LANDCARE RESEARCH
MANAAKI WHENUA

# Waimea Community Dam: Peer review of Waimea Plains hydrology underpinning the proposal

# Waimea Community Dam: Peer review of Waimea Plains hydrology underpinning the proposal

**Andrew Fenemor**

*Landcare Research, Nelson*

**Julian Weir**

*Aqualinc Research Ltd, Christchurch*

*Prepared for:*

**Tasman District Council**

189 Queen Street
Private Bag 4
Richmond 7050

**September 2016**

| *Reviewed by:* | *Approved for release by:* |
|---|---|
| Dr John Bright | Dr Chris Phillips |
| Research Director | Portfolio Leader |
| Aqualinc Research | Landcare Research |

*Landcare Research Contract Report:* LC2659

**Disclaimer**

*This report has been prepared by Landcare Research and Aqualinc Research for Tasman District Council. If used by other parties, no warranty or representation is given as to its accuracy and no liability is accepted for loss or damage arising directly or indirectly from reliance on the information in it.*

# Contents

# Summary

## Project and Objectives

Tasman District Council has sought a peer review of the hydrological science underpinning the design and operation of the proposed Waimea Community Dam, and the associated Waimea water allocation provisions of the Tasman Resource Management Plan (TRMP).

The review has been prompted by some community and councillor concerns about whether the release of water from the dam will recharge the Waimea Plains aquifers effectively, and whether future water demand justifies the proposed dam.

## Approach Taken

As presented in the following four sections, the peer review has been structured around questions raised by ratepayers Mr Ron Heath and Mr Murray Dawson on the Waimea Plains groundwater modelling, the interpretation of hydrological monitoring data, and questions raised by (but not detailed review of) their own calculations.

## Adequacy of Waimea Plains river-aquifer modelling

River-aquifer (groundwater) models such as the three generations of MODFLOW models developed for the Waimea Plains are widely used as they replicate the physics of water movement and enable scenarios of future water release and water abstraction to be simulated.

Based on the good match between measured and modelled river flows and groundwater levels for the dry 1982/83 and 2000/01 years and the average 2004/05 year, we consider the GNS model well calibrated. The calibration for the 2000/01 summer (now assessed as a 29-year drought) has been replicated by Aqualinc in the latest version of the model.

The adequacy of MODFLOW's stream (STR) method for modelling exchange of water between the river channel and the unconfined aquifer in the way used in the Waimea Plains models has been confirmed in correspondence with the model developers, the US Geological Survey.

Messrs Dawson and Heath have identified some reporting errors in the 2003 GNS modelling report (e.g. the over-reporting of modelled aquifer flow rates as daily rather than weekly values), which GNS needs to correct. We suggest that all such reports need full peer review in future to avoid such errors. The errors are drafting errors rather than modelling errors of consequence for decision-making.

## Applying modelling results to water management questions

Modelling scenarios have been run to achieve specified outcomes for the Waimea Plains, which include maintaining an 800 or 1,100 l/sec minimum Waimea River flow, and preventing seawater intrusion into pumped bores. These outcomes apply for a specified

frequency (return period) of drought. Achieving these outcomes means that much of the stored aquifer water cannot be accessed, as pumping excess groundwater would dry up the river or draw in salt, both of which have happened previously.

It is important to recognise that river flows and groundwater levels at any time are a consequence of the prior (transient) behaviour of the system, which is a strength of the Waimea groundwater model compared with regression or snapshot analyses.

Modelling scenarios, measured river low flow and pumping data, and climate change projections were among the data used to evaluate the 'with dam' and 'without dam' provisions decided by independent commissioners for TRMP plan changes C45-48. The modelling confirms that the 'without dam' water allocation regime, including its minimum flow target of 800 l/sec in the lower Waimea River, is likely to have a very significant economic impact on all Waimea water users if some form of water augmentation is not provided.

**Modelling for the Waimea Community Dam**

Council documents back to the early 1990s indicate a very comprehensive assessment of water augmentation options, which led to the implementation of the Kainui Dam for water augmentation of the Wai-iti Valley and the current Lee Dam proposal for augmenting supplies to the rest of the Waimea Plains.

It is our view that if any future water demands are to be satisfied and the planned river minimum flow achieved, increased efficiencies, more conservation measures and new technologies would be insufficient to match water demand and availability without water augmentation.

We are satisfied that the calculated irrigation water demand based on a peak weekly application rate of 30 mm/week is scientifically based. It remains a valid question whether the 100-year projected irrigable areas will all end up irrigated, and whether the assumptions about future regional, urban and industrial demand will prove accurate. However, those assumptions have been assessed and peer reviewed using a robust methodology by Tonkin and Taylor and the Waimea Water Augmentation Committee to calculate the planned dam volume of 13 million cubic metres and the planned 50-year security of supply standard. The incremental cost of providing more water storage now is relatively small compared to the cost of the first increment of storage.

A key question has been whether water released from the Waimea Community Dam would recharge the aquifers and satisfy additional pumped water demands, or mostly flow out to the estuary. The model is physically based, meaning that all water must be accounted for within the water balance. Generally, as river flows increase, so too does river recharge to groundwater.

The peer review has produced water balances for the dry 2000/01 year under the Calibration (without dam) and Dam Release scenarios. Under the Dam Release scenario, during the January-March 2001 driest months there would have been an average 1,000 l/sec extra water available for groundwater recharge and to maintain the 1,100 l/sec minimum river flow. The modelling shows that an average of 459 l/sec of that 1,000 l/sec would have recharged groundwater with the remainder providing the minimum flow. Additional water would already have been taken upstream via the Waimea East Irrigation infrastructure and for the planned future water demand, for example to Nelson City.

We have also evaluated the effects of daily variability of pumping on river low flows and conclude that modelling sub-daily river flows does not noticeably affect the groundwater model's predictions, particularly for the extended stable, dry periods where water management is critical.

There has been criticism of an equation derived by Tonkin and Taylor from the GNS modelling to determine how much water would need to be released from the dam to meet the Waimea minimum flow requirements. Aqualinc has tested this for 2000/01 and shown in the model that the GNS relationship achieves the target 1,100 l/sec minimum flow.

It has also been asserted that there is an upper limit to the amount of groundwater recharge achievable from released water. A range of plots of daily river losses has been provided in this report from modelled simulations, which convinces us that in terms of the water balance the dam releases will provide sufficient recharge to meet projected demands while maintaining the target minimum flow.

**Potential contribution of weirs and pumped water distribution**

Many commentators have rightly pointed out that building rock weirs has the effect of raising groundwater levels. As part of the peer review, we have modelled the effects on groundwater levels and net river recharge of building five weirs in the Wairoa and Waimea rivers. The modelling confirms localised benefits but the scale of the added recharge created by weirs is small in comparison with the change in recharge from flow releases from an upstream dam. In addition, without augmented river flows during low flows, upstream weirs may deprive flow from downstream reaches, drying the lower river sooner.

A review of the benefits of flow releases from the Kainui water augmentation dam in the upper Wai-iti Valley confirms that run-of-river water augmentation can work, as is planned for the rest of the plains with the proposed Waimea Community Dam.

However, a caveat is that some of the projected water demand including irrigation water demand on the Waimea Plains will require additional infrastructure which has not been costed within the project cost for the dam. Potential locations and costs of providing water to those areas were assessed in a report for Waimea Water Augmentation Committee (WWAC) by Landcare Research.

**Conclusions**

It is our opinion based on the review of documents, comparison of GNS and Aqualinc modelling results and additional modelling of scenarios that, subject to the observations in this report, the hydrological and modelling basis for recommendations affecting design and operation of the proposed Waimea Community Dam is fit for purpose.

## 1 Purpose of Peer Review

Tasman District Council has sought a peer review of the hydrological science underpinning the design and operation of the proposed Waimea Community Dam, and the associated Waimea water allocation provisions of the Tasman Resource Management Plan (TRMP).

The review has been prompted by some community and councillor concerns about whether the release of water from the dam will recharge the Waimea Plains aquifers effectively, and whether future water demand justifies the proposed dam. Some ratepayers have suggested that building weirs or smaller storages nearer the plains would be sufficient to meet future water demands.

## 2 Process of Peer Review

Based on emails and documents exchanged on the topic between Tasman District Council, and community members Mr Murray Dawson and Mr Ron Heath, we developed a draft technical scope for the review. Mr Dawson is a retired secondary school maths teacher and Mr Heath is a retired oceanographer and university researcher.

On 27 July 2016, we held a half-day meeting with Mr Dawson and Mr Heath to discuss the issues and to ensure all relevant aspects had been included in the scope of the peer review. They provided responses to both the draft scope and our notes from that meeting. The draft scope was also provided to Mr Joseph Thomas and Mr Dennis Bush-King at the council. The issues and questions listed in sections 3 and 4 of this report comprise the detailed scope of the review.

During preparation for the peer review, there has been extensive exchange of commentaries with Mr Heath and Mr Dawson on the earlier groundwater modelling, the interpretation of hydrological monitoring data, and on their own modelling. This has greatly helped us in focussing our responses to the issues.

The peer review has also been informed by issues raised in an informal meeting on 25 July by lead author Andrew Fenemor with Messrs Max Rogers, Graeme Murray and Don Yelverton, residents of the Waimea Plains. Issues raised included the benefits of weirs and the funding of the dam – the latter is out of scope of this review.

The peer review has involved perusal of technical documents related to river-aquifer interaction across the Waimea Plains, and to the release of water from the proposed dam. These are available at http://www.tasman.govt.nz/tasman/projects/water-augmentation-projects/waimea-dam/wwac-document-library/.

On 2 September we held an afternoon meeting with Messrs Dawson, Heath, Bush-King and Thomas to review a draft of this report, and have made modifications in response to those discussions. On 15 September, our final report and summary findings were presented to a council workshop attended also by Messrs Dawson and Heath.

We understand that we have been tasked with this peer review because of our knowledge and past work on the hydrology of the Waimea Basin. This has not prevented us taking an objective and critical view of the queries raised for review.

## 3 Issues Addressed in the Peer Review

Rather than addressing a series of quite specific critiques, questions about the modelling and review of alternative analyses underpinning the Waimea Plains hydrology (with and without the proposed dam), we have contextualised the questions as summarised below. This allows a more comprehensive review for council purposes.

This context provides the structure for the remainder of this report. Responses on general topics are provided in each of the following chapters of this report:

- Modelling the Waimea River-aquifer system
- Applying modelling results to water management questions
- Modelling for the Waimea Community Dam
- Potential contribution of weirs and pumped water distribution.

Specific questions raised in our discussions with community members are addressed within each topic and ***shown in bold italics,*** preceded by the text ‘***Q:***’. Our summary answers to these questions are found at the end of each of these topics, also ***shown in bold italics*** and preceded by the text ‘***A:***’.

## 4 Modelling the Waimea River-aquifer system

The use of computer models to predict the response of environmental systems to development is now common worldwide. River-aquifer (groundwater) models are useful because they can replicate the response of river and groundwater systems to variable river flows and changing temporal and spatial patterns of water use. They enable scenarios of future water release and water abstraction, such as proposed in the Waimea plains, to be simulated.

### 4.1 Groundwater Models

***Q: Is it possible to rely on measured data rather than models for future management?***

To be able to trust the predictions from a groundwater model, it is critical that the model uses all available geohydrological data and is calibrated to replicate past measured conditions, including groundwater levels, river and spring flows. Therefore, the first test for any model is how well it is calibrated over the range of conditions where management of the system is most critical.

It may not be possible to calibrate a model for the full range of future conditions, because those conditions may not have been experienced in the past (for example, extreme low flows). In order to have some trust in modelled management scenarios, groundwater modellers need to take particular care that, where deterministic, physically based models are used, the physics of the system is properly represented. This requires understanding which parameters most affect the outcomes of concern within the system; this is commonly tested using sensitivity analysis in which each model input parameter is varied (e.g. by ±20%) to investigate the effect on critical output parameters.

In a geohydrological system like the Waimea basin, a well-calibrated model is most critical during the driest periods. This is because the driest 'return periods' (e.g. the 10-year drought, or drier) are the times when management interventions (e.g. water use restrictions or dam flow releases) are most needed and when water users and stakeholders need confidence that the interventions will achieve desired outcomes (e.g. minimum river flows, or avoidance of seawater intrusion).

However, river flows and groundwater levels at any time are a consequence of the prior (transient) behaviour of the system. Simulating transient behaviour of the system is a strength of groundwater models such as MODFLOW, when compared with regression or snapshot analyses at a particular time.

Furthermore, some components of the groundwater system currently cannot be measured (e.g. subsurface flows offshore) yet can be important for water management (e.g. seawater intrusion at the coast). Consequently, models are needed to understand the effects on these components of the water balance.

***A: Measured data only takes us so far. It does not allow us to predict the response of a scenario that has not yet occurred, nor the response on 'unmeasurable' components of the water balance. As long as a model is adequately calibrated over the range of conditions for which management of the system is most critical, the model can be used to inform future water management decisions. A well-calibrated groundwater model is a widely accepted and useful tool for exploring the way a hydrological system works and for testing future management scenarios.***

### 4.2 History of groundwater modelling of the Waimea Plains

Three generations of groundwater models have now been developed and tested for the Waimea Plains. The original model (Fenemor 1988, 1989) was a quasi-3D precursor to the US Geological Survey (USGS) MODFLOW model and was developed on the Ministry of Works mainframe computer. The model was based on a thorough assessment of the hydrogeology of the plains (Dicker et al. 1992), and calibrated through the 1982/83 dry summer. We note that modelling was completed for the economically useful extent of the aquifers, not necessarily the full geological extent of each stratum.

This first model was used to set the water allocation limits across the water management zones of the plains in the Waimea Catchment Water Management Plan, including a target minimum flow of 225 l/sec corresponding to the lowest ever measured up to that time (March 1983). A 1997 post-audit of the applicability of the first groundwater model supported the conclusions reached (White 1997). By 1992, Waimea water resources were fully allocated up to the management plan limits, with the Wai-iti 91% over-allocated.

To support a review of water allocation limits to incorporate in the TRMP – including possible increased minimum river flows – the council contracted GNS Science in 2000 to develop an updated model able to run on a PC (Hong 2000). This MODFLOW model was calibrated for June 1999 – July 2001 and incorporated 1997 riverbed survey data for simulating river-aquifer recharge with the STREAM package. Calibration included the 2000/01 dry summer.

Various scenarios of water allocations (by management zone) and minimum flows were tested using the GNS model, which was also recalibrated in the course of running the scenarios. Initial scenarios included groundwater and Waimea East Irrigation Company (WEIC) abstractions achieving minimum river flows of 500, 250 and 0 l/sec during various drought return periods (GNS 2003). Further scenarios (Hong and Thomas 2007) simulated the occurrence of 100, 250, 500 and 1,100 l/sec river low flows during an average year (2004/05).

To provide data on flow releases needed from an upstream dam, the model was further upgraded with updated river cross-section data and improved rainfall recharge and groundwater abstraction sub-models. A scenario was simulated (Hong and Zemansky 2009) of projected future water demand with a dam, and achieving a minimum flow of 1,100 l/sec (at TDC's Nursery site on the Waimea River) under climate conditions of recent driest years (2000/01 and 1982/83). Changes in groundwater level under these minimum flow conditions were also used to define the 'zone of effect' – broadly speaking, the extent of the groundwater system where the model showed groundwater levels would rise as a consequence of water released from the dam.

Due to temporary loss of groundwater modelling expertise from GNS, the third generation of the MODFLOW Waimea Plains groundwater model has been developed by Julian Weir (Aqualinc 2013). This version is largely based on the previous GNS model that incorporates the upgraded river-aquifer interaction STR package, and has so far been well calibrated for the 2000/01 year. It also adequately reproduces the river flows and groundwater levels reported in the GNS results for the water augmentation scenarios described above. This model is continuing to be upgraded for informing future water management decisions by the council.

### 4.3 Adequacy of model calibration and fitness for simulating water management options

***Q: How much can we rely on the MODFLOW groundwater modelling?***

Due to the severity of the drought, the 2000/01 year (July-June) has been key to informing decision-makers on matters of water allocation on the Waimea Plains. Consequently, modelling efforts by both GNS and Aqualinc have primarily focussed on ensuring that the model suitably replicates measured conditions over this season.

A comparison between modelled and measured groundwater levels and river flows over the 2000/01 season is provided in Aqualinc (2013). Similar comparisons for the GNS model are provided in Hong and Zemansky (2009). Both models adequately reproduced low river flows (at TDC Nursery) and groundwater levels for the 2000/01 season, and as a result can be used with confidence for scenario predictions.

***A: The groundwater flow model is well calibrated and can be relied on to predict the response of the groundwater system to varying scenarios of water management.***

***Q: Did GNS' model adequately replicate conditions for years other than 2000/01 season?***

Hong and Zemansky (2009) present similar comparisons for the model simulating the 2004/05 season (an average year). Good calibration is also demonstrated for this simulated period. A model of the 2004/05 season has not yet been developed by Aqualinc. Hong and Zemansky also report model outputs for the dry 1982/83 year, but no comparisons between measured and modelled river flows or groundwater levels are provided.

