Otago Regional Council

Hāwea Basin Groundwater Model & Allocation Review

Matt Dumont, Jens Rekker, and Zeb Ethridge

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Lincoln/Head Office

Lincoln Agritech Limited / Engineering Drive / Lincoln University
PO Box 69133 / Lincoln / Christchurch 7640 / New Zealand

P +64 3 325 3700 / F +64 3 325 3725

Hamilton/Regional Office

Ruakura Science Centre / East Street
Hamilton 3240 / New Zealand

P +64 7 858 4840

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DOCUMENT ACCEPTANCE

ACTION	NAME	SIGNED	DATE
Draft 1	Matt Dumont		**4 May 2023**
Review	Patrick Durney		**5 May 2023**
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EXECUTIVE SUMMARY

The Hāwea groundwater basin is an extensive and economically significant area of agricultural and residential land lying between the Upper Clutha Lakes and Central Otago basin landscapes. Groundwater is available in significant quantities from underlying glacial outwash aquifers and has become an increasingly important water resource for the district.

The main body of the groundwater system is bounded to the north by Lake Hāwea which provides substantial replenishment of groundwater, contributing up to 60% of flow in the system. The glacial gravels hosting groundwater are highly permeable and through-flow rates in parts of the groundwater system are very rapid as a consequence. The Hāwea River coursing down the western edge of the main body of the basin also exchanges water with the Hāwea Flat and Terrace aquifers. Land surface rainfall recharge, irrigation losses / recharge, range-front recharge and river recharge are also significant components of the groundwater basin water balance. The Hāwea River and Clutha River / Mata Au are the principal receptors of (up to 96%) groundwater outflow.

The Hāwea Basin has been modelled with the help of MODFLOW, PEST and MT3D-usgs as part of this study, including the use of time-series surface water level, groundwater level and flux records collected over many decades. The cornerstone of this transient modelling effort has been the multi-year groundwater level time series from seven bores (data from 2014 to 2020) used in calibration and optimisation of the ultimate model realisation.

This study has identified that the groundwater system is highly connected to Lake Hāwea, with the seasonal lake level variations propagating through the aquifer to the Clutha River. This study also found that a complex geological structure at the Lake Hāwea moraine is required to reproduce the observed groundwater levels in the recent high frequency monitoring data. The proposed geological structure predicts that if Lake Hāwea levels fell below a certain threshold value, the Hāwea groundwater system would become disconnected from the Lake. If the disconnect occurred for a long period of time, a large number of groundwater bore may run dry. This study was not able to identify the threshold value but suggests it is at an elevation between 326 m and 337 m msl.

A review of the allocation zones and the current allocation caps suggests:

1. The distinction between river proximal galleries and true groundwater abstraction should be better constrained. If all the river proximal bores in the Hāwea domain were to transition into the centre of the aquifer there would likely be significant groundwater impacts
2. Combining the current Hāwea Flat – Hill and Hāwea Flat – Lake zones into one Hāwea Flat zone should be considered as most of the zone shows evidence of a connection with Lake Hāwea.
3. Creating a new allocation zone (Grandview Zone) to the east of the inferred Grandview Fault. Because basement rock in this area may be upthrust and cause a disconnect from this portion of the aquifer and Lake Hāwea. The boundary for this zone is approximate, so we suggest a mechanism for potential water users to demonstrate that they fall in the Hāwea Flat zone.
4. Groundwater abstraction at current use levels is very likely to be sustainable assuming similar climate and Lake Hāwea management.
5. That if water users were to take their full allocation water levels, or if the full current allocation caps were issued, groundwater levels would fall significantly, but in most of the basin this decrease in groundwater levels is unlikely to cause problems with reliability for adequately penetrating bores. (see the exception below)
6. An exception to 5. is the Maungawera Valley, where if users took their full allocation significant groundwater level impacts are likely. Our modelling suggests a reduction to 60-70% of the current allocation is necessary to reduce the likelihood of impacts occurring to 5% or less.

1. INTRODUCTION AND BACKGROUND

1.1 Introduction

Otago Regional Council (ORC) has commissioned Lincoln Agritech Ltd to undertake the development of a groundwater conceptual model and numerical transient modelling of groundwater flow in the Hāwea Basin, Queenstown Lakes District. The sole substantive previous study of this type was a groundwater allocation review in the late 2000's. Interim reviews within the ORC resource science unit had identified deficiencies in the numerical approach supporting allocation recommendations, including the use of a steady state groundwater model to simulate seasonal irrigation pumping and a lack of certainty concerning the segmentation of the main basin into allocation zones. An update of the Hāwea Basin numerical model is required to support the determination of groundwater allocation limits and zonation as part of the proposed Otago Land & Water Regional Plan (pOLWRP) process, scheduled for notification in June 2023.

Hāwea Basin is within the Clutha / Mata Au Freshwater Management Unit (FMU) and straddles the Upper Clutha Lakes (including Lake Hāwea) and Dunstan rohe boundary. As such the basin lies at the confluence of the relatively abundant lake inflows, nationally significant hydro-electricity storage in the lake, irrigated farmland in the centre & south of the basin, tourism, and the high net value land uses in the form of intensive pastoralism and residential settlements. Managing the water resources of the Hāwea Basin and associated water bodies requires it to be informed by quantitative analysis and interpretation. Analysis of past and current groundwater dynamics derives substantial benefit from predictive groundwater computer modelling to test several alternate groundwater management proposals for their likely future consequences. This report details the preparation of a conceptual water resources model and transient groundwater numerical modelling of the Hāwea Basin, and the conclusions relevant to water allocation that could be drawn from model results.

1.2 Key Management Issues

The present management issues for the Hāwea Basin are similar to those at the time of the allocation review in 2011-12. These continue to be –

- Changing land use (from moderate intensity to high intensity) and changing water use arising,
- Competition for groundwater in pasture irrigation as the main alternative to the over-subscribed surface water race scheme,
- A growing number and density of un-serviced, rural residential or low-density residential land use in the Hāwea Flat locality, all needful of water supply from individual bores,
- Localised sensitive environments potentially affected by lower groundwater levels, and
- The operation of Lake Hāwea hydroelectricity storage behind the Hāwea Dam is influential on day-to-day water levels in the main Hāwea Flat and Hāwea High Terrace aquifers.

