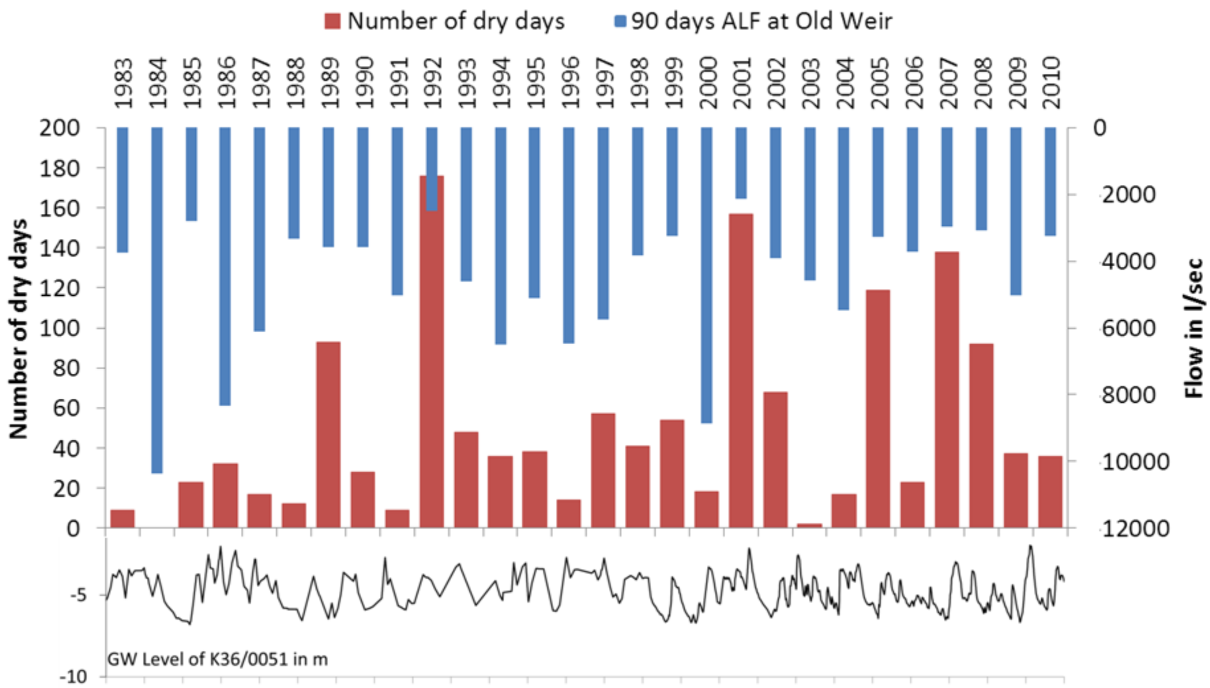

Figure 36 **Number of dry days at Digbys Bridge, 90 days ALF at Old Weir and groundwater level in K36/0051**

Nevertheless this hypothesis cannot be verified because there are too many uncertainties, especially concerning the complex groundwater system.

b) *Flow losses on the North Ashburton between all gauging sites from the Old Weir recorder site to the confluence with the South Branch are higher at higher flows throughout the reach.*

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Losses from the North Branch to the surrounding groundwater systems are important for understanding the Ashburton River water resources (Horrell, 2001). The losses and gains in Horrell's study (2001) were calculated by comparing two runs of concurrent gaugings – where abstractions and bywash were measured to naturalise flow at each location.

For this study nine gauging runs shown in Table 12 for summer 2011/12 were undertaken but no such measurements or corrections were made. All gauging data measured on the North Branch are listed in Appendix VI.

From the Old Weir site downstream to Thompsons Track Road for the 2011/12 summer there was a significant mean loss of 107 l/sec per km length of reach. From Thompsons Track Road to Shearers Road the mean loss amounts to 151 l/sec per km length of reach. On four gauging runs from Shearers Road to Ollivers Road, when the flow was very low, there was a flow gain, mainly from Mt Harding stream inflows. On these occasions there was no flow at Shearers Road.

Measurements indicate a larger flow loss when the river had higher flows and a gain when flows were very low. It is important to remember that there will be always be bed losses occurring, but because there was an overall increase (Mt Harding inflow), the value is represented as gain.

From Ollivers Road to Digbys Bridge there are major losses of more than 280 l/sec/km from the channel when there is high flow throughout the reach and reduced losses of 16 to 67 l/sec/km when the flow is decreasing (dry at Digbys Bridge).

From Digbys Bridge to the confluence with the South Branch there was always a gain with a mean of 110 l/sec/km. This gain could be sourced from upstream losses re-entering the stream (Horrell, 2001).

The mean total North Branch losses between the Old Weir recorder and the confluence were 83 l/sec/km or a total of 3,503 l/sec and at high flow throughout the reach up to 136 l/sec/km or a total of 5,781 l/sec.

Table 12 **Losses and gains on the North Branch in l/sec per km length of reach (red= lossing reach, green= gaining reach, white= no change as already dry)**

Date	Old Weir to Thompsons Track Road	Thompsons Track Road to Shearers Road	Shearers Road to Ollivers Road	Ollivers Road to Digbys Bridge	Digbys Bridge to Confluence
25/11/2011	-58	-202	-173	-243	255
02/12/2011	-128	-196	-95	-288	130
05/01/2012	-88	-166	-129	-100	147
12/01/2012	-111	-163	-17	-67	118
19/01/2012	-111	-167	55	-47	87
25/01/2012	-115	-147	45	-38	118
01/02/2012	-115	-126	29	-25	67
08/02/2012	-110	-95	18	-16	33
14/02/2012	-123	-99	0	0	29
Mean	**-107**	-151	-30	**-92**	**110**
Loss/gain rate Horrell, 2001	-19	-99	145	*-194*	182

c) *The North Ashburton outflow at Digbys Bridge is directly related to the inflow at Old Weir at high river flow, no matter what the groundwater levels are, and conversely when Old Weir flows are low, the flow at Digbys Bridge is closely related to groundwater levels and Old Weir flows.*

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When the North Branch at Digbys Bridge went dry, the flow at Old Weir was less than 4.7 m^3/sec, showing a direct relationship with flow observed at Digbys Bridge (Figure 37). However, when nearly dry, dry and then with extended dry reaches, the groundwater level in Figure 38 becomes important.

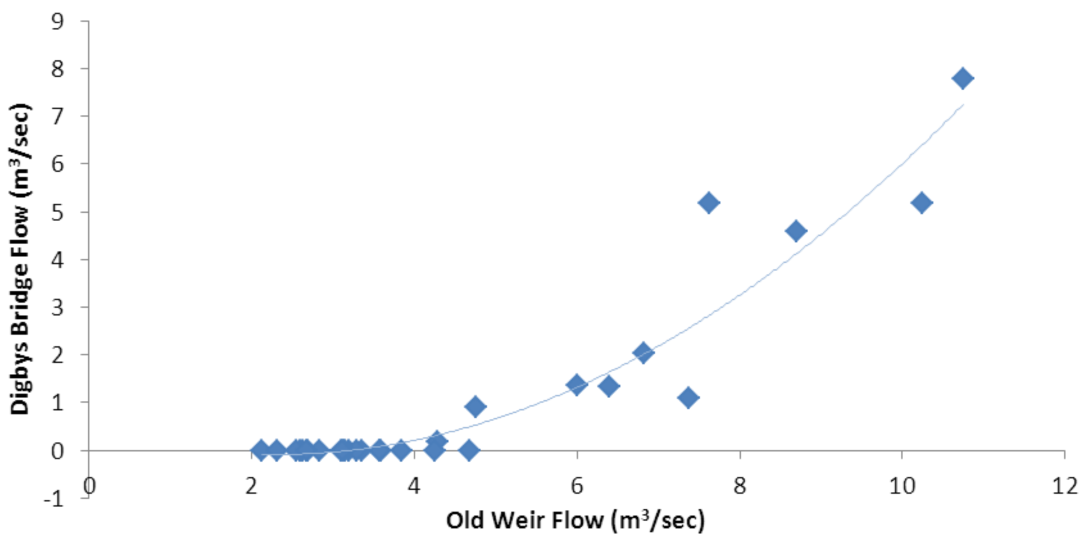

Figure 37 **Flows at Digbys Bridge and Old Weir**

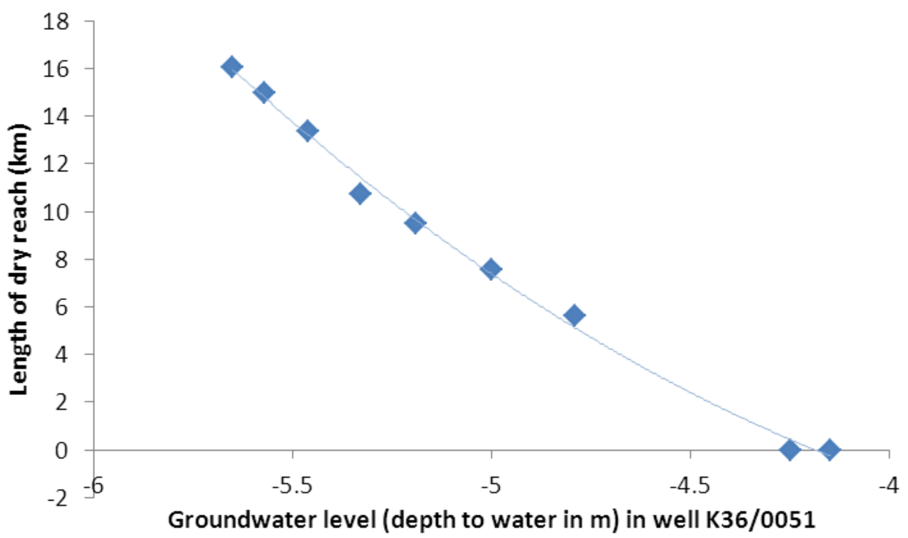

Figure 38 **Length of dry reaches and groundwater level in K36/0051**

The Old Weir recorder is about 38 km upstream of Digbys Bridge. A relationship with the closer (about 19 km upstream) site, Thompsons Track Road, was also observed during the field study. Losses between Old Weir site and Thompsons Track Road during the field study were observed to be mostly between 2.1 and 2.5 m^3/sec, no consideration of abstraction was undertaken. When flow was observed at Digbys Bridge it was between 3.2 and 3.9 m^3/sec less than at Thompsons Track Road; again, no consideration of abstraction was undertaken.

During field work, groundwater levels in the vicinity were constantly decreasing. This decline was not altered even when a high flow occurred (caused by artificial discharge of Rangitata River water from the Rangitata Diversion Race). Also, the graphs in Figure 39 and Figure 40 show that at low groundwater levels, small freshes do not reach Digbys Bridge.