***A: GNS' models adequately replicate river flow and groundwater levels for the average year 2004/05 and for the earlier dry year 1982/83.***

***Q: Are the adjustments to the parameters the same for the 1983 and 2001 runs of the model?***

Model hydraulic parameters (aquifer geometry, hydraulic conductivity, storativity, riverbed conductance) in all years modelled (1982/83, 2000/01 and 2004/05) are identical. However, daily time series of model stresses (river flows, pumping and land surface recharge[1]) are different for each year as they have been calculated for the specific climate conditions and water demands for the season being simulated. This is essential.

***A: Model hydraulic parameters are identical for each version of the model.***

---

[1] Land surface recharge comprises the portion of daily rainfall and irrigation infiltrating the uppermost aquifer. It can vary at each model cell depending on local rainfall, soil type, crop type and irrigation occurring at that location.

### 4.4 Surface-water representation

To replicate the connectivity between groundwater and leaky rivers, the MODFLOW modelling software uses a surface-water package, and there are several to choose from. The GNS and Aqualinc Waimea Plains models have been constructed using MODFLOW's stream (STR) package. The first model incorporated a specifically designed code that functioned in the same way as the subsequent STR package. Also available for use are the more simplified river (RIV) package and the more complex streamflow routing package (SFR2, which supersedes SFR1).

***Q: Is the SFR1 package for modelling river-aquifer interaction (and the alternative SFR2 and STR packages) in the MODFLOW model fit for purpose in the Waimea modelling?***

This question is relevant because part of the supply (recharge) of water into the Waimea aquifers comes from infiltration losses from river flows along the Wairoa and Waimea rivers. If the reproducibility of flow losses in the groundwater model is poor, we would have less confidence in the modelled scenarios that include proposed flow releases from the Waimea Community Dam.

Mr Dawson refers to a cautionary statement in the documentation of the SFR1 package. Although this package is not used, it is worthy of further exploration because the principles also apply to the STR package. In referring to the SFR1 documentation, Mr Dawson refers to the following statement:

> *"The Package is not recommended for modelling the transient exchange of water between streams and aquifers when the objective is to examine short-term (minutes to days) effects caused by rapidly changing stream flows."*

The developers of the SFR2 package (USGS) have provided additional commentary on this cautionary statement, as follows:

> *"The cautionary statements in the SFR1 document were written to address 2 different types of model errors.*
>
> *The first type of model error is caused by the assumption [of] steady flow in stream channels. Steady flow means that a flood wave is assumed to travel the length of the connected stream network during a model time step. For regional models that use daily or sub-daily time steps, a flood wave could possibly take longer than a model time step to pass through the model boundary. The model will simulate an instantaneous arrival of the flood wave at all tributary stream reaches. Additionally, the flood wave will be simulated as a square pulse of water with a flow and depth that is averaged over the time step. Thus, the simulated flows and depths in the channel will be different than the measured instantaneous flows and depths. This averaging can affect sub-daily simulated seepage processes, most notably due to errors in hydraulic gradients between the stream and groundwater. Note that SFR2 has a transient routing option that reduces this error. Also, recent papers studying routing in the Nile River demonstrated that errors in transient routing were small relative to errors caused by errors in channel geometry.*
>
> *The second type of model error is caused by spatial averaging of the groundwater head within a MODFLOW cell. MODFLOW calculates groundwater head using the Dupuit-*

> *Forchheimer assumption, and neglects vertical head loss within the model cell connected to a stream reach. Additionally, SFR2 calculates seepage in a stream reach using a single groundwater head and stream head that are averaged over the groundwater model cell and stream reach, respectively. This assumption also results in errors in the hydraulic gradients beneath the stream and the calculated seepage.*
>
> *Despite these errors, SFR1 and SFR2 use a robust approach for simulating SW-GW interactions for daily and sub-daily simulations relative to other SW-GW models. SFR uses an implicit formulation for calculating stream depth and seepage, and it supports input of sub-grid channel geometries, which are typically the most important factors for simulating SW-GW interaction.*
>
> *The hydraulic properties of streams and surrounding aquifers are typically uncertain. Thus, models must be calibrated to streamflow measurements and groundwater heads beneath streams. Uncertainty in streambed and aquifer hydraulic properties results in errors that are typically greater than the errors caused by aforementioned assumptions, and applying more complicated modelling approaches may not provide improved simulation results.*
>
> *These errors are important for evaluating model accuracy and applicability, and thus they are highlighted in the SFR1 documentation report. However, these considerations should NOT be taken to mean that the SFR1 and SFR2 packages are not suitable for simulating SW-GW interactions at daily or sub-daily time steps."*
>
> *[Richard Niswonger, USGS, email correspondence: 15 July 2016]*

The statement above needs to be put in light of the litigious culture in the USA. While in theory there are some limitations, there may be some remote situations where the SFR2 package does not perform completely as expected. The SFR2 package is regularly used throughout the world with daily stress periods. Furthermore, an example model in Appendix A of the SFR2 documentation uses 10-hour time steps.

For the Waimea Plains model, daily time steps are used. Changes in flows would easily pass between the gorge and the coast within this timeframe. We comment later on the modelled responses to flow fluctuations of less than a day.

***A: The package used to represent surface waters in the model is appropriate, well tested and is commonly used throughout the world in the way used in the Waimea models.***

## 4.5 Relevance of scenarios modelled

The scenarios modelled by GNS were:

- 2004/2005 : cited as an average year (now calculated as a 2-year return period dry summer[2])
- 1991/1992 : cited as a 1-in-10 year river-flow drought (now calculated as an 18-year autumn drought)
- 1982/1983 : cited as a 1-in-20 year river-flow drought (now 30-year)
- 2000/2001 : cited as a 1-in-24 year river-flow drought (now 29-year).

Each model was run with daily time steps from 1 July to 30 June of the respective years. Being able to reproduce groundwater levels and river responses for a range of varied climate, river flow and pumping scenarios is a good test of the usefulness of the model. It is acknowledged that there are some differences in performance between the three versions of the model due to approximations needed to represent the input datasets and the complexity and variability of field conditions.

For example, the GNS model simulations have been run with the riverbed conditions from the 1990s, and using a different method for estimating pumping than used earlier (e.g. input datasets from the first Waimea model were lost in the transition from mainframe computer to PC). Also, the GNS model simulations did not incorporate the cutbacks in pumping when council's water rationing was implemented in recent dry years, so the results are conservative. This reflects the trade-off between time and monetary costs of detailed modelling versus the benefits of a more accurate calibration. Modelling resources are limited.

Also, being able to reproduce system responses for average to dry years provides confidence in the conclusions able to be drawn about council management interventions for years of increasing drought return period (assuming those interventions such as cutbacks in water use are complied with). This includes conclusions about flows to be released from an augmentation dam needed to achieve specified minimum flows in the Waimea River.

---

[2] Based on a Gumbel analysis of annual 7-day lowest Gorge flows from 1 August 1858 to 1 August 2016

## 4.6 Errors in modelling reports

***Q: What effects have the errors in the units in the modelling report had on the dam design, if any?***

Mr Dawson and Mr Heath have noted some errors in the 2003 GNS report, and have rightly raised queries about the editing and peer review processes for such reports. We are informed that reports produced for the three phases of the Waimea Water Augmentation Committee investigations were subject to peer review, either internally by Tonkin and Taylor as lead consultant or by contracted external reviewers.

However, the GNS (2003) report was not a Waimea Water Augmentation Committee (WWAC) contracted report but was produced for TDC. Its results have been the basis for further work subsequently carried out by GNS for WWAC, which was peer reviewed.

The errors noted relate to the units used in Figure 11 of GNS (2003) (reproduced below in Figure 1) and Table 8, where the groundwater through-flow is over-reported by a factor of 7 because weekly ($m^3$/week) rather than daily ($m^3$/day) data have been plotted, and these data are also described too loosely as 'available groundwater flow' when this water is not all 'available' for extraction. These are reporting errors rather than a modelling error and have not affected any of the conclusions reached by GNS in that report.

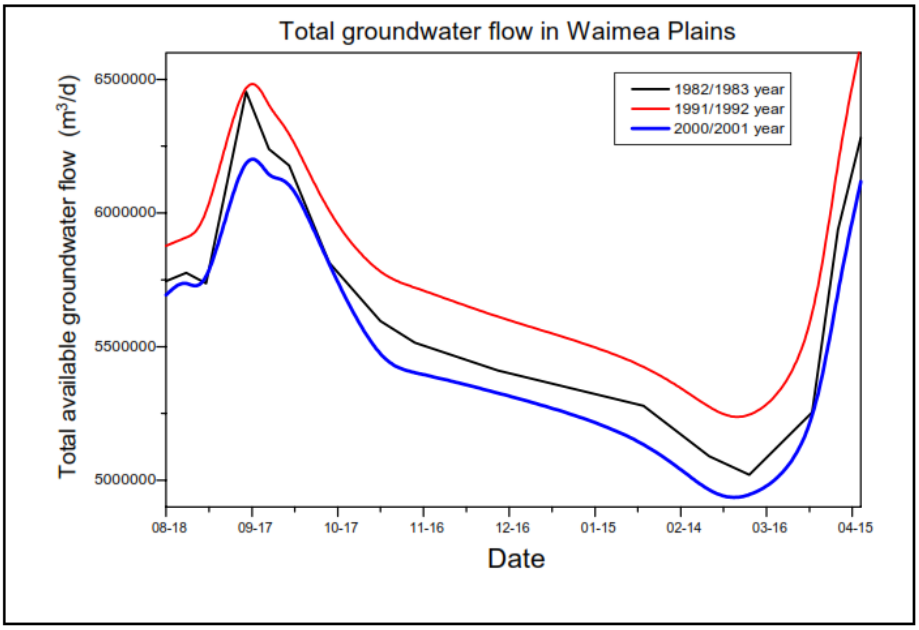


Figure 1: Total groundwater flow in the period of November and April in the Waimea Plains (reproduced from Fig. 11 of GNS, 2003)

Mr Dawson has also noted that some of the model simulations reported in GNS (2003) do not adequately match measured data from that time. For example, that under the actual water usage scenario in 1982/83, the river only reached a minimum flow of 225 l/sec while Table 3 and Figure 10 of the GNS report gave modelled predictions of the river going dry. We note that the 2000/01 simulations more closely match monitored data.

The inaccuracy of the 1982/83 simulations is likely to be because groundwater pumping was only crudely estimated, and the riverbed profiles from the 1990s (rather than from the 1980s) were used in that model. Given this, and the dynamic nature of river-aquifer interactions, we consider the modelled outcomes are reasonable. Of course, more could be done to improve those model inputs, and this has been achieved with the more recent modelling efforts, especially with the work on the dry 2000/01 summer.

***A: We have contacted GNS Science about correcting the reporting errors in their 2003 report. These changes can apparently be made and the revised report made available online. The errors are drafting errors rather than modelling errors of consequence for decision-making.***

# 5 Applying modelling results to water management questions

## 5.1 Water management and how modelling helps

***Q: How does the modelling relate to the management objectives of the TRMP and of the proposed dam?***

The management objectives amount to the following:

- Prevent seawater intrusion into aquifers, and avoid seawater intruding upriver where river water containing salt could end up being pumped laterally into a riverbank bore.
- Maintain spring flows in Neimann and Pearl Creeks during droughts to protect instream and bird habitat.
- Provide for recreation, aquatic ecosystem and other amenity values in the lower Waimea River by maintaining a minimum flow of 1,100 l/sec, or 800 l/sec when the drought exceeds a 1-in-40 year return period (Table 1A, Schedule 31C, TRMP).
- Limit loss of well yields caused by excessive pumping drawdowns by, for example, specifying minimum distances between pumped bores.

The management scenarios tested using the groundwater model incorporate prescribed outcomes, such as minimum river flows and groundwater levels maintained above mean sea level, which would prevent seawater intrusion into coastal wells.

Groundwater modelling is needed because pumped groundwater temporarily depletes the volume of groundwater stored in the aquifers while at the same time inducing leakage of river flow from river channels. The main drivers of recharge of groundwater from rivers are the difference between river water level and underlying groundwater level along the river channel, plus the permeability of the riverbed and the wetted area of riverbed. These drivers are built into the river-aquifer interaction software (e.g. the STR package) described above.

Groundwater water levels change from day to day, as does the volume of water stored in the aquifers. This is why transient (time-varying) simulation is needed in a groundwater model to adequately test the response of the system to stresses including river freshes, pumping, rainfall and irrigation infiltration.

During periods of high pumping, the model calculates the loss of storage and induced river recharge. Model and geohydrological system performance can then be described in various forms, including plots of groundwater level change for selected wells, variability in river flows downriver and day-by-day, and through calculations of water balance components (rates of pumping, nett river recharge, spring flows, inter-aquifer leakage and outflows to the coast) described below.

***A: The objectives of TRMP policy, whether with water augmentation or not, are to achieve the outcomes bulleted above, and this is normally planned for a particular return period of drought. Statements such as 'what is the safely available volume of groundwater for extraction' are determined from the achievement of these goals.***

***Q: Why is maintaining a minimum flow part of the dam design?***

Among the reasons water augmentation has been investigated for the Waimea Plains for the past 20 years is that summer water demand – whether from surface flows or from groundwater pumping – depletes river flows to the extent that in dry summers the Waimea River dries up. The water rationing regimes implemented through TRMP rules and guided by the council's Dry Weather Task Force have proven insufficient to prevent river drying during droughts exceeding a c. 20-year return period.

The groundwater model can test river flow response to various water allocation and management regimes, with and without flow releases from a water augmentation source, but only through the use of scenarios, not currently for 'real time' management during a drought.

***A: In planning for water augmentation, WWAC proposed a minimum flow in the Waimea River of 1,100 l/sec as one of the design objectives for planning the size of water storage needed. The GNS groundwater model was run to estimate the flow releases needed from a storage dam (on top of natural flows as measured at Wairoa Gorge since 1957) to achieve this minimum flow while accounting for recharge losses to groundwater to satisfy current and projected water demand for a range of return periods. Without water augmentation, if more water were pumped from groundwater storage during dry summers, it would not be possible to maintain the desired minimum river flows.***

***Q: What evidence is there that seawater intrusion is a real risk and how much does pumping increase its risk?***

As early as the 1970s, seawater intrusion into the coastal aquifers was identified as a potential risk of groundwater pumping near the coast. The concern at that time was the Richmond wellfield into the Lower Confined Aquifer (LCA), which draws the aquifer head several metres below sea level along Lower Queen St in summer. Limits were first put on water allocation from the LCA in the 1980s after increased water salinities were measured in the Chipmill monitoring bore during the 1982/83 drought. It is now thought that those readings were anomalous and may have been caused by a high spring tide allowing seawater to run down the outside of the bore casing.

In the 2000s, the risk of excessive seawater intrusion into the Delta Zone of the Appleby Gravel Unconfined Aquifer became a focal point. The two most downstream wells of the Waimea water supply had to be shut down after seawater intruded from a plume of seawater in the adjacent Waimea River at high tide. Those wells remain shut down. Pumping from unconfined aquifer wells nearest the coast could result in similar effects for other wells.

***A: Groundwater modelling of the type carried out for the Waimea Plains is able to assess this risk by showing the parts of the plains and times of year when the local water table is close to, or below, mean sea level. Simulations that either remove coastal pumped wells or cease or reduce pumping during lowest river flows can show how to mitigate the risk. Alternatively, given the current pattern of pumped coastal wells, maintaining a minimum river flow of at least 800 l/sec would minimise the risk.***

***Q: How has WEIC pumping direct from the river affected the need for a dam?***

Some commentators have claimed that direct water take from the Wairoa River gorge since the mid-1980s by the Waimea East Irrigation Company (WEIC) has caused the water shortage across the plains. WEIC supplies piped irrigation water to up to 1,100 ha of primarily horticultural land. The scheme was developed to increase water supply reliability to the area overlying the intermittent Hope aquifers, which run out of usable groundwater in dry summers. The scheme is efficient and the scheme manager reports (Alistair Paton, pers. comm.) that it has pump capacity to expand its supply area if its supply reliability can be assured.

***A: It is true that WEIC's river water take has a direct and immediate effect in reducing downstream river flows, as discussed further below. However the RMA would recognise the scheme as part of the 'existing environment' of the plains and its water allocation is subject to water rationing at the same rates as groundwater takes in the Reservoir Zone.***

## 5.2 How and why TDC manages allocations through a summer

A critical decision for managing water allocations is the setting of:

1. minimum flow with flow triggers for water rationing steps
2. water allocation limits (for an average year, i.e. without rationing) in each zone
3. the planned security of water supply to users.

The National Policy Statement for Freshwater Management (2014) requires councils to avoid 'over-allocation'. In our view, a system would be considered 'fully allocated' if all of the above three parameters are only just not exceeded; further allocation could occur if there was 'spare capacity' in the parameters; 'over-allocated' means that one or more are exceeded.

An allocation limit is the maximum sustainable rate of water take able to be allocated in a water management zone when the take is not under restriction. In the TRMP it is the sum of weekly allocations on water permits for that zone, lawfully able to be taken during a normal irrigation season. Until the 2001 Waimea water management plan change, water allocation limits were specified for each zone in the plan. In that plan change, to avoid any further allocations (even as non-complying activities), most allocation limits were removed from the plan and replaced with policy preventing any new allocation or re-allocation of water.

Allocation limits (or now, total current allocations in a zone) apply in conjunction with three sequential water rationing steps imposed on water permits when drought triggers are reached. A first trigger flow applies at Wairoa Gorge to maintain the target minimum river flow. A second trigger is when conductivity in a Delta Zone monitoring bore exceeds 1.0 mS/cm indicating seawater intrusion (Table 1B, Schedule 31C, TRMP).