A newly revealed key management issue is that of the previously poorly delineated hydrogeological interaction between Lake Hāwea and the main basin aquifer. Through a combination of geological and hydrological factors, the groundwater from the lake must pass over an abrupt drop, potentially termed an "underground waterfall" before the groundwater at the foot of the "fall" continues onwards to feed the Hāwea Flat and High Terrace aquifers. This phenomenon had significant implications to the modelling methodology and had potentially important implications for the joint future management of lake and groundwater system.

1.3 Methodology

The highlights of the methodological approach to the current groundwater numerical modelling project include –

- Pre-processing water meter data of past water use rates and in-filling missing data,
- Calculating land surface recharge as a daily soil-moisture balance,
- Calculating hill creek recharge using estimates of hill catchment runoff based on historical flow correlations with the Lindis River at Lindis Peak,

- Calculating water race infiltrating groundwater recharge using loss rates as a proportional of transfer flow rate,
- Calculating groundwater extraction rates using a variety of methods to represent likely past and future groundwater pumping from irrigation bores,
- Special-purpose simulation of bore pumping effects on the two basin wetland complexes to highlight protection zones surrounding each wetland area,
- Surface water dominated bore pumping zones were also delineated to resolve issues of riparian galleries or river-proximal bore fields being used to pump primarily Hāwea River or Clutha / Mata Au river water as distinct from bores being used to pump water primarily from the available groundwater resource, and
- Scenario modelling to test various groundwater and bore pumping regimes for their effects on groundwater conditions in the Hāwea Basin allocation zones.

Model development also included extensive calibration parameter optimization using PEST software to develop the best set of numerical parameters for the groundwater system simulated within the groundwater numerical model. Calibration records of groundwater level were available for relatively restricted periods from 2017 to early 2021. Transient simulations were also run over longer periods in order to generate statistically significant synthetic data for the groundwater system under historic influences of lake level, river flow, hill creek recharge, and land surface recharge. This approach also allowed the generation of groundwater responses to climate or hydrological extremes.

1.4 Report and GitHub Repository Structure

1.4.1 Report Structure

This report is structured and written to convey the Hāwea Basin setting, principal methodological steps and main model results in the context of groundwater allocation review. This report has the following headline structure:

New Scientific Insights – The conceptualisation and preparation of a Current State Report had revealed several fresh scientific insights that deserved highlighting.

Groundwater Resource Development Model Methodology – The approaches taken in moving through the conceptualisation and structuring of the modelling project outline is covered in this section. The geology, hydrology and climate are described, alongside the approaches used to simplified and quantify these aspects of the Hāwea Basin.

Calibration & Optimisation – The outline approach to parameterising the succession of model realisations is described in this section. Most attention is focused on initial parameterisation and the pathway through optimisation to arrive at model providing good correlations between observations and model predictions.

Scenario Modelling – The scenarios specifically formulated for each allocation zone where modelling is undertaken is outlined in this section. The groundwater pumping scenario results in terms of groundwater levels predicted at different parts of each allocation zone are examined and used as a basis for informing potential choices around allocation limits.

Conclusions and Implications – The model project and the report are summarised with an emphasis on covering the aspects of the exercise relevant to the key management issues.

1.4.2 What is GitHub

Github is a widely used cloud-based storage system that works in conjunction with the open-source version control package git. We have used GitHub to host the repository for this model because it allows us to track changes, easily manage access, and provides a more robust and accessible point of access than many internal filesystems. Github also can render reStructuredText, which is the format we used to develop the various readme files in this repository. These files may also be downloaded and hosted locally, but any future changes to the model will not be updated.

1.4.3 Relationship to GitHub Repository

A key component of the modelling process is to allow future users to build on an existing model, improve it with additional data and constraints, and use it to answer novel and unexpected questions. To this end we have developed a detailed model repository which houses all the scripts that were used to develop and run the model as well as all the necessary data and the model results. This repository provides a wealth of information beyond what is typically available in a model report. The repository write up is tailored for a groundwater scientist with moderate experience in groundwater modelling, though some of the results can be understood and interpreted by a general hydrogeologist. Using the raw data and running the model would require familiarity with Python and flopy additional familiarity with NetCDF4, pickle, and HDF stores would be beneficial. The repository is currently hosted as a GIT repository on Github.com (https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model). The location of the final repository may change, but this report will be updated with the final location. If for some reason you are unable to access the model repository, please contact Matt Dumont (matt@komanawa.com) and he will be able to advise you on the best way to access the repo.

A distinct advantage of this process is that future modellers have the opportunity and mechanisms to create a fork (new working version that links back to the original model). If this fork is a significant improvement on the Hāwea model, then the fork can be added back to the model repository so that the repository contains the living model.

Rather than a traditional model report we have chosen to split the reporting process into two parts. This report includes a summary of the model development, parameterisation, optimisation, and model scenarios process as well as the key outcomes and recommendations. However much of the detailed methodology is housed in the model repository as readme files. The modelling process was broadly undertaken in the following steps; each step has its own readme document detailing its methodology and, where applicable, the results of the step:

1. Model build: build the model structure and boundary conditions (https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst).
2. Model targets: define the model targets and objective function (https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/targets_and_sensitive_sites/README.rst).
3. Model Parameterisation: define the initial model parameters and parameterisation (https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_parameterisation/README.rst).
4. Model Optimisation and limitations: optimise the model to the available data (https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/optimisation/README.rst).
5. Model Scenarios: run a series of scenarios to better understand the model behaviour and to predict the systems response to changing conditions (https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/Scenarios/README.rst).

We have included all these readme documents as an appendix to the model report so that the information is available should accessing the model repository become challenging. These appendices will not be included in the version of this report that is hosted in the model repository.