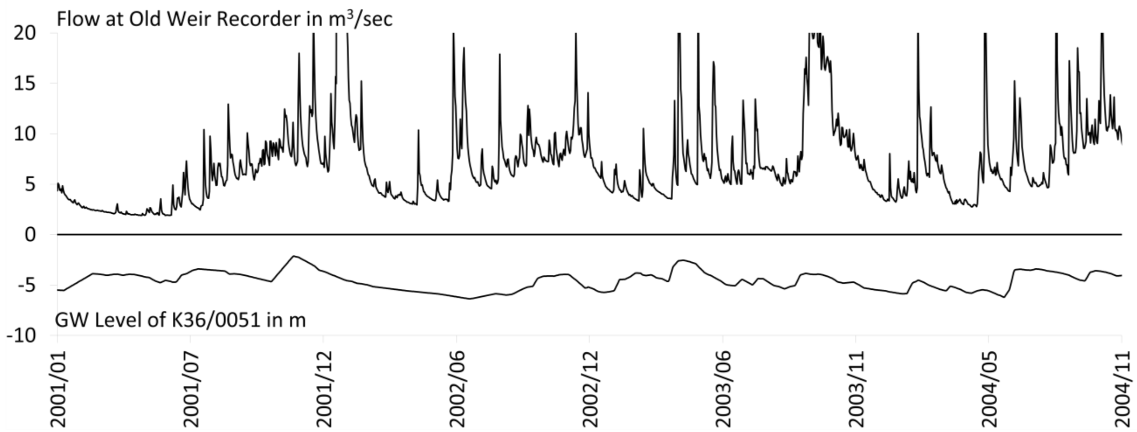

Figure 39 **Old Weir Flow and groundwater level in K36/0051**

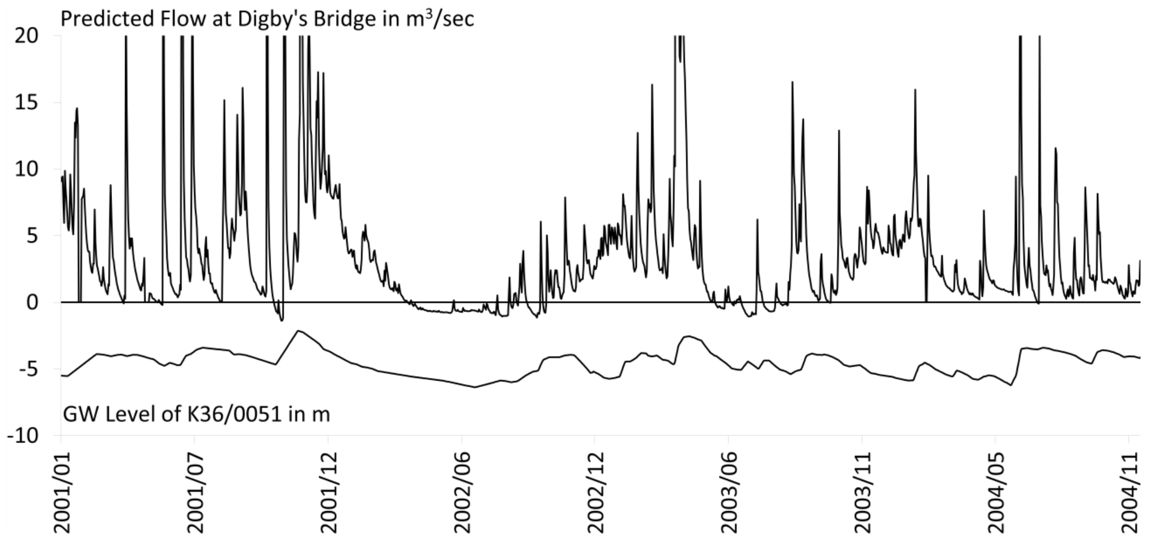

Figure 40 **Predicted Digbys Bridge flow and groundwater level in K36/0051**

In April-June of 2002 and at the end of 2003 especially it is observed that the groundwater level was not influenced by higher flows at Old Weir. At the same time in April-June 2002 at Digbys Bridge the low groundwater level caused a dry period (see Figure 40).

From this it can be concluded that the dryness and length of reaches of dryness of the North Branch at Digbys Bridge and upstream is influenced by the groundwater level.

7.2. Accuracy of the study

Prediction of dry reaches in the North Branch may have been more detailed and accurate with a gapless data set. There were even some small gaps in river flow data from the Old Weir recorder, so these few dates were not considered within the study. Moreover the data of the wells was not ideal as some wells were only read monthly. A data set of daily measured well levels would improve accuracy.

While Shearers Road and Digbys Bridge went from flowing to immediately dry, water depth at the confluence with the South Branch site became shallower at every single gauging. Figure 41 shows how the discharge was distributed in the cross section at the confluence on three different gauging days.

On the 25th of November 2011 the depth was 25 cm in the shallow areas of the river bed and up to 40 cm in deeper areas. The total recharge resulted in 6.11 m^3/sec evenly distributed through the whole riverbed.

At exactly the same cross section on the 12th of January 2012 the total discharge was 440 l/sec with water flowing shallow at the true left but still 40 cm deep on the true right of the river. The shallow areas were not easy to gauge as the water was only around 10 cm deep.

At the last gauging on the 14th of February 2012, the total discharge was 108 l/sec with the main discharge concentrated at the true right (deepest point 34 cm). The water was still flowing at about 16 m width but very shallow, mainly less than 10 cm.

Unfortunately the Flow Tracker had problems with gauging water depths less than 10 cm and produced a lot of error warnings. Also, rising wind caused the shallow water to move upstream and made single spot measurements inaccurate; they had to be repeated. Some of the errors could be settled (remove stones in the vicinity of the probe or wait for the wind to stop) but others had to be ignored.

Nevertheless, the results seemed to be reasonable and all measurements were used within the study.

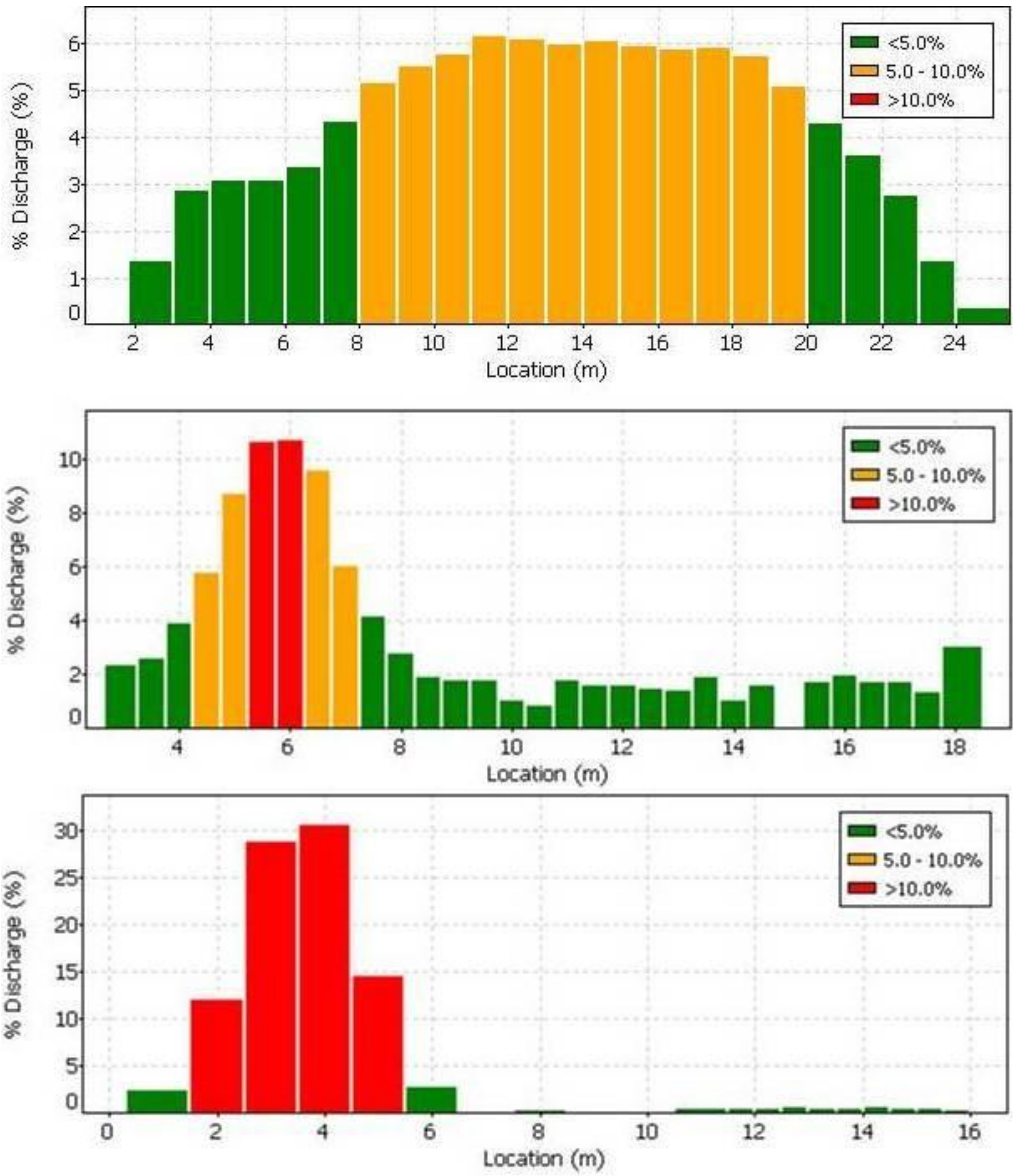

Figure 41 **North Branch at the confluence with the South Branch gauging cross-section: errors in discharge based on shallow water, FlowTracker plots from 25th November 2011 (top), 12th January 2012 (middle) and 14th February 2012 (bottom)**

Groundwater takes in the vicinity of the North Branch are obviously large. The dataset available for this study included groundwater takes of shallow wells - those pumping from 40 m deep or less. Thus not all takes were considered.

Also this dataset summed up all takes within the total Ashburton catchment and so provides only an indication of what is happening at the North Branch. Therefore this dataset was not used for calculations but only to show information graphically.

8. Conclusion

Studies investigating modern environmental pressures and human impact on hydrological systems are essential as those factors impact upon the quantity and quality of surface and groundwater resources and as a consequence (drinking) water supplies.

If the trend of increasing dairy farming and intensification of irrigated agriculture continues, water demand in New Zealand will increase to an unprecedented amount. As Canterbury contains currently 63 % of New Zealand's irrigated land, studies of the impact of abstraction on braided rivers become increasingly important. Also pumping groundwater from aquifers effects surface water as aquifers are not isolated components of the hydrologic system. Sustainable water management is essential to protect the water resource.

The Ashburton River North Branch, located in mid-Canterbury is already a highly allocated river but an increase of water abstraction would have very undesirable consequences. This river has been the focus of numerous studies. Besides establishing the natural flow regime without abstractions it determined that it would not go dry under natural conditions. None of the previous studies had the aim of predicting length and duration of zero flow periods.

Consequently, within this study another model was constructed to provide further clarity on the location, frequency and duration of drying in the North Branch in recent years.