TRMP policy 30.2.14 indicates that rationing at Step 2 can be expected every 10 years on average. When rationing is triggered, irrigation water users are subjected to cuts in allocation in sequential steps, normally at no less than two-weekly intervals, of 20% (Step 1) then 35% (Step 2) then 50% (Step 3) cuts of the weekly allocation on each water permit. Any greater cut requires council to use its emergency powers by issuing a Water Shortage Direction. Water metering data confirm that for some water users who are using less than 80% of their full weekly allocations, the initial rationing cut would have no effect on their water usage; however, the second and third steps would reduce their water usage.

The severity of water rationing implemented by TDC during the 2000/01 drought was greater than ever imposed before. The drying up of the Waimea River, when a minimum flow of 225 l/sec was expected to be maintained, was unexpected and the consequential cuts in usage of up to 60% of allocations were difficult for water users to cope with. The 2000/01 drought was, however, the most significant drought since 1972/73.

***Q: What is the current situation for water users and river low flows under the recent TRMP plan changes on Waimea water allocation, with and without a dam?***

TRMP plan change C47 made provisions for two water allocation and management regimes for the Waimea catchment: ‘with dam’ and ‘without dam’. If no water augmentation is provided, the plan change provides that water users would have their water take allocations reduced according to a stringent ‘bona fide’ test of their current water need, and through the imposition of new consent conditions would likely be subject to rationing restrictions at least every second summer to achieve a target minimum flow of 800 l/sec. The plan change puts in place rationing steps of up to a 70% cut in allocation.

For the ‘with dam’ provisions, the minimum flow would be set at 1,100 l/sec, reducing to 800 l/sec in a drought exceeding a 40-year return period. The currently proposed Waimea Community Dam would be able to supply with 100% reliability all projected water demands and maintain these minimum flows in a drought of up to 50-year return period.

A minimum flow of 800 l/sec is very likely to prevent seawater intrusion into any currently pumped coastal bores.

Water rationing is triggered by flows at Wairoa Gorge despite there being a recently installed flow recorder at TDC Nursery above the Appleby Bridge. The reason why flows are not triggered by flows measured at the Nursery recorder is that the gravel riverbed is constantly changing; therefore, the relationship between measured water level and calculated flow (the ‘rating’) is unreliable.

Flows at Nursery (and beyond) are effectively a pressure relief off the top of the groundwater table. During dry periods when the river is not flowing its full length, the Nursery river site goes dry when groundwater levels at the site drop below the bed of the river. However, even when this happens, there is still groundwater flow that carries on under the river bed to the coast.

***A: The Commissioners' decisions on TRMP plan changes C45-48 are likely to have a very significant economic impact on all Waimea water users if some form of water augmentation is not provided for; specifically the 'without dam' minimum flow target of 800 l/sec in the lower Waimea River.***

***Q: What about climate change?***

Climate change modelling by NIWA for 2040 and 2090 suggests a small increase in annual catchment precipitation, but this would be counteracted by increased temperatures, evapotranspiration and drought risk.

For 1990–2040, annual mean air temperatures may rise by 0.9°C; for 1990–2090 mean temperatures could increase by 2°C. Looking at the measured trends to date, NIWA compiled mean annual air temperature data for seven sites for the 100 years from 1908 to 2008; these show a statistically significant rise in mean annual air temperature of almost 1°C over that time. The days of frost are expected to decline markedly. Measured pan evaporation and calculated evapotranspiration since 1950 show a statistically significant increase averaging about 4.5 mm/y, in tandem with the temperature increase. We conclude that the projected temperature increases and associated increased evapotranspiration of crops will increase the water needs of crops, and to a lesser extent for urban supply.

Compensating slightly for the increased evaporation and water demands are modelled predictions of +2% and +4% changes in annual mean rainfall for 1990–2040 and 1990–2090, respectively. However, measured rainfall data indicate a decreasing but not statistically significant trend of c. –11 mm/y since 1993. For river flow at Wairoa Gorge, there has been no statistically significant change overall in median flow from 1958 to 2009, although flow data since 1993 show a small, statistically significant decline.

Projected increased rainfalls are more likely in summer, autumn and winter rather than spring. However, these rainfalls are not uniformly spread through those seasons; rather, they will likely be the result of more extreme storm events. What is currently a 20-year drought (analysed in terms of increased evapotranspiration) is expected to occur every 10–15 years. We conclude from the rainfall projections that the small increases would add more water to the storage reservoir but probably have little direct beneficial effect on the plains during summer.

A GNS climate change study of Waimea Basin water resources brings all this data together to assess impacts in 30 and 80 years' time. For a year like that of the 2000/01 summer, the climate change projections would have translated into reductions in Waimea River low flows of about 100 l/sec within the driest 2 months. With the Lee Dam in operation, flow releases from the dam would compensate for the reduced water availability, providing drought security for water users. But the ability of the reservoir to maintain reliability of supply may be reduced below the proposed 50-year security.

Without water augmentation, the risk of seawater intrusion into coastal wells is also likely to increase during periods of low Waimea River flows because of sea level rise. Records from the major ports recorded over the last 100 years (Auckland, Wellington, and Lyttelton) indicate that the local sea level has risen by 15–20 cm in the last 100 years. Advice from the

Ministry for the Environment is that a sea level rise of at least 80 cm should be planned for by 2090. We can expect an equivalent rise in the water table adjacent to the coast, and for the salt-water wedge to reach 0.8 m higher in elevation up the Waimea River than currently.

Inspection of river level and groundwater level contours suggests that in the absence of higher summer river flows, a 0.8 m rise in sea level would push the saline interface c. 500 m further inland, as shown conceptually in Figure 2. The inland blue line for the seawater interface in 2090 would be likely to be further towards the coast the higher the minimum flow maintained in the Waimea River during summer, as proposed if the water augmentation scheme proceeds.

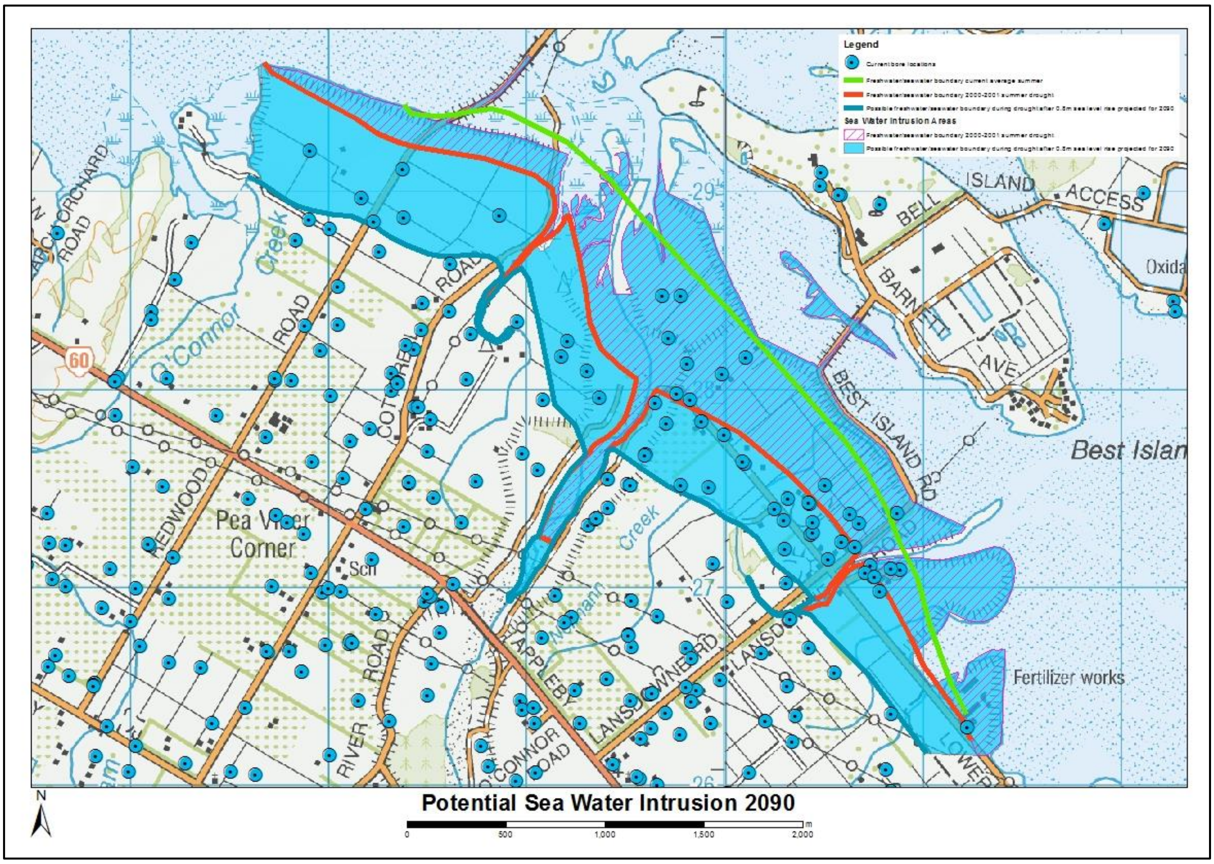


Figure 2: Waimea river mouth showing three locations for freshwater–seawater interface: average summer currently (green), during 2001/01 drought (red) and during 2000/01 drought conditions as a worst case if they occurred in 2090 after 0.8-m rise in sea level (blue).

The current phase of the Pacific Decadal Oscillation (PDO) commenced approximately in 2000. The previous phase spanned approximately 1978–2000. The dam has been sized based on a 50-year period of flow records from the Wairoa River at the Gorge (1958–2008), which spans two PDO phases. Furthermore, the groundwater models developed by GNS cover dry periods within both of these last two phases. As a result, in our view, risks of climate change have been adequately accommodated.

***A: Potential risk of climate change would be mitigated, but not completely avoided, by ensuring that assessments are made over a representative range of climatic conditions that span the current and previous PDO phases. This provides some confidence in the applicability of the modelled scenarios for the longer term.***

# 6 Modelling for the Waimea Community Dam

## 6.1 Options investigated for water augmentation

***Q: Have options other than the Lee Dam been adequately canvassed?***

The first Waimea Water Augmentation Committee comprising TDC, Nelson City, and irrigator and industry representatives was formed in 1992 to investigate options for solving the water shortage in the Waimea Basin.

Early investigations involved drilling a 900-m deep bore at Waimea West, investigating the use of treated sewage for irrigation and updating the likely cost of piping water from Nelson Lakes and the Gowan River. All these options proved to be too expensive for irrigation and at that time the bulk of the demand was in the Wai-iti Valley.

Investigations then focused on the progressive construction of four (or so) moderate to large earth dams on Moutere Gravels in the side valleys of the Wai-iti catchment. The initial study concentrated on a single dam at Trass Valley and involved the release of storage over summer to augment the natural flow as and when required. None of these options had sufficient storage to meet potential water demand over the whole of the plains.

In the late 1990s the Wai-iti Water Augmentation Committee, facilitated by TDC, committed to the Kainui Dam, which was built in the upper 88 Valley with a volume of 800,000 m$^3$. The Kainui Dam is funded by water users in the Wai-iti Valley through a special rate. Water is released during most summers to maintain flows and to recharge unconfined groundwater for extraction down the Wai-iti River as far as Brightwater. The Kainui Dam has operated as planned and provides a model for the effectiveness of released dam water for the rest of the Waimea Plains.

Since the early 2000s, the Waimea Water Augmentation Committee has pursued a similar mandate from the council and from current water users of investigating dam sites and commissioning technical studies to support their proposal for a dam in the upper Lee Valley. The supporting documentation for their three stages of investigation, which led to consents being granted for the dam is available at http://www.tasman.govt.nz/tasman/projects/water-augmentation-projects/waimea-dam/wwac-document-library/.

There have been variants of the proposal put forward by community members, including the suggestion that constructing weirs to enhance groundwater recharge might be sufficient, and most recently (Nelson Mail 23 August 2016) a proposal to pump water from storage ponds at the mouth of the Wairoa Gorge similar to those built at Rangitata Gorge by Rooney Construction. The weir option is discussed below.

***A: Council documents back to the early 1990s indicate a very comprehensive assessment of water augmentation options, which led to the implementation of the Kainui Dam for water augmentation of the Wai-iti Valley, and the current Lee Dam proposal for augmenting supplies to the rest of the Waimea Plains.***

## *Q: Could more efficient water use, prioritising crops by value, advances in water use technology (etc.) address the water shortage problem?*

Table 1 summarizes current land use for the Waimea catchment below the Wairoa Gorge (reproduced from Fenemor et al. 2015):

Table 1: Land Use classes for the Waimea catchment 2013

| **Land use class** | **Area (ha) within Waimea Plains catchment (below Wairoa Gorge)** | **Comments on this class** |
|---|---|---|
| Berries | 114 | Raspberries, boysenberries |
| Grapes, Olives | 1,003 | Predominantly grapes. Both have low irrigation water demands |
| Hops | 48 | |
| Kiwifruit | 65 | |
| Pipfruit, other tree crops | 893 | Predominantly apples. Other tree crops include stonefruit, hazelnuts, avocado |
| Outdoor vegetables | 705 | Includes land in vegetable production even if temporarily in pasture |
| Nursery | 114 | Comprises horticultural nurseries on leased land as well as permanent nursery production |
| Glasshouses | 30 | Includes vegetables, floriculture, plastic houses |
| Dairy | 615 | Commercial scale dairy farms |
| Pasture | 12,350 | Includes sheep & beef, grassed surfaces of lifestyle blocks |
| Scrub | 2,159 | Includes riparian shrublands including willows |
| Forest | 19,797 | Predominantly exotic pine plantings |
| Non-Agricultural | 2,691 | Includes buildings, roads, urban, industrial areas, curtilage |
| Water | 61 | Rivers, significant streams, ponds, reservoirs |
| **TOTAL AREA** | **40,645 ha** | |

The irrigable part of the plains predominantly grows horticultural crops and features widespread use of microsprinklers and drippers. Unlike Canterbury with widespread pastoral uses and irrigation being converted from inefficient border dyke to pressurised sprinklers, there is less scope for water savings from technological improvements on the Waimea Plains.

We understand the council has considered prioritising particular crops for water rationing but has been reluctant to 'pick winners'. The Dry Weather Task Force may have some scope to take into account critical crop water needs at the time rationing steps are being implemented.

***A: It is our view that increased efficiencies, more conservation measures and new technologies would be insufficient to match water demand and availability without water augmentation.***

## 6.2 How the groundwater model has been used to size the dam storage

The size of the proposed Lee Valley Dam has been based on an assessment of likely future water demand over the next 100 years. Taking account of these water demands, the scheme storage has been sized to maintain a minimum flow in the Waimea River of 1,100 l/sec, and 100% reliability of supply in a drought with a return period of up to 1-in-50 years. Based on projections of future development in the Waimea basin and adjacent areas, additional water will be needed for:

- present and future irrigation development at a maximum allocation rate of 30 mm/week (300 $m^3$/ha/week)
- reticulated water requirements from urban residential, commercial and industrial growth
- environmental river flows in average to dry summers to make up a shortfall between current water usage and future restricted usage under TRMP plan change C47 if a water augmentation scheme does not proceed (the ‘without dam’ scenario)
- an allowance for climate change risk.

The cost of an incremental increase in dam volume (i.e. a taller dam) is relatively small compared to the initial outlay costs of constructing a dam in the first place. Given the expenditure required, it is therefore prudent to minimise future risk by providing a dam larger than needed for little additional cost.

***Q: What assumptions have been made about future urban, regional and irrigation water demand used in the modelling?***

The Lee Dam proposal is based on providing water for up to 5,850 ha of irrigation in the Waimea Basin, of which 3,800 ha are currently irrigated but with insufficient supply reliability.

Water demand varies throughout the year and between years in relation to the severity of drought. Therefore, the water storage must be designed considering both the long-term water demand (i.e. annual volume) as well as the short-term water demand (i.e. ability to deliver a peak weekly rate of flow). In average to wetter summers there is less of a water shortage.

Table 2 summarises the reported water demands to be met by a combination of natural river flows and dam releases.

Table 2: Projected water demand

| **Water Demand** | **Hectare equivalents** | **l/sec equivalent in any week** |
|---|---|---|
| Existing irrigated area (lacks full reliability of supply) | 3,800 | 1,885 |
| New irrigation | 945 | 469 |
| New irrigation (water distribution infrastructure required) | 1,105 | 548 |
| TDC current reticulated water (urban & industry) | 620 | 307 |
| TDC future reticulated water demand (urban & industry) | 780 | 387 |
| Future regional demand (e.g. NCC reticulated water) | 515 | 255 |
| **TOTALS** | **7,765** | **3,852** |

Estimating future water demand requires a multitude of assumptions about population growth, future land use, and per capita water usage. For example, we understand that future TDC urban demand is a 50-year projection and includes urban and industrial water needs across the plains, into Stoke and to Mapua and beyond. An estimate of future regional need is a reference to water needs beyond those areas including Nelson City and potentially towards Motueka. Similarly, future irrigation demand is based on a weekly allocation of 30 mm/week when some current crops will require 35 mm/week and others 20 mm/week. There will be debate about the assumptions behind future water demand, but the incremental cost of a slightly higher dam will be small.