2. NEW SCIENTIFIC INSIGHTS

Our previous understanding of the Hāwea Basin groundwater system no longer matches the new information provided by time series groundwater monitoring and rigorous analysis. The salient insights highlighted by the analysis of new and previous information include the following –

- Conceptual structure of the Lake – Aquifer interface differs markedly from the previous representation of the relationship between the two water bodies and now includes the concept of an "underground waterfall",
- Existence of a "lake wave" of water level in response to hydro-electric management that propagates the length of the main Hāwea Basin,
- Low Lake Hāwea operating levels (lower than the current consented levels) may induce a precipitous decline in Hāwea Basin groundwater levels and hence the water resource,
- Fresh understanding of the importance of range-front creek inflow to the aquifers at the basement – outwash boundary throughout the main basin and off-shoots,
- Continued uncertainty as to the disposition of the Grandview Fault in the northeast of the basin and the fault's impact on aquifer connectivity,
- Fresh appraisal of the sensitivity of Butterfield and Campbell wetlands in the south of the main basin allows delineation of allocation exclusion zones, and
- The need to exclude near-river groundwater abstractions (galleries and riverbank bore-fields) from both allocation and numerical modelling framework.

2.1 Lake – Aquifer Interface

Comparison of the hydrographs (i.e., water level times series plots) of Lake Hāwea and the closest monitoring bore reveal a substantial and unexpected drop in the groundwater elevation into the aquifer. Figure 1 shows a comparison of water level elevation in Lake Hāwea and monitoring bore G40/0415 from 2 November 2017 to 31 December 2021. The pattern of water level fluctuation shows reasonable correspondence (R^2 = 0.7), however the offset in the mean water levels is almost 12 m, which is at odds with the monitoring bore (G40/0415) lying only 1,150 metres to the south of the closest lake shore, a hydraulic gradient of 1.1% (0.011 metres per metre). As the Hāwea Flat Aquifer in the general area has recorded transmissivities in the tens of thousands of square metres (m^2/d), including one determination 430 metres from G40/0415 of 30,000 m^2/d, the high hydraulic gradient seems unlikely. The quandary is compounded by the fact that were the lake boundary of low hydraulic conductivity, the water level fluctuations from the lake would be significantly attenuated whereas the fluctuations are substantially preserved between lake and monitoring bore.

An alternative and decidedly more plausible explanation for the phenomena is the existence of a subsurface low permeability rampart associated with the Hāwea terminal moraine and encompassed in downstream high permeability outwash sandy gravel. Indeed, such a setting was encountered in exploration and development of a public water supply from bores for Lake Hāwea Township (Edkins, 2012). Figure 2 shows an interpretative cross-section at the bore-field taken from bore logs and elevation measurements. There is a clear drop of almost 3 m in water level between the lake and the high transmissivity aquifer, plus the presence of a low permeability glacial till layer intervening between aquifer and lake.

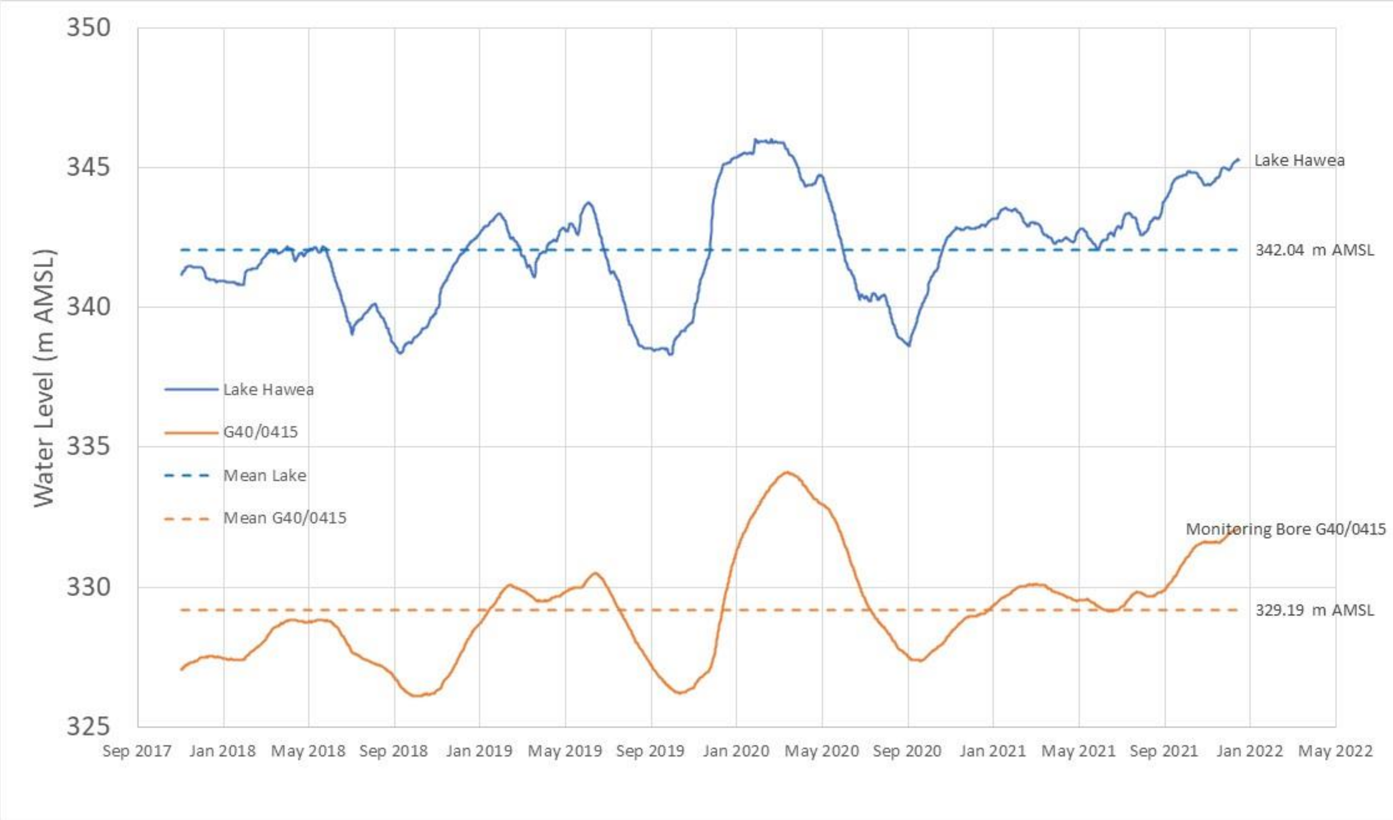

Figure 1: Comparison of water level elevation in Lake Hāwea and monitoring bore G40/0415 from 2 November 2017 to 31 December 2021

