Hydrogeological Support for the Orari Environmental Flow and Water Allocation Plan

Prepared for Environment Canterbury

Report No 1050-7

Lee Burbery

February 2011

LINCOLN VENTURES LIMITED

TABLE OF CONTENTS

EXECUTIVE SUMMARY

An environmental flow and water allocation plan is being developed for the Orari River, South Canterbury. In 2006/07, an integrated field study of surface water shallow - groundwater was undertaken of the region. As part of the study, shallow groundwater levels started to be monitored throughout the catchment. These levels provide a useful data series from which the dynamic properties of the shallow Orari aquifer can be studied and information gained on probable aquifer recharge mechanisms.

The hydrodynamics of the shallow Orari aquifer were characterised, based on analysis of daily time series hydrograph data available from 10 shallow monitoring wells. A Groundwater Data Analysis tool that is built around the mathematical Eigen-model, and which has recently been developed by Lincoln Venture Ltd was applied for this purpose.

The effective role of river storm-flows in providing aquifer recharge and potential bank storage effects associated with these events was assessed. A case study has been provided that explains the effective differences between river recharge and land surface recharge (LSR), as well as their significance to dynamic aquifer recharge.

The analyses have shown the shallow Orari alluvial aquifer is a very dynamic system with very rapid drainage characteristics; much of the groundwater drains to the multiple groundwater-fed surface waters in the catchment.

The effective hydraulic storage residence time evaluated for the shallow aquifer is in the order of one week to just over one month. Hence, the shallow groundwater resource possesses very little dynamic storage capacity. From the perspective of surface water resource management, this means that surface waters in the catchment are highly vulnerable to stream depletion effects attributed to shallow groundwater abstraction, because there is limited buffering capacity in the aquifer system.

The variable groundwater storage that is measurable from fluctuating groundwater levels supplements a base-level storage component of the aquifer that is attributable to constant river recharge inputs, and supplies constant discharge (base-flows) to groundwater-fed surface waters. Quantification of the steady-state basal river flow conditions requires consideration of the catchment water mass balance. The aquifer hydrodynamic properties that have been evaluated might be incorporated into the systems model previously applied to compute a water balance for the catchment, although the reliability of any water mass balance remains constrained by a lack of information on the volumes of water drained via the spring-fed streams. In particular, there is limited knowledge of how much water transfers from the Orari to the Waihi River, via the historic Umukaha river channel, that is now Dobies Creek. Recording of flows in either Dobies Stream, or the Waihi River, down-gradient of the Dobies confluence, is recommended for the purpose of facilitating a catchment water balance.

The results of the bank storage assessment show pressure waves resulting from fluctuations in river levels transmit rapidly into the shallow alluvial aquifer. This suggests little reason for any streambed conductance effects to be considered when evaluating dynamic recharge from the Orari River to shallow groundwater.

An Orari river flow-river loss relationship was developed for the purpose of simulating river recharge inputs to groundwater. The non-linear model is a modification of a linear model recently equated by Environment Canterbury and is probably a more realistic simulator of Orari flow losses.

It appears that Orari River storm-flows contribute significantly to the dynamic shallow groundwater level behaviour observed upstream of Springs Farm on Coopers Creek. The variable contribution of aquifer recharge from the Orari River and LSR processes has been quantified for this part of the catchment.

There is a paucity of data on the deep groundwater system of the Orari, although vertical leakage effects have shown up in nearly all constant rate pumping tests conducted in the deep Orari aquifer. Thus, it is recommended that from an allocation perspective the deep groundwater resource is lumped together with shallow groundwater resource. From an assessment of potential impacts to Orari river flows, it is suggested that the net effective daily rate of deep groundwater abstraction be assumed as river base-flow depletion.

Although of no aid to the impending Orari flow and allocation plan being developed, it is recommended an investigative strategy be established for deep groundwater in the Orari catchment and adjoining Orton plain, for the purpose of accruing knowledge of the hydraulic functioning of this system and establishing its relationship with the Orari and Rangitata rivers. A survey of the piezometric levels for deep groundwater across the Rangitata – Orton – Orari plain is seen as a priority, from which the flow paths of deep groundwater can be mapped.

Groundwater in the Orari is presently allocated as part of the more extensive Opihi-Orari groundwater allocation zone (GWAZ). In terms of land surface recharge area, the Orari coastal catchment constitutes just 40% of the GWAZ. To gain some perspective on existing groundwater allocation in the catchment, a water budget of hydrological inputs to the Orari lowland coastal catchment has been evaluated. The budget processed long-term climate and hydrological records, hence is a more reliable evaluation of system inputs than was completed for the 2006/07 field investigation.

Total LSR, i.e. active rainfall recharge to the Orari shallow groundwater system is estimated to be in the range of $41x10^6$ – $61x10^6$ m^3/year. This latest estimate is close to previous estimations used in the setting of GWAZ limits, and which were based on more simplified assumptions. By comparison, the Orari River discharges an average of $291x10^6$ m^3 of water per year to the coastal plain at the Gorge. As much as $180x10^6$ m^3 (62%) of this water leaks to the groundwater system, which signifies that the groundwater resources of the Orari are heavily dependent on river recharge inputs for their sustainability. Flows in the lower reaches of Orari River, and the spring-fed streams are directly related to the condition of the groundwater resource.

$45x10^6$ m^3 of groundwater is consented to be abstracted from the Orari aquifer system, annually. This equates to 63% of the total volume of allocable groundwater from the Opihi-Orari GWAZ, which from the perspective of the current allocation limit, suggests that groundwater resources in the Orari catchment are over-allocated. It is recommended that annual water budgets not be used in setting allocating limits of shallow groundwater resources in the Orari, because of the limited hydrodynamic storage of the shallow aquifer.

Because of the low dynamic storage potential offered by the aquifer system, it is recommended that shallow groundwater use is managed in conjunction with surface water use, for the purpose of controlling stream depletion effects attributed to groundwater abstractions, i.e. water use restrictions are applied unilaterally to both surface and shallow groundwater takes, regulated by low (river/stream) flow criteria.

1 INTRODUCTION

Canterbury Regional Council (CRC) is in the process of drafting an environmental flow and water allocation plan for the Orari River catchment, South Canterbury; the plan aims to contribute towards the goal of integrated catchment management. In September 2010, CRC contracted Lincoln Ventures Ltd. (LVL) to provide hydrogeological support to the plan development. This report documents the work completed by LVL for that purpose.

2 BACKGROUND

An intensive integrated field investigation of surface water and shallow groundwater of the Orari hydrological catchment was recently conducted over the irrigation year 2006/07. The investigation allowed collection of technical data and improved scientific understanding of the Orari hydrological system. The information gained from the investigation provides technical guidance for the Orari flow and allocation plan and water resource management in the Orari Catchment.

Details of the field investigation and associated findings, and recommendations are reported in CRC Technical Report R10/36 (Burbery and Ritson, 2010). They are summarised here:

The investigation involved:

- monitoring groundwater levels in the shallow aquifer;
- hydrochemical analysis of surface and groundwater; and
- gauging of stream flows.

From these data:

- groundwater flow paths have been mapped;
- the origin of water in the numerous spring-fed streams of the catchment has been identified, based primarily on water chemistry;
- the general pattern of flow losses and gains along the main-stem of the Orari River has been evaluated; and
- the approximate boundaries of the hydrological catchment have been delineated.

The study confirmed the conceptual model that surface waters and shallow groundwater in the Orari catchment are strongly inter-related, albeit it refrained from directly quantifying these relationships in terms of flow.

Burbery and Ritson (2010) did, however, attempt to evaluate a 2006/07 water balance for the Orari hydrological system, through applying a simple systems model. The model treated the Orari catchment as a system of six hydraulically-connected sub-basins. The model failed to account for any time lag effects associated with groundwater storage, which is likely to have contributed to errors in the final water balance. One recommendation was that further analysis should be conducted of the groundwater monitoring data collected in the Orari catchment, with the intention of evaluating the hydraulic properties of the aquifer and quantifying the dynamics of the surface water – shallow groundwater system. The results from such analysis could then be integrated into the Orari flow plan.

3 PURPOSE AND SCOPE OF WORK

The purpose of the work reported herein is to advance the scientific understanding of the shallow groundwater system of the Orari catchment in terms of hydraulic performance, and relationship with surface waters of the catchment. The report is written to provide technical support for the development of the Orari flow and water allocation plan. Five topics are addressed:

3.1 Determination of hydrodynamic properties of the Orari shallow aquifer

The hydrodynamics of an aquifer refer to changes in water levels/flow over time. The magnitude and rate of change is driven by variable aquifer recharge (e.g. rainfall and river inputs) and discharge (e.g. water abstraction and seepage of groundwater into rivers), and are monitored through measurement of groundwater levels. Several physical aquifer properties determine the hydrodynamics of an aquifer and we evaluate these for the Orari system, providing a technical measure of how rapidly water flows through (and out of) the shallow aquifer.

Our evaluation is based on application of the Groundwater Data Analysis (GDA) tool that is being developed by LVL as an Enviro-link tools project. The GDA-tool is built on the mathematical concepts of Eigen-modelling, explanations of which can be found in Pulido-Velazquez et al. (2005) and Bidwell (2010) – a brief overview of the Eigen-model, together with the underlying assumptions and limitations are provided in Section 6.3.1. Continuous, time-series groundwater level datasets for the shallow Orari aquifer are analysed in conjunction with river flow and climate datasets – concurrent datasets that date back to August 2006 are available.

3.2 Is a sub-catchment management approach practicable for the Orari?

To evaluate a water budget, Burbery and Ritson (2010) sub-divided the Orari catchment into six sub-basins, based on their conceptual understanding of the hydrological system and distribution of available monitoring data. McEwan (2001) similarly split the catchment into discrete hydrogeological zones based on consideration of local geology/geomorphology and suggested they might represent individual groundwater management zones. Unfortunately, the groundwater level monitoring data available for the Orari catchment do not match directly to all the geographic-zones identified in previous reports. Nonetheless, analyses of the groundwater level datasets (that are themselves spatially distributed over the catchment) has allowed for some assessment of whether or not the water resources associated with the Orari River might lend themselves to resource management at the sub-basin scale.

3.3 Stream depletion

Some work has been conducted by CRC surface water scientists to naturalise Orari River flows, based on consideration of the cumulative stream depletion effects of shallow groundwater abstractions. The stream depletion assessments were conducted employing the “Jenkins-model”, based on a fixed assumption of aquifer storativity (0.1) and spatially variable transmissivity (estimated at the well-scale (point-scale) through application of the modified “Bal-equation” (pers. comm., Matt Smith, CRC hydrogeologist, September 2010)).

The GDA-tool allows reliable estimation of aquifer parameters from measured groundwater level data. The resulting parameter estimates are characteristic of the bulk physical properties of the aquifer system, and are commensurate to catchment-scale physical processes. The resulting aquifer parameter values can be substituted into future stream depletion assessments, which would allow for a more rigorous analysis of potential environmental effects.

3.4 Deep groundwater resource

Limited data and resources preclude reliable in-depth understanding of deep – shallow groundwater relationships within the Orari catchment. Notwithstanding, a commentary on this topic is provided based on review of the current distribution of groundwater take consents and knowledge about the Orari hydrogeology. Some possible deep groundwater resource management options are provided.

3.5 Catchment water budget

In terms of existing groundwater allocation quotas, the Orari hydrological catchment is collectively managed with the Opihi catchment, as the Orari-Opihi groundwater allocation zone (GWAZ). The Orari-Opihi GWAZ constitutes an area of 472 km^2 that is the coverage of Quaternary sediments within both the Orari-Opihi hydrological catchments over which land surface recharge (LSR) is assumed effective (note: this is significantly smaller than the area of the combined surface water catchments). The existing allocation limit for the Orari-Opihi GWAZ is $71.1x10^6$ m^3/year and was evaluated in 2004 (Aitchison-Earl et al., 2004). This limit assumes $58.5x10^6$ m^3 land surface recharge (LSR) component (equivalent to 15% of assumed annual rainfall) and $12.6x10^6$ m^3 river recharge component (50% of assumed total river recharge (Orari + Opihi)). Aitchison-Earl et al. (2004) report that the Orari River alone supplies approximately $15.75x10^6$ m^3 of recharge water to the groundwater resource (50% of which is assumed allocable for abstraction).

The water balance calculated by Burbery and Ritson (2010) for the year 2006/07 was for the lower Orari coastal catchment (combined with the adjacent Waihi catchment). The extent of this area is much closer to that likely to be managed under the Orari flow and water allocation plan. Burbery and Ritson (2010) estimated active LSR in the joint Orari-Waihi catchment to range from 18% of rainfall at the coast to 43% about the foothills (where there is lower evapotranspiration and freer draining soils). These estimates were consistent with those of Scott (2004), who calculated LSR to be 33% of annual rainfall for the Orari-Opihi GWAZ. Burbery and Ritson (2010) estimated the Orari River contributed almost 74% of the total annual water inputs to the hydrological system on the coastal plain in 2006/07.

A more reliable evaluation of the basic inputs to the lowland Orari coastal catchment water budget is evaluated here, based on analysis of extensive historic climate and river flow datasets. Scientific information gained from the hydrodynamic analyses is incorporated into the evaluation. The purpose is to provide an accurate assessment of the scale of river versus LSR inputs for the Orari catchment. Groundwater allocation volumes are also reviewed, to give some perspective of the current consented groundwater allocation status. The aim of this work is not to recommend any water allocation volumes, although the data are useful for that purpose.

4 ENVIRONMENTAL SETTING OF THE ORARI RIVER/SHALLOW AQUIFER

A brief overview of the Orari hydrological system is provided here to describe the physical context of the problem, and illustrate the complex boundary-value problems that are posed in the Orari catchment. A full account is available in Burbery and Ritson (2010).

The Orari River is located on the southern margin of the Canterbury Plains (Figure 4-1). The catchment is divided into a (mountainous) upland and (plains) lowland catchment. The upland catchment drains water from the Four Peaks range, discharging water via the Orari Gorge from where it flows across the coastal plain, to discharge into the Pacific Ocean. The Gorge and adjacent foothills provide a convenient upper boundary to the lowland (coastal plain) catchment system; similarly the Pacific Ocean serves as a constant head, well-defined boundary. However, the hydrology of the catchment over the coastal plain is complex due to strong surface water – groundwater inter-relationships. This means that the lateral boundaries of the shallow aquifer are poorly constrained and hydraulic-boundary conditions vary with time.

Below the Gorge, the upper-reach of the Orari main-stem loses water to the subsurface; the middle reach of the river system often dries out during summer months. In the lower reaches of the Orari River, emergent groundwater replenishes the river, generally downstream of the SH1 road crossing (approximately 23 km downstream from the Gorge). Flows recorded at the mouth of the Orari River are less than those recorded at the Gorge, since much of the water lost from the upper reaches (in the order of >50% of the annual amount of water discharged from the Gorge (Burbery and Ritson (2010)) is transmitted as groundwater that tends to flow southwards, supplying the Ohapi Creek systems (which drain back into the Orari River) and Dobies Stream (which discharges to the Waihi River). The Orari River was historically mapped as a tributary of the Waihi River, and the buried (Umukaha) river channel (which Dobies Stream essentially follows) inevitably plays a significant role in determining the losses from the present day Orari system. It remains uncertain exactly how much water "lost" from the Orari is transferred to the Waihi catchment due to poor constraints on stream flow data; for the year 2006/07 it was roughly estimated to be 15×10^6 m^3, or 6% of the effective annual Orari River flow recorded at the Gorge (Burbery and Ritson, 2010).

Spring-fed surface waterways are located throughout the catchment (Figure 4-1). The main systems comprise: Coopers Creek at Springs Farm, Dobies Stream and Ohapi Creeks, all of which have demonstrated hydrochemical signatures characteristic of water originated from the Orari River. On the other-hand, the spring-fed Worners Creek and Raukapuka Creek (which like Dobies Stream, feed into the Waihi River), together with Rhodes Drain (in the Clandeboye region) and Burkes and Orakipaoa Creeks (close to Temuka) have exhibited chemical signatures more indicative of water sourced from land-surface recharge. An advisory note is given here that although the hydrochemical evidence (based on a single assessment conducted September/October 2006) for many groundwater and spring water samples did not necessarily demonstrate a direct relationship to Orari River water, water chemistry is not an indication that the systems analysed are not hydraulically inter-connected; the mechanisms by which groundwater hydraulics and solute transport operate are different.

The Orari shallow aquifer refers to groundwater stored within sandy gravel deposits that constitute modern and historic Orari River alluvium, as well as older Rangitata fan deposits into which the Orari River has incised. The "shallow" groundwater resource is assumed to be that found within 20 m of ground level. Very few wells tap groundwater within the depth range 20 – 40 m, whereas the majority of "deep" wells in the catchment are screened in the range 60 – 80 m.

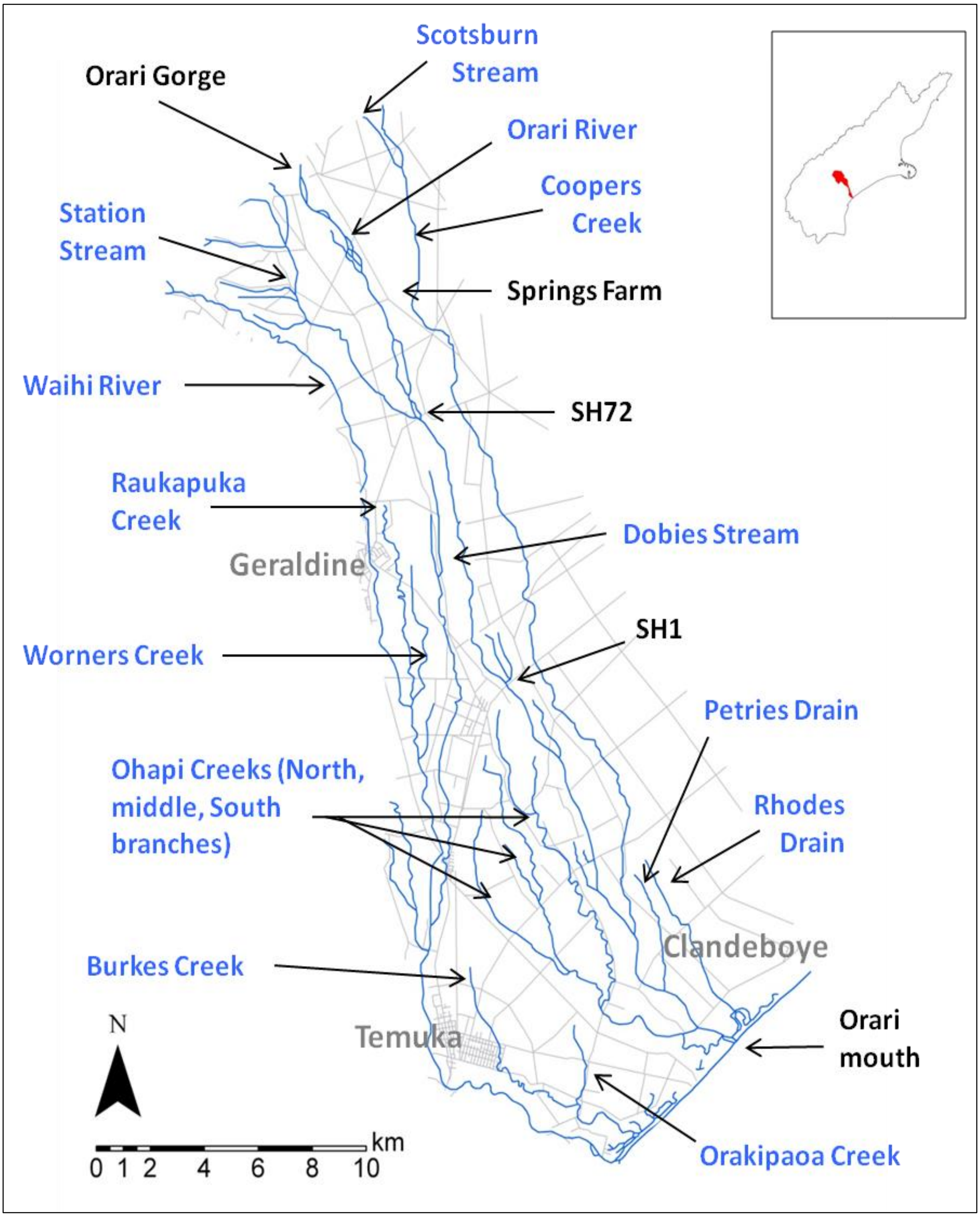

Figure 4-1: Map of lowland, coastal Orari catchment with main surface waters (blue), towns and roads (grey) and geographic reference points (black) labelled.

McEwan (2001) hypothesised that the spatial heterogeneity of the shallow aquifer hydraulic properties can be related to the pattern of avulsion channels and Rangitata fan surfaces. However, Burbery and Ritson (2010) show that the aquifer-testing data (including well yields, specific capacities and aquifer test data) do not reliably support such an argument (see their Figures 2-10 to 2-12). As a consequence these data do not provide information upon which micro-management of the water resource could be based. We speculate that much of the well-test data measured in the catchment is likely to have been affected by boundary conditions (i.e. the proximity of surface water recharge boundaries) that have generally not been accounted for in the data interpretation methods.

The current knowledge of the hydraulic properties of the Orari shallow aquifer remain constrained by the results of 11 pumping tests that provide local-scale assessments of the aquifer transmissivity and storativity. Reported transmissivity estimates range from 120 – 10 500 m^2/day (Table 2-1 in Burbery and Ritson, 2010). The study of aquifer hydrodynamics conducted in this current body of work using the Eigen-modelling approach effectively constitutes characterisation of the shallow aquifer at a much larger scale. In this respect, the groundwater level data analysis using the GDA-tool can be imagined as interpretation of a large scale aquifer test, interpreting aquifer response to recharge stresses applied over the catchment scale.

5 DATA ANALYSED

The hydrodynamics of an aquifer can be inferred from relating the behaviour of groundwater levels to hydraulic stresses. These stresses include recharge and discharge processes that are: land surface recharge (from rainfall and irrigation water), river recharge, groundwater abstractions and discharge to surface waters. The data recording the temporal variability of these processes, used for analysis are listed here.

5.1 Shallow groundwater levels

Monthly groundwater levels were monitored at 62 locations as part of the 2006/07 field study, and CRC continue to routinely monitor monthly levels in a large number of these wells. However, Burbery and Ritson (2010) noted from qualitative analysis of groundwater level data that the response time of shallow groundwater to storm-flow events in surface waters appeared to be in the order of hours to days, from which they suggested the water level data from wells fitted with data loggers (recording at 15 minute intervals) provide the most meaningful data from which to infer information of the aquifer hydrodynamics.