To predict low flow regimes and the number of days of dry reaches in the vicinity of Digbys Bridge back to 1982, regression analyses were undertaken using data from various sources. At 176 days, 1992 is the year with the highest number of days. Between 2001 and 2010 the frequency of days is markedly higher than in years before, in 2001 there were 157 days of no flow at Digbys Bridge. Since then there appears to be a large number of days which are not related to acknowledged droughts, this may be driven by the occurrence of lower groundwater levels.

Additionally measurements of the length of dry sections on the North Branch showed that they increased significantly from the first observation on January 5th, 2012 to the last on February 14th, 2012 That day the North Branch between Thompsons Track Road and the confluence with the South Branch was more dry (16,057 m) than flowing (6,790 m). Due to lack of data it was not possible to predict the extent of the dry sections in the vicinity of Digbys Bridge back to 1982.

Nevertheless it is uncertain whether the low flow regime and the length of dry sections in the North Ashburton at Digbys Bridge are increasing with the increase of groundwater abstraction in the vicinity in the last 10 years because of the complex behaviour of the groundwater system. One explanation of the high number of dry days in the last 10 years is the natural increase in low flows measured at Old Weir combined with a drop of groundwater levels, which could be natural, and/or intensification in groundwater abstraction.

To investigate research gaps found in previous studies, three hypotheses were tested combining existing data with obtained measurements. For summer 2011/12 it could be verified that losses on the North Ashburton between all gauging sites from the Old Weir recorder site to the confluence with the South Branch are higher during high flows throughout the reach. Losses occur mainly due to abstraction although bed losses always occur. A gain within the reach arises mainly from spring fed stream inflows or upstream losses re-entering the stream. Measurements indicate larger flow losses when the river had higher flows with a gain in flow when flows were very low.

Considering all available information, the intensification of irrigated agriculture sourced from groundwater is probably the main driver of an increase in the number of days of low flow/dry days at Digbys Bridge. Nevertheless this cannot be verified absolutely because there are too many uncertainties.

It could be verified that the North Ashburton flow at Digbys Bridge is directly related to the flow at Old Weir recorder during high river flow, no matter what the groundwater levels are and, conversely, when Old Weir flows are low, the flow at Digbys Bridge is more closely related to groundwater levels and to a lesser extent Old Weir flows. Observations in the field were supported with long term plots and showed that the groundwater levels were not influenced by higher flows at the Old Weir. On this basis it can be concluded that the dryness of reaches in the North Branch at Digbys Bridge and upstream is largely influenced by groundwater level.

Even if the actual reason for the dryness of some reaches near Digbys Bridge couldn't be identified with certainty within this study it is obvious that human impact (water abstraction) plays an important role and management of this is needed to prevent further deterioration of the situation. To make sure that more water is staying in the natural system, so that water is flowing in the North Branch, restrictions on farm takes ought to be a consent condition on water permits.

The results were presented to the Ashburton River Zone Committee on April 24^{th} 2012 which is currently investigating its options to secure flow in the North Branch all year round.

9. Perspectives

This study concerns an element of a very interesting, highly complex topic. Problems with periodically dry river beds are not only limited to the Ashburton North Branch but can be expected to occur all over the Canterbury Plains in the near future. With the help of extensive research it would be possible to give actual reasons and for some cases also provide solutions. One of the most important questions is what role the allocation of surface- and groundwater plays. Unfortunately time and possibilities within this study were limited and ideas for future studies are given in this chapter.

Additional data sources

One way of measuring the length of past, present and future dry reaches in any river bed would be analyse aerial photographs or satellite images. For this it is necessary to find a good source of aerial photographs or satellite images with appropriate resolution at the appropriate time of the year.

If this information is not available for the past, reviewing old newspapers and other archives as well as interviewing elderly people living in the vicinity of the river could be helpful.

Monitoring & governance

To support future studies it is essential to keep recorders operating on a large number of groundwater wells. It was a serious problem for this study to have a small number of long term records available together with large gaps in the data.

Having access to numerous well records would be helpful to getting a better idea of the whole groundwater system rather than just relying on what's happening in one bore on the Plains. Additionally, the applied model would have been more accurate with actual, and not interpolated, data.

The same problem occurred with river flow data downstream of the Old Weir recorder. Regular gaugings at several sites along the North Branch would provide a good basis for future work. Also, periodical measurement of dry reaches in the vicinity of Digbys Bridge could solve the problem that emerged in the present study owing to lack of data and would facilitate predicting the length of the dry reaches back to 1982.

Within the present study there was no data available for actual takes for the study area. The sum of total allocation only for the whole Ashburton catchment was used, as well as some annual abstractions from the North Branch and its tributaries. Graphs and tables were created but this information was not taken into account within the model.

To improve the prediction of duration and length of dry reaches in the vicinity of Digbys Bridge one of the most important steps is to include actual numbers for takes in the model. For monitoring the actual takes it would be necessary to have access to complete records or notes from all water takes in the vicinity. This could evolve with change in water management and governance. At the moment water meters are not obligatory for every single well and a lot of allocation information is based on the consent data base which does not detail the actual amount of water taken.

Land use change & scenarios

As intensification of irrigated agriculture and an increase of dairy farming are undisputed reasons for increased allocation in the Canterbury Plains and especially in the Ashburton Catchment, it would be important to develop and model future scenarios from a hydrological point of view. What would happen if all suitable farmland is converted to irrigated dairy farming in the near future? Would the RDR cope with the future water demand or will there be a need to take more water from within small catchments? Would soils and groundwater suffer from nitrate surplus? Is it possible to establish a 'healthy' threshold for the number of farms/cows for a certain area with a certain amount of allocation?

Converting dry land grazing to dairy farming does not only include irrigating meadows but also a huge demand in stock water and water for providing hygienic conditions in milking sheds. What is the direct impact on surface and groundwater systems in the vicinity?

On the Canterbury Plains there is a trend to convert from border dyke irrigation to spray irrigation systems accompanied by the building of large number of irrigation ponds to provide water for those systems. Are these ponds going to affect the groundwater system (in a positive way)?

An observation during fieldwork gives rise to another question: on the 21st of February 2012 artificial discharge of Rangitata River water from the RDR caused a flow of 5.34 m^3/sec at Thompsons Track Road. Flow also occurred at Shearers Road and Ollivers Road for the first time since 19th of January 2012. This was confirmed by the RDR manager that they started spilling a varying amount of water down the North Branch on the 18th of February. Nevertheless, the river bed was dry at Digbys Bridge for 2,719 m (see Figure 42), so how much inflow does the North Branch need for how long to restart the whole section from Thompsons Track Road to the confluence with the South Branch flowing?

Additionally, it was observed that at the same time of the RDR spill the underground flow caused more outflow near the confluence, whereas the former gaugings (when Shearers Road, Ollivers Road and Digbys Bridge were dry) were 100 to 120 l/sec, the 21st of February measurement was 452 l/sec for the cross section at the confluence with the South Branch.

During fieldwork the massive extent of willows along the North Branch, mentioned by Horrell (2001), was confirmed. Water uptake by willows is also contributing to zero flows and shouldn't be underestimated. To get an idea about their importance, the area of willows was mapped with the help of an aerial photograph and is shown in Figure 43. All the area of willows between Thompsons Track Road and the confluence amounts to 442 ha and so the water uptake by these plants is a major factor within the vicinity of the North Branch and should definitely be incorporated in future studies.

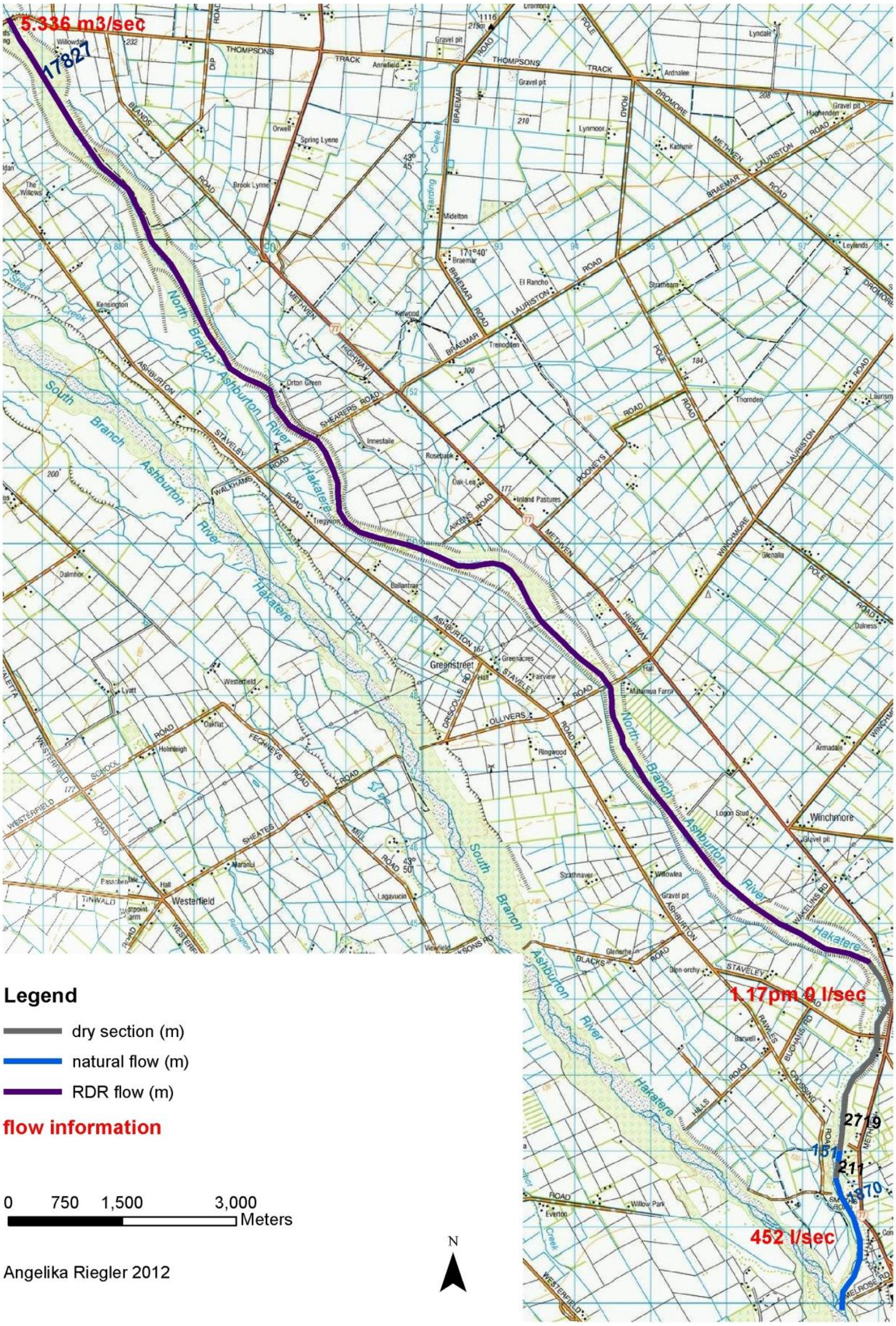

Figure 42 **RDR spill and dry sections at the North Branch between Thompsons Track Road and the confluence with the South Branch (21st February 2012)**