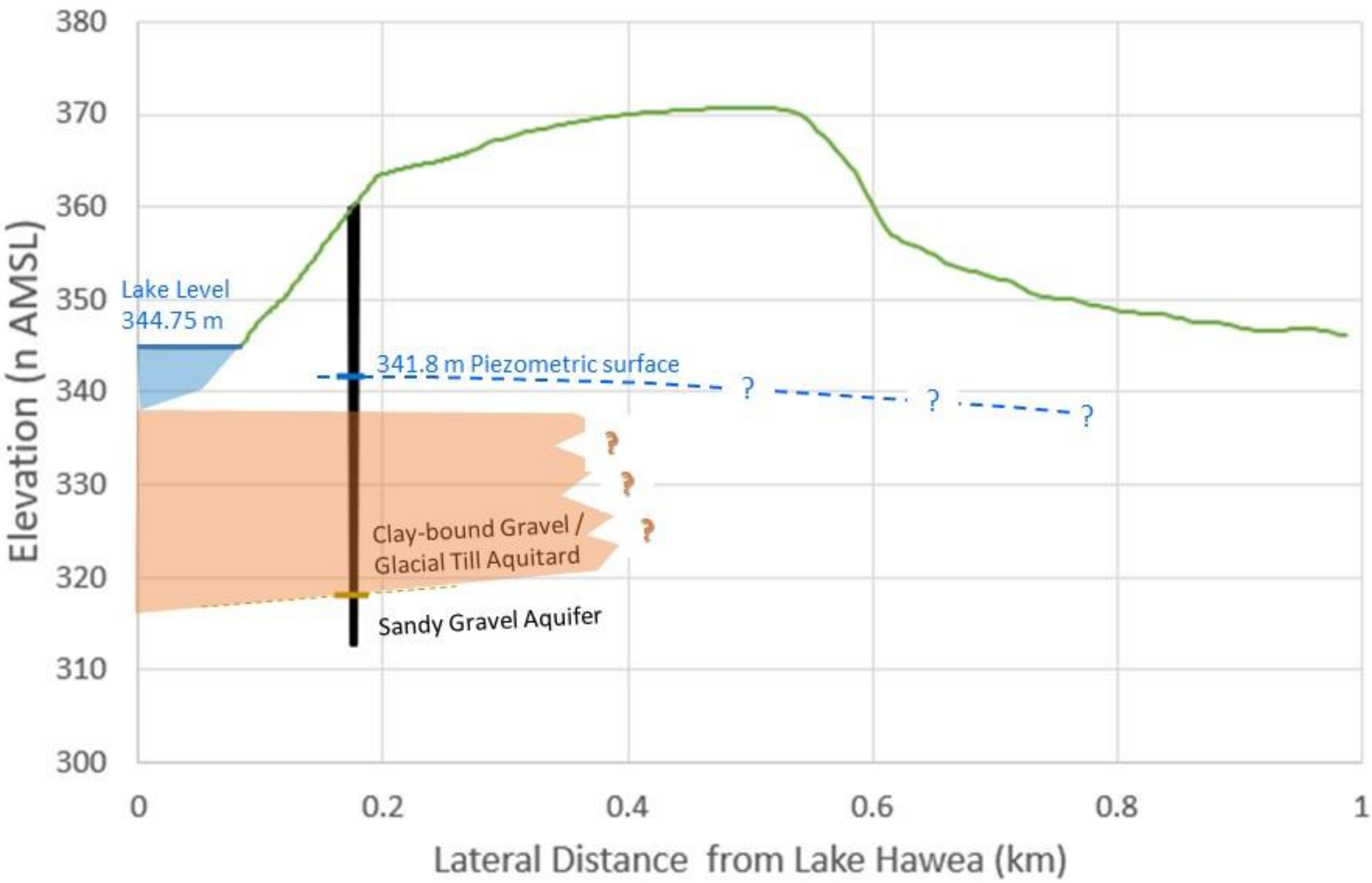

Figure 2: Interpretative cross-section drawn from data contained within Edkins (2012) at the QLDC bore-field at Lake Hāwea Township

Based on these and other inferences from independent observations along the lake margin, a conceptual model envisaging a low permeability core to the terminal moraine was developed. The concept is illustrated in Figure 3 as a north to south cross section of the lake, Hāwea terminal moraine and the downstream outwash Hāwea Flat Aquifer.