We have restricted our study to analysis of such logged groundwater level data, which has been collected from a total of ten shallow wells across the Orari catchment since August 2006, albeit recording ceased in three wells after the field study was completed in September 2007. The longest length of record available for analysis was 3½ years, August 2006 to April 2010. The well locations are shown in Figure 5-1, from which it is evident that there is a paucity of high-frequency monitoring data for the shallow aquifer about the Clandeboye region (Rhodes Drain surface water catchment).

5.2 Surface water flows

Continuous flow records were available for analysis for the Orari River, measured at the Gorge and upstream of the Ohapi Creek confluence (see Figure 5-1). Flows at the Gorge are unaffected by water abstraction therefore provide the most reliable reference dataset and the one employed whenever the dynamics of river recharge was simulated.

A recorder site is located on the Orari River at Victoria Bridge (i.e. SH1 road crossing), albeit this site is in fact a groundwater monitoring well (K38/2157) that is used as a surrogate for river stage - the river often dries up along this reach. The groundwater level data at K38/2157 was analysed and a threshold corresponding to dry river conditions has been determined. The data record at K38/2157 was subsequently used as a reference indicator for dry river conditions within the catchment, which is useful to know when analysing groundwater level data, because when river recharge/discharge boundary conditions become dry it complicates the mathematical analyses of data. The Eigen-model we employed in our data analyses, assumes linearity in the hydrogeological system, which is a state not met when a river boundary goes dry.

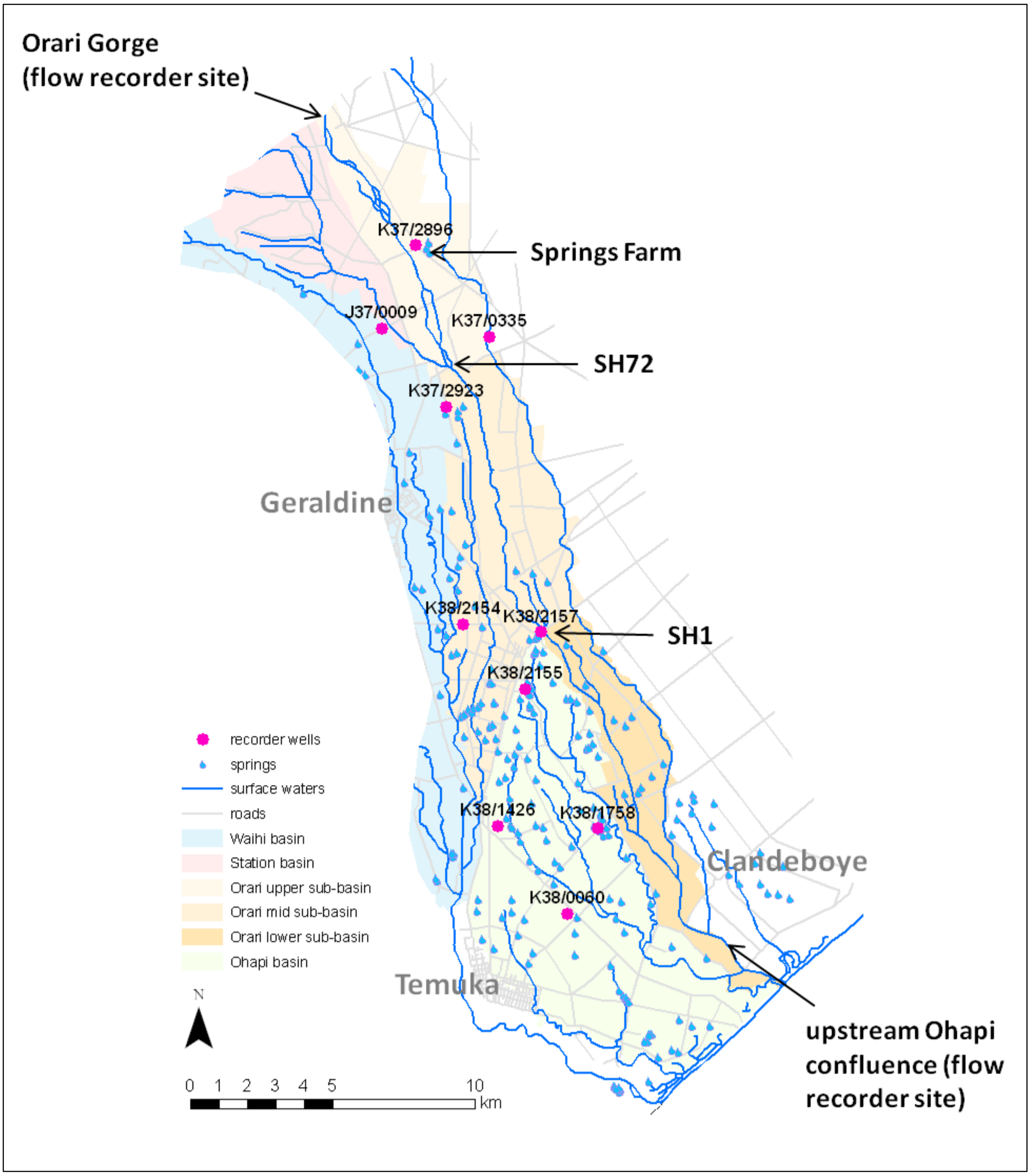

Figure 5-1: Location of shallow groundwater monitoring wells for which hydrograph records were analysed. Sub-basins refer to those defined in the water balance/systems model of Burbery and Ritson (2010).

5.3 Climate data

Daily rainfall data from five NIWA climate stations were employed in the hydrodynamic data analyses (Table 5-1). Average rainfall was calculated for the three geographic zones (upland, central and coastal) marked in Figure 3-1 of Burbery and Ritson (2010). Daily rainfall records for the three regions are included as Appendix A.

Data from NIWA's virtual climate station network were used in the calculation of the catchment's annual water budget, since longer historic records are available of this virtual form of data. The virtual climate data comprises estimations of rainfall and potential evapotranspiration (PET) at every point on a 5 km grid. The data are generated by NIWA, based on sophisticated interpolation of field measurements, such as data from the rainfall gauging sites listed in Table 5-1.

Table 5-1: NIWA rain gauges from which daily rainfall records have been interpolated

NIWA gauge ID	Gauge name	Easting	Northing	Geographic zone
H31926	Orari Gorge	2365288	5691031	Upland
H41131	Orari Estate	2374586	5674419	Central
H41101	Kakahu Bush	2358010	5671510	Central
H41211	Waitawa	2363690	5656850	Coastal
H41153	Coldstream no.3	2393380	5671563	Coastal

A review of monthly rainfall patterns between 2006 and 2010 shows that generally abnormal weather patterns have occurred, relative to the averaged monthly data from the past 30-years (Figure 5-2). 2006 was marked by an extremely dry September leading in to the irrigation season and an abnormally wet December, which as noted by Burbery & Ritson (2010), led to a particularly low irrigation water demand. The year 2007 appears to have been a generally dry year, whereas 2008 experienced a dry summer and very wet winter. Similarly, extremes of dry and wet months persisted throughout 2009, finishing with below average rainfall over the winter period, which is generally perceived as the most significant period for groundwater recharge. May 2010 proved an extremely wet month leading to significant flood events, albeit this event falls outside of the groundwater level record period analysed.

For the hydrodynamic analyses, PET data were provided from CRC's Arundel-Belfield climate weather station that was installed in October 2006 and removed November 2009. PET values recorded at NIWA's Winchmore climate weather station, located 42 km north-east of the Orari catchment, were substituted in the data gaps that existed in the early (August 2006 - October 2006) and late (November 2009 – April 2010) parts of the record.

PET values from NIWA's virtual climate network were used in the catchment water budget calculations. However, unlike rainfall measurements, NIWA do not undertake any physical PET measurements within the Orari catchment, hence PET data are less reliable than rainfall data and their accuracy is strongly determined by the interpolation techniques employed by NIWA.

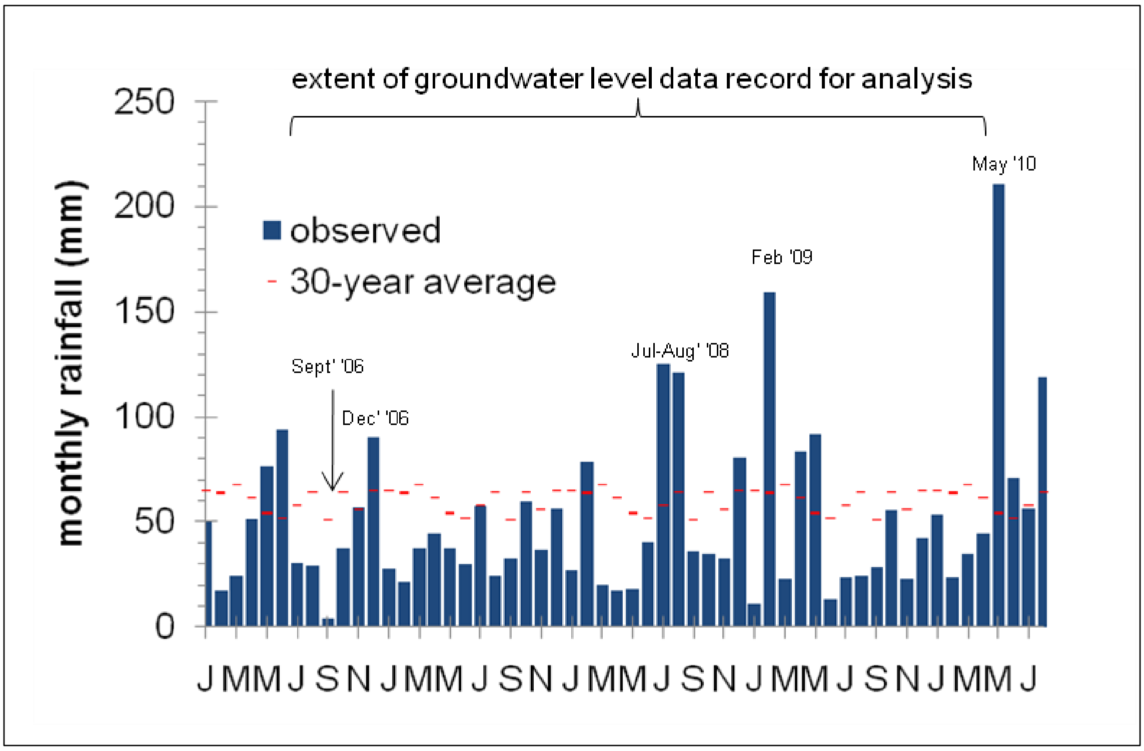

Figure 5-2: Rainfall pattern in Orari catchment for period over which shallow groundwater level data have been analysed. Rainfall record, as recorded at Orari Estate rain gauge.

5.4 Groundwater abstractions

For the year 2006/07, the water use records returned as part of the 2006/07 field study were used to quantify groundwater abstractions.

For periods after the 2006/07 irrigation year, groundwater usage was simulated using the same methods recently employed by CRC to naturalise Orari River flows for groundwater takes. That is: the records of eight metered groundwater takes, returned from six individual farms distributed within the Coopers Creek and Rhodes Drain sub-catchments provided a reference dataset from which the average fraction of consented effective daily volume of irrigation water actively used was estimated. It was then assumed that the volume of groundwater abstracted across any studied region mirrored the effective usage demonstrated by the reference dataset (pers. comm. Jen Ritson, CRC hydrologist, September 2010).

Comparison of the reference dataset with the recorded usage for the 2006/07 field investigation period shows the eight reference takes are not accurate representations of irrigation patterns within the catchment hence, errors are to be expected in data analyses conducted for the irrigation seasons (Figure 5-3). Such discrepancies are likely to mainly result from bias in the reference dataset, which relate to consents associated with dairy/pasture irrigation, therefore fail to capture irrigation patterns associated with arable farming practices. To reduce the significance of errors associated with uncertainty of actual water usage, we focussed on calibrating the Eigen-model to groundwater level data corresponding to winter (non-irrigation) periods.

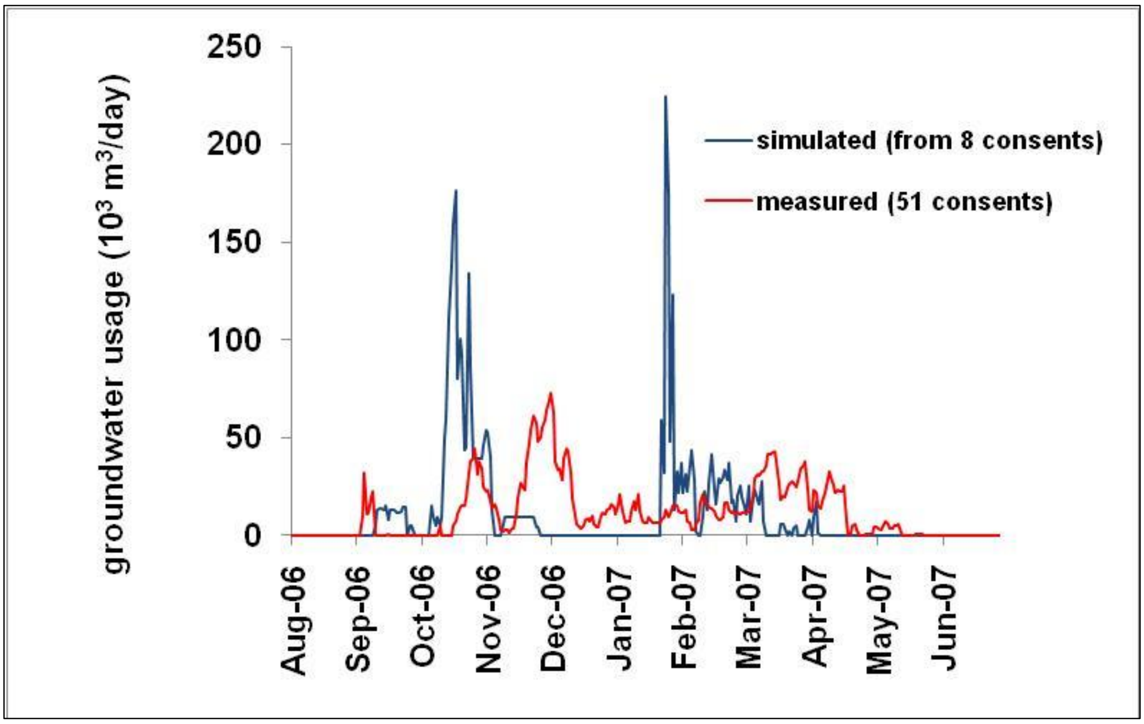

Figure 5-3: Illustration of errors in assumed groundwater usage model vs. actual water usage. Red line indicates actual water usage based on return of 50 water usage records as part of 2006/07 field investigation. Blue line is simulated water usage when based on water meter records of eight reference consents, scaled up to Ohapi sub-catchment. Assumed groundwater usage after 2007 has relied on the eight reference consents.

6 METHODS OF ANALYSIS

6.1 Qualitative assessment of hydrographs

It was presumed from the qualitative analysis of water level data reported in Burbery & Ritson (2010) that the shallow aquifer of the Orari catchment is highly dynamic and likely to have a strong hydraulic connection with the Orari River. To assess potential storage of recharge water in the Orari hydrological system along its main stem, we started our analysis by reviewing storm-flow events in the two Orari River hydrographs (Gorge and upstream of Ohapi confluence) for periods when the river was dry along its mid-reach. Three such periods were analysed; April – July 2007; December 2007 – January 2008; February 2008 – July 2008. For these periods it was possible to eliminate (fast) open channel flow linking the two recorder sites, instead observe solely the effects of subsurface flow in the downstream hydrograph record, and possibly determine the time-lag factors involved in groundwater transmittance down the length of the catchment.

Burbery and Ritson (2010) noted that some groundwater hydrographs failed to exhibit an exponential (concave) recession limb, which they speculated might indicate delayed land surface recharge effects. A qualitative assessment of groundwater hydrograph data was also completed and allowed for common characteristics to be identified in the data. This facilitated grouping of well records based on apparent aquifer hydrodynamic properties.

6.2 Evaluation of possible bank storage effects

The hydrograph from well K38/2157 was analysed for the purpose of using it as an indicator of times when the river system was likely to be dry. Due to the close proximity of K38/2157 to the Orari River it was assumed that the hydrograph pattern of K38/2157 provided an example of systematic groundwater response to river recharge events. Moreover, it was presumed that the shallow groundwater resource in this locality is likely to include “bank storage”, whereby the shallow aquifer is periodically recharged by a river storm-flow event, but conversely discharges to the same river when the river levels subside. Bank storage effects have not previously been studied for the Orari system. It was considered useful to characterise these effects since they might provide valuable insight into understanding groundwater processes and storage potential applicable to the catchment.

To assess the effects of potential bank storage, a mathematical model describing groundwater level response to a step-wise fluctuation was utilised (Verruijt, 1982):

$$h = h_0 + \Delta h \, erfc \left[\frac{x}{\sqrt{4Tt/S}} \right] \tag{1}$$

where h is the groundwater level [L], h_0 is the initial groundwater level [L], Δh is the step-change in water level [L] (i.e. the rise in river level), x is the distance of the observation point from the river boundary [L], t is time (T), T is the aquifer transmissivity [L/T^2] and S is the aquifer storage coefficient. Convolution of (1) enabled simulation of groundwater level behaviour observed in K38/2157 considering the variation in river levels during storm events. The change in river stage at the Orari Gorge occurring in a specific storm-event provided the measure of Δh, based on a daily time step and assuming the river stage at SH1 is a constant factor of the stage at the Gorge, i.e. $\Delta h_{SH1} = \alpha \, \Delta h_{Gorge}$, where α is a constant of proportionality.

The randomly selected storm-events for which groundwater level changes in well K38/2157 were studied for bank storage effects are marked in Figure 6-1. Potential bank storage effects were also assessed for some of the storm-flows events marked in Figure 6-1, for wells K37/2896 and K37/2923 (located close to the Orari main-stem), and J37/0009 (located close to Station Stream) (Figure 4-1 and Figure 5-1).

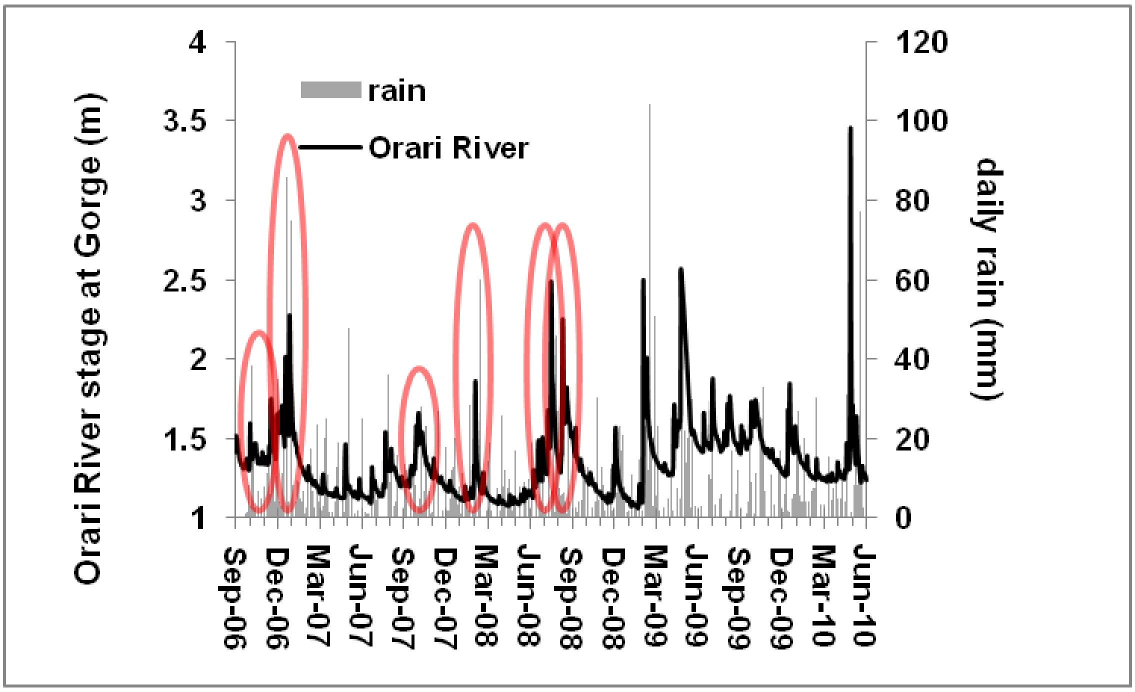

Figure 6-1: Storm events for which possible bank storage effects were studied using groundwater level monitoring data recorded in well K38/2157. Black line is the Orari River hydrograph; grey bars show rainfall, measured at the Orari Gorge.

6.3 Characterising aquifer hydrodynamics using the Eigen-model approach

6.3.1 Mathematical overview of the Eigen-model

The Eigen-model is an analytical solution to the Dupuit-Boussinesq equation describing transient groundwater flow:

$$T\frac{d^2h}{dx^2} \pm Q = S\frac{dh}{dt} \tag{2}$$

which can be applied to model two-dimensional heterogeneous aquifers. *Q* denotes the sum of all recharge or discharge processes (e.g. land surface recharge (*LSR)*, river recharge (*R*), groundwater abstraction *(GW)*, aquifer discharge to surface waters (*D*)). A no-flow boundary is assumed at one end of the system, and a discharge boundary at the other – this being the aquifer discharge, potentially to a stream.

Note: the Eigen-model constitutes the groundwater modelling component of the GDA-tool that was applied for the groundwater hydrograph analysis. The GDA-tool also incorporates a land surface recharge (LSR) model component (described below) and a vadose zone storage model component, which provide coupled input to the Eigen-model. Inversion problems using the Eigen-model comprised the estimation of four governing parameters, which are explained below.

In physical terms, the Eigen-model characterises the dynamics associated with an infinite number of linear storage reservoirs, each of which drains at some exponential rate (the Eigen-values). For most cases, most of the dynamic behaviour can be represented with just a few Eigen-values and their Eigen-function sets. In the model set-up used here, the linear storage components (number of Eigen-values) was truncated to twenty. The Eigen-functions are a state representation of the physical aquifer system. A thorough and highly accessible explanation of the Eigen-model can be found in Bidwell (2010) and is not provided here.