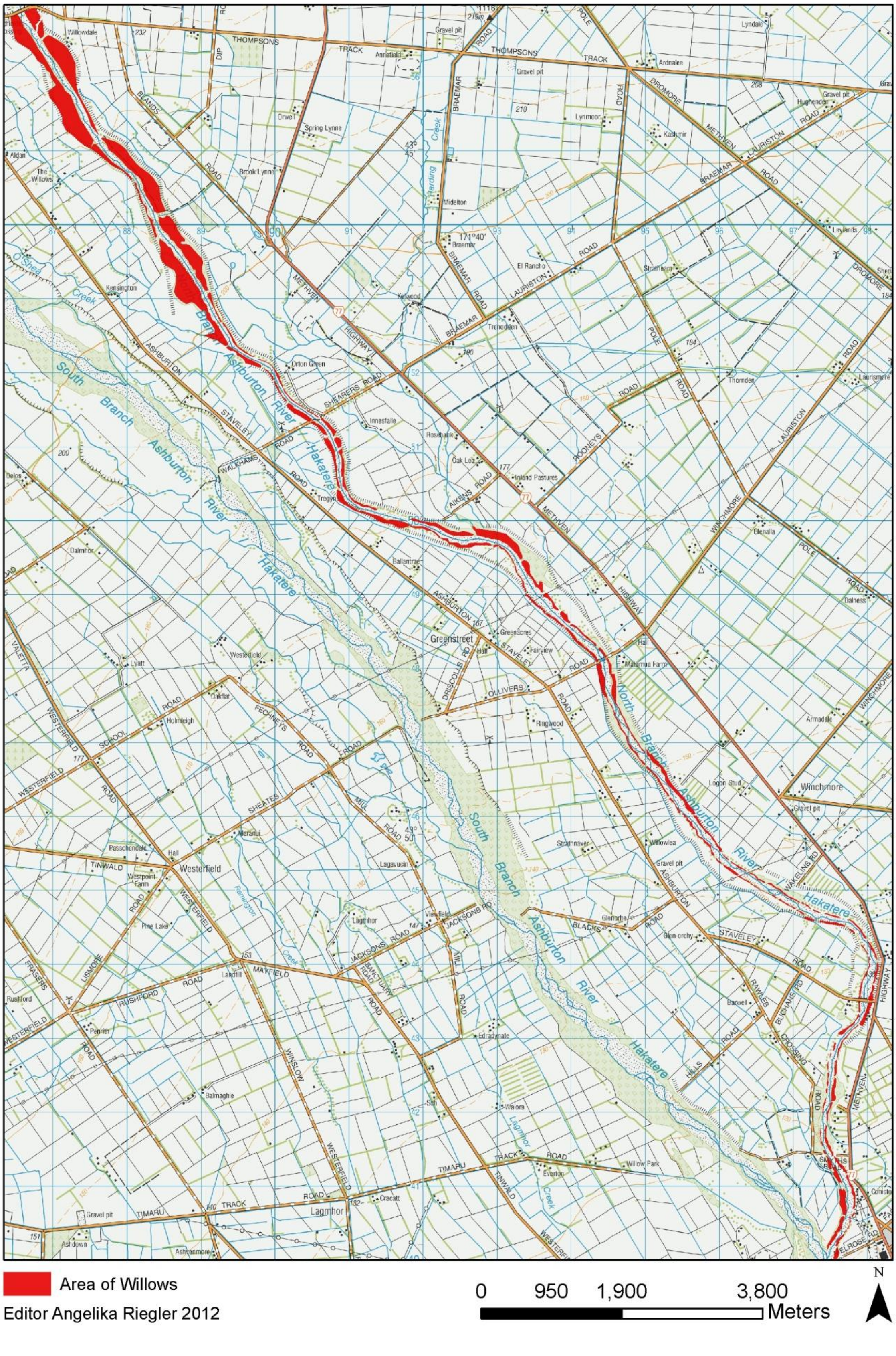

Figure 43 **Area of willows on the North Branch between Thompsons Track Road and the confluence with the South Branch**

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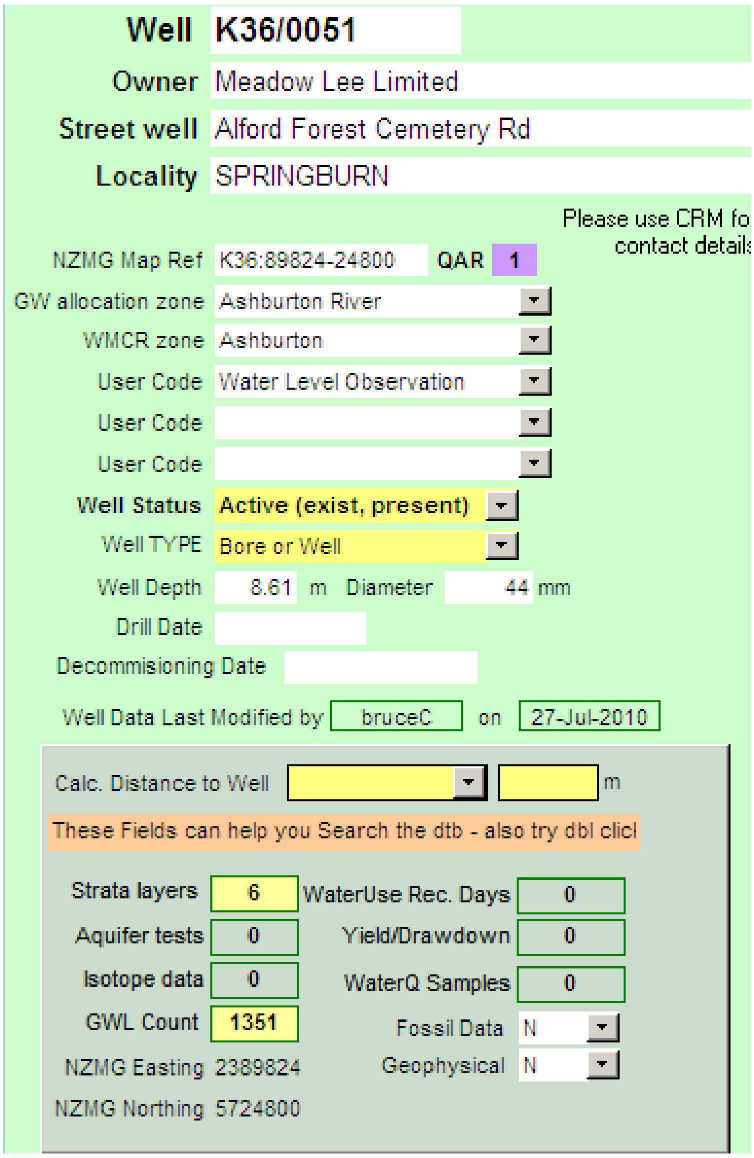
Appendix I

Well details



Well	K36/0051
Owner	Meadow Lee Limited
Street well	Alford Forest Cemetery Rd
Locality	SPRINGBURN

Please use CRM fo contact details

NZMG Map Ref	K36:89824-24800 QAR 1
GW allocation zone	Ashburton River
WMCR zone	Ashburton
User Code	Water Level Observation
User Code	
User Code	
Well Status	Active (exist, present)
Well TYPE	Bore or Well
Well Depth	8.61 m Diameter 44 mm
Drill Date	
Decommisioning Date	

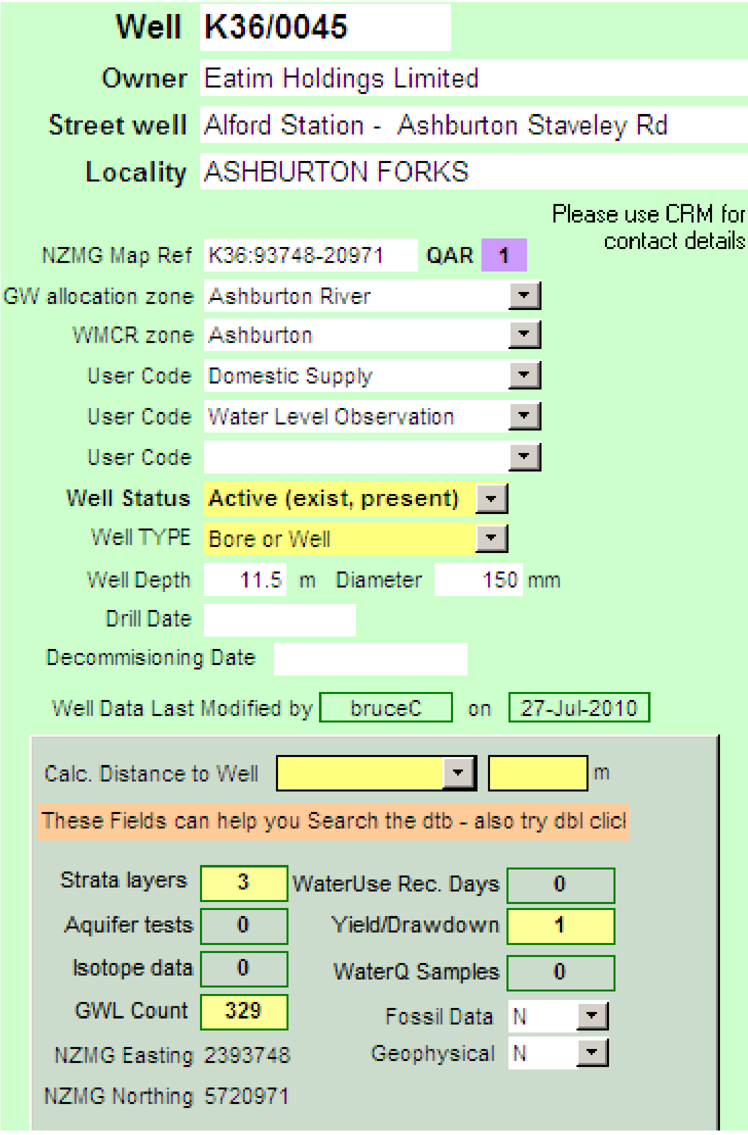
Well Data Last Modified by bruceC on 27-Jul-2010

Calc. Distance to Well m

These Fields can help you Search the dtb - also try dbl clicl

Strata layers	6	WaterUse Rec. Days	0
Aquifer tests	0	Yield/Drawdown	0
Isotope data	0	WaterQ Samples	0
GWL Count	1351	Fossil Data	N
NZMG Easting	2389824	Geophysical	N
NZMG Northing	5724800		

ECan well’s database information and photos



Well	K36/0045
Owner	Eatim Holdings Limited
Street well	Alford Station - Ashburton Staveley Rd
Locality	ASHBURTON FORKS

