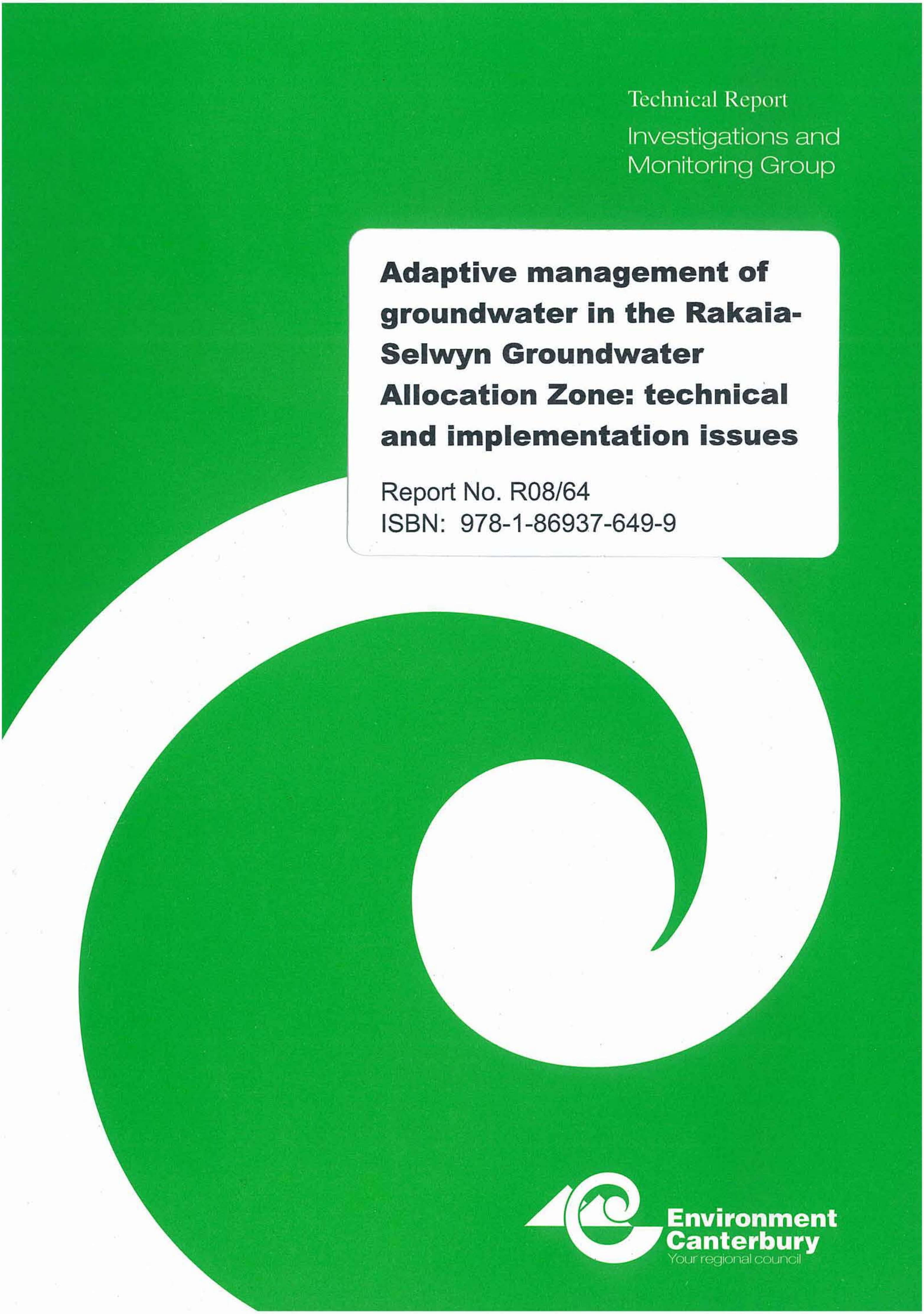

Technical Report

Investigations and
Monitoring Group

Adaptive management of groundwater in the Rakaia-Selwyn Groundwater Allocation Zone: technical and implementation issues

Report No. R08/64
ISBN: 978-1-86937-649-9

Environment
Canterbury
Your regional council

Adaptive management of groundwater in the Rakaia-Selwyn Groundwater Allocation Zone: technical and implementation issues

Report No. R08/64
ISBN: 978-1-86937-649-9

Howard Williams
David Scott
Vince Bidwell

December 2008

Environment Canterbury
Your regional council

Environment
Canterbury
Your regional council

Report U08/64
ISBN: 978-1-86937-649-9

58 Kilmore Street
PO Box 345
Christchurch
Phone (03) 365 3828
Fax (03) 365 3194

75 Church Street
PO Box 550
Timaru
Phone (03) 688 9069
Fax (03) 688 9067

Website: www.ecan.govt.nz
Customer Services Phone 0800 324 636

Foreword

This report represents advice to the Canterbury Regional Council and any views, conclusions or recommendations do not represent Council policy.

The information in this report, together with other information, may be used by the Council to formulate resource management policies, e.g., in the preparation or review of regional plans.

Executive summary

This report recommends that a recharge-based groundwater management method be implemented.

We describe a groundwater management method based on annual supply of recharge. The method varies the quantum of groundwater abstraction in the Rakaia-Selwyn Groundwater Allocation Zone to correspond with the state of the resource as measured by the land surface recharge to groundwater. We suggest an allocation volume held by consent holders be made up of a base (fixed) entitlement and an adaptive (variable) entitlement.

We recommend use of this method over those involving groundwater trigger levels alone because:

- it avoids the complications of localised interference effects;
- it may be adapted to deal with climate change effects;
- it allows prediction of environmental outcomes and may be tailored or adapted to achieve these outcomes.

The recharge-based management method, using climate data for the period from 1960 to 2008, indicates the following indicative reliabilities as a percentage of full allocation that is available for abstraction in a year:

- 100% in 20 years out of 49;
- greater than 90% in 32 years out of 49;
- greater than 75% in 41 years out of 49; and
- between 60% and 75% in 8 years out of 49.

Restrictions based on antecedent recharge will not necessarily occur at times of high demand. Comparison of calculated demand and with restrictions based on antecedent recharge indicates that in some years entitlement is greater than the demand, and as a result no practical restriction would have been experienced by users (e.g. 1990-91). In some years demand is higher than entitlement, meaning that real constraints would have applied (e.g. 2001-2008).

We recommend July 1st as the primary date when the adaptive entitlement should be assessed.

We have modelled the relationship between restrictions in water use resulting from the recharge-based method, and the corresponding increase in discharge from the aquifer system. Using one of the spring-fed streams, Harts Creek, as the indicator of the health of the discharge from the system, we have modelled an indicative increase in flow at Harts Creek of the order of 200 L/s between managed and un-managed abstractions during periods of low flow.

Robust water use data will improve certainty with which we predict environmental outcomes resulting from the implementation of the recharge-based method.

The recommended, recharge-based method allows prediction of environmental outcomes and to be effective within the framework of the Proposed Natural Resources Regional Plan Variation 1 and the proposed Restorative Programme for Lowland Streams it needs to be:

- based on precise data that are easy to measure;
- be robust and straightforward, in order that it can be understood;
- produce technically correct verifiable results straightforward enough to be communicated to non-technical user groups;
- a potentially equitable solution to the management of cumulative effects; and
- able to predict environmental outcomes in the form of surface flows; these have been achieved.

Monitoring data requirements are largely in place but further monitoring and analysis are recommended, such as:

- telemetry of monitored groundwater level data from four existing multi-level piezometer wells to further our knowledge of the dynamics of groundwater flow through the aquifer system;
- monitoring of daily mean flows in more spring-fed streams (River Irwell, Boggy Creek) is undertaken to allow for measurement of the short- and long-term dynamics of discharge from the aquifer system. Such monitoring will allow verification of the choice of indicator site, hydraulic-connection effects and provide valuable input to the proposed management method;
- better definition of environmental outcome. In this report, the minimum flow at Harts Creek has been chosen;
- that a programme of analysis of climatic data in association with the data derived from the metering of all consented takes, be initiated in order that the relationship between climate and water use, between use and effects, and between soil and use are better understood. These data will strengthen the technical justification, community acceptance and eventual operation of the adaptive management mechanism.

Table of contents

List of figures

Appendices

List of tables

Glossary

The following words and phrases have been used in this report and are defined here; many definitions are those used in Chapter 5 of the PNRRPV1.

Adaptive entitlement: A variable proportion of the annually consented allocation for each consent holder that in sum with the base entitlement for an allocation zone equals the total annual allocation for that consent. (See also ‘entitlement’ below)

Adaptive management: Adaptive management as originally envisaged by Holling (1978) is variably defined according to the several disciplines that use the concept, but for the purposes of this report can be considered as a structured, iterative process of decision-making in the face of uncertainty, with an aim of reducing uncertainty over time via system monitoring and prediction, in order to obtain a sustainable outcome.

Allocation limit and interim allocation limit: Volume of water that may be used in any year within a groundwater allocation zone set at a level to avoid unacceptable effects. The term applies to an entire groundwater allocation zone. The word ‘interim’ is used because the volume may be modified, depending upon improved knowledge through monitoring of effects.

Anisotropic: Materials with properties that vary dependent upon the direction of measurement are said to be anisotropic.

Annual volume: the total amount of water authorised via a water permit (consent) over a one year period.

Aquifer: Fractured or porous rocks or unconsolidated strata from which groundwater may be abstracted economically.

Aquifer system: A sequence of water-bearing strata showing direct or indirect hydraulic connection; a hydro-stratigraphic unit.

Base entitlement: A fixed proportion of the allocation for each consent that in sum with the adaptive entitlement (see above) for an allocation zone is the variable total entitlement.

Cumulative effects: Effects resulting from the accumulation of individual effects from every abstraction, integrated over space and time.

Effective allocation: the total amount of water currently allocated from an allocation block (PNRRP 2004).

Eigen model: A condensed form of groundwater model whereby time series of groundwater levels or aquifer discharge may be related to recharge and abstraction.

Entitlement: An annually variable volume for each consent comprising the sum of an assured base volume plus a volume dependent on the annually assessed state of the resource in the zone.

Evapotranspiration or EVT: Is the return of water vapour to the air by evaporation from land and water surfaces and by transpiration of water from vegetation (PNRRP 2004).

Exponentially weighted moving average or EWMA: A smoothing statistic for monitoring a process that averages time series data in a way that gives decreasing weight to data more distant from the time under consideration. The value of the smoothing coefficient alpha (α) changes according to the need to highlight pre-existing over recent data. In effect, it is a moving mean with a variable ‘memory’ of previous data.

Fluvio-glacial deposits: Deposits of gravel, sand, silt and clay derived from rapid transport and sedimentation as a result of glacially-fed rivers, commonly in the form of alluvial fans on the Canterbury Plains. The deposits generally contain a large range of grain sizes and may contain high porosity channel structures and thin, discontinuous fine-grained units.

Hydro-stratigraphic unit: A unit mappable on the basis of hydraulic properties that has considerable lateral extent and that also forms a geological framework for a reasonably distinct hydrogeologic system (Maxey 1964). Maxey identified the need to define groundwater units that are based not solely on specific lithological characteristics but also included parameters that apply especially to water movement, occurrence and storage. A hydro-stratigraphic unit may occur in one or more litho-stratigraphic units (Seaber 1988).

Land-surface recharge: Drainage infiltrating into the groundwater system, derived from rainfall and irrigation.

Lateral continuity of strata: Strata cannot be laterally continuous to infinity, and some are only continuous for metres or tens of metres. In the context of this report, gravel strata are unlikely to be laterally continuous down the direction of transport for more than a few kilometres; across the transport direction they may be continuous for hundreds of metres or less.

Leakage: Flow (usually vertical) of groundwater across strata layering. Under natural conditions, leakage is the process that allows groundwater in the upper plains to migrate to deep strata and vice versa in the lower plains. Under conditions where deep groundwater is being abstracted, leakage allows groundwater to move from upper to lower units.

Seasonal allocation (Schedule WQN9): A calculated volume considered sufficient for a consent holder to irrigate land for a specified farming system. Schedule WQN9 in the PNRRPV1 describes the method of calculation of the volume of water that may be taken in any year that is sufficient to meet irrigation demand in four years out of five. Schedule WQN9v3 refers to an improved version, currently being used in the context of the Restorative Programme for Lowland Streams (RPLS).

Strata: A geological term describing layers or lenses of sediment or sedimentary rock.

User: Registered owner of a consent to take groundwater for consumptive use such as irrigation, commercial users of water, and community suppliers of water for domestic, industrial and commercial use.

Water restriction: reduction in the authorised take during periods of low flow or water level in order to share the water that is available for abstraction and use, and is usually included as a condition of consent.

1 Introduction

This introduction briefly describes the events that led up to the research that underpins this investigation into adaptive management.

The remainder of the report contains:

- a description of the conceptual hydrological model of the Rakaia-Selwyn Groundwater Allocation Zone (RSGAZ) and the cumulative environmental effects displayed there;
- a description of the concept of adaptive management and how it may be used in the RSGAZ to manage cumulative effects by varying annual volumes on a seasonal basis;
- the data requirements for adaptive management;
- a description of the recommended method of adaptive management;
- technical issues associated with implementation of the preferred method;
- conclusions; and
- technical recommendations.

1.1 State of the water resource in the Rakaia-Selwyn Groundwater Allocation Zone (RSGAZ)

The RSGAZ is bounded by the Rakaia and Selwyn rivers, the coast and the foothills (Figure 1-1).

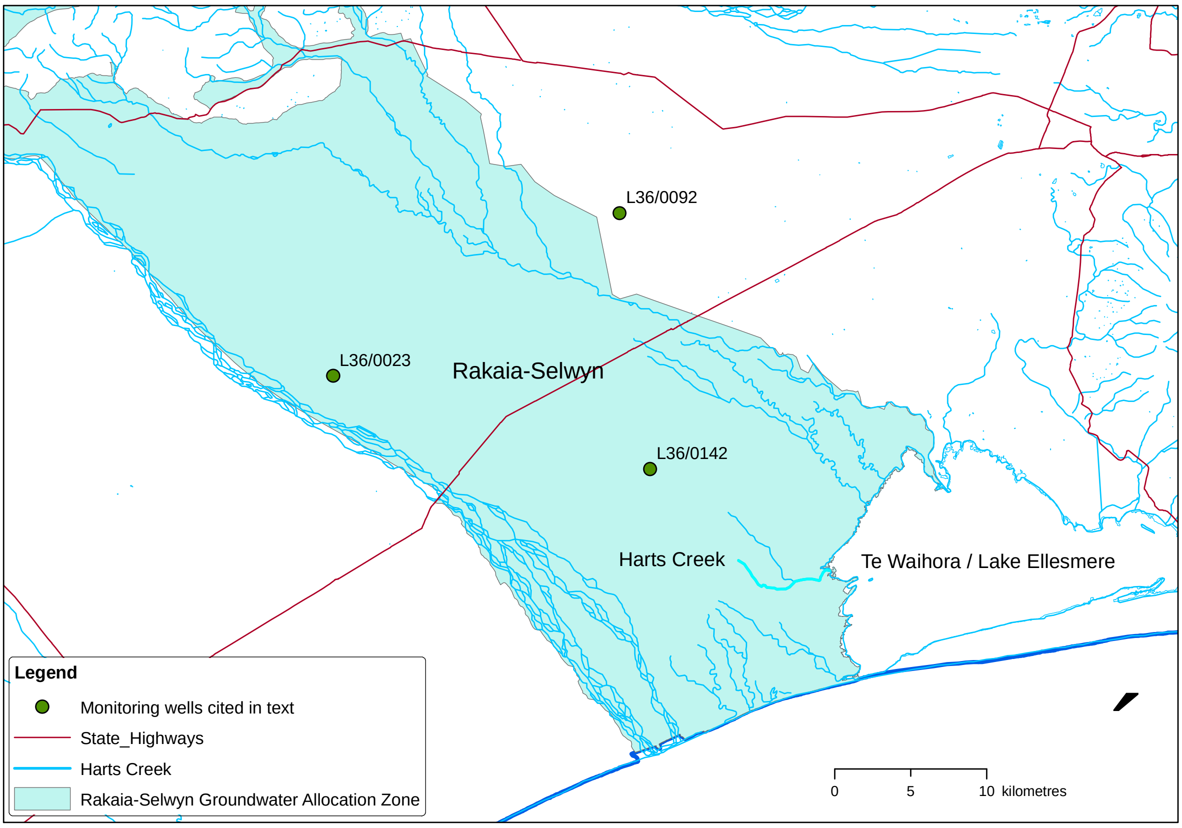

Figure 1-1 Map showing Rakaia-Selwyn Groundwater Allocation Zone, locations of monitoring bores L36/0142, L36/0023 and L36/0092, and Harts Creek

For the last twenty years there has been increasing concern over the state of the surface water and groundwater resources in the Central Plains of Canterbury[1]. The concept of management of the groundwater resource, tailoring use to the resource state, was reviewed as long ago as 1994 (CRC 1994) and also in draft guidelines prepared at the request of the Ministry for the Environment in 2002 (Lowry and Bright 2002). These concerns culminated in 2004 with the development of reports detailing the establishment of groundwater allocation zones and allocation limits (Aitchison-Earl *et al*. 2004).

This technical report provides a solution to the issue that management of cumulative effects of groundwater abstractions in the Rakaia-Selwyn Groundwater Allocation Zone has not been achieved by using the zonal allocation limit, provided for in the PNRRPV1, by itself.

1.2 Provisions for groundwater management in the PNRRPV1

The RMA requires that regional councils prepare plans to manage resources. Environment Canterbury produced a proposed Natural Resources Regional Plan (PNRRPV1 2004). This plan contains Policy WQN14 in the Water Quantity chapter, proposing allocation regimes, limits and corresponding management methods to deal with cumulative effects. It also provides for reviews of resource consents, at any time specified for that purpose in the consent. Such reviews would consider any adverse effect on the environment arising from the exercise of the consent which might be necessary to correct at a later stage. It was envisaged that in addition, a variation to the NRRP could be notified to introduce a new groundwater management regime into Schedule WQN3. Once such a variation became operative, consents would be reviewed accordingly.

The goals of groundwater management scheme aims to achieve specific environmental outcomes and be consistent with Policies WQN3 and WQN9 of the PNRRPV1. In addition, management should be consistent with the goals in the Sustainable Water Programme of Action[2]. That is: '*clear environmental limits will be set for water quality and the quantity available for allocation*'. The goal that levels and flows should be protected is consistent with Objective 2 of the proposed National Environmental Standard on Ecological flows and water levels discussion document (MfE 2008): "*To ensure that all resource consent decisions on applications to take, use, dam and divert water from rivers, lakes, wetlands and aquifers are made in the context of a clear specification of available water*". Our approach is also consistent with the "Dealing with Uncertainty" section of the NES: "*providing an adaptive mechanism that allows for environmental monitoring information (including impacts on associated natural values) to be incorporated into a review of environmental flows and water levels*."

In Schedule WQN4 of the PNRRPV1, long-term effects were, in 2004, considered manageable initially by capping total allocation (interim allocation limit) to a fixed proportion of the calculated land-surface recharge; more robust and adaptive approaches were anticipated in PNRRPV1. Monitoring data have since suggested that these limits may not always be sufficiently conservative and that an alternative management method, provided for under Policy WQN19(4), is required to reduce unacceptable environmental effects by restricting abstracted volumes based on the amount of recharge to the aquifer system.

1.3 The Lynton decision

The Lynton decision made by the Environment Court in 2005 (EC 2005) on appeal of an earlier Environment Canterbury decision to turn down an application for groundwater abstraction at Lynton Dairies, stated that:

[23] "*We conclude that all takes should be subject to controls as to the seasonal and annual volumes permitted*".

[138] "*We conclude from all the evidence that the major contributor to lower lowland flows is increased abstractions*".

---

[1] North Canterbury Groundwater Yearbook (1988) states that most of the plains between the Rakaia and Waimakariri rivers was showing signs of over-use of groundwater and that the North Canterbury Catchment Board was currently assessing the safe limits of groundwater use in this area.

[2] see Ministry for the Environment for details http://www.mfe.govt.nz/issues/water/prog-action/index.html

[186] "*the Regional Council should now move to establish a similar policy to the above*[3] *for the Irwell River and possibly other lowland streams*".

[199] "*it is clear that there is a need for urgent review by the Regional Council of the consents adjacent to the Irwell and Lower Selwyn Rivers*".

The decision in effect advised Environment Canterbury to take action on the lowland stream issue and to develop seasonally variable entitlements to a consented allocation volume.

1.4 The restorative programme for lowland streams (RPLS)

Prior to the Lynton decision, over the period 2000 to 2005, there had already been concern over the poor ecological and hydrological state of streams in the RSGAZ. The Lynton decision prompted discussion of options for managing the groundwater resource, especially in the RSGAZ, within the constraints of the Resource Management Act (1991) and the PNRRPV1. This concern, coupled with the Lynton decision, led to the Restorative Programme for Lowland Streams (RPLS) project, announced in July 2006, which is intended to restore stream flows.

The RPLS contemplated four initiatives as the basis of a review of all groundwater consents in the RSGAZ:

1. setting a annual maximum volume on all consents (Schedule WQN9v3 or equivalent annual volume[4]) by placing annual limits on the volume of water for each consent;
2. measuring, by metering, how much water is taken by all consented takes;
3. review of minimum stream flows, assessment of stream depletion (Policy WQN8), and consent conditions, imposition of stream depletion controls on abstraction from wells that individually affect stream flows; and
4. implementing adaptive management to allow allocation of the resource to be varied year-by-year depending on how much water is stored in the groundwater system (Policy WQN19(4)).

In an effort to move towards adaptive management of groundwater, technical work was initiated in February 2006 to understand the dynamics of the RSGAZ. The objective of this work was to develop adaptive management for effectively managing the combined surface water and groundwater resource.

Although this report deals specifically with the RSGAZ, it is anticipated that there will be a more general application within the Canterbury region over time.

The direction for this research work was officially signalled by a letter and technical summary sent to consent holders in the RSGAZ in June 2007 (ECan 2007a), included here as Appendix C. The technical summary outlines the reasons for the consent review being largely due to the need to restore flows in spring-fed streams that are largely dependent upon groundwater levels, and has been updated by Williams (2008).

1.5 Climate change and adaptive management

The most recent Inter-governmental Panel on Climate Change report AR4 (IPCC 2007; Ministry for the Environment 2008), confirms and amplifies previous predictions that human activities are affecting the natural processes of climate variability, with temperatures increasing at previously unheard of rates. The many effects of these raised temperatures include: changes in regional patterns of temperature and rainfall; changes in sea level due to both increased melt from icecaps plus thermal expansion. The IPCC 2007 report states: "*As a result of reduced precipitation and increased evaporation, water security problems are projected to intensify by 2030 in southern and eastern Australia and, in New Zealand, in Northland and some eastern regions*."

A NIWA (2007) response derived from the AR4 report states (our emphasis in bold): "*Projections show that drought events are likely to increase in both frequency and severity in the eastern lowlands of*

---

[3] Refers to Policy WQN 8 (3) which provides for the review of permits to take groundwater adjoining a surface water body.

[4] Schedule WQN9 of the PNRRP contains a method to determine an allocation volume for irrigation based on effective summer rainfall, soil type and land use.

*New Zealand. Ongoing water security problems are very likely to increase by 2030 in those parts of eastern New Zealand that are distant from major rivers. The report says increasing demand for water has already exceeded supply in some catchments but "**ongoing and proposed adaptation strategies are likely to buy some time**.*"

The Ministry for Environment report on May 2008 states (our emphasis in bold): "*Thus, councils and communities should be giving serious consideration to the potential future impacts of climate change on their functions and services. Particularly important are infrastructure and developments that will need to cope with climate conditions in 50–100 years' time. Examples include stormwater drainage systems,* ***planning for irrigation schemes****, development of low-lying land already subject to flood risk, and housing and infrastructure along already eroding coastlines.*"

Despite the monitored lessening of the upward trend in temperature in this current decade, perhaps as a result of cyclic changes in ocean temperature and currents (Pacific Decadal Oscillation or PDO), in the long term, these climatic trends will induce water security issues making irrigated agriculture vulnerable. Environment Canterbury's response to climatic variability in general is contained within its July 2004 Natural Resources Regional Plan where adaptive management of groundwater resources is explicitly described within Policies WQN14 and WQN19 relating to allocation of groundwater and, restriction of groundwater during times of low water availability. The recommended method of management proposed herein can achieve the objectives from which these policies stem.

The proposals for adaptive management of the water resource contained in this report are a potential means to manage or mitigate some of the adverse effects of climate change. These proposals future-proof the policies in the Environment Canterbury plan: PNRRPV1.

1.6 Outline of management options

Management of groundwater was first undertaken in New Zealand in the Tasman area as a result of work in the Waimea alluvial basin (Dicker 1980, Dicker *et al*. 1992). This work ultimately became an integral part of the Tasman District Plan (Tasman 1999) and will be briefly described. Similarly, Otago Regional Council has operative plans that manage water resources using groundwater level triggers (Otago 2004).

Fifteen years ago, Canterbury Regional Council (CRC 1994) reviewed different management strategies and recommended a water level trigger for groundwater management based on the conceptual knowledge of, and limited data regarding recharge to the groundwater system at that time (Refer to Issue 2 in CRC 1994).

Before recommending a groundwater management method, we briefly describe management mechanisms already implemented:

- Tasman region
- Christchurch-West Melton zone;
- Woolston-Heathcote zone;
- Marlborough region method;
- Otago region method;
- "Davoren method", adopted for applicants in the Rakaia-Selwyn and Selwyn-Waimakariri Groundwater Allocation Zones; and
- Groundwater Management Areas (GMAs) described by Goulburn-Murray Water (2007) and established in parts of Victoria (Australia)

These methods are quite different from the recharge mechanism described in Section 5 herein, in that they are reactive[5] methods involving simple trigger levels. All these methods are now briefly described; it is important to understand that not one of them can be accurately called '*adaptive management*' as per Holling (1978).

1.6.1 Tasman method

The Tasman method used a number of groundwater trigger levels measured in monitoring wells to determine if sufficient groundwater was present at the beginning of, or at any time during, the irrigation season for abstraction to continue. The criterion for setting the triggers is related to maintaining Waimea River flows. This method is dependent upon groundwater triggers alone and suffers the drawback that localised and cumulative well-interference effects can distort and affect the monitoring wells used to impose restrictions.

This management mechanism appears to work effectively in small aquifer systems but becomes less practical in large ones because of the time lag between cause and effect.

1.6.2 Marlborough

Since the 2000/01 drought groundwater triggers have been used on an informal basis to stabilise groundwater levels in the 'Southern Valleys' area of the Wairau aquifer in Marlborough[6]. It is a voluntary approach at this stage. However staff are likely to recommend to the Marlborough District Council that in this water-short area it be adopted long-term in conjunction with seasonal quota. The seasonal allocation is based on the difference between a community-defined low groundwater level and the refill point in spring prior to the start of each irrigation season. A yield versus aquifer level relationship based on meter readings is used to derive the seasonal allocation.

1.6.3 Otago method

The Otago method (Otago 2004, Schedule 4, page 317 *et seq*.) uses a series of triggers for 25%, 50% and 100% restriction, dependent upon the level of groundwater in each aquifer for which the mechanism is implemented. The management objectives for this mechanism are that groundwater levels be maintained to within a specific interval. It works effectively in these small hydraulically-isolated aquifer systems but would be less practical in large ones because of the time lag between cause and effect (See Appendix A) and potentially suffers from the same drawbacks as the Tasman method.

1.6.4 Christchurch – West Melton (CHWM) method

In 1990, as a result of concern[7] for declining groundwater levels, relative to typical bore depths in the Christchurch – West Melton area to the west of Christchurch city, Environment Canterbury instituted groundwater level triggers monitored from a network of monitoring bores. The concept is similar to that proposed in the report on groundwater management (CRC 1994). As groundwater levels decline and pass through a series of triggers, each consented abstraction of groundwater is restricted in proportion to each total take. Generally, three triggers are used, with the result that users are restricted to two-thirds, one-third, or no take.

This mechanism for restricting abstractions reduces the volumes taken when the groundwater levels are low. It appears to work in that there has been no serious long-term decline in groundwater levels, but, significantly, restrictions have been required for longer periods over the last few years. The reasons for increasing restrictions include:

---

[5] Reactive mechanisms imply that resource stress induces a management response. There is neither prediction of resource state nor adaptation of the response mechanism.

[6] Peter Davidson, Groundwater Hydrologist, MDC, pers. comm. September 2008

[7] Consent applications and decisions set the precedent for this approach dated 1986 (Pitt) and 1989 (Wilson).

- prolonged dry periods;
- cumulative drawdown effects from outside the zone;
- intensification of permitted activity use (lifestyle blocks); and,
- gradual intensification of existing consented groundwater use both within and outside the zone (increased uptake of consented volume, and increased number of consents).

This method could work more effectively in a small hydrologically-distinct area that responds quickly to changes in abstraction. However, the resource in the CHWM zone is hydraulically connected to the neighbouring Selwyn-Waimakariri Groundwater Allocation Zone (SWGAZ) where no groundwater management mechanism has yet been implemented for all consents. Therefore, increasing takes from this neighbouring zone are thought to have affected the reliability of supply in the CHWM zone.

The CHWM zone is managed using simple trigger levels – there is no adaptation of the restriction mechanism as understanding of the resource recharge, discharge and use is improved.

1.6.5 Woolston-Heathcote (WH) method

In 2001, occurrences of saline water in some bores required re-assessment of the groundwater budget in the localised coastal area of Woolston-Heathcote (south-eastern Christchurch). Monitoring of groundwater composition and levels indicated that bedrock highs restricted groundwater flow into this confined aquifer.

Monitoring showed that as groundwater levels declined there was corresponding evidence of saline water in the aquifer, determined from taste and electrical conductivity measurements. Given the proximity of the area to the coast, the source of the saline water was not in doubt, but the mechanism of its introduction to the confined aquifer was.

Regardless of the mechanism, it was clear that aquifer pressures needed to be increased in order to reduce the incoming saline flow and contamination. The management response was to reduce abstraction by instituting a water user group charged with keeping within specific use volumes and groundwater level targets.

Users now have specific annual volume allocations and, in addition, groundwater level triggers are used to require reductions in these volumes. As groundwater levels decline, usually during the summer months, three separate triggers, based on daily, monthly and annual rolling means, come into play. Each trigger passed requires a one-third reduction in daily volume.

The WH method seems to have had success because there has been some remediation of the contamination, groundwater levels have increased, and no trigger levels have been breached. As with the CHWM and Tasman methods, this method works in a small area, largely because it has limited hydraulic connection with other zones.

1.6.6 Goulburn-Murray method

Groundwater Management Areas (GMAs) have been described by Goulburn-Murray Water (2007) and established in parts of Victoria (Australia) where groundwater has been intensively developed or has the potential to be developed. Caps to extraction, (the maximum volume that can be taken from an aquifer system in a GMA) have been established in these areas, based on estimates of sustainable limits of an aquifer. There is also allowance made to vary the water use on a seasonal or annual basis where there is connection between groundwater and surface water, as described by Brodie *et al*. (2007).

1.6.7 Davoren method

An ‘adaptive management’ method was proposed on behalf of 69 applicants for abstraction consents in the RSGAZ in 2006-7 and 41 recently-granted consents in the neighbouring Selwyn-Waimakariri zone to the east (Davoren 2007).

The method relies upon triggers related to the state of the groundwater resource at both the beginning and end of the irrigation season while making allowance for cumulative effects by assessing the expected recession in groundwater levels over that period. If, at the abstraction location, sufficient groundwater was present at the beginning of the season to allow for the expected recession, then full entitlement to the annual volume could be exercised by a consent holder.

The method does not address existing adverse effects in the combined groundwater – surface water system, only the adverse effects of additional takes. Description and critical analysis of this method is included as Appendix E. The method does not conform to the definition of adaptive management of Holling (1978).

1.7 Recommended management option and outline of method

This brief review of methods for managing cumulative effects from Canterbury and elsewhere in New Zealand concludes that they are not suited to large aquifer systems such as the RSGAZ. The reasons are laid out in Table 1.1 (overleaf).

In the remainder of this report we describe a groundwater management method based on the history of supply of recharge to the groundwater system. We recommend use of this method over those involving groundwater trigger levels alone because it:

- avoids the complications of localised interference effects;
- may be adapted to deal with any climate change effects;
- allows prediction of environmental outcomes and if not initially successful, may be tailored or adapted to achieve these outcomes.

The recommended method is therefore an adaptive management approach as envisaged by Holling (1978) because it allows feedback from the observed outcome targets of management (e.g. improved flows) to inform the management process and modify it if necessary.

In the RSGAZ, the challenge in designing an adaptive management method is to provide effective and sustainable water resource management to manage the effects of variable input (recharge) on the desired natural output (discharge as spring-fed streams) from the system. The recommended adaptive management method is described in Section 5.

Table 1.1: Methods of groundwater management, their data requirements for implementation, advantages and disadvantages

Method	**Data required**	**Advantages**	**Disadvantages**
Tasman Otago CHWM W-H types	⇒ Groundwater levels ⇒ Surface water flows ⇒ Metered use	⇒ Simple to operate, allows restrictions based on trigger levels accepted by community	⇒ Not suitable for large aquifer systems with time lags between cause and effect ⇒ Not suitable where inflows or effects derived from adjacent zones occur
Davoren	⇒ Pre-set trigger levels based on site specific groundwater levels ⇒ Site-specific aquifer parameters ⇒ Metered use	⇒ Attempts to account for cumulative effects of new takes	⇒ Difficult to predict reliability of supply ⇒ Each user required to submit an annual report on state of resource prior to obtaining go-ahead (labour intensive) ⇒ No specific environmental outcome predicted
Recharge-based method with Eigen model prediction of effects (Method recommended in this report)	⇒ Metered consented groundwater use, ⇒ Rainfall recharge, ⇒ EVT, ⇒ Soil type ⇒ Irrigated area ⇒ Monitored groundwater levels & surface water flows	⇒ Simple to operate ⇒ Shows causative link between restrictions and environmental outcomes (true adaptive management) ⇒ Allows base and adaptive entitlements ⇒ Allows good indication of reliability of supply statistics ⇒ Eigen model can be used to predict potential for saline intrusion	⇒ Requires good understanding of the relationship between climate and water use ⇒ Requires improved surface water monitoring

2 Conceptual model of the RSGAZ and cumulative effects

2.1 Conceptual model of the RSGAZ aquifer system

The RSGAZ is a part of the Canterbury Plains aquifer system which has been described in detail in a review by Brown (2001). In brief, the plains are composed of a set of inter-connected glacio-fluvial fans of gravel-dominated strata largely developed during the Pleistocene glaciations. These fans have at their eastern border interacted with the marine environment and are inter-leaved with finer-grained deposits indicative of marine and transitional environments.