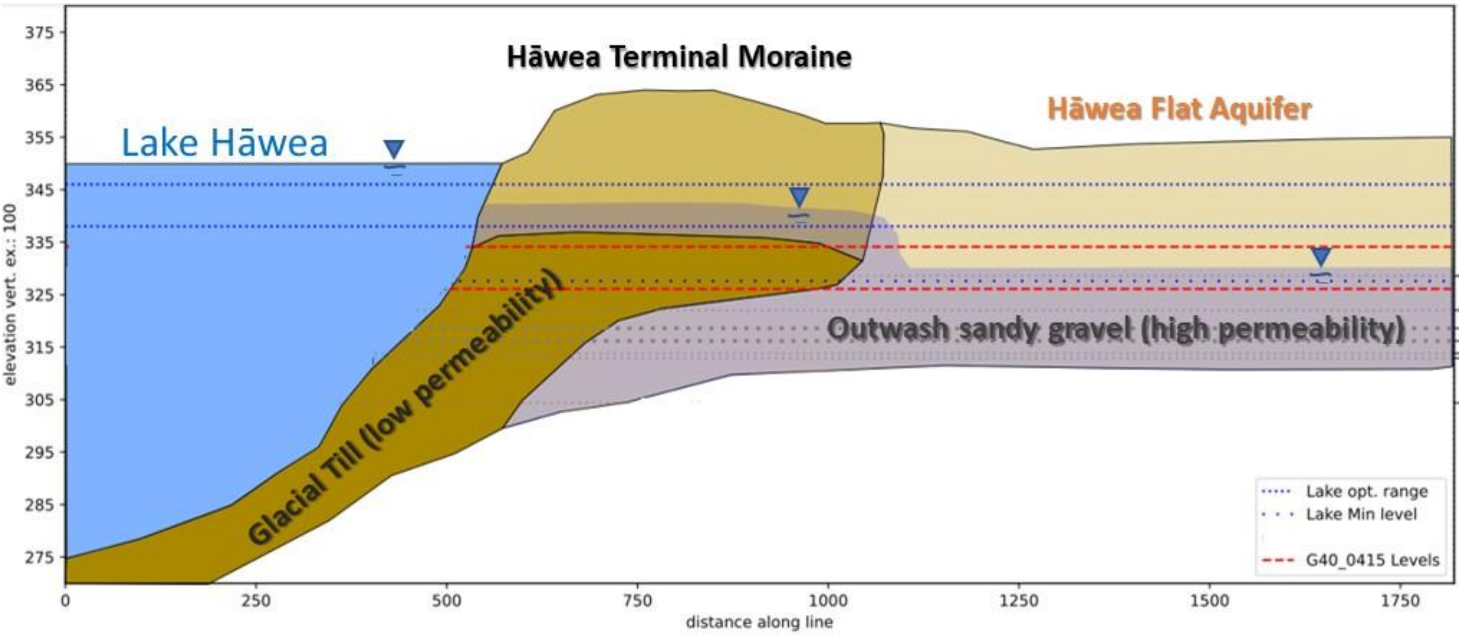

Figure 3: North to south cross section of Lake Hāwea, Hāwea terminal moraine and the downstream outwash Hāwea Flat Aquifer

The conceptual representation shows median lake water level lapping the permeable outwash gravel part of the shoreline above the till, inducing the southward flow of water over the berm until the southern edge of the till where a transition to the lower groundwater level would become established at the foot of the inferred drop. The phenomena outlined above was capable of being reproduced in the MODFLOW model transient simulations.

The conceptual structure detailed above has a key implication for groundwater management – at some elevation (e.g. the top of the low permeability sediments) the groundwater system will become disconnected from Lake Hāwea and groundwater levels will respond in a non-linear fashion. The precise elevation or spatial geometry for the top and bottom of low permeability glacial till is not possible to constrain with the available information. Based on anecdotal evidence from historic low lake levels, bore logs, and the transient record of groundwater levels in G40/0415, we believe that the low permeability sediments most likely have a base c. 320 m msl and a top between 327 – 337 m msl. A full discussion of possible geometries, supporting evidence, and model implementation is available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst#multi-layer-3d-model-structure

2.2 Lake Wave Phenomenon

Examination of the hydrographs of monitoring bores installed in the 2010s revealed signs of a water level wave correlated with highs and lows in Lake Hāwea and propagating southwards or generally down-gradient of the lake shore through the Hāwea Flat and High Terrace aquifers (see exerted hydrograph 2020 peaks in Figure 4). The height of water level magnitude changes little between Lake Hāwea (7.2 m) and the closest monitoring bore G40/0415 (6.7 m). However, 5.1 km down-gradient at Loach Street, Hāwea Flat settlement, the monitoring bore (G40/0367) manifested only 1.7 m rise due to the lake. Even at the opposite side of the High Terrace Aquifer and measured in monitoring bore G40/0366 a rise of 0.9 m was still perceptible in the late summer of 2020. The propagation of the 2020 level wave was also lagged by 25 days, 75 days, and 175 days between the lake, bore G40/0415, bore G40/0367 (Hāwea Flat) and bore G40/0366 (Campbell Wetland), respectively (Figure 4).

The regularity and magnitude of peaks and troughs in Lake Hāwea level is related to its management as a hydro-electric storage reservoir for the Clutha River (Mata Au) hydro-electric scheme that generates electricity at Clyde and Roxburgh power stations, lying further downstream. That water storage is intentionally depleted over the winter to generate maximum power, typically resulting in the year's lowest level in early spring. The lag in the passage of the lake wave might result in the seasonal low groundwater level arriving at Hāwea Flat rural residential area in late November in a typical year. Late November can see the beginning of high rates of groundwater irrigation bore pumping, so competitive drawdown or generalised water table lowering may in these circumstances combine with the depressed groundwater levels to accentuate these effects on bore water levels in the locality.

The transient MODFLOW model developed as part of this study was capable of reproducing the "lake wave" from historic input data with reasonable precision.