A fundamental assumption of the Eigen-model methodology is that the aquifer is a linear system; that is there is no vertical flow gradient and that aquifer discharge is proportional to the saturated aquifer thickness. Unconfined aquifers such as the Orari shallow aquifer, are non-linear systems, however it can be assumed to operate linearly, provided the changes in groundwater levels are small relative to the saturated thickness of the aquifer. In some locations, measured groundwater fluctuations in the shallow Orari aquifer are significant, for example in well K38/0060 the range between maximum and minimum recorded groundwater levels is 1.3 m, which equates to approximately 8% of the average aquifer saturated thickness (assuming the base of the shallow aquifer is 20 m below ground level (bgl)). Similarly, where river boundaries dry up, the system dynamics are altered and Eigen-functions and Eigen-values require re-evaluation. Although solutions have been developed for handling dry streams within the Eigen-modelling mathematical framework (Pulido-Velazquez et al., 2009) they are not built into the GDA-tool and were not incorporated into the Eigen-model that was applied in this analytical study.

Although it is possible that the linearity assumptions of the Eigen-model are stretched to their limits in some parts of the shallow unconfined Orari aquifer - ultimately contributing to error in any resulting interpretation - no attempt has been made to quantify such errors. Given the situation that there is little information known of the physics of the Orari shallow aquifer, any such errors are considered to be insignificant and omissible at this stage. Care was taken not to analyse data that clearly did not conform to the assumptions of linearity, as explained in Section 6.3.2.

The Eigen-model is applicable for describing groundwater flow systems that can be simplified as one-dimensional linear systems. Unlike the large Canterbury Plains aquifer systems, where the Eigen-model has been successfully applied in the past to interpret aquifer hydrodynamics (e.g. Bidwell and Morgan, 2002), the Orari shallow aquifer is a much smaller and hydrologically complex system, comprising a dense network of spring-fed surface water systems that drain water laterally from the catchment in places and occasionally go dry. Due to the simplicity of the model assumptions, it is likely that the Eigen-modelling methods will fail or provide spurious results in some situations within the catchment. Despite these drawbacks, it is anticipated that some useful scientific knowledge might still be inferred from the modelling.

6.3.2 Modelling approach

Owing to the non-linearity associated with drying river reaches and uncertainty involved with reliably simulating irrigation processes, we focussed on interpreting groundwater hydrograph records for periods when the Orari River was not dry (as determined from the K38/2157 hydrograph) and outside of the irrigation season. These periods are shown on Figure 6-2. This process of matching simulated groundwater levels to observed data was treated as a “calibration” process, from which the underlying physical properties of the aquifer and overlying soil/vadose zone storage properties were estimated.

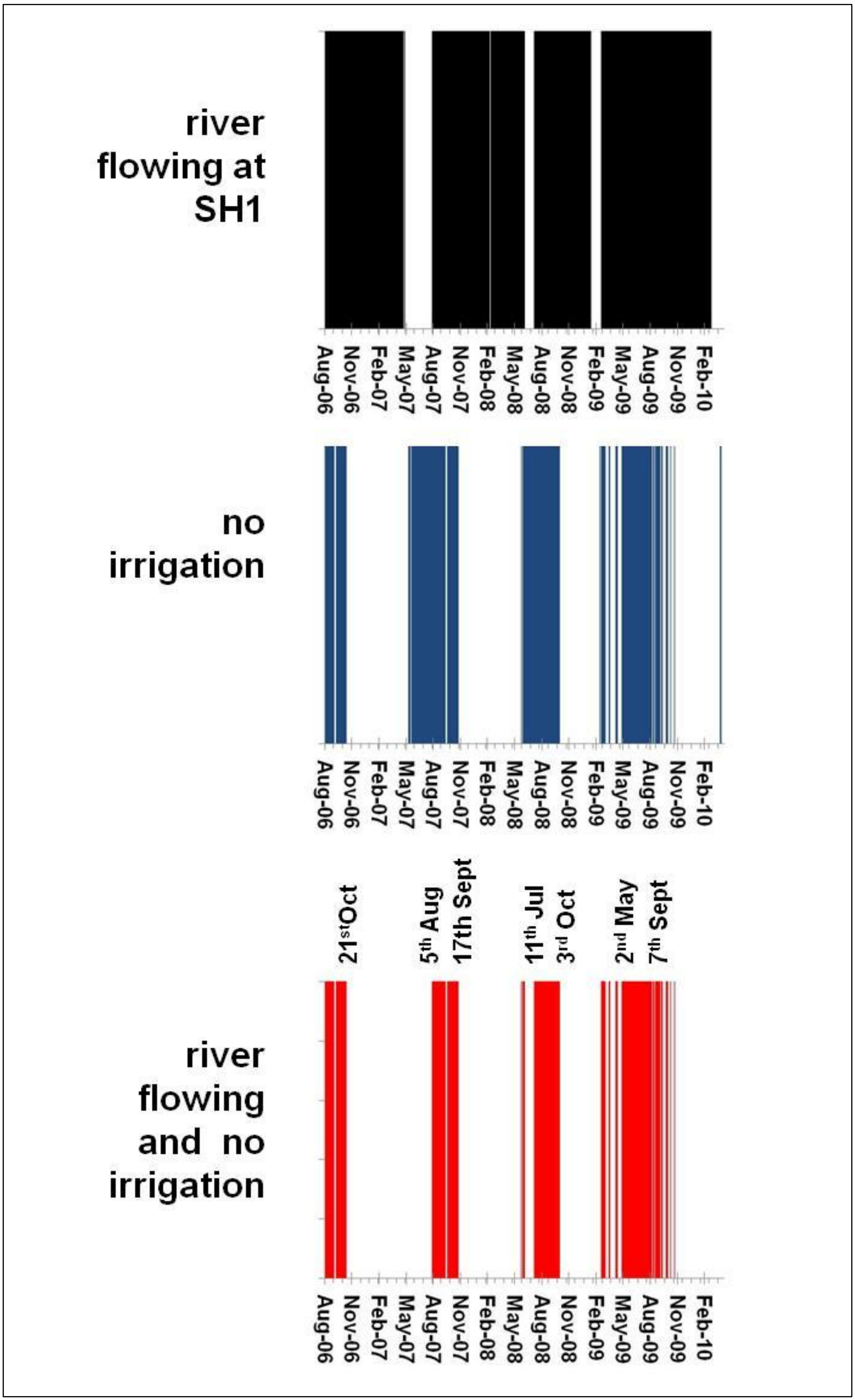

Figure 6-2: Times identified for which Orari River was flowing at Victoria Bridge (SH1) and irrigation was not active. Analysis of aquifer hydrodynamics/Eigen-model calibration focussed on these periods.

In total there were nine parameters requiring optimisation in the model calibration exercise. These are listed in Table 6-1. The GDA-tool is built as a Microsoft Excel utility and the iterative solver function within Microsoft Excel was applied to solve for the unknown parameters by minimising the sum of square errors between simulated and observed groundwater level data. Initial parameter value estimates used in the solver function were provided from the results of preliminary hydrograph data assessments conducted using an exponentially weighted moving average model that is also built into the GDA-tool (details can be found in Bidwell, 2010). Model fits were evaluated using the coefficient of efficiency index, E, described by Nash and Sutcliffe (1970):

$$E = 1 - \left[\frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O_{avg})^2}\right] \tag{3}$$

where for n water level observations, O_{avg} is the average of all the observed levels and P denotes the level predicted with the model. Possible values of E range from negative infinity to +1, with unity being a perfect match of simulated data to observation data. E = 0, is the equivalent of simply applying the average value of observed data to describe the entire data series.

In the format available for this work, the GDA-tool does not have the capability to evaluate any uncertainty statistics of parameter estimates and these are not provided. Similarly, the short datasets precluded any verification of the calibrated models.

Table 6-1: Adjustable model parameters in the hydrograph simulation exercise (see Bidwell (2010) for full explanation).

Eigen-model		**LSR model**	
Effective aquifer diffusivity [T^{-1}]	T/SL^2	Crop factor [-]	C
Aquifer storativity [-]	S	Soil water holding capacity [L]	W
Effective position of observation point [-]	x/L	Parameter in evaporation reduction function [-]	a
Base level groundwater datum [L]	H_0	Soil drainage threshold [L]	D_T
Vadose zone storage model			
Effective vadose zone residence time [T]	t_v		

The Eigen-value estimates resulting from the calibration process reflect the state condition of the shallow aquifer system in terms of its distributed diffusivity and storativity properties. An effective aquifer storage residence time was obtained from the first eigen-value that is determined from T/SL^2. The base level groundwater datum, H_0, can be conceived as the reference datum of steady river recharge to the aquifer.

In theory, the eigen-values of an aquifer are the same everywhere. However, owing to the complicated distribution of boundary conditions in the Orari catchment, groundwater hydrograph interpretations were conducted on an individual basis, with T/SL^2 allowed to vary. The results from individual hydrograph analyses were compared. This comparison provides some general assessment of the distributed nature of aquifer characteristics across the integrated catchment but presumes that the system functions as a number of discrete mini-aquifers related to discrete surface water catchments.

In effect, the hydrographs from the calibrated Eigen-model provide an example of the groundwater levels expected to have occurred if only natural processes (rain and river flows) were active within the catchment. For the cases of K37/2896 (near Springs Farm, Coopers Creek) and K38/0060 (Ohapi sub-basin) an attempt was made to supplement groundwater abstraction effects on to calibrated datasets. In the case of K38/0060, land surface recharge resulting from irrigation practises were also factored into the simulation.

6.3.3 Simulated land surface recharge

There are two categories of land surface recharge (LSR): dry-land LSR and irrigated-land LSR. The former is the active component of rainfall recharge; the latter comprises the coupled effect of rainfall and irrigation. Dry-land LSR was a consistent factor in all stages of the modelling process, whereas irrigated-land LSR was only considered in the single case of attempting to refine the groundwater levels simulated over the irrigation seasons for observation well K38/0060.

The LSR model in the GDA-tool is essentially the same that was applied in the 2006/07 Orari water budget analysis by Burbery & Ritson (2010). In brief, it constitutes a soil moisture model that allows recharge from rainfall infiltration to occur when the holding capacity of the soil is exceeded. The only difference between the LSR model in the GDA-tool and that previously used in Orari studies is that a maximum drainage threshold, D_T [L], is included in the LSR-model of the GDA-tool, which provides for direct run-off under intense rainfall events. A crop coefficient, C [-] (Allen et al., 1998), is also included in the function converting PET to actual evapotranspiration that did not feature in the previous Orari study. Experience has shown that the coupled LSR/Eigen-model is relatively insensitive to D_T and C and in most cases these parameters were tightly constrained, in an expectation that more reliable estimates might be obtained of other variables (listed in Table 6-2).

Reliable simulation of irrigated-land LSR remains a difficult task, even when metered irrigation water records are available, for reasons explained by Burbery and Ritson (2010). In the single case where irrigated-land was simulated, it was evaluated at the farm/consent-scale, considering groundwater usage records and irrigated land coverage associated with individual consents located within the Ohapi surface water catchment zone. The spatially-weighted average of LSR estimates for all the irrigated land parcels was then applied over the entire zone. Recognising that the LSR-estimates will be in error owing to an inherent lack of knowledge of the actively irrigated land area on any individual day, the relative proportion of the sub-catchment area irrigated versus that assumed dry-land was treated as an estimable parameter. Resulting estimates were considered against recorded irrigated land areas and assumptions about the sub-basin area. The application of irrigation water derived from surface water abstraction was not incorporated in the irrigated-land LSR estimates hence the simulated process was expected to be under-estimative.

6.3.4 Simulated river recharge

Water "lost" from the upper reaches of the Orari River constitutes a mechanism for recharge of the shallow aquifer, as confirmed by the hydrochemistry data reported in Burbery and Ritson (2010). In calibrating the Eigen-model for each observation well record, we initially assumed LSR as the only aquifer recharge process. A second calibration was performed assuming a dynamic river recharge component of the system, for the purpose of assessing whether river inputs contribute to the aquifer hydrodynamics, and if so to what degree.

In their recent attempt to naturalise flows in the Orari River, CRC have assumed constant minimum flow losses of 3000 L/s and maximum losses of 6000 L/s (pers. comm. Jen Ritson, CRC hydrologist, September 2010). Within this range a constant linear flow loss has been assumed, based on linear regression of river flow gauging data (see Figure 6-3). In conducting our Eigen-model assessments we noticed that the maximum river loss assumed by CRC under-estimated some recharge events, hence we increased the limit of potential river losses (groundwater recharge). Where we have considered river recharge, we have assumed the same linear relationship CRC have for when river flows at the Orari Gorge are less than <7000 L/s (no minimum limit has been assumed). Beyond this, we have assumed losses trend to an asymptote of 12,000 L/s according to a non-linear model similar to that described by Rushton and Tomlinson (1979), with k_1 = 12,000 L/s and k_2 = 0.0001, respectively (Figure 6-3):

$$river\ loss\ (\mathrm{L/s}) = 0.858\, Q_{gorge}; \qquad 0 < Q_{gorge} < 7000\ \mathrm{L/s}$$
$$= k_1\left(1 - e^{-k_2 Q_{gorge}}\right); \qquad Q_{gorge} > 7000\ \mathrm{L/s} \tag{4}$$

To convert river flow losses (L^3/T) (i.e. Equation 4) to an equivalent head of aquifer recharge water (L) (as required for Eigen-model input), a proportionality constant was assumed and formed one of the variable parameters in the model calibration process.

Although the Eigen-model can handle spatially distributed aquifer recharge/discharge processes, at this stage of knowledge development of the Orari environment, a parsimonious approach was adopted and a single uniform recharge model was assumed. The expectation was that the need for added complexity might be learned from the resulting outcomes. Where dynamic river recharge was added to a model, it was assumed to be concentrated along the upper-boundary of the model domain. In some cases, the spatial area over which river recharge inputs were distributed was adjusted manually to examine how the model reacted to these assumptions.

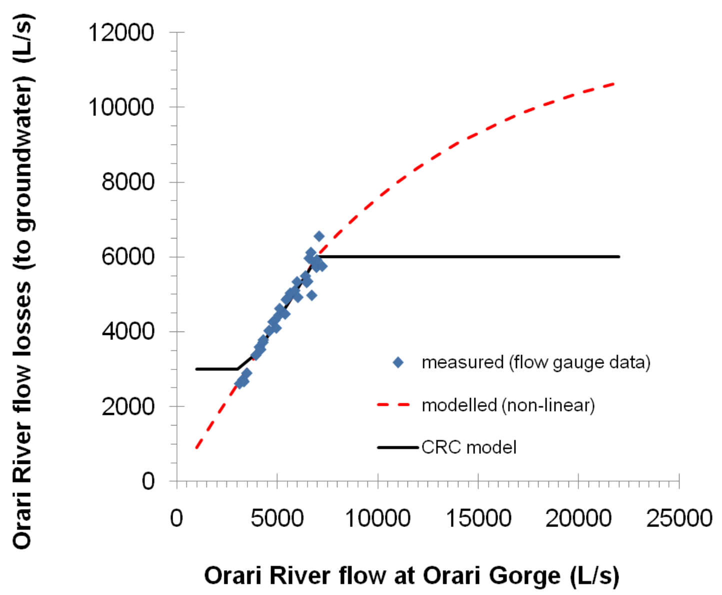

Figure 6-3: Relationship between Orari flows and losses (to groundwater). CRC model included for comparison.

6.3.5 Simulated groundwater abstractions

Groundwater abstraction effects were simulated for the case of hydrograph records from K37/2896 and K38/0060. Effects were only considered after the model had been calibrated for natural recharge phenomena. To convert volumes of groundwater abstracted to effective depth equivalents over the modelled domain, the total daily water volume was divided through by an area that was automatically estimated based on an attempt to further reduce the sum of square error relating to the irrigation period (that was not evaluated in the initial model calibration exercise).

6.4 Catchment water budget

An average annual water budget of basic hydrological inputs to the Orari catchment was calculated, based on processing 27 years of hydrological data (1983 – 2009) and 50 year climate record (1960 - 2009). No attempt has been made to balance hydrological inputs and outputs, for the reason that there is insufficient data available with which to reliably evaluate drainage from the catchment. The catchment area for which the water budget was completed is shown in Figure 6-4. It is useful to note that the area outlined in Figure 6-4 differs slightly from the area previously considered by Burbery and Ritson (2010), who recommended that Waihi River catchment, Burkes and Orakipaoa Creeks should be lumped in with the Orari hydrological catchment. The reason these systems have not been included in the assessment is because they are incorporated in the Opihi River plan, hence are not likely to be incorporated in the Orari environmental flow and water allocation plan (pers. comm., Luisa Magalhães, CRC planner, November 2010).

Recharge processes were not evaluated for the upland, mountainous catchment since it was assumed any water draining from this area is accounted for in the Orari River flows recorded at the Orari Gorge. Water draining off the foothills along the northern margin of the coastal catchment was assumed to operate as storm flow in the Scotsburn and Kowhai Streams that feed Coopers Creek. Flows in these systems are unrecorded, so a simplifying assumption has been that all rain falling on greywacke bedrock in these catchments constitutes ephemeral storm flow/direct surface run-off that is routed to the Orari River via Coopers Creek.

LSR in the Ohapi sub-catchment was evaluated separate from the main Orari system, because Ohapi Creek is subject to its own minimum flow regime. This is not meant to cloud the fact that Ohapi Creeks are hydraulically connected to, and sourced from, the Orari River.

The spring-fed streams about Clandeboye (e.g. Petries and Rhodes drains) have historically been treated as a component of the Orari River catchment. The recent hydrochemical evidence in Burbery and Ritson (2010) tends to indicate these spring-fed drains are most probably related to rainfall draining from the Orton plain. However, because there remains no reliable physical evidence of the hydraulic processes driving flows in the drain network about Clandeboye, the drains have been lumped in with the Orari River catchment, as a precautionary measure.

LSR has been calculated separately for both an upper and lower portion of the Orari catchment. The upper/lower division closely follows a draft internal planning zone boundary advised by CRC (pers. comm., Luisa Magalhães, CRC planner, November 2010). Both Station Stream and the upper reaches of Coopers Creek have been lumped in with the upper Orari zone.

LSR was estimated for each of the three zones marked in Figure 6-4, using the LSR-model component of the GDA-tool. Daily rainfall and PET data from NIWA's virtual climate network were summed over the zones. In an effort to incorporate some uncertainty bounds, two sets of parameter values were assumed in the soil water budget model, these being:

1) LSR-model parameter values estimated in the groundwater hydrodynamic analyses of this report; and
2) average zonal soil profile available water (PAW) values published on Landcare's [soil] SMap assumed for *W*, together with the coefficient *a* set to a value of 5, i.e. the same assumptions applied by Scott (2004) and Burbery and Ritson (2010).

The results for the case of a drainage threshold value, as well as the case of no such limit were assessed, although the former case probably yields the more reliable result.

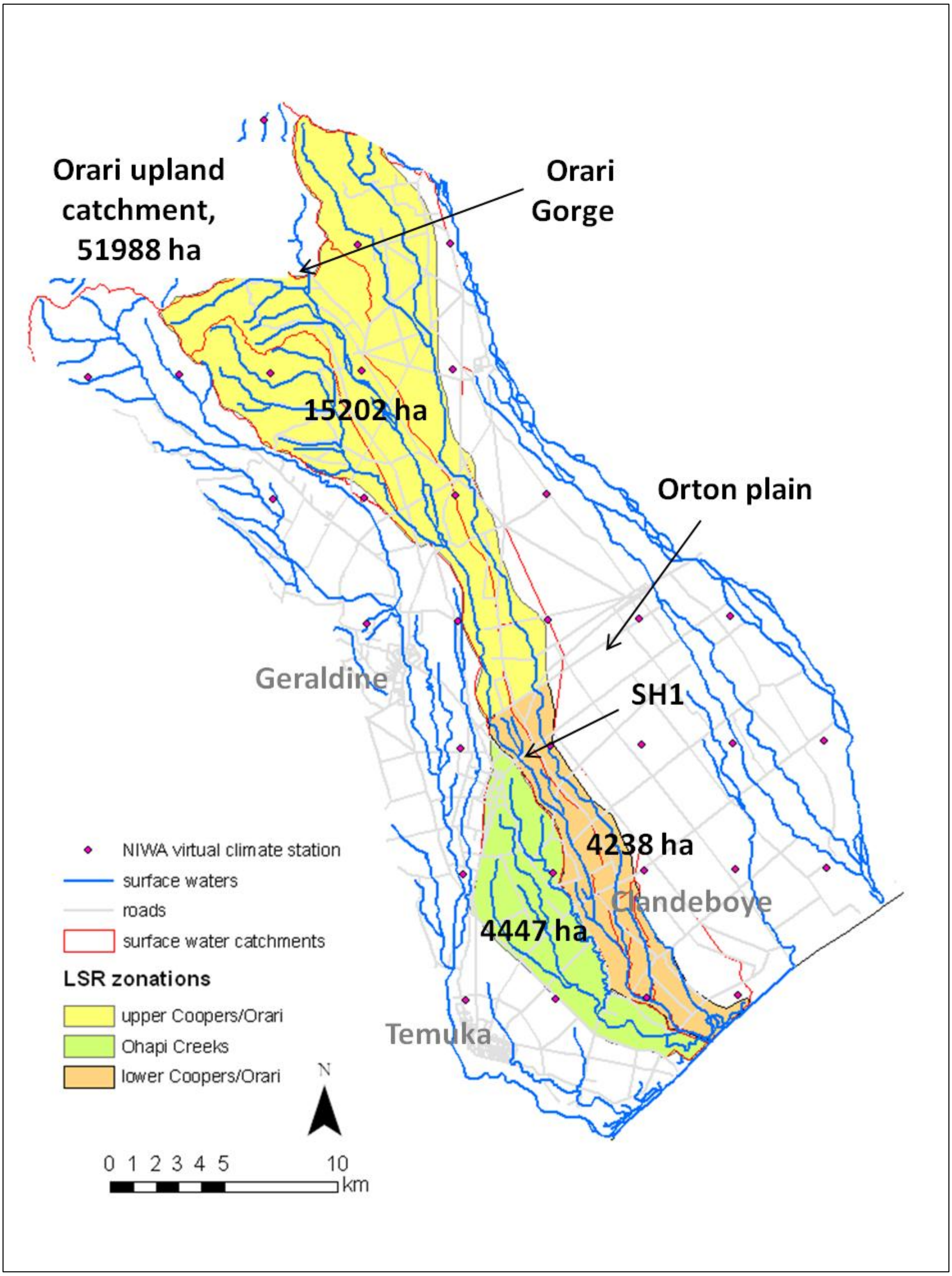

Figure 6-4: Zones over which LSR budgets have been evaluated; zone areas labelled. All recharge in the upland catchment is assumed to drain via the Orari Gorge. Dots mark the 5 km square grid network for which NIWA virtual climate data are available. Surface water catchment boundaries included for reference.