Recharge to the aquifer system consists of a base, relatively constant recharge derived from the alpine rivers that continue to cross the fan system, coupled with a more variable recharge derived from rainfall and foothills rivers. Rainfall and foothills river recharge are available mostly in the upper and mid plains while alpine river recharge occurs mainly in the mid and lower plains.

Occurrence of fine-grained sand and mud strata to 70 km offshore at the continental shelf break (Carter & Herzer 1979; Herzer 1981a, Herzer 1981b), in conjunction with relatively constant groundwater pressures at the coast, suggests that leakage of groundwater through (under) the coastline is likely to be relatively constant, especially in comparison with other terms in the water budget such as surface discharge[8]. Williams (2007) used data from piezometers at different depths, and calculated hydraulic gradients in water-bearing strata around Lake Ellesmere to model the sub-surface discharge from the system to the ocean at less than 10 m^3/s, within a total mean water budget output from the RSGAZ of approximately 25 m^3/s (Horrell 2006). This conclusion is consistent with monitoring, as reported in Horrell (2006), in Taylor (1996) and from theoretical considerations by Krom (2007).

The size of the aquifer system means that effects of recharge and discharge take a long time to develop and decay. It will be shown in Section 5 that several months of above average recharge are required to augment groundwater levels. Similarly, groundwater levels decline via natural discharge, even in the absence of abstraction. Monitoring of groundwater levels and Eigen model analysis by Bidwell (2003) demonstrates that the fundamental aquifer characteristics are relatively ubiquitous.

The large aquifer system, over time scales of months and years, acts as a single entity.

Over shorter time scales, local drawdown effects caused by abstraction are being managed by a combination of controls on location and rates of abstraction.

A conceptual model of the dynamics of the water resource depends upon understanding the component variables that make up the water balance or budget. These variables have been recently described by Horrell (2006) and represent a modification of earlier work reported by Horrell in Taylor (1996). The RSGAZ consists of a large-scale multi-layered alluvial fan groundwater – surface water system. As a result of variation in climate and water use this system is in a continuous state of dynamic change: surface flows and groundwater pressures and levels never reach a true equilibrium. This complex dynamic system may be represented by the simple continuity equation below, or as a water budget, as illustrated in Figure 2-1.

---

[8] Groundwater flow under the coastline can only be relatively invariant if the gradient there is constant. Such a situation can occur if the groundwater gradient changes mainly in the strata westwards of the locus of the spring-fed streams.

Variable inputs = Variable outputs ± Storage

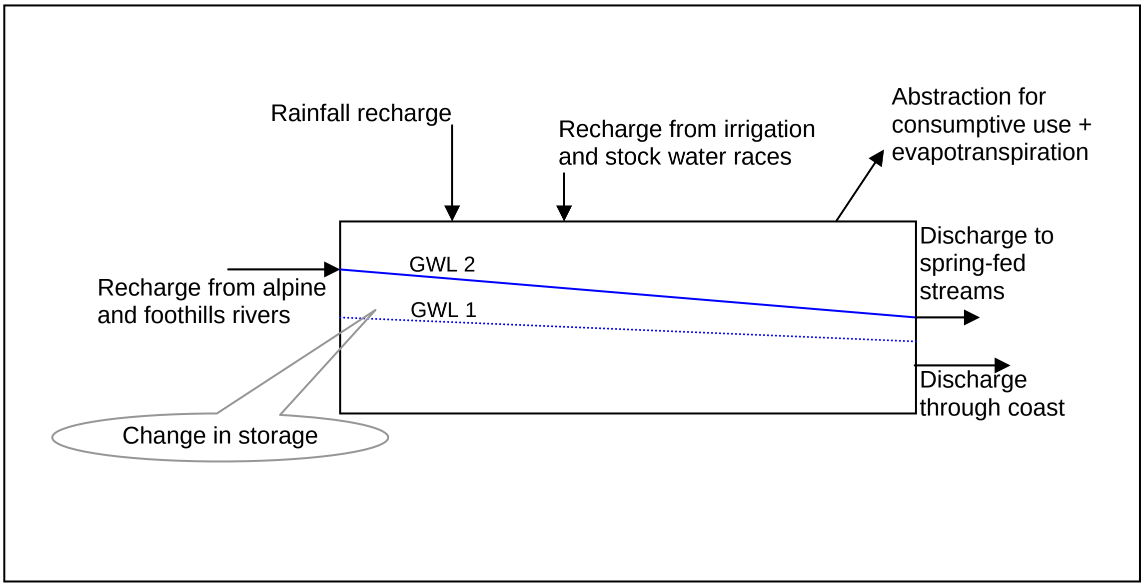

Figure 2-1: Schematic representation of the inputs and outputs to the Rakaia-Selwyn Groundwater Allocation Zone. GWL 1 & 2 represent changes in storage as a result of change in groundwater level

Unfortunately, the magnitudes of the components within the variables used in the continuity equation are imperfectly known, so a groundwater management method using only variables that can be reliably measured or estimated is required.

In the RSGAZ, land-surface recharge derived from rainfall and irrigation is the most variable input to groundwater but arguably the most easily quantified. Other less variable inputs include: seepage from the alpine rivers and continuously-flowing streams. Deep groundwater sourced from the fractured rocks comprising the foothills is likely to be negligible. Whilst rainfall varies from year to year, seepage from the Rakaia River is considered to be relatively constant because the wetted area and depth of the river is largely unchanged from year to year, and from season to season (Bidwell 2003). The effect of river recharge is considered to be relatively constant because variations are damped, according to the properties of aquifer dynamics, to a steady state value within a few kilometres of the river.

Outputs from the groundwater system consist of five variables: deep groundwater discharge direct to the ocean; discharge to spring-fed streams; groundwater discharge to Lake Ellesmere; evapotranspiration; and groundwater abstraction. Since it is essential to maintain outflows to the sea and environmental flows in the streams, it follows that abstractions (also known as ‘takes’) must be less than the estimated total recharge to the aquifers.

In our modelling we used informed estimates of the magnitude of groundwater use in the zone.

Outputs vary from year to year, as does groundwater abstraction. The magnitude and seasonal variability of the deep discharge to the ocean can only be estimated as the imbalance of all other components in the water budget.

We do not know exactly how much groundwater discharges directly to the ocean under the coastline.

In Section 5 we describe a mechanism that relies on variables that are easily measured and verified and which produces predictions when used in association with Eigen modelling (refer to Appendix A). It is expected that these predictions may be assessed for their accuracy and precision by use of a verified three-dimensional numerical flow model once more robust water use data become available.

The combined surface water – groundwater system is dynamic, driven by variable inputs of climatically-driven recharge, and outputs consisting of natural discharge and water use. Present monitoring of the state of the groundwater and surface water resource shows a direct relationship between climate and use of groundwater.

Experience in South Canterbury has shown (Thorley *et al*. 2008) that in small but connected aquifer systems, the locally-variable recharge from surface water seepage means that allocation of groundwater should be spatially distributed relative to locally available recharge. In this way localised changes in recharge may be identified, and some reserved to protect stream discharges. Such subdivision of the RSGAZ is not yet contemplated because the larger aquifer system generally reacts as a single entity[9].

Variation in groundwater storage is a complex function of groundwater level in the various water-bearing strata and can best be determined from changes in groundwater levels over the zone. Storage and discharge from storage can also be modelled using an Eigen method (Appendix A). Further theoretical work by Scott and Hunt (2007), following from Hunt and Scott (2007), indicated that the volume of groundwater moving (leakage) from one water-bearing stratum to another as a result of abstraction can be a significant proportion of the pumping rate. Our conceptual model of the aquifer system is of set of water-bearing strata that, in the time scale of months to years, acts as a single but heterogeneous unit. Water levels in each stratum change according to the seasonal variation in recharge and abstraction stresses. Monitoring has shown that different depth levels and areas of the RSGAZ respond differently to these stresses.

Despite our support of the work of Davey (2006) who developed a concept of aquifers based on preferred screened intervals and geological criteria, neither Davey nor the authors of this report subscribe to the hypothesis that the aquifer system can be sub-divided into discrete ‘aquifers’ for management or modelling purposes, a view supported by White (2008, page 50).

Analytical modelling indicates that cumulative abstractions create a broad spectrum of drawdown effects. Although near-field responses are distinctly seasonal, far-field effects, as close as three kilometres from an abstraction bore, contribute to a steady long-term decline in levels and flows.

Preliminary modelling indicates that total cumulative effects take up to 10 years to develop (Williams *et al.* 2006). The corollary is that the currently observed effects resulting from abstractive increases and variable climate may reflect only a portion of the anticipated total resulting from changes throughout the previous decade.

These current adverse effects also have to be seen in light of expected climate change within the period of time of abstraction.

2.2 Cumulative effects

For nearly 70 years scientists have understood that abstraction of groundwater from an aquifer system has an effect on its natural discharge to surface water (Theis 1940). Water budget calculations using monitored inputs, outputs and storage, illustrate how aquifer systems work much like a bank balance

---

[9] The Rakaia riparian sub-area in the Southbridge area benefits from seepage derived from the Rakaia River and ECan is currently investigating whether a formal sub-zone is warranted.

with a continual expense claim (natural discharge) whose magnitude depends upon the balance, a sort of tithing or taxation [10].

Cumulative effects are those that result from the sum of individual effects from every abstraction, integrated over space and time. Cumulative effects may be different in magnitude and timing at different locations. The cumulative effects of groundwater pumping for irrigation develop as the irrigation season progresses and may continue to develop even after abstraction has ceased due to the time-lag of effects from distant takes. In addition, such effects are likely to accumulate, season upon season, year upon year.

Any abstraction of groundwater must involve one or more of the following processes:

- a reduction in the amount of groundwater storage;
- increase in recharge from surface water to groundwater; or
- reduction in the discharge to surface water or through the coast.

In Section 4 we demonstrate the positive correlation between climatic variables, groundwater resource state and surface flows.

Cumulative effects may manifest themselves as lowered stream flow, lowered groundwater levels, higher pumping costs and saline intrusion at the coast. Maintenance of groundwater pressures above a prescribed level allows maintenance of both groundwater levels and stream flows and also reduces the potential for saline intrusion.

2.3 Cumulative effects – can they be measured?

The characteristics of cumulative effects mean that they are difficult to measure against the background ‘noise’ of variable groundwater levels caused by infiltration of rainfall, barometric pressure change, and localised pumping.

A pertinent and topical analogy for the relationship between direct and cumulative effects is the relationship between commuter traffic and the general increase in car use over time in a typical city. The general year-on-year increase in traffic is a gradual cumulative effect and is hard to actually measure precisely over the noise of the short-term effects caused by traffic interaction. Temporary effects such as frustrating traffic jams and grid-lock are easy to measure (direct interference effects) and seem to worsen with time.

Field-verified Hunt algorithms have been used to simulate large-scale stream depletion effects (e.g. Thorley 2006), whilst modelling by Williams *et al.* (2006) and by Bidwell (Appendix A) show how effects lag in time from the abstraction causing them.

2.4 Cumulative effects – can they be modelled?

Cumulative effects are difficult to distinguish from local interference effects by direct measurement. This is because each individual effect may be small and variably lagged behind the causative event so they are ‘lost’ among the larger and more rapid responses to local changes such as stream depletion, or well interference. Therefore, direct measurement of cumulative effects relating to a single, or group of abstractions, may not be possible; such effects, however, can be modelled.

The spatial distribution of effects and the relationships between localised interference effects and cumulative effects have been investigated by recent analytical modelling. This has shown that even within a radius of 3 km of an abstraction bore, cumulative effects may be comparable to or greater than localised effects. Cumulative effects reduce groundwater levels in summer, at times most critical to the spring-fed streams, but also in winter. Analytical modelling has illustrated the relationship

---

between cumulative drawdown effects of abstractions with distance from a well. Indications are that up to 50% of drawdown effects in a monitoring well may develop as a result of abstractions from wells more than 3 km distant.

> We can model cumulative effects now but we anticipate that the accuracy of our models will improve with additional data (water use in particular).

Prediction of cumulative effects relies on variables that are inherently uncertain, such as estimation of rainfall recharge. Therefore, whilst cumulative effects can and should be modelled, we are not yet in a position to verify the recommended groundwater management method without data for real water use and comprehensive surface flow measurements. The quantum of calculated rainfall recharge has been field-verified against monitored data from groups of lysimeters in the Canterbury Plains.

Modelling cumulative effects has been based on our existing and steadily improving monitoring data. As more precise and frequent assessments of recharge, water takes, groundwater levels and flows in streams become available, precise modelling of cumulative effects will be possible. However, measurement of these variables is expensive and raises significant technical and modelling issues (e.g. measuring losses from gravel-bedded rivers; variable evapotranspiration related to short-term variation in land use, ground cover and soils).

2.5 Cumulative effects in the RSGAZ

A technical report (Environment Canterbury 2007a) on the adverse cumulative effects on flows in spring-fed streams and groundwater levels in this zone was produced in 2007 (located in Appendix C). The effects of lowered groundwater levels on spring-fed streams and Te Waihora is described in Williams (2008).

> Abstraction of groundwater in concert with changes in climate is continuing to cause discharge to Te Waihora to decline below minimum flows for extended periods.

3 What is adaptive management?

The term 'Adaptive management' as originally defined by Holling (1978) is used for the purposes of this report as: "*a structured, iterative process of decision-making in the face of uncertainty, using the best prediction method, with an aim of reducing uncertainty over time via system monitoring, in order to obtain a sustainable outcome*".

Comprehensive adaptive management means that all consented users of water can expect changes in their seasonal entitlement to a proportion of their annual volume. The entitlement would be based on an established and reliable means of assessing the state of the resource and any change in seasonal climate during the irrigation period. Adaptive management is expected to be implemented along with management of localised stream depletion effects; the two are complementary, not exclusive.

The advantage of adaptive management is that it does not require a base line dataset prior to implementation; the adaptation process allows progression towards stated environmental outcomes. The way the entitlement is calculated can change as other factors change, such as climate and the intensity of use (Figure 3-1).

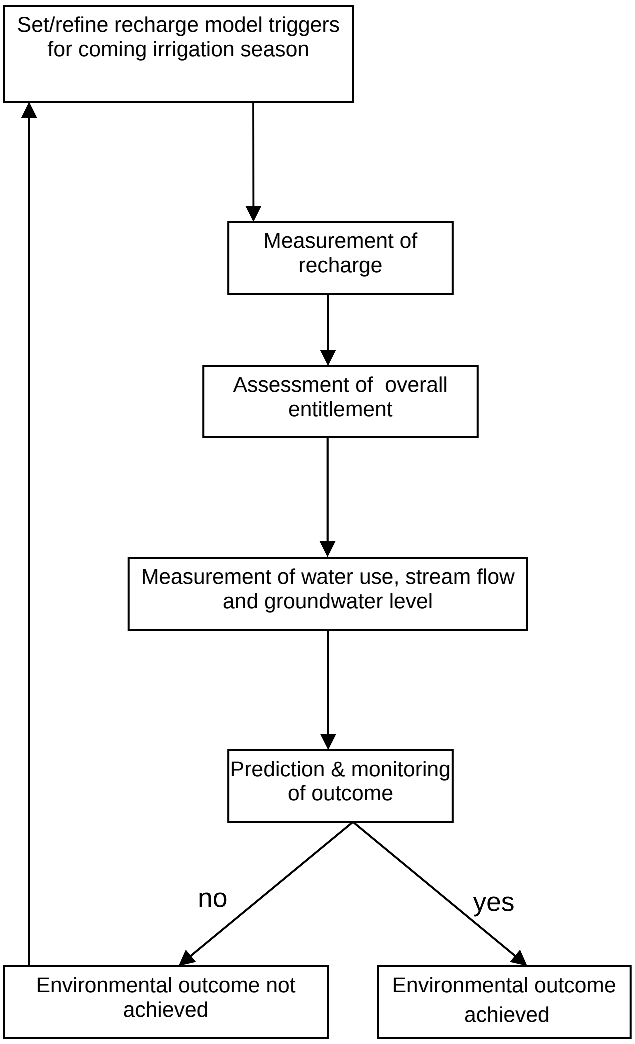

Figure 3-1: Schematic representation of an adaptive management process

In the RSGAZ, adaptive management is required to address observed cumulative effects resulting from all abstractions. In this report, the management method described is based on estimated recharge combined with an Eigen modelling technique to predict discharge outcomes which may then be fed back to fine-tune or 'adapt' the method (Figure 3-1).

In Figure 3-1, the adaptive part of the method is represented by the first step: "*Set/refine recharge model triggers for coming irrigation season*". All other steps simply vary entitlements according to the calculated recharge.

Nationally (MAF undated) and internationally (e.g. Brodie *et al*. 2007; Seward *et al*. 2006), adaptive management of water resources is seen as the most appropriate method to manage the adverse or unacceptable environmental effects of abstraction and use. Some workers use the term: "*learning by doing*" to describe adaptive management, where much is learnt about the resilience of the resource by managing and monitoring the results of that management. In everyday life it would simply be called 'common sense', the difficulty is to establish and agree on a method of implementation.

This method of adaptive management can be implemented now with changes made as we progress to agreed outcomes.

3.1 Why is adaptive management necessary?

The Resource Management Act 1991(s6 and s30c)[11] requires that surface water flows are protected from continuing unacceptable adverse effects of abstraction. For this reason, 'minimum flows', 'low flows' or 'environmental flows' have been set in regional plans across the country, as per s30e of the RMA.

In the context of this report, the management outcome is the maintenance of environmental flows in the spring-fed streams flowing into Te Waihora (Lake Ellesmere) but in reality this would be discussed more thoroughly and agreed with the affected community.

If these flows fall below agreed levels during the summer months it would trigger reductions to the abstractions. In recent times minimum stream flows have been used to manage groundwater abstractions that have immediate and localised effects. These are referred to in the PNRRPV1 as hydraulically connected takes. These environmental or minimum flows are determined collaboratively with the community. There are no 'bottom line' constraints in the RMA and the related instrument such as the NES is not yet operative.

What has become increasingly evident in the last decade, in line with the work of Theis (1940), is that all abstractions, over long time periods, have an effect on groundwater discharge (e.g. stream flows), regardless of their distance from the waterway.

Modelling (see Appendix A) demonstrates that all abstractions, even those distant from waterways, and those taking from deep strata, will have a small, diffuse, time-lagged effect on spring flows. In total these may be substantial.

Climate variability is marked in Canterbury and contributes to variability in the availability of, and seasonal demand for, irrigation water. Fortunately, the rate of change of climate variability is small in comparison to Regional Plan length (10 years). Currently, groundwater allocation zone volumes are based on rainfall and other recharge sources and are assessed on the basis of average values. Consented allocation for irrigation (WQN9 seasonal volume) is related to the 80 percentile of demand

---

[11] s6: *"The preservation of the natural character of the coastal environment (including the coastal marine area), wetlands, and lakes and rivers and their margins, and the protection of them from inappropriate subdivision, use, and development"*; s30c(iii)*: The maintenance of the quantity of water in water bodies and coastal water; and* s30c(iii)a (Reprint as at 28 March 2007)*: the maintenance and enhancement of ecosystems in water bodies and coastal water.*

for a given location and soil type. Stream ecosystems have to cope with climate variability. In a very dry year, or a succession of dry years, recharge to groundwater may be insufficient to sustain groundwater levels and, therefore, spring-fed surface water flows. Abstraction worsens this situation by capturing groundwater that would otherwise have discharged via the springs which feed the streams. Lower stream flows are experienced more frequently and for longer periods.

Adaptive management of groundwater and surface water use is required to moderate the combined effects of increasing abstraction and variable climate.

We have no control over current climatic conditions and it remains to be shown whether efforts to reduce the adverse effects of climate change will be successful. We do have control over the magnitude of abstraction of groundwater through variable consent conditions relating to a management mechanism that is itself adaptive.

The environmental outcome sought through a management strategy should be to arrest the inter-seasonal decline in groundwater levels with accompanying maintenance of surface waters to specified and agreed minimum environmental flows[12]. Environmental flows are increasingly being set using a combination of ecological, social, recreational, and economic criteria. Indicators of success of a sustainable management mechanism for all water takes are set out in Table WQN5 in the PNRRPV1 (page 5-198), but they are only qualitative. Policy WQN9 states: "*Where water level or artesian water pressure records of 20 years or longer show a groundwater abstraction-induced continuing decline, this will require management in order to prevent further decline.*" [13]

Several years ago, Aitchison-Earl *et al.* (2004), recognised that groundwater abstraction in the Central Plains was having an unacceptable effect, with allocation still less than 50% of the average land surface recharge. As a result, the allocation limit was set to 50% of the land surface recharge.

The relationship between robustly justified key environmental indicators with groundwater levels and discharges from the aquifer system needs to be explored further and this can be achieved within an adaptive management method.

3.2 How will adaptive management work?

Adaptive management can accommodate a broad range of initiatives tailored to local environmental, hydrological and climatic conditions - there is no single optimal adaptive management method but a family of methods. In an ideal world, an adaptive management method should be reviewed whenever new knowledge indicates that improvement in outcomes or predictions may be achievable – such a review might occur annually, or be less frequent.

In much of the central Canterbury region groundwater levels are declining long term. The trend is most marked over the last five to ten years, especially during the summer season (ECan 2007b). This decline in groundwater levels in association with observed declines in surface water flows prompted the RPLS.

Eigen-modelling (Williams 2006) has demonstrated that discrete abstraction and climate signatures are recognisable within the groundwater monitoring record. In addition, Williams and Aitchison-Earl (2006) presented monitoring data showing groundwater levels and pressures to be the primary driver of stream flows in spring-fed streams. Hydrogeological analysis, such as Eigen modelling, is now able to predict the environmental effects of groundwater abstraction, both in terms of groundwater levels and surface flows.

Environment Canterbury consent data indicate that the RSGAZ has an effective allocation that is currently at 114% of the allocation limit, with a further 2% in process as at October 2008. As a result,

---

[12] Policy WQN3(2)(d): limit all groundwater abstractions which cumulatively reduce groundwater levels and thereby cause or are likely to cause a significant increase in the frequency, duration or severity of breaches of a minimum flow, or adversely affect the hydrology of wetlands.

[13] As technical experts in the management of groundwater, we believe that twenty years is probably too long to wait to recognise abstraction-related decline when groundwater – surface water interactions are the lifeline of the lowland streams.

allocation of additional consented groundwater in this zone is, or is expected to be, constrained by policies within the Natural Resources Regional Plan (PNRRPV1). Sustainable and equitable allocation and use of groundwater requires a 3rd order approach[14] whereby allocation limits are tied to specific environmental outcomes accepted by the community. The objective is to maintain groundwater levels and hence lowland stream flows consistent with healthy stream eco-systems (Policy WQN3 in PNRRPV1).

In 2006, Variation 4 of the PNRRP proposed that interim allocation limits be specified explicitly. That variation and chapter 5 of the PNRRPV1 have yet to pass through the hearing process.

The current allocation limit may be sustainable during moderate to wet years when land-surface recharge is sufficient to limit the effects of abstractions on groundwater levels. It can be argued for the RSGAZ, that if the limit is set at an appropriate level it should be sufficient in dry years, with the corollary that there may be a 'surplus' in wet years. Without an allocation limit, groundwater levels are declining as storage is reduced and natural discharge to the environment via the lowland spring-fed streams is decreasing (Environment Canterbury 2007a, refer to Appendix C). It can also be argued that continued granting of consents over the allocation limit such, as happened in the RSGAZ in May 2008 (Environment Canterbury 2008), will only exacerbate the already unacceptable environmental effects.

Our modelling shows that in some years, allocation needs to be reduced for all or part of an irrigation season in order that regional-scale adverse environmental effects are avoided.

Issues to consider include:

- Should irrigation be locally constrained before or during an irrigation season, in order that adverse environmental effects are minimized, as anticipated in Schedule WQN3 of PNRRPV1 (This proposal would deny users access to water at the time when they may most need it);
- Should annual fixed allocation limits (interim limits) be set so low that regional-scale environmental effects are avoided even in dry years (This proposal would deny some users the opportunity to use water at any time and would almost certainly require reduction of entitlements under existing consents);
- Managers cannot constrain consents until they are formally reviewed, and reviews cannot be initiated until an established allocation system is shown to be problematic;
- What are the expected effects of climate change? (Mullen (2006) in a NIWA report has predicted that 1 in 20 year droughts are likely to occur perhaps as often as 1 in 5 years, according to the Hadley Centre[15] model).

Climate change may reduce groundwater recharge to values not hitherto seen, and an adaptive management mechanism can take this stress in its stride.

For an adaptive management method to be effective within the framework of the PNRRPV1 and the proposed RPLS it needs to be:

- based on precise data that are easy to measure;
- robust and straightforward, in order that it can be understood; and,
- produce technically correct verifiable results straightforward enough to be communicated to non-technical user groups.

---

[14] 1st, 2nd and 3rd order approaches to defining allocation limits relate to an increasing degree of certainty, a topic explained fully in Aitchison-Earl *et al.* (2004).

[15] The Hadley Centre model is one of a number of climate change models used by the Intergovernmental Panel on Climate Change (IPCC). For example, see http://www.niwa.cri.nz/ncc/clivar/scenarios.

The method recommended herein can be adapted iteratively to progress towards or produce a desired environmental result. It is anticipated for the purposes of this report that the desired result from the viewpoint of environmental managers, users and the community at large is moving towards:

- reduced frequency and duration of low flows and extent of dry sections in spring-fed streams (Policy WQN3(2)(d));
- maintenance of groundwater levels to an extent that the ability of existing users to access groundwater is not adversely affected (PNRRPV1 Objective WQN4(2) states: "*Allocation regimes are established that identify at least one allocation block within which the reliability of supply of water does not become a factor that limits the long-term economic viability of uses that are dependent on that block of water*"). [16]

Ideally, a management tool should reduce the frequency and duration of low flows. Realistically, the target should be to agree on a maximum number of instances of flows falling below the 'minimum' flow. The alternative policy is that no groundwater abstraction could occur when storage drops below a trigger level, as per the Otago and other similar methods.

3.3 Groundwater – surface water interaction

Whilst the initial driving force behind the RPLS was the need for protection of flows in spring-fed streams, a major stressor leading to adverse environmental effects is considered to be climate, exacerbated by groundwater abstraction (Environment Canterbury 2007a, see Appendix C). Surface water and groundwater are often (as in Canterbury) connected by leaky river beds, i.e. they are essentially the same resource (Theis 1940) though reacting at very different time-scales. River flows and levels change quickly and groundwater slowly. Managing one induces changes in the other so managing both as a single resource is much more complex. The next section illustrates this complementary relationship.

In the RSGAZ, surface water becomes groundwater, and vice-versa. Flow from the Selwyn River seeps into the ground in the upper plains, flows underground, and re-appears as spring discharge near Lake Ellesmere (Environment Canterbury 2006; McKerchar and Schmidt 2007; Rupp *et al*. 2008). These reports and peer-reviewed research papers present results of flow gaugings that indicate the volume of flow lost by the Selwyn River is approximately equal to that re-appearing near Lake Ellesmere. Groundwater abstraction intercepts a significant proportion of this volume, causing the outflows in the lower plains to be less than the inflows. It is for this reason that the flow lost from the Selwyn River is not included in the groundwater allocation block recharge calculations and not included in the volume available for allocation. Also not included in the allocation is the seepage from the major alpine rivers such as the Rakaia and Waimakariri. The decision to exclude that recharge contribution is consistent with the approach to determining a sustainable yield limit proposed in the Canterbury Strategic Water Study (CSWS 2002) which recognised that the alpine rivers provide steady base flow to the system. In addition, international experience shows that it is unwise to allocate a large proportion of the recharge, from any source, if sustainable management of the discharge from the resource is intended. In this respect, the prescient paper by Theis (1940) is pertinent.

Aitchison-Earl *et al*. (2004), when discussing allocation limits in Canterbury, reviewed the CSWS recommendations on the proportion of recharge that could be allocated in the area between the Rakaia and Waimakariri rivers (the Selwyn zone in the CSWS). The CSWS study suggested that allocating an additional 30% of dryland surface recharge above the then current level of abstraction might be sustainable in terms of effects on spring-fed stream flow. That proposition was rejected on the basis that it would result in unacceptable additional impacts on stream flows which were already under stress. Instead, the authors noted that the "*current actual take in the area was 46% of average land-surface recharge and proposed that further allocation should be not exceed the 50% level until additional work was undertaken.*" This was the basis for the interim allocation limit adopted in the PNRRPV1.

---

[16] Policy WQN14(7) provides guidance, unless an alternative catchment specific approach is more appropriate, for the size of the A allocation block to be set so that all takes from the block have a level of reliability that will provide, on average the full seasonal allocation in eight years out of ten and 60% or more of the full seasonal allocation in 19 years out of 20.

In the RSGAZ, the amount of hydraulically-connected groundwater, and surface water abstracted from the Selwyn River and other waterways such as Harts Creek and Irwell River is small compared to the magnitude of groundwater taken, but this abstracted surface water does have an immediate effect on flow.

Currently there is no ‘cap’ to the consented volumes removed from these streams (the surface water equivalent of an ‘annual volume’), only a maximum rate of abstraction, so the volumes actually used can only be estimated. Estimates of surface water use indicate that it represents less than 5% of the total water abstraction from the RSGAZ. Surface water abstractions are, therefore, not included in this adaptive management mechanism because the amount and effects are well enough understood and are able to be adequately managed under current and proposed plans and rules.

> In the longer term full integration of surface and groundwater allocation may be a worthwhile goal.

In any event, the environmental effects of surface water abstractions are already managed: abstraction ceases when the minimum flow is breached.

Adaptive management of the resource could at a later stage include complementary management of surface water in such a way that volumes of surface water abstracted are measured and included in the total water budget.

4 Data required for effective adaptive management of groundwater

We have most of the data needed to implement the recommended adaptive management method although some of the data are patchy and have varied lengths of record. Validation and continuous operation of the method require robust water-use data.

Current status of RSGAZ data sets:

- Monthly monitoring of groundwater levels in over 20 wells some going back to the 1950s;
- Continuous monitoring of 4 multi-level piezometer wells;
- Monthly monitoring of spring-fed stream flows;
- Continuous monitoring of Selwyn River at Coes Ford, and Harts Creek at Timberyard Point Road.

Data required to satisfy the demands of the recharge-based model include:

- time-series data on rainfall and evapotranspiration; and
- spatial distribution of soil type, thickness, and profile available water within the allocation zone.

Three data sets are required to verify and model the environmental effects predicted by the recharge-based method:

- groundwater level monitoring data;
- surface water flow monitoring data; and
- water use data.

All these data, other than the water use data are already being collected and analysed.

4.1 Data necessary for adaptive management

The most reliable data at hand are groundwater levels, surface flows, rainfall and evapotranspiration data. Derived from the rainfall data are estimates of rainfall recharge for the allocation zone as a whole, having made allowance for spatial and temporal variation in evapotranspiration and soil type. Rainfall and evapotranspiration as gridded data are supplied by NIWA. We have used these data to estimate a monthly series of rainfall recharge for the entire allocation zone, using methods described in Scott (2004c) and Davoren and Scott (2005). These calculated data compare favourably with actual recharge volumes measured by a sparse network of lysimeters.

It is generally accepted that the major driver of the groundwater system is the long-term variability in rainfall and we present in this section a number of plots showing the correlation. However, abstraction is thought to be a significant and increasing stressor on the system, though without precise metered water use data[17] the quantum is uncertain. Flows for many of the lowland waterways have been monitored over the last ten years but at widely different intervals, which makes comparison and analysis problematic.

Water levels in rivers such as the Selwyn River, Harts Creek and Doyleston Drain are monitored every 15 minutes which allows calculation of continuous river flow. Many other streams are gauged regularly so that a correlation can be drawn between these gaugings (referred to as secondary sites), groundwater levels and the continuously monitored streams. A synthesised record can be derived from this correlation at the secondary sites.

---

[17] Pumping power records have been used to validate demand calculated from EVT and effective rainfall (Sanders 1997).

The choice of an indicator site for surface water is dependent upon a number of variables:

- length of monitoring record;
- magnitude of correction required to naturalise the flow for up-stream abstractions;
- response to groundwater levels both locally and regionally.

There is no ideal site in the RSGAZ, but Harts Creek measured at Timberyard Point Road is the best available. Harts Creek shows good relationships with groundwater (Williams and Aitchison-Earl 2006), but other streams, such as the Irwell River, exhibit a greater and earlier response to low and declining groundwater levels, and the Selwyn River record is a complex of winter quick flow with base flow.

4.2 Use of a data smoothing function

Stream flow and groundwater level data collected at regular intervals sometimes benefit from use of a smoothing function to reduce short-term variability before they can be usefully plotted against each other. We have found that for regularly-monitored groundwater level data, an exponentially weighted moving average (EWMA) is a useful method to weight recent data differently from older data by using the smoothing function alpha (α). Further details of this method are included in Appendix B. The value of the smoothing function used was determined by optimizing the correlation coefficient for the two variables. The EWMA method was superior to simple three-year moving averages in reducing scatter.

The magnitude of alpha is related to the time-dependent behaviour of the variable i.e. how strongly the current value correlates with previous values. For example, although rainfall recharge is not itself directly affected by antecedent values, the soil moisture state determines how much of the subsequent rainfall will infiltrate into the groundwater. Similarly the storage state of an aquifer, effectively the driving force for groundwater levels and surface flows, is highly dependent upon the previous storage state and recent recharge history.

4.3 Relationship between the water resource and climate

Figure 4-1 illustrates the relationship between recharge to the aquifer system, and the flow in Harts Creek.