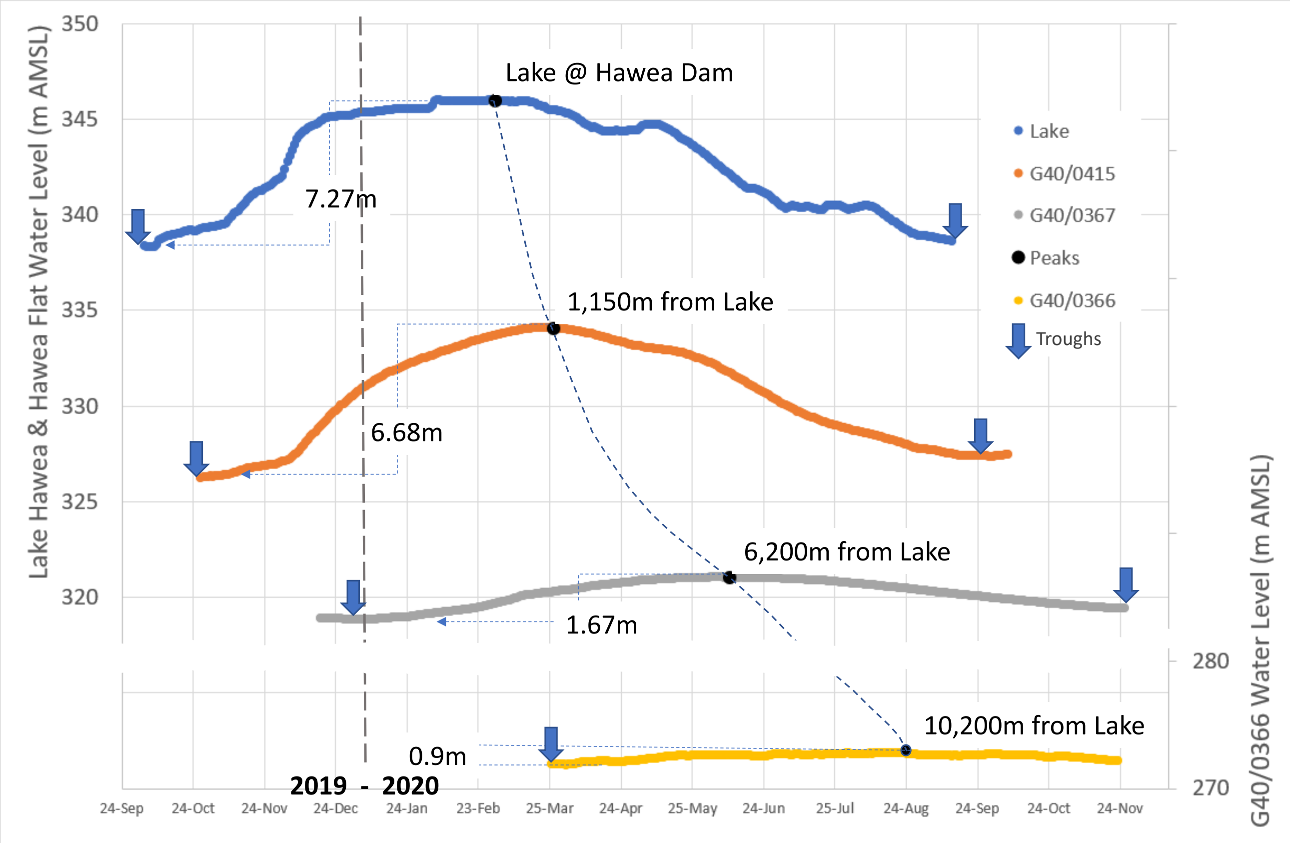

Figure 4: Indications of the progression of the "lake wave" southwards and down-gradient through Hāwea Flat and High Terrace aquifers

2.3 Hill Creek Catchment Inflows

The Wilson (2012) modelling project realised the importance of hillside creeks to the water balance of the Hāwea Basin aquifers due to the tendency of creek flow to accrue over the schist and semi—schist parts of the creeks until the creek course flowed out onto the outwash gravels. Flow tends to be entirely lost to the ground and provide recharge for the underlying aquifer. The main Grandview Range hillside creeks are Grandview Creek, Reservoir Creek, Patterson Creek, Dalton Gully, and Lagoon Creek. Grandview Creek and Lagoon Creek have had flow monitoring sites installed for almost four years. While the flow record is fragmented and partial in most of those years, approximate estimates of mean, median and $MALF_{7d}$ are listed in Table 1, including a common specific $MALF_{7d}$ (in litres per second per square kilometre).

To better estimate the hill creek catchment flows the catchment area of each tributary creek was estimated using the python package Pysheds. The daily flows in Lindis River (which forms a watershed with the Grandview Range), Lagoon Creek and Grandview Creek were area normalised and $MALF_{7d}$ statistics generated. Logarithmic regressions of the MALF versus catchment area were also generated. Following this, multiple linear regressions were undertaken and most suitable regression was used to predict daily flow rates from September 1976 to March 2021. These synthetic daily flow rates were used to simulate hillside creek catchment recharge to the closest part of the groundwater system. More information on the modelling of the hillside creek inflows is available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst#hillside-stream-inflows-hillside-inflows

Table 1: Grandview Range tributaries hydrological flow statistics from ORC flow data

	Area (km^2)	Record Length (years)	Mean (L/s)	Median (L/s)	Minimum (L/s)	Naturalised * $MALF_{7d}$ (L/s)	Specific $MALF_{7d}$ ($L/s/km^2$)
Grandview Creek at LHS	11.5	4	95	65	2	20¥	1.7
Lagoon Creek at GVS	9	4	35	25	5	15¥	1.7

Note: * Upstream water takes minor in terms of quantity taken. ¥ Short flow record with gaps, including one of 102 days. Note also, flow record is only four years when the minimum statistical significance is five years, and gaps are present in the records (Mar-May 2019 at Grandview Creek; and Apr – Jul 2020 at Lagoon Creek). LHS = Lake Hāwea Station. GVS = Grandview Station.

Long-term and discrete period hillside creek flow inputs were generated for each significant hillside creek entering the basin along the main basin, Sandy Point Te Awa, Maungawera Flat or Maungawera Valley sub-basins. The more complex Grandview Creek and John Creek boundary conditions have been implemented as linear STR stream boundaries in MODFLOW. This recognised the tendency for longitudinal flow to extend along intermittent water courses sometimes as far as Lake Hāwea. A further 20 hillside creeks form simulated boundary conditions using the MODFLOW WEL boundary package, placing a set of 9 WEL cells per creek at the basement – aquifer contact (Figure 5).