Please use CRM for contact details

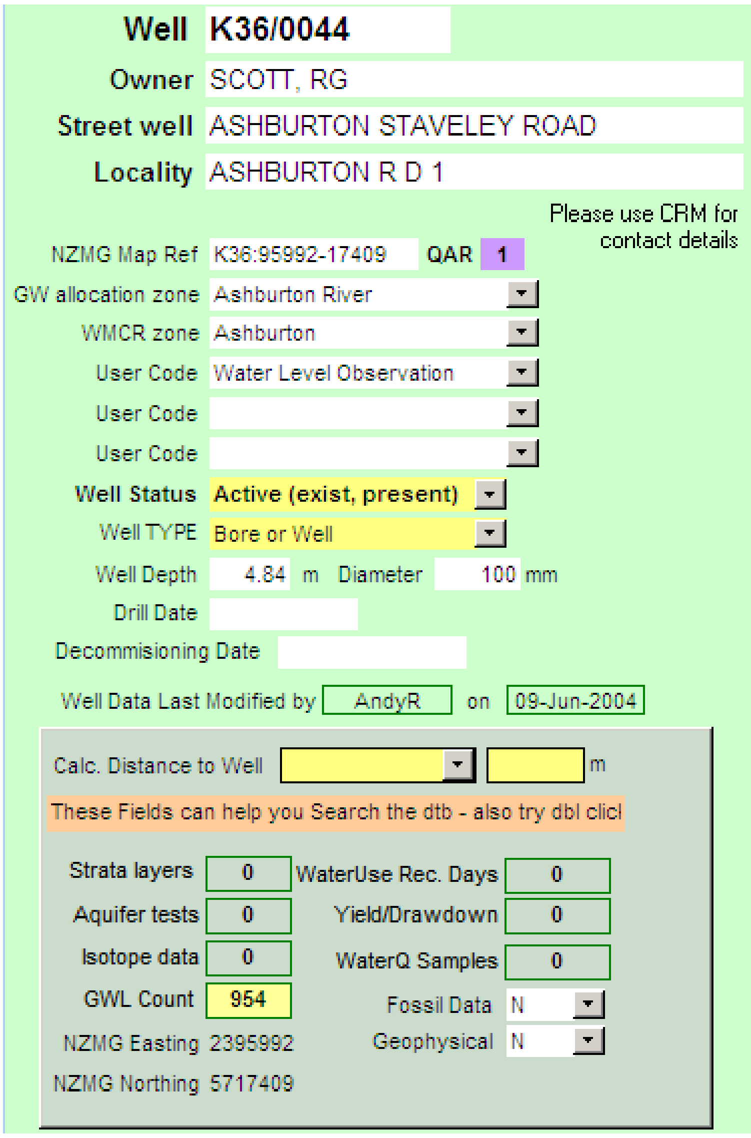
NZMG Map Ref	K36:93748-20971 QAR 1
GW allocation zone	Ashburton River
WMCR zone	Ashburton
User Code	Domestic Supply
User Code	Water Level Observation
User Code	
Well Status	Active (exist, present)
Well TYPE	Bore or Well
Well Depth	11.5 m Diameter 150 mm
Drill Date	
Decommisioning Date	
Well Data Last Modified by	bruceC on 27-Jul-2010

Calc. Distance to Well m

These Fields can help you Search the dtb - also try dbl clicl

Strata layers	3	WaterUse Rec. Days	0
Aquifer tests	0	Yield/Drawdown	1
Isotope data	0	WaterQ Samples	0
GWL Count	329	Fossil Data	N
NZMG Easting	2393748	Geophysical	N
NZMG Northing	5720971		

ECan well's database information with location information and photo



Well	K36/0044
Owner	SCOTT, RG
Street well	ASHBURTON STAVELEY ROAD
Locality	ASHBURTON R D 1

Please use CRM for contact details

NZMG Map Ref	K36:95992-17409 QAR 1
GW allocation zone	Ashburton River
WMCR zone	Ashburton
User Code	Water Level Observation
User Code	
User Code	
Well Status	Active (exist, present)
Well TYPE	Bore or Well
Well Depth	4.84 m Diameter 100 mm
Drill Date	
Decommisioning Date	

Well Data Last Modified by AndyR on 09-Jun-2004

Calc. Distance to Well m

These Fields can help you Search the dtb - also try dbl clicl

Strata layers	0	WaterUse Rec. Days	0
Aquifer tests	0	Yield/Drawdown	0
Isotope data	0	WaterQ Samples	0
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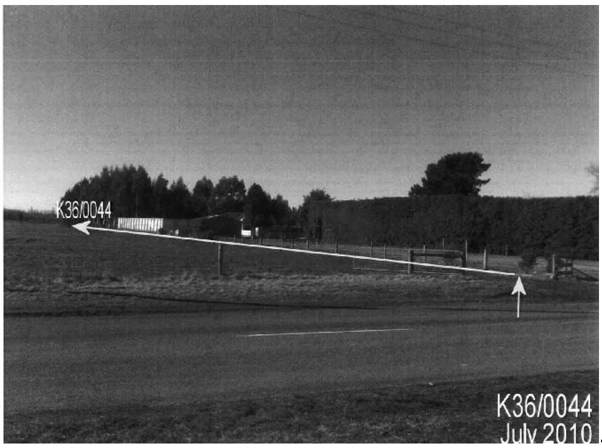


ECan well's database information with location information and photo

Well	**K36/0106**
Owner	SHEARER, A.D.
Street well	ASHBURTON RAKAIA GORGE RD
Locality	Greenstreet -GIS

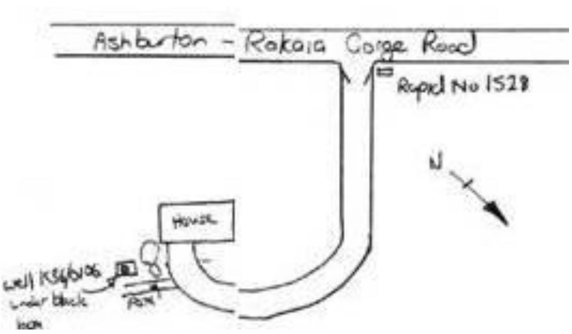
Please use CRM for contact details

NZMG Map Ref	K36:01053-14433
QAR	1
GW allocation zone	Ashburton-Lyndhurst
WMCR zone	Ashburton
User Code	Domestic Supply
User Code	Water Level Observation
User Code	
Well Status	**Active (exist, present)**
Well TYPE	Bore or Well
Well Depth	17.98 m
Diameter	150 mm
Drill Date	
Decommisioning Date	
Well Data Last Modified by	DavidE
on	18-Aug-2008

Calc. Distance to Well m

These Fields can help you Search the dtb - also try dbl clicl

Strata layers	4	WaterUse Rec. Days	0
Aquifer tests	0	Yield/Drawdown	0
Isotope data	0	WaterQ Samples	1
GWL Count	162	Fossil Data	N
NZMG Easting	2401053	Geophysical	N
NZMG Northing	5714433		



ECan well’s database information with location information and photo

Well	**K37/0010**
Owner	HULME
Street well	WINCHMORE SCHOOL RD
Locality	Winchmore -GIS

Please use CRM for contact details

NZMG Map Ref	K37:07558-09025 QAR 1
GW allocation zone	Ashburton-Lyndhurst
WMCR zone	Ashburton
User Code	Domestic Supply
User Code	Water Level Observation
User Code	
Well Status	Active (exist, present)
Well TYPE	Bore or Well
Well Depth	28.65 m Diameter 150 mm
Drill Date	17-May-1973
Decommisioning Date	
Well Data Last Modified by	ClareW on 08-Jan-2010

Calc. Distance to Well m

These Fields can help you Search the dtb - also try dbl clicl

Strata layers	7	WaterUse Rec. Days	0
Aquifer tests	0	Yield/Drawdown	1
Isotope data	0	WaterQ Samples	0
GWL Count	186	Fossil Data	N
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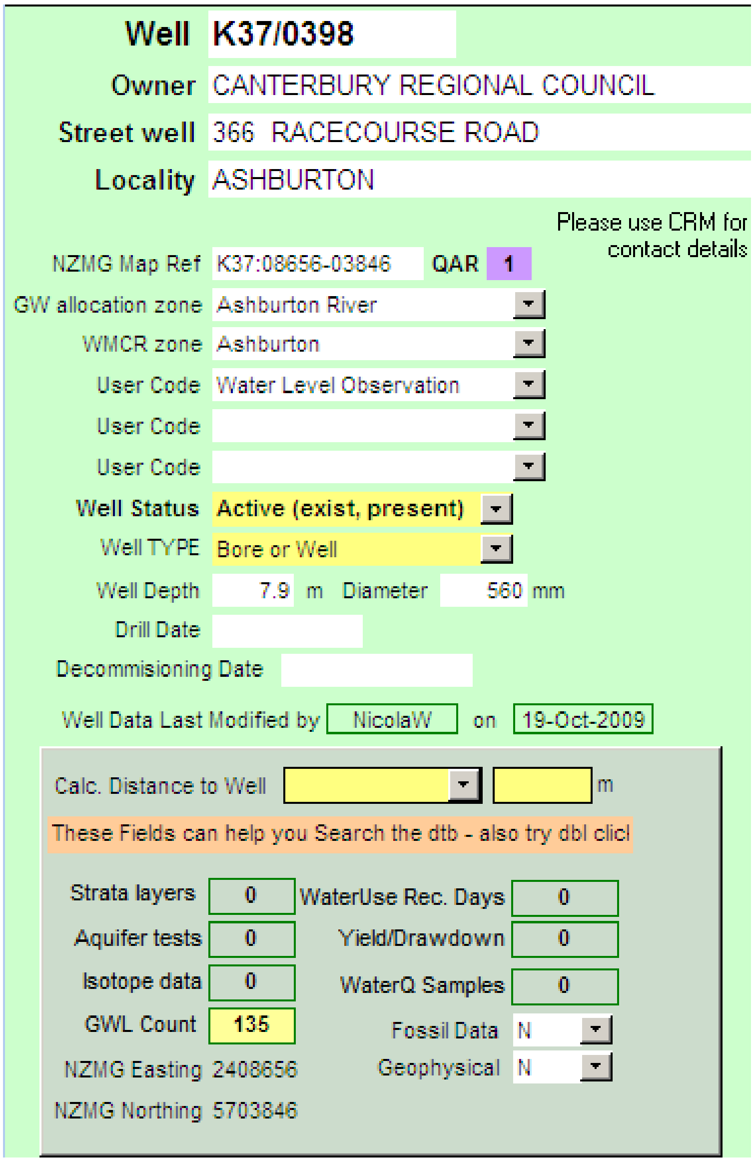
NZMG Northing	5709025		

ECan well's database information with location information and photo



Well	K37/0398
Owner	CANTERBURY REGIONAL COUNCIL
Street well	366 RACECOURSE ROAD
Locality	ASHBURTON

Please use CRM for contact details

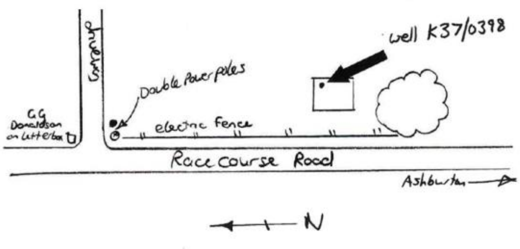
NZMG Map Ref	K37:08656-03846 QAR 1
GW allocation zone	Ashburton River
WMCR zone	Ashburton
User Code	Water Level Observation
User Code	
User Code	
Well Status	Active (exist, present)
Well TYPE	Bore or Well
Well Depth	7.9 m Diameter 560 mm
Drill Date	
Decommisioning Date	