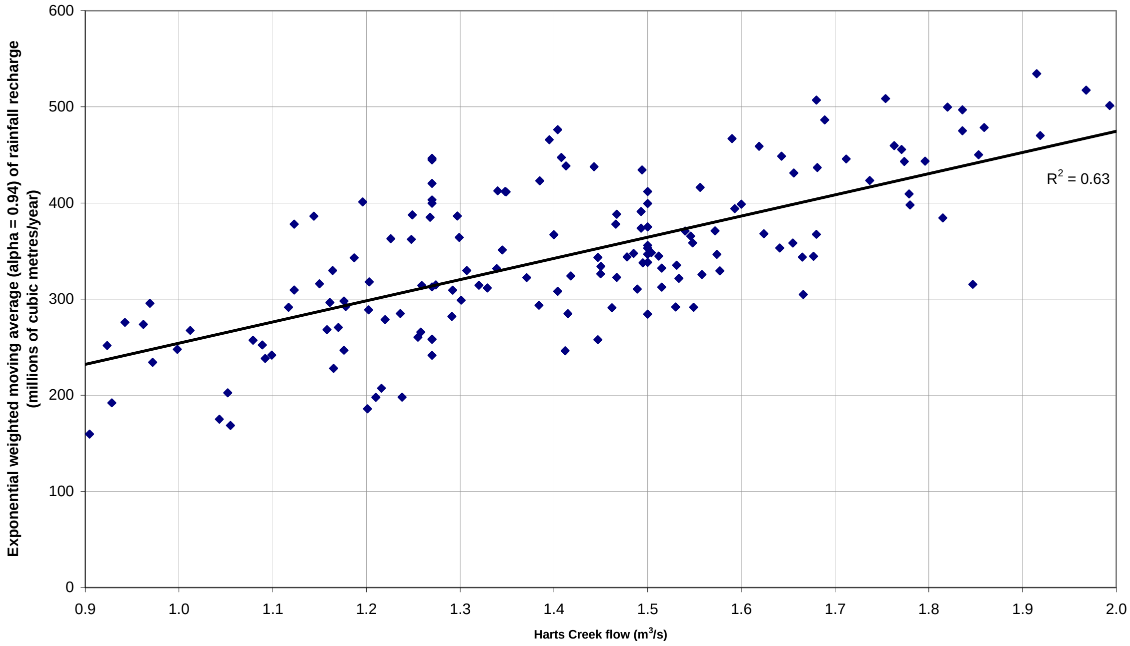

Figure 4-1: Plot of EWMA of rainfall recharge versus Harts Creek flow

Harts Creek is the preferred index of lowland stream discharge from the system because it has a regularly monitored monthly record; is relatively unaffected by surface takes up-stream; and its flows do not fall to zero in summer.

The relationship shown in Figure 4-1 is the correlation between the exponentially weighted moving average (EWMA) values of recharge over the entire zone and regular spot measurements of surface flow, showing that outputs from the system as measured, using just one flow site, are related to inputs. The scatter is not surprising given the variable lags of drainage from recharge across the zone. In addition, there is a relationship between the recharge and spot measurements of groundwater level, such as at the monitoring bore L36/0142 at the head of Harts Creek (Figure 4-2).

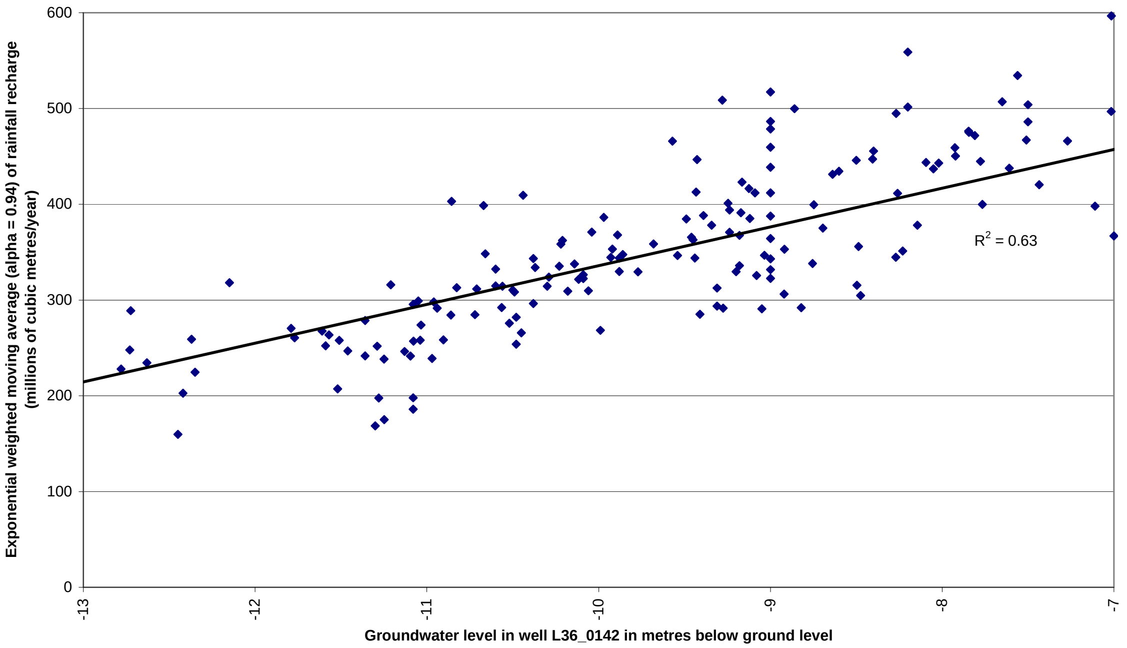

Figure 4-2: Plot of EWMA of rainfall recharge versus groundwater levels in bore L36/0142

Together, Figures 4-1 and 4-2 allow the inference that increased groundwater levels (pressures) and spring-fed stream flows correlate with increased recharge.

Figure 4-3 presents the time-series of estimated rainfall and rainfall recharge for the entire RSGAZ as determined from NIWA climate data; it indicates that increased rainfall is the driver for this increased rainfall recharge. Figure 4-3, Figure 4-4 and Figure 5-1 all show that less than 50% of rainfall contributes to recharge.

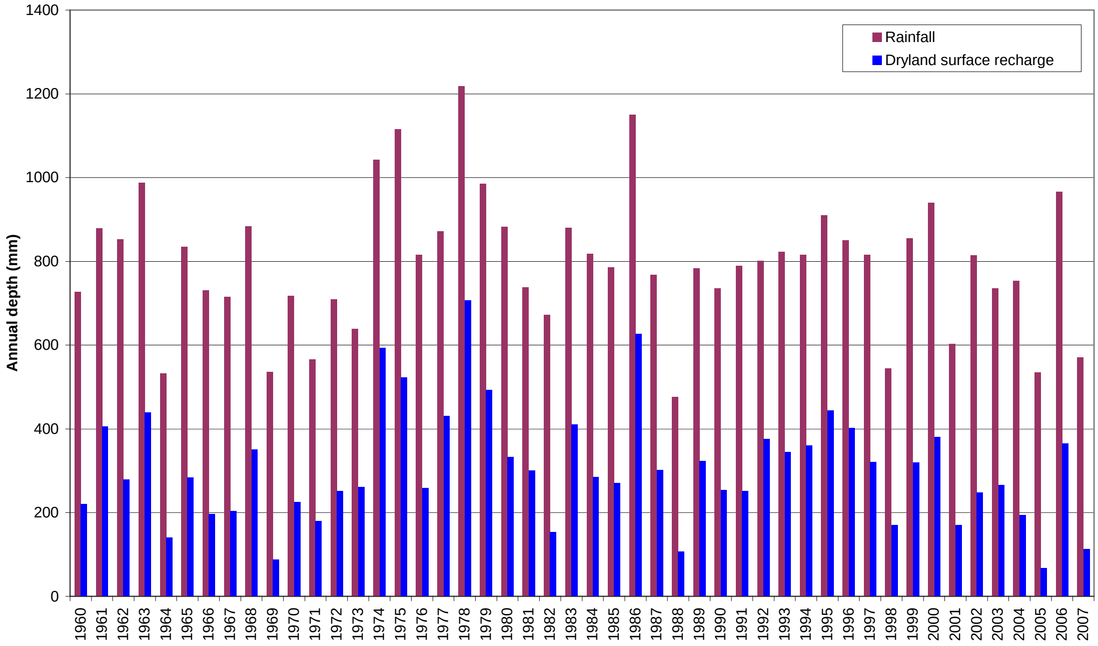

Figure 4-3: Time series plot of rainfall and rainfall recharge in the RSGAZ as an annual depth. Long-term mean rainfall recharge is equivalent to an annual volume of 397 million cubic metres per annum

For the purposes of this report, the recharge calculation and allocation years start on July 1st and end at the end of June in the subsequent calendar year.

Recharge-based adaptive management method (refer also to Table 1):

Pros: Designed to achieve an environmental outcome. Allows managed response to actual outcome by alteration of the trigger levels that activate and control the relationship between resource state and consented takes.

Cons: Requires water use data. Aquifer response will be slow, extending over several years

Our recommended recharge-based adaptive management method described in Section 5 is favoured over all others based on groundwater level triggers alone. We accept that groundwater levels and surface flows provide a reliable estimate of resource state, but local levels and pressures are distorted by abstraction. We recognise uncertainties in our estimation of rainfall recharge, though field-verification indicates that the uncertainties can be as low as 5%. We do not make allowance for extra recharge from irrigation or leakage from races because these are difficult to measure, are seasonal in nature and some will decrease if distribution efficiency is increased and races phased out[18].

We are confident, on the basis of recharge-based Eigen model simulation of observed groundwater levels, that a supply or recharge-based method of assessing resource state is less prone to observation error than the alternatives.

Using recharge data for the RSGAZ up to and including September 2008, 50% of modelled rainfall recharge is 198.5 million cubic metres per year, based on the 1960-2008 rainfall recharge figures

---

[18] In this report, values of recharge and allocation limits do not match those used in the PNRRPV4 because more recent data are used. The values in this report should be treated as indicative numbers, used to illustrate process, not actual or revised volumes.

(Figure 4-3)[19]. The long-term mean of rainfall recharge is approximately equivalent to a depth of 300 mm per year over the entire RSGAZ (area: 128 547 ha). This compares with the long term mean annual rainfall over the same zone of about 800 mm. The current allocation limit set by ECan is half of the long-term mean land surface recharge (rainfall plus irrigation) which is less than the effective allocation (consented use), currently 223.9 million cubic metres, expected to rise to 244.45 million cubic metres now that an additional 69 applications have been granted. The consent review initiated in June 2007 will impose Schedule WQN9, or equivalent, annual volumes but it is not clear if the effective allocation for RSGAZ will decline as a result. Existing entitlements will then be expected to meet irrigation demand in four years out of five (80% ile). There is also the possibility that more water could be allocated under an adaptive management regime, providing that restrictions are applied when the resource state is poor.

Figure 4-4 presents the expected correlation between rainfall and estimated rainfall recharge; expected because rainfall is the dominant contributor to the calculation of recharge. Figure 4-4 compares favourably with work undertaken by Thorpe and Scott (1999, Figure 3).

The data in Figures 4-3 and 4-4 indicate that rainfall is the major contributor to rainfall recharge. Enhanced rainfall recharge as a result of irrigation is not included in these estimates of calculated recharge. Irrigation return water and leakage from irrigation structures increase the total recharge. Once reliable water use data are at hand, inclusion of irrigation return water to the recharge may be made.

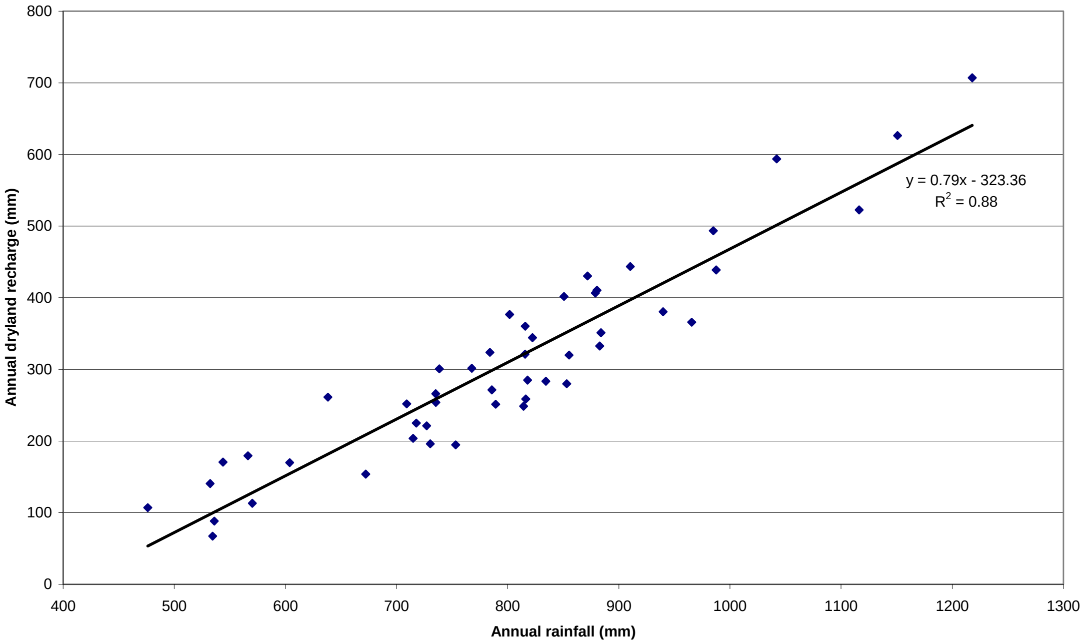

Figure 4-4: Relationship between annual rainfall and rainfall recharge for the Rakaia-Selwyn Groundwater Allocation Zone

The groundwater, surface water and recharge data show that there is a generally consistent relationship between these variables and that there is considerable dispersion of the data about a linear relationship (Figures 4-1 & 4-2). It is these relationships that underpin the rationale for an adaptive management tool.

---

[19] Environment Canterbury used 50% of rainfall recharge. The proposed NES (MfE 2008) uses a less conservative calculation of recharge, 35% of both rainfall and river recharge.

5 The recommended management method

5.1 Introduction

This section of the report is long and it may be useful to introduce its structure and content. The section begins with a description of the preferred method of subdividing the consented allocation into entitlements. This is followed by an introduction to a recharge-based model necessary for modifying the entitlement relative to the antecedent conditions. Then follows an assessment on the reliability of access to groundwater, based on the recharge method. We then show how, with the use of eigen modelling, we can predict discharge from the aquifer system and how those predictions inform the adaptive management process. Finally, we discuss various issues related to the method.

5.2 The groundwater management method

The recharge-based management method described in this section is based on established theoretical and monitored relationships between total aquifer discharge and recharge. Considerable analytical effort underpins this proposal which is similar to a method briefly described by Bright (2006). Other methods have been studied and found wanting for various reasons (Chapter 1).

The recharge-based method proposes entitlements being divided into two parts: a base entitlement, and an adaptive one. For each user, the base entitlement would be a fixed percentage of the consented annual allocation volume. The adaptive entitlement is assessed in terms of the recent recharge history. This base entitlement could be adjusted up or down but would be guaranteed, in that it would only be reviewed only if:

- there was significant climate variability that made this entitlement too generous or too restrictive in terms of its effects;
- continued consented allocation of groundwater resources, in excess of the PNRRPV4 allocation limit, caused continued degradation of spring-fed stream and other environmental indicators such as groundwater levels;
- monitoring and investigation demonstrated that an increase in the base entitlement would not compromise desired environmental outcomes.

Initially, the ratio of the base to adaptive entitlements for the entire zone has been set at 50:50 because we do not anticipate a need to reduce the base entitlement to below half the current allocation limit.

The recharge value that triggers onset of restrictions has initially been set as the long-term mean of annual rainfall recharge.

Decisions on the ratio of the two entitlements and the recharge level triggering restrictions can be reviewed if they are found to be too conservative, or not conservative enough, making the method adaptive. The challenge will be to get the adaptive portion of the entitlement ‘right’, leading to attainment of the environmental outcome. In addition, the timing of an assessment of the entitlement has been set as 1st July.

The timing and basis for this assessment of entitlement partially meets the expectations of users for a decision as early as possible, and our need for minimising uncertainty in the entitlement assessment.

The magnitude of the adaptive part of the entitlement would be determined after assessment of the EWMA quantum of recharge prior to each irrigation season. The recharge-based system is flexible, based on monitoring of flow or groundwater levels, allowing ECan, with potential for community input, to change the proportion of the base to adaptive entitlements, and the thresholds that trigger restriction of the adaptive portion. In this way, the method is truly adaptive. It has in-built resilience and can respond to changes in recharge such as that induced by climate change, or by large surface water-sourced irrigation projects.

These triggers, and the timing of assessment may be changed if they are found not to produce the desired environmental results.

Options to limit future management of water to specific types of users have not been assessed. We propose that for the management method to live up to the expectations proposed by Holling, it will be necessary to allow for changes to the adaptive rules, as well as adapting the trigger levels themselves.

In the RSGAZ, the allocation limit is already breached and further grants should be part of a ‘B’ block allocation with a lower reliability of supply managed more conservatively than for existing consent holders (See Section 6.3.2).

We are confident that implementation of a ‘B’ block can be achieved simply, using the recommended method, by changing the ratio of base to adaptive entitlement and by using different triggers and algorithms for calculating the adaptive part.

The proposed adaptive management method is dependent on knowledge of rainfall recharge. The soil moisture model described by Scott (2004c) has been used to calculate monthly rainfall recharge volumes in the zone from 1960, using climate data provided by NIWA. We now describe how these data are used to underpin the recommended method.

5.3 Recharge-based model as a prerequisite to adaptive management

Figure 5-1 presents the monthly time series of EWMA of rainfall (blue line), and the EWMA of calculated rainfall recharge (magenta line). Individual periods of drought and wet seasons are clearly distinguished on this plot. Notable climatic events are labelled.

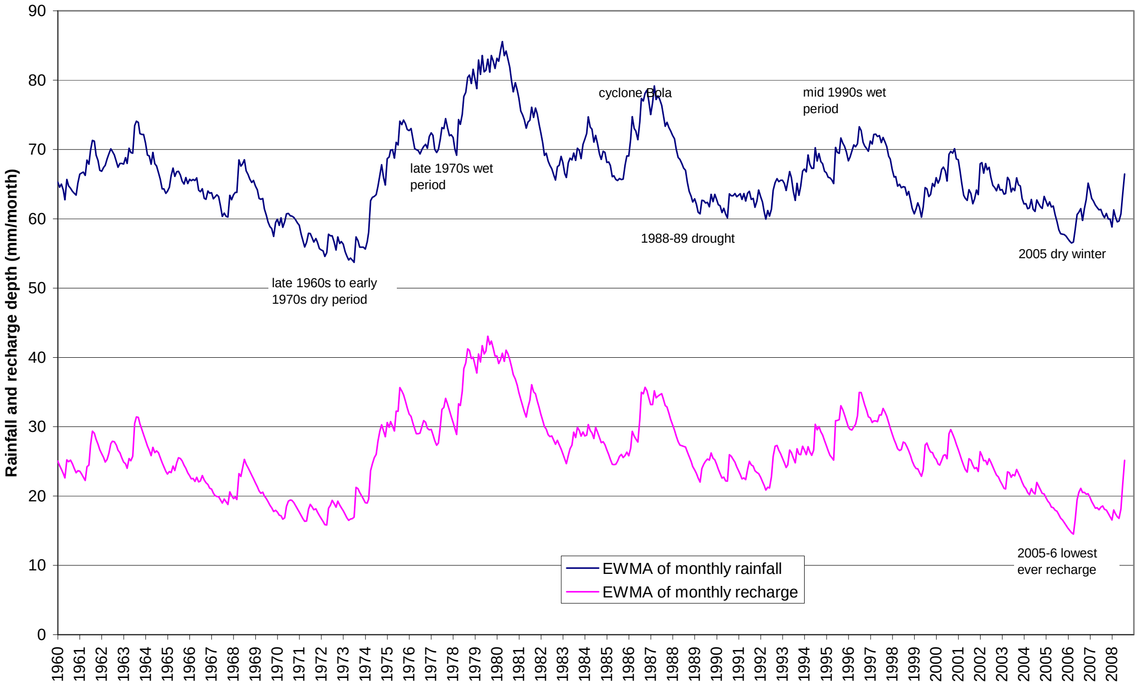

Figure 5-1: Time series plot to show relationship between EWMA of monthly rainfall and estimated rainfall recharge in millimetres per month for the RSGAZ

The EWMA smoothing process (α = 0.97) reduces noise but does not change the general shape and magnitude of the data and has been found to be more effective than rolling arithmetic means. The relatively slow rate of change of the EWMA of recharge with time (which reflects groundwater storage and the damped nature of the aquifer discharge characteristics) provides a relatively stable index of the resource state.

Calculated rainfall recharge has been proposed as the basis for management since recharge, not rainfall, is the effective input to the groundwater budget component, as demonstrated by the strong relationship between calculated rainfall recharge and groundwater levels from eigen modelling (Bidwell 2003).

Figure 5-2 shows EWMA rainfall recharge in relation to the long-term mean (dark blue) and 50% of the value (light blue) which is comparable to the zone allocation limit.

The total entitlement, determined from the fixed base entitlement and the EWMA recharge dependent 50:50 adaptive entitlement, is shown by the green line.

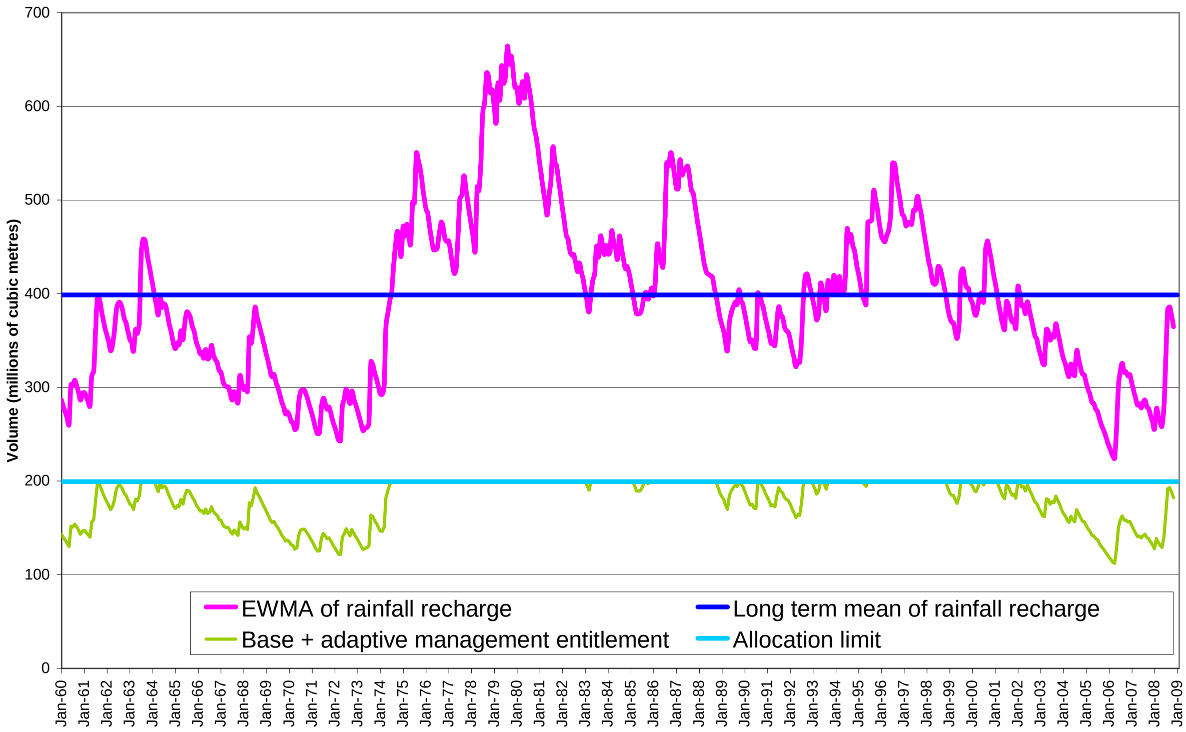

Figure 5-2: Time series plot (magenta line) of EWMA of annual rainfall recharge volume in cubic metres (alpha = 0.97) and corresponding time series of adaptive allocation (green line)

On the basis of the proposed method as long as EWMA rainfall recharge exceeds half the long-term mean[20] (197 million cubic metres), then users would be eligible for the base entitlement plus the full adaptive entitlement. The use of half the long-term mean as the trigger is also an initial decision and may have to be varied as part of the adaptive process.

Note in Figure 5-2 that over the final ten years the exponentially weighted moving average of recharge (magenta line) has been significantly less than the long-term mean (as was 1964 to 1974). The reason for using the EWMA method is that it faithfully mimics the change in storage represented by moderate to deep groundwater levels, which similarly respond slowly to recharge.

Three options are proposed, based on the exponentially weighted mean recharge calculated on 1st July each year:

- If EWMA is **above** its long-term mean (*e.g.*: 1975 to 1982 on Figure 5-2) the full base entitlement, plus a full adaptive entitlement (397 million cubic metres) will be available;

- If EWMA is **below** its long-term mean but **greater** than half its long-term mean (*e.g.*: January 1988 to January 1994 on Figure 5-2) the full base entitlement (~198 million cubic metres), and a proportion of the adaptive entitlement will be available;

- If EWMA is **less than** half its long-term mean (~198 million cubic metres) then only a base entitlement, and no resource for the adaptive entitlement, will be available. (This situation has not occurred during the period covered in Figure 5-2, although 2005-6 came close).

For the purpose of forewarning users, this assessment is ideally carried out well prior to the irrigation season. We have chosen 1st July (Figure 5-3) on the basis that earlier decisions produce too much uncertainty regarding the state of the resource for the upcoming irrigation season. We recognise that

---

[20] The long-term mean is a fixed value for a given period. The method could accommodate recalculation of that value to include long-term variation as a result of climate change or inter-decadal oscillations.

significant recharge may occur during July and August, perhaps sufficient to allow upward revision of the July decision.

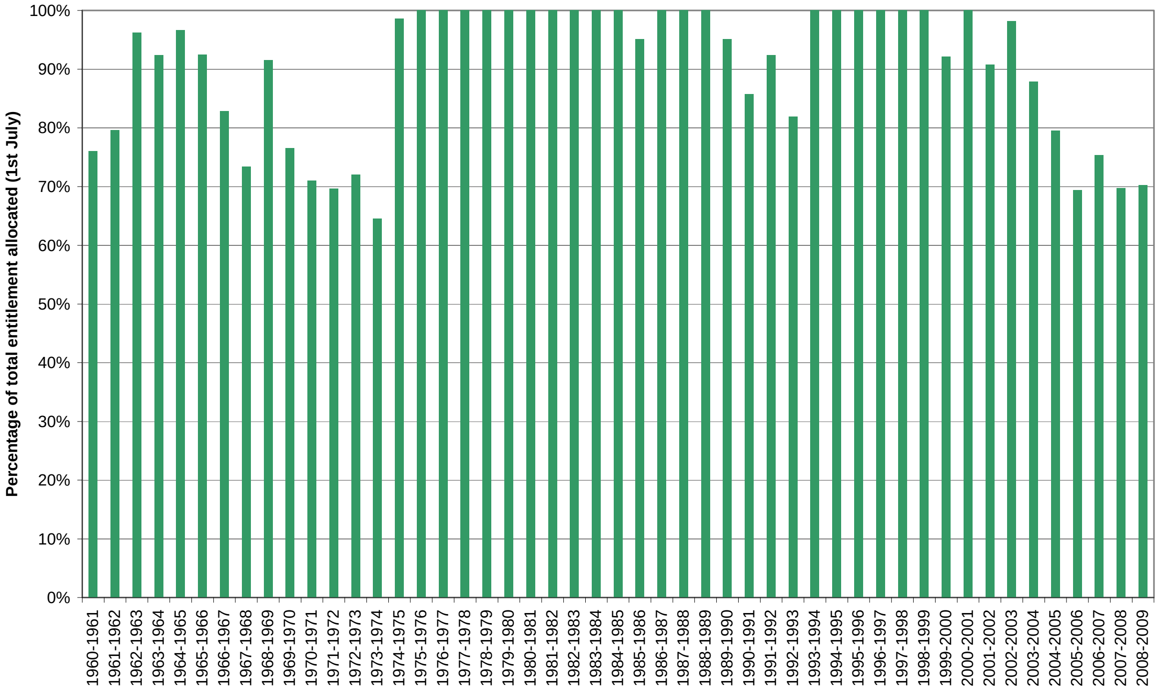

Figure 5-3: Time series plot showing magnitude of total entitlement as a percentage of presently consented allocation of groundwater for each irrigation season as determined at 1st July had the recharge-based mechanism been implemented (refer to Table 5.1)

If the EWMA of recharge is close to one of the prescribed trigger levels, then a conservative assessment of the resource state is required to ensure that adaptive allocation does not cause adverse effects. As it stands, the recharge method alone does not itself predict changes in aquifer state.

5.4 Reliability – simple recharge model

On the basis of a 1st July assessment of recharge history the proposed management method would have allowed the following degree of entitlement over the last 49 years as indicated in Figure 5-3 as a percentage of full allocation that is available for abstraction in a year:

- 100% in 20 years out of 49;
- 90% in 32 years out of 49;
- 75% in 41 years out of 49; and
- Between 60% and 75% in 8 years out of 49.

A review of the initial assessment in the subsequent months of October, and January, commonly results in some relaxation of constraints (orange and green columns in Figure 5-4) as listed in Table 5.1. This reassessment allows for recharge occurring after 1st July. In some years, restrictions might be expected to tighten if reviews were undertaken through the irrigation season (e.g. 2005-6). The quoted reliabilities for entitlement in October and January relate only to periods after that assessment, until the end of the irrigation season.

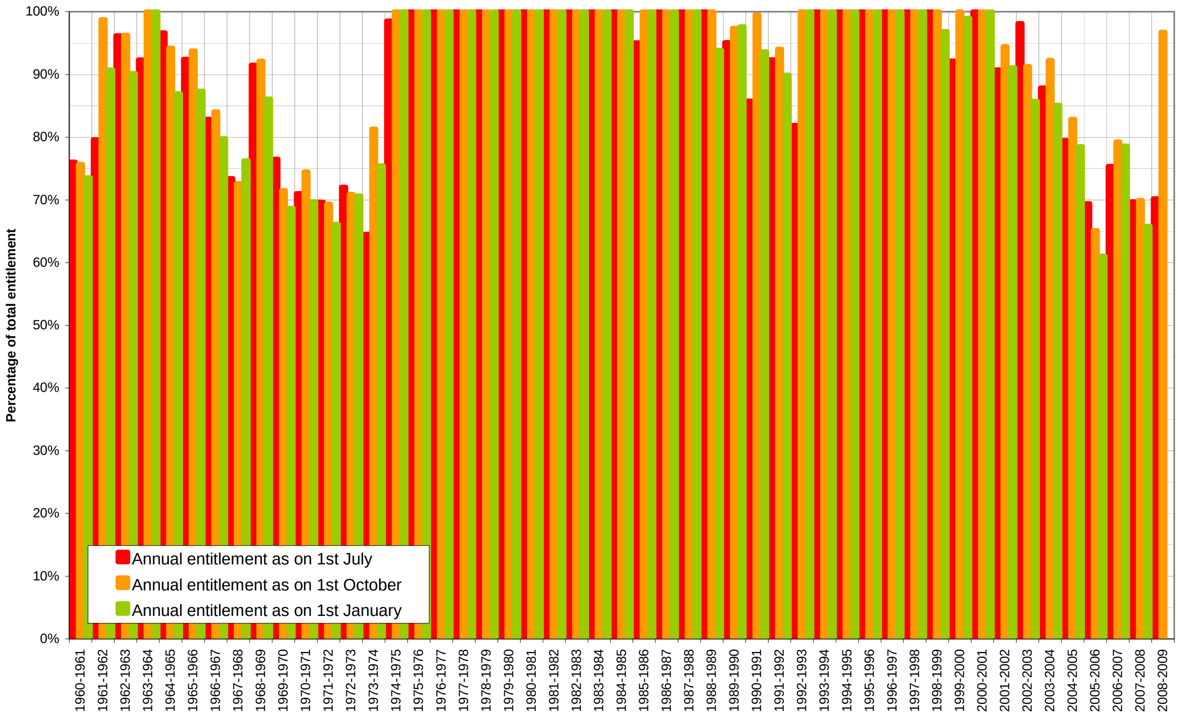

Figure 5-4: **Time series plot showing percentage of total entitlement for each irrigation year, determined at 1st July, 1st October and 1st January had the recharge-based mechanism been implemented**

Note in Table 5.1 that the reliability changes slightly as later months are used to determine the entitlement but that the degree of entitlement does not change dramatically with changes in the date of assessment.

Table 5.1 **Indicative degrees of entitlement in years out of a total of 49 years**

Degree of entitlement	July (49)	October (49)	January (48)[21]
100%	20	25	22
> 90%	32	37	31
>75%	41	42	41
<75%	8	7	7

Restrictions based on antecedent recharge will not necessarily occur at times of high demand. To explore this situation we have analysed calculated demand (refer to Appendix F for details of method) and compared this with the restrictions based on antecedent recharge (Figure 5-5).

> Were the recharge assessment to be done in October, users would have less lead time to accommodate restrictions, despite the advantage that by spring most of the annual recharge will have occurred and there would be greater certainty about the seasonal water availability.

---

[21] Assessment on January 2009 still to come.

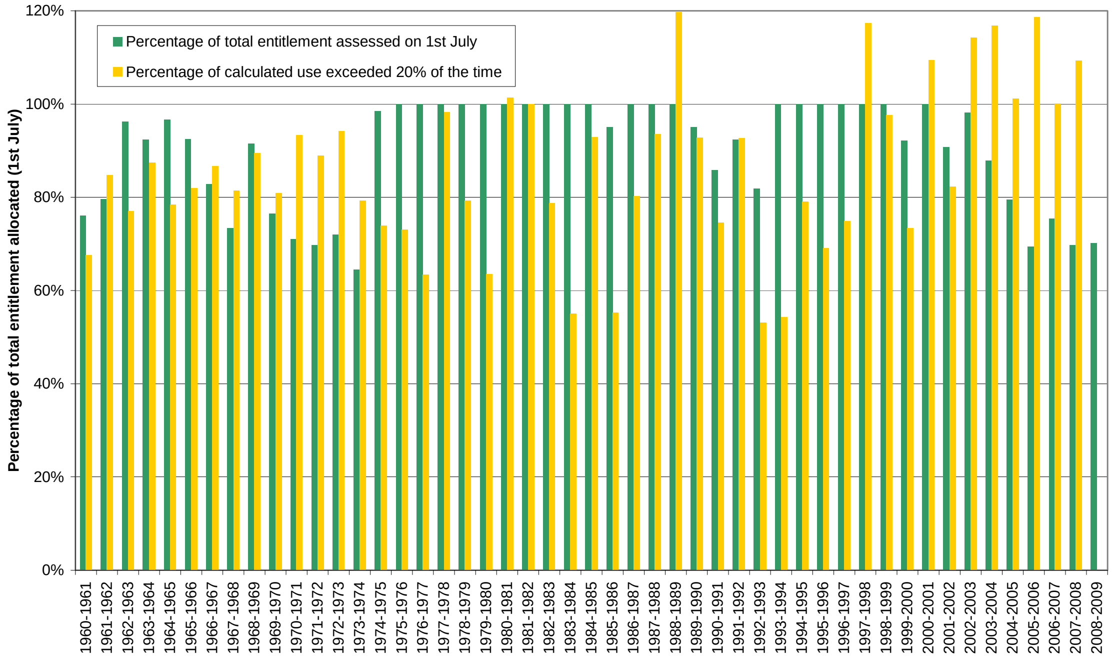

Figure 5-5 Calculated irrigation season demand expressed as a percentage of the 80 percentile plotted together with the 1st July based entitlement (as shown in Figure 5-3)

The demand for irrigation water in any particular season is not particularly influenced by the previous recharge. Hence, recharge-based limits on total entitlement will not always result in real constraints. Figure 5-5 illustrates this by presenting an irrigation demand series (yellow columns) together with the annual entitlement series, based on recharge, shown in Figure 5-3. If the entitlement percentage (green) is greater than the demand percentage (yellow), then it is likely that no practical restriction would have been experienced by users (e.g. 1990-91). However, if the demand percentage is higher than the entitlement, then real constraints would have applied (e.g. 2001-2008).