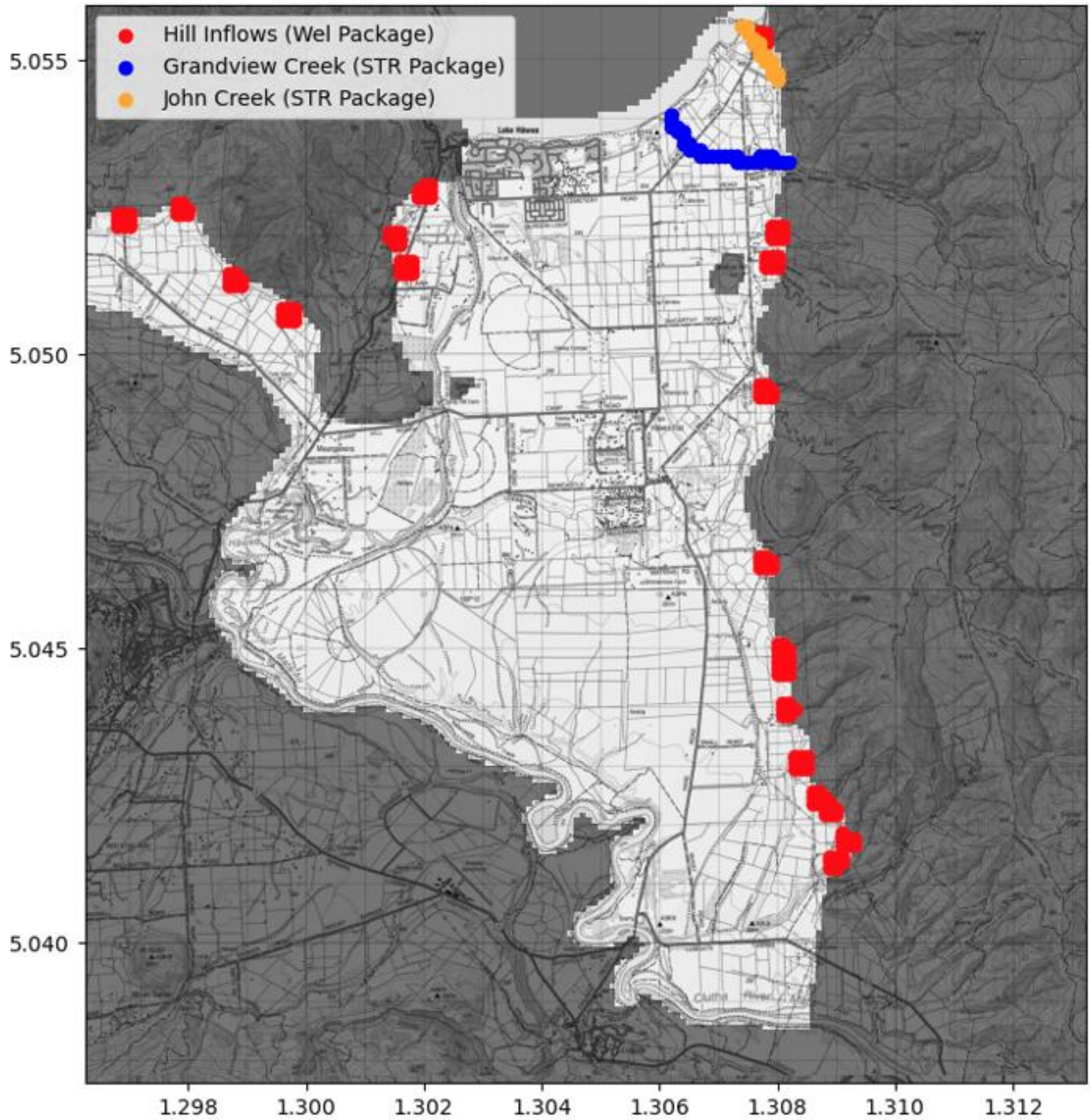

Figure 5: Mapping of model simulated stream (STR) boundaries for Grandview and John creeks, plus simpler creek injection (WEL) boundaries

2.4 Butterfield & Campbell Wetland – Groundwater Allocation Questions

Wetland and wetland remnants have hydrological 'bottom-lines' by merit of the National Policy Statement for Freshwater of 2020 (NPS-FM 2020). The two identified wetlands on lower terraces on the edge of the Hāwea main basin are Butterfield Wetland opposite the Alberttown camping area and the Campbell pond and fringing wetlands in the Campbell reserve in the south of the basin and adjacent to the Clutha River / Mata Au. Both wetland areas owe their hydrology to groundwater seepage or springs. For instance, simultaneous monitoring of the Campbell Wetland and adjacent groundwater found almost complete correspondence, while visible springs feed the wetlands at Butterfields.

Consideration was given whether the wetland areas would be better protected by setting them as special criteria in model scenarios used in setting zone groundwater allocation, or by special localised assessment measures. Both approaches were employed and assessed using the MODFLOW transient model.

2.5 Near-River and Wholly-Aquifer Groundwater Takes

The Hāwea Basin contained several examples of large, near-river water takes from bores or galleries. The markedly high transmissivity and stiff groundwater gradient from the aquifers into rivers meant that conventional means of differentiating water takes drawn predominantly from surface water from those drawn predominantly the core aquifer are of less value. The distinction assumed greater importance because of the established practice in the Hāwea Basin of utilising groundwater pumped adjacent to the main rivers, Hāwea River or Clutha River / Mata Au and transferring by pipeline onto the High Terrace for spray irrigation of pasture under pivot irrigators. Figure 6 maps the distribution of the identified near-river groundwater takes, including their magnitude. The counterpart to Figure 6 is Figure 7, which maps the aquifer-depleting groundwater takes. This suggests six large capacity groundwater takes at the Hāwea River bend downstream of Camphill hydrological monitoring site on the Devon Dairies property, plus a further two to three takes on the Clutha River / Mata Au at Campbell Reserve. The aquifer-depleting groundwater takes shown in Figure 7 are generally smaller and more evenly distributed across the model domain.

These near-river takes are considered to be largely river-depleting rather than aquifer-depleting. Their presence in the transient model causes extensive model cell drying, which is inconsistent with the understanding of the system. It was decided to separate consideration of near-river and genuinely aquifer water takes. Only the genuinely aquifer water takes were included in the MODFLOW model. However, these near-river water takes will require explicit quantification and effects assessment within any future review of the Clutha Catchment / Mata Au main stem rivers' allocation settings.