7 RESULTS

7.1 Evidence of groundwater storage in river hydrographs

The hydrograph recession curves representing the three Orari storm-flow events at the Gorge, for times when the river contained dry reaches are shown in Figure 7-1. The hydrograph data have been normalised with respect to the peak flow recorded at the start of the storm-flow event. No attempt has been made to naturalise the flow data from the recorder site located in the lower reach of the Orari River, upstream of Ohapi Creek (red hydrographs in Figure 7-1).

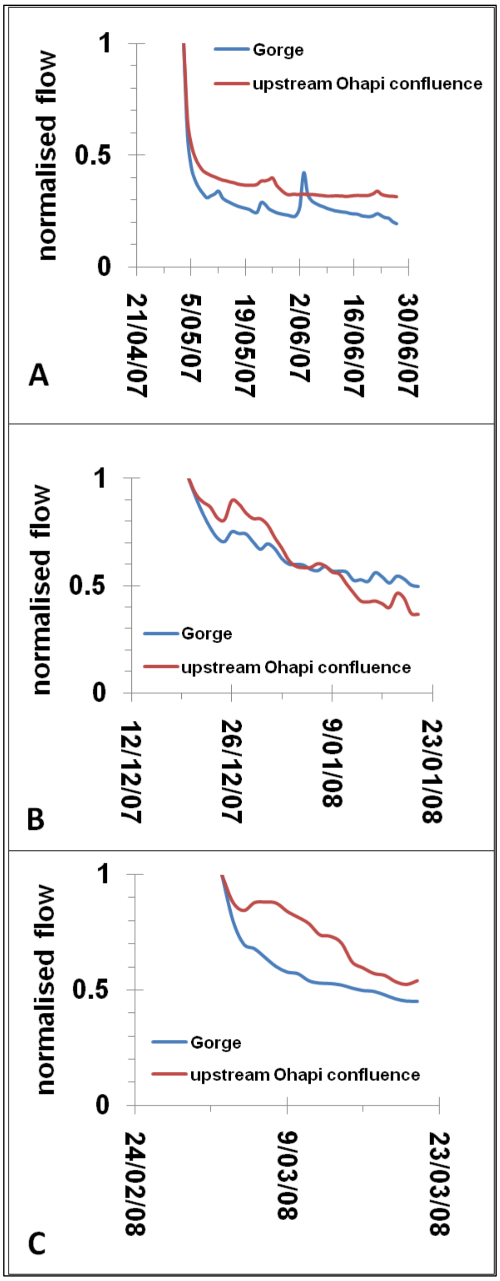

Figure 7-1: Recession curves in hydrograph records for Orari River at Gorge recorder and upstream Ohapi Creek recorder sites, corresponding to storm-flow events when Orari main-stem was dry at SH1. Flows have been normalised with respect to peak storm-flow for each event.

It is evident that the recession of storm-flow in the lower reach of the Orari River is slower than that observed at the Gorge. This suggests some attenuation mechanism is active within the hydrological system that can be attributed to groundwater storage. In December 2007, flow in the lower reaches of the Orari continued to drop, even when flows upstream, at the Gorge, appeared to flatten out at a base-level (see Figure 7-1b). It is probable that water abstractions for irrigation were responsible for the depletion of flows observed at the down-stream end of the river.

7.2 Commonality in aquifer responses

Based on visual analysis of the 10 groundwater level hydrographs, datasets corresponding to individual wells have been grouped into four general categories, according to the tenor of their data. These groupings are summarised in Table 7-1, the hydrographs from which the inferences have been made are included in Figure 7-2.

Table 7-1: Grouping of wells according to their general visual hydrograph characteristics. Geology code refers to GNS QMap codes: Q1a, Gravel sand and mud of modern and post-glacial flood plains; Q2a, Gravel sand and silt of low river terrace.

group	well #	easting	northing	depth (m)	geology	surface water
1	K37/2896	2370072	5687591	9.2	Q2a	Orari – Coopers
	J37/0009	2368884	5684651	11.2	Q2a	Stn Stream
	K38/2154	2371735	5674228	8.0	Q2a	Raukapuka / Dobies
	K38/1426	2372961	5667097	7.6	Q2a	Ohapi (Sth)/Waihi
2	K38/2155	2373900	5671930	8.2	Q2a	Orari/Dobies – Ohapi (mid)
	K38/2157	2374460	5673942	7.5	Q1a	Orari
3	K37/0335	2372662	5684362	18.4	Q2a	Coopers
	K37/2923	2371150	5681886	8.6	Q2a	Orari – Dobies
4	K38/1758	2376460	5667010	14.0	Q2a	Ohapi (Nth)
	K38/0060	2375369	5664020	8.7	Q2a	Ohapi (Sth)

There do not appear to be any obvious geological factors that categorically divide the hydrograph datasets. According to the GNS geological map (Cox and Barrell, 2007) all the wells screen fluvial deposits, with K38/2157 located within the youngest material, this being the Orari river bank. Some of the common characteristics associated with the groups can be attributed to geographical/physical variables that are explained below (see Figure 5-1 for location plan of wells):

Group 1: Relatively stable groundwater levels exhibiting consistent base-flows, hence shallow aquifer appears to be strongly linked to source of constant recharge/discharge, e.g. springs/perennial surface water.

Group 2: Large variations in water levels, clearly sensitive to groundwater abstraction, although effects appear to be buffered by reasonable connection to surface water recharge boundary that can disappear in summer months, i.e. close to ephemeral streams.

Group 3: Similar pattern to group 2, albeit variations show less correlation to periods when rivers are dry, from which it may be presumed that wells are farther removed from surface waters and show characteristics of aquifer distant from recharge boundaries.

Group 4: Mixture of groups 1, 2, 3. Reasonably large water level fluctuations occur in well K38/0060, from which it may be presumed that groundwater is relatively disconnected from an Ohapi Creek boundary condition. In contrast, K38/1758 shows relatively stable water level conditions, from which a reasonable hydraulic connection with Ohapi Creek is inferred.

The conceptualised river recharge boundaries were factored into the Eigen-modelling.

The analysis of a threshold groundwater level for well K38/2157, as an indicator for dry river conditions for the Orari River is included as Appendix B.

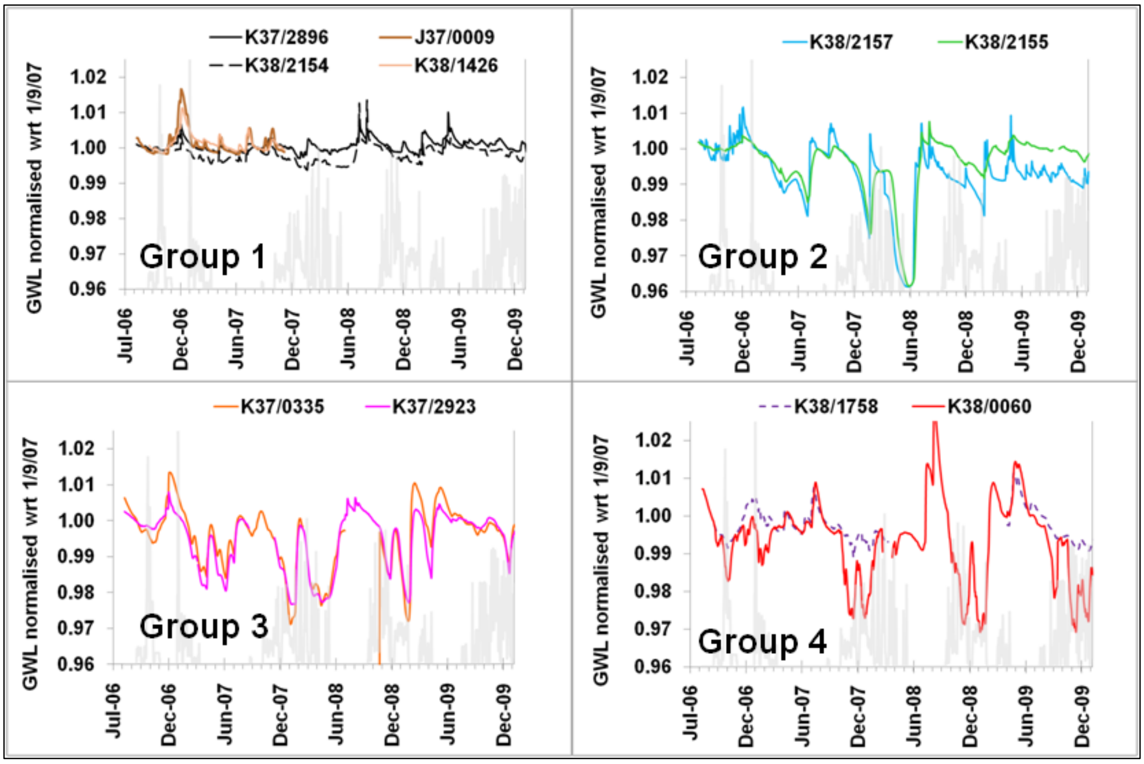

Figure 7-2: Grouping of groundwater level hydrographs based on visual assessment of similarities. All datasets have been normalised with respect to water level measured on 1st September 2007. Grey series in all figures is the relative irrigation water usage for the catchment (explained in Section 6.3.5).

7.3 Evaluating possible bank storage effects

The attempts at modelling the groundwater level response in K38/2157 subject to a variable head recharge boundary of the Orari River (as per Equation 1) are shown in Figure 7-3. In all cases, the separation distance between the well and the river, x, was assumed to be 75 m. The only parameters in the problem requiring estimation then were the ratio T/S (known as the aquifer diffusivity) and the proportionality constant to correct the Orari River stage recorded at the Gorge to an effective stage at SH1.

For the 2008 storm-flow recharge events assessed, the aquifer dynamics at K38/2157 could be reliably explained by a variable head boundary (i.e. the dynamics were entirely determined by the river stage), as per Equation 1. In these cases, the estimated optimal proportionality constant for the assumed Gorge-SH1 stage relationship was 1.0 and the aquifer diffusivity 16 666 m^2/day. The same values have been assumed in the other simulated datasets in Figure 7-3, albeit the proportionality constant, α, has been allowed to vary by +/- 10% to account for the natural dynamics of river bed – stage relationships.

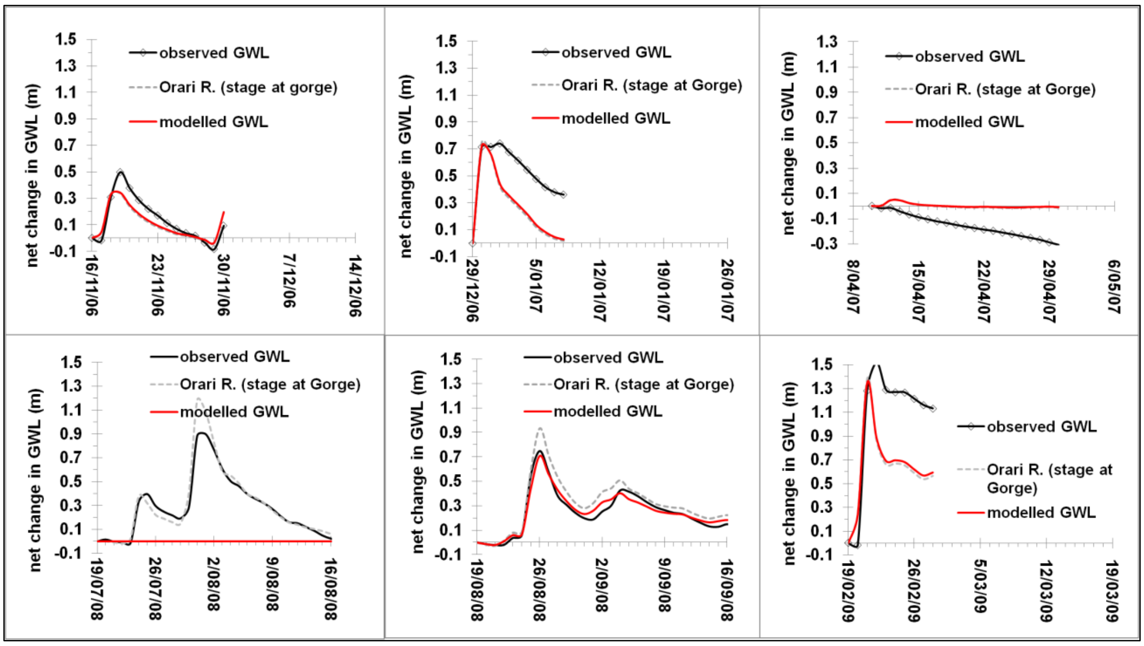

Figure 7-3: Application of Equation 1 to model groundwater levels observed in well K38/2157 for various river storm-flow events, assuming aquifer recharge is driven by river stage.

Assuming an effective aquifer porosity of between 0.06 - the average measured in all Orari pumping tests - a transmissivity value for the recent Orari river bank material is estimated to be in the realm of 10 000 m^2/day. This is close to the maximum transmissivity estimate reported for the Orari aquifer of 10 500 m^2/day evaluated at well K38/0658 (see Table 2-1 in Burbery & Ritson (2010)).

From the 2008 assessments, it can be inferred that there is effectively no active aquifer storage capacity in the Orari river bank material – essentially the groundwater levels at K38/2157 perfectly correlate with the river levels with very little lag effect. It can be conceived that as effective the river is at recharging the aquifer locally, it is similarly effective at draining the aquifer once the flood wave passes. Wave propagation theory determines that river recharge from individual storm-flow events is an ineffective mechanism for recharging the bulk aquifer system. Despite apparently large amplitudes of groundwater level change observed at K38/2157 stemming from the river inputs, these effects are unlikely to propagate far into the shallow aquifer system, normal to the direction of the river channel, due to attenuation of the pressure wave. Similarly they do not translate to large water volumes, as is demonstrated in Appendix C, using the storm-flow event of July 2008 shown in Figure 7-3 as an example. The timing of effects realised in the aquifer, in response to storm-flow events, is proportional to the separation distance from the river.

However, on other occasions, despite the close proximity to the river, the groundwater levels at K38/2157 cannot be explained by river recharge alone and some effective aquifer storage appears to be active. For the scenarios assessed this is notable for the January 2007 and February 2009 recharge events. The difference in system response cannot be explained by the antecedent groundwater level, as apparent from Figure 7-4. Rather, the condition appears to be related to rainfall distribution. It would appear from the rainfall record (Figure 5-2) that on these occasions, intense rainfall was experienced across the coastal plain, whereas for the two 2008 events assessed it appears the river storm-flow events were driven predominantly by rainfall concentrated in the upland catchment. These observations serve to demonstrate that in terms of dynamic groundwater storage potential (i.e. variations in groundwater levels); land surface recharge is more effective than recharge derived from the river. This does not alter the fact that the Orari shallow aquifer system receives a constant, essentially base-flow, input from the Orari River that maintains the base-flows in the spring-fed surface waters of the catchment.

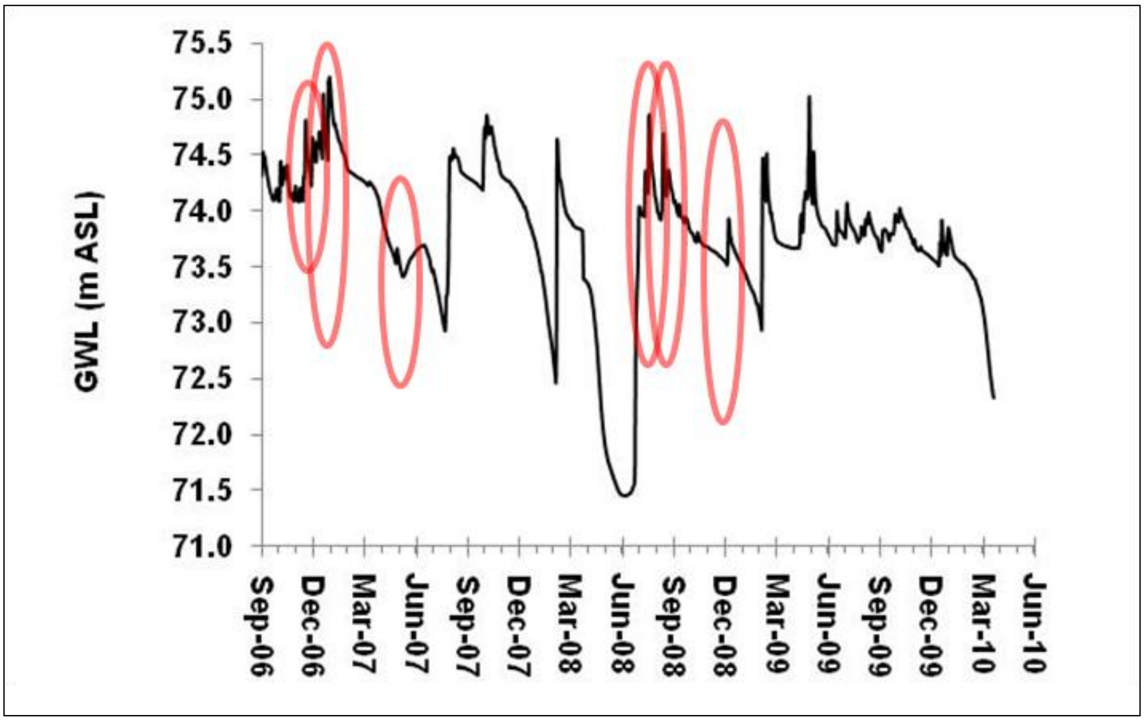

Figure 7-4: Groundwater level (GWL) record measured for well K38/2157. Red rings mark selected recharge events for which potential bank storage effects assessed (see Figure 6-1 for corresponding river hydrograph and rainfall record).

In April 2007 there was no measurable recharge of the shallow aquifer despite the brief rainfall event, rather, groundwater levels continued to decline. At the time of this storm event, the Orari River was dry at SH1 and irrigation was active. It would appear that the storm-flows occurring at the Gorge on this occasion were insufficient to restore groundwater levels to a state that supported river base-flow at SH1. It can be inferred that all the water discharged from the Gorge at this time went to recharging the shallow aquifer at the top end of the catchment; the effects were insufficient to impact the groundwater system at the centre of the catchment or further down. This observation demonstrates that river storm flow has limited potential to recharge the bulk of the aquifer, yet it also highlights that the flow regime of the Orari River is sensitive to shallow groundwater conditions; hence, river flows are susceptible to the cumulative effects of groundwater abstraction.

The groundwater hydrograph records for wells J37/0009, K37/2923 and K37/2896 were similarly assessed for direct river recharge/bank storage effects, using the same methods. These wells are all located with 1 km of the Orari main-stem, or, in the case of J37/0009, 300 m of Station Stream. They were, therefore, presumed to potentially be responsive to river recharge, like K38/2157. However, none of the storm-flow event records analysed could be reliably described using Equation 1. In all cases, unrealistically large stage coefficients (values of α) were required to explain the amplitudes of the groundwater responses and delayed storage effects were apparent (as per the January 2007 and February 2009 case studies of K38/2157 in Figure 7-3). From these observations, it is inferred that river recharge/bank storage effects are unlikely to play a significant role in the hydrodynamics of the bulk of the Orari aquifer system, beyond possibly the most modern river terrace.

7.4 Aquifer hydrodynamics as determined using the Eigen-model

7.4.1 Upper Orari/Coopers Creek: K37/2896

The monitoring well K37/2896 is located between the Orari River and the springs of Coopers Creek, at Springs Farm in the upper region of the Orari catchment (see Figure 5-1). The shortest distance between the well position and the Orari River is just over 300 m, and 360 m to the closest of the four mapped springs. The springs are known to flow continuously all year around, and the groundwater levels at K37/2896 tend to suggest the shallow aquifer in this region has a relatively constant recharge and/or discharge boundary condition, as explained in Section 7.2. It was considered that K37/2896 may be a useful well from which to determine the hydrodynamic properties of the shallow aquifer system connecting the Orari River and the springs feeding Coopers Creek.

The results of the 2006/07 field study confirmed the Orari River as the source of spring water sampled at Springs Farm in September 2006. However, the field conditions at the time of the sampling were exceptionally unusual - September 2006 was the driest month experienced in the catchment over the last 4 years. There remains some uncertainty regarding whether or not the springs at Springs Farm might, under more normal conditions comprise water derived from land surface recharge. This prior knowledge pertaining to the shallow groundwater relationship with the Orari River was built into our model of the natural system.

Given the drought condition experienced in September 2006, it is possible to analyse this period of the K38/2896 hydrograph record assuming no active land surface recharge component; any dynamics exhibited in the shallow groundwater system must be attributed to river recharge inputs. One measurable river storm-flow event occurred in September 2006, from which it is possible to identify that a lag time of less than three days occurring between storm-flow events at the Orari Gorge and groundwater level response at K37/2896 (Figure 7-5). Using the Eigen-model to interpret the aquifer properties based on this single recharge event, and assuming a river recharge boundary at the upper end of the model domain, resulted in an effective hydraulic residence time estimate of eight days (see first column of data in Table 7-2). The model inferred the observation well to be located approximately one third along the length of the aquifer domain.

Application of the Eigen-model to interpret hydrograph records over individual finite winter periods yielded inconsistent Eigen-value estimates. Eigen-values mathematically represent the physical characteristics of the aquifer system, thus are independent of time. The variability displayed in the Eigen-values in the Eigen-modelling results based on individual winter assessments reflects the non-uniqueness of the mathematical problem. To constrain this, aside from the September 2006 event, all Eigen-model calibrations were set to interpret continuous hydrograph records, spanning multiple non-irrigation seasons.

Figure 7-6 shows the resulting Eigen-model simulation of K37/2896. The resulting efficiency index of 0.91 indicates that the mathematical model is a very good descriptor of the observed system. Similarly well-fitting models can be achieved if LSR is considered the only active aquifer recharge component albeit the resulting aquifer parameter estimates are less realistic than those derived when potential river recharge is also factored into the model (see Table 7-2). This tends to strengthen the case that the Orari River is responsible for some of the hydrodynamic behaviour of the shallow aquifer in the vicinity of Springs Farm. The Eigen-model proved to be insensitive to the scale of the river recharge area simulated.

Table 7-2: Resulting parameter estimates and model efficiency statistics for Eigen-(groundwater)-model / LSR model applied to characterise aquifer hydrodynamics as observed through groundwater levels observed in well K37/2896. Parameters are explained in Table 6-1.