From our assessment of restrictions based on rainfall recharge it appears that use in some, but not all, high demand seasons (e.g.:1973-4, 2004-5, 2005-6, 2006-7)[22] would have been constrained to 60 to 70%. This is because, during these irrigation seasons, the entitlements would likely fall short of demand. In all but eight years, users would have been entitled to at least 75% of their total allocation, as can be seen in Figures 5-3 and 5-5. Using the data presented in Figure 5-5, a modified version of Table 5.1, is presented as Table 5.2.

Table 5.2 Indicative relationship between entitlement and calculated demand for 48 complete irrigation years

Degree of entitlement	Number of years when 1st July entitlement > demand	Number of years when 1st July entitlement is < demand
100%	16	4
90% to 99%	10	2
75% to 89%	3	6
<75%	0	7
Total	29	19

---

[22] Significantly in these four irrigation seasons, flows were amongst the lowest ever recorded. Some spring-fed streams went dry.

Comparison of the data in Tables 5.1 & 5.2 shows that in the 20 years when there are no restrictions based on recharge, then demand exceeds supply in four years. In drier conditions the proportion of years when demand exceeds entitlement increases. There has been a suggestion that when the recharge state is good, then additional entitlement (greater than 100%) could be allowed, which in part might reduce the number of years when demand is greater than entitlement. This topic is further explored in Section 5.10.

In summary, this method of varying entitlements is based solely on the recharge input. It has the potential to manage use of groundwater during an irrigation season as recharge assessments and modifications to entitlements could be made.

The proposed entitlements created by the adaptive management method indicate a good reliability of supply except in the 'drought' years of the early 1970s, 1990-93, and the recent period 2004 to 2007.

The RPLS initiative requires that adaptive management restores flows in streams and the recharge method of management just described will do this. However, in its present form, the environmental outcome from this type of management is not directly predictable and is not adaptive in the strict sense. All that can be expected is that, by reducing allocation during periods of resource stress, groundwater levels and surface flows would not decline as much as they otherwise would have.

Although the simple recharge-based management method is a workable approach for managing the groundwater resource in an adaptive fashion it is not directly linked to an environmental outcome. A truly adaptive management system must incorporate responses to such observed environmental outcomes. It could be argued that the proposed modest reductions in entitlement will not make a significant difference. Time will tell.

We will now explore how modelling of reductions provides a prediction of effects by describing a more complex management method, that allowing prediction of environmental outcomes and uses these to modify the management – a truly adaptive approach.

5.5 Use of Eigen modelling to predict discharge and inform the recharge-based method

An Eigen model approach can be used to complement the recharge-based management method, allowing it to predict environmental outcomes which can be fed back to fine-tune the management variables – a true adaptive management approach.

Whilst it is possible to calculate the variable entitlement from the recharge signature analysis alone, it is helpful to link the recharge variable to the actual state of the resource, by examining flows in spring-fed streams, and/or groundwater levels.

To explore this approach, we have assessed a recharge-based mechanism using an Eigen model technique (Bidwell 2003, and see Appendix A). This modelling demonstrated a strong relationship between the recharge to an aquifer system and its total discharge (natural and abstraction). The recharge component used in the Eigen model is the same as that used in the preceding analysis, being calculated from rainfall-EVT[23]-soil moisture modelling and is applied as uniformly distributed recharge cross the entire land surface of the allocation zone. The modelled discharge represents the entire aquifer discharge, including surface and sub-surface flows, and abstraction. The abstraction component has been estimated by determining potential irrigation demand from rainfall and EVT data and known irrigated area. In the future, actual use data will substitute for this estimate.

---

[23] EVT: evapotranspiration (see glossary)

One significant effect in large aquifer systems is the de-coupling of cause and effect. In an attempt to model this we have divided the aquifer system in the discharge Eigen model into three sub-areas of equal dimensions but with differing distances from the discharge end. These three sub-zones are the areas close to Te Waihora / Lake Ellesmere, the mid-plains, and the upper plains. The variation in distance of abstractions from the discharge point (spring-fed streams) causes different lag times between cause and effect. Similarly, the differences in depth to groundwater in the three sub-zones is taken into account. Allowance for the distance of an abstraction relative to the aquifer discharge zone (spring-fed streams, Te Waihora and coast) has been included in the current analysis, allowing for a combination of near- and far-field effects to be modelled; refer to Appendix A for details.

This subdivision is useful in modelling the total response to abstractions from the three sub-zones in a way that is consistent with our conceptual model of the aquifer system and it has been verified by use of simple three-dimensional numerical groundwater models.

5.6 Introduction to Eigen modelling

Eigen modelling can predict either groundwater levels or total aquifer discharge from a series of monthly recharge data (Bidwell 2003). Before describing the means of varying an entitlement, we first describe the Eigen model and what it can represent. Pertinent details of the Eigen model method are described in Appendix A. To understand how we have used this method it is worthwhile using an analogy: the model works much like a prudently managed bank balance, with deposits (recharge) and withdrawals or expenditure (natural discharge and abstractions). The rate of discharge (expenditure) from the aquifer, as measured by stream flow, or by groundwater level recession, is dependent upon the state of the resource (balance: groundwater storage).

Modelling, confirmed by observations, indicates that groundwater storage in the Central Plains loses about 5% of its volume per month (equivalent to a T1 eigenvalue of about 20 months as used in CSWS (2002) and also in Bidwell (2003) and Williams (2006). This eigenvalue is also loosely linked to the value of alpha used in the EWMA (refer to Appendices A4 & B) and is related to the size and shape of the aquifer system, its gross hydraulic characteristics, and most significantly, the hydraulic pressure gradient.

5.6.1 Eigen modelling of aquifer discharge

There is a correlation between groundwater levels (i.e. storage) and the rate of discharge from the aquifer system. This has been modelled to produce a time series plot of total aquifer discharge for a given recharge input. When this discharge plot is overlaid by a time series plot of groundwater level monitoring data from wells or flows from a surface water site (e.g. Harts Creek), there is a general but rather poor correspondence in trends (Figure 5-5) during the period prior to intensive development of irrigation (pre-1990).

However, post-1990, the correlation is poorer and this is, in part, because groundwater abstraction removes groundwater from storage, and thus distorts the system’s discharge signature and hence, Harts Creek flow.

Note that in the following time-series plots of discharge, the units of discharge are divided by the allocation zone area to produce units of mm/month, similar to the way we portray rainfall statistics.

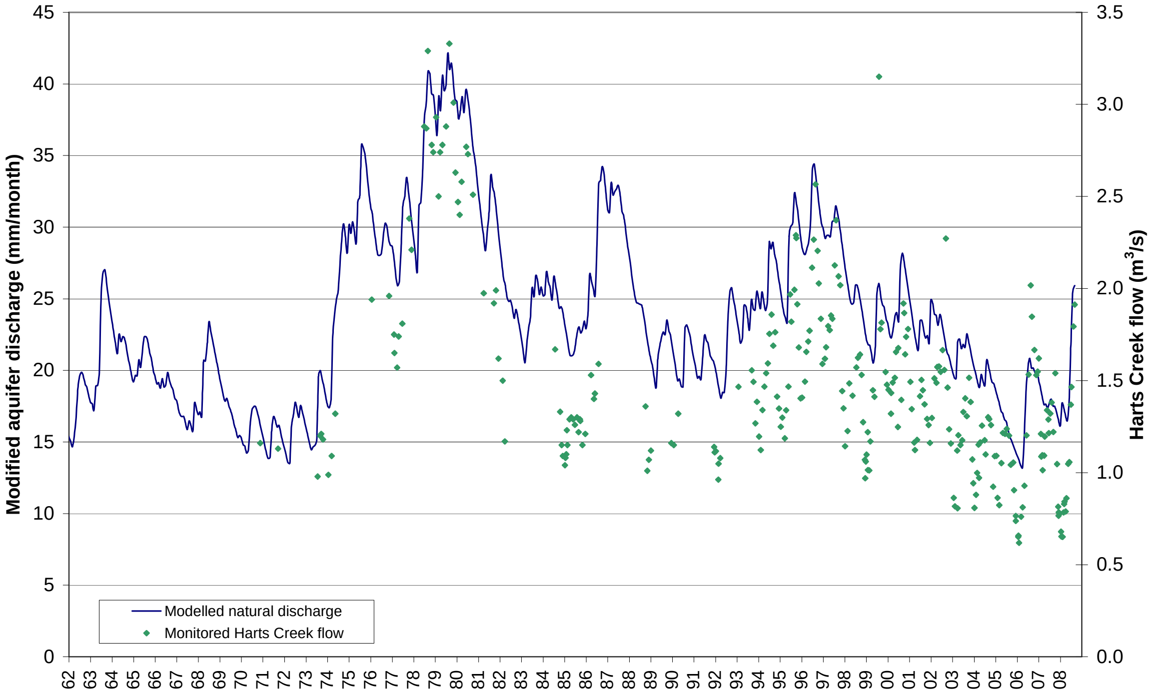

Figure 5-6: **Time series plot of Eigen modelled natural discharge and Harts Creek flow monitoring data**

Figure 5-6 shows that whilst there is a general correspondence between modelled natural and observed discharge, the measured flows differ increasingly from the modelled natural discharge for the latter part of the record, arguably because of abstraction. This indicates that abstraction should be included to better describe the relationship between recharge, discharge and aquifer state. However it will be some time before comprehensive metering data is available from the RSGAZ.

Prior to the metering of all consented groundwater takes, two methods have been used for estimating actual use of groundwater:

- by estimating water use for irrigation of land on the basis of consented volume, irrigated area, soil type, rainfall, and evapotranspiration (Scott 2004c, see also Appendix F);
- use of pumping power records or actual metered water use. In effect, these records have been used locally to validate the first method (Sanders 1997).

In the absence of metered water use for irrigators, we have used a mean value of 300 mm depth of applied water per season, representing approximately 60% of the mean WQN9 annual volume for users in the RSGAZ. In order to account for abstraction of groundwater from storage in the aquifer (red line in Figure 5-7) we have apportioned this volume time-wise over an irrigation season lasting seven months. The apportionment is in line with expected demand based on the rise and fall of EVT. Until such time as meter data become available, our analysis is only indicative and may overstate or understate the response to adaptive management. Figure 5-7 shows how including estimates of water use for a progressively increasing irrigated area (i.e. what actually happened) improves the correspondence between modelled (red) and monitored surface water discharge (green). The Eigen model has accommodated the varying time-lagged responses of abstractions at different distances from the discharge zone (see Appendix A).

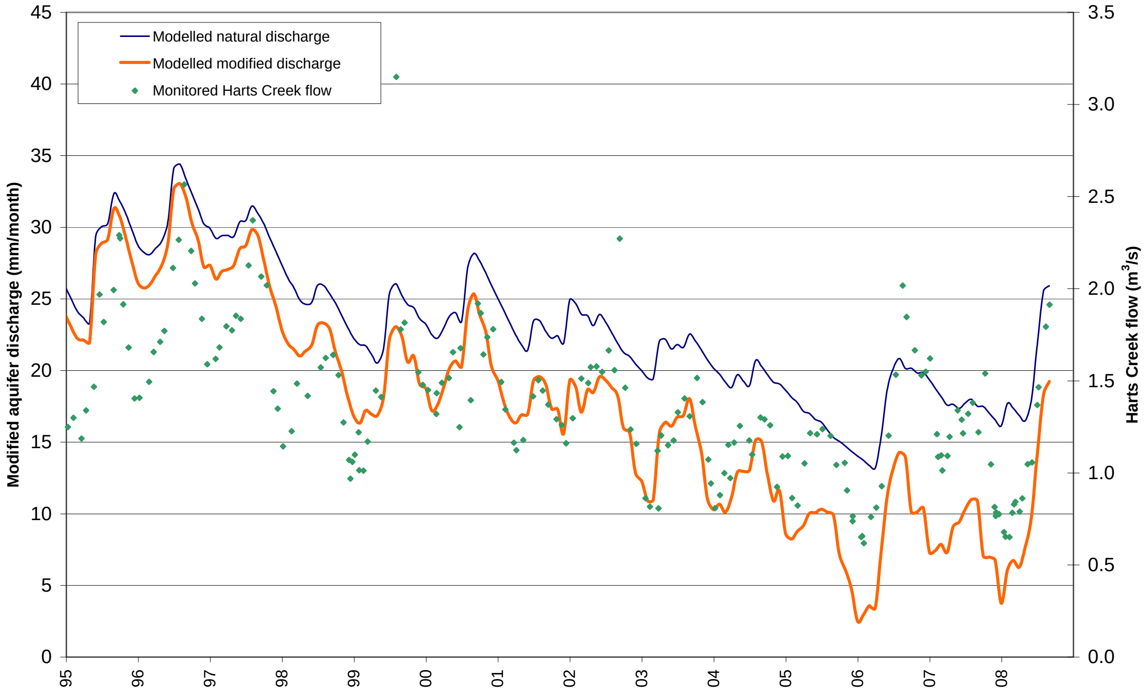

Figure 5-7: Time series plot of Eigen modelled total natural discharge modified to account for estimated abstraction (modelled modified discharge) and monitored Harts Creek flow

Figure 5-7 shows an improved correspondence in the later part of the time series once abstraction is taken into account in the discharge modelling. The detailed plot also shows that abstraction creates a saw-tooth annual pattern in the modelled discharge (modelled modified discharge), making it more closely resemble the monitored flow pattern. Note that the thin blue line in Figure 5-7 indicates the modelled natural discharge (no abstraction) expected from the recharge input, and that this line gradually deviates from the green points and orange line.

Normally, use of monitored flows in streams requires 'naturalisation' to account for abstractions up-stream of the monitoring point. Currently, the minor abstractions from Harts Creek are unlikely to change the shape and magnitude of the monitoring record. When estimated use can be replaced by actual use in the modelling, any potential disparity between modelled and monitored data should be reduced. This current disparity does not mean that the method is invalid, but that the results are not precise, which the description as 'indicative' acknowledges.

5.6.2 Eigen modelling of groundwater levels

Eigen modelling of groundwater levels and comparison with monitored groundwater levels has been undertaken by Bidwell (2003), and by Williams *et al*. (2006). Comparison of Eigen modelled and monitored groundwater levels is good when allowance is made for groundwater abstraction and the correspondence between Eigen modelling of aquifer discharge and groundwater levels in selected ECan monitoring bores is better than that achieved with flows. See Figure 1-1 for the locations of L36/0092 (Figure 5-8), L36/0023 (Figure 5-9) and L36/0142 (Figure 5-10).

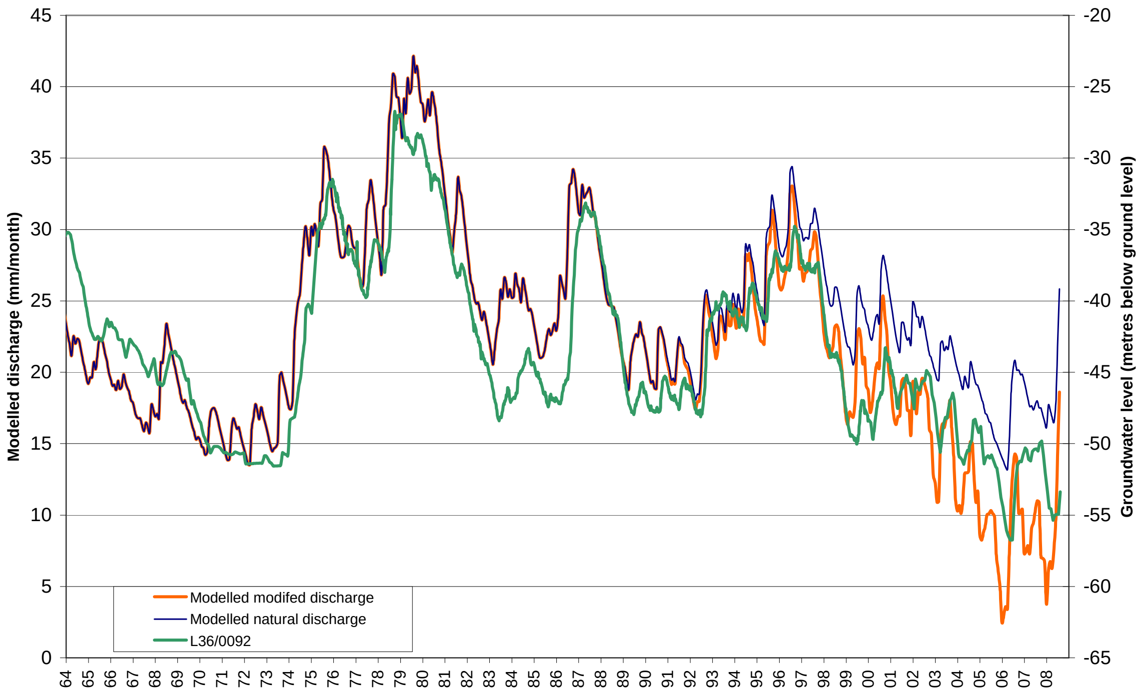

Figure 5-8: **Time series plot of monitored depth to groundwater in bore L36/0092, and modelled natural and modelled modified discharge**

In Figures 5-8 to 5-10, the modelled natural discharge and the modelled modified discharge are calculated in the Eigen model. The modelled modified discharge makes allowance for abstraction, as in Figure 5-7.

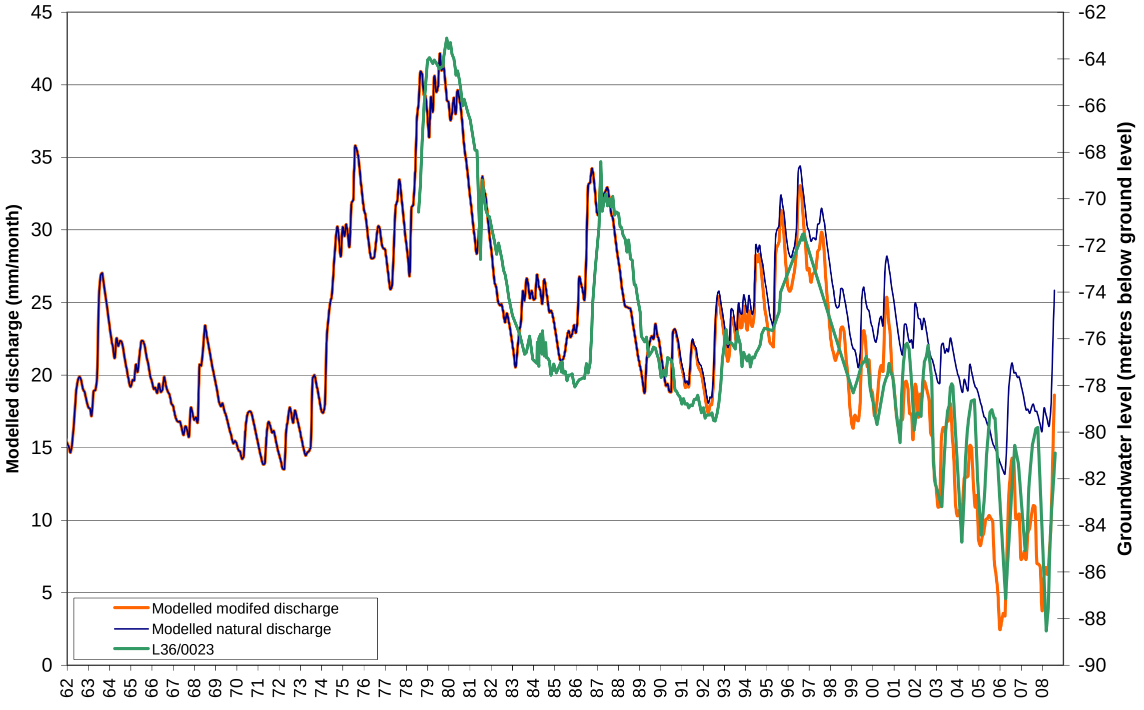

Figure 5-9: **Time series plot of monitored groundwater level in bore L36/0023, and modelled natural and modified discharge**

Note that in each of Figures 5-8 to 5-10 there is an increasing departure between the modelled natural discharge and the groundwater signatures; the natural discharge becomes progressively higher than the groundwater signature as time passes. This departure is lessened by modifying the discharge signature to account for abstraction (orange line).

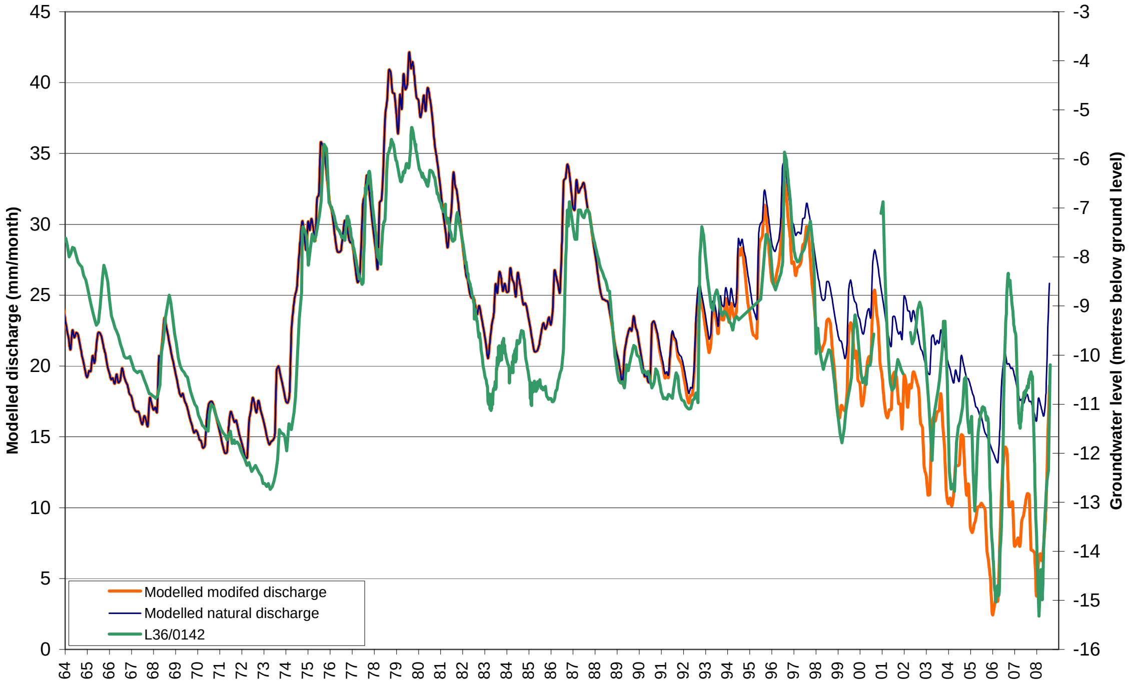

Figure 5-10: Time series plot of monitored groundwater level in bore L36/0142, and modelled natural and modified discharge

> Metered water use data will be needed to ensure that the model predictions can be verified against observations.

When allowance is made for abstraction of groundwater, there is not only an improved relationship between modelled modified discharge and actual groundwater levels (Figures 5-8 to 5-10), but also with a proxy for total discharge, such as Harts Creek flow (Figure 5-7).

5.6.3 Eigen modelling summary

> The advantage of using the Eigen model technique for assessing the state of the resource is that it can be updated monthly with observations of environmental indicators such as groundwater levels and surface flows.

The Eigen model, which is already showing reasonable relationships with groundwater monitoring data but poorer relationships with surface flow data, can be validated continuously by comparing modelled results with monitoring data as they become available.

The recharge-based method and the Eigen model can now be used together to create an adaptive management tool.

5.7 Eigen model and adaptive management

We have demonstrated how representation of estimated abstraction in the Eigen model modified the predicted outputs, such as modelled discharge. This demonstration leads us to the development of a genuine adaptive management method that reflects the relationship between use management and environmental outcome. The method can be related, as required, to specific flow or groundwater level triggers such as an environmental or minimum flow. Currently, the Eigen model can allow comparison between predictions of total aquifer discharge and actual surface flow monitoring on a monthly basis.[24]

A particular season's adaptive entitlement could be reduced or increased as required during the season but the slow response time of this large aquifer system means that this should not be usually be done so frequently. However the results should be monitored monthly. Realistically, annual adjustments to the coming year's entitlement are most appropriate. The trigger levels for such adjustments might be groundwater levels, or surface water flows (e.g. Harts Creek).

In the absence of more specific environmental flow targets in the PNRRPV1 we have used the minimum flow currently set for Harts Creek (1000 L/s).

The recommended management method uses monitored discharge of Harts Creek to ensure that when the flow drops below a specified value, a review of the entitlement using the recharge adaptive management mechanism would be required, either for that season, or for the next season.

5.8 Adaptive management based on recharge with prediction of flows

We have introduced two concepts:

- a recharge-based method to indicate how management of seasonal volumes could be structured and calculated;
- a relationship between recharge and discharge (or groundwater level), based on Eigen discharge modelling.

We now show how the method may be used to predict environmental outcomes, by using the Eigen model described in the previous section. The advantages of such a mechanism is that it is proactive, in that at an early stage, the recharge is assessed, the environmental outcomes predicted, and the entitlement adjusted as necessary.

If the environmental outcomes predicted by the model are unacceptable (too low, or too high), the proportion of rainfall recharge used to calculate the allocation limit (currently 50%) may be changed. Although the proportion of base to adaptive entitlements has initially been set at 50:50 [25], it is straightforward to change this ratio as part of the process. Monitoring of the results will lead to potential adaptation of the ratio, either up, or down, as conditions permit.

Such a mechanism is truly adaptive in that the seasonal entitlement may be modified by relating it to the antecedent recharge history, and by changing the basis for calculating the zone allocation limit i.e. 50:50, 60:40 etc.

---

[24] Monitoring of weekly median flows, having removed floods and freshes, is preferred.

[25] Rather than deal with individual consent holders in this report, this base volume would be half of the total allocated volume of groundwater for the zone.

5.8.1 Predictions of a recharge-Eigen allocation model option

Predictions of discharges from the aquifer system can be determined from the simple recharge model used in association with Eigen modelling. Linkage between the recharge model and the Eigen model can be achieved simply by taking the seasonal allocation from the recharge model and using that as the input into the Eigen model to predict a discharge, as depicted schematically in Figure 5-11. The predicted discharges can be used to feed back into the recharge model, for example, by changing the proportion of adaptive entitlement and, or the thresholds at which restriction occurs.

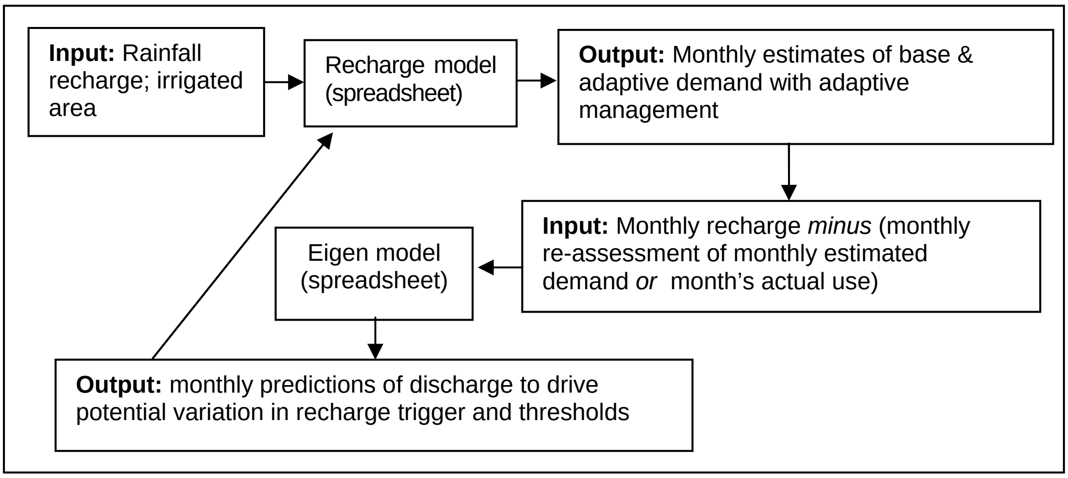

Figure 5-11: Schematic representation of the linkages between the recharge and Eigen models, and the associated data inputs and outputs

Prediction of discharge or groundwater level effects can be undertaken by use of the recharge model in conjunction with the Eigen model. This means that the recharge model can be proactive or anticipatory, rather than reactive.

Our experience of modelling and management of hydraulic connections between groundwater and surface water indicates that management actions do not have immediate effects. For example, recovery in spring-fed streams only occurs rapidly as a result of restrictions being applied to abstractions located close to the stream (i.e. directly hydraulically connected).

Abstractions at depth, and, or at great distance from the discharge, result in a much longer response time, in the order of months or years, often beyond the end of the irrigation season (Williams *et al.* 2006 and see Appendix A).

At the beginning of an irrigation year in July, the recharge record over the previous year can be used to signal potential issues, while the Eigen model can produce predictions of flows during, and at the end of, the forthcoming irrigation season. If these predictions of flow indicate that the minimum flow is certain to be breached, then a further management constraint, over and above that used for the recharge model, can be implemented that season, or, more realistically, in subsequent seasons. Conversely, if late winter or spring recharge is larger than expected, restrictions could be eased.

Figure 5-12 shows the effects on the modelled discharge from the aquifer system of managing use in accord with monthly recharge-based entitlements based on the data presented in Figures 5-2 & 5-3.

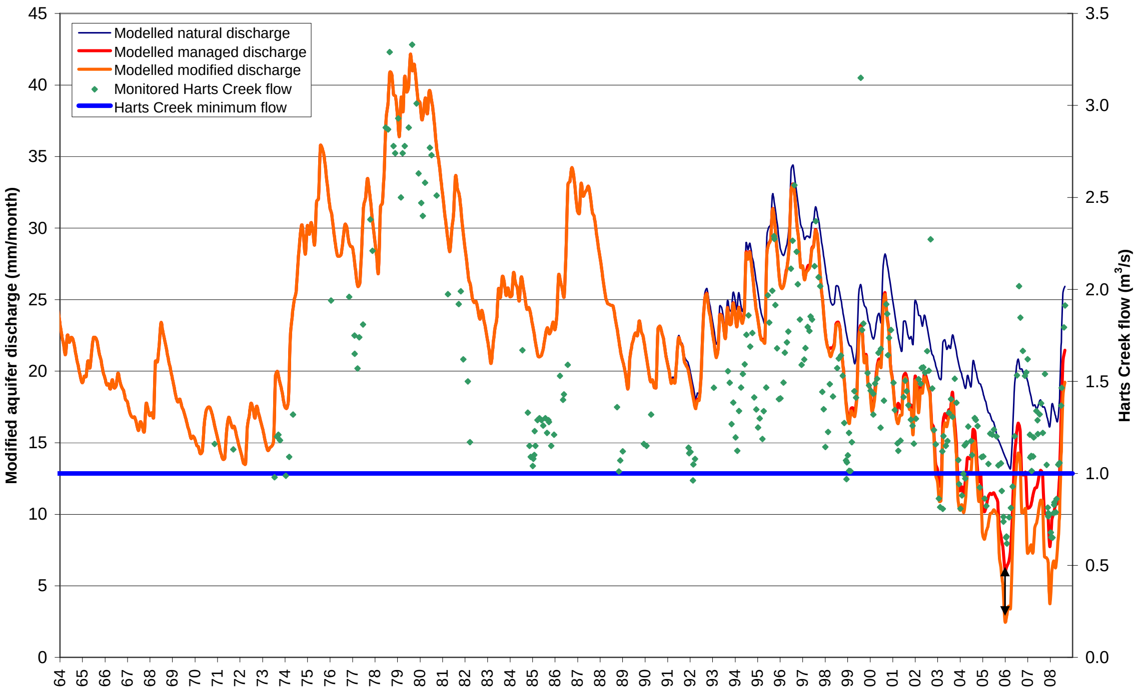

Figure 5-12: Time series plot showing modelled natural, modified and managed discharge. Included in the plot are spot measurements of Harts Creek flow (green points) and the value of its environmental minimum flow (blue line)

In Figure 5-12, the orange line represents the modified (un-managed) discharge, where no restrictions were undertaken. The managed discharge line (red) represents the discharge resulting from recharge-based restrictions placed on the adaptive entitlement, based on Eigen modelling. The black arrow in Figure 5-11 illustrates the difference between modelled aquifer discharge predicted from managed and un-managed abstractions.

We have used Harts Creek as a proxy for modelled aquifer discharge, so the gain in modelled total discharge is expected to result in a gain in flow to Harts Creek of over 200 L/s, as shown in Figure 5-12. Monitoring of other streams in the RSGAZ could lead to Eigen modelling and predictions of their flows and assessment of any benefits of management to them.

Warning of the likelihood of a restriction may be determined from the recharge method. Manipulation of the triggers within the recharge model, using the Eigen model as a predictive tool, provides an easy to understand means of tailoring use in any subsequent year to avoid repetition of trigger level breaching.

Adaptive management is essentially an experimental process; seasonal reductions in entitlement should be sufficient to ensure that a desired flow regime is not compromised at more than a specified frequency. Monitoring would then determine whether the basis for determining the seasonal entitlement needs to be modified. This would probably occur after several years rather than on a year by year basis.

5.8.2 Mechanisms to make the recharge-based method 'adaptive'

We have shown how the recharge-based managed entitlements relate to modelled natural, modified and managed discharge. It remains to show how the recharge model can be modified to produce changed outcomes. There are two simple ways of doing this:

- Changing the ratio of base to adaptive entitlement i.e. 50:50 etc.;

- Changing the recharge threshold for reduction of entitlement.