For design of the reservoir storage, as described in Tonkin & Taylor (2009), the types of water demand in Table 2 have been calculated as time series of daily water demand corresponding to the 50-year period of flow records from the Wairoa River at the Gorge, i.e. 1958–2008. The reservoir is sized to provide sufficient water storage such that 100% of water demand could be supplied for a reservoir return period exceeding 50 years (the calculated supply security is for a reservoir return period of 66 years but it is prudent to provide for cut-backs in flow releases when the 50-year level is reached, in case a drought worse than 66 years eventuates). This means the reservoir storage is sufficient to cater for design water demand during any of the dry summers in living memory, including 1972/73, 1982/83 and 2000/01.

To calculate the volume of water required to meet the irrigation demand in Table 2, a daily irrigation-scheduling model was developed. The model calculates for each day how much irrigation water was needed, over and above measured rainfall, to maintain pasture (the highest water use crop) on each of the three major soil types across the Waimea Plains. Figure 3 shows the variability of total annual irrigation demand for the 5,850 ha of projected irrigation in Table 2. The red bars in Figure 3 represent the 3 drought years mentioned above. Irrigation demand from both the Waimea aquifers and Wairoa River peaks at 2,470 l/sec over a day. Peak annual irrigation demand, as shown in Figure 3, would have been c. 28 million cubic metres had the drought conditions of 1972/73 occurred after full development of irrigation described in Table 2.

We are satisfied the irrigation scheduling model adequately represents the variability in water demand through the year, though the amount of land which will end up irrigated will have more uncertainty.

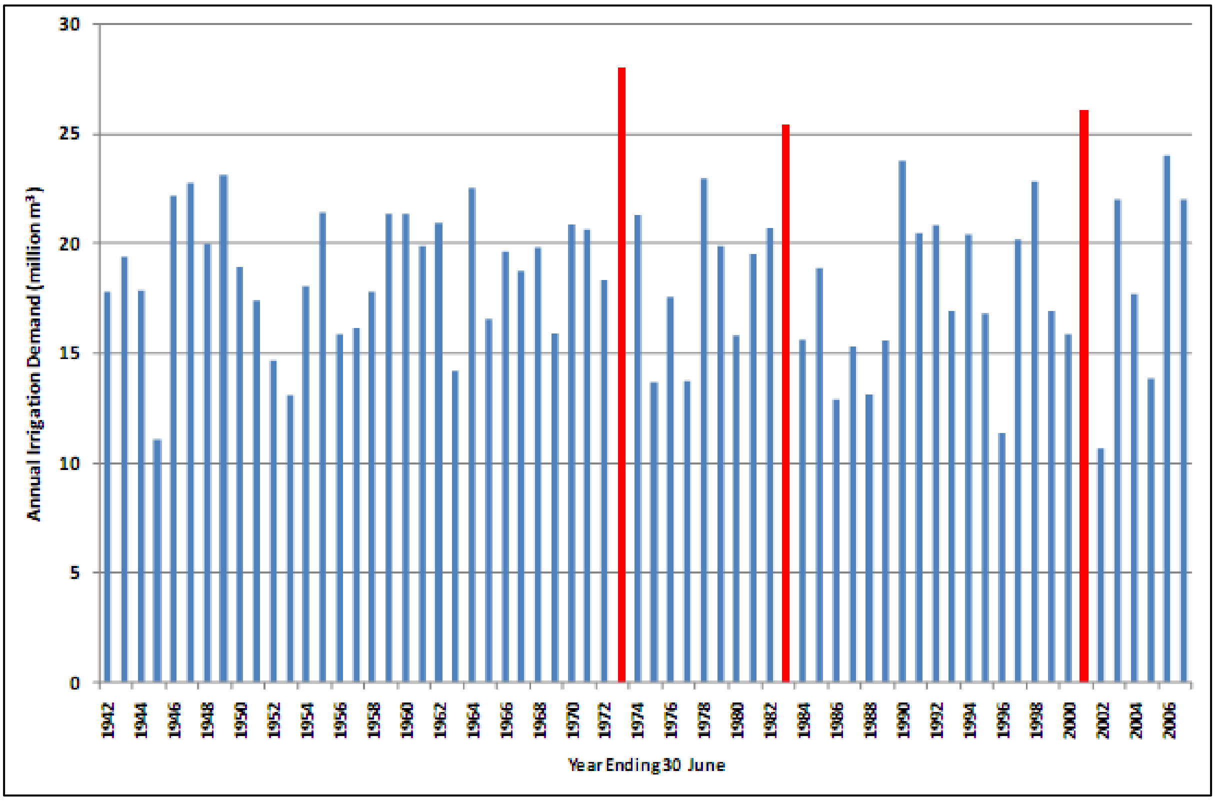


Figure 3: Annual irrigation water demand volumes (1942–2007)

TDC's projected 100-year urban and industrial water demand (Table 2) is scaled up from the existing pattern of water use through over a year to a peak daily demand of 60,000 $m^3$/d, equivalent to 694 l/sec. The future regional demand is 22,000 $m^3$/d, equivalent to 255 l/sec. Only the future regional demand in Table 2 has been assumed to be needed every day of the year. The irrigation, urban/industrial and future regional water demands were summed by Tonkin & Taylor to produce a 50-year time series of total water demand.

What can immediately be noticed is that these water volumes (e.g. in Figure 3) are much higher than the proposed storage volume of the dam (13 million cubic metres). This is because that water demand is met from release of stored water plus natural flows from the Wairoa and Roding catchments, plus water stored in the Waimea aquifers.

To calculate the reservoir storage volume needed, the GNS model (Hong & Zemansky 2009) was run as described earlier; results are described in Tonkin & Taylor (2009). The model uses the projected water demand across the plains while maintaining a minimum flow in the Waimea River near Appleby Bridge of 1,100 l/sec to calculate how much water needs to be available each day at Wairoa Gorge. The component of water supplied from the Lee Dam was then calculated taking into account river flow records for the Wairoa and Lee rivers. Hydrological analysis of flows available at the Lee Dam site shows that over the past 50 years at least 60 million cubic metres of water passes the site each year; this is useful to compare with the planned storage volume of 13 million cubic metres to confirm the significant volume which will pass the dam each year.

***A: Future water needs have been projected 50 years out. They are based on extrapolating current trends and usage rates and will always be somewhat uncertain. It is relevant that the incremental cost of providing more water storage now is relatively small compared to the cost of the first increment of storage.***

***Q: How do river losses to groundwater below Wairoa Gorge relate to changing gorge flows, pumping rates and depths to the groundwater table?***

The exchange of water between rivers and groundwater depends on several factors including the river stage (which is flow dependent) and the relative height difference between the river water surface and underlying groundwater level. Rivers gain more or lose less flow during periods of high groundwater levels; conversely they gain less or lose more flow during periods of low groundwater levels (even if the river flow is the same). If river flows are higher, then the river may lose more flow to (or gain less flow from) groundwater, even if groundwater levels remain stable. If river flows are lower, then the river may lose less or gain more for the same groundwater level. The system is dynamic and highly variable.

The model's ability to replicate measured flow losses is presented in Figure 4 for the 2000/01 model period. Here, both modelled and measured losses in the Wairoa River between the gorge and the Wai-iti confluence are plotted (allowing for WEIC takes). This is generally the losing reach of the river. To demonstrate the relationship with groundwater levels, losses are presented for periods of low, moderate and high groundwater levels based on Delta Zone well CW2 as an indicator.

Figure 4 presents this relationship for low gorge flows (up to 5 $m^3/s$ [3]). Though it appears there is an upper limit to the river losses, at higher flows the losses are a little greater (and more variable). This is demonstrated in Figure 5. Although there are only a few measurements with which to compare, the model is consistent with the few that are available.

At a broader scale, modelled and measured river flow differences between the gorge inflows (both Wairoa and Wai-iti rivers combined) and flows at TDC's Nursery site (on the Waimea River) have been compared. This provides more measurements of flows with which to compare (there are more flow measurements at the Nursery site than above the Wai-iti confluence in the 2000/01 year). The resulting comparison of measured and modelled flow differences is shown in Figure 6 for low gorge flows (up to 5 $m^3/s$) over the 2000/01 model period. Figure 7 expands the plot to include moderate flows.

---

[3] 1 $m^3/s$ is 1 cumec which is equivalent to 1000 litres per second (l/sec)

There are no measurements during moderate and high groundwater level periods to present. Apart from a few outliers, measured and modelled data compare favourably, particularly for the low-flow periods.

Overall, there are differences between measured and modelled river losses and flow differences. However, this will always be the case with models that have to simplify a real world system. Regardless, the dynamic response and general model outputs (presented here and in Aqualinc, 2013) are adequate to inform likely responses from future scenarios (such as dam releases).

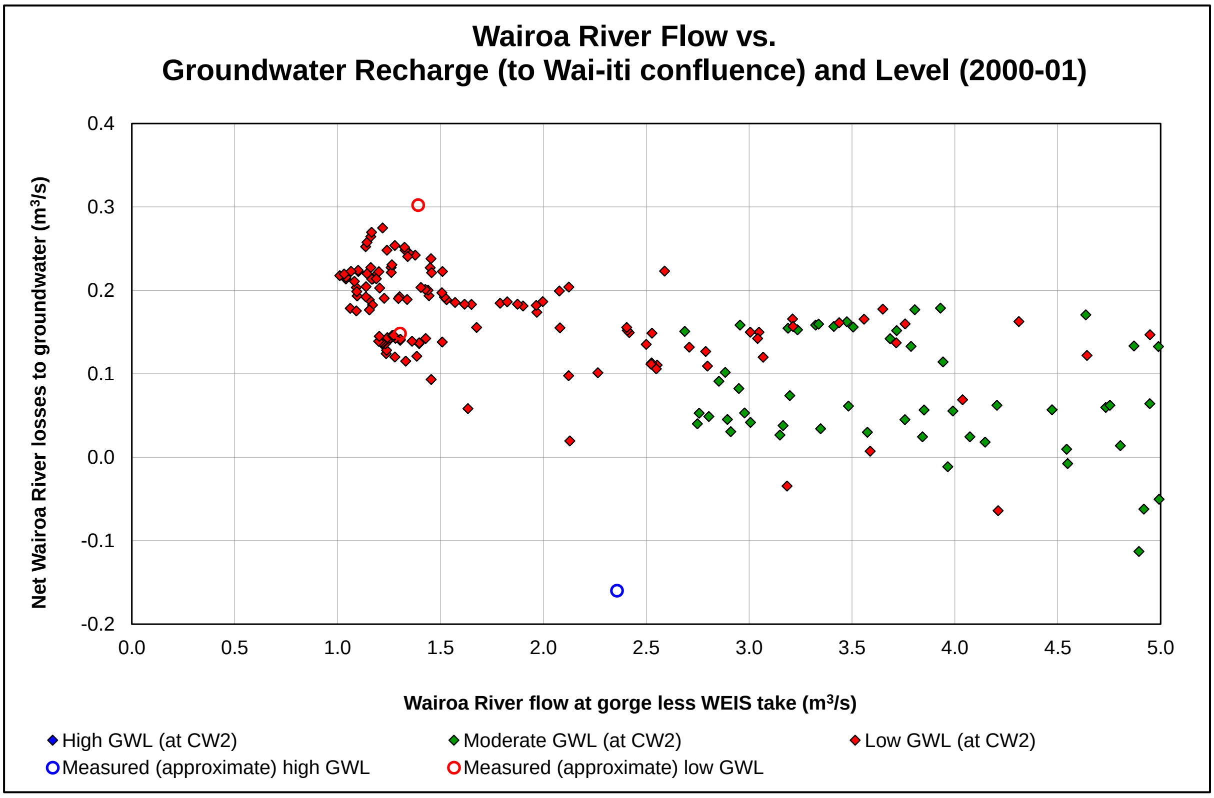


Figure 4: Modelled and measured Wairoa River flows versus losses (to Wai-iti confluence): low flows

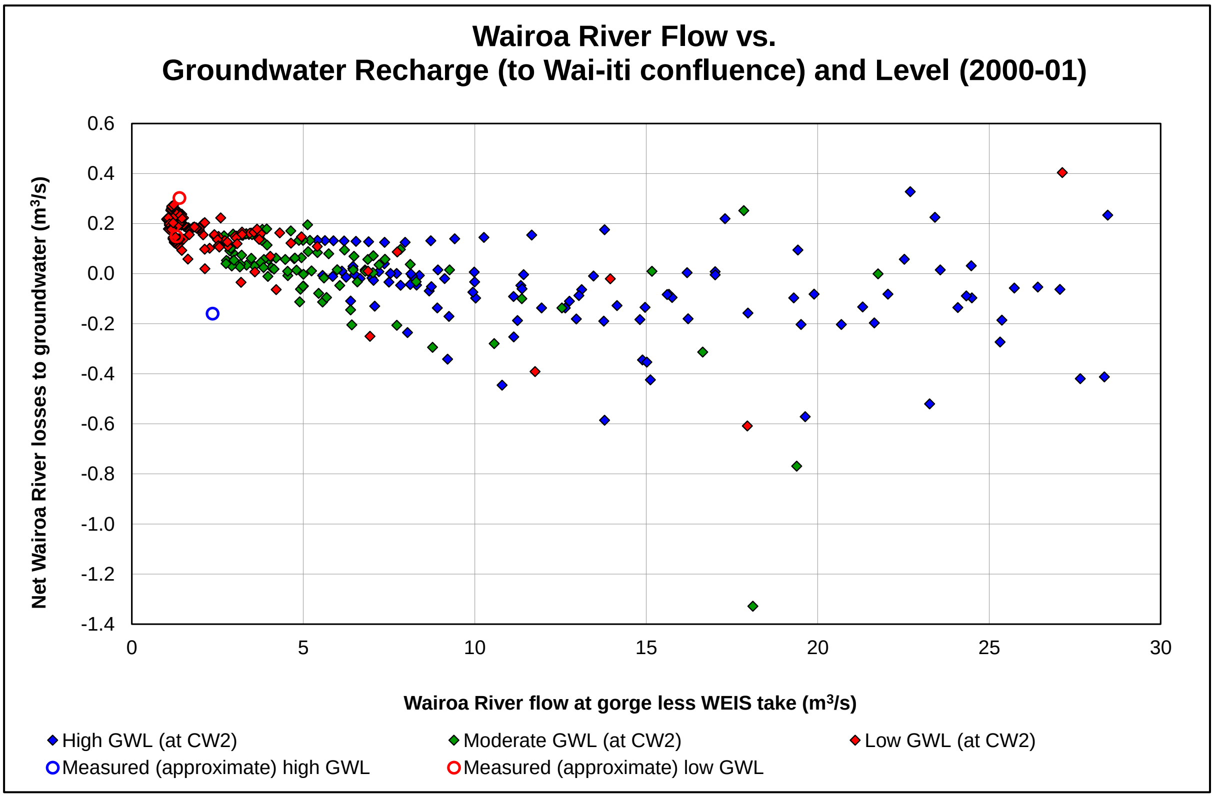


Figure 5: Modelled and measured Wairoa River flows versus losses (to Wai-iti confluence): low–moderate flows

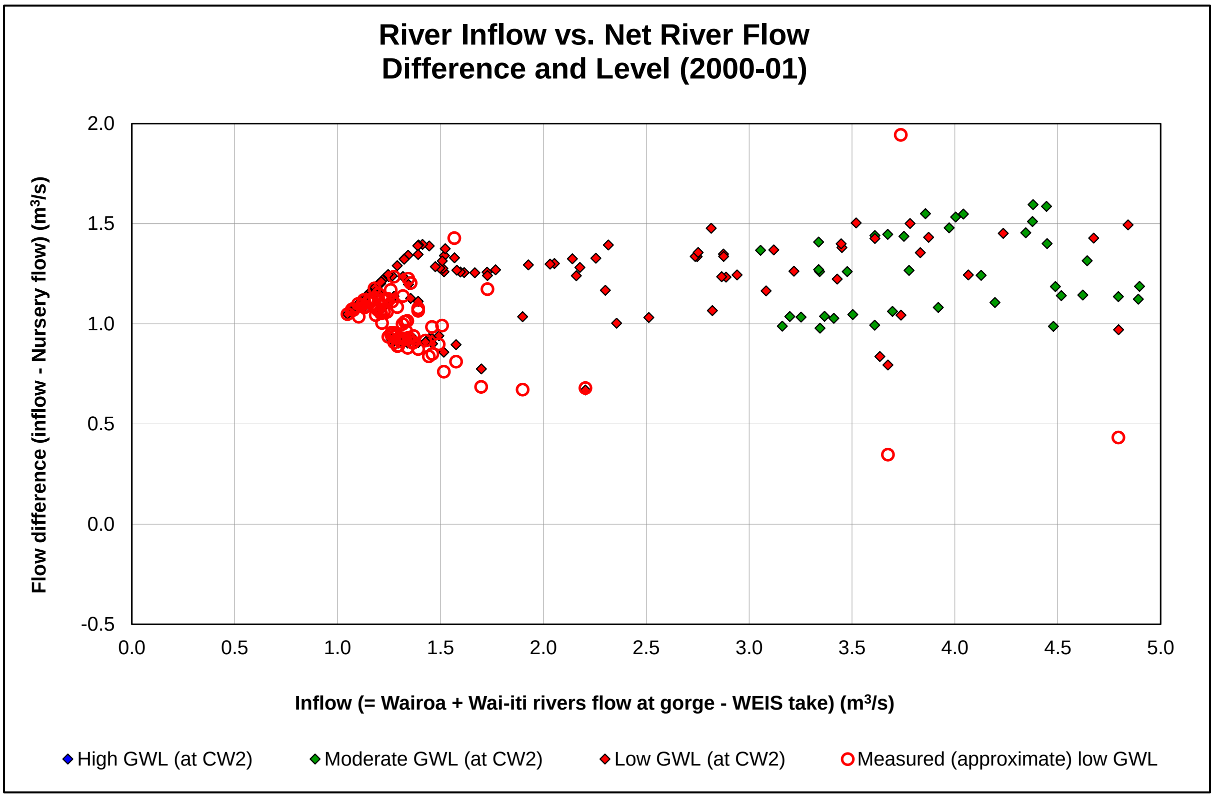


Figure 6: Modelled and measured Wairoa-Waimea river flows versus flow differences (to Nursery, above Appleby Bridge): low flows