	Period of record analysis	September 2006	2006 - 2010	2006 - 2010	2006 -2010
	Recharge assumptions	River recharge only (distributed over 1% of aquifer)	LSR only (distributed over 100% of aquifer)	LSR (over 99% of aquifer) + river recharge (over 1% of aquifer)	LSR (over 99% of aquifer) + river recharge (over 1% of aquifer) + abstraction
Eigen-model parameters	T/SL^2 **(m²/day)**	0.053	0.0048	0.030	0.030
	S	0.06	0.001	0.09	0.09
	x/L	0.33	1.0	0.11	0.11
	H_0 **(m asl)**	184.69	184.42	184.58	184.58
Vadose zone	t_v **(days)**	n/a	85	1.6	1.6
LSR model parameters	C	n/a	1.05	1.0	1.0
	W **(mm)**	n/a	17.3	15.0	15.0
	A	n/a	2.8	1.0	1.0
	D_T **(mm)**	n/a	17.3	15.0	15.0
River recharge model	**Convert river flow from L/s to mm/d**	n/a	n/a	0.029	0.028
Irrigation abstraction model	**Estimated catchment area, based on pumping effects (ha)**	n/a	n/a	n/a	2627
Model efficiency measures	E **(for calibration periods)**	0.98	0.75	0.91	0.91
	E **(for entire record)**	n/a	n/a	0.79	0.82
	Effective storage residence time (days)	8	85	13	13

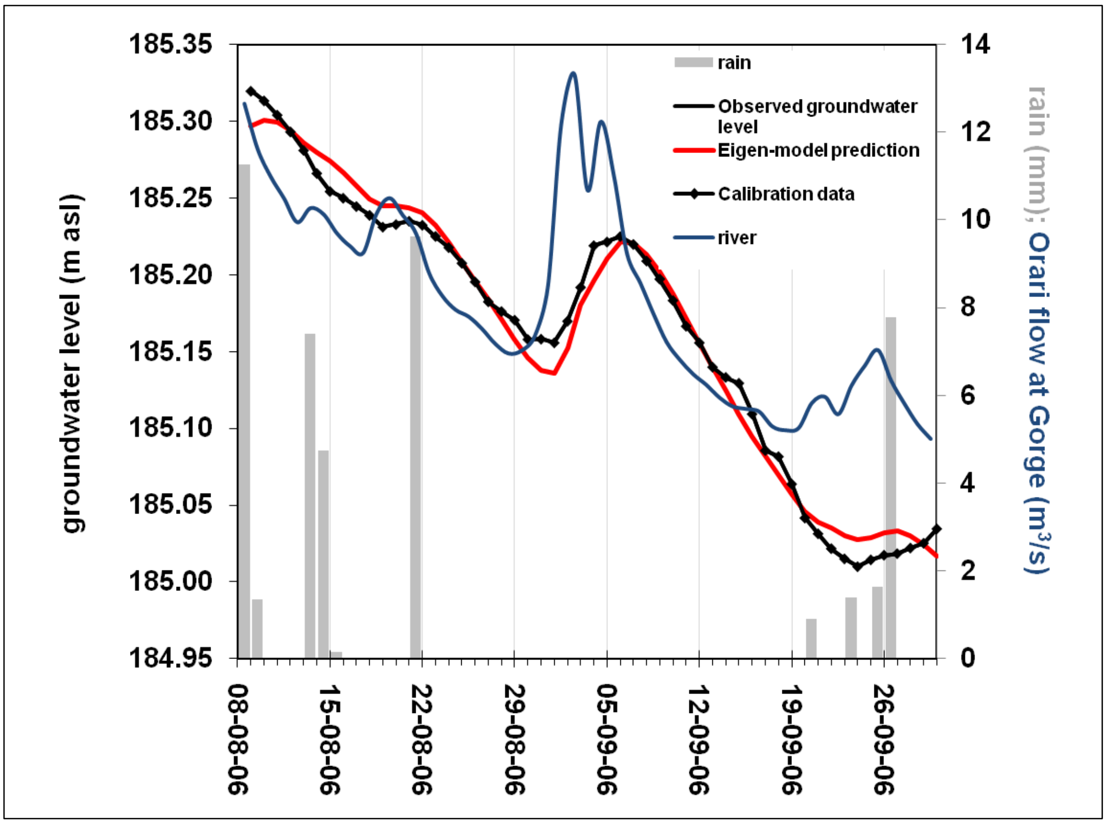

Figure 7-5: Eigen-model applied to simulate groundwater levels at K37/2896 over dry month of September 2006. Model efficiency fit, E = 0.98.

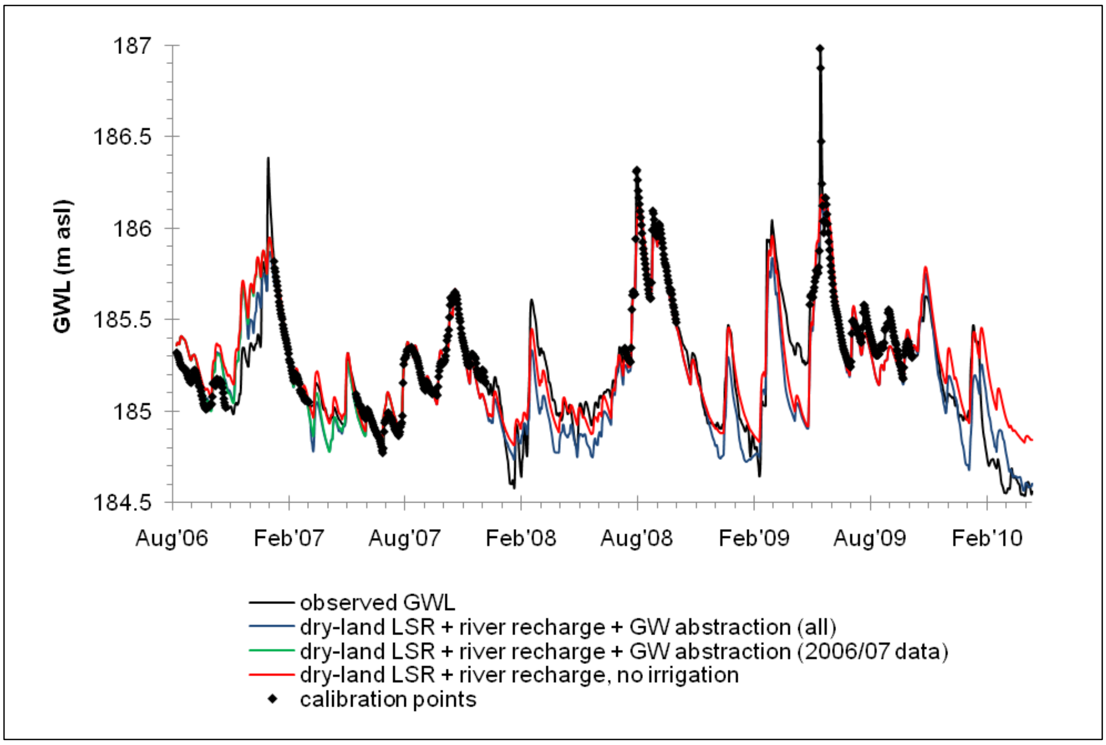

Figure 7-6: Simulated groundwater level observed at well K37/2896, based on Eigen-model application calibrated to non-irrigation periods. Model efficiency, E = 0.91. Difference between black and blue lines incorporates effects of water abstraction.

Using the Eigen-model it is possible to evaluate how river recharge and LSR individually contribute to the fluctuations in observed groundwater levels, and therefore aquifer discharges. From K37/2896 hydrograph data it is possible to infer that on any day between November 2006 and April 2010, discharge from a unit width of the shallow aquifer comprised between 0.6 and 3.0 litres of water derived from river storm-flow inputs and between 0.03 and 5.2 litres from LSR. Note: these estimated discharges are on top of any steady-state discharge/base-flow component. Equivalently, between 16% and 67% of the variability in groundwater discharges from the shallow aquifer is estimated to have derived from river storm-flow inputs and 3% - 84% from LSR, respectively (Figure 7-7).

The Eigen-model predicted an effective base groundwater level, H_0, of 184.5 m above sea level (asl) for the aquifer characterised by K37/2896. According to the topographical map, this coincides with the approximate elevation of the springs at Springs Farm, which is consistent with the conceptual model that the springs are a constant head discharge boundary in the local aquifer system. The groundwater level dynamics exhibited at K37/2896 are characteristic of a well, positioned in the upper region of the aquifer system (x/L = 0.1), i.e. close to the assumed no-flow boundary. This characteristic distance inferred by the model does not appear to match the physical scale of a conceptual model that assumes a closed system bounded by the Orari River and the springs of Coopers Creek. Because of the complex, potentially transgressive and multi-dimensional hydrogeological boundaries that exist in the real Orari environment, it is probable that the dimensional characteristics estimated from the Eigen-model calibration will be fuzzy and so should be treated with caution.

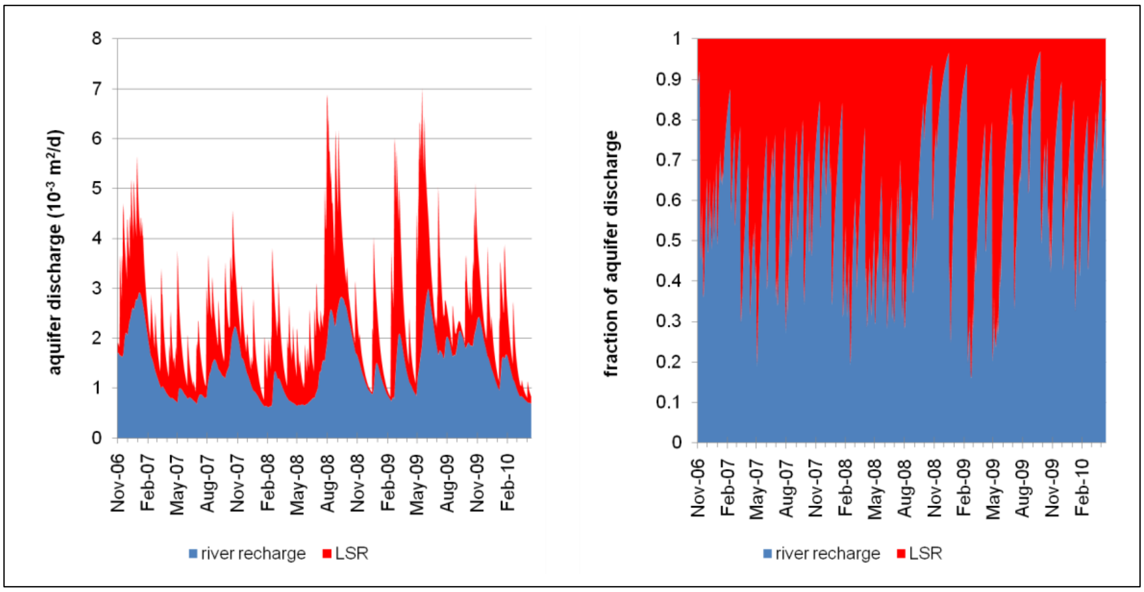

Figure 7-7: Contributions of LSR and river recharge to simulated dynamic daily aquifer discharge, for the calibrated Eigen-model shown in Figure 7-6. [Left:] actual discharge, per unit aquifer width; [right:] relative contribution.

The effective hydraulic residence time determined from the calibration with three seasons of data was 13 days (i.e. half-life of approximately 9 days). These are slightly slower drainage characteristics values than those evaluated for the same system, considering only September 2006 data, but nonetheless still signify that the shallow aquifer in the upper Orari region is very dynamic and exhibits limited storage characteristics.

The soil water holding capacity estimated for the LSR model in the calibration process of 15 mm is relatively low, but is consistent with the soil profile available water values reported by Landcare Research that cover the Orari River terrace (e.g. Lynn et al. (1997)) – see Figures 2-3 and 2-5 in Burbery & Ritson (2010).

Figure 7-6 also shows the simulated water levels, when irrigation effects are included in the calibrated model, subject to the assumptions outlined in Section 5.4 and assuming that the groundwater take consents in the upper Orari region defined by Burbery and Ritson (2010) reflect the active takes within the aquifer catchment. The simulation does not consider aquifer recharge effects attributed to irrigation-LSR. Generally, the inclusion of groundwater abstraction data into the model provides a more accurate representation of observed groundwater level changes over the irrigation periods, certainly for the 2006/07 season when the most reliable water metering data were available. Consideration of irrigation trends for farms beyond the limits of the Upper Orari sub-basin led to more reliable estimates of groundwater fluctuations than when only the groundwater usage of seven active, local groundwater irrigators was considered. This may be a reflection that the shallow aquifer system at the upper end of the catchment is sensitive to abstractions on a larger regional scale than the sub-basin outlined in Burbery & Ritson (2010), which is consistent with the concept that the shallow aquifer is extensive and groundwater abstractions throughout the entire Orari catchment have a far-reaching, cumulative effect. The resulting estimates of parameter values and model fit statistics for the model scenarios of K37/2896 are summarised in Table 7-2.

7.4.2 Ohapi Creek: K38/0060, K38/1758, K38/1426

Well K38/0060 is located west of Ohapi Creek (south branch), approximately 715 m from the creek itself. At 4.2 km, it is the farthest monitoring well from the Orari main-stem. Its hydrodynamic characteristics are likely to be representative of the Ohapi sub-basin, extending south to Temuka. In Burbery & Ritson (2010), the hydrochemical characteristics of the groundwater in this locality were indicative of probable land surface recharge origin. The waters sampled from Ohapi Creek during the field study were characteristic of Orari River water. The conceptual model of this area was such that aquifer discharge from this region of the catchment was either be to Ohapi Creeks, Orakipaoa Creek, or quite possibly direct to the ocean.

Efficient model to data fits (E = 0.92) were achieved using the Eigen-model when calibrated to water levels covering non-irrigation periods. It appears from the simulated data (Figure 7-8) that in the summers of 2007 through 2008, that groundwater abstraction in the Ohapi sub-basin contributed to almost half-metre drops in groundwater levels at K38/0060 based on what might reasonably have been expected if irrigation were not active; the difference between black and red lines in Figure 7-8 includes effects of water abstraction.

Compared to the aquifer system monitored via K37/2896, the hydrograph signals at K38/0060 are reflective of a well located close to the end of the system/close to the final discharge boundary (x/L was estimated at 0.97). The dynamic storage properties of the system about K38/0060 are slightly greater than those characterised for the aquifer about K38/2896; an effective hydraulic storage residence time of 37 days was estimated (i.e. half-life of approximately 26 days). It is interesting to note that ten day vadose zone storage was evaluated from the hydrograph data. This effective attenuation of LSR is likely to be indicative of a perched water condition above the level at which the well screens. The description of a surficial clay layer on the bore log of K38/0060 is consistent with this theory.

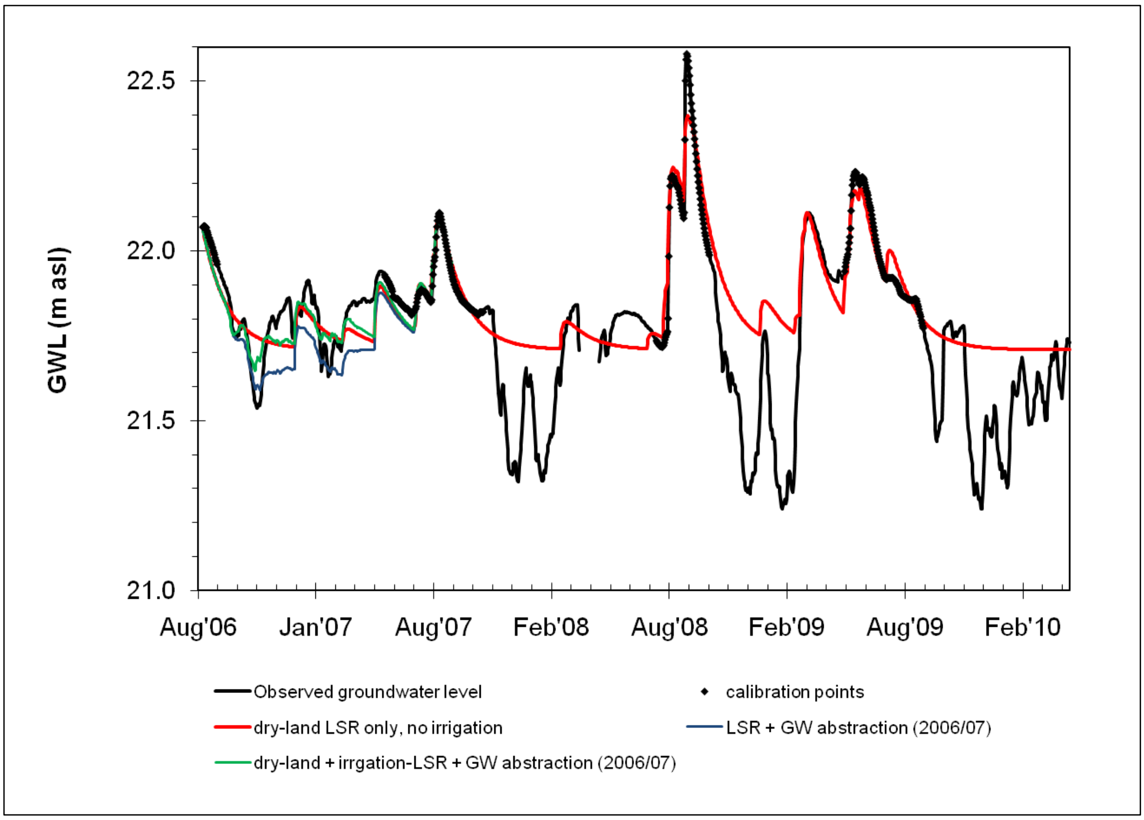

Figure 7-8: Simulated groundwater level observed at well K38/0060, based on Eigen-model application, calibrated to non-irrigation periods. Model efficiency, E = 0.92.

Groundwater abstractions were simulated in the case of well K38/0060 data analysis, albeit the focus was on 2006 – 2007, for which the most reliable water metering records were available. The resulting hydrograph data (blue line in Figure 7-8) demonstrated marginal improvement, although a significant improvement resulted when both groundwater abstractions and irrigated-LSR processes were incorporated into the model (green line in Figure 7-8). Surface water abstractions were not factored into the simulations and this could explain the apparent under-estimation of groundwater levels over the irrigation season, since irrigated-land LSR is likely to be greater than that simulated. In support of this argument is the suggestion of Burbery & Ritson (2010) that irrigation using surface water from Ohapi Creeks could be responsible for the mixed chemical signals observed in groundwater of the Ohapi basin.

Only two years of groundwater level monitoring data are available for analysis for well K38/1758, located adjacent to the north branch of Ohapi Creek, and only one year of data for well K38/1426, located between Dobies Stream and the Ohapi Creek south branch (see Figure 5-1 for locations). Substitution of the eigen-values from analysis of data at K38/0060, yielded reasonable model to observed data fits for the hydrograph record at K38/1758, (E = 0.97), which suggests that the aquifer characteristics are similar. Conversely, no similar characteristics appeared to define the hydrodynamics observed at well K38/1426, which is positioned between Dobies Stream and Ohapi Creek. The aquifer at K38/1426 shows faster drainage characteristics than were evaluated at either K38/0060 or K38/1758, with storage residence times in the order of 11 – 13 days best describing the hydrograph recession curve.

7.4.3 Middle Orari/Central catchment: K38/2154, K38/2923

The prevalence of dry river reaches throughout the central region of the Orari shallow aquifer posed complications to interpretation using the Eigen-model approach, given the limiting mathematical assumption of linearity. Nonetheless, the short portions of the groundwater hydrograph records from wells K38/2154 and K38/2923 for which stable boundary conditions could be assumed demonstrated reasonably similar dynamic characteristics, with storage residence times of approximately 17 and 13 days, respectively. These characteristics apply to the system only for the periods when the Orari (and it has been presumed, Dobies Stream) is flowing and to which the Eigen-models were calibrated. The storage potential measured in these locations is comparable to that measured at well K38/1426, in the Ohapi sub-basin.

The base groundwater level determined for the dynamic response evaluated for K38/2923 was 139.0 m asl. This level coincides with the approximate topographic elevation of the spring source of Dobies Stream, which is probably the effective drainage point of the aquifer in this region. Similarly, the base groundwater level determined for the dynamic response evaluated for K38/2154 was 80.5 m asl. This is the approximate topographic elevation of the spring source of Worners Creek that is likely to act as a local drainage point.

The modelled groundwater level responses for both well records are shown in Figure 7-9. The dramatic drops in groundwater levels at K38/2923 are indicative of the loss of recharge and storage potential associated with the drying of reaches in both the Orari River and Dobies Stream, to which the aquifer is connected. Inclusion of a river recharge component in the system to the aquifer system characterised by K38/2154 was required to drive the system response. A model efficiency of only 0.58 could be achieved when LSR was assumed the only dynamic recharge component.

Limitations on time precluded any Eigen-model interpretation of groundwater levels at well K38/2155, at the head of Ohapi Creek (north branch).

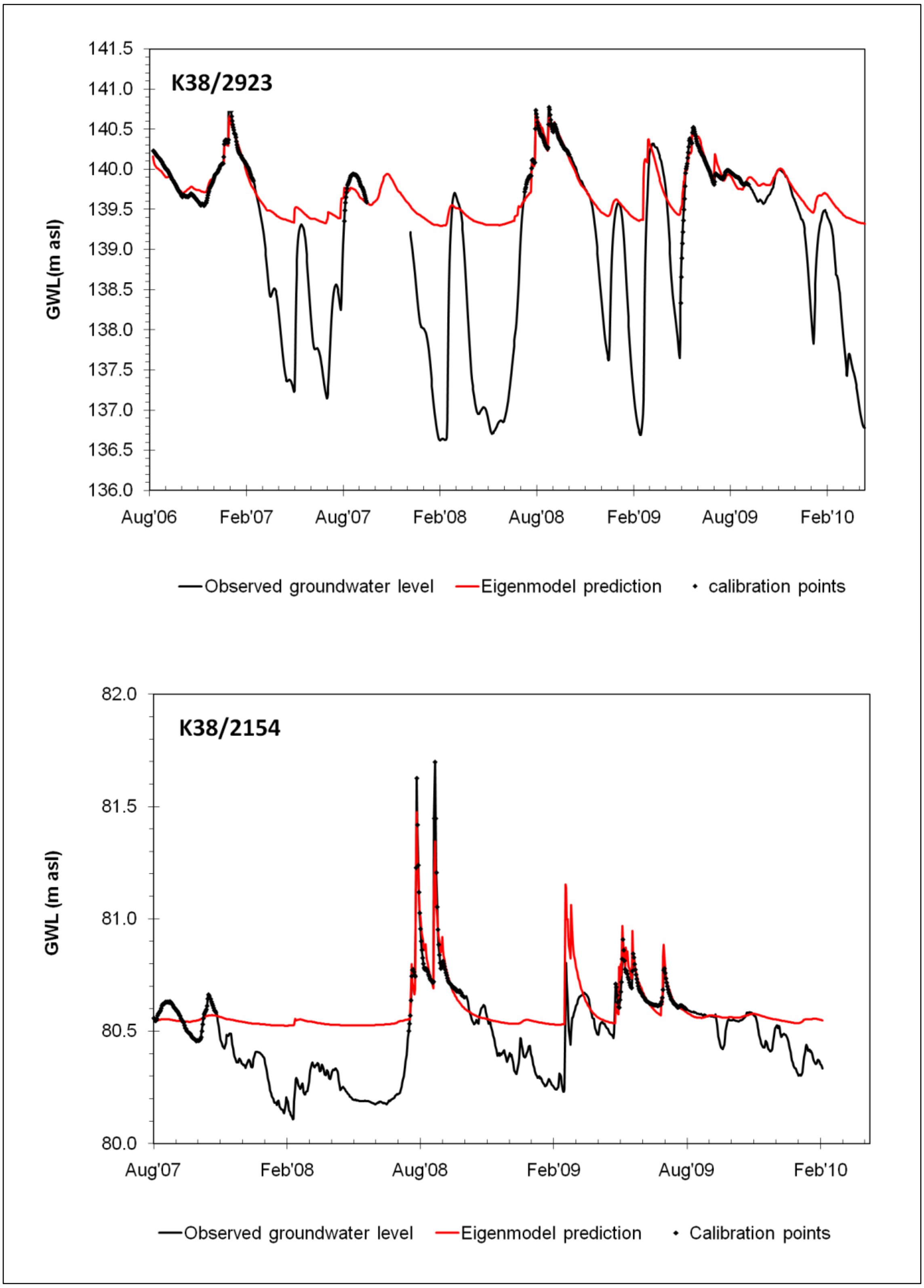

Figure 7-9: Simulated groundwater levels observed at wells K38/2923 (top) and K38/2154 (bottom), based on Eigen-model application, calibrated to non-irrigation periods. Model efficiencies, E = 0.83 and 0.86, respectively. Difference between black and red lines includes effects of water abstraction and drying of river reaches, neither of which have been quantified.