The ratio of base to adaptive entitlement was initially set at 50% each. By changing this proportion the sensitivity of the entire entitlement to change in recharge can be increased (decreasing base entitlement percentage) or decreased (increasing base entitlement percentage). Without actual water use data it is not possible at this stage to show how such variation in the proportion would impact on the modelled discharges.

In Section 5.2 we proposed that the threshold for applying management should be when the EWMA of recharge became less than the long-term mean of recharge. We offer the following justification for choosing this threshold or trigger value (Figure 5-12).

In Figure 5-13, both Harts Creek flow and the entitlement percentage are plotted. When Harts Creek flow is greater than about 1300 L/s it corresponds with full entitlement (100%). With decrease in Harts Creek flow to 600 L/s, entitlement falls to 50%.

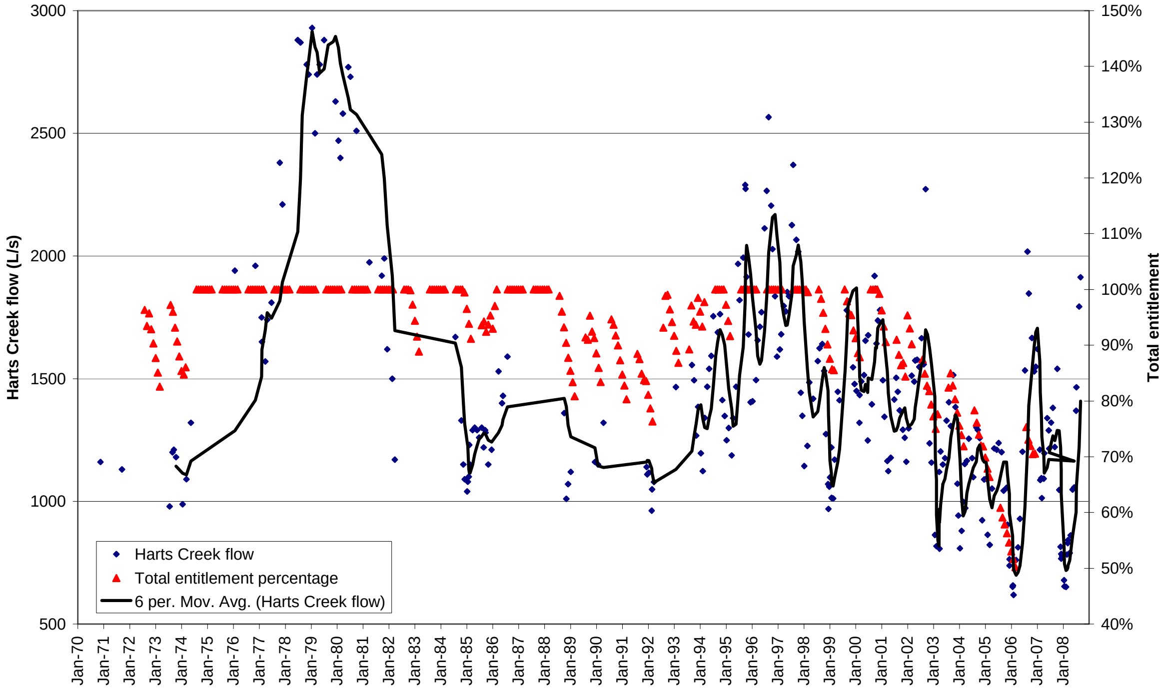

Figure 5-13: Time series plot indicating the relationship between entitlement determined from recharge, and Harts Creek flow

Figure 5-13 indicates that imposition of this change in entitlement, using the base to adaptive entitlement ratio of 50:50, and management of entitlement triggered when the recharge drops below the long-term mean, might release 200 L/s of flow to Harts Creek. By altering the ratio, and changing the recharge threshold at which management starts, the recharge method of management can be made more, or less, conservative.

Preliminary analysis indicates that changes in entitlement caused by manipulation of the threshold and the proportion of base to adaptive entitlement, together are sufficient to modify the modelled discharges.

5.9 What are the predicted effects of management?

It is understandable that water users and resource managers would want to know the predicted effects of the management. This section looks at the change in flow regime resulting from the proposed management method.

Previous plots have shown time-series variation in modelled discharge or groundwater levels, with and without management. Surface water hydrologists use flow duration curves to indicate effects of management or climate on a flow regime (Figure 5-14). A similar plot relating discharge model results compared with groundwater level is shown in Figure 5-15.

Figure 5-14 shows the similarity of shape of monitored flow and modelled discharge data. It illustrates the positive effect on modelled discharges to be gained by management, corresponding to an increase in flow of up to 200 L/s in Harts Creek at low flows. Given the uncertainties in the present water use estimates, it is likely that this gain (or loss) will be revised and adaptation to the recharge method trigger values made where appropriate.

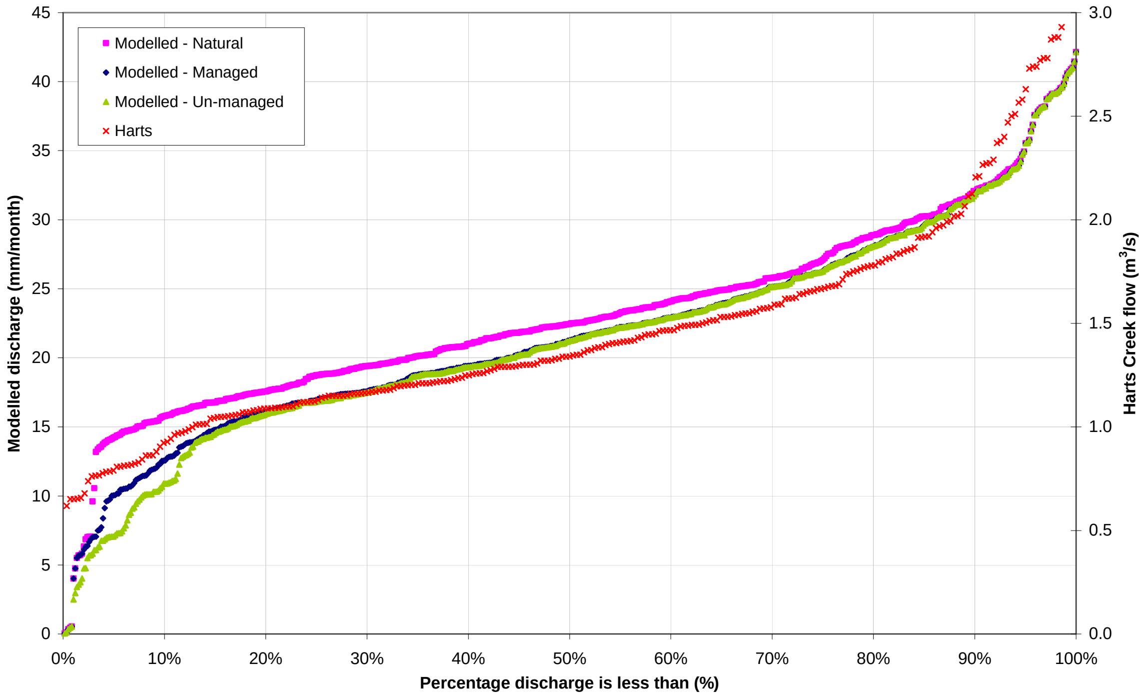

Figure 5-14: Flow and modelled discharge duration curves for the recharge-based eigen model and for spot gaugings on Harts Creek

In Figure 5-15, the modelled discharge series are plotted against groundwater levels in a duration curve format that illustrates the similarity of shape between groundwater level and modelled discharge data.

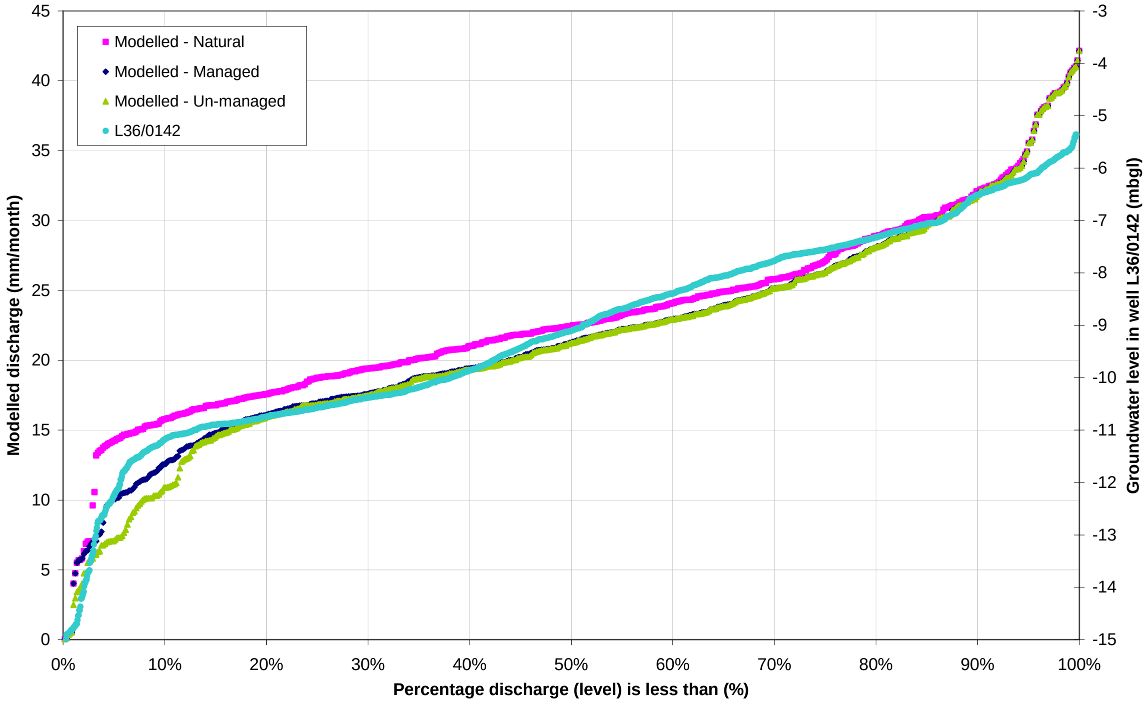

Figure 5-15: Groundwater level and modelled discharge duration curves for the recharge-based Eigen model and for well L36/0142

Figures 5-14 and 5-15 illustrate the percentage of flow or modelled discharge or groundwater level that is less than a particular value. Note that the spot gaugings for Harts Creek are largely dominated by monthly readings over the last thirty years, and that no attempt has been made to naturalise these gaugings for peak flow removal or for surface water abstractions. As more frequent flow, level and water use monitoring is introduced in the RSGAZ, more detailed analysis will be forthcoming.

Creation and analysis of plots of 48 and 24 years length of modelled discharge for the preparation of Figure 5-13 showed that use of series of differing time length did not affect the general trend and slope of the discharge curves nor their relationship with the Harts Creek flow data.

Figures 5-14 and 5-15 reinforce the analysis undertaken in Section 4 that shows the relationships between flow, groundwater level and recharge that are fundamental to the management model.

5.10 Discussion on constraints inherent in the recharge-based Eigen model

There are several issues relating to implementation and verification of the predictions created by the recharge-based Eigen model that need discussion.

When should the restrictions be imposed:

- at the start of the season only; or
- at several times during the season, such as monthly?

The former means that there will only be a blunt approach to management with the likelihood that the prediction could be inaccurate, with the accompanying restriction too lenient, or too conservative.

The latter option means that predictions at a number of intervals during the season will likely be more accurate, but the change in entitlement during a farming season may be onerous, and hard to manage. However, such a change is similar to that already experienced by surface water abstractors.

An issue with monthly changes to entitlement is that with the slow response of the aquifer system, frequent changes may not allow significant responses to be observed before the next one is scheduled.

The time for a conservative approach is at the beginning of an irrigation season, with the potential for the management restrictions to be relaxed as the season progresses[26]. The opposite, being lenient at the beginning, and imposing progressively more stringent conditions during the season, although similar to that already accepted by most surface water users, would be harder to introduce and enforce. Climate records (Table 5.1) indicate that it is unusual for rainfall recharge to be so significant in summer that the smoothed recharge value could be reassessed to allow an increase in entitlement.

There is a need for a definitive decision on when entitlement should be assessed. In this report we recommend 1st July.

Decisions on the frequency of management interventions and the method of alterations to entitlement are significant to any discussion on adaptive management. Figure 5-11 illustrates only one indicative set of effects, using the recharge method if managed monthly. We anticipate that the discharge results of frequent changes in entitlement would not be manifest in this monthly time period. The exercise does, however, show what can be done.

The advantage of using the environmental outcome to modify abstractive entitlement is simply that the community of consented abstractors is given a set of consent conditions similar to those meted out to surface water consent holders. If recharge and corresponding discharges change, the corresponding amount of entitlement for a given period also alters.

A number of issues have yet to be resolved with this type of management:

- ECan has only a small amount of continuously metered water usage data to test the algorithm and trigger levels, so there is considerable uncertainty in assessment of the past and current usage patterns. Until monitored use data become available, the reliability of supply of this mechanism cannot be assessed other than in an indicative or general way;
- Similarly, there is uncertainty in the past and current recharge values which are based on climate–soil moisture balance modelling. Continued monitoring of groundwater recharge using lysimeters is crucial to verifying the recharge-based method;
- Any hydraulically connected abstraction may have a near-field effect on the stream discharge, that could potentially alter the recharge management outcomes and distort the process when using a method solely based on groundwater levels. The recharge method of adaptive management is less prone to such distortion and could result in Objective 4 of the PNRRPV1 being better achieved;
- Successful adaptive management could mean that the restrictions on groundwater takes will improve flows in streams, and hence the reliability of supply for surface water consent holders. Currently, the reliability of both surface water and hydraulically-connected takes has been poor, an effect of increased groundwater abstraction generally. The result of this reduction in reliability is that surface water and hydraulically-connected consent holders have been driven ‘underground’ or deeper respectively. Until we have better use data this issue should be kept in mind because successful management of groundwater resources might effect a reversal in the recent trend away from surface water use;
- Use of the demand series indicates that in some years, the restrictions applied using the recharge-based method are not onerous because the volume should still be sufficient to meet demand. However, in ‘dry’ years, when demand is high, and the recharge state is poor, then demand usually exceeds entitlement. The relationship between the recharge-based series of entitlement, and the demand series, in conjunction with flow monitoring, will inform assessment

---

[26] The 2008-9 irrigation season is a case in point; the 1st July 2008 recharge-based entitlement would have increased from 70% to 97% by 1st October 2008.

of whether the method is too conservative or too lenient and addresses similar issues to those presented in Aqualinc (2008).

5.11 Effect of location and depth of abstraction on the environmental response to adaptive management

Bidwell in a series of unpublished Lincoln Ventures reports and spreadsheets developed a 'stream depletion' Eigen model which allows for coarse zoning of effects related to abstraction at different distances from the stream. This work is described briefly in Appendix A. Bidwell then developed the Eigen discharge model which allows the modeller to apportion abstraction to a number of zones of different distances from the discharge end of the model.

These two Eigen analytical models describe the magnitude and timing of effects on the aquifer discharge resulting from abstractions at differing distances from the discharge end of the model. The conclusions derived from the use of these models are that:

- abstractions taken from close to the discharge end of the model have a near-immediate effect on the total aquifer discharge, and typically create large seasonal swings in the discharge magnitude as a result of intra-seasonal changes in the degree of abstraction;

- for abstractions from more distant locations, whilst their mean abstraction magnitude and consequent mean reduction in system discharge might be no different from those close to the discharge area, have a much reduced effect on seasonal variation of discharge.

A most significant issue associated with the recognition and measurement of cumulative effects is that the timing of abstraction may be totally removed from the time of its environmental effect.

We cannot over-emphasise the significance of this timing issue; it could prove to be a major constraint on the efficacy and equitability of any adaptive management mechanism. In countering any argument of the unfairness of such a system that does not treat deep or distant takes differently, we would point out that, unlike near-field takes, these deep/distant takes affect the system discharge throughout the year. They dominate the effect after cessation of abstraction, not just in the summer abstraction season.

The Eigen modelling we have used to predict discharge from the aquifer system has sub-divided the plains into three portions with differing distances from the discharge (spring) zone. The aquifer response characteristics of each of these three zones have been tailored to mimic the expected delay between cause and effect. Deep abstractions from wells close to the discharge zone will also create a delayed effect. Currently, the model has not taken such near-field deep abstractions into account because there are not many deep wells in the coastal zone close to the springs. However, the number of deep near-field takes is increasing as existing and new abstractors elect to drill wells deeper to avoid being assessed as hydraulically connected with the spring-fed streams. This is an issue that requires future modification of the Eigen model.

5.12 Conclusions from recharge - Eigen adaptive management

The recharge trigger mechanism, based on Eigen modelling to predict discharge outcomes, could be initiated once the recharge signature state indicates that restrictions need to be applied.

The modelling of restrictions gives an indication of what might be achieved should adaptive management be used on a monthly basis and tied to flows in one or more surface waterways. For example, in the irrigation year 2005-6, users would have received their base entitlement, but, after a re-assessment in October following a very dry winter, almost no adaptive entitlement.

Until such time as all consented water use is metered, and this type of management actually enforced, the predictions and sensitivity of this model to near field effects can be only estimated. Once these estimates are firmed up with reliable monitored use data, then different triggers and ratios of base to adaptive entitlements could be given to individual new applicants for consents, that are less permissive, in order to protect existing users' rights.

Distinguishing between climatic and abstraction environmental effects is difficult. The recharge method recommended can be used in a truly adaptive manner (i.e.: '*suck it and see*') to manage the allocation during times of resource stress, because it allows predictions that can be tested by subsequent observations.

A major issue with adaptive management of the water resource is that predicted effects will always be affected by subsequent changes in land use, water abstraction and climate variability, so the prediction must inherently change with time, becoming increasingly uncertain as the forecast period is increased.

Uncertainty inherent in the recommended method will be cold comfort to water users who require as much certainty as is possible; such certainty is not available and it is, perhaps, unreasonable to expect it.

6 Implementation issues

6.1 Data requirements

Requirements for implementation of the recommended recharge-based adaptive management option include the following, as listed in Table 6.1.

Table 6.1: Implementation issues and data requirements

Issue	Requirements	How to resolve
Groundwater level data	Improve monthly monitoring, add continuous monitoring	Telemetry of shallow monitoring bores, naturalisation of groundwater levels
Surface water flow data. Naturalisation of surface flows, removal of freshes and floods	Improved understanding of base flow variation and its relationship to groundwater levels; staff analytical time	Daily monitoring (reported as weekly median); current telemetered sites include Selwyn and Doyleston. Harts (planned), Boggy, Irwell, Waikekewai
Water use data	Reported or telemetered as weekly mean	Telemetered water use of large surface water and groundwater takes within zone; monthly reporting of small takes
Staff resources	To set up and monitor flow sites, correction of data (naturalisation of flows)	Efficient allocation of staff time; appropriate prioritisation of effort. Sponsored post-graduate research projects.
Relationship between groundwater levels and surface water base flows	Concurrent monitoring of groundwater levels and stream flows	Analysis as improved naturalised data on flows become available.
Recharge estimation	Better rainfall, evapotranspiration, soil type and depth, soil moisture and lysimeter data	More sites, greater density of data for ground-truthing NIWA data. Useful to relate rainfall to volumes of recharge recorded in lysimeters and, or soil moisture data, neutron probe data.
Hydraulic connection	Stream-bed conductance data	Research in progress
Website to display up to date data on the resource	Design work, automation of data updates, staff time	Update of groundwater website planned
In-stream flow requirements	Values to be protected	Environmental flows currently in review
Five-year effectiveness monitoring	To determine whether method works	Audit method, update model if necessary, review outcomes
Review of groundwater abstraction consents hydraulically connected with Rakaia River	Assessment of volume of hydraulically connected surface water	Recent review for NRRP hearings

6.2 Salt-water intrusion

Effective management of groundwater should reduce the risk of salt water intrusion. Salt-water intrusion occurs when groundwater flow under the coastline and, or groundwater pressures close to the coast, are insufficient to keep the dense salt water at bay. The presence/absence of salt water in the coastal monitoring well network is used as an indicator of salt-water intrusion. From a zone perspective, it may be expected that as long as spring-fed streams or near-coastal streams are flowing, then there will be sufficient groundwater pressure to maintain the fresh/salt-water interface at a safe distance seaward from the coast, or at sufficient depth at the coastline. Localised salt water intrusion effects can still be dealt with using the methods in the PNRRPV1.

If saline water were to intrude inward of the coast, then this signals a need for a more conservative approach to adaptive management – particularly a substantial reduction in water use near the coast.

6.3 Other issues

Three further issues associated with the implementation of adaptive management of groundwater resources are now described: banking; so-called ‘B’ permits; revision of the allocation limit.

6.3.1 Banking of entitlement

In the interests of improving the security of supply (entitlement) for individual users, there may be an advantage to reward careful consented users of water by allowing them to carry forward or ‘banking’ unused portions of the adaptive entitlement into the following irrigation year. It might be necessary to limit the total carried forward in any year to a fraction of the base or adaptive entitlement. Currently, there is no theoretical or practical basis for the degree to which (fraction of entitlement) water can be banked. Although banking of water could be modelled within the adaptive management methods described in Section 6 in order to determine the environmental effects, the current precision on our estimates of water use precludes this being a useful exercise. We propose that banking of entitlement is re-visited when robust meter data on use and effects are available and when data are available from a proposed banking experiment by Synlait.

From an implementation perspective, there is an advantage permitting limited banking of water for reason that it rewards the careful user and allows them a nominal degree of control of their allocation. However, there is a potential for adverse environmental effects that needs careful modelling. We therefore urge caution on this issue that needs further study.

6.3.2 ‘B’ permits

Management of surface water resources has a history of defining Class A, Class B and Class C permits that are distinguished by having differing reliabilities. Class A has a higher reliability than B, and B greater than C.

The proposed adaptive management method may be adapted to cope with any need for groundwater consents with different reliabilities, simply by changing the trigger value at which restrictions to entitlement occur and the algorithm that controls the relationship between recharge and entitlement. Successful trials at producing B permits have been achieved.

6.3.3 Revision of the allocation limit

In Section 5 we described how it is possible, by means of managing the trigger level at which entitlements are constrained, to not only decrease entitlement when conditions require, but to allow an increase in entitlement when climatic conditions permit. In effect, this is similar to short-term revision of the allocation limit.

Decisions relating to the recharge level triggering restrictions can be reviewed if they are found to be too conservative, or not conservative enough, making the method adaptive.

Such flexibility in approach is in line with a recent proposal for dynamic allocation (Aqualinc 2008) and, once robust water use data become available is straightforward to model. The proposed method of management has the capability of revising the allocation for a groundwater management zone up or down and assessing the environmental outcomes of that revision.

7 Conclusions

The following conclusions have been drawn from the analysis and discussion in this report:

a) We recommend a recharge-based method of adaptive management of groundwater resources to restore the flows in spring-fed streams and arrest continued decline in groundwater levels;

b) The recommended method is potentially an equitable solution to the management of cumulative effects;

c) The recommended method of applying use restrictions implies that all users have similarly-timed effects on the environment. Modelling shows this not to be the case, but to account for this variation in timing of effects would require separate trigger levels within sub-zones, and might involve considerably more work to be undertaken for consent holders, at their cost. Significantly, deep and distant takes still have an effect eventually, thus there is little to be gained from a sub-zonal approach in terms of the overall groundwater management for this zone, except possibly for the Little Rakaia sub-area;

d) Table 7.1 shows the data required, and the advantages and disadvantages of three broadly different methods of groundwater management.

Table 7.1: Methods of groundwater management, their data requirements for implementation, advantages and disadvantages

Method	Data required	Advantages	Disadvantages
Tasman Otago CHWM W-H type	⇒ Groundwater levels ⇒ Surface water flows ⇒ Metered use	⇒ Simple to operate, allows restrictions based on trigger levels accepted by community	⇒ Not suitable for large aquifer systems with time lags between cause and effect ⇒ Not suitable where inflows or effects derived from adjacent zones occur
Davoren	⇒ Pre-set trigger levels based on site specific groundwater levels ⇒ Site-specific aquifer parameters ⇒ Metered use	⇒ Attempts to account for cumulative effects of new takes	⇒ Difficult to predict reliability of supply statistics ⇒ Each user required to submit an annual report on state of resource prior to obtaining go-ahead (labour intensive) ⇒ No specific environmental outcome predicted
Recharge-based method with Eigen model prediction of effects	⇒ Metered consented groundwater use, ⇒ Rainfall recharge, ⇒ EVT, ⇒ Soil type ⇒ Irrigated area ⇒ Monitored groundwater levels & surface water flows	⇒ Simple to operate ⇒ Provides causative link between restrictions and environmental outcomes (true adaptive management) ⇒ Allows base and adaptive entitlements ⇒ Allows good indication of reliability of supply statistics ⇒ Eigen model can be used to predict potential for saline intrusion	⇒ Requires good understanding of the relationship between climate and use ⇒ Requires improved surface water monitoring ⇒ Some time to achieve full potential?

For an adaptive management method to be effective within the framework of the PNRRPV1 and the proposed RPLS it needs to:

- be based on precise data that are easy to measure;
- be the most robust option from a theoretical standpoint; in order that it can be understood and justified;
- simple enough in principle to be understood by lay people;
- produce technically correct verifiable results straightforward enough to be communicated to non-technical user groups;
- have predictable environmental outcomes which have been estimated.

The recommended management method meets these criteria.

8 Technical recommendations

The recharge-based method of adaptive management, as described in Section 5, is recommended over all other management methods reviewed.

The recharge-based method could be implemented as soon as there is a representative sample of metered consented takes likely in 2010-11 irrigation year[27]. The method requires robust information on the relationship between climate and use, and predicts an environmental outcome, chosen as flow in Harts Creek, as a proxy for total aquifer discharge.

The following recommendations are made as a result of the analysis of data presented in this report:

a) That 15-minute interval monitoring, at four established multi-level piezometer wells, of groundwater levels at different depths is undertaken to further our knowledge of the dynamics of groundwater flow through the aquifer system. Such monitoring will complement the existing groundwater level monitoring programme and allow provide valuable input to the management method;

b) That more regular monitoring of flows in spring-fed streams (Irwell River, Boggy Creek) is undertaken to provide daily mean data for assessment of the short- and long-term dynamics of discharge from the aquifer system. Such monitoring will allow verification of the choice of indicator site and provide valuable input to the management method;

c) That better definition of environmental outcome(s) is developed.

d) Although in this report the minimum flow on Harts Creek has been chosen as the proxy for aquifer discharge state, there may be better potential sites;

e) That a programme of analysis of climatic data, in association with the data derived from the metering of all consented takes, be initiated in order that the relationship between climate and use, between use and effects, and between soil and use are better understood. These data will strengthen the technical justification, community acceptance and eventual operation of the adaptive management mechanism.

---

[27] Once robust data handling systems are in place, some metering data will be available in the 2009-10 season but the first year where the majority of takes are metered is projected to be the 2010-11 season (John Young, ECan, pers. comm. October 2008).

9 Acknowledgements

This report has benefited from contributions and trenchant criticism by and discussions with present and past members of the Groundwater, Surface Water Resources & Ecosystems, Planning, and Monitoring & Enforcement sections at Environment Canterbury.

Tom Heller (Director: Water and Environment, Environmental Associates Ltd), Dr Alistair McKerchar (Hydrologist: NIWA) and Dr Hugh Thorpe have provided useful external peer reviews of various versions of this document.

We should pay regard to the words of the internationally-acclaimed mathematician and philosopher, Gregory Chaitin, *“if you write a report that offends no-one and you make sure that everything you write is 100% correct, then you end up writing nothing”.* Whilst every effort has been made to ensure that the contents of this report are as accurate as possible, there is no question that as the adaptive mechanism progresses and additional data come to hand, the method will become an increasingly useful and effective resource management tool.

10 References (including those in Appendices A & B)

Aitchison-Earl, P, Scott, D and R Sanders 2004: Groundwater allocation limits: Guidelines for the Canterbury Region; *Environment Canterbury Report* U04/02, 60 p.

Aqualinc (2008): Dynamic allocation of groundwater for irrigation; Report prepared for Dairy New Zealand, Aqualinc Report C08081/1, 59 p + appendices.

Bidwell, V 2003: Groundwater management tools: analytical procedure and case studies; *Ministry of Agriculture and Forestry (MAF) Technical Paper* 2003/06, 56p.

Bidwell, V; Callander, P; Moore, C 1991: An application of time-series analysis to groundwater investigations and management in Central Canterbury, New Zealand. *Journal of Hydrology (NZ)*, 30, 16-36.

Bright, J 2006: Risk management methods for efficient water allocation and use in agriculture; Abstract of presentation at New Zealand Hydrological Society Inc. Conference Programme and Abstracts p.21.

Brodie, R, Sundaram, B, Tottenham, R, Hostetler, S, and T Ransley, 2007: An adaptive management framework for connected groundwater-surface water resources in Australia. Bureau of Rural Sciences, Canberra.

Brown, L J 2001: Canterbury; *In* Groundwaters of New Zealand, M R Rosen and P A White *(eds)* New Zealand Hydrological Society Inc, Wellington. p 441-459.

Carter, L & R H Herzer 1979: The hydraulic regime and its potential to transport sediment on the Canterbury continental shelf; *New Zealand Oceanographic Institute Memoir* 83, 32 p.

CRC 1994: Water allocation issues and options report; *Canterbury Regional Council Report* U94/61, prepared by Davie, Lovell-Smith Ltd. and Pattle Delamore Partners Ltd., 64 p.

CSWS 2002: Canterbury Strategic Water Study. Prepared for Ministry of Agriculture & Forestry, Environment Canterbury, and Ministry for the Environment, by Morgan, M, Bidwell, V, Bright, J, McIndoe, I and C Robb. *Lincoln Environmental Report* No. 4557/1.

Davoren, A 2007: unpublished evidence presented at Rakaia-Selwyn and Selwyn-Waimakariri Groundwater Allocation Zones Hearings and submissions to Variation 4 of PNRRPV1 in relation to adaptive management consent conditions.

Davoren, A and D Scott 2005: Schedule WQN9 Revision – Review of seasonal approach included in proposed NRRP; *Environment Canterbury Technical Report* U05/15/1, 32 p.

Dicker, M J I 1980: The hydrogeology of the Waimea alluvial basin, New Zealand. *M.Sc. Thesis, University of Canterbury*, 390 pages (Volume 1, maps and section Volume 2).

Dicker, M J I , Fenemor, A D and M R Johnston 1992: Geology and groundwater resources of the Waimea Plains, Nelson. *New Zealand Geological Survey Bulletin* 106, 59.

Environment Canterbury 2006: Summary of estimated recharge from the Selwyn River and tributaries to the Rakaia-Selwyn Groundwater Allocation Zone, Internal memorandum dated 2 Feb 2006 to Water Allocation Group, Environment Canterbury.

Environment Canterbury 2007a: The Rakaia Selwyn Groundwater Zone – Technical summary of the effects of groundwater abstractions on stream flows and reliability of groundwater; *Letter addressed to consent holders in the Rakaia-Selwyn Groundwater Allocation Zone*, dated 26 June 2007, Environment Canterbury.

Environment Canterbury 2007b: State of the Canterbury region water resource, October 2007; Environment Canterbury Technical Report U07/67, 65 p.

Environment Canterbury 2008: *Final Decision of Canterbury Regional Council Independent Commissioners*, 69 Rakaia-Selwyn Groundwater Allocation Zone applications, Environment Canterbury, 174 p.

Glover, R; Balmer, C 1954: River depletion resulting from pumping a well near a river. *American Geophysical Union Transactions*, 35: 468-470.

Goulburn-Murray 2007: Groundwater Management Plans (Webpage accessed on 22nd August 2008: http://www.g-mwater.com.au/policy/groundwater-management-plans-redirect).

Herzer, R H 1981a: Late Quaternary stratigraphy and sedimentation of the Canterbury continental shelf, New Zealand. *New Zealand Oceanographic Institute Memoir* 89.

Herzer, R H 1981b: Ellesmere sediments / interpretation of sediment distribution; Map at scale 1:200 000. Department of Scientific and Industrial Research.

Holling, C S (ed.) 1978: Adaptive Environmental Assessment and Management. Chichester: Wiley. ISBN 0-471-99632-7.

Horrell, G 2006: Evidence presented at the Rakaia-Selwyn Groundwater Allocation Zone Hearing (July-August 2006), unpublished.

Hunt, B and D Scott 2007: Flow to a well in a two-aquifer system; *Journal of Hydrologic Engineering* 12, 146-155.

IPCC 2007: Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report Climate Change 2007: Climate Change Impacts, Adaptation and Vulnerability

Krom, T 2007: Professional opinion on coastal discharges from the Canterbury Plains aquifer system; *Memorandum submitted to Environment Canterbury* 11/4/2007, Touch Water Ltd.

Larsen S and G Horrell 2005: Evaluation of drought at Lincoln, Canterbury. *Environment Canterbury Technical Report* R05/29, 64 p.

Lowry, T and J Bright 2002: Draft guideline for groundwater allocation management; Report submitted to Ministry for the Environment, 5th July 2002, 21 p.

MAF undated: website article located at http://www.maf.govt.nz/mafnet/rural-nz/sustainable-resource-use/water-efficiency/groundwater-management-tools/groundwater06.htm

Maxey, G 1964: Hydrostratigraphic Units. *Journal of Hydrology* 2, 124–129.

McKerchar, A.I., Schmidt, J., 2007. Decreases in low flows in the lower Selwyn River? *Journal of Hydrology* (NZ) 46(2): 63-72.

MfE 2008: Proposed National Environmental Standard on ecological flows and water levels; Discussion document, Ministry for the Environment, Wellington, 61 p.

Ministry for the Environment 2008: Climate Change Effects and Impacts Assessment: A Guidance Manual for Local Government in New Zealand. 2nd Edition. Mullan B; Wratt D; Dean S; Hollis M; Allan S; Williams T, Kenny G and MfE; Ministry for the Environment, Wellington, 149 p.

Mullen, B 2006: Climate change scenarios and drought; Abstract of presentation given at Royal Society of New Zealand Climate Committee – Drought workshop, 10/4/2006. http://www.mfe.govt.nz/publications/climate/drought-risk-may05/html/page4.html and http://www.rsnz.org/advisory/nz_climate/workshopApr2006/BrettMullan.pdf

NIWA 2007: Impacts: New Zealand & the South Pacific; NIWA climate change report (April 2007) sourced from: http://www.niwa.co.nz/data/assets/pdf_file/0010/57736/ipcc_4.pdf

Otago 2004: Regional Plan - Water for Otago; Otago Regional Council, ISBN 0-908922-40-X, 456 p.