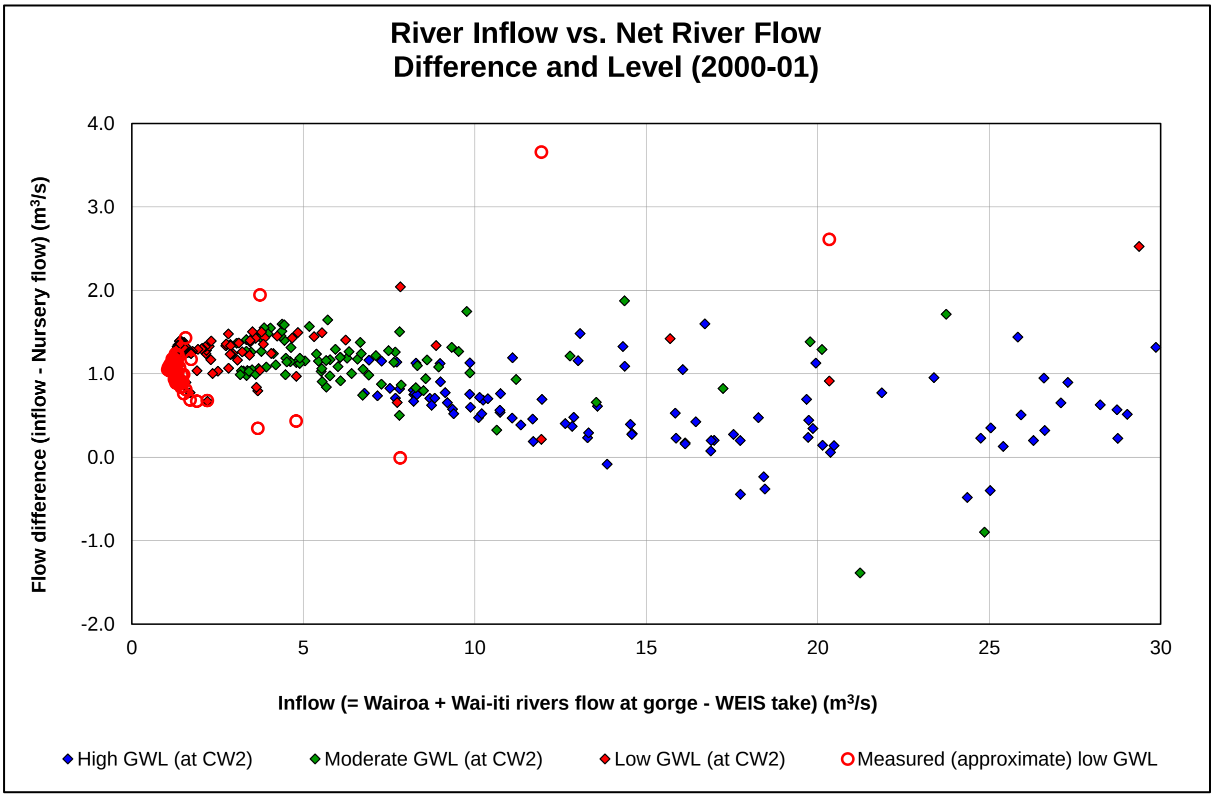


Figure 7: Modelled and measured Wairoa-Waimea river flows versus flow differences (to Nursery, above Appleby Bridge): low–moderate flows

***A: River recharge to groundwater is dynamic, highly variable, and dependent on multiple factors, including river stage height and depth to underlying groundwater. Generally, as river flows increase, river recharge to groundwater increases. Similarly, as groundwater levels drop, river recharge to groundwater increases. Modelled response is consistent with measured.***

***Q: Do diurnal variations in river flows and pumping affect model predictions?***

Time series of model stresses (river flows, groundwater pumping and land surface recharge) have been assigned as daily averages. However, in reality, there is variation in these stresses at a sub-daily interval. To test the influence of a daily-averaged assumption, the calibrated model has been reconstructed with hourly-averaged values of river flows (both in the Wairoa and Wai-iti rivers). Furthermore, groundwater pumping has been represented assuming 80% of the daily average pumped volume (for all wells) is abstracted evenly between 6 am and 6 pm each day, and the remaining 20% is abstracted evenly between 6 pm and 6 am (at night). The modelled prediction of river flows at TDC's Nursery site on the Waimea River is provided in Figure 8.

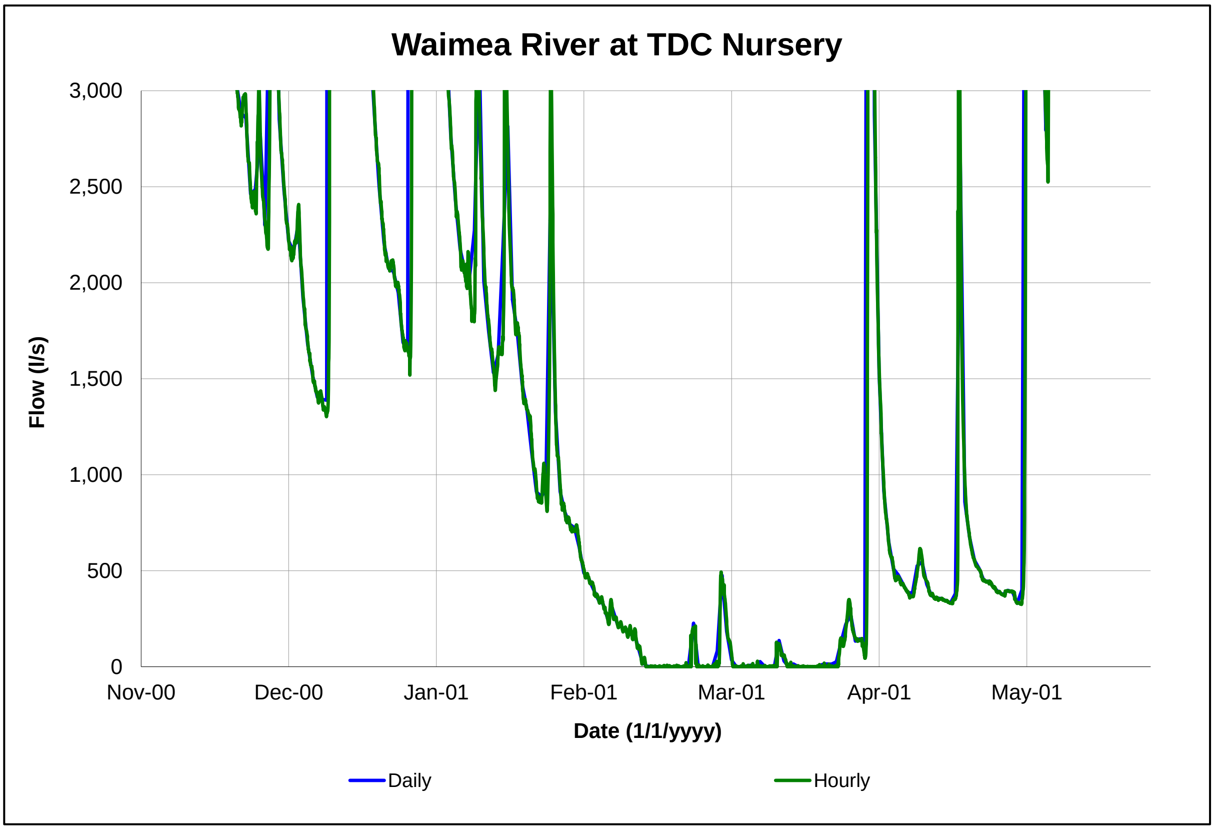


Figure 8: Modelled TDC Nursery site river flows comparing daily stresses with hourly river flows and diurnal groundwater pumping

Based on Figure 8, the predicted flows at TDC's Nursery site are very similar whether daily or hourly river flows are used, particularly during the low-flow periods when important management decision are being made. A few points to note:

- For the hourly model, WEIC surface water takes are still simulated as daily-averaged time series. Sub-daily data is not available for use. By and large, most of the groundwater use data are reported weekly (as a volume) and daily averages are implied from there.

- Land surface recharge is also simulated as daily-averaged time series. The groundwater system stores and buffers recharge, and anything less than daily values is smoothed through the groundwater system.

- Stream ecology and associated management are often assessed on daily average flows or 7-day flows (e.g. 7-day MALF). Consequently, a temporal resolution less than this is unusual in current water management based decision-making.

In Figure 9, the same diurnal pumping assumption has been applied to the WEIC river water take below Wairoa Gorge. The time-varying river flows propagate downstream to the Nursery site in the Waimea River. However, this level of river flow fluctuation is not seen in the recorded flows available at the TDC Nursery recorder site and therefore appears unrealistic.

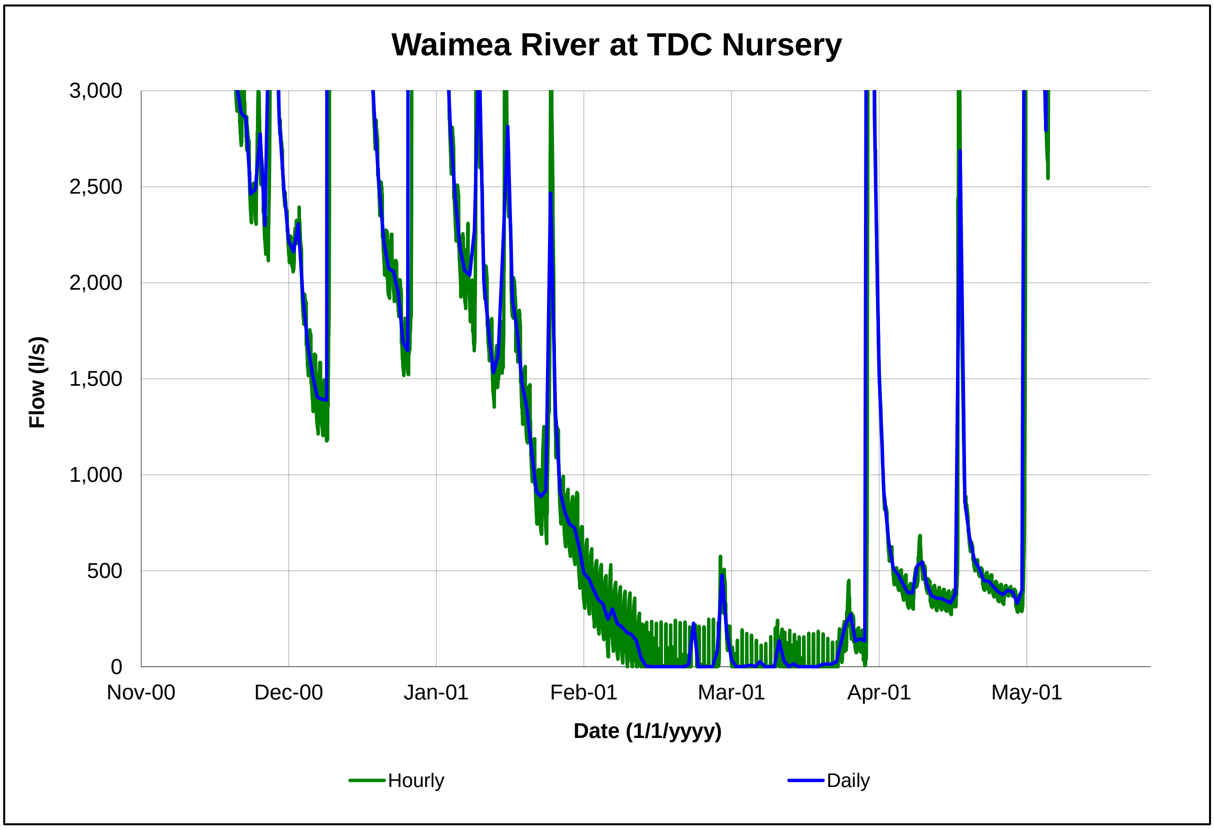


Figure 9: Modelled Nursery river flows comparing daily and hourly river flow stresses with diurnal groundwater and WEIC pumping

***A: Modelling sub-daily river flows does not noticeably affect the groundwater model's predictions, particularly for the extended stable, dry periods where water management is critical. No pumping data are available to test the effects of sub-daily values of groundwater abstraction, but due to the storing and buffering nature of the groundwater system, there is also likely to be an insignificant difference compared to the assumption of daily-averaged abstraction.***

***Q: Has the simplification of the relationship between gorge flow, groundwater pumping and downstream river flow (the 'Leong quadratic') affected the scheme design?***

Because the GNS' model was not able to be run by Tonkin and Taylor or in 'real time' for the design of the water augmentation scheme, results of modelled scenarios were used by David Leong of Tonkin and Taylor to develop an approximate relationship between Gorge river flow, plains pumping and downstream low flows at Nursery over 1982/83, 2000/01 and 2004/05. The so-called 'Leong quadratic' was then used to calculate what Gorge flow on average would be needed to achieve a targeted minimum flow downstream (e.g. 800 or 1,100 l/sec), as described in section 3.2 of Tonkin and Taylor (2009). This equation has only been applied for low flows as it gives quite erroneous results at higher flows, as pointed out by Mr Heath, and recognised by Mr Leong.

***A: As noted above, a minimum Wairoa River gorge flow of 3,077 l/sec (including provision for WEIC and future regional supply) as modelled in Table 18 of Hong and Zemansky (2009) was found in the more recent Aqualinc modelling to achieve a target minimum flow of***

***1,100 l/sec downstream. We agree that there will be considerable variability between summers of differences in flows between the gorge and further downstream. A more sophisticated management regime (perhaps an improved flow monitoring site downstream, or within-day adaptive management of flow releases) may be needed for day-to-day decisions on how much water to release from a water augmentation dam to achieve 1,100 l/sec downstream.***

### 6.3 Groundwater Flow Budgets

Groundwater flow budgets summarise the individual components of flows into and out of a model. These are helpful for two purposes:

- Firstly, they provide an indication of the flow accounting precision of the model, as a check that water is not being lost or created through the modelling process (inflows should equal outflows, and the difference is the budget error).
- Secondly, flow budgets tell us how the groundwater system rebalances as a result of changes in water use (e.g. increased pumping or augmented river flows).

***Q: What are the proportions of pumped water derived from river recharge versus groundwater storage with and without the dam?***

Table 3 presents a summary of the model groundwater flow budgets for the Calibration and Dam Release scenarios, averaged over the full model period.

Table 4 presents similar flow budgets but only for the dry period spanning 1 January to 31 March 2001. During this 3-month period, modelled average Wairoa River flow below the WEIC intake was 1,900 l/sec pre-dam compared with 3,200 l/sec with dam water release. The Dam Release scenario incorporates an increased river take by WEIC plus 300 l/sec for a future supply; therefore, the net dam release flow is 2,900 l/sec, an average increase of 1,000 l/sec.

Table 4 shows that of this extra 1,000 l/sec, some 544 l/sec (i.e. 2,734–2,190) infiltrates as additional recharge to groundwater with the remainder maintaining the minimum flow of 1,100 l/sec. Groundwater flows into Waimea Inlet and springflows reduce slightly in the Dam Release scenario, indicating that the additional groundwater pumping possible with the water augmentation also allows more depletion of groundwater storage while maintaining the desired minimum river flow.