7.5 Catchment water budget

Table 7-3, Table 7-4 and Table 7-5 summarise the annual budgets of hydrological system inputs that were evaluated for the zones mapped in the Figure 6-4, based on analysis of 50 years of climate record and 27 years of river flow record. Minimum values are reported to illustrate a probable worst-case scenario.

*Table 7-3: Annual LSR estimates (depth equivalents) for zones mapped in Figure 6-4. *indicates spatially-averaged data. LSR assumed only active over Quaternary geological deposits.*

		Upper Orari	Lower Orari	Ohapi	Total
	Area (ha)	15 202	4 238	4 447	23 887
	Area subject to recharge (ha)	9 777	4 238	4 447	18 462
	Average rainfall (mm)	1 007	644	649	837*
	Average PET (mm)	737	842	845	787*
	Minimum rainfall (mm)	635	372	377	512*
Average annual AET (mm)	Eigen-model calibration 1	373	398	426	391*
	Eigen-model calibration 2	n/a	n/a	491	n/a
	SMap properties	560	456	474	515*
Average annual LSR (with drainage threshold) (mm)	Eigen-model calibration 1	446	203	195	329*
	Eigen-model calibration 2	n/a	n/a	149	n/a
	SMap properties	309	131	120	222*
Average annual LSR (no drainage threshold) (mm)	Eigen-model calibration 1	634	249	225	447*
	Eigen-model calibration 2	n/a	n/a	159	n/a
	SMap properties	448	188	175	322*

Table 7-4: Annual LSR estimates (water volumes) for zones mapped in Figure 6-4.

		Upper Orari	Lower Orari	Ohapi	Total
	Average rainfall ($10^6 m^3$)	153	27	29	209
	Average rainfall on recharge area ($10^6 m^3$)	98	27	29	155
	Minimum rainfall on recharge area ($10^6 m^3$)	62	16	17	95
Average annual AET ($10^6 m^3$)	Eigen-model calibration 1	36	17	19	72
	Eigen-model calibration 2	n/a	n/a	22	n/a
	SMap properties	55	19	21	95
Average annual LSR (with drainage threshold) ($10^6 m^3$)	Eigen-model calibration 1	44	9	9	61
	Eigen-model calibration 2	n/a	n/a	7	n/a
	SMap properties	30	6	5	41
Average annual LSR (no drainage threshold) ($10^6 m^3$)	Eigen-model calibration 1	62	11	10	83
	Eigen-model calibration 2	n/a	n/a	7	n/a
	SMap properties	44	8	8	60

Table 7-5: LSR as proportion of total rainfall, by zone mapped in Figure 6-4.

		Upper Orari	Lower Orari	Ohapi
	Average rainfall	100%	100%	100%
	Average PET	73%	131%	130%
	Minimum rainfall	63%	58%	58%
Average AET	Eigen-model calibration 1	37%	62%	66%
	Eigen-model calibration 2	n/a	n/a	76%
	SMap properties	56%	71%	73%
Average LSR (with drainage threshold)	Eigen-model calibration 1	44%	32%	30%
	Eigen-model calibration 2	n/a	n/a	23%
	SMap properties	31%	20%	19%
Average LSR (no drainage threshold)	Eigen-model calibration 1	63%	39%	35%
	Eigen-model calibration 2	n/a	n/a	24%
	SMap properties	44%	29%	27%

Assuming there is some limiting daily infiltration rate (i.e. drainage threshold), it is estimated that total LSR within the Orari catchment plot in Figure 6-4 is, on average, in the realm of $41x10^6$ to $61x10^6 m^3$/year. LSR in the Ohapi catchment is in the region of $5x10^6$ to $9x10^6$ m^3/year, i.e. approximately 12-14% of the total catchment LSR. The estimate of what fraction of rain actively recharges the groundwater doesn't differ much from what Burbery and Ritson (2010) previously estimated; somewhere between 19 and 44%, varying dependent upon location within the catchment.

The average annual volume of water that flows in the Orari River via the Gorge is $291x10^6$ m^3/year. The minimum annual volume over the last 27 years has been $162x10^6$ m^3, or 56% of the average annual flow. Clearly drainage from the upland catchment via the Gorge constitutes the greatest water inputs to the system. The average volume of water passing through the Gorge, discharging onto the coastal plain is almost twice the net rainfall inputs on the plain itself, and quite feasibly seven times estimated LSR inputs (active rain). This reflects the fact that the lowland coastal catchment is only 46% the area of the mountainous upland and receives less than half the depth of rain the upland system receives.

If one assumes that rain falling on bedrock in the headwaters of Coopers Creek makes its way as surface water storm-flow that contributes to the Orari River then it is calculated that Coopers Creek headwaters drain approximately $22x10^6$ m^3 of water per year as direct storm run-off. This equates to approximately 7.5% of the annual Orari River flow recorded at the Gorge. In reality, this storm-flow contribution is likely to be lower owing to some evapotranspirative losses, plus infiltration to groundwater. Indeed, in their 2006/07 water balance, which was constrained by Coopers Creek stream gauging made at SH72, Burbery and Ritson (2010) estimated just $3x10^6$ m^3 of surface water discharged from the upper reaches of Coopers Creek. This equates to just 1% of the total annual Orari River flow at the Gorge. Moreover, it implies that much of the water inputs in the upper Coopers Creek sub-catchment must be lost to ground and possibly constitute recharge of the Orton plain aquifer. It is apparent that there is gross uncertainty in the volume of water drained to the Orari via Coopers Creek; therefore results should be interpreted with caution.

The various estimated recharge components are depicted in Figure 7-10. The question mark assigned to the Coopers Creek storm flow component in the figure highlights the gross uncertainty in this water flux. Table 7-6 summarises the results in terms of groundwater recharge, based on the assumption that only $3x10^6$ m^3 of the storm-water calculated as running off the foothills enters the Orari River, the remainder ($19x10^6$ m^3) is assumed to infiltrate to groundwater.

Assuming flow losses from the Orari River above SH1 modelled according to the flow-loss model presented in Equation (3), on average the Orari River leaks $180x10^6$ m^3 of water to the subsurface over the course of a year (about 62% of water exiting the Gorge). Based on the lowest annual flow record, the minimum annual loss is estimated at $130x10^6$ m^3. It is this "lost" water that emerges downstream and sustains the flows in the lower reaches of the Orari River, Ohapi Creek, Dobies Stream, and flows in other spring-fed systems. A catchment water balance would be required to ascertain how the net groundwater recharge inputs evaluated in this budget are likely to be distributed as discharges from the hydrological catchment. Burbery and Ritson's (2010) efforts at processing hydrological data for the year 2006/07 remains the only attempt at such a water balance.

Table 7-6: Summary of average annual hydrological inputs to the Orari groundwater system. Minimum and maximum encapsulate uncertainties in assumptions about soil water balance model parameters (not river flows), as explained in text; active drainage threshold assumed in all LSR data.

	10^6 m^3/year		**as percentage of total groundwater recharge**	
	minimum	maximum	minimum	maximum
river recharge:				
Orari River	180.0	180.0	75.0	69.3
Coopers Creek	19.0	19.0	7.9	7.3
Total river recharge	**199.0**	**199.0**	**82.9**	**76.6**
LSR:				
Upper Orari	30.2	43.6	12.6	16.8
Lower Orari	5.6	8.6	2.3	3.3
Ohapi	5.3	8.7	2.2	3.3
Total LSR	**41.2**	**60.9**	**17.1**	**23.4**
GRAND TOTAL	**240.2**	**259.9**	**100.0**	**100.0**

According to the CRC consents database, the full estimated allocation volume of groundwater from the LSR zones considered in this report is $45x10^6$ m^3 per year. The distribution of takes between the individual sub-zones is provided in Table 7-7. Because multiple wells can be tied to a single consent, it is difficult to divide the annual volume into shallow and deep abstractions with any reliability. However, such deep/shallow classification has been done for the maximum instantaneous rate of abstraction and effective daily rate (maximum volume divided by number of consecutive days) since this information is bore (i.e. well) specific. The results of this comparison are included in Table 7-7.

Table 7-7: Allocated groundwater usage, by zone mapped in Figure 6-4 and separated in to shallow (<20 m bgl) and deep (>20 m bgl) groundwater takes.

	Upper Orari			**Lower Orari**			**Ohapi**			**Total catchment**		
	shallow	deep	combined	shallow	deep	combined	shallow	deep	combined	shallow	deep	combined
Full annual allocation (10^6 m^3/year)	n/a	n/a	8.9	n/a	n/a	22.5	n/a	n/a	13.6	n/a	n/a	45.0
Maximum rate of instantaneous consented abstraction (L/s)	942	357	1299	1004	1162	2166	981	598	1579	2927	2117	5044
Effective maximum rate of prolonged abstraction (m^3/day)	56807	13308	70115	69771	97847	167619	70863	47200	118063	197441	158355	355796

n/a not applicable

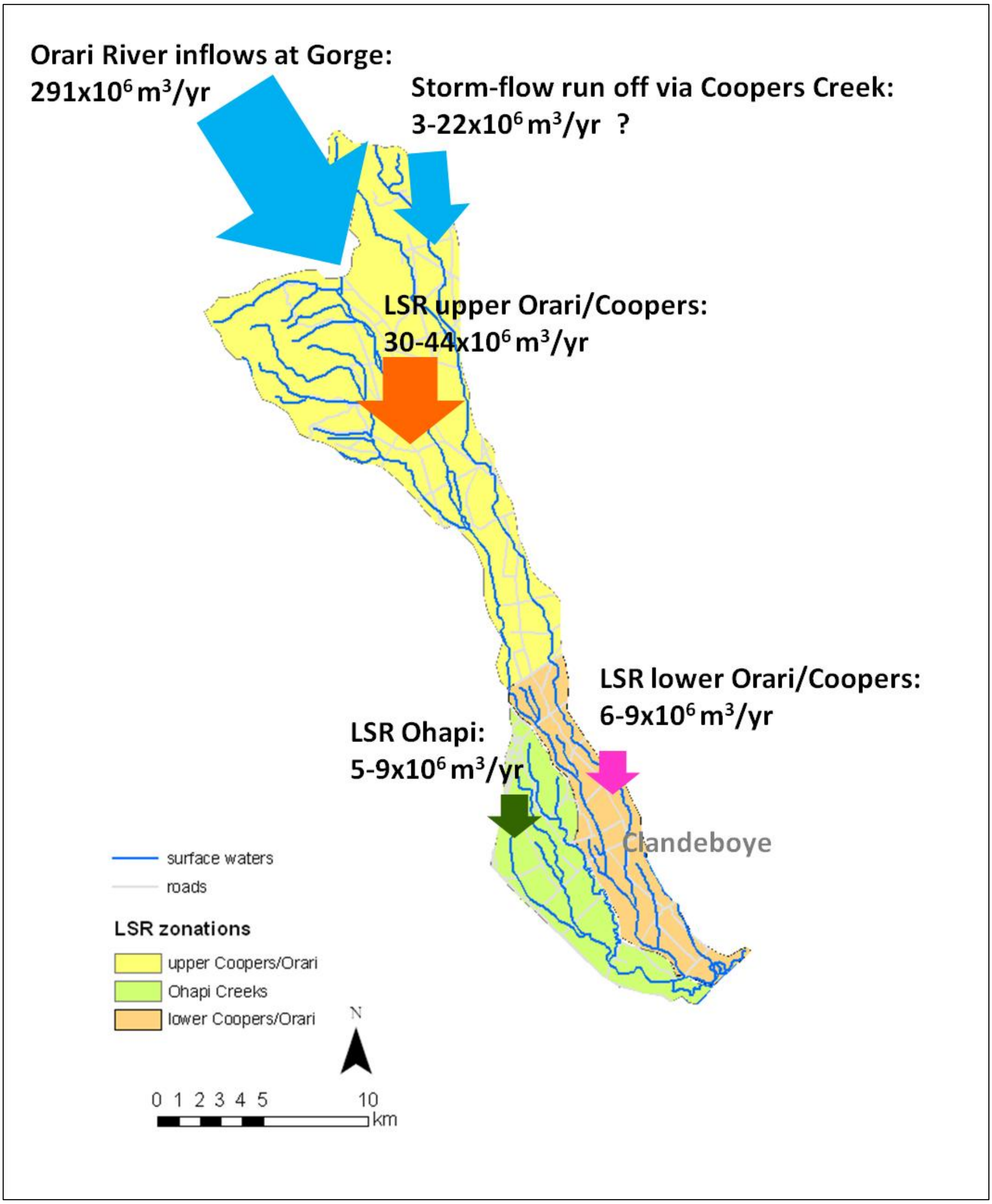

Figure 7-10: Estimated annual recharge components for the Orari coastal catchment.

8 DISCUSSSION AND CONCLUSIONS

8.1 Hydrodynamics of the Orari shallow aquifer

The GDA-tool, of which the Eigen-model is a fundamental mathematical component, has been applied to infer the hydrodynamic properties of the Orari shallow aquifer system. Of the ten sets of continuous–logged shallow groundwater level data available that cover four years (2006 – 2010), five have been analysed: K37/2896, K37/2923, K38/2154, K38/0060 and K38/2157. Three datasets that comprise only a short or discontinuous record were only briefly studied: J37/0009, K38/1758 and K38/1426. Similarly, two complete datasets: K37/0335 and K38/2155 allowed more in depth analysis, but were only qualitatively analysed due to time limitations. Due to the same resource constraints, it was not possible to attempt a calibration of the Eigen-model considering multiple observation well datasets, collectively.

Theoretically, the Eigen-values should be the same anywhere in a single aquifer system because with their corresponding Eigen-function set they capture the spatial distribution of the aquifer diffusivity and storativity values. An explanation for why inconsistent Eigen-values were determined for the individual well data records analysed mainly derives from the fact that no attempt was made to fully integrate the set of well monitoring records in the model calibration, across the scale of the entire catchment. The internal groundwater sink features attributed to a complex distribution of river boundaries and spring discharge points is far from the simplified single aquifer unit concept assumed in the Eigen-model. Nonetheless, the influence of many of these internal sinks appear have been characterised at the sub-catchment scale, using the Eigen-model. On the basis of studying individual observation data separately, it has been possible to infer that local areas of the shallow Orari hydrogeological system appear to function almost as sub-basins, which are inevitably hydraulically inter-connected both via groundwater and surface water routes. This is consistent with the systems model of groundwater – surface water relationships of the Orari hydrological catchment, conceived by Burbery & Ritson (2010).

Useful scientific knowledge could be gained from application of the Eigen-model to simulate the entire collective set of monitoring well records, as a single grouped calibration, i.e. integrate the sub-basins over the full catchment to improve reliability in the findings.

Even without the results of a full catchment calibration, it can be concluded from the latest findings that on the whole, groundwater in the Orari shallow aquifer is very dynamic. The entire system exhibits a relatively high effective diffusivity. The effective aquifer storage time displayed by the principal Eigen-values evaluated for the system from various hydrograph records is estimated to be in the range of one week to a maximum time of 37 days (effective half-life for recharge water of between 9 and 26 days). For comparison, storage residence times for the Waimakariri-Selwyn aquifer in Central Canterbury have been estimated at 20 months (Bidwell and Morgan, 2002).

This result suggests that any recharge entering the shallow aquifer rapidly drains out of the system – discharged to surface waters, such as the numerous spring-fed streams in the catchment, as well as emergent flow at the lower reaches of the Orari main-stem. The implication of this finding is that the Orari shallow aquifer is incapable of storing recharge for any substantial period of time, e.g. any recharge occurring over winter (non-irrigation months) will have naturally drained from the system before the summer (irrigation) season. Based on the findings, it could be justified to manage all shallow groundwater abstractions in the Orari catchment as surface water depleters.

The most rapid drainage properties have been characterised for the upper Orari sub-basin that appears to drain to the springs supporting Cooper Creek up-gradient of the SH72 crossing. It was inferred in Burbery & Ritson (2010), from hydrochemical evidence, that Orari River water provides a base-flow component to the springs at Springs Farm feeding Coopers Creek. The mathematical interpretations of well hydrograph data from K38/2896 in this study indicate that fluctuations in Orari River levels most probably also contribute significantly to the spring flow dynamics. The river recharge contribution to spring flows above a constant base groundwater level of approximately 184.5 m is estimated to range between 16 and 67%. The remainder of the spring flow dynamics must be driven by land surface recharge.

The longest aquifer storage residence times detected so far are for the Ohapi sub-basin system and are estimated to be in the region of 37 days. Land surface recharge processes appear to explain most, if not all the hydrodynamic response experienced in the Ohapi shallow aquifer system. Groundwater levels in the Ohapi sub-basin can experience substantial variations, especially during the summer season, that are explained by irrigation. From attempting to simulate groundwater abstraction and land surface recharge effects in the Ohapi sub-basin it is suspected that land surface recharge from irrigation plays a minor active role in the dynamic behaviour of groundwater levels in the Ohapi sub-catchment. There has been no obvious indication from the hydrodynamic evidence to reject the hypothesis and concept that shallow groundwater everywhere in the Ohapi area is hydraulically connected with, and drains to the creeks.

The groundwater dynamics in the central area of the Orari catchment are complicated by the transgressive and dry surface water boundary conditions that are active. For the periods when these effects are not in play, such as over the winter months, the hydrodynamic properties of the buried Umukaha river channel have been characterised as having an effective storage residence time of between 13 and 17 days. The resulting Eigen-model parameter values support the physical concept that the shallow groundwater in this region of the catchment drains to springs that supply Dobies Creek and Worners Creek, if not also Raukapuka Creek.

There is knowledge to be gained from analysing the groundwater data from K37/0335 and K38/2155 using the Eigen-modelling methods, which has yet to be undertaken. In the case of K37/0335, the data are likely to provide general characteristics of the older alluvial fan material that forms the northern boundary of the Orari catchment. So far analysis has mainly been restricted to wells on the true right of the Orari River. The groundwater dynamic response at K38/2155 might reveal more information on the hydraulic relationship between the Orari River and Ohapi Creeks. This information could be used to constrain the eigen-values that have been evaluated for the other wells in the middle-Orari and Ohapi sub-basins, as of course would an integrated calibration of all well records.

There are no high frequency groundwater level monitoring data available to characterise the aquifer in the Clandeboye region (near Petries and Rhodes drains), towards the bottom of the catchment. It is probable that in this lower part of the catchment, where clayey geological deposits are prevalent, and which functions as the catchment drainage area, groundwater dynamics are characteristically slower, such as observed for the system characteristics about Ohapi. For this reason, and for the purpose of gaining useful technical insight of the dynamics of groundwater feeding the lowland drains about Clandeboye, it is recommended that any groundwater level monitoring data collected by CRC on a monthly basis from this region should be analysed using the GDA-tool package that was applied here.

Although this study has focussed on characterising the hydrodynamics of the shallow aquifer, it is reiterated that the dynamic responses are themselves superposed on top of a steady-state flow contribution – the effective groundwater base level assessed in the Eigen-model. This base-level can be imagined as the datum at which dynamic effects are no longer measurable. Close to an obvious discharge boundary, such as the coast, they would represent a constant head sea level datum. There is a steady-state recharge mechanism that must support this base level and in the case of the Orari it is attributed to the continuous flow losses from the Orari main-stem. The only way of evaluating this constant system input/output is to complete an accurate system mass balance, such as was attempted in Burbery & Ritson (2010).

If flow records for the spring-fed surface waters in the Orari catchment were available it would permit correlation of aquifer discharges computed with the Eigen-model to monitored discharges, hence reduce the uncertainty associated with the model results that so far have yet to be verified for their accuracy.

The bank storage assessment carried out as part of the study demonstrated that river storm-flow events are generally less effective than land surface (rainfall) recharge in terms of dynamic recharge. River recharge constitutes a more passive, continuous input to the aquifer system. Because of the relatively narrow width of the Orari catchment and the dynamic nature of the groundwater system that has limited potential to store rainfall recharge water or buffer from the effects of abstraction, every water abstraction within the catchment presents a high risk of affecting surface water flows whether it be a direct connection, interception of water that would otherwise have transmitted to a surface water, or a diversion of groundwater flow away from its natural path.

8.2 Is a sub-catchment management approach practicable for the Orari?

The mathematical analyses undertaken in this study certainly tend to suggest that drainage of the shallow aquifer in the Orari catchment is controlled by the numerous spring features, consistent with the hydraulic effect of an aquifer sub-catchment embedded within the regional hydrogeological system. Modelling and monitoring indicate that the aquifer sub-catchments in the alluvial gravels must be hydraulically connected to neighbouring systems.