PNRRPV1 2004: Proposed Natural Resources Regional Plan – Variation 1: Water Quantity chapter, Environment Canterbury, July 2004.

Pulido-Velazquez, M, Sahuquillo-Herraiz, A, Ochoa-Rivera, J, and D Pulido-Velazquez 2005: Modeling of stream-aquifer interaction: the embedded multireservoir model. *Journal of Hydrology*, 313: 166-181.

Rupp, D, Schmidt, J, Woods, R and A. McKerchar 2008: Modelling spatio-temporal variability of streamflows in an intermittent alluvial plain river *Geophysical Research Abstracts* 10, EGU2008-A-01091.

Sahuquillo, A 1983: An eigenvalue numerical technique for solving unsteady linear groundwater models continuously in time. *Water Resources Research*, 19(1): 87-93.

Sanders, R A, 1997: ‘Irrigation water use survey: report on a three year survey of groundwater use on the Canterbury Plains 1994-97’ *Environment Canterbury Technical Report* U97/39.

Scott, D 2004a: Groundwater allocation and Schedule WQN4: Technical and policy background; *Environment Canterbury Technical Report* U04/12, 15 p.

Scott, D 2004b: Net use of groundwater for irrigation – a review of the concept; *Environment Canterbury Technical Report* U04/53, 31 p.

Scott, D 2004c: Groundwater allocation limits: land-based recharge estimates; *Environment Canterbury Technical Report* U04/97, 39 p.

Scott, D and B Hunt 2007: A water budget perspective of leaky aquifer response to pumping; NZHS conference abstract, Rotorua, November 2007.

Scott, D and H Williams: Modelling cumulative effects of groundwater abstraction in the Canterbury Plains (manuscript in review).

Seaber, P R 1988: Hydrostratigraphic Units. In Hydrogeology: The Geology of North America, ed. W Back, J S Rosenshein, and P R Seaber, O-2, 9–14. Boulder, CO.: Geological Society of America.

Seward P, X Yongxin and Brendonck L 2006: Sustainable groundwater use, the capture principle, and adaptive management; Water South Africa, published by Water Research Commission, Pretoria, 32, 473-482.

Tasman 1999: Water Part 1: Tasman District water allocation, A summary of the water management options for the Tasman district. Tasman District Council Water Allocation Policy.

Taylor, K 1996: The natural resources of Lake Ellesmere (Te Waihora) and its catchment; *Environment Canterbury Technical Report* 96(7), 322 p.

Theis, C V 1940: The source of water to wells - Essential factors controlling the response of an aquifer to development. *Civil Engineering* 10 (5), 277-280.

Thorley, M 2006: Evidence presented at the Rakaia-Selwyn Groundwater Allocation Zone Hearing (July-August 2006), unpublished.

Thorley, M, Aitchison-Earl, P, Ritson, J, and S Hayward 2008: Proposed Additions to South Canterbury Groundwater Allocation Zones; *Environment Canterbury Technical Report* No. R08/42, 35 pp.

Thorpe, H R and D M Scott 1999: An evaluation of four soil moisture models for estimating natural groundwater recharge; Journal of Hydrology (NZ) 38, 179-209.

White, P A 2008: Central Plains Water – Technical assessment for Te Runanga o Ngai Tahu, document in support of Evidence submitted to the Central Plains Hearing (GNS Report 520W2161); Environment Canterbury, August 2008.

Williams, H 2006: Eigen-modelling in the Rakaia-Selwyn groundwater allocation zone; *Environment Canterbury internal file note,* dated 15th June 2006.

Williams, H 2007: Groundwater level variation near the coastline in the Rakaia-Selwyn Groundwater Allocation Zone; *Environment Canterbury internal file note*, dated 11/6/2007.

Williams, H 2008: Groundwater and the ‘Living Lake’: a tale of dependency. *In* Hughey, K.F.D., and Taylor, K.J.W. (Eds.), *Te Waihora/Lake Ellesmere State of the Lake Report* (in press). EOS Ecology, Christchurch.

Williams, H and P Aitchison-Earl 2006: Relationships between groundwater pressures and lowland stream flows in the Lake Ellesmere area; *Environment Canterbury Technical Report* No. U06/31, 25 p.

Williams, H, Bidwell, V and D Scott 2006: Application of the Eigen model to groundwater assessment in Canterbury; Abstract of paper presented at the New Zealand Hydrological Society conference, Christchurch, November 2006, p. 159-160.

Williams, H R and S Gabites 2008: Response to Selwyn-Waimakariri Hearing Commissioners s41C(4) request for further information, dated 31st January 2008; Environment Canterbury (unpublished).

Appendix A: Aquifer Systems and Groundwater Dynamics

The material in this appendix has largely been written by Dr. Vince Bidwell of Lincoln Ventures Ltd. It introduces the basic concepts of Eigen modelling, its history, the assumptions made for the modelling, its prediction of groundwater levels and aquifer discharge flows from input of recharge series data. This appendix also shows how the modelling may be used to determine the effects of abstraction and as a groundwater allocation zone management tool. References in this section are listed in Section 10 of the main document.

A.1 Basic concepts

Groundwater dynamics refers to the response of groundwater pressures and flows to time variations of inflowing recharge water fluxes that replenish an aquifer, as well as to the influence of passive and active discharges from the aquifer. Discharges to springs, surface waters and constructed drainage are passive. Pumped abstractions are active discharges. Our interest in groundwater dynamics is for the purpose of quantifying the sustainable use of an aquifer in terms of knowledge about recharges, proposed active discharges, and the response to these of groundwater pressures and passive discharges.

The term “aquifer system” formally recognises that an aquifer is a spatially-distributed geological body in which all zones, or components, are interconnected by means of the groundwater held within. In general, aquifers are systems of complex, heterogeneous, zones of spatially-varying hydraulic properties that can range in value over several orders of magnitude. Even if there were to be no spatial variation of these properties, the spatially distributed nature of an aquifer would still constitute a system. It is the aim of dynamic analysis to quantify the dynamic response of a system and to simplify the description of this response, where possible, in terms of the purpose of the investigation.

In an analogous context, such as earthquake engineering of a building, the designer recognises that the building is a system comprising the elements of the structure. The response of stresses within these elements to the time-varying forces of an earthquake is of paramount importance. Dynamic analysis shows that the oscillations of the building during an earthquake comprise a set of different frequencies. The particular mixture of frequencies, in relation to those imposed by the earthquake, are the key to safe building design. The design engineer refers to these building frequencies as the Eigenvalues of the analysis. The term “Eigen” means “characteristic”, and is also used to name the analytical methods described in the following applications to groundwater dynamics.

Although frequencies of oscillation are suitable Eigenvalues for characterising the response of a building to earthquakes, groundwater scientists use a different measure for quantifying the response of groundwater to recharge and pumped abstraction. In this case, the Eigenvalues are the drainage rates of simple water storages that constitute a system equivalent to the dynamic behaviour of an aquifer for the purpose of an investigation. For some kinds of investigations, the number of simple storages is few and considerable simplification of the analysis can be achieved.

A.2 History

An example of such simplification, in Central Canterbury aquifers, was demonstrated in the time-series analysis by Bidwell *et al.* (1991) of the response of the monthly piezometric record of well L36/0092 to the monthly totals of land surface recharge calculated from a water balance model. The resulting dynamic model explained 90 % of the observed statistical variance, with only two storage elements in the model. The authors did not present their model within an Eigenvalue context but subsequent analysis shows that their method is mathematically equivalent.

Application of the Eigenvalue approach to groundwater modelling owes much to the theoretical developments during the past 25 years at the Polytechnic University of Valencia, Spain. Sahuquillo (1983) shows that an aquifer with spatially variable properties can be represented in Eigenvalue formulation as a set of simple water storages. He also demonstrates the mathematical equivalence between the Eigenvalue approach and the more commonly used numerical groundwater models.

This formal Eigenvalue approach was first applied in New Zealand to the groundwater resource evaluation that contributed to the first stage of the Canterbury Strategic Water Study (CSWS, 2002). These mathematical tools used for the CSWS were developed into a set of procedures and examples and made publicly available in the form of a MAF Technical Report (Bidwell, 2003). The term “Eigenmodel”, as used in the MAF report, became a descriptor for this kind of approach to groundwater modelling.

A.3 Assumptions used in Canterbury applications

In the course of developing procedures for the CSWS, an important addition was made to the original Eigenvalue approach of Sahuquillo (1983). This was the addition of a storage element that specifically represents the dynamic effect of water moving through the vadose zone, including the effect of groundwater perched above a leaky aquitard. This means that the dynamic effects of land surface recharge can be represented differently from those of pumped abstraction in particular circumstances.

The alluvial aquifers of the Canterbury Plains have two significant sources of natural recharge; leakage from the rivers that cross the plains (river recharge); and soil-water drainage from the overlying land use (land surface recharge). The groundwater pressure effects of these two recharge sources are distinctly different, and this difference is exploited in the Eigenmodel method.

Variation in groundwater levels (pressure effects) due to time-variations in river recharge can be observed in wells close to rivers but this variable effect is rapidly damped to a steady effect, usually within a few kilometres from the river. There is a sound theoretical basis for this observation, and it enables river recharge pressure effects to be modelled as steady, but spatially varying, values.

Natural time-variations in groundwater are caused primarily by time variations of land surface recharge. Provided that the spatial pattern of land surface recharge is constant, in terms of relative magnitudes, then the time variations of this spatial pattern can be represented by a single index of recharge (Sahuquillo, 1983). This enables the time-series of a single, area-weighted value of land surface recharge to be used in analyses of natural variation of groundwater levels.

The Eigenmodel procedure separates the observed groundwater level record of a well into a steady level, representing river recharge effect, and variable components caused by land surface recharge and pumped abstraction.

A.4 Eigenmodel of natural recharge effects

The Eigenmodel approach to modelling groundwater levels and groundwater discharge in response to time variations of land surface recharge is particularly efficient in terms of model simplicity and accuracy of predictions. Experience in Central Canterbury is that a model with only three storage elements (two for groundwater, one for vadose zone) can predict 90 % of the time variability in monthly observations of natural groundwater level.

Eigenvalue theory states that the storage elements representing groundwater dynamics should have the same drainage value for every location in the aquifer system, but the weighted mix of storages does vary with location. Our results for the Central Canterbury aquifers demonstrate that one of the two storage elements representing groundwater is always dominant and has the same calibrated drainage rate (within statistical limits) at every location. The second storage element is much less significant, and has a drainage rate that is an order of magnitude higher. Therefore, it contributes to improved prediction of peak groundwater levels but is not significant in terms of storage over several months for groundwater management. The dominant storage element typically accounts for at least

80 % of the variable natural storage in an aquifer system and accounts for all of the natural effect during a long drought.

The dominant storage element for Central Canterbury aquifers has been calibrated to have a drainage rate of 0.05 per month (CSWS 2002; Bidwell 2003; Williams 2006). This means that 0.05, or 5 %, of the groundwater ascribed to land surface recharge, is draining away every month. Thus, for the purposes of sustainable management this aquifer system can be considered as a water storage with a mean storage time of 20 months, which is replenished by land surface recharge.

A.5 Effects on surface waters

The bulk of natural drainage from aquifer storage is effectively groundwater discharge to surface waters, including wetlands, constructed drainage, lakes and ocean. Surface waters can also receive groundwater discharge as a steady contribution from groundwater volume ascribed to the effect of river recharge. The particular mix of steady groundwater discharge and time-varying groundwater discharge determines whether a surface water body is “sensitive” to time variations in land surface recharge. These land surface recharge variations are caused by local climate and changes in land use, and groundwater abstraction.

The variable component of groundwater discharge to surface waters comprises a weighted mix of the drainage from the storage elements of the groundwater Eigenmodel representation. During periods of natural low flow in streams, the dominant drainage rate of 0.05 per month (in Central Canterbury) governs the variable part of groundwater discharge to stream flow.

The effects of groundwater abstraction on groundwater-fed surface waters are often expressed in terms that are functions of stream flow variability such as duration of flows less than a specified threshold. This variability, under natural conditions, is driven by land surface recharge through a dynamic response that can be well calibrated in an Eigenmodel representation. This is the reason for the use of land surface recharge, which is well estimated from water balance models, as an index for determining the quantity of groundwater that can be sustainably used from the aquifer system.

A.6 Eigenmodel of groundwater abstraction from a well

The dynamic effect on stream flow of pumped abstraction from a single well (stream-aquifer effect) can also be represented as an Eigenmodel (Pulido-Velazquez *et al.*, 2005). This model comprises a larger number of the storage elements than the land surface recharge model, but the drainage values of each corresponding element are the same in both models. The vadose zone storage element is not used in the groundwater abstraction model.

The calibrated value of the dominant storage element obtained from the land surface recharge model (0.05 per month for Central Canterbury) can also be used for the first storage element of the stream-aquifer Eigenmodel. However, there are no calibrations for the remaining set of storage elements with their increasingly faster drainage rates. We get around this difficulty by using the Eigenmodel solution for stream-aquifer dynamics in a simplified aquifer system that has the same dominant drainage rate as the calibrated value. The other drainage rates, and the appropriate mix of storages, are then computed automatically in the Eigen model.

This simplified aquifer system treats the Central Plains aquifer as being bounded by impermeable foothills, with groundwater discharging to surface waters near the coast, and extending along the length of the Plains. This system has bulk hydraulic properties, corresponding to the calibrated aquifers, but does not explicitly contain identifiable layers or zones of different properties. The dynamic response of groundwater discharge to groundwater abstraction is then dependent on the distance of the well from the discharge zone, in relation to the horizontal extent of the aquifer. The resulting model (Pulido-Velazquez *et al.*, 2005) predicts the same depletion as the analytical Glover and Balmer (1954) equation in the earlier time period but then, more realistically, accounts for the finite extent of the aquifer. There is no layer depth control explicit in the model though it has been verified using Modflow that deep abstractions react similarly to distant ones in terms of the model.

A.7 Eigenmodel of groundwater abstraction zones

For the purposes of groundwater management, it is sometimes more practicable to consider abstraction effects from zonal areas of land rather than on an individual well basis. The single-well Eigenmodel has been further developed into a zonal Eigenmodel for the purposes of this report on adaptive management. The zones can be designated in terms of distances from the groundwater discharge point.

Figure AA.1 shows example predictions from the zonal Eigenmodel (calibrated for Central Canterbury) applied to (in this case) four equal-area zones in which groundwater is abstracted at a constant unit pumping rate for four months in each year.

Zone 1 is furthest from the groundwater discharge point and Zone 4 is nearest. The response of depletion in groundwater discharge, caused by abstraction in each zone, is expressed as a time series in terms of the proportion of unit pumping rate. The time series begins when pumped abstraction is first applied and is shown in Figure AA.1 for a period of 20 years (240 months).

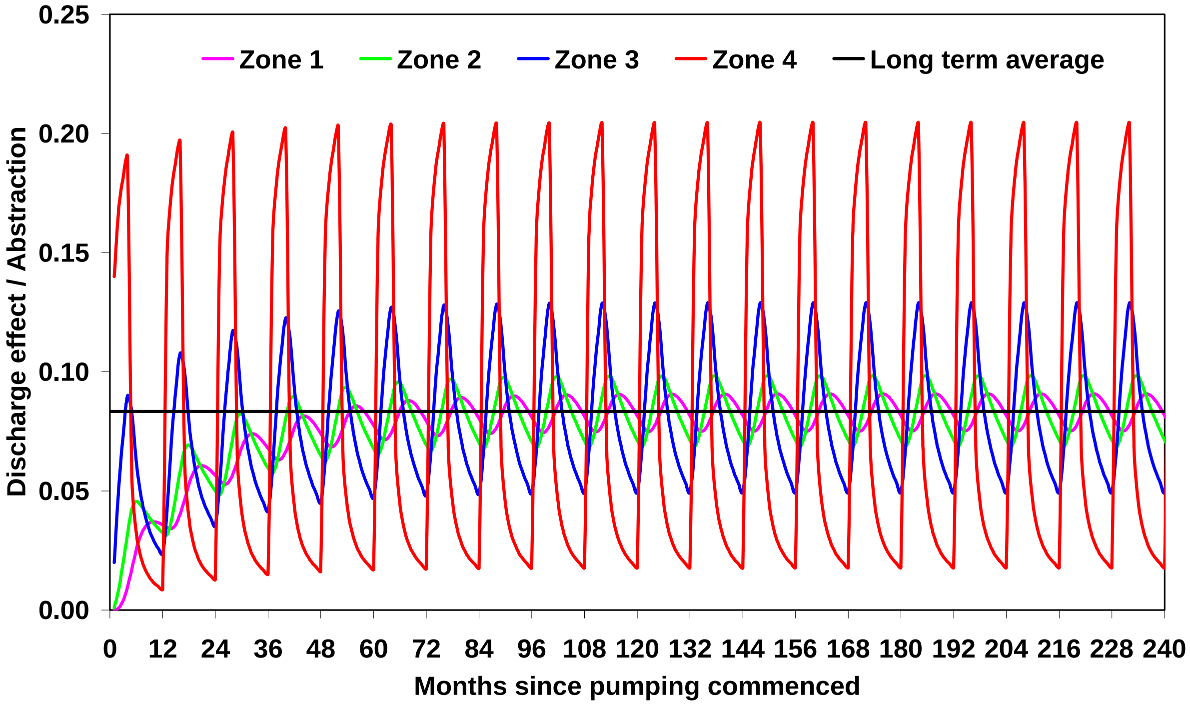

Figure AA.1: The reduction in groundwater discharge, as a proportion of pumping rate, caused by pumped abstraction for four months of the year in each of four equal-area groundwater zones. Zone 1 is furthest from the discharge point and Zone 4 is nearest.

The expected long term average depletion caused by each zone is given by the calculation:

Unit pumping x (4 months/12 months) x 1/4 land area per zone = 1/12 = 0.083.

This value is shown as “Long-term average” in Figure AA.1.

There are three important observations to be made about the results shown in Figure AA.1: the difference in magnitudes of annual fluctuations in depletion caused by abstraction in each zone; the time taken for the depletions from each zone to achieve their long-term annual pattern; and the difference in timing of the peak depletion in each year.

The depletion effect from Zone 1, furthest from the discharge point, has the smallest long-term annual peak value of 7 % deviation above the average line. It takes about seven years of operation for the full effect to occur, and the final peak value in year 7 is 2.4 times the value in year 1.

The depletion effect from Zone 4, nearest to the discharge point, has a long-term annual peak value that is 144 % above the average line. The annual peak increases by only 7 % from year 1 to year 7.

The time of occurrence of long-term peak depletion from Zone 1 occurs four months after the annual cessation of pumping, whereas the peak depletion from Zone 4 occurs at the end of annual pumping.

In summary, abstraction in Zone 4 has a large immediate effect at the end of the irrigation season when groundwater discharge to surface waters is usually at a minimum. In contrast, abstraction from Zone 1 has an effect close to the average value but the full effect is achieved only after several years. The small annual peak is also likely to occur during winter months when surface waters are less stressed. It is important to recognise that the long-term effect from Zone 1 will occur and will cause surface waters to become more sensitive to the larger annual peak depletions from Zone 4.

A.8 Significance of Eigen modelling to adaptive management

The foregoing description of the Eigenmodel method and its applications allows the following significant conclusions to be made:

1. Abstractions of groundwater in areas close to the natural discharge of the aquifer into spring-fed streams produce short-lived, seasonally variable declines in discharge.
2. The further an abstraction is from the natural discharge zone, the longer the period before which maximum effects are developed, but there is little respite from these effects during the period between abstractions.
3. Management of abstractions in inland areas will not produce short-term remediation of effects but will produce mitigation in the long term.

Appendix B: Exponential weighted moving average (EWMA)

The use of exponentially weighted moving averages (EWMA) is has the following advantages in comparison to simple moving averages (MA):

- Recent data are weighted more than past data
- It has a theoretical basis in statistical estimation of the time-varying mean of a time series
- Computation does not require storage of long datasets
- The EWMA can be initiated at the start of a time series with a prior average value, whereas MA requires a settling in series equal to the “window” length
- A continuous-time form of EWMA can be applied to data observed at uneven time intervals

Two helpful sources for the EWMA technique are footnoted below[28].

The exponential weighted moving average of a series of recharge values R_k, for example, can be calculated from the recursive function:

$$(EWMA)_k = \alpha*(EWMA)_{k-1} + (1-\alpha)*R_k \qquad (B1)$$

The parameter α in equation (B1) determines the relative weights given to the current observation R_k and the most recent value of $(EWMA)_{k-1}$. The table below indicates the percentage of prior values used in an exponential weighted moving average for different values of alpha and time period.

For example, for monthly data and an alpha of 0.35, approximately 50% of the weighted mean relates to values over the preceding 6 months, with the remainder relating to values prior to that. Similarly, 65% of the weighted mean relates to the current value, the remaining 35% relates to the weighted mean calculated from the preceding months.

	Alpha														
Months	**0.995**	**0.99**	**0.98**	**0.97**	**0.96**	**0.95**	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**	**0.4**	**0.35**	**0.3**	**0.25**	**0.2**
1	100%	99%	98%	97%	96%	95%	90%	80%	70%	60%	50%	40%	35%	30%	25%	20%
2	99%	98%	96%	94%	92%	90%	81%	64%	49%	36%	25%	16%	12%	9.0%	6.3%	4.0%
3	99%	97%	94%	91%	88%	86%	73%	51%	34%	22%	13%	6.4%	4.3%	2.7%	1.6%	0.8%
4	98%	96%	92%	89%	85%	81%	66%	41%	24%	13%	6.3%	2.6%	1.5%	0.8%	0.4%	0.2%
5	98%	95%	90%	86%	82%	77%	59%	33%	17%	7.8%	3.1%	1.0%	0.5%	0.2%	0.1%	0.0%
6	97%	94%	89%	83%	78%	74%	53%	26%	12%	4.7%	1.6%	0.4%	0.2%	0.1%	0.0%	0.0%
12	94%	89%	78%	69%	61%	54%	28%	6.9%	1.4%	0.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
20	90%	82%	67%	54%	44%	36%	12%	1.2%	0.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
24	89%	79%	62%	48%	38%	29%	8.0%	0.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
36	83%	70%	48%	33%	23%	16%	2.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
48	79%	62%	38%	23%	14%	8.5%	0.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Using an example with a much larger value of alpha, say 0.97, then only 3% of the mean relates to current data, the remaining 97% relates to preceding data.

The plots of recharge versus groundwater level (Figure 4-2) and surface flow (Figure 4-1) in the main body of this report have been prepared by optimising alpha by means of least-squares regression.

---

[28] Dealing with measurement noise: http://lorien.ncl.ac.uk/ming/filter/filewma.htm
Averaging and exponential smoothing models: http://www.duke.edu/~rnau/411avg.htm

The result of this is an improved relationship that yields information about the sensitivity of the mean to the inclusion of preceding values.

The mathematical form of equation (B1) is the same as that used for calculating drainage from the simple water storages that form the elements of the Eigenmodel of groundwater dynamics, described in Appendix A. This mathematical correspondence enables us to add a degree of physical realism to the value of the parameter α. Appendix A reports the dominant groundwater drainage rate for the Central Canterbury aquifer system as being 0.05 per month. The equivalent value of α for monthly data is given by: $\alpha = \exp(-0.05) = 0.951$. If this value is used for applying equation (B1) to smoothing monthly values of recharge, then the resulting EWMA series is very similar to the Eigenmodel predictions.

Appendix C: (ECan 2007a)

The Rakaia Selwyn Groundwater Zone – Technical summary of the effects of groundwater abstractions on stream flows and reliability of groundwater

Table of Contents

1. Introduction

1.1 Overview

In July 2006 Environment Canterbury (ECan) began the Restorative Programme for Lowland Streams. The programme aims to increase flows in lowland streams to ensure flows that will meet the requirements of lowland aquatic ecosystems, and improve reliability of supply for water users in the zone. The programme was initiated because instream values are being adversely affected due to lower than normal flows, and the reliability of supply for existing water users has reduced.

Following this, ECan announced its intention to consider reviewing water abstraction consents in the Rakaia-Selwyn groundwater allocation zone (the Rakaia Selwyn zone) in Canterbury. The aim of consent reviews would be to reduce the effects of water abstractions on lowland streams and provide long-term security of supply for existing consent-holders. Groundwater and surface water consents in the Rakaia Selwyn zone will be considered for review to achieve three key outcomes on consents:

1. Place annual limits on the volume of water allocated;
2. Provide for water metering to enable the measurement of actual use of water in the zone; and
3. Restrict groundwater abstractions directly linked to surface waterways during periods of minimum flow.

The fourth aim of the consent review initiative was to provide for varying seasonal limits depending on availability of water in the groundwater system – referred to by ECan as adaptive management or variable annual allocation. However, it has been decided not to consider applying adaptive management conditions to existing consents at this time. It is considered that more time is needed to develop an appropriate method for applying the adaptive management approach to existing consent holders.

1.2 Report Scope

The purpose of this report is to summarise the key information which is relevant to the effects of water abstractions in the Rakaia Selwyn zone. This information includes:

- Technical reports relating to the management of water in Canterbury, and the effects of water abstractions on groundwater and surface waterways.

- Chapter 5 of the proposed Natural Resources Regional Plan (NRRP) and Variation 4 to the PNRRP. This chapter deals with water quantity issues and was notified on July 2004. The variation was publicly notified on 23 June 2007. The plan is not yet operative. However the plan does contain objectives and policies which provide guidance on methods for managing the effects of groundwater abstractions on surface waterways.

- Evidence presented at the resource consent hearing held throughout 2006 to consider multiple consent applications to take and use groundwater in the Rakaia-Selwyn Groundwater Allocation Zone.

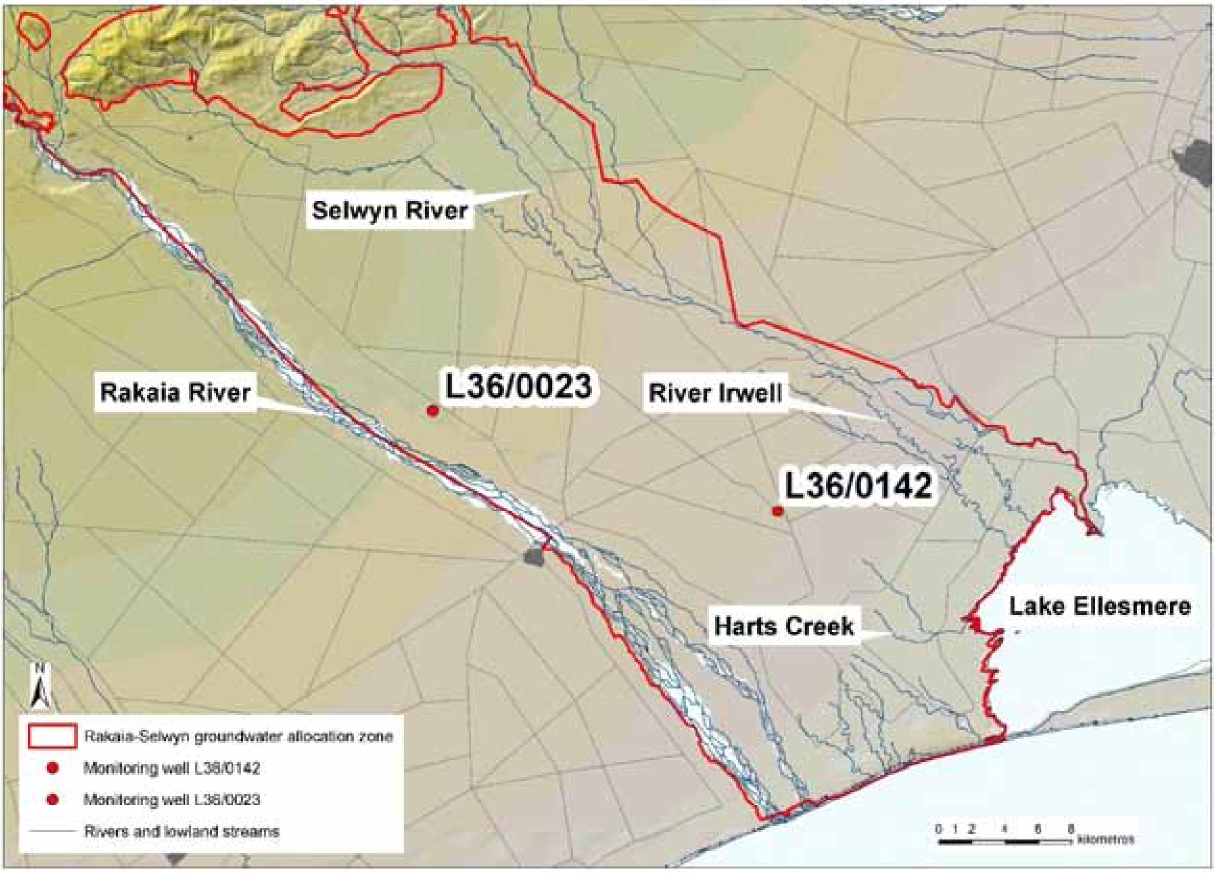

Figure 1.1: Map showing location of Rakaia-Selwyn groundwater allocation zone, waterways and monitoring wells named in text.

2. The Rakaia Selwyn Groundwater Zone

2.1 Introduction

The Rakaia-Selwyn Groundwater Allocation Zone was identified by ECan in 2004 (Environment Canterbury, 2004a). The location of the Rakaia-Selwyn Groundwater Allocation Zone is shown in Fig. 1.1. The zone covers an area of 128,452 hectares and forms the larger part of the Central Plains area between the Waimakariri and Rakaia rivers.

Chapter 5 of the proposed NRRP and the proposed Variation 4 sets out a groundwater allocation regime and allocation limits for each groundwater zone in Canterbury. A zone is considered to be over-allocated where ECan's assessment shows that the total amount of groundwater currently allocated exceeds the allocation limit. Up-to-date information about the effective allocation (as defined in the proposed NRRP) for all groundwater zones is available from ECan's website (www.ecan.govt.nz). As of 22 June 2007, the effective allocation for the Rakaia Selwyn Zone is 223.90 million m^3/year, which is 104.1% of the proposed allocation limit. Therefore the Rakaia Selwyn Zone is considered to be more than fully allocated, and categorised as a red zone.

2.2 Water resources issues in the Rakaia Selwyn Zone

In the Rakaia-Selwyn zone, surface water and groundwater are highly connected. Changes in groundwater level induce changes in the flow of spring-fed streams. Streams in the upper part of the catchment lose water to the ground; in the bottom part of the catchment, groundwater discharges to surface.

There are data that show groundwater levels and stream flows are reducing in the Rakaia-Selwyn Groundwater Allocation Zone (Figure 2.1).

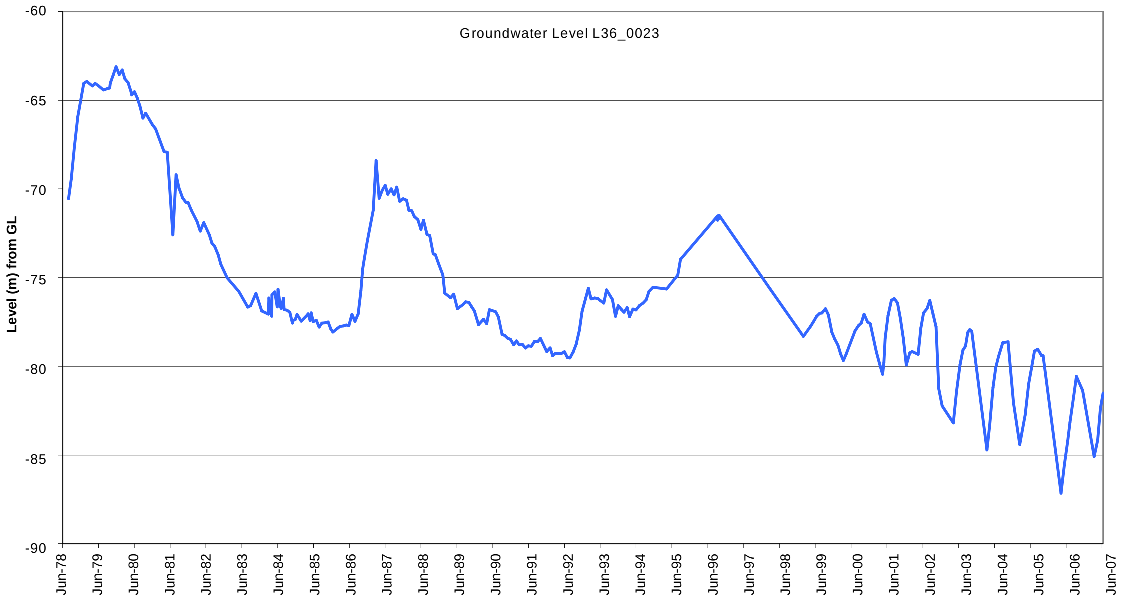

Figure 2.1: Plot of groundwater levels as monitored in bore L36/0023 (108.8 m deep) at Te Pirita

In the inland and mid-plains areas of the zone, groundwater levels have shown an inter-seasonal declining trend, particularly from 2002-2006, with current groundwater levels at similar or lower than levels during a dry period in the 1970's (Williams and Aitchison-Earl, 2006). Monitoring records show that the seasonal range in groundwater levels within individual wells is greater than at any time in the monitoring record. Some measurements suggest that drawdown can begin at the start of an irrigation season before full recovery from the previous season has been completed. Two examples are shown in figures 2.1 and 2.2.

Note that Figure 2.2 includes the 55 years of monitoring. With the exception of those flowing from within the Little Rakaia Zone south of Southbridge, the majority of flows in streams within the Rakaia-Selwyn Groundwater Allocation Zone are reducing (Horrell, 2006). The average number of openings per year of Lake Ellesmere/Te Waihora is also decreasing from 3.6 to 2.6 openings per year, causing the residence time of water in the lake to increase (Horrell 2006).