Well Data Last Modified by NicolaW on 19-Oct-2009

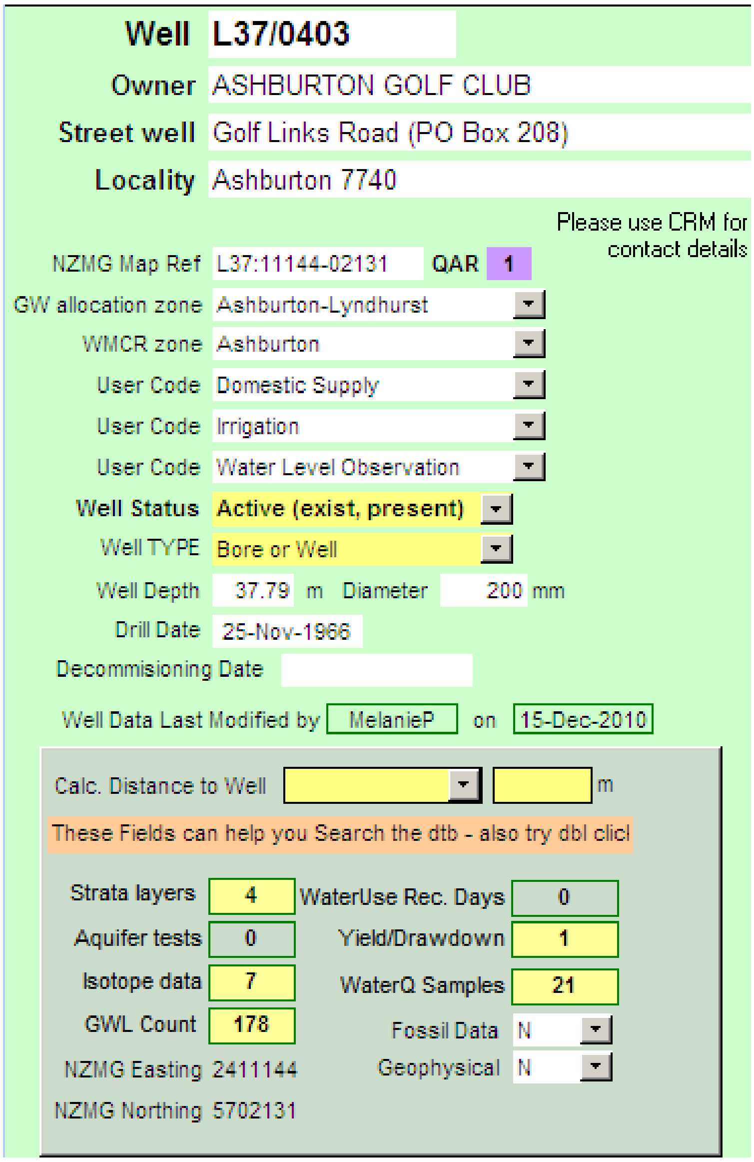
Calc. Distance to Well m

These Fields can help you Search the dtb - also try dbl clicl

Strata layers	0	WaterUse Rec. Days	0
Aquifer tests	0	Yield/Drawdown	0
Isotope data	0	WaterQ Samples	0
GWL Count	135	Fossil Data	N
NZMG Easting	2408656	Geophysical	N
NZMG Northing	5703846		



ECan well's database information with location information and photo



Well	L37/0403
Owner	ASHBURTON GOLF CLUB
Street well	Golf Links Road (PO Box 208)
Locality	Ashburton 7740

Please use CRM for contact details

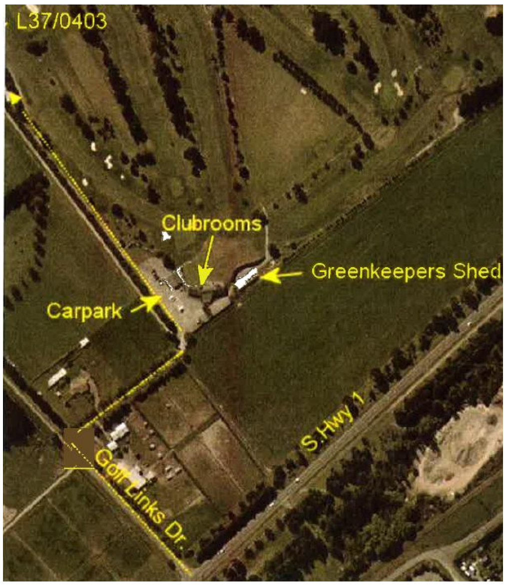
NZMG Map Ref	L37:11144-02131 QAR 1
GW allocation zone	Ashburton-Lyndhurst
WMCR zone	Ashburton
User Code	Domestic Supply
User Code	Irrigation
User Code	Water Level Observation
Well Status	Active (exist, present)
Well TYPE	Bore or Well
Well Depth	37.79 m Diameter 200 mm
Drill Date	25-Nov-1966
Decommisioning Date	

Well Data Last Modified by MelanieP on 15-Dec-2010

Calc. Distance to Well m

These Fields can help you Search the dtb - also try dbl clicl

Strata layers	4	WaterUse Rec. Days	0
Aquifer tests	0	Yield/Drawdown	1
Isotope data	7	WaterQ Samples	21
GWL Count	178	Fossil Data	N
NZMG Easting	2411144	Geophysical	N
NZMG Northing	5702131		



ECan well's database information with location information and photo

Appendix II

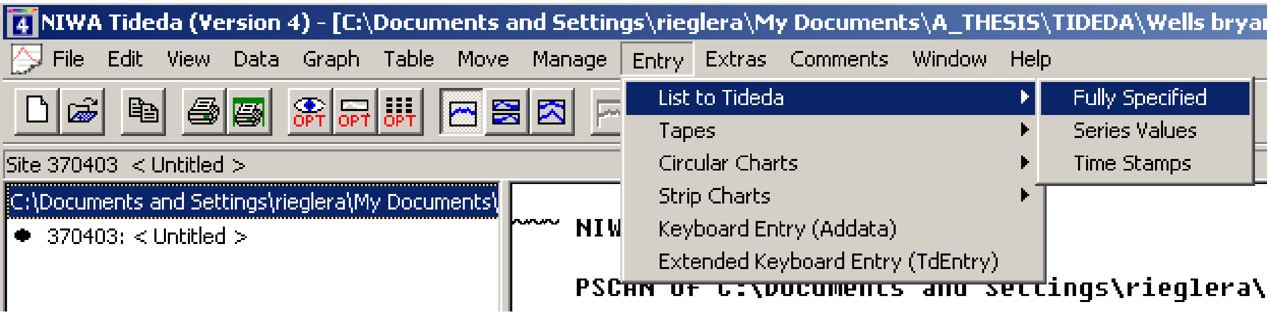
Import of well data into TIDEDA

As a first step the well data from the ECan wells database had to be converted into csv files. Therefore it was important to use the following consistent header:

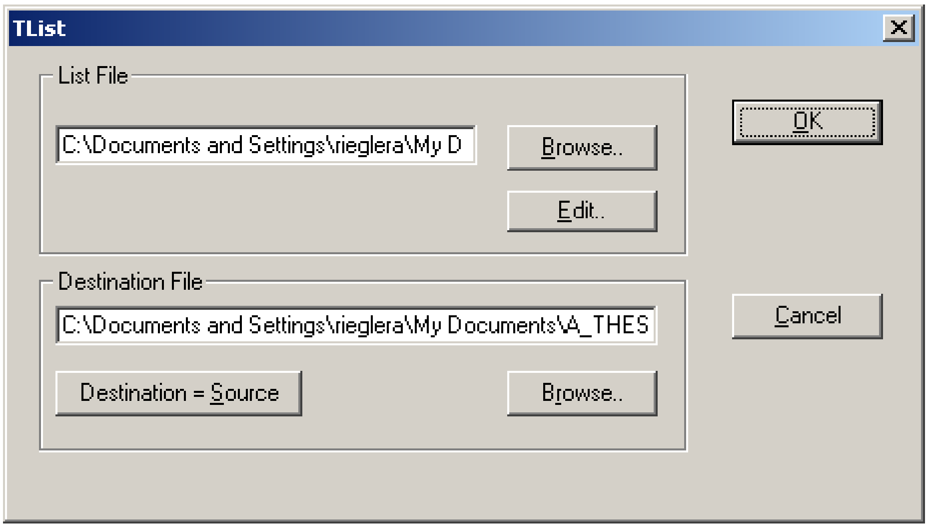
- Header: wellnumber (e.g. 360045) / 1 / instant
- Data: mm to water / yyyymmdd / 0

	A	B	C	D	E
1	360045	1	instant		
2	-4340	19740520	0		
3	-5060	19750710	0		
4	-4820	19750814	0		
5	-4300	19750912	0		

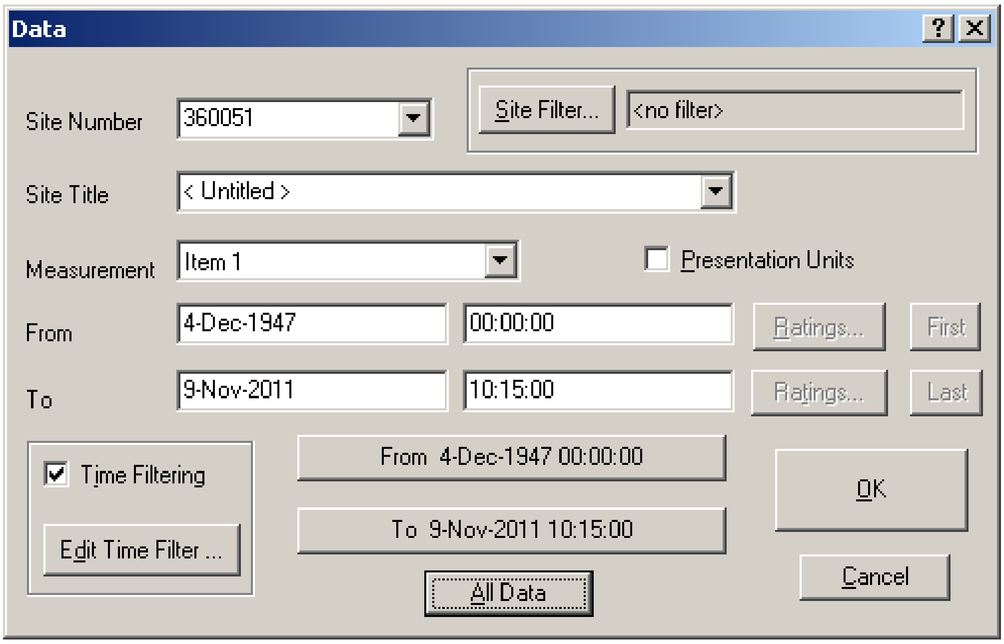
After opening the TIDEDA Program, *File / Create new file* had to be selected; also in this step the file location had to be set. To insert an Excel file the following path was necessary *Entry / List to Tideda / Fully Specified*



After the 'TList'-window opened , and in the section 'List File' the source of the csv file had to be browsed (and selected with *Open*) while the 'Destination File' path for the output file had to be set.