However, there is insufficient information and technical understanding at present to define any clear-cut groundwater divides within the Orari catchment that could form a practicable flow management plan. The problem of this definition of internal boundaries is confounded by the surface drainage features such as Dobies Stream that effectively bleed water from Orari catchment into the Waihi at a rate that is not measured. The water balance equated in Burbery & Ritson (2010) crudely estimated that potentially 6% of Orari River water is transmitted to the Waihi system via Dobies Stream. It is recommended that before refining any water use allocation limits for the Orari catchment, some practical measure of the system flow losses to the Waihi is undertaken; the water budget evaluated in this report focussed only on water inputs to the hydrological system.

The hydrodynamic aquifer properties, as well as land surface recharge model parameter estimates evaluated and reported here have useful application in improving the reliability of the systems model employed in Burbery & Ritson (2010) and evaluating the annual catchment water balance. The reliability of any such re-evaluation of water balances in the system would be improved if values of the system drainage via Dobies Creek could also be substituted in to the balance equation.

At this stage, there is no recommendation to separately manage the water resources of the sub-catchments in the Orari catchment. Orari groundwater flows tend to be directed southwards to Ohapi Creek sub-basin and it would be prudent to recognise that allocation of groundwater from the Ohapi sub-basin will potentially lead to indirect flow impacts on the Orari River, through a diversion of groundwater away from its main-stem channel. While not yet evaluated other than from well performance data, the shallow geological formation extending from the true left bank of Coopers Creek, northwards onto the Orton Plain is less transmissive than that on the true right, tracking south. Thus, the mapped soils/geomorphologic historic river terrace features (e.g. Lynn et al., 1999) could serve as a suitable guide for delineating a northern limit, any shallow abstraction south of which should be recognised as having high potential for impacting surface flows.

8.3 Stream depletion

The bank storage concept that is covered in detail in Appendix C, demonstrated the dynamic behaviour of groundwater – surface water interaction along the banks of the river. The diffusivity estimate of 16 666 m^2 estimated for the Orari river bank material at SH1 is relatively high, implying strong hydraulic connectivity and suggesting that consideration of any streambed conductance features on the Orari main-stem is unwarranted.

Given the lack of information available of the likely spatial scale of any groundwater catchments characterised using the Eigen-model, it is difficult to translate the dimensionless Eigen-value estimates to unique physical parameters. This could be done if necessary, albeit there will be gross uncertainty in any physical aquifer values estimated this way.

It is worth noting that the simulated irrigation pattern for the catchment based on eight reference water metering datasets appears to be a very inaccurate descriptor of general irrigation practice in the catchment. For most times it failed to identify active irrigation within the catchment. This oversight of irrigation pattern probably stems from the fact that the reference irrigation datasets are for dairy/pasture consents, so fail to capture the water demands of crop farmers that make up a considerable portion of the catchment area (e.g. Burbery and Ritson, 2010). Stream depletion assessments or flow naturalisation using the simulated water usage dataset is likely to under predict the duration of irrigation practices.

Experience with the Eigen-model applied to simulate groundwater level variations, tended to indicate that Orari flow losses are likely to be more than has been previously assumed by CRC when they attempted to naturalise Orari river flows downstream of the primary Gorge recorder site. A non-linear relationship between Orari Gorge flows and river system losses to groundwater has been developed that curtails maximum flow losses at 12 000 L/s.

8.4 Deep Orari groundwater

According to CRC's consents database, there are 81 consented deep (>20 m) groundwater takes on the Orari coastal plain when the hydrological catchment is treated as that described by Burbery and Ritson (2010) and the allocation zones managed under the current planning regime. The locations of the 81 wells are mapped in Figure 8-1. 46 of the wells fall within the LSR zone areas that have been considered in this report (marked in Figure 7-10), and are distributed as follows:

Upper Orari/Coopers – 8
Lower Orari/Coopers – 29
Ohapi – 9

The median depth for deep wells is 65 m (Figure 8-2).

The annual effective daily volume of deep groundwater currently allocated from the 46 deep wells within the LSR area is 158 355 m^3/day. This equates to approximately 45% of the effective daily rate of all groundwater consented to be pumped from the same area (Table 7-7). Of the deep groundwater consented, 62% is taken from the Lower Orari/Coopers zone and 30% from the Ohapi zone, only 8% is taken from the upper Orari/Coopers zone.

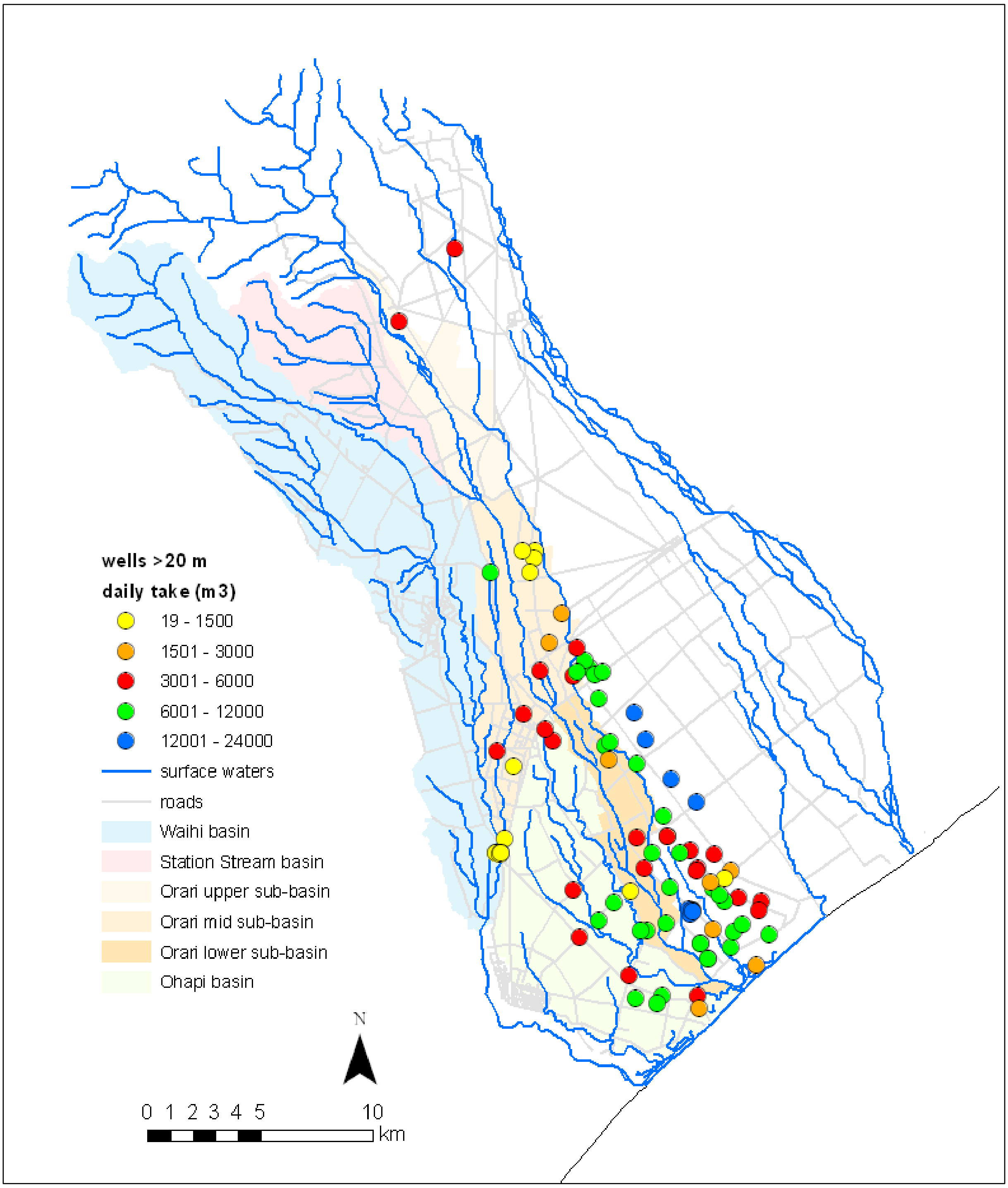

Figure 8-1: Location of (81) deep wells (>20 m) in the Orari catchment.

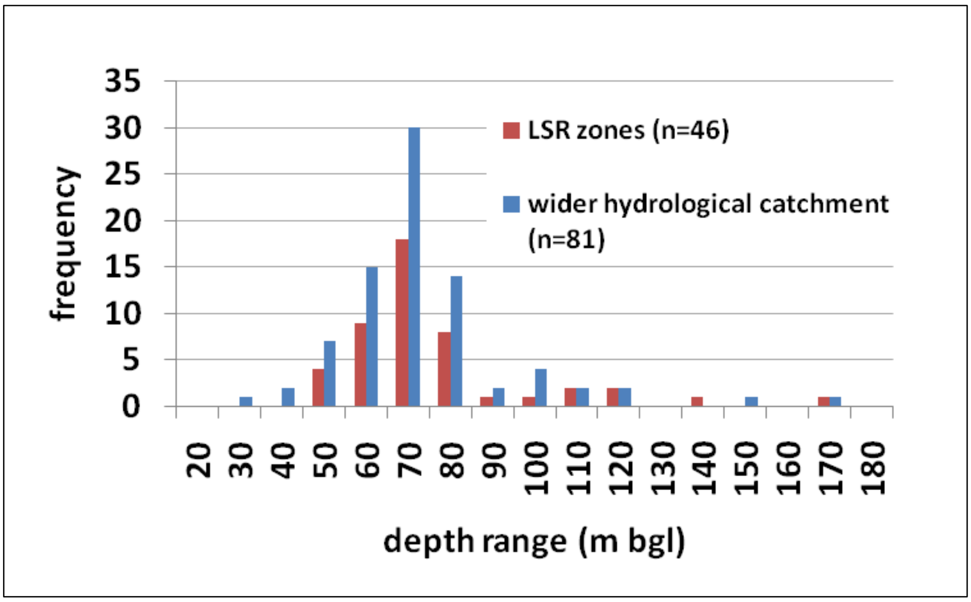

Figure 8-2: Distribution of well depths for deep wells in the Orari catchment.

The bulk of the deep abstractions are located on the margin of the Orton plain and about Clandeboye, which is where Fonterra operates a cluster of deep wells for industrial milk processing (e.g. Figure 8-1). A general understanding is that the deep sediments yield relatively low quantities of water in the mid Ohapi basin and towards Geraldine Flat. This probably relates to the lateral distance from the Rangitata River that originally deposited the sediments. It may also relate to the fact that Geraldine and Temuka mark the southern extent of the Canterbury plains and margins of the fluvio-glacial outwash sediments that constitute the plains alluvial aquifer. South of Temuka, older Tertiary sediments start to be encountered and, there, constitute the deep aquifers.

Because of the vertical separation distance that introduces a lag effect between a deep well screen and surficial waters, it is more appropriate to consider the potential impacts of deep groundwater abstraction based on assessment of long term average water abstraction, rather than considering maximum effective rates. Unfortunately, to calculate what volume of the annual groundwater quota is sourced from the deep groundwater resource requires a more rigorous analysis of the consents database than was achievable in this report.

With exception of wells very close to the coastline, where truly confined conditions have been reported (e.g. Burbery and Ritson (2010)), all constant rate pumping test data collected from the deep aquifer system have signalled vertical leakage effects. On this basis, there is potential for deep groundwater takes to have an indirect impact on surficial water levels and therefore affect river flows.

Given the current lack of knowledge of the dominant recharge pathway for deep groundwater, i.e. whether it is either:

i. extensive rainfall-derived land surface recharge across the Orton plain;
ii. surface water recharge by seepage from the Rangitata and, or Orari Rivers;
iii. surface water draining to the bottom of the foothills and infiltrating into the gravels, or;
iv. all of the above,

a logical, yet conservative approach would be to lump deep groundwater abstractions in the Orari catchment along with the shallow consents. The average effective daily abstraction rate, calculated from the annual volume of abstracted groundwater might then be applied to estimate a potential Orari River base-flow impact. This resource management option would be reasonably protective of the Orari flows.

The chemistry of Orari deep groundwater sampled at Clandeboye and during the 2006/07 field investigation showed a distinctively high bicarbonate content that appeared representative of either Rangitata or Orari River water that had spent a reasonably long contact time in the inert greywacke alluvial gravel aquifer. Thus, recharge mechanism (iii) above could be inferred to be a significant one. Burbery & Ritson (2010) hypothesised that from consideration of oxygen-18 evidence and the origins of the deep aquifer matrix (that constitutes old Rangitata fan material) it could be construed that Rangitata River water may in fact recharge the deep aquifer system. A piezometric survey of deep groundwater across the Rangitata – Orton – Orari region was recommended, for the purpose of gaining some knowledge of the primary flow direction of the deep groundwater. This recommendation is repeated here.

There are no long term monitoring records of deep groundwater levels in the Orari catchment. The closest and most representative record of deep water level trends is provided by K38/0013, located on the Orton Plain. K38/0013 screens between 73.0 m and 79.0 m. Although there is clear evidence that the magnitude of drawdown effects of deep groundwater levels is increasing with successive years because of intensified deep groundwater usage for irrigation, there is no indication, at K38/0013 at least, that groundwater abstraction is leading to a noticeable downward trend in static deep water levels outside of the irrigation season (Figure 8-3).

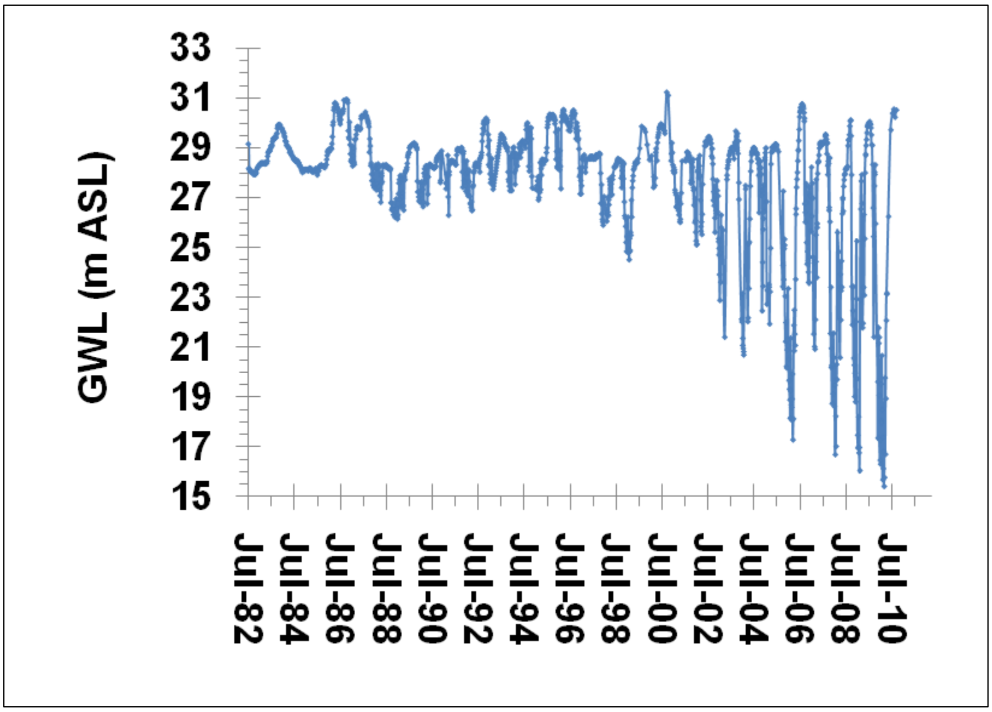

Figure 8-3: Long term groundwater levels monitored at K38/0013 on the Orton Plain.

8.1 Catchment Water Budget

Total LSR for the Orari coastal catchment has been estimated here at somewhere between 41×10^6 and 61×10^6 m^3/year, based on an assumed annual rainfall volume of 155×10^6 m^3. In setting the existing groundwater allocation limits for the Orari-Opihi GWAZ, Aitchison-Earl et al (2004) assumed 390×10^6 m^3 of rain falls annually on the full Orari-Opihi GWAZ (472 km^2) - an area 255% larger than the 185 km^2 Orari coastal catchment considered in this report. If the Aitchison-Earl et al. (2004) annual rainfall budget is scaled down to the area of the Orari coastal catchment it equates to 153×10^6 m^3, which is close to the 155×10^6 m^3 evaluated here.

In the absence of LSR data, Aitchison-Earl et al. (2004) apportioned 15% of the total annual rainfall as allocable groundwater volume; for the Orari coastal catchment this would be 23×10^6 m^3. This equates to somewhere between 38 – 56% of total LSR calculated here, hence is close to the 50% LSR guideline adopted by CRC for allocating groundwater resources, and explained in Aitchison-Earl et al (2004). 50% of total LSR evaluated in this latest study is in the region of 21×10^6 to 30×10^6 m^3/year.

Although it appears that there are no substantial differences between assuming 15% total rainfall or 50% LSR when calculating allocable groundwater volumes. The significance is whether groundwater that is allocated across the Orari-Opihi GWAZ is distributed proportional to the catchment area, i.e. if current consented groundwater allocation in the Orari catchment is more than 36.3 $\times 10^6$ m^3/year (40% of 71 .1$\times 10^6$ m^3 + 7.8×10^6 m^3) then it could be stated that Orari groundwater is "over-allocated", in review of the current allocation framework. 45.0 $\times 10^6$ m^3 of groundwater is consented to be abstracted annually from the 185 km^2 recharge area assessed in this study, therefore it is concluded that groundwater resources in the Orari are "over-allocated".

Due to the very small dynamic hydraulic storage capacity of the shallow aquifer, demonstrated by the Eigen-model results, allocation of Orari shallow groundwater resources on the basis of annual recharge budgets (as discussed above) is likely to under-estimate cumulative effects on Orari surface water flows. To limit these, a more precautionary approach would be to set quotas for allocable groundwater volumes from the shallow aquifer based on assessment of seasonal recharge volumes, i.e. monthly or potentially quarterly evaluations. Another alternative would be to collectively manage shallow groundwater abstractions in the Orari catchment under the same principles as surface water abstractions, i.e. set time-variable pumping restrictions governed by the river flow regime.

Although the water budget results are suggestive that an uncertain, yet potentially large proportion of the LSR estimated for the upper Coopers Creek region actually infiltrates to groundwater and most probably flows beneath the Orton plain (Figure 6-4), flows in the spring-fed streams about Clandeboye (e.g. Petries and Rhodes drains) are conceived to be supported by water from the Orton plain (Burbery and Ritson, 2010). As there remains a lack of knowledge about the stream flows in the Clandeboye region, at this stage, for allocation purposes it could be assumed that the storm-run off from the foothills that infiltrates to ground indirectly supports the shallow groundwater system about Clandeboye.

It is evident from the water budget results that a substantial proportion (in the region of 75%) of groundwater recharge is derived from the Orari River. In comparison, LSR accounts for about a quarter of the annual water inputs to the shallow aquifer. The volume of Orari River water that is estimated to route as groundwater through the catchment is substantially more than the 15×10^6 m^3/year river recharge component referenced by Aitchison-Earl et al (2004). This discrepancy in assumed river-loss component does not however alter the fact that the shallow groundwater is what maintains the flows in the surface waters, and because of this inter-relationship, any change in flows in either resource will affect the other.

9 RECOMMENDATIONS

From the conclusions above, several recommendations are made, aimed at supporting development the Orari environmental flow and water allocation plan. These are:

1. On the basis of the limited hydraulic storage potential due to the fast drainage characteristics of the Orari shallow aquifer and strong hydraulic relationship with the Orari River and other surface waters in the catchment, it is recommended a pragmatic solution to controlling stream depletion effects from shallow groundwater abstractions would be to manage shallow groundwater abstractions in the Orari catchment under the same principles as surface water abstractions, i.e. set time-variable pumping restrictions governed by the river flow regime.

2. The recommendation above could be effected through establishment of a conjunctive (surface water – groundwater) use management zone. Such a zone should extend southwards, to incorporate the Ohapi catchment, since the Ohapi Creek system and associated groundwater are strongly hydraulically linked to the Orari River system. Although the hydrodynamics of groundwater on the true left of the Orari are yet to be analysed, it is suspected, based on piezometric and hydrochemical evidence that shallow groundwater on the true left (north) of Coopers Creek is less influenced by the Orari River. Thus, it is recommended that geological properties be used as a guide for delineating a northern limit of a conjunctive use zone. The LSR zones mapped in Figure 6-4 correspond to the area of such a management zone.

3. It is recommended that in defining allocable volumes of water, the deep groundwater resource be lumped together with shallow groundwater resource. For an assessment of potential impacts to Orari river flows, it is suggested that it be assumed deep groundwater abstraction causes river base-flow depletion equivalent to the net effective daily rate of abstraction.

4. River flow naturalisation and groundwater modelling results rely on the accuracy of water use data. The irrigation water usage analogue model for the Orari should be improved to correct for the bias evident in the reference water metering dataset. It is recommended that the number of irrigation records used to compile the dataset is increased and incorporate data from a variety of farming activities undertaken in the Orari, not simply pasture irrigation.

The following recommendations are not directly targeted at supporting the Orari environmental flow and water allocation plan that is currently under development. Rather, they are provided to guide the future technical investigation and monitoring of the Orari groundwater system, and address gaps in the current scientific understanding of surface water – groundwater relationships in the Orari. Hence, they are useful for future plan developments.

5. The hydrograph records from wells for K37/0335 and K38/2155 remain to be analysed. It is recommended this is undertaken for completeness and to extract information about the hydrodynamic characteristics of the shallow aquifer on the true-left of the Orari River, extending out onto the Orton plain. Similarly, it is recommended the Eigen-model be applied to simulate the entire collective set of monitoring well records, as a single grouped calibration, i.e. integrated the sub-basins over the full catchment to improve reliability in the findings.

6. There are no high frequency groundwater level monitoring data available for analysis from the Clandeboye area, at the lower end of the coastal catchment, where it is believed LSR from the Orton plain potentially discharges. Similarly, flows are not recorded in any of the spring-fed drains of this region. It is recommended recording of shallow groundwater levels and stream-flows on at least one of the drains (e.g. Rhodes Drain) commence in this region, for the purpose of collecting data from which the system hydrodynamics can be inferred.

7. A reliable catchment water mass balance is crucial for understanding how water - most notably that leaked from the upper reaches of the Orari River - is routed through, and discharged from the catchment. Burbery and Ritson (2010) explained how the lack of knowledge about how much Orari water is transmitted across into the Waihi catchment is a current constraint on the accuracy of any catchment water balance. It is recommended that flows discharging to the Waihi River via Dobies Stream are recorded, for the purpose of facilitating a more reliable catchment water balance. Knowledge of how much Orari water transfers to the Waihi is also helpful to any flow and allocation plan applicable to the Waihi River.