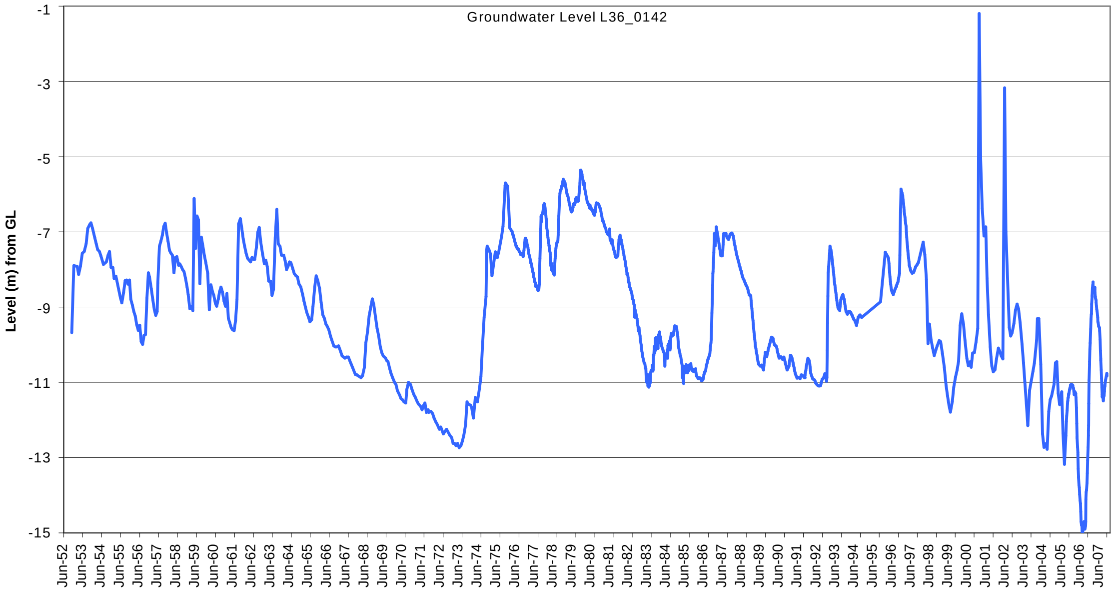

Figure 2.2: Plot of groundwater levels as monitored in bore L36/0142 (16.3 m deep) at Irwell-Rakaia Road

2.3 Effects of lowered groundwater levels and stream flows

2.3.1 Effects on water users

Reduced groundwater levels impact on groundwater users, and can cause supplies to dry up, or become less reliable. Anecdotal evidence from newspaper reports and complaints to Environment Canterbury indicates that groundwater users are being affected through wells going dry, or having a reduced yield. Similarly, reduced flows in streams may impact on both groundwater and surface water users who are subject to consent conditions requiring them to cease taking water when minimum flows are reached. There is some evidence that the reliability of supply to these consent holders is decreasing, as the length of time that streams are on restrictions or without flow has increased. Horrell (2006) presents data indicating that the Irwell was on restriction for 60 days in 1973/4, and the frequency of restrictions has increased to a mean value of 150 days per year in the last five years.

2.3.2 Effects on water quality and aquatic ecology

The surface waterways within the Rakaia-Selwyn Groundwater Allocation Zone have a range of values from limited value to very high cultural and ecological value (Hayward, 2006). The lowland streams feed into Lake Ellesmere/Te Waihora, which is recognised as one of New Zealand's most important wetland systems, and has very high cultural, ecological and commercial values. The streams and drains in the zone contribute about half to three-quarters of the water inputs to the lake, and reductions in inflows of freshwater may have significant impacts on lake ecosystem functioning (Hayward, 2006).

The water quality in the lowland streams in the Rakaia-Selwyn Groundwater Allocation Zone is typical of lowland streams in Canterbury, with the exception of the Irwell River (Hayward, 2006). Available data for the Irwell River shows that there has been a serious deterioration in the water quality and habitat value in the Irwell River as a result of low flows and dry periods (Hayward, 2006). The Irwell River is considered to be an indicator of the type of effects associated with severe flow reduction. For other waterways in the zone, such as the Selwyn River/Waikirikiri, Harts Creek and Birdlings Brook, moderate to high ecological and fishery values have been maintained, but are in serious threat of decline as a result of diminishing flows (Hayward, 2006).

While land use activities and stream maintenance works will also impact on stream health, there is evidence that declining base flows also contribute to the poor stream health (Hayward, 2006). Further loss of base flow in the lowland streams is likely to result in further and more permanent deterioration in stream health, which, combined with a loss of suitable physical habitat, is likely to result in the decline and possible permanent loss of sensitive invertebrate and fish species (Hayward, 2006). As winter baseflows decline over time, spawning gravels become unsuitably shallow for spawning trout. There is evidence that trout spawning reaches in the headwaters of the tributaries have lower baseflows than in the past, and lower numbers of spawning trout (Taylor, 2006). It is likely that in waterways throughout the Rakaia-Selwyn Groundwater Zone, lower baseflows, combined with poor riparian management, has adversely affected trout spawning reaches (Taylor, 2006).

2.4 Causes of lowered groundwater levels and stream flows

2.4.1 Climatic factors

Climatic variation will contribute to reduced rainfall recharge to groundwater, and hence reduced flows in streams. However, work done to date indicates strongly that the observed declines in groundwater levels and stream flows is not solely caused by changes in rainfall recharge (Williams, 2006). Data from the National Institute of Water and Atmospheric Science (Figure 2.3) demonstrates a slight decrease in monthly mean rainfall over the past 35 years.

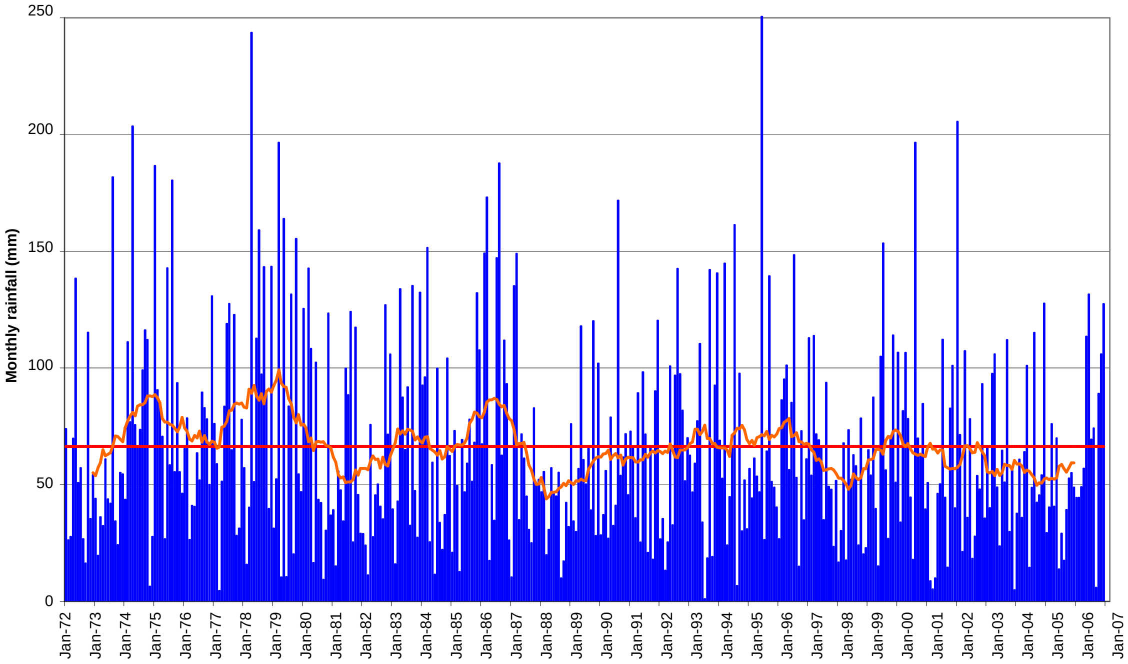

Figure 2.3: Plot of calculated monthly rainfall within the Rakaia-Selwyn groundwater allocation zone from data provided by NIWA. Red line represents monthly mean rainfall, orange line represents trend of 24-monthly mean.

2.4.2 Water Abstractions

Estimated volumes of groundwater allocation to resource consents have increased five-fold, from 42 million cubic metres to 228 million cubic metres since 1990, with the most rapid increases occurring after 2000 (Scott, 2006). Groundwater abstraction has increased to the extent where it is now a major part of the water budget for the Rakaia-Selwyn zone with the allocated amount of groundwater of 223.9 million cubic metres per year being a significant proportion of the estimated mean annual land surface recharge of 381.2 million cubic metres per year (Scott, 2006). Therefore groundwater abstractions are likely to be having a significant impact on groundwater levels in the zone (Williams, 2006).

Abstractions of surface water from lowland streams will have a direct effect on flows in the streams. Groundwater abstractions affect surface waterways through the following processes:

1. The direct effect of individual wells in the vicinity of flowing streams and springs (predominantly within 2 km, but dependent on the abstraction rate) over an irrigation season;
2. The effects of all groundwater abstractions that result in cumulative changes of stream and spring flows over an irrigation season;
3. Inter-seasonal, cumulative changes causing regional scale lowering of groundwater levels, and consequently, reducing flows into surface water ways.

Of these, the localised direct effects on streams can be managed by minimum flow conditions on consents for surface water abstractions and abstractions of hydraulically connected groundwater.

ECan carried out a preliminary desktop assessment to estimate the stream depletion effects of groundwater abstractions on lowland streams in the Rakaia-Selwyn Groundwater Allocation Zone (Environment Canterbury, 2006). The assessments were carried out in accordance with the guidelines in Chapter 5 of the proposed NRRP. The desktop assessment identified 130 consented abstractions which are likely to be hydraulically connected to streams and having a stream depletion effect. The total estimated stream depletion rate is 3073 L/s, of which 2610 L/s is assessed as having a low, moderate or high degree of hydraulic connection with surface waterways in accordance with Policy WQN8 of the PNRRP. The remainder of the effect would not be managed through minimum flow conditions under Policy WQN8 of the proposed NRRP. This suggests that impacts on flows in lowland streams can be reduced by the review of any consents abstracting hydraulically connected groundwater which are not currently subject to minimum flow conditions.

In addition to the direct impacts of hydraulically connected wells, there is evidence indicating that the reduced flows in lowland streams could in part be due to the cumulative effect of groundwater abstractions in the zone (Horrell, 2006). This is based on ECan records which show that for most streams, the number of surface water takes and shallow groundwater takes have not increased since 1990, whereas the number of deeper groundwater takes has increased. Streams showing declining flows have not exclusively experienced increases in direct surface abstraction or shallow groundwater abstraction.

A recent investigation into trends in the lower Selwyn River flows also suggests that water abstractions throughout the zone are contributing to reduced stream flows (McKerchar and Schmidt, 2007). In this study, Selwyn River flows monitored upstream at Whitecliffs from 1964 and downstream at Coes Ford since 1984 were compared to recharge and soil moisture deficit data. A multiple linear regression equation was developed to predict seasonal low flows at Coes Ford. A comparison of the predicted trend with observed values showed that the predictions provided were very good estimates of 90-day low flow events at Coes Ford. The trend implies that the low flows at Coes Ford have decreased at a rate of about 32 L/s per year over the 22 year period, after the effect of recent low-rainfall years is accounted for. The trend term in the equation is consistent with increased abstractions from Central Plains groundwater over the period of the recording. While it is concluded that the increase in irrigation abstractions is one reason for the decrease in flows, the impact is difficult to quantify without measurement of irrigation abstractions and data on irrigated area and irrigation use.

2.5 Proposed management of water allocation in the Rakaia Selwyn Zone

There is a range of management options to restore flows in waterways as part of the Lowland Streams Programme. Many are non-regulatory, and fall outside the consent review process. Of the regulatory methods, the four key outcomes that could be achieved through the consent review process are; setting limits on the amount of water abstracted annually, measurement of water use, minimum flow conditions, and adaptive management of water abstracted each season. As discussed earlier, ECan is not seeking to apply adaptive management conditions to existing consents at this time, as further work and consultation with consent holders needs to occur prior to a suitable adaptive management regime being devised. The other three outcomes being sought are outlined below.

2.5.1 Management of water abstracted seasonally.

The annual allocation limit is a coarse mechanism to limit abstractions to a volume able to be recharged and still allow an acceptable natural discharge from the groundwater system to be maintained. A varying seasonal limit (or adaptive management) is required to maintain the natural discharge of the system, or maintain groundwater levels, taking into account the recharge history and current resource state.

Schedule WQN9 and Policy WQN17 of the PNRRP will be used for guidance in determining reasonable and efficient use of water. Schedule WQN9 (Variation 2) of the PNRRP describes the methodology for determining seasonal irrigation demand (Environment Canterbury, 2005). Under the Schedule, seasonal irrigation demand is determined using land use, soil types, and effective irrigation season rainfall. The methodology uses values from Table WQN24 and Figure WQN12. Table WQN24 provides the total seasonal demand for different land uses and soil types. Figure WQN12 provides a map of effective irrigation season rainfall for northern and central Canterbury.

2.5.2 Measurement of water abstractions.

It is essential that water abstractions are accurately measured to allow for effective management of a water resource. Without accurate measurement of the volume of groundwater actually used, a comprehensive assessment of the state of the resource and the mechanisms by which the components of the resource respond to stress is uncertain. Therefore the requirement for flow meters and data loggers to measure and record water use will assist ECan in making decisions on water allocation, and effectively manage the resource.

2.5.3 Minimum flow conditions

The setting of minimum flow conditions on consents allows the direct impact of water abstractions on stream flows to be managed, as required under Policy WQN3 of the PNRRP. As discussed in section 2.4.2 of this report, a desktop study by ECan suggested that there could be approximately 130 consented groundwater abstractions having a direct impact on stream flows in the Rakaia Selwyn Zone. These consents will be considered further for review to determine if low flow conditions should be applied to these consents. The method set out in Policy WQN8 of the PNRRP will be the main method used to determine if low flow conditions are necessary, and in accordance with the policy, low flow conditions should be applied to any water takes considered to have:

- A high degree of hydraulic connection to a surface waterway (calculated for a seven day pumping period); or
- A moderate degree of hydraulic connection (calculated over a 150 day pumping period) and an estimated stream depletion effect exceeding 5 L/s.

For the preliminary assessment to determine which consents should be reviewed, the Jenkins (1977) method has been commonly used to assess potential stream depletion effects. It is acknowledged that other methods, such as the Hunt (1999), and Hunt (2003) method, may be more appropriate if sufficient data describing aquifer hydraulics and stream-bed clogging are available.

All surface water consents in the Rakaia Selwyn Zone will also be considered for review if they do not already include a low flow condition.

3. Summary of Proposed Review Outcomes

The potential review outcomes and the issues that they are related to are outlined below, with references to the key reports. These issues all relate to the key effects of concern - the impact on lowland stream ecology due to reduced stream flows, and the issue of reliability of supply for groundwater users.

Proposed review outcome	Issues	Key references
Annual allocation limits.	▪ Reasonable and efficient use of water. ▪ Cumulative effects on groundwater levels and consequently lowland stream flows. ▪ Reliability of supply for groundwater users.	▪ PNRRP – Chapter 5. ▪ Evidence from Rakaia Selwyn groundwater zone consent hearings. ▪ ECan report U04/02 on groundwater allocation limits.
Water metering to measure actual use.	▪ Lack of certainty about actual amount of water abstracted in the Rakaia Selwyn groundwater allocation zone, makes it difficult to determine the impact of abstractions on stream flows. ▪ Will enable compliance with consent allocation limits to be monitored, which will help manage reliability of supply issues, and impacts on stream flows.	▪ McKercher, A., and Schmidt, J (2007). ▪ PNRRP – Chapter 5. ▪ ECan report U04/02 on groundwater allocation limits.
Low flow restrictions on all surface water takes, and groundwater takes with high, medium or low connection (as per NRRP).	▪ Direct effects of abstractions on lowland stream flows.	▪ ECan report U06/03 on stream depletion effects within the Rakaia Selwyn Zone. ▪ Evidence from Rakaia Selwyn groundwater zone consent hearings. ▪ PNRRP – Chapter 5.

Howard Williams.
Groundwater Resources Scientist, Environment Canterbury. June 2007.

4. References

Environment Canterbury, 2004. Proposed Canterbury Natural Resources Regional Plan. Chapter 5: Water Quantity. 3 July 2004. Report No. R04/15/5

Environment Canterbury, 2004a. ‘Groundwater Allocation Limits: Guidelines for the Canterbury Region’. Environment Canterbury report U04/02.

Environment Canterbury, 2005. ‘Schedule WQN9 Revision. Review of seasonal use approach included in Proposed NRRP’. Environment Canterbury report U05/15/1.

Aitchison-Earl, P 2006. ‘Stream Depletion of the spring-fed lowland streams of the Rakaia Selwyn Groundwater Allocation Zone’. Environment Canterbury Report No. U06/3.

Environment Canterbury, 2006. Evidence presented at the hearings for consent applications to take and use water from the Rakaia Selwyn Groundwater Allocation Zone.

Haywood, S 2006. Evidence presented at hearing for Rakaia-Selwyn multiple applications, April 2006.

Horrell, G 2006. Evidence presented at hearing for Rakaia-Selwyn multiple applications, April 2006.

Hunt, B. 1999. ‘Unsteady stream depletion when pumping from semi-confined aquifer’ Ground Water, 37 (1), 98-102.

Hunt, B. 2003. Unsteady stream depletion when pumping from semi-confined aquifer. ASCE Journal of Hydrologic Engineering, 8, no.1: 12-19.

Jenkins, C.T., 1977., ‘Computation of rate and volume of stream depletion by wells’ in Techniques of Water Resources Investigations of the United States of Geological Survey, Chapter D1, Book 4, Rd Edition.

McKerchar, A.I. and Schmidt, J. 2007 Trend in the lower Selwyn River low flows? Submitted to Journal of Hydrology (NZ) 20 February 2007.

Scott, D 2006. Evidence presented at hearing for Rakaia-Selwyn multiple applications, April 2006

Taylor, K 1996. The natural resources of Lake Ellesmere (Te Waihora) and its catchment; Environment Canterbury Technical Report 96(7), 322 p.

Taylor 2006. Evidence presented at hearing for Rakaia-Selwyn multiple applications, April 2006.

Williams, H and P Aitchison-Earl 2006. Relationships between groundwater pressures and lowland stream flows in the Lake Ellesmere area; Environment Canterbury Technical Report No. U06/31, 25 p.

Williams, H 2006. Evidence presented at hearing for Rakaia-Selwyn multiple applications, April 2006.

Appendix D: Summary of estimated recharge from the Selwyn River and tributaries to the Rakaia-Selwyn Groundwater Allocation Zone (ECan 2006)

2 February 2006 Ref :

MEMORANDUM

FROM : **SURFACE WATER AND GROUNDWATER SECTIONS**

TO : **WAG**

CC

SUBJECT : **SUMMARY OF ESTIMATED RECHARGE FROM THE SELWYN RIVER AND TRIBUTARIES TO THE RAKAIA-SELWYN GROUNDWATER ALLOCATION ZONE**

Background

A 2nd order allocation limit has not yet been adopted for the Rakaia–Selwyn Groundwater Allocation Zone (GAZ) because of uncertainty in the recharge contribution from the Selwyn River and its tributaries.

A 1st order limit for the zone included a provisional estimate of 50 million m^3/year intermittent recharge from the Selwyn River. However, Scott (2004) advised caution before including provisional intermittent stream recharge estimates in highly allocated zones and recommended that the intermittent contribution from the Selwyn River to its adjacent zones (Rakaia–Selwyn and Waimakariri–Selwyn) should be critically reviewed before an allowance is included in updated limits. Recent work in the Rakaia–Selwyn Zone has looked at bringing the zone into a second order allocation regime, and has included an assessment of Selwyn River contributions to the groundwater limit.

As a result of the work detailed in this memorandum, it is considered that there is **no net-gain** from the Selwyn River to the Rakaia-Selwyn zone. Losses to groundwater from the Selwyn River and its tributaries are believed to be largely retained within the uppermost Burnham and Springston Formation gravels associated with the Selwyn Fan (within which the river flows). This groundwater emerges from these gravels to supply the lower Selwyn River, Wood Creek, the Irwell River, and arguably, the Hanmer Road Drain.

Figure 1 presents the locations of surface waterways and gauging sites described in this memorandum. Figure 2, modified from NZGS (1989), shows the geology of the upper part of the Selwyn catchment. Figure 3 presents a schematic oblique cross section, along the line shown in Figure 2.

The Selwyn Fan (Figures 2 and 3) is recognised as a litho-stratigraphic unit separate from the adjacent Rakaia and Waimakariri fans. It is significant to this study that a recent artificial recharge trial in the conceptually similar Eyre River has shown that most of the groundwater response to river flow has occurred within the Springston and Burnham gravels associated with that river, and that adjacent aquifers are relatively unaffected.

Whilst it is acknowledged that there are surface water losses to aquifers underlying the Selwyn River and its tributaries, upwards groundwater pressures adjacent to Lake Ellesmere force most of this groundwater to the surface to contribute to the lower catchment streams. These streams are considered to be particularly dependent on the upstream inputs from the Selwyn River and are distinct from the streams and drains further south (including Doyleston Drain and Harts Creek) which are driven by groundwater derived mainly from land based recharge. Accordingly, no inputs from the Selwyn River should be included in a 2nd order allocation limit.

The calculations and reasoning associated with the Selwyn River contribution to the Rakaia - Selwyn Groundwater Allocation Zone are summarised below and were covered in more detail in a Surface Water Section Memorandum (Gabites et al., 24/11/05).

Calculation of Net Recharge Contribution from the Selwyn River and Tributaries

Selwyn River Inputs

Rivers considered in this assessment include the Selwyn, Hororata and the Waianiwaniwa (formerly Waireka), as shown in Figure 1. The Hawkins River, which flows into the Selwyn from the northwestern side of the plains, rarely links with the Selwyn River, and is considered to contribute most of its flow to the Waimakariri - Selwyn Groundwater Allocation Zone. Therefore, any flow contribution by the Hawkins to the Selwyn is brief, and has been excluded from this assessment (Figure 4).

All of the flow from these upper catchments is lost to groundwater for the majority of the year, with the result that the middle reaches of the Selwyn River are typically dry. The Selwyn only flows for its full length after extended periods of heavy rain, and the surface flow length is highly dependent on groundwater levels. High groundwater levels mean that water drains out of the river more slowly, and vice versa. In the lower reaches of the river, flows normally emerge from groundwater at about McGregors or Withells Road fords (Figure 1).

Whilst it is conventional to characterize river flow by the value of its median flow statistic, such an approach is not valid when dealing with annual volumes. Mean flow provides the best estimate of inflow to (and outflow from) a groundwater system as it includes flow regime variability, including floods and low flows. Mean flow allows assessment of the volume of flow over a period, making it appropriate for the assessment of recharge volumes; rather than using median flow values that measure only central tendency.

Flow statistics for the three upper Selwyn tributaries were derived by comparison of selected gauging sites with low, median, and mean flow statistics for 41 years of recorder data from the Selwyn River at Whitecliffs (Figure 1). The gauging sites were the main stem of the Selwyn River at Coalgate, the Hororata River at SH72, and the Waianiwaniwa River at Malvern Hills Road. Regression analyses were used to compare gauging data from the three tributaries to the Whitecliffs data and subsequently derive the statistics summarised in Table 1. The regression relationships showed good matches with r^2 values between 0.88 and 0.98 (Table 1).

Table 1: Flow statistics for the three upper tributaries of the Selwyn River contributing to the Rakaia – Selwyn Groundwater Allocation Zone.

Tributary Gauging Site (Inputs)	**Mean Flow (L/s)**	**Regression fit with Selwyn River at Whitecliffs (r^2)**
Selwyn River at Coalgate	4152	0.98
Hororata River at SH72	554	0.92
Waianiwaniwa at Malvern Hills Rd	142	0.88
Total	**4848**	
Flow already accounted for by rainfall recharge in RSGAZ (to be subtracted) [Pink on Figure 4] (see box below)	660	
Area outside RSGAW zone that may contribute water at mean flows (to be added) [Blue on Figure 4] (see box below)	107	
Estimated total recharge from Upper Selwyn Catchment	**4295**	

Adjustments to inputs

Figure 4 shows that there are some areas where groundwater allocation zone (GAZ) boundaries do not fully incorporate or match surface catchment boundaries, e.g. the upper Hawkins catchment lies within the Waimakariri-Selwyn GAZ, while the upper Selwyn catchment lies within the Rakaia-Selwyn GAZ. This is due to the fact that the boundaries of groundwater allocation zones are driven by geological and planning considerations. Surface water catchments are delineated by topography alone. Where this overlap or mismatch occurs, some adjustments to the way in which the calculations for each groundwater allocation zone water budget need to be made.

Figure 4 contains areas in pink that represent parts of the GAZ that lie within the upper Selwyn catchment whose contribution to flow (660 L/s) is measured at Coalgate (Table 1). A flow of 660 L/s was estimated from Environment Canterbury's annual mean discharge isohydal map for these pink areas. To avoid 'double accounting', their contribution should be removed from the Selwyn flow, because their contribution is assessed as part of the GAZ land surface recharge. The small areas on the south-eastern side of the foothills (shown in blue in Figure 4) which lie outside the boundaries of the Rakaia- Selwyn GAZ contribute an estimated mean flow of 107 L/s, which has been included in the assessment of total surface water recharge (Table 1). These additions and subtractions have been based on estimates derived from ECan isohydal maps.

Evaluation of intermittent stream flow contributions to the Rakaia-Selwyn GAZ has been based on isohydal map-based catchment yields that are effectively equivalent to soil moisture model based rainfall recharge estimates. The validity of this method has been verified by comparing the yield and recharge estimates for a sub-catchment of the upper Selwyn catchment in the Rakaia-Selwyn GAZ (labelled 'A' in Figure 4). The following statistics have been derived to identify the intersection of the upper Selwyn catchment and the Rakaia-Selwyn GAZ and to calculate the weighted sum of the calculated mean annual total drainage within that area:

Rakaia-Selwyn GAZ sub-area = 1543 ha
Mean annual rainfall recharge = 460 mm/y
Equivalent flow rate = 225 L/s

The isohydal based estimate of catchment yield for the same area 'A' is 110 L/s which, given the uncertainties involved in calculating these quantities, could be regarded as being approximately equivalent to the rainfall recharge.

It has been estimated (Gabites, et al, 24/11/05) that the Selwyn River at Coalgate contributes 4152 L/s to the zone, 110 L/s (Suzanne Gabites, pers. comm.) of which is derived from the 1543 ha included in the Rakaia-Selwyn GAZ. However, a mean annual recharge rate of 460 mm/y from that sub-catchment has already been incorporated in the zone total. If it is assumed that the catchment yield includes negligible surface runoff then this suggests that 49% (110/225) of the sub-catchment recharge contributes to the surface flow at Coalgate, which seems a reasonable proportion. The calculated catchment yield of 4152 L/s should, therefore, be reduced by the sub-area contribution (110 L/s) to provide an estimate of the net surface water contribution. This type of calculation has been undertaken for all the pink and blue areas, to produce the combined totals in Table 1.

A total mean flow for the upper Selwyn tributaries of 4295 L/s was derived (Table 1), almost all of which is lost by seepage to groundwater. This loss occurs either before the tributaries reach the Selwyn or before the Selwyn main stem reaches Ridgens Road.

Freshes and floods will contribute to this mean value, however, these events have relatively short duration. For example, the Selwyn River at Whitecliffs flows at greater than 20 m^3/s (a sizeable fresh) for only about 1% of the time. Hence these flood events do not skew the long term mean volume to excessively high values. This is reasonable since even floods such as the one in August 2000 (the largest on record) did not have a significant long-term impact on local groundwater levels (a rise of 1 to 2 m in wells close to the Selwyn lasted for several months).

Outputs

Regression equations derived by Facer and Horrell (2002) were also used to estimate flow statistics for the streams and springs (Figure 1, blue dots) emerging from groundwater in the lower Selwyn catchment. These include the Selwyn River at Coes Ford, Wood Creek, Irwell River and the neighbouring Hanmer Road Drain (Table 2). These streams are considered to be predominantly dependent on upstream losses from the Selwyn River because of the close proximity of their headwater springs (Figure 1) to the Selwyn River. These streams respond to varying flows in the Selwyn River because they rise from the same shallow gravel unit which is locally recharged by the upper Selwyn. Water quality data suggest that there is a component of direct plains rainfall recharge included in these waters, but that river recharge, characterised by low nitrate concentrations, is significant (Hanson 2002). Although rainfall recharge over the Selwyn River area will supplement river recharge, this will be balanced in part by water lost from the upper Selwyn River contributing to the broader (and deeper) groundwater system.

Less water is available to recharge groundwater in the upper Selwyn catchment than is indicated by the derived mean flow in Table 1 because an average flow rate of 557 L/s is allocated to consented surface water abstractors. A large proportion of this is for stock water and rural supplies, and these are considered to be abstracted throughout the all year; only 80 L/s average daily abstraction rate is consented for irrigation. The total calculated annual abstracted volume is 15.6×10^6 m^3/y (represented by 15×10^6 m^3/y for stock/rural supplies; and 0.6×10^6 m^3/y for irrigation using a Schedule WQN9 based assessment of permitted annual volume).

The total mean output from these four streams, all of which are dominantly derived from seepage from the Selwyn River, is assessed as 4357 L/s (Table 2).

Table 2: Flow statistics for four streams associated with the Selwyn River emerging in the lower catchment of the Rakaia – Selwyn Groundwater Zone.

Springfed Stream Gauging Site (Outputs)	Mean Flow (L/s)
Selwyn River at Coes Ford	3341*
Wood Creek at The Lake Road	33
Irwell River at The Lake Road	687
Hanmer Road Drain at The Lake Road	296
Total	**4357**

NB: * denotes actual Selwyn flow record at Coes Ford. Wood Creek and Irwell River are estimated from Coes Ford base flow record. Hanmer Road Drain is estimated from Doyleston Drain record.

Summary and recommendation

On the basis of these calculations the water balance for the Selwyn River in the Rakaia – Selwyn Groundwater Zone is summarised in Table 3.

Table 3: Water balance.

Components of Water Balance	Average Instantaneous Rate (L/s)	Average Yearly Volume (x 10^6 m^3)
Upper Selwyn tributary inputs	***4295***	***135.4***
Allocated Upper Selwyn surface water takes	***557***	***15.6***
Total Upper Selwyn contribution	3738	119.8
Lower Selwyn catchment stream outputs (excluding Hanmer Road Drain)	4061	128.2
Net contribution of Selwyn River to Allocation Zone	**-323**	**-8.4**

Table 3 shows that the mean inflow at the top of the catchment totals 4295 L/s (135.4 x 10^6 m^3/y), but after consideration of existing allocation from surface water this figure reduces to 3738 L/s (119.8 x 10^6 m^3/y).

Even when the discharge to Hanmer Road Drain is excluded on the basis that rainfall recharge on the plains influences this stream more than for streams closer to the Selwyn River, the flow emerging from the gravels associated with the Selwyn Fan is approximately equivalent to the total upstream loss. **Hence there is no net gain to the groundwater zone from the Selwyn River.**

The 2nd order allocation limit and resulting zone status based on the above figures is set out in Table 4.

Table 4: Rakaia-Selwyn Groundwater Allocation Zone Status

	Annual Volume ($\times 10^6$ m^3/y)
Land-based recharge estimate (Scott, 2004)	***429.9***
Selwyn River contribution (this study)	0
Recommended 2nd order groundwater allocation limit	**215.0**
Current effective allocation (valid 19/12/2005)	228
Current part of effective allocation drawn from Rakaia River by stream depletion (valid 18/1/2006)	7.8
Adjusted current effective allocation*	**220.2**
Current zone status	**Over allocated by 5.2 x 10^6 m^3/y (RED), i.e. 102% allocated**

NB: * 'effective allocation' means calculated usage by consented users.

References

Anderson, B. (1994) *Groundwater between the Selwyn and Rakaia rivers, Canterbury, New Zealand,* MSc thesis, University of Otago.

Facer, S. and G. Horrell (2002) *Estimates of Mean Annual Low Flows for Lake Ellesmere tributaries and streams in the Little Rakaia Zone*, Environment Canterbury Unpublished Report No. U02/29.

Gabites, S., Ettema, M., & G. Horrell (2005) *Estimated input from the intermittent flows of the Selwyn River and tributaries to the Rakaia- Selwyn and to the Waimakariri – Selwyn Groundwater Allocation Zones,* Environment Canterbury internal memorandum, 24 November 2005.

Hanson, C. R. (2002) *Nitrate concentrations in Canterbury groundwater – a review of existing data.* Environment Canterbury Report No. R02/17, ISBN 1-86937-457-6.

NZGS (1989) *Quaternary Geology of Northwestern Canterbury Plains*. Miscellaneous Series Map 14, New Zealand Geological Survey, Department of Scientific and Industrial Research.

Scott, D. (2004) *Groundwater Allocation Limits: Land-Based Recharge Estimates.* Environment Canterbury Unpublished Report No. U04/97.

Smith, E. (2004) *Seven Day Mean Annual Low Flow Mapping for the Upper Selwyn River Catchment*, Environment Canterbury Unpublished Report No. U04/50.