To load data *File / Source = Destination* – and to open the imported data *Data* /sec*elect data* had to be selected. In the next step the time frame was set (specify 'From' – 'To' or select *All data*)

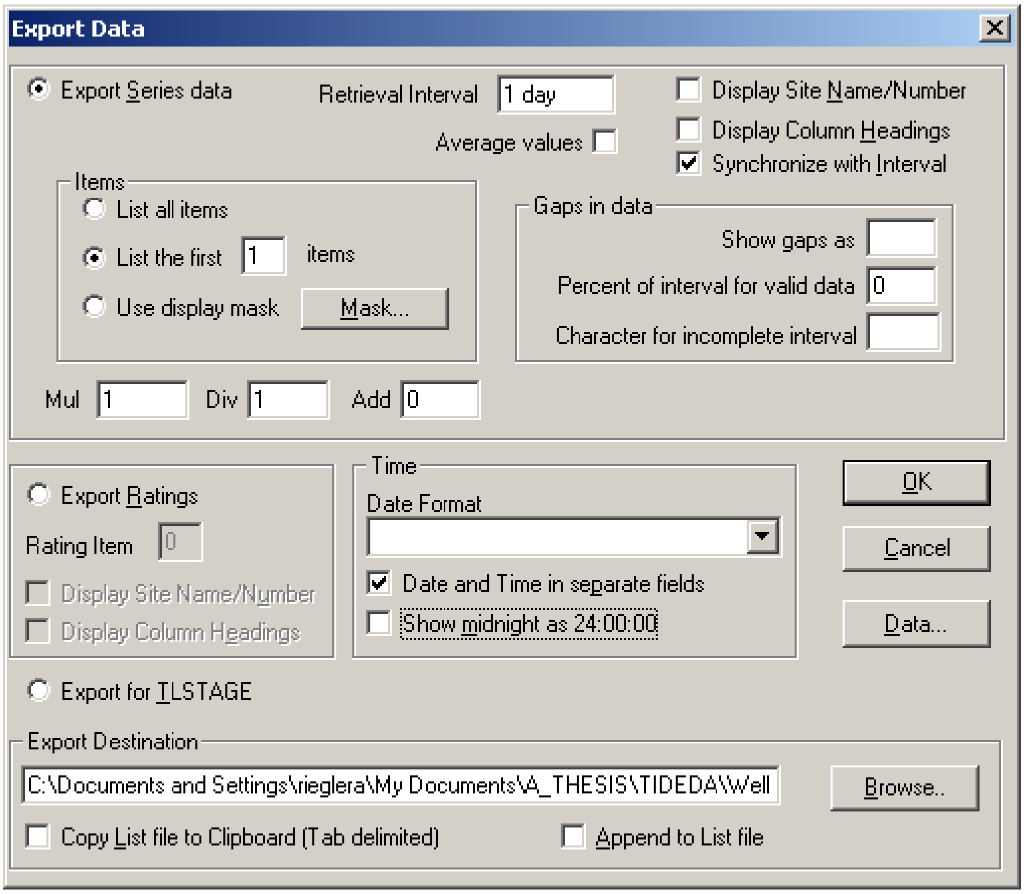


In the next step an overview of the data could be plotted (*Table / Quick Extremes, see example following screen shot*), data could also be shown as a table (*List*) or converted to daily/monthly values (*Table / Calendar / Daily*)

```
~~~ NIWA Tideda ~~~ NIWA                                    23-FEB-2012 16:33
~~~ PEXTREME ~~~
Source is 360051.MTD Site 360051 < Untitled >
From  4-Dec-1947 00:00:00 to  9-Nov-2011 10:15:00
Interval =       86400
Warning: With a non-zero interval the reported values are for
   fixed discrete time partitions. You might consider using
   the Moving mean process (PMOVE) for true extreme values.
Item 1
                 Coeff.
 Year    Mean    of Var.  Minimum          Date            Maximum          Date
 ----    ----    -------  -------          ----            -------          ----
*1947  -3893.6     0.00  -3903.5    30-Dec-1947 24:00   -3883.0      3-Dec-1947 24:00
 1948  -4043.4    -0.02  -4181.8    30-Dec-1948 24:00   -3904.3     31-Dec-1947 24:00
 1949  -4321.3    -0.02  -4459.3    30-Dec-1949 24:00   -4182.6     31-Dec-1948 24:00
 1950  -4598.9    -0.02  -4736.9    30-Dec-1950 24:00   -4460.1     31-Dec-1949 24:00
 1951  -3809.6    -0.10  -4746.0    11-Jan-1951 24:00   -2774.0      8-Mar-1951 24:00
 1952  -4840.7    -0.43  -8184.0     8-Jun-1952 24:00   -1250.0      3-Dec-1952 24:00
 1953  -3839.9    -0.14  -5033.1    30-Dec-1953 24:00   -1925.9     31-Dec-1952 24:00
```

Export of well data in daily values

To fill the gaps and interpolate the data, *Table / Export* had to be selected. In the ‚Export Data' window (see following screen shot), 'Retrieval Interval' 1 day was selected. Then 'Synchronize with Interval' as well as 'Date and Time in separate fields' were ticked. After Browsing for the Export Destination, the values were written into a csv file.



The final csv output had three columns; date, time and depth to water in mm (see following screen shot at left). As the time was not relevant, the column was deleted. For the final file, a header was inserted (well number and depth to water) and the depth was converted into meters (see following screen shot at right).

	A	B	C	D
1	19471203	240000	-3883	
2	19471204	240000	-3884	
3	19471205	240000	-3885	
4	19471206	240000	-3885	
5	19471207	240000	-3886	
6	19471208	240000	-3887	
7	19471209	240000	-3888	
8	19471210	240000	-3888	

	A	B	C
1	K360051	Depth to water in m	
2	19471203	-3.883	
3	19471204	-3.884	
4	19471205	-3.885	
5	19471206	-3.885	
6	19471207	-3.886	
7	19471208	-3.887	
8	19471209	-3.888	

Appendix III

Gauging Sites

Thompsons Track Road

Shearers Road

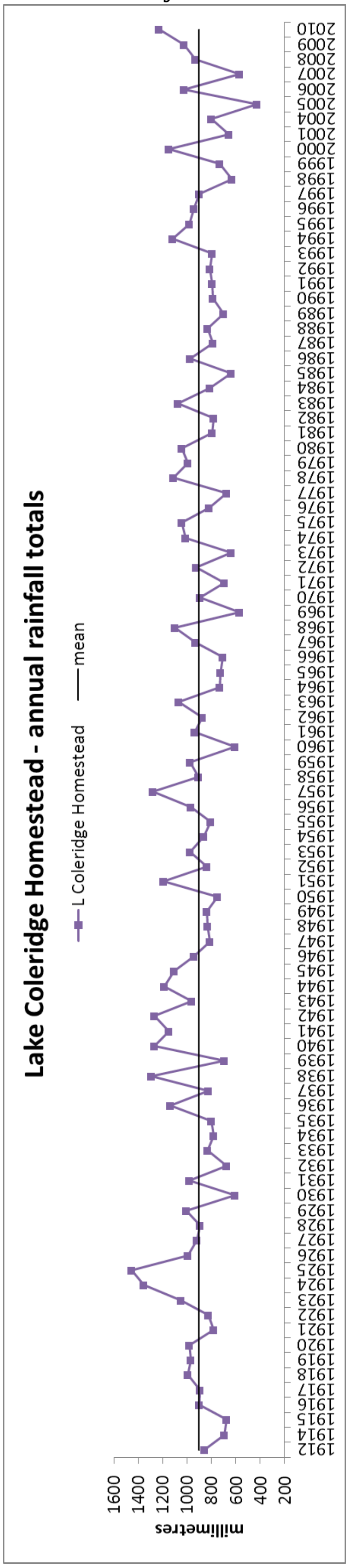
Ollivers Road

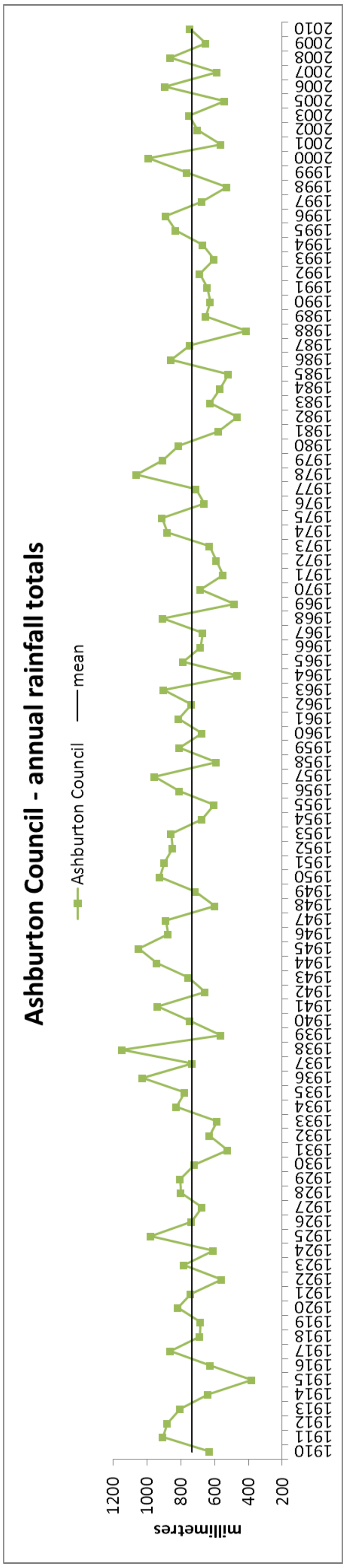
Digbys Bridge

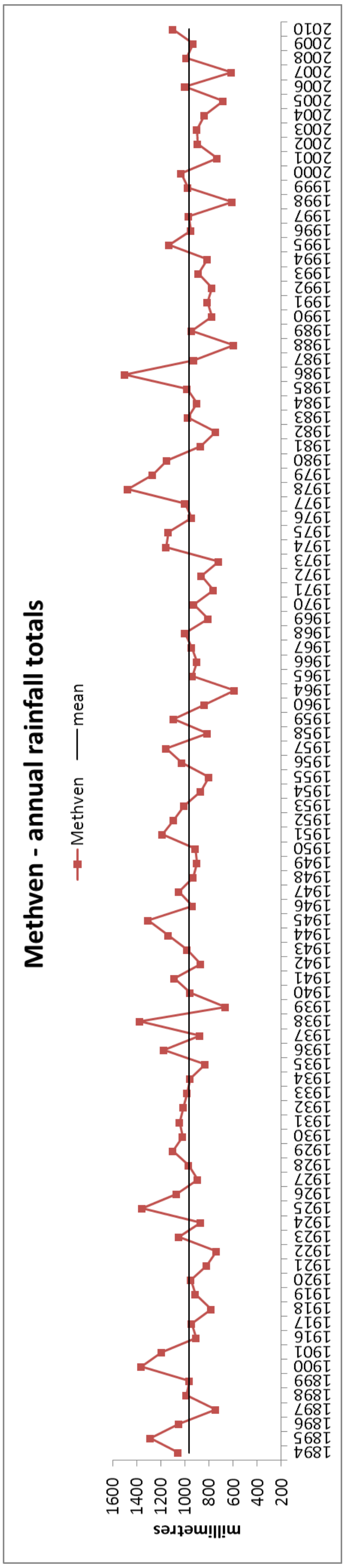
North Branch near Melrose Road (confluence with South Branch)