Table 3: Average model flow budgets for the full simulation period

| **Flows (l/sec)** | **Storage** | **Groundwater pumping** | **Rivers** | **Springs** | **Boundary flows (e.g. off shore)** | **Land-surface recharge** | **Total** |
|---|---|---|---|---|---|---|---|
| | | | ***Calibration*** | | | | |
| **Inflows** | 1,329 | - | 2,375 | - | 552 | 1,319 | 5,575 |
| **Outflows** | 1,351 | 578 | 2,448 | 391 | 806 | - | 5,574 |
| **Inflow-outflow** | -22 | -578 | -73 | -391 | -254 | 1,319 | 1 |
| | | | ***Dam Release*** | | | | |
| **Inflows** | 1,090 | - | 2,455 | - | 604 | 1,319 | 5,468 |
| **Outflows** | 1,168 | 945 | 2,247 | 336 | 772 | - | 5,468 |
| **Inflow-outflow** | -78 | -945 | 208 | -336 | -168 | 1,319 | 0 |

Table 4: Average model flow budgets for the dry period 1 January-31 March 2001

| **Flows (l/sec)** | **Storage** | **Groundwater pumping** | **Rivers** | **Springs** | **Boundary flows (e.g. off shore)** | **Land-surface recharge** | **Total** |
|---|---|---|---|---|---|---|---|
| | | | ***Calibration*** | | | | |
| **Inflows** | 1,003 | - | 2,190 | - | 759 | 53 | 4,005 |
| **Outflows** | 182 | 1,165 | 1,932 | 193 | 535 | - | 4,007 |
| **Inflow-outflow** | 821 | -1,165 | 258 | -193 | 224 | 53 | -2 |
| | | | ***Dam Release*** | | | | |
| **Inflows** | 874 | - | 2,734 | - | 832 | 53 | 4,493 |
| **Outflows** | 179 | 2,017 | 1,641 | 168 | 487 | - | 4,492 |
| **Inflow-outflow** | 695 | -2,017 | 1,094 | -168 | 345 | 53 | 1 |

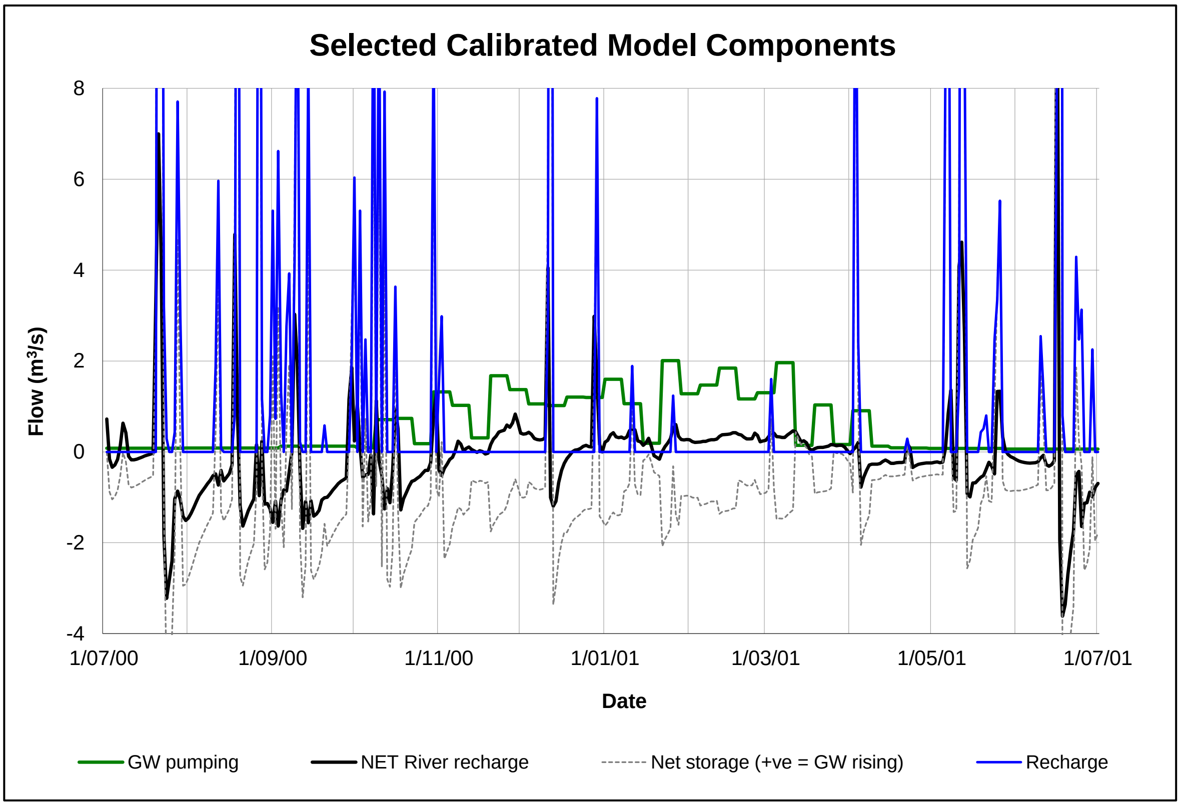
Further to the average model balances presented in Table 3 and Table 4, time series of selected model components are shown in Figure 10 for the calibrated model and in Figure 11 for the Dam Release scenario. Also included are time series of river flows and rainfall (model inputs[4] and outputs). These plots demonstrate that:

- Modelled groundwater pumping is variable over time, peaking at approximately 2 $m^3/s$ during the 2000/01 season under the calibrated scenario and approximately 2.7 $m^3/s$ under the Dam Release scenario.
- Groundwater storage closely follows river recharge. As river recharge increases, groundwater storage increases. An increase in groundwater storage equates to a rise in groundwater levels.
- Groundwater storage is also affected by groundwater abstraction; the greater the abstraction, the greater the reduction in groundwater storage (a lowering of groundwater levels), until it is replenished by a river fresh and/or rainfall.
- Groundwater abstraction is greater and temporally more variable under the Dam Release scenario compared to Calibration due to the inclusion of future water use.
- Net river recharge is larger under the Dam Release scenario (compared to Calibration) due to the increased river flows (during dry periods) and increased groundwater abstraction.
- River flows respond to rainfall.
- Nursery flows and gorge flows are correlated (they have similar responses to rainfall).
- Groundwater pumping reduces or turns off when there is sufficient rainfall (e.g. mid-January and mid-March).

Although not formally documented, Aqualinc has run a ‘no-pumping’ scenario that simulates no groundwater abstraction from the plains (all wells are turned off). This resulted in a lowest flow at the Nursery site of approximately 600 l/sec over the 2000/01 season, whereas it went dry with pumping. This demonstrates the effects of groundwater pumping on river flows.

---

[4] Rainfall is not a direct model input, but it is used to calculate land surface recharge, which is a model input.



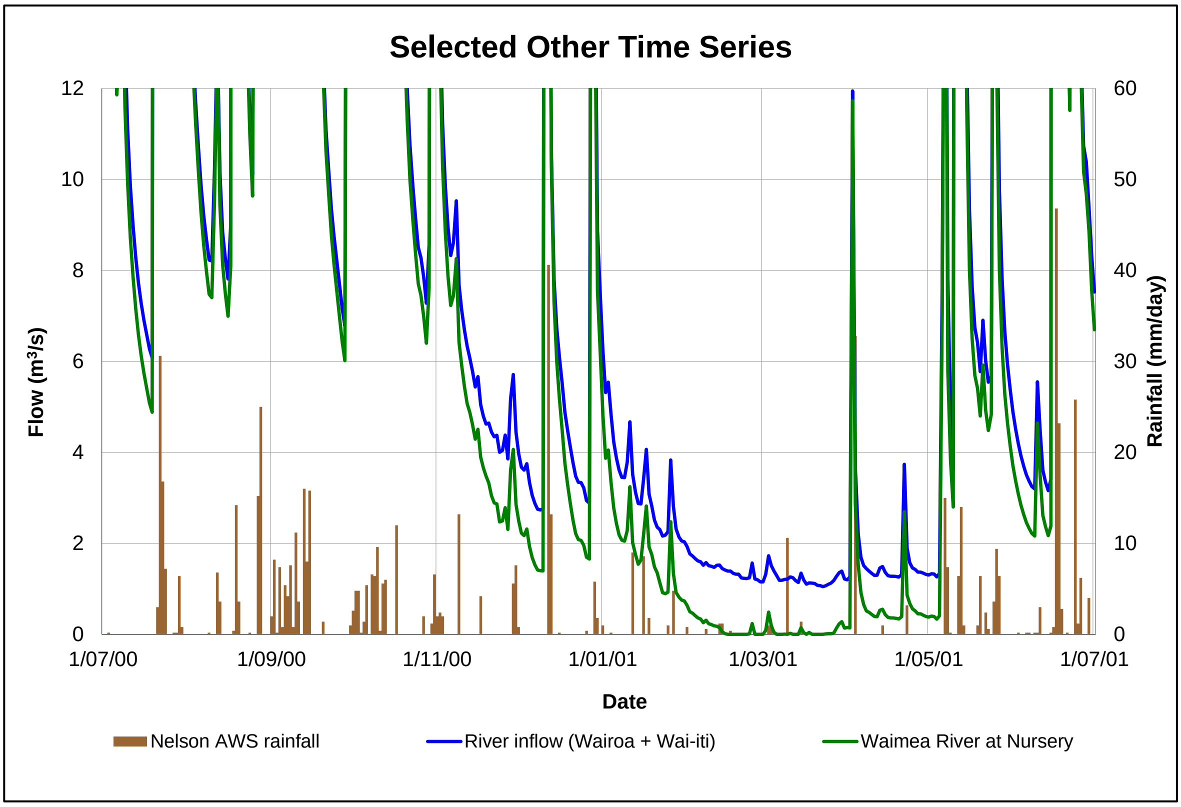
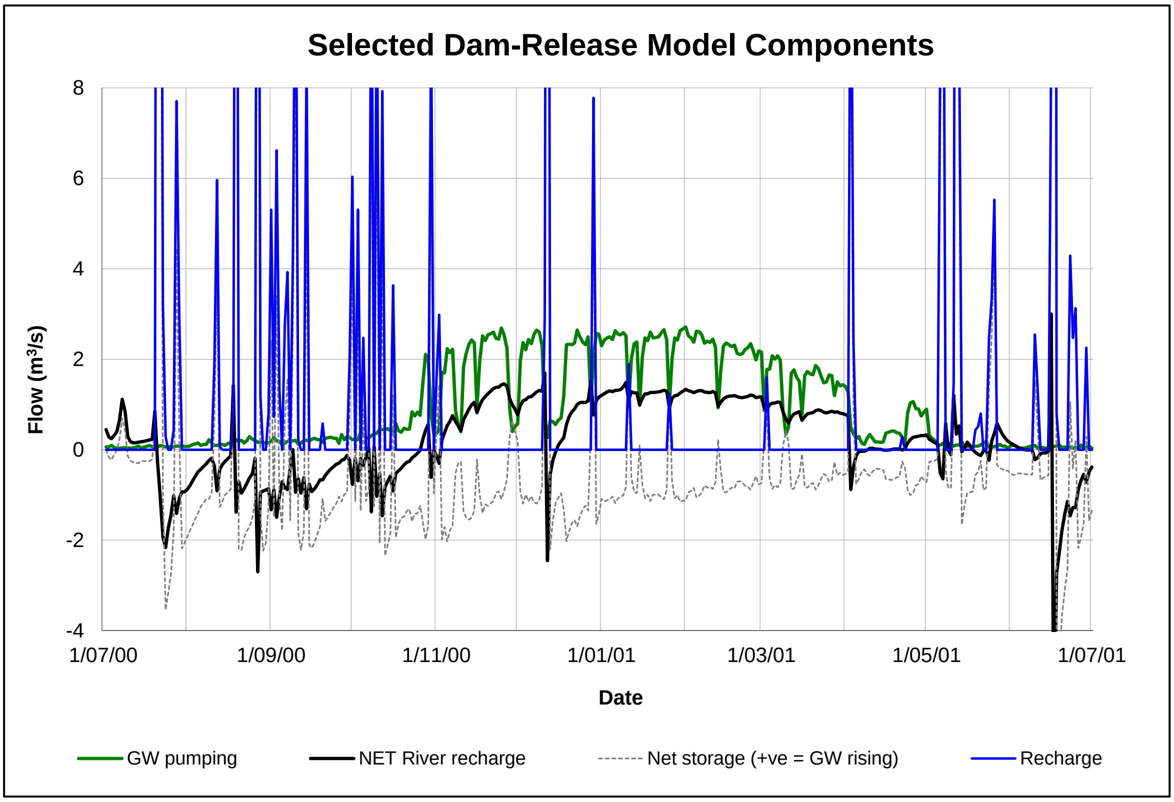


Figure 10: Time series of selected model components: Calibration scenario 2000/01



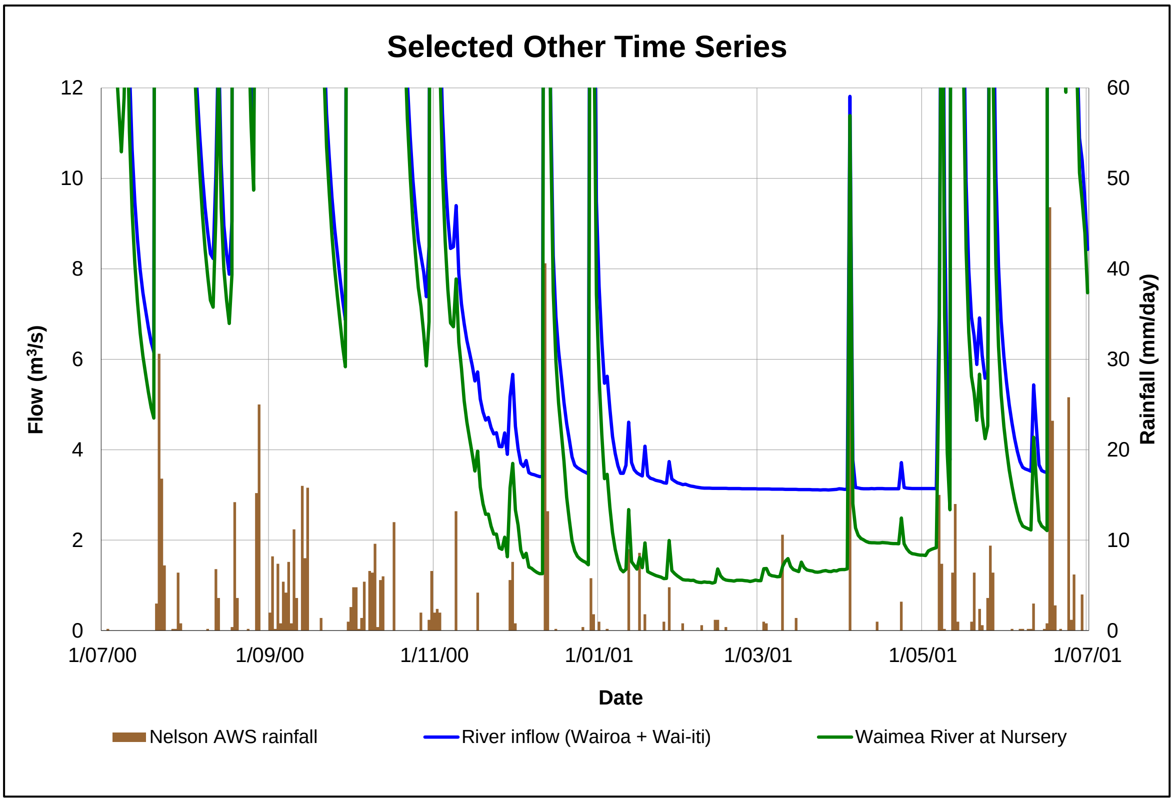


Figure 11: Time series of selected model components: Dam Release scenario 2000/01

From Figure 10 and 11, as pumping increases, groundwater storage depletes. During dry periods, much of the pumped water is sourced from storage (and groundwater levels drop as a result). Storage is replenished (groundwater levels rise) when groundwater inflows are greater than outflows (such as when a river fresh comes along or when pumping reduces or ceases).

***A: The proportion of pumped water taken from storage is variable. Much of the water is taken from storage during dry periods, and this is replenished when river freshes occur or pumping stops.***

***Q: How does modelled river recharge change with and without flow releases from the proposed dam?***

From Table 3 and 4, river recharge to groundwater increases as a result of the additional river flow released from the dam. Additional pumping is included in the Dam Release scenario. This additional pumping balances all of the additional river recharge and also results in a small reduction to springflows and offshore flow.

In both of these scenarios, the WEIC take has been removed from the Wairoa Gorge flow time series as the take occurs downstream of the river flow measurement site (Irvine's).

Modelled flows at TDC Nursery are presented in Figure 12 for both the calibrated model and the Dam Release scenario. A minimum river flow of 1,100 l/sec was targeted and this was achieved with a minimum Wairoa River gorge flow of 3,077 l/sec (before WEIC and future regional supplies are removed).