8. Burbery and Ritson (2010) developed a simple Orari hydrological systems model that they used in their determination of water fluxes through the catchment, for the year 2006/07. The model is suitable for evaluating a catchment water mass balance, albeit in its current form it fails to account for lag effects associated with groundwater storage because historically these processes have never been characterised for the Orari. However, the hydraulic storage properties of the Orari shallow aquifer system have now been characterised, through Eigen-modelling. It is recommended that this new knowledge be incorporated into the systems model described by Burbery and Ritson (2010) and the model be applied to refine a catchment water mass balance in the future, subject to recommendation 7, above.

9. There is a paucity of information about the Orari deep aquifer that is composed of Rangitata fan material and into which the Orari River has incised. Groundwater recharge mechanisms for the deep aquifer remain to be characterised, albeit there is evidence from pumping test data to suggest vertical leakage occurs between the shallow and deep groundwater systems. It is recommended that a deep groundwater monitoring well positioned in the mid-upper regions of the coastal plain would be useful for gathering information on the hydrodynamics of the deep aquifer. Furthermore, a survey of the piezometric levels for deep groundwater across the Rangitata – Orton – Orari plain is strongly recommended, from which the flow paths of deep groundwater can be mapped.

10 REFERENCES

Aitchison-Earl, P., Scott, D., Sanders, R., 2004. Groundwater Allocation Limits: Guidelines for the Canterbury Region, Canterbury Regional Council Report U04/02, 60 p.

Allen, R.G., Pereira, L.S., Raes, D. and Smith, M., 1998. Crop evapotranspiration - Guidelines for computing crop water requirements - FAO Irrigation and drainage paper 56. FAO - Food and Agriculture Organization of the United Nations, Rome, 1998, 465 p.

Bidwell, V.J. and Morgan, M.J., 2002. The eigenvalue approach to groundwater modelling for resource evaluation at regional scale. Proceedings of the 4th International Conference on Calibration and Reliability in Groundwater Modelling, Prague, 17-20 June 2002:92-95.

Burbery, L.F. and Ritson, J.S., 2010. Integrated Study of Surface Water and Shallow Groundwater Resources of the Orari Catchment. Environment Canterbury Technical Report R10/46, 188p.

Cox, S.C. and Barrell, D.J.A., 2007. Geology of the Aoraki Area. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 15.

Lynn, I.H., Harrison, J.M, Basher, L.R. and Webb, T.H., 1997. A Geomorphic Interpretation of the Orari-Waihi-Temuka and Opihi Rivers. Technical Report U097/34, Canterbury Regional Council, 46 p.

McEwan, G., 2001. The Hydrogeology of the Orari River Shallow Aquifer, MSc thesis, University of Canterbury, Department of Engineering. , 129 p.

Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models Part 1 – a discussion of principles. Journal of Hydrology 313: 166-181

Rushton, K.R. and Tomlinson, L.M., 1979. Possible Mechanisms for Leakage between Aquifers and Rivers, Journal of Hydrology, 40, pp. 49-65.

Pulido-Velazquez, M.A., Sahuquillo-Herraiz, A., Ochoa-Rivera, J.C. and Pulido-Velazquez, D., 2005. Modelling of stream-aquifer interaction: the embedded multi-reservoir model. Journal of Hydrology, 313, pp. 166-181.

Pulido-Velazquez, D., Sahuquillo, A. and Andreu, J., 2009. Treatment of non-linear boundary conditions in groundwater modelling with Eigenvalue methods. Journal of Hydrology, 368, pp. 194-204.

Scott D, 2004. Groundwater Allocation Limits: land-based recharge estimates. Environment Canterbury Technical Report U04/97, 39 p.

Verruijt, A., 1982. Theory of Groundwater Flow (2nd ed.), Macmillan, London, 152 p.

Appendix A: Rainfall records

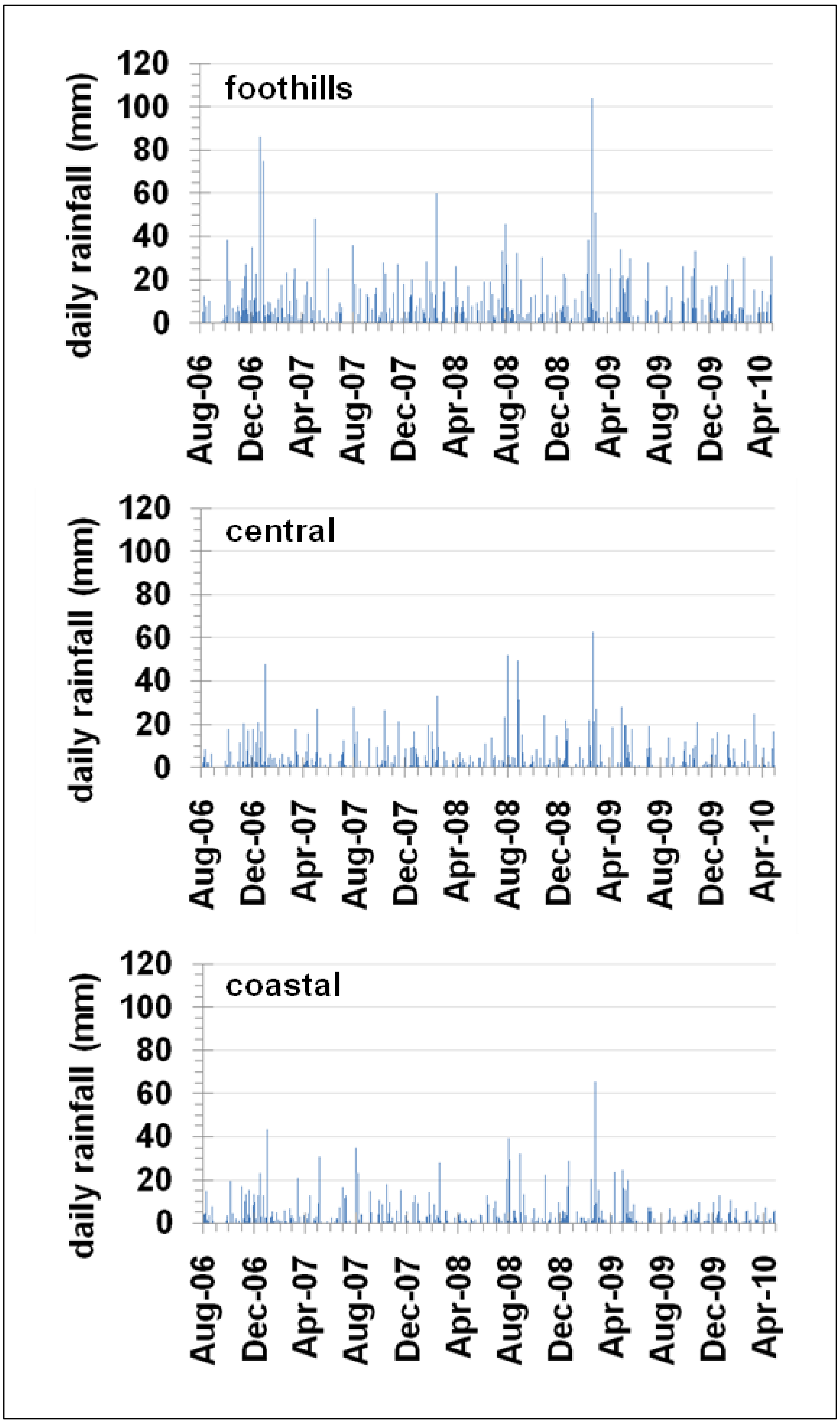

Figure A1: Daily rainfall patterns for the three geographical zones in the Orari catchment that were defined in Burbery and Ritson (2010) (see Figure 3-1 therein). Simulated rainfall in the Eigen-model assumed a basic inverse distance weighting method applied to the rainfall zonal groups, based on separation distance to any specific observation monitoring well.

Appendix B: Threshold water-levels in K38/2157

Groundwater levels recorded at well K38/2157 are used by CRC as an analogue of Orari River stage at SH1. The well is positioned on the true right river bank, approximately 75 m from the closest open channel of water. Below is a plot of the SH1 river stage gauging run data provided by CRC, from which an apparent groundwater level threshold has been inferred. Qualitative analysis of the tenor of the K38/2157 groundwater hydrograph record supports the estimate threshold limits.

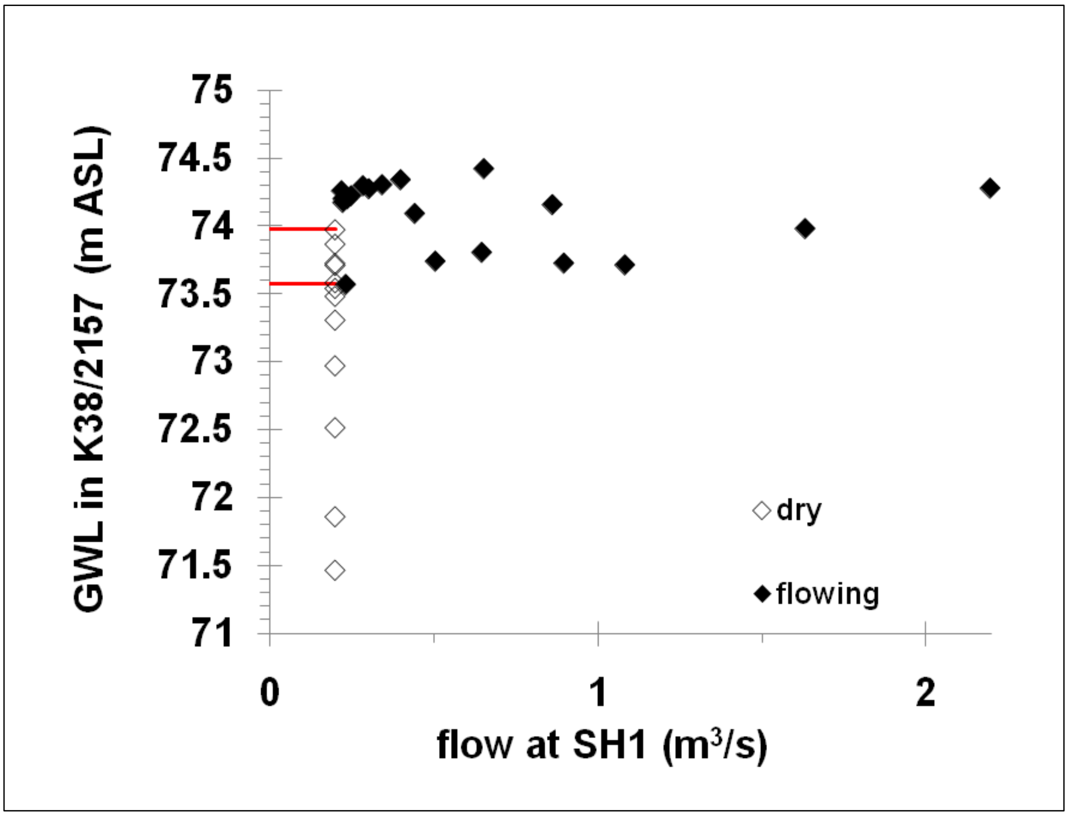

Figure B1: Concurrent Orari River flow data gauged at Victoria Bridge (SH1) and groundwater levels logged at well K38/2157 (based on gauging runs completed between 2006 and 2010). Groundwater level threshold, below which dry river conditions can be expected to prevail, is in the region of 73.6 - 74.0 m above sea level.

Appendix C: River recharge put in context

This Appendix contains a detailed proof of concept for dynamic aquifer recharge from river storm-flow events, i.e. the concepts of bank storage effects, and how these relate in terms of provision of storable groundwater volumes. The mathematical concepts and assumptions used in this proof are those described for Equation 1 of the main report. Actual monitoring data from the Orari catchment are applied in the proof.

On the 23rd July 2008, a storm-flow event occurred on the Orari River. Based on the initial condition of 23rd July, river stage levels remained elevated for 4 weeks, during which the peak amplitude of the flood wave was 1.1 m (Figure C1). In Section 7.3 it was shown that the equation of transient groundwater flow, subject to a variable head input (Equation 1) provides a reasonable descriptor of the groundwater response experienced at well K38/2157 during the recharge event.

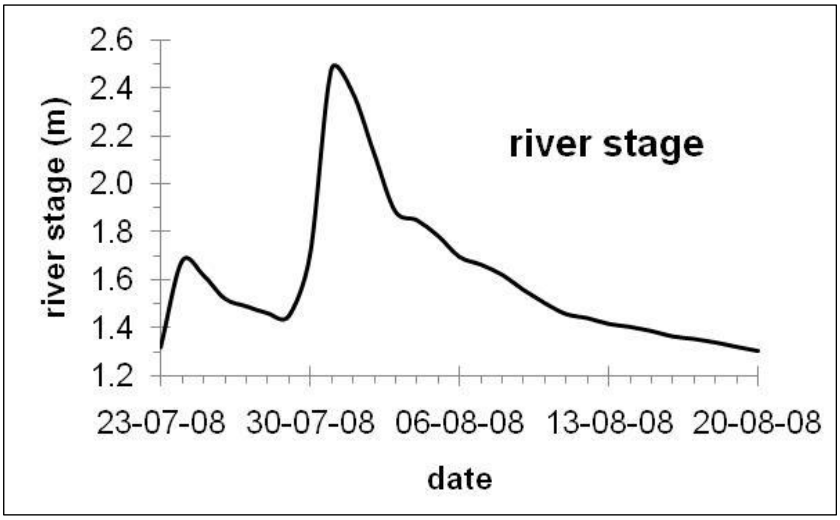

Figure C1: Orari river stage during storm-flow event of July 2008.

The groundwater level response function at varying distances from the river boundary are plot in Figure C2; assuming the shallow aquifer conditions inferred at K38/2157 are representative of the bulk of the Orari shallow aquifer (T/S = 16 666 m^2/day). Note; the response function at 75 m distance equates to that observed at K38/2157, as was shown in Figure 7-3.

The propagation of the groundwater wave front over a distance of 10 km is shown in Figure C3. Ten kilometres is an arbitrary distance, but as seen from Figures C2 and C3, it appears to be beyond the limit at which groundwater impacts were experienced from the rise in river levels. From Figure C3 it can be seen that 16 days after the start of the storm-flow event (i.e. on 8th August 2008), the input wave effectively reverted and groundwater started to discharge back into the river.

Integration of the waves in Figure C3 provides the volume of water stored in the aquifer at any time, as a consequence of the river recharge event. Assuming an aquifer porosity of 0.06, the maximum volume of water delivered to the aquifer, per unit length of river was 50 m^3, on day 12. At the time the river levels had regressed back to their initial condition, after 28 days, almost 30 m^3 of water was left in aquifer storage (see Figure C4). It is feasible that in reality, groundwater will drain from the aquifer more rapidly than demonstrated here, given we have assumed only a 1-dimensional transect of the river/aquifer system and in the natural world the regional topographic gradient drives flow parallel to the river. Notwithstanding, such multi-dimensional flow processes are not apparent in the water level dataset applied for this example of bank storage concepts. A rudimentary assessment of Orari River flow history suggests that the peak flow of 27 168 L/s, experienced on 24th July 2008, represents about 4% of the flow conditions of the Orari. Thus, storm-flow recharge events of the magnitude examined here are relatively uncommon.

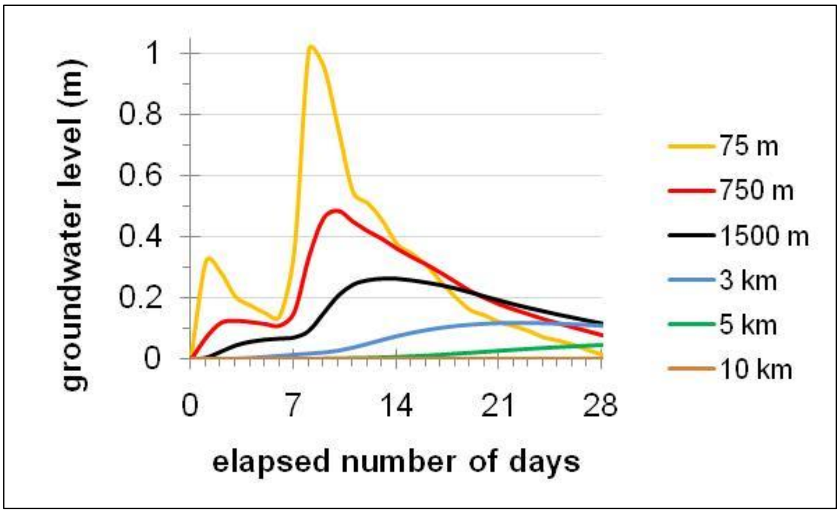

Figure C2: Groundwater levels at varying lateral distances from the Orari River at SH1, simulated using Equation 1, provided with variable head input function related to river stage shown in Figure C1. Each plot effectively traces the theoretical groundwater wave experienced at a set observation distance from the river boundary.

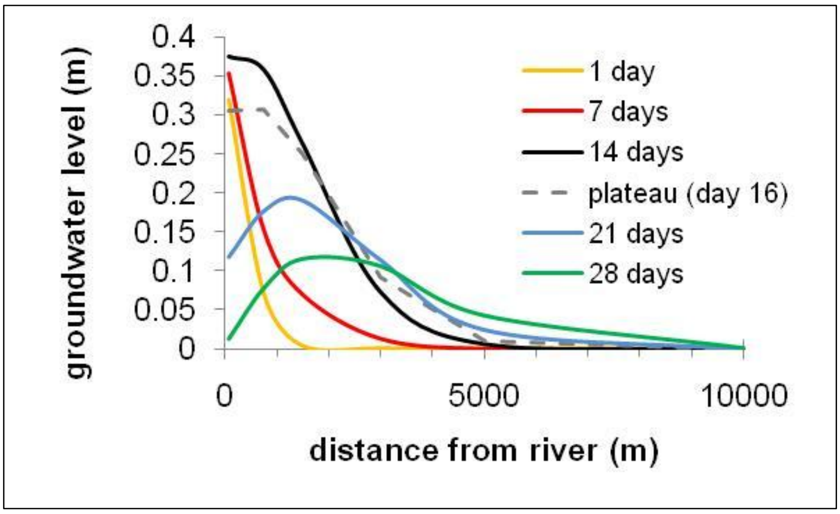

Figure C3: Simulated groundwater wave front. 16 days after the start of the river storm-flow recharge event, groundwater started to discharge back into the river.

It is possible to evaluate the effective active daily rainfall recharge that would be required to supply the same volume of water that was estimated to reside in a 10 km strip of aquifer extending out from the river bank, over the course of the July 2008 recharge event being considered. Since rainfall recharge occurs over a 2-dimensional area, the implications of lateral flow through the aquifer do not need to be considered, and the theoretical equivalent active daily rainfall is simply calculated from dividing the stored volume of water plot in Figure C4 through by the unit lateral strip being considered (i.e. 1 m x 10 km, or 10 000 m^2). The result of this is shown in Figure C5, from which it is evident that for the case of this one month river recharge event, a consistent daily average rainfall of less than 1 mm/day could easily have delivered the same result over the same timescale.

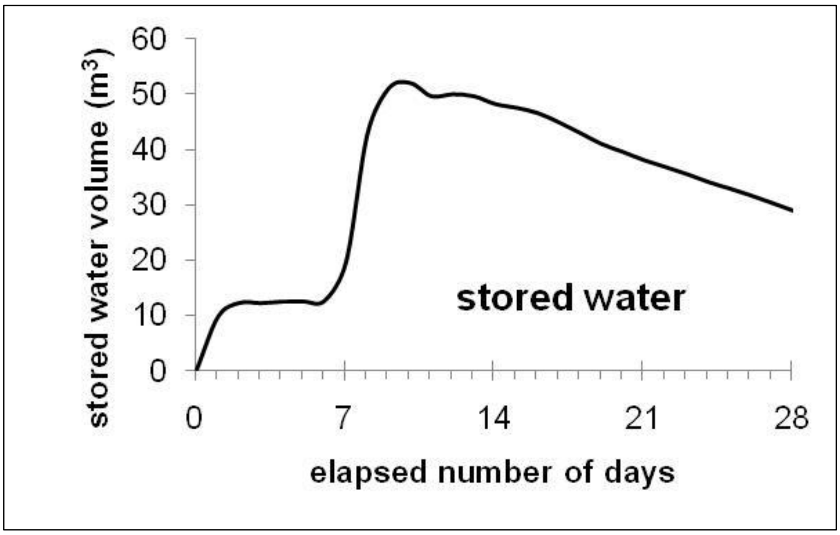

Figure C4: River recharge input as water as active groundwater storage, per unit length of river reach and integrated over a distance of 10 km.

Considering the average annual rainfall in the Orari catchment ranges from 600 mm at the coast to 1000 mm at the foothills, and Burbery and Ritson (2010) estimated possibly 23% of rainfall active contributes to land surface recharge, the average daily active rainfall in the Orari catchment possibly ranges between 0.4 and 0.63 mm/day. Thus, land surface recharge for a normal climatic condition could have had the same recharge effects as the unique storm-flow event of July 2008. Furthermore, in practice, rainfall inputs occur over an area much broader than the 10 km arbitrary distance considered in this example.

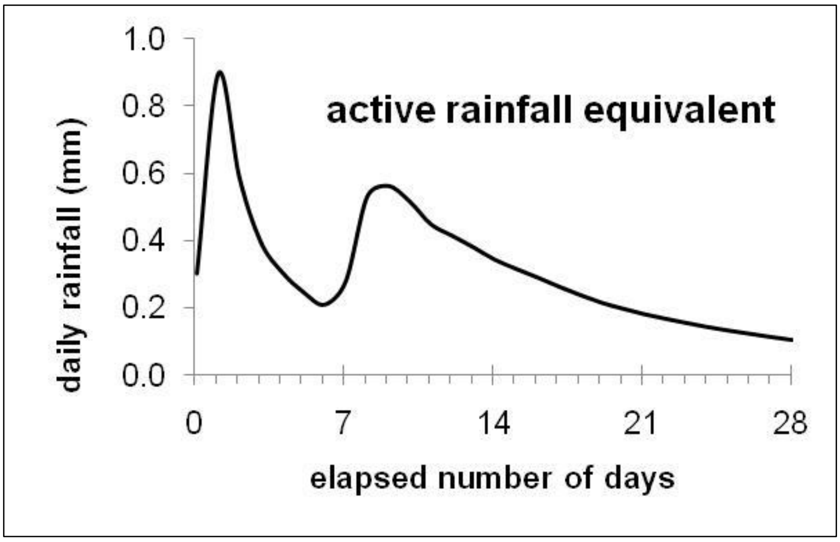

Figure C5: Consistent daily average (active) rainfall required to generate groundwater volume equivalent to that plot in Figure C4, assuming a 10 000 m^2 strip of land.