Appendix IV

Mean monthly rainfall in the Ashburton Catchment







Appendix V

Data selection: Digbys Bridge

Date	Old Weir Flow (m^3/sec)	Digbys Bridge Flow (m^3/sec)	Date	Old Weir Flow (m^3/sec)	Digbys Bridge Flow (m^3/sec)
18/11/1985	7.623	5.177	27/07/2007	3.573	0
02/03/1995	3.198	0	**04/05/2011**	**7.839**	**12.141**
03/03/1995	3.101	0	**11/10/2011**	**9.625**	**1.821**
01/04/1995	3.570	0	12/10/2011	10.748	7.772
20/01/1999	2.620	0	14/10/2011	8.700	4.586
29/01/1999	2.594	0	25/11/2011	10.240	5.164
05/02/1999	2.682	0	02/12/2011	7.369	1.103
11/02/1999	2.544	0	**13/12/2011**	**6.029**	**5.085**
25/02/1999	2.118	0	**23/12/2011**	**5.934**	**11.653**
09/03/1999	2.318	0	05/01/2012	4.254	0
23/03/1999	3.596	0	12/01/2012	3.849	0
26/03/1999	4.749	0.899	19/01/2012	3.359	0
23/06/1999	6.816	2.044	25/01/2012	3.290	0
25/06/1999	6.007	1.352	01/02/2012	3.154	0
30/06/1999	4.282	0.178	08/02/2012	2.825	0
21/12/1999	6.403	1.331	14/02/2012	3.121	0
29/02/2000	4.672	0	21/02/2012	2.671	0
14/06/2005	3.131	0			

The four red marked datasets were not used in this study. Due to renovation work on the Highbank power station, RDR water not used for irrigation was spilled into the North Branch. This happened on the 13th and the 23rd of December as the flow was relatively high in relation to Old Weir. The RDR operation manager Neill Stevens confirmed this information. The gauging on the 11th of October 2011 was taken during a rainstorm event and as the flow at Old Weir was too high this value was not relevant for this study.

Appendix VI

River flow and gauging data: North Branch

Date	**2011-11-25**	**2011-12-02**	**2012-01-05**	**2012-01-12**	**2012-01-19**	**2012-01-25**	**2012-02-01**	**2012-02-08**	**2012-02-14**	**mean**
Oldweir flow (l/sec)	10240	7369	4254	3849	3359	3290	3154	2825	3121	**4607**
Old Weir to Thompsons Track Road (loss, gain in l/sec)	*-1145*	*-2522*	*-1738*	*-2191*	*-2200*	*-2269*	*-2277*	*-2167*	*-2433*	**-2105**
Thompsons Track Road flow (l/sec)	9095	4847	2516	1658	1159	1021	877	658	688	**2502**
Thompsons Track Road to Shearers Road (loss, gain in l/sec)	*-1406*	*-1362*	*-1156*	*-1131*	*-1159*	*-1021*	*-877*	*-658*	*-688*	**-1051**
Shearers Road flow (l/sec)	7689	3486	1360	527	0	0	0	0	0	**1451**
Shearers Road to Ollivers Road (loss, gain in l/sec)	*-958*	*-526*	*-714*	*-93*	*303*	*248*	*162*	*103*	*0*	**-164**
Ollivers Road flow (l/sec)	6731	2960	646	434	303	248	162	103	0	**1287**
Ollivers Road to Digbys Bridge (loss, gain in l/sec)	*-1567*	*-1857*	*-646*	*-434*	*-303*	*-248*	*-162*	*-103*	*0*	**-591**
Digbys Bridge (l/sec)	5164	1103	0	0	0	0	0	0	0	**696**
Digbys Bridge to Confluence (loss, gain in l/sec)	*951*	*485*	*549*	*441*	*326*	*439*	*248*	*123*	*109*	**408**
Confluence (l/sec)	6115	1588	549	441	326	439	248	123	109	**1104**

Angelika Riegler (Ing.)

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angelika.riegler@gmx.net
0043 664 5900666
*born on March 20, 1986 (Lilienfeld, Austria)

Personal profile

My strengths are my dedication to any job that I am given, my accuracy, my team work skills and my genuine interest in water issues.

Education

2009 - 2012	Studies of Theoretical and Applied Geography (Applied Geomorphology focus), University of Vienna
2006 - 2009	Studies of Geography, University of Vienna
2000 - 2005	Federal College for Agriculture, Horticulture and Nutrition, Sitzenberg, Lower Austria
1992 - 2000	Primary School and Secondary School, St. Veit, Lower Austria

Employment History

09/2011 – 04/2012	Intern at National Institute of Water and Atmospheric Research, Christchurch
07/2005 - 08/2011	Employee at Statistics Austria, Directorate Spatial Statistics, Vienna (2005 - 2008 fulltime, 2009 - 2011 30 hrs/week)

Personal skills and competences

Language skills

German	first language
English	fluent (spoken and written)
French	basic knowledge

Computer skills

Microsoft Office, SAS, SPSS, Arc GIS, Adobe CS

Methodical skills

Fieldwork (esp. river flow gaugings and groundwater measurements), statistical analysis, time series analysis, analysis of aerial photographs, literature research

Key skills

Team work

+ In my jobs I am used to work in a team and solving problems jointly
+ At university I was used to work through projects in teams too
+ College colleagues and teachers had confidence in me as the spoke person for all students of the college

Time management

+ Tight deadlines at work means that I had to manage my time to make sure that I get all my work done
+ I had a lot of work in my job to balance with my study which taught me to prioritise and balance my responsibilities

Willing to learn

+ I am very willing to learn from specialists and to use that knowledge to get a better understanding of physical geography and especially water issues

Reliable

+ Always on time and ready to work on new projects

Interests

Travelling, cooking, photography, reading, tramping

Referees

Referees supplied on request

NIWA Seminar: Angelika Riegler

Emily Lane Sent: Tuesday, 17 April 2012 2:15 p.m.

Required: All Christchurch

When: Thursday, 19 April 2012 12:30 p.m.-1:30 p.m..

Location: Room VC Christchurch Tekapo Seminar

Show time as: Busy

Meeting status: Accepted

Description:

Kia ora tatou,

Angelika Riegler, who has been a student at the University of Vienna and has been working here for the last 7 months, is presenting the work she has done for her master's thesis. This will be a brown bag seminar over lunch on Thursday. I hope you can make it.

Title: Influence of groundwater levels on zero river flow: North Branch, Ashburton River, New Zealand

Date: Thursday 19 April 2012

Venue: Tekapo Seminar Room, NIWA Christchurch

Time: 12:30 pm-1:30 pm

Speaker: Angelika Riegler

Abstract:

Many of the alluvial rivers in New Zealand are modified by water abstraction, dam construction, gravel mining and other human activities, which began shortly after European colonization in the 19th century. They continue to the present and can modify or eliminate braiding and surface water – groundwater exchange. Water demand in New Zealand has increased significantly since the 1980's, mainly caused by increasing dairy farming and intensification of irrigated agriculture.

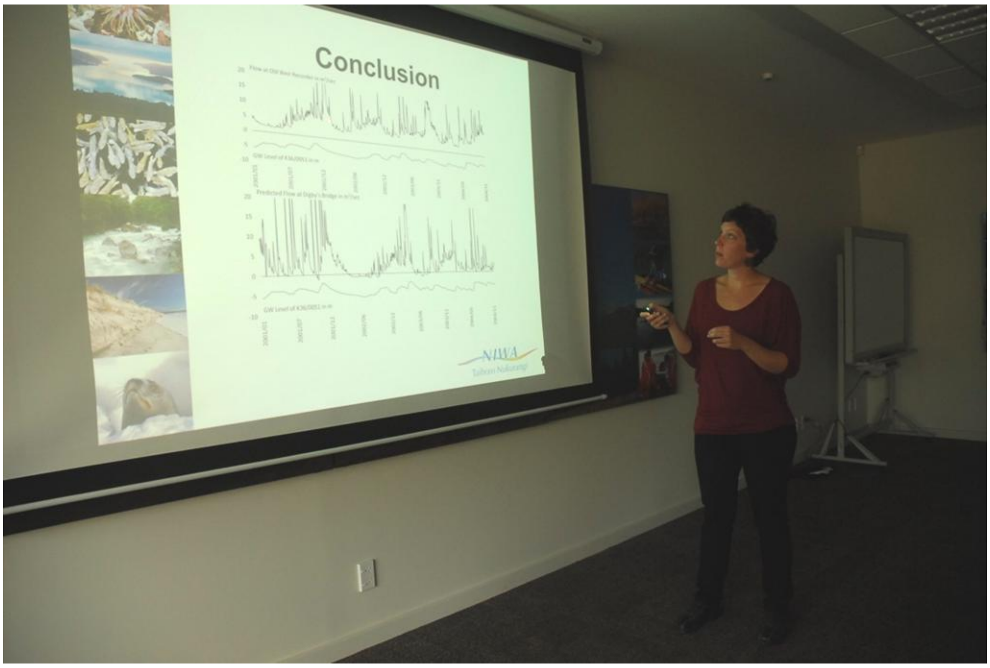
In this study a model was constructed for the highly allocated North Ashburton River, to predict low flow regime durations and dry sections in recent years. Regression analysis was undertaken combining existing data with obtained measurements to answer hypothesis concerning the influence of groundwater on zero river flow.

It could be verified that the North Ashburton flow at Digbys Bridge is directly related to the flow at Old Weir recorder during high river flow, no ma6er what the groundwater levels are and, conversely, when Old Weir flows are low, the flow at Digbys Bridge is more closely related to groundwater levels and to a lesser extent Old Weir flows. Additionally for the summer of 2011/12 it could be verified that losses on the North Ashburton between all gauging sites from the inflow at Old Weir recorder site to the ou9low at the confluence with the South Branch is highest during medium to high flows throughout the reach. It is uncertain if the low flow regime and the length of dry sections in the North Ashburton at Digbys Bridge are increasing with the increase of groundwater abstraction in the vicinity in the last 10 years, because of the complex behaviour of the groundwater system.

Any questions please contact me.

See you all there

Emily



Final presentation at NIWA Christchurch, April 19th 2012 (S: Myriām Guēguen 2012)