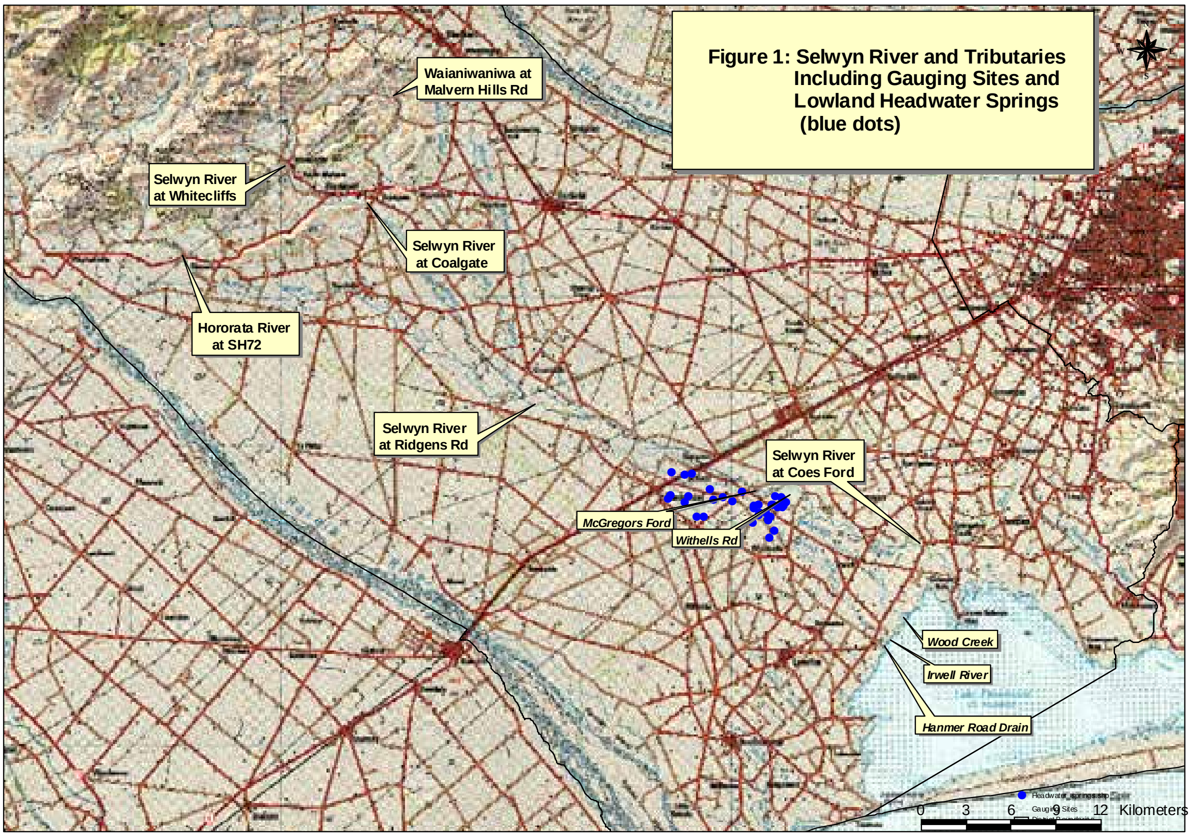

Figure 1: Selwyn River and Tributaries Including Gauging Sites and Lowland Headwater Springs (blue dots)

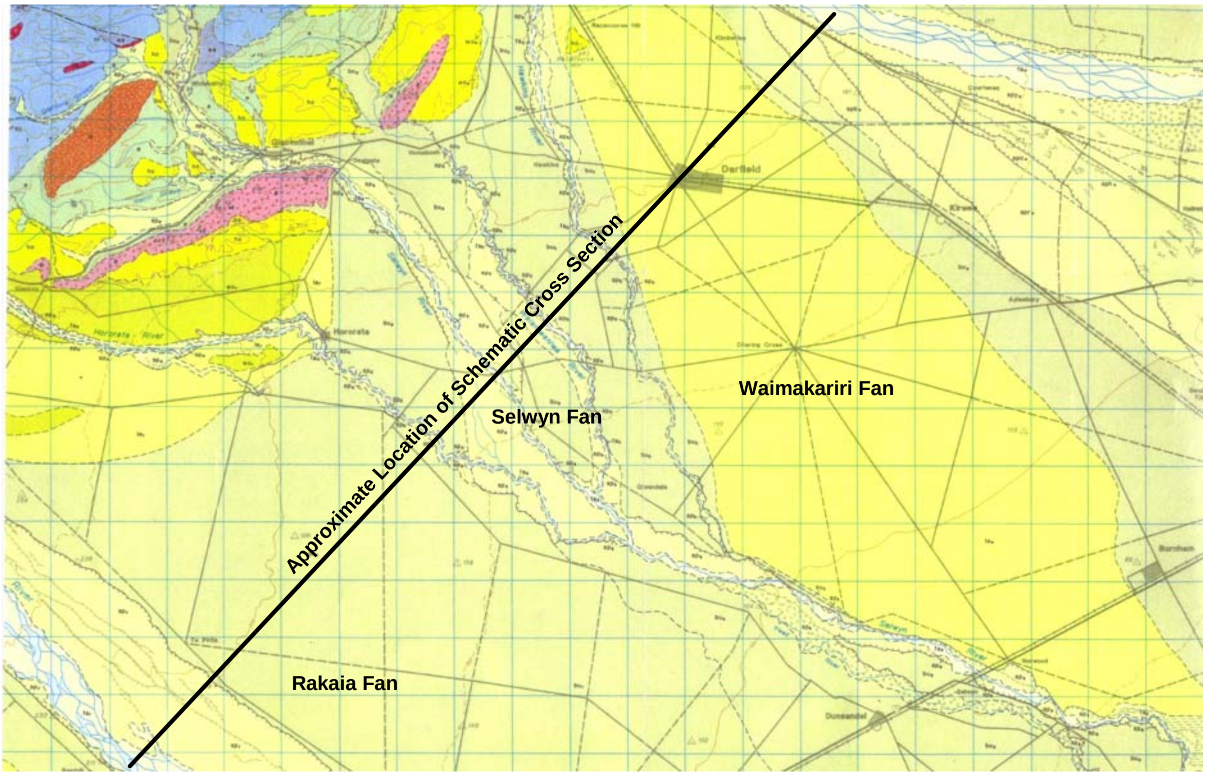

Figure 2: Geology of the upper and mid Selwyn catchment (modified from NZGS, 1989).

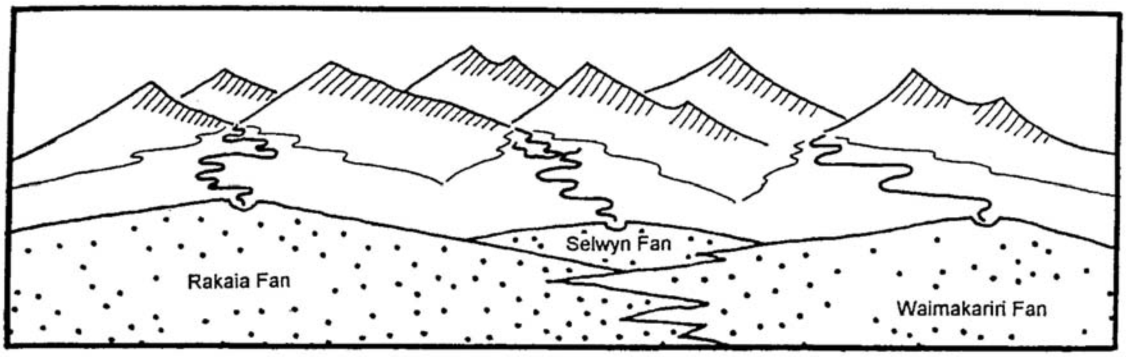

Figure 3: Schematic oblique view cross section, looking northwest, showing alluvial fan structure of the Selwyn plains (Anderson 1994).

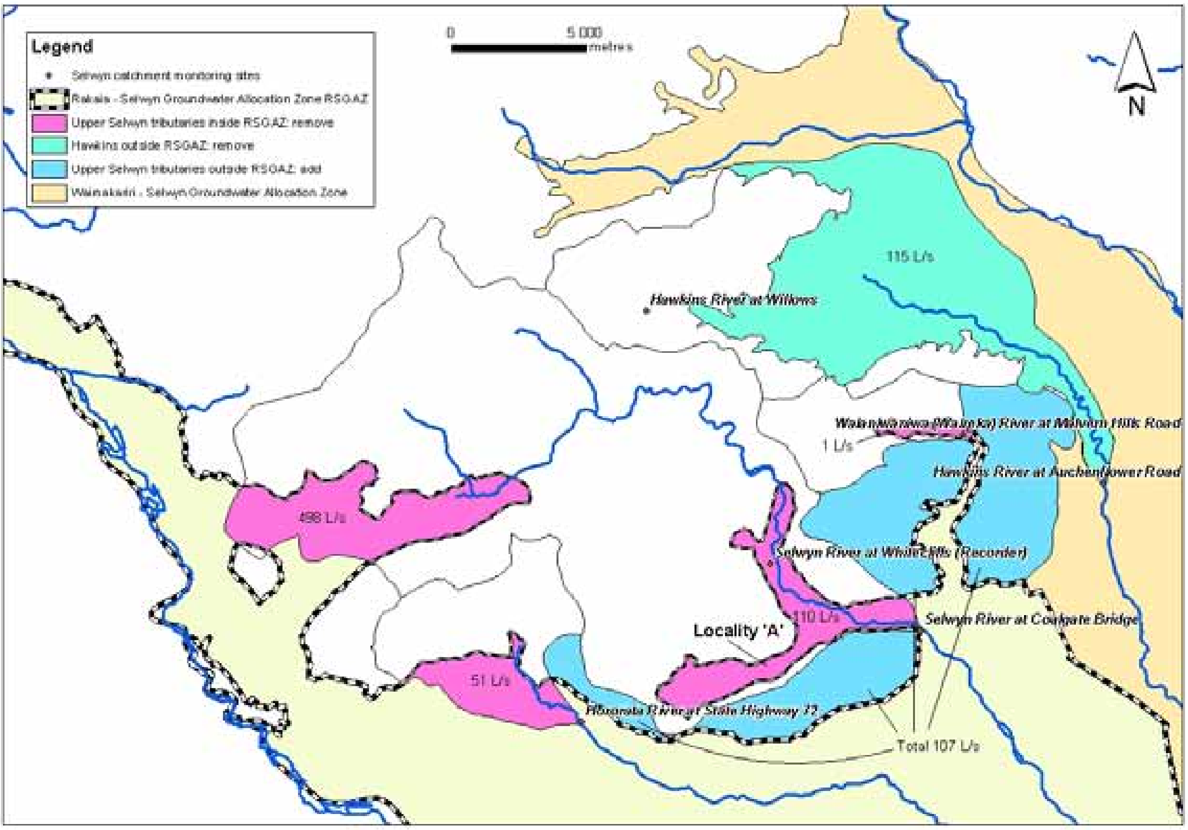

Figure 4: Map showing boundaries of the Groundwater Allocation Zone, the catchments and sub-catchments of the Selwyn main stem and their contributions, and Area 'A'.

Appendix E: Description and critical assessment of the Davoren adaptive management method

A means of providing adaptive management was developed on behalf of a large number of applicants for abstraction consents in the Rakaia-Selwyn groundwater allocation zone in 2006-7 (Davoren 2007). This method is described in detail here because it is complex and it is necessary to show why the Region has not chosen it as the preferred method.

There is merit in the conceptual thinking behind in the Davoren method. Difficulties associated with its implementation mitigate against our recommending the Davoren method to Council.

The method relies upon triggers related to the state of the groundwater resource at both the beginning and end of the irrigation season and made allowance for cumulative effects by assessing the expected recession in groundwater levels over that period. If sufficient groundwater was present at the beginning of the season to allow for the expected recession, then full entitlement could be exercised. In this section we briefly describe the method, and then indicate some of its advantages and drawbacks.

The Davoren mechanism of adaptive management is being implemented for over sixty-five Rakaia-Selwyn applicants, and for 41 Selwyn-Waimakariri applicants, a decision on this hearing was published recently, but is yet to be implemented. For the RSGAZ the first season will be the 2008-09 irrigation season as a result of it being approved as a method by the Commissioners for the Rakaia-Selwyn hearing (Final decision released February 2008).

Currently, the Davoren method is to be implemented for over 65 recently-decided takes in the Rakaia-Selwyn Groundwater Allocation Zone and has been mooted for a further 41 takes in the neighbouring Selwyn-Waimakariri Groundwater Allocation Zone. During the Rakaia-Selwyn Hearing, the Commissioners suggested that Environment Canterbury might like to entertain implementation of the Davoren method for all existing takes in that zone. Submitters to Variation 4 of the PNRRP took the Commissioners’ suggestion and proposed that it be implemented right across the Region.

Overview of Davoren method

The method is under-pinned by the reasonable assumption that although the cumulative effects of individuals are hard to isolate and quantify, a method can be devised to manage the long-term decline in groundwater levels, so that at least part of the adverse effects of additional takes can be managed (Figure AE.1).

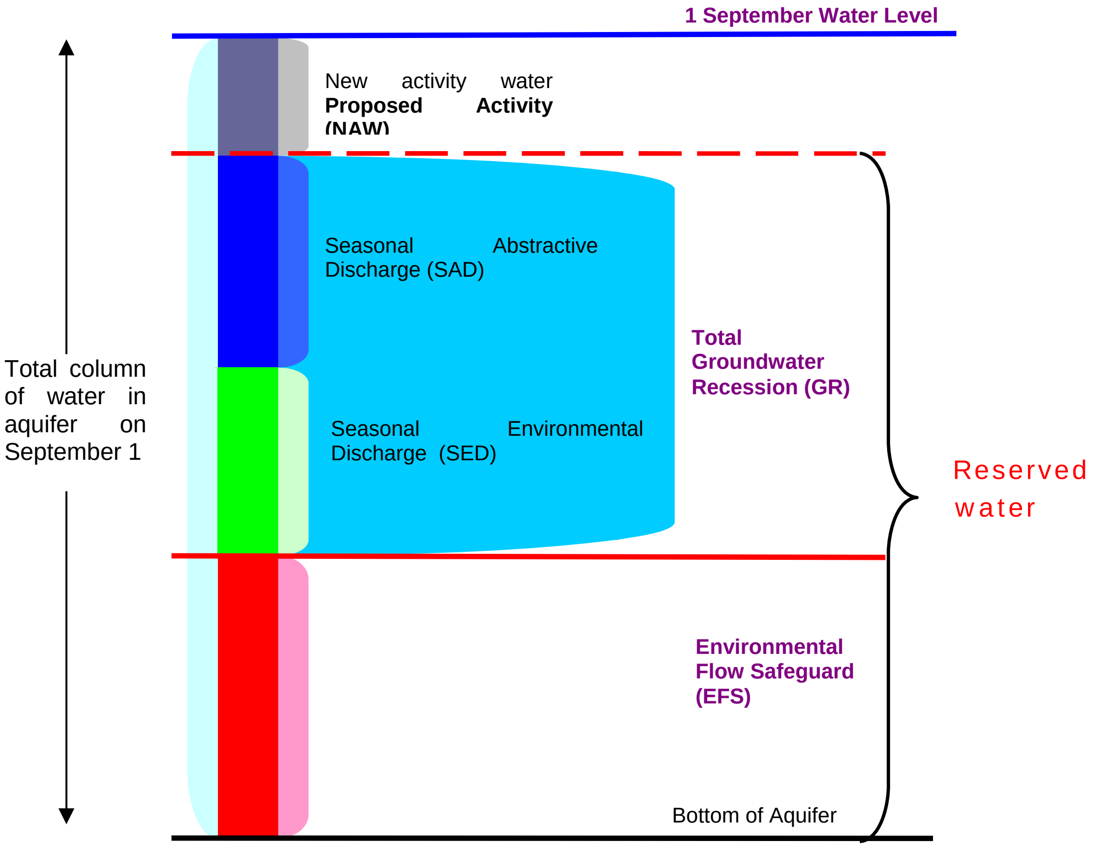

Figure AE.1: **Schematic representation of groundwater level triggers and recession thicknesses associated with Davoren method**

Groundwater levels naturally decline during the summer season because recharge cannot keep up with natural discharge to streams and through the coast (referred to as: SED, green in Figure AE.1). In the Central Plains, especially, the magnitude of this decline or ‘recession’ has for some decades been modified by increased abstraction and use for irrigation (referred to as: SAD, dark blue in Figure AE.1). The current monitored groundwater recession therefore includes components caused by both natural and abstraction causes (referred to as: GR, medium blue in Figure AE.1).

The Davoren method relies upon groundwater level triggers related to the state of the groundwater resource at both the beginning (September 1st) and end (30th April) of the eight month irrigation season and makes allowance for cumulative effects by assessing the expected recession in groundwater levels over that period.

ECan is mandated to protect the summer flows in spring-fed streams. To do this effectively, a realistic groundwater level trigger (Environmental Flow Safeguard EFS, red line in Figure AE.1), operating much like a target, has been set, below which the resource state should not decline, on a specific date, currently 30th April. This is problematic because not all parts of the aquifer system will be at their lowest at the same time, and not necessarily at 30th April. Ideally, the EFS should be set in such a way that a desirable environmental outcome is likely. Once set, then the corresponding trigger at the start of the irrigation season (1st September, dashed red line in Figure AE.1) can then be calculated as the EFS plus the recession.

The increased recession resulting from a new consent is not measured; instead a proxy is used, represented by the 150 day drawdown in a virtual bore at a distance of 750 m from the applicant's bore (known as: NAW, grey in Figure AE.1). This drawdown resulting from the applicant's activities is also added to the EFS and Groundwater Recession.

For a **new** consent, if at 1st September groundwater levels are higher than the combined total of these three values (EFS, GR and NAW), then the applicant has an entitlement to take water. If insufficient groundwater is stored, and groundwater levels at the beginning of the irrigation season are below this combined trigger, and are not more than the sum of EFS and the GR, then no groundwater entitlement can be allocated. If the stored groundwater is at a level between these two triggers, then the entitlement volume is pro-rated such that the lower trigger is not breached.

For **existing** consents that are being reviewed or renewed, then only the EFS and GR are used to develop the triggers. This is on the basis that existing consent holders have been contributing to the overall recession (cumulative effects), so their continued activity will not necessarily increase it.

Although aquifer specific EFS triggers have been set they may not be sufficiently conservative to prevent groundwater levels to dropping below those that contributed to the low flows during the period 2001 to 2006. Ideally, the EFS should protect the discharges of lowland streams from dropping below their minimum (environmental) flows. In the RSGAZ, even the **existing** consent conditions failed to do this; the 69 new consents, regardless of any adaptive management conditions, will likely exacerbate these low discharges in streams under certain prevailing climatic and recharge states because the trigger levels (EFS) will allow these low flows and groundwater levels to be re-visited. It should be recognised, however, that the Commissioners in the Rakaia-Selwyn decision were convinced that there would be times when more abstraction could occur without inducing more than minor effects.

One side effect of implementing adaptive management of groundwater throughout the RSGAZ is that it will improve the reliability of existing consent holders constrained by Davoren-method conditions.

Data required for implementation

If the Davoren method is to be implemented for the entire RSGAZ, and indeed for the whole Region, the data required of each user prior to implementation would consist of the following:

A report for each new user detailing:

- a seven day constant rate aquifer test to provide information on aquifer properties, including transmissivity, storativity, leakage, in order that the NAW, stream depletion effect and leakage from overlying aquifers may be calculated.

A report for each existing user detailing:

- For many existing users, where a good pumping test is not available, a seven day constant rate aquifer test, as per new users, to provide information on aquifer properties, including transmissivity, storativity, leakage, in order that the stream depletion effect and leakage from overlying aquifers may be calculated to determine whether stream depletion conditions related to the uppermost water-bearing strata need to be imposed.

For all users, a report detailing:

- a localised assessment of groundwater levels on 1st September and 30th April involving one or more bores neighbouring the user, or failing that, a modelled value until such time as actual values can be determined;

- A localised assessment of the EFS by relating groundwater levels for each applicant bore to a standard EFS;

- For each new user, the calculated drawdown (NAW) in a virtual bore at 750 m distance from each applicant caused by the applicant's abstraction, the localised drawdown effect acting as proxy for the applicant-induced recession;

- Use of aquifer properties and pumping rate to yield an assessment of the likely drawdown effects on groundwater levels in overlying strata that could result in reduction in discharge to spring-fed streams.

In addition to these one-off reports, a report detailing the groundwater levels and recessions for each user would be required for verification by monitoring and enforcement staff just before the onset of each upcoming irrigation season; approximately 600 in the RSGAZ alone, some 2800 for the Region as a whole. This maximum natural and abstraction-related groundwater recession (in metres) for the period between 1st September and 30th April would be determined from measurements, or modelled until such time as user-specific measurements become available. This has implications on staffing levels, and on costs that the Rakaia-Selwyn decision indicated would lie with the consent holder.

Ease of implementation

New users and those seeking increased volumes would be required to undertake a seven day pumping test in order to determine their potential effects on other users, to determine the NAW depth, and any effects on overlying water-bearing strata and spring-fed streams. Existing users subjected to this management proposal would not need to undertake an aquifer test, providing their existing aquifer test informed a precise assessment of the level of leakage and effects on overlying strata and spring-fed streams.

Although Environment Canterbury technical officers favour more comprehensive aquifer testing, they are of the opinion the Davoren method is likely to be arduous, time-consuming and expensive to monitor and enforce, leading to large seasonal changes in effort and necessary manpower. These disadvantages were foreshadowed by a report for Environment Canterbury that looked into issues and options for water allocation (CRC 1994).

Our reason for this opinion is that there is a large number of consents in each allocation zone in Canterbury, and for each consent there is much data to collect before the method can be implemented. The costs of the implementation and enforcement of the conditions, would likely fall on the consent holder, according to the Council's user pays policy.

Although many users have had rudimentary aquifer tests carried out on their bores, few have had good quality constant-discharge test data collected that would satisfy the requirements of the Davoren-type consent conditions. As a result, the drawdown in a virtual bore, or NAW, a means of assessing the applicant's contribution to a regional-scale interference effect, is poorly constrained. Similarly, the absence of well-documented hydraulic connection with overlying aquifers means that potential effects on bores in overlying strata are poorly-constrained, and adverse effects on spring-fed streams, unknown.

In addition, few users have collected sufficiently precise groundwater monitoring data to allow a localised assessment of their individual groundwater trigger levels for 1st September and 30th April. The Canterbury Plains aquifer system commonly exhibits differences in groundwater level in wells screened at different depths. Therefore, the EFS for a particular well needs to be measured, or modelled. In this respect, the Davoren method splits users into groups based on the depth of their screens, relating to different water-bearing layers. Although groundwater levels at these various depths can be modelled, reliable monitoring data for all wells, at the many different screen depths, is available, but not sufficiently precise to use for a robust prediction of EFS and Recession for each individual well. Similarly, the accuracy of numerically modelled groundwater levels is unlikely to be sufficient to provide users, or the Council, with a robust means of justifying the entitlement on the basis of predicted EFS and Recession values.

Priority of entitlement

In Canterbury, priority of entitlement is currently based on 'first come, first served'. Implementation of the Davoren adaptive management mechanism may mean that some users will be denied an entitlement if their groundwater levels have failed to rise above the trigger. The reliability of a user's entitlement will not be known until the mechanism has been running for a few years and, for the Rakaia-Selwyn applicants, it is anticipated that deeper takes and, those distant from the spring-fed streams will initially enjoy better reliability as a result of the permissive[29] EFS values imposed by Commissioners on behalf of Environment Canterbury.

Current holders of consents shortly to be constrained by the Davoren method will have differing supply reliabilities contingent upon the specific aquifer properties in the area around their particular abstraction and on their leakage potential. It would appear from preliminary examination of the aquifer characteristics around each consent holder that in any season, some users may have water available, others not. It is expected that the reliability of access to an entitlement will increase with depth though this has yet to be proven by monitoring.

Similarly, although modelling of seasonal groundwater level recessions has been undertaken, the accuracy of these is variable. Comparison of modelled and monitored groundwater levels and recessions for the Commissioners in the Rakaia-Selwyn Hearing indicated that the accuracy of modelled groundwater recessions does not provide a robust means of justifying a consented entitlement.

If the Davoren method of adaptive management were to be adopted over an entire allocation zone, and the triggers set were subsequently found to be incapable of providing the environmental protection required to maintain environmental flows in streams, then further changes to the EFS and perhaps the GR would be required. Such changes would require consent reviews, with cost and time implications similar in scale to that incurred for the Restorative Programme for Lowland Streams.

Prediction of environmental effects

A major disadvantage of the Davoren method is that it does not allow direct correlation of cause and effect. It is designed to reduce the likelihood of continuing long-term decline in groundwater levels, which only indirectly would arrest the decline in spring-fed stream flows. In this regard, the mechanism is no better than the Schedule WQN4 approach. Given the generous (permissive) trigger levels implemented for most of the Rakaia-Selwyn consent holders abstracting from deep bores, ECan technical officers are of the opinion that there will be considerable long term decline in levels and flows before the triggers start to bite. The consequent effects on stream flow will be significant. It is not clear how effects might be predicted in order to audit the success of the method.

During the hearing leading up to the Rakaia-Selwyn decision, there was, and still is considerable doubt as to the robustness of the data leading to the modelling of the EFS and Recession values for each aquifer. In addition, the EFS values set by the Commissioners were overly generous (too low) and will force a return of spring-fed stream flows to the low levels experienced in the summer of 2005-6. Indeed, the EFS values proposed for the deeper water-bearing strata are even more generous such that they will likely cause even worse flow conditions than those experienced in 2005-6. The Restorative Programme for Lowland Streams and this Adaptive Management research programme were instituted to avoid a repetition of these conditions, not cause a common return to them.

Comparison of monitored groundwater levels with those produced by the applicants' numerical groundwater modelling, undertaken for the ~69 applicants in the Rakaia-Selwyn and for the ~41 in the Selwyn-Waimakariri Groundwater Allocation Zones, shows that it is insufficiently accurate and precise to predict September and April groundwater levels and recessions (where they have not previously been measured). In addition, the method does not predict discharge and groundwater level outcomes.

---

[29] Permissive in the opinion of ECan technical officers, not necessarily so in the eyes of the RSGAZ hearing commissioners.

Environmental outcomes

Environmental outcomes derived from management of groundwater, based on the Davoren method, are not easy to quantify. The stated outcome is the arrest of long-term decline of groundwater levels resulting from the applicants who are part of the management mechanism. Separating the cumulative effects of the new consent holders from those existing consent holders is problematic. The Davoren method has no other stated environmental outcomes and is thus not strictly an adaptive management method. Adaptive management requires that the resource manager (ECan), in conjunction with resource users, can institute a means of varying the entitlement assessment method in a simple fashion as a result of comparing predicted with monitored outcomes. Without this continued iteration using predicted and monitored outcomes, then the Davoren method can hardly be called adaptive management.

Advantages of the Davoren method

The advantages of the Davoren method are:

- management constraints are imposed at the beginning of the irrigation season with no option of a change in management restrictions during the season; and;
- the stated objective that decline in groundwater levels would be arrested, eventually.

Both these objectives can be realised using other, simpler, methods.

Specific drawbacks of the Davoren method

There are specific implementation drawbacks to this method mainly stemming from:

- Based on Council experience with the ~69 Rakaia-Selwyn applicants, the Davoren method would be more administratively complex to roll out as a method for all 600 or so existing consent holders. Indeed, were the Davoren method to be implemented across the Region, then a massive amount of work would be required to propose and justify the trigger levels, test wells for leakage and stream depletion, accept and verify annual reports from each consent holder on groundwater levels;
- For all existing users to be treated equally, each user would need to rely on different EFS and Groundwater Recession triggers dependent upon the depth of their screens and on the potential their abstraction has to induce leakage of groundwater from overlying strata;
- With the Davoren method, there is no mechanism for controlling water levels or takes within a season and, in addition, no redress appears to be required should a user breach the trigger levels set in their consent, other than a time-consuming and costly review of consent conditions;
- The Davoren method cannot deal with long-term cumulative effects that are still developing, other than by instituting appropriate (conservative) trigger levels at commencement. For the RSGAZ this has not been done; in fact, the trigger levels currently proposed would be too generous even for existing users. It is expected that continued decline in groundwater levels and discharges to spring-fed streams will occur until a new equilibrium is reached. In the meantime, minimum flows continue to be breached, even outside the irrigation season (e.g.: Harts Creek and Selwyn River in June 2008);
- The Davoren method does not allow direct correlation of cause and effect and it is not related to specific environmental outcomes;
- Current consent holders that are constrained by the Davoren method have differing supply reliabilities contingent upon the aquifer properties in the area around their abstraction (i.e.: in any season, some users may have water available, others not).

Appendix F: Irrigation demand series

An irrigation demand series has been calculated for this report, based on daily rainfall and evapotranspiration data provided by NIWA. The demand data are output in the form of monthly demand in millimetres depth of water required to satisfy soil moisture. These are then accumulated over the irrigation year (Figure AF.1) and ranked according to size (Figure AF.2).

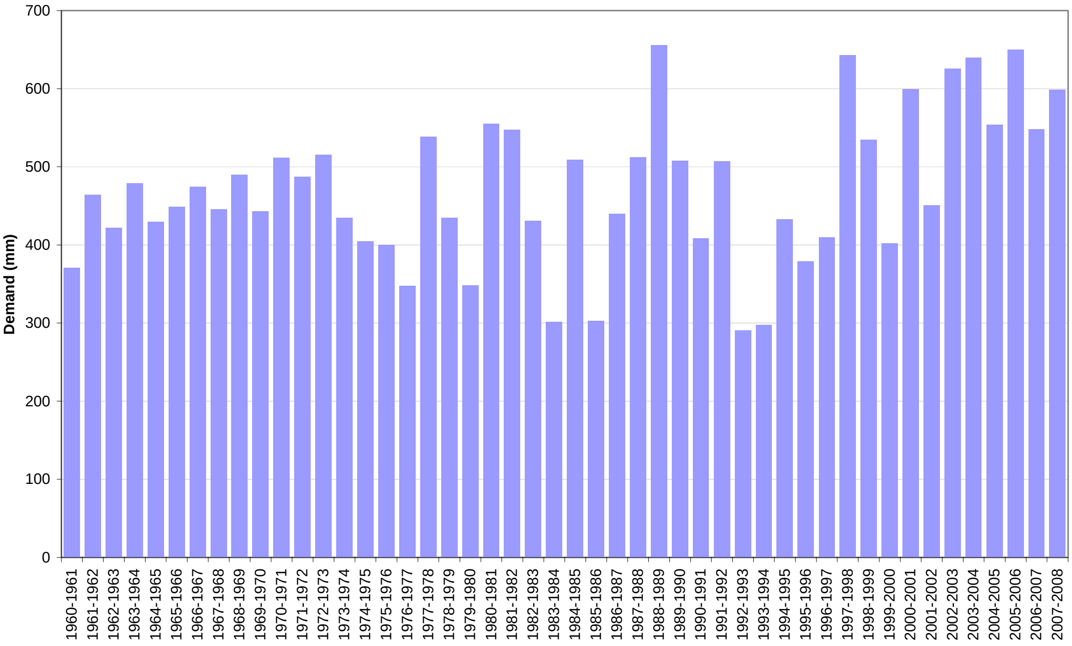

Figure AF.1: Time series of calculated demand for the RSGAZ

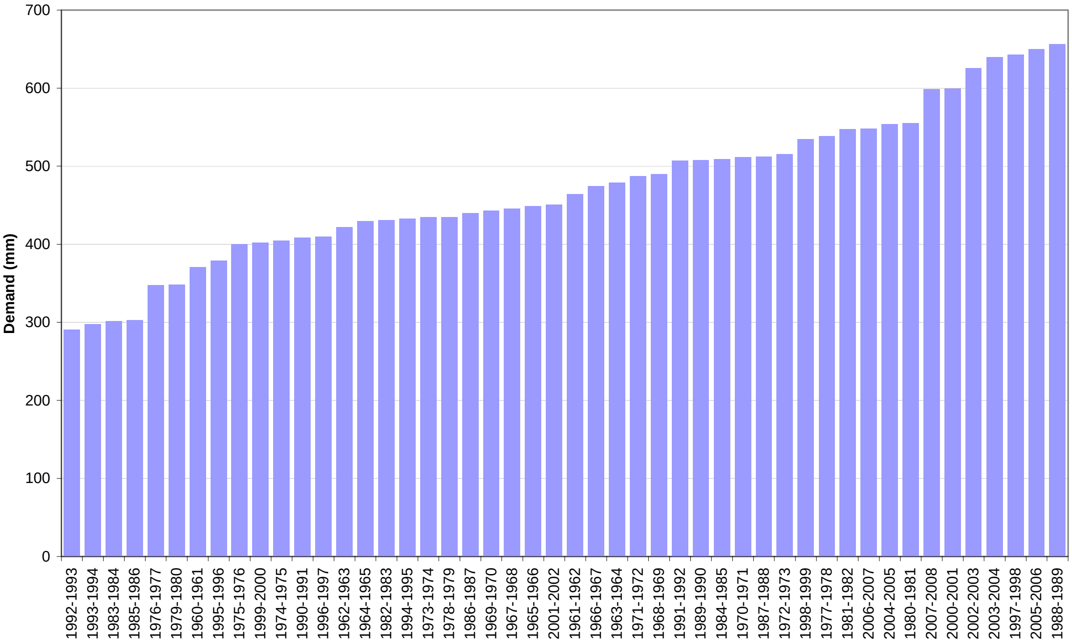

Figure AF.2: Ranked demand series for the RSGAZ

The size of calculated demand exceeded one year in five (80th percentile), is approximately 547 mm/year. Expressing the demand as a percentage of this number is a useful indicator of the relative amount of water required for irrigation as compared to the theoretical maximum (Figure AF.3).

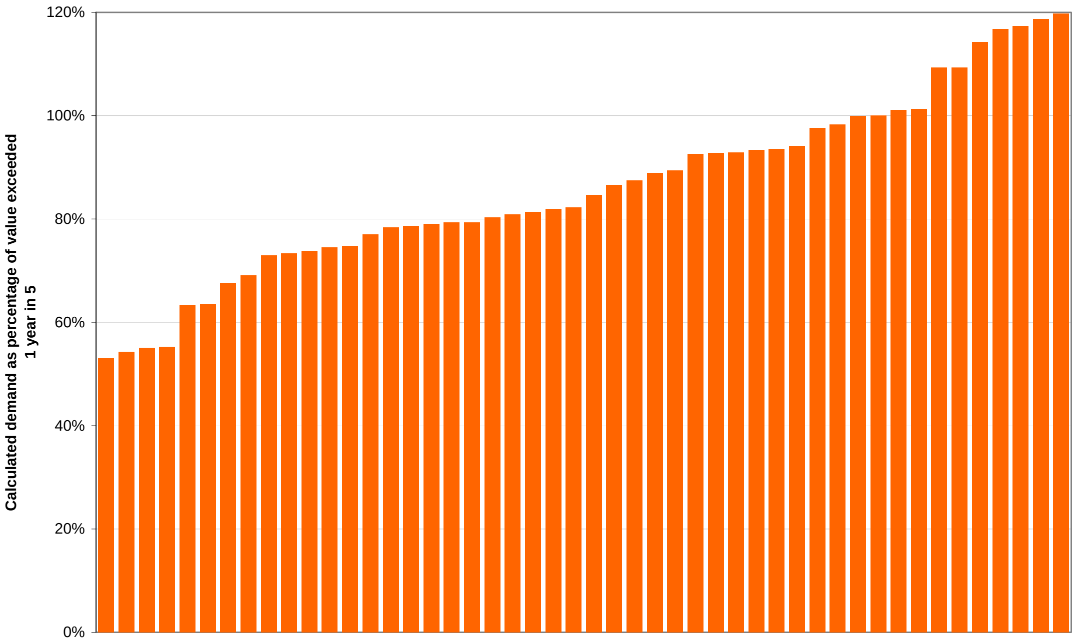

Figure AF.3: Ranked demand series for the RSGAZ expressed as a percentage of the value exceeded one in five years

----

Christchurch
58 Kilmore Street, PO Box 345, Christchurch

General enquiries: (03) 365-3828
Fax: (03) 365-3194

Customer services: (03) 353-9007
or: 0800 EC INFO (0800 324 636)

Timaru
75 Church Street, PO Box 550, Timaru

General enquiries: (03) 688-9069
Fax: (03) 688-9067

www.ecan.govt.nz