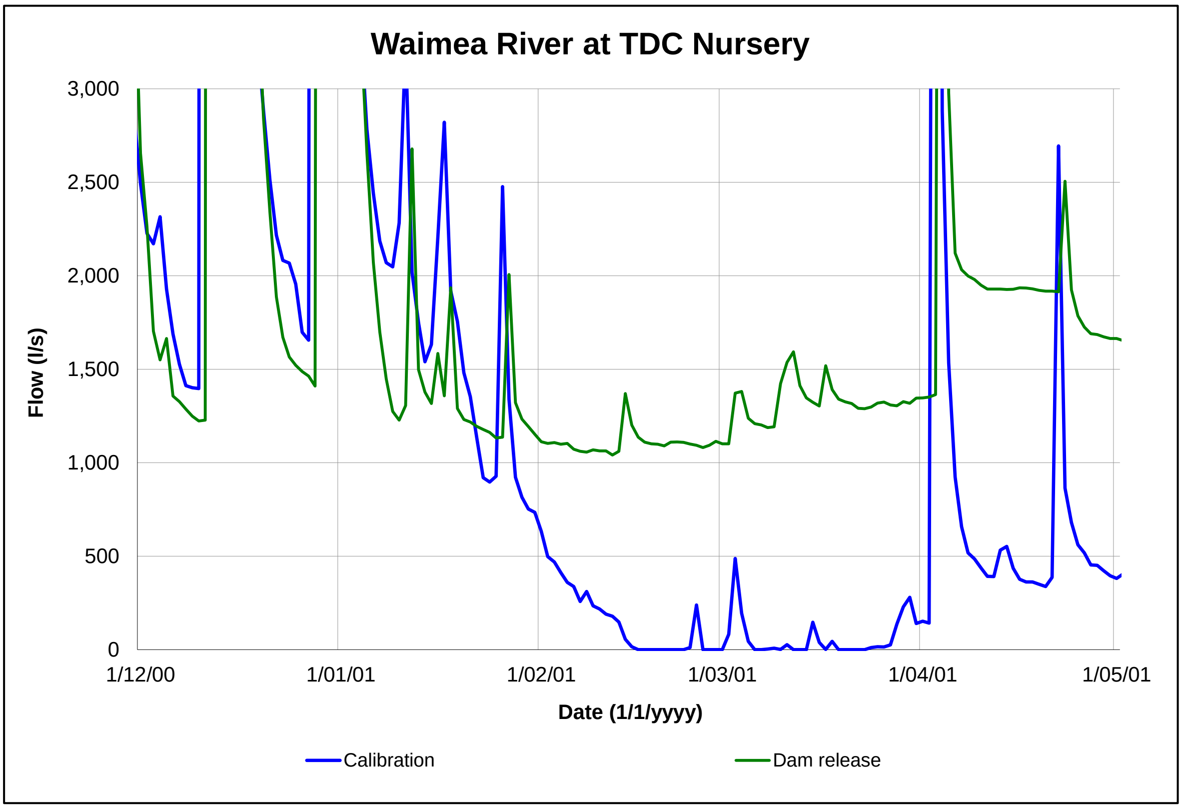


Figure 12: Modelled flows at Nursery for calibrated state and with dam flow releases

Comparing Table 3 and 4 with Figure 12 shows that while additional groundwater recharge is generated from the augmented river flows, a reasonable proportion of the additional flow remains in the river system and travels down to directly augment surface flows in the lower reaches. This additional surface flow mitigates the additional stream depletion effects from the extra groundwater pumping, and supplies a larger minimum river flow (improving aquatic habitat). Higher river flows also reduce the risk of seawater migrating upstream.

As can be seen in Figure 12, modelled flows over the dry summer period with the Dam Release are substantially higher than without. River flows under the Dam Release scenario are lower over December and January because natural flows at the Wairoa gorge are (by and large) greater than 3,077 l/sec and dam releases have been switched off. Lower flows then result from the additional stream depletion effects of the additional groundwater pumping simulated in the catchment, without mitigation from released water.

***A: When river flows are augmented from dam releases, recharge to groundwater increases. However, not all of the augmented water recharges groundwater; some remains in the river channel to increase downstream river flows directly and maintain the desired minimum flow.***

***Q: Is there a maximum recharge rate achievable from dam flow releases?***

Darcy's law states that the flow through porous media is a function of the driving head (hydraulic gradient) and the hydraulic conductivity of the media. Therefore, in theory, there is no upper limit to the amount of river recharge. However, there are practical limits driven by the range of flows that can be expected down the river and the associated stage height and wetted widths, and underlying groundwater levels.

At low flows, there is little hydraulic gradient able to drive substantial river recharge. However, when a fresh comes down the river, the stage height in the river rises sharply and this provides a pulse of river recharge. These freshes can contribute a significant volume of water into the groundwater system that replenishes groundwater storage and is then available for later abstraction and discharge to rivers. This is visible in Figure 10 where groundwater storage rises sharply as river freshes come through. Such freshes also explain (in part) the scatter observed in Figure 5.

If the proposed Lee Valley dam releases additional water to maintain a minimum flow of 1,100 l/sec, the river flows will be higher and so too will groundwater recharge. This is demonstrated in Figure 13, which compares modelled Wairoa River losses under the Calibration scenario (which is the same modelled data presented in Figure 4) with losses under the Dam Release scenario. River losses are larger while the dam releases water during low flow periods because river flows are higher. The target minimum flow of 1,100 l/sec is achieved with a minimum gorge flow of 3,077 l/sec at the Irvines recorder site, which reduces to approximately 2,730 l/sec after the WEIS take is removed; this is clearly visible on the plot with a range of river losses to groundwater of 40–430 l/sec occurring as a consequence of flow releases from dam releases. Additional groundwater pumping in the Dam Release scenario also means that losses at other non-low-flow periods are also different.

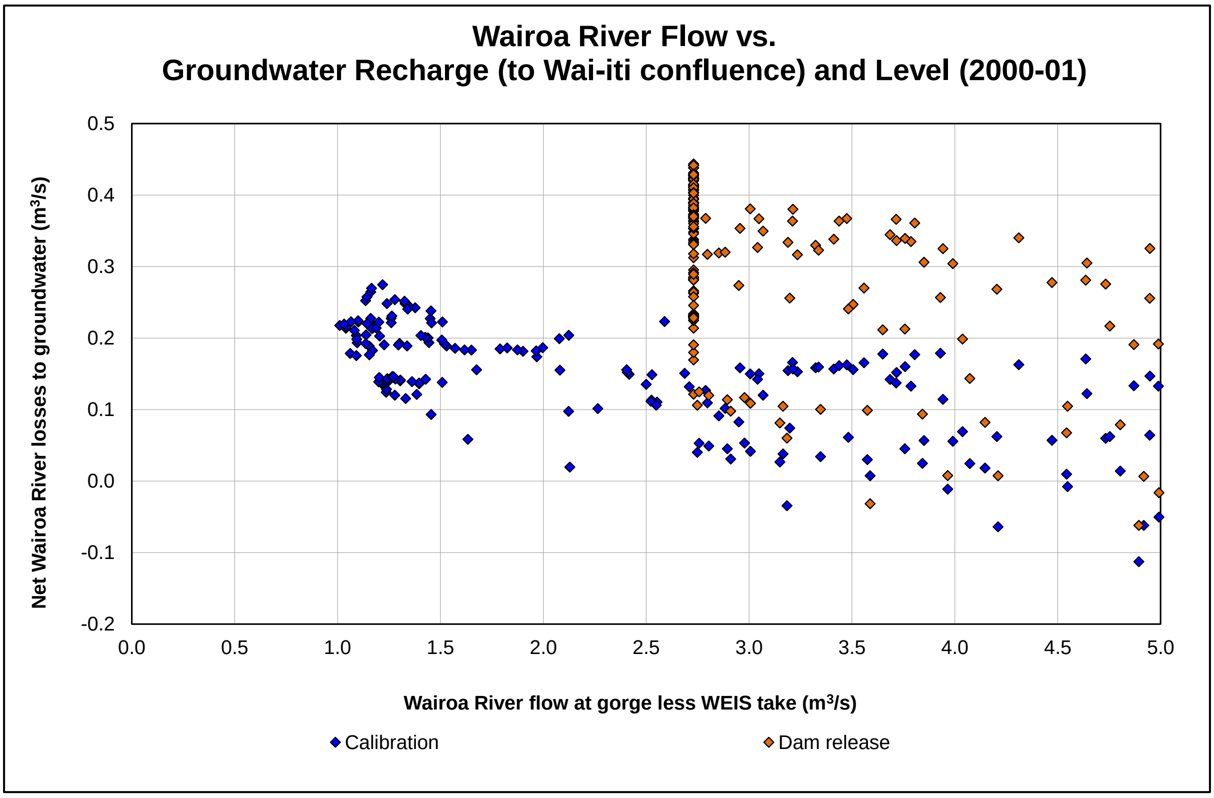


Figure 13: Modelled Wairoa River losses comparing Calibration and Dam Release scenarios

***A: The amount of water that can be infiltrated into the groundwater system is limited by the driving head between the river and groundwater and the ability of the groundwater system to receive the water. Larger river flows (as would be expected with augmented river flows) will result in increased river recharge.***

# 7 Potential contribution of weirs and pumped water distribution

## 7.1 Artificial enhancement of recharge by weirs

Many commentators have rightly pointed out that building rock weirs has the effect of raising groundwater levels. An important question is how significant is this benefit and are there disadvantages.

***Q: Can weirs be used to augment natural groundwater recharge from the rivers instead of the proposed dam?***

By way of background, we note that three rock weirs were installed by council in the Wai-iti River to enhance river recharge, and those weirs are still in place, one being visible immediately below the Brightwater Bridge over the Wai-iti River. In the 1980s the Nelson Catchment Board experimented with building a gravel weir in the Wairoa River near the SH6 bridge but that weir was washed away in a flood soon after monitoring of groundwater levels began. Riverbed levels in the Wairoa were reduced by scouring during the large January 1986 flood, which necessitated the building of the current rock weir below the WEIC intake at the gorge.

To test the effectiveness of weirs in the Wairoa and Waimea Rivers, the STR package in the calibrated groundwater model was adjusted to simulate the stage and wetted width changes that would likely be experienced by the installation of weirs in the rivers. Five weirs were simulated, located as shown in Figure 14.

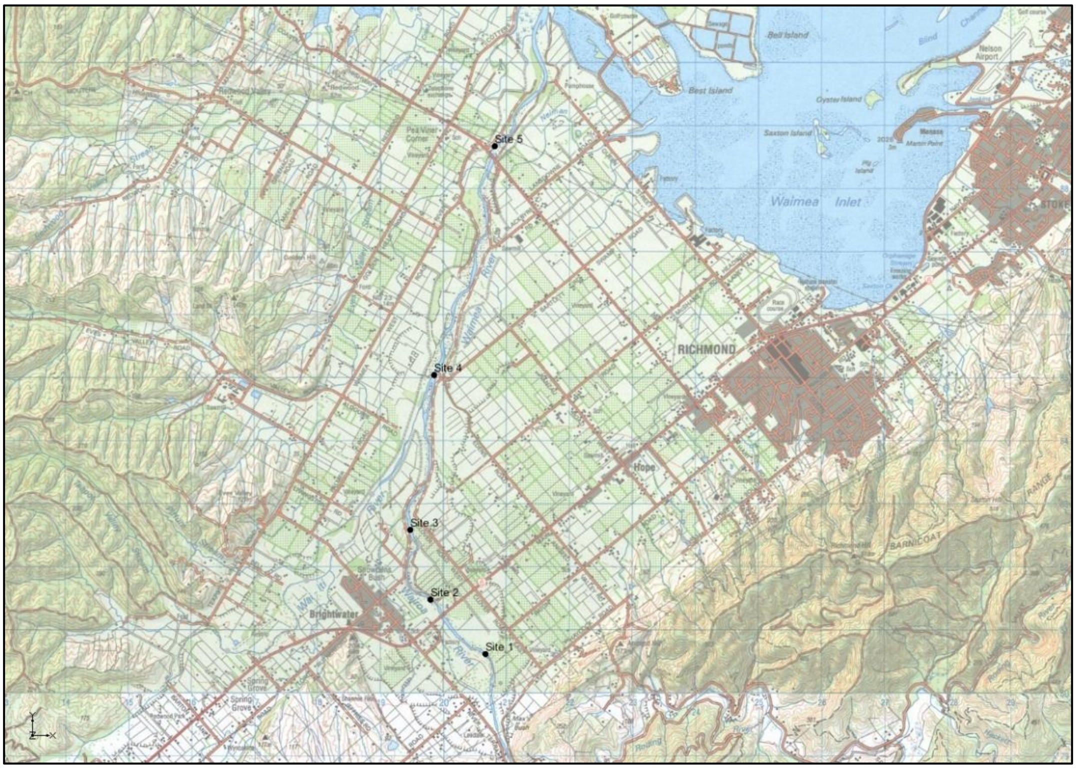


Figure 14: Locations of simulated weirs

At each location, the following simple assumptions were applied:

- Weirs at sites 1–4 have a 3-m simulated change in water stage; at site 5, a 1-m change was applied as the river grade is too flat for a 3-m weir.
- The river wetted width doubles.
- The water surface backs up approximately flat to where it intersects the natural river surface grade again.

This model was then run with and without dam releases. Figure 15 presents the net river recharge (for the full model domain) for both the calibrated model and the dam release model, comparing without weirs (the solid line) and with weirs (the dashed line). A very small increase is predicted due to the weirs, considerably less than the difference in recharge comparing Calibration and Dam release scenarios.

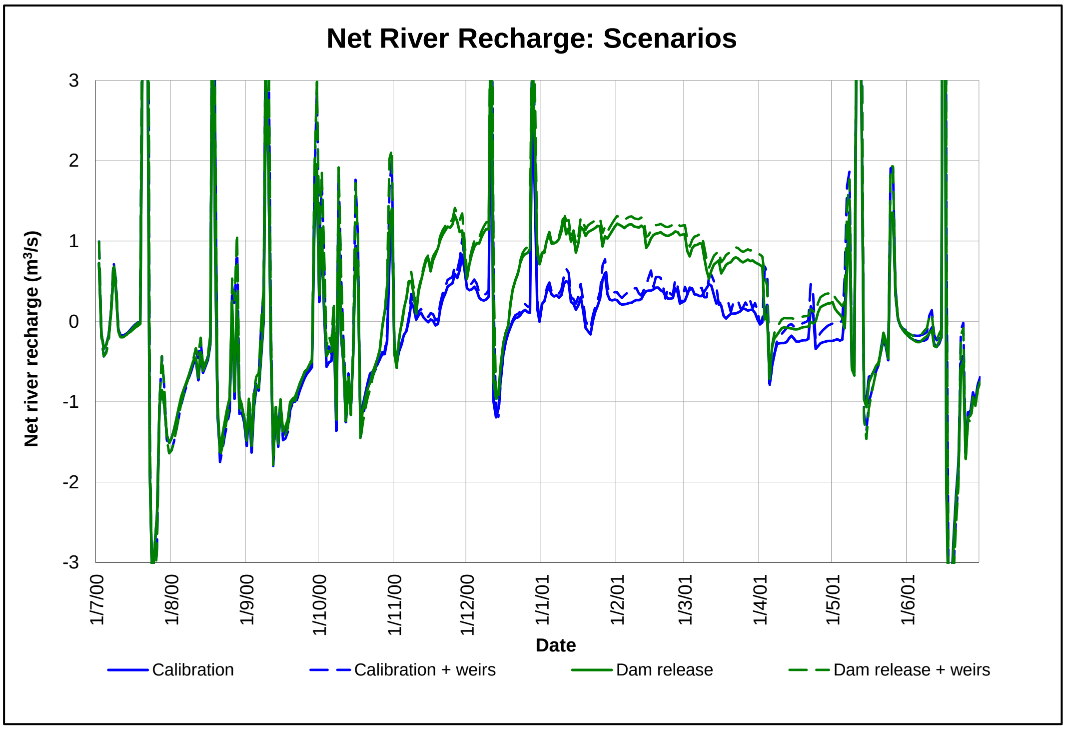


Figure 15: Net river recharge for various scenarios with and without weirs

The resulting change in river recharge to groundwater results in a change in groundwater levels. The difference for the Calibration scenario (with and without weirs) is mapped in Figure 16. Similarly, the difference under the Dam Release scenario is shown in Figure 17. Both of these figures present the modelled changes on 23 March 2001 to represent the extreme dry period where any benefit from the weirs is likely to be maximised. Little change is predicted at Site 5 due to the flatter nature of the river there and the necessary smaller weir height.

Groundwater level increases due to the weirs with and without the dam releases are similar, though the Dam Release scenario's is slightly larger due to the extra river flow available for recharge behind the weirs. Much of the groundwater level change is focussed within c. 1 km from the weirs. Average groundwater levels (over the full model period) at TDC's CW2 monitoring bore are predicted to increase by c. 0.2 m as a result of the weirs. However, a disadvantage of having weirs during periods when the river would have been dry is that the upstream weirs may deprive downstream reaches of flow earlier than no weirs are present.

Overall, based on this modelling, there is likely to be only a small additional and localised benefit from the installation of these weirs. Due to the local nature of the recharge, the additional volume of groundwater generated by the weirs provides little benefit beyond their immediate vicinity. Furthermore, without augmented river flows during low flows, upstream weirs may deprive flow from downstream reaches, drying the lower river sooner. Conversely, additional recharge from dam-released water is able to dissipate over a much larger area and provide benefit over most of the plains. This is demonstrated in Figure 44 of Hong and Zemansky (2009), which is reproduced in Figure 18.

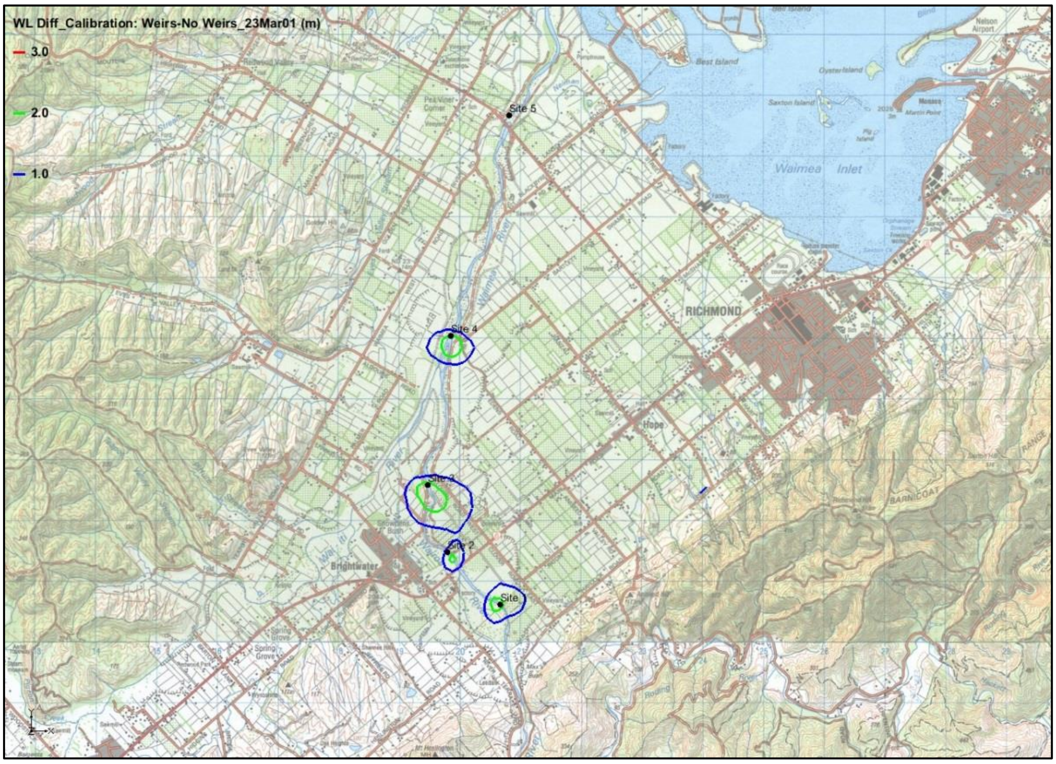


Figure 16: Groundwater level difference due to weirs: Calibration 23 March 2001

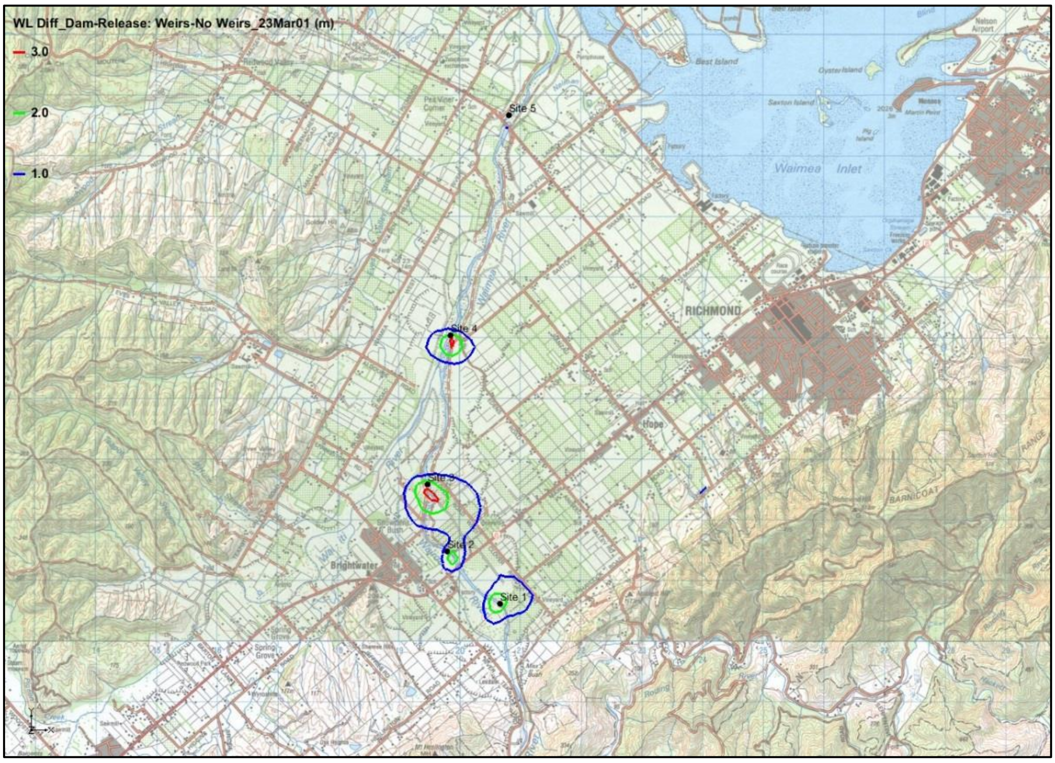


Figure 17: Groundwater level difference due to weirs: Dam Release 23 March 2001

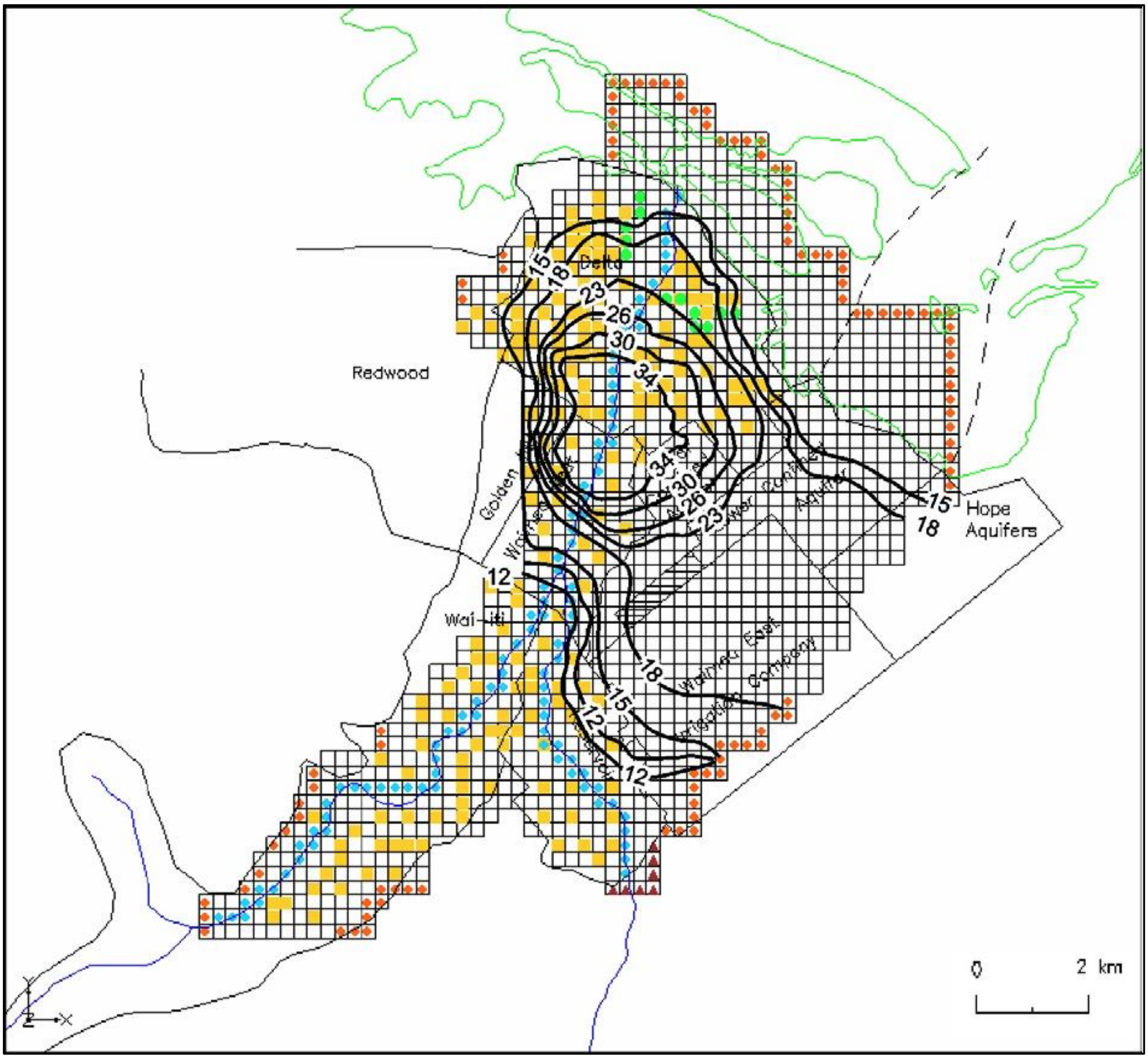


Figure 18: Groundwater level changes (cm) from dam-released water, reproduced from Hong & Zemanksy (2009)

***A: While weirs do increase the river recharge to groundwater other than in periods when the river is dry, their positive effect is likely to be limited to the vicinity of the weirs, and considerably less than the positive effects of augmented river flows. In addition, without augmented river flows during low flows, upstream weirs may deprive flow from downstream reaches, drying the lower river sooner.***

## 7.2 The Kainui Dam

***Q: Does TDC experience with Wai-iti's Kainui Dam give confidence the Lee Dam will work as intended?***

The response of the releases from the Wai-iti (or Kainui) Dam has been considered to provide a real-world example of flow augmentation on the Waimea Plains. This is provided in Figure 19.

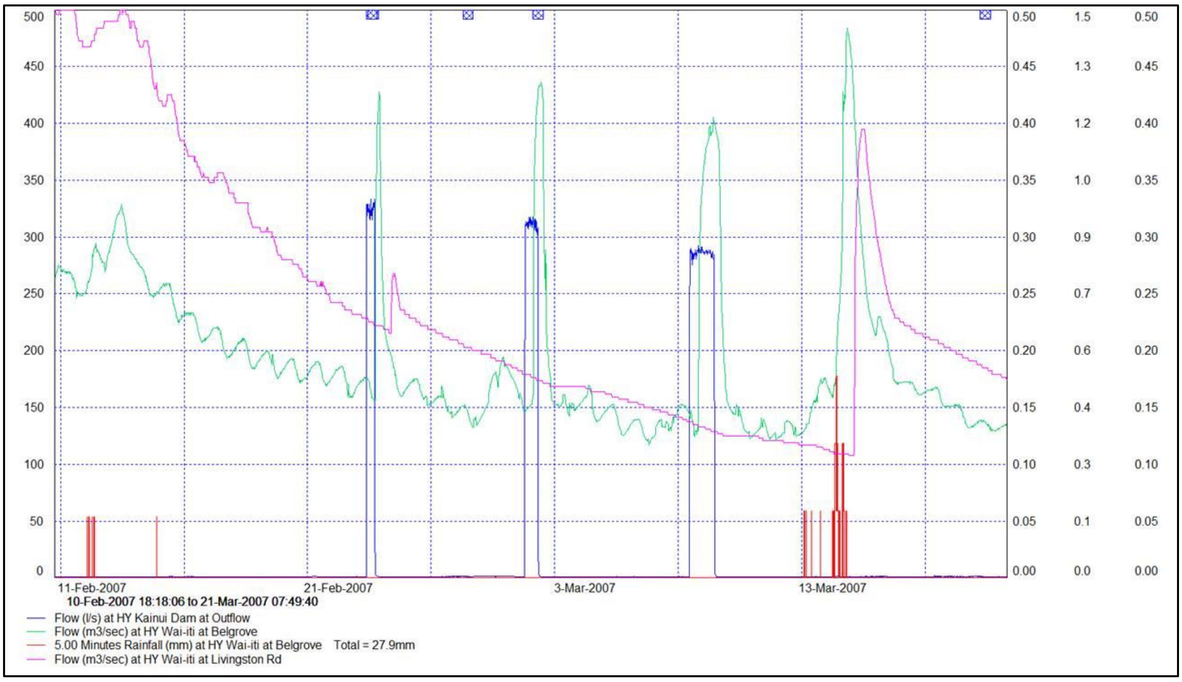


Figure 19: Measured Wai-iti dam releases and downstream responses

From Figure 19, a clear and immediate response is observed at the down-gradient Belgrove river site as the release is switched on and off. TDC staff try to maintain a flow of 100 l/sec at Livingston Road by releasing water from the dam during dry periods. When they achieve this, the river usually dries just below the bottom weir during dry periods. Prior to the dam, the river would normally go dry much further upstream of the weirs.

The primary purpose of this dam is to provide additional river flow and associated shallow groundwater recharge so that additional water can be taken from the riparian zone along the Wai-iti River during dry periods. Water is released from the dam when water permit holders need to take water. Many of the takes are from groundwater located within 20–100 m of the Wai-iti River. Water is not released specifically to augment groundwater, but to supply water for downstream takes. There have been few (or no) restrictions on water permit holders since the dam has been in operation, whereas prior to that there were severe restrictions during extreme dry periods.

Typically just enough water is released for the water permit holders' use; if there is insufficient water in the river to take, then the users let TDC know and a higher flow rate is released, if this is available. Water is not released sufficiently that the Wai-iti River remains flowing down to the Wairoa River confluence as this would run the dam dry quite quickly.

***A: The Wai-iti Dam is somewhat smaller than the proposed Lee Valley Dam, and designed for a more constrained purpose (riparian supply rather than catchment augmentation). However, it is clear from the little data available that releases from the dam do provide obvious and rapid responses in groundwater through increased river flows and recharge.***

### 7.3 'Zone of effect' of recharged groundwater, and how users can access water outside this zone

***Q: What is the safe storage available for extraction from the 'zone of effect'?***

Water released from a water augmentation dam will be available to meet downstream demands either via direct river pumping or from groundwater recharged by the increased river flows. The area experiencing the effects of the additional river recharge has been called the 'zone of effect'.

The zone of effect comprises the parts of the aquifers where increased river flow is predicted to raise the water table (or piezometric levels) of the aquifers, or which already have adequate well yields even if the water table is not projected to rise, or which have adequate reticulation to supply part of the projected water demand (for example, the Waimea East and Redwoods Valley irrigation schemes).

***A: The question of what 'safe storage' is available for extraction implies that pumped groundwater is taking only from aquifer storage and this storage does not replenish. The question would be better framed as 'what is the sustainable conjunctive water take from the aquifers and rivers?' The response is not a lump sum, because of the spatial variability of effects from (for example) taking water from one part of the plains (or aquifer) versus another. The groundwater modelling enables us to explore this spatial and temporal variability.***

***Q: Do water users realise that the benefits of groundwater recharge from dam releases won't extend right across the plains?***

It is correct that projected water demands to be met by the Waimea Community Dam do not take into account how the water would be provided to all the locations of those demands.

A small project was completed for WWAC to estimate the additional costs of distributing water to parts of the plains beyond the zone of effect (Fenemor & Bealing 2009). Those costs have not been included in the scheme costings and would be additional costs incurred by water users in those particular areas. This may well affect the viability of distributing water to those areas.

That project also estimated the costs of installing the five weirs modelled above, with weir costs ranging from $75,000 to $250,000 ($2009) depending on river width. It would certainly be desirable, in our opinion, to build weirs in conjunction with dam construction to maximise recharge of river flows to groundwater.

***A: It is correct that projected water demands to be met by the Waimea Community Dam do not take into account how the water would be provided to the locations of those demands.***

## 8 Acknowledgements

We acknowledge the constructive dialogue with Ron Heath and Murray Dawson during the peer review process, and thank them for the extensive analyses of the issues that they have provided. This acknowledgement does not however imply that they agree with all the findings.

Thanks also to Tasman District Council staff Joseph Thomas and Dennis Bush-King for providing relevant reports and information to enable the review, and to Lindsay Mackenzie for facilitating discussion of results with councillors and concerned citizens.

## 9 References

Aqualinc 2013. Waimea Plains groundwater flow model – results. Memorandum to Tasman District Council dated 26 June 2013.

Dicker MJI, Fenemor AD, Johnston MR 1992. Geology and groundwater resources of the Waimea Plains, Nelson. Geological Bulletin, DSIR Geology and Geophysics. 59 p.

Fenemor AD 1989. Groundwater modelling as a tool for water management: Waimea Plains, Nelson. Journal of Hydrology (New Zealand) 28(1): 17–31.

Fenemor AD 1988. A three-dimensional model for management of the Waimea Plains aquifers, Nelson. Publication No. 18 of DSIR Hydrology Centre. 133 p.

Fenemor AD, Bealing J 2009. Enhancing water distribution from the Waimea Water Augmentation Project. Landcare Research contract report LC0910/019 for the Waimea Water Augmentation Committee. 25 p.

Fenemor A, Green S, Dryden G, Samarasinghe O, Newsome P, Price R, Betts H, Lilburne L 2015. Crop production, profit and nutrient losses in relation to irrigation water allocation and reliability - Waimea Plains, Tasman District: final report. MPI Technical Paper No: 2015/36. Landcare Research. 65 p. http://www.mpi.govt.nz/document-vault/9899 (accessed September 2016).

GNS 2003. Effects of abstraction on groundwater levels and river flows in the Waimea Plains: modelling and management scenario simulations for droughts inclusive of various Waimea East Irrigation Scheme (WEIC) pumping scenarios. Prepared for Tasman District Council. Client report 2003/69.

Hong T 2000. Waimea Plains groundwater flow modelling with the STREAM package. GNS Client Report 2000/34 for TDC.

Hong T, Thomas J 2007. Groundwater-river interaction model and determination of water allocation limits in an average year for the Waimea Plains, Nelson. GNS Science Consultancy Report 2006/140 for Tasman District Council.

Hong T, Zemansky G 2009. Waimea water augmentation project feasibility study: phase 2 modelling report. GNS Science Consultancy Report 2008/185 for the Waimea Water Augmentation Committee.

Tonkin and Taylor 2009. Waimea water augmentation phase 2 – water resource investigations. Report to Waimea Water Augmentation Committee. 164 p.

White, P.A. 1997. A post-audit study of the Waimea Plains aquifer model. Institute of Geological & Nuclear Sciences science report 97/17. 91p.