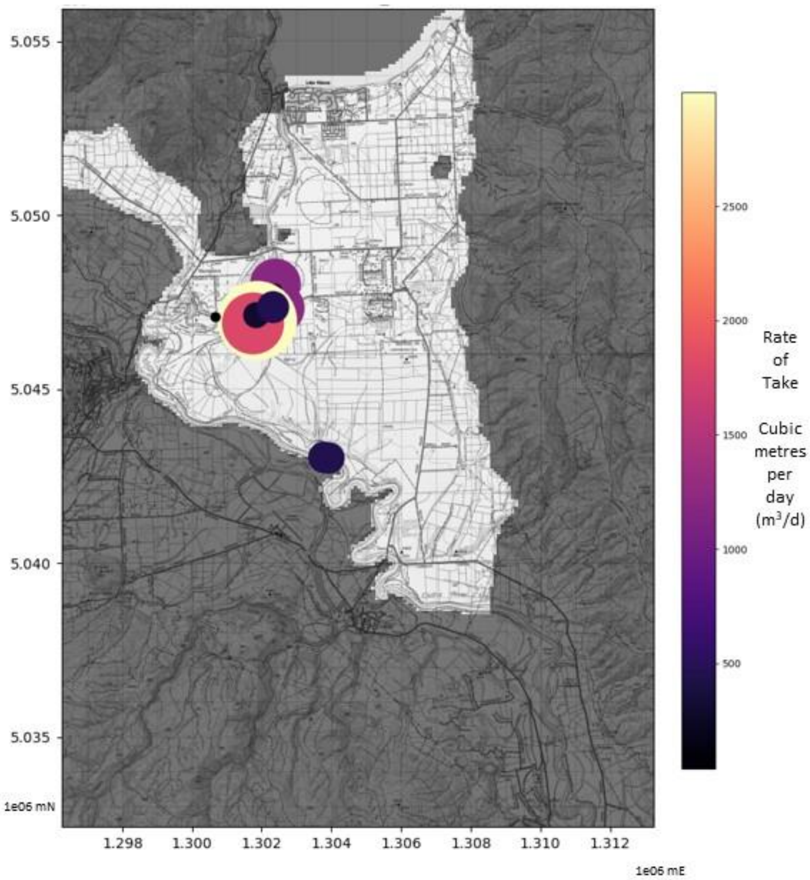

Figure 6: Location and magnitude of near-river groundwater takes adjacent to Hāwea River and Clutha River / Mata Au

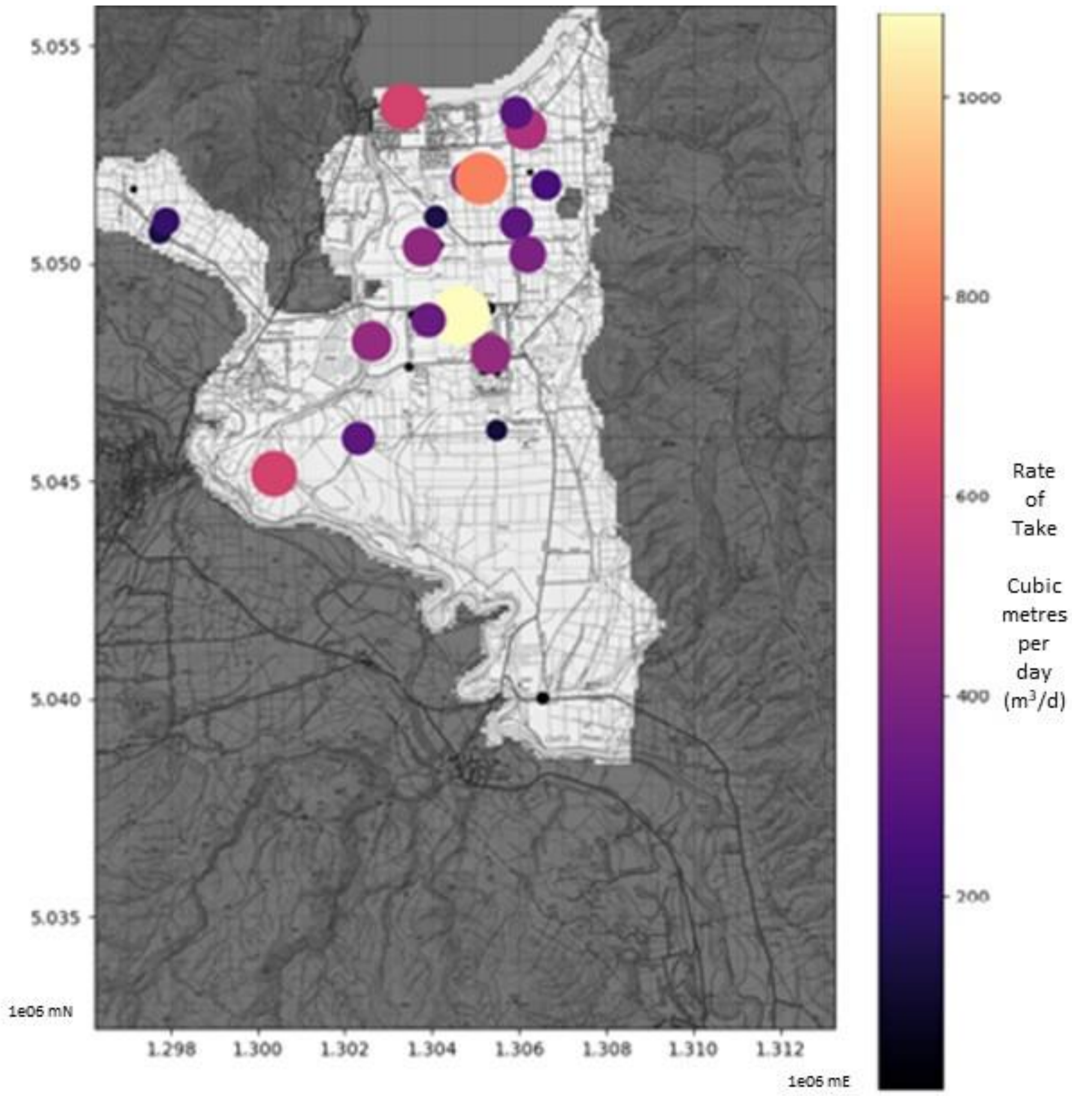

Figure 7: Location and magnitude of aquifer-depleting groundwater takes within the Hāwea Basin

3. GROUNDWATER RESOURCE DEVELOPMENT MODEL METHODOLOGY

3.1 Current State Characterisation

These aspects of reporting have largely been covered in a stand-alone report titled "Hāwea Basin Current State Review, 7 March 2022". The concluding comments from the Current State Report are repeated below in outlining the current state characterisation in March 2022.

3.1.1 Land Use & Irrigation Trends

There have been significant increases in land use intensity in the Hāwea Flat, High Terrace and Sandy Point and land units within the basin. Irrigated grazing is the norm in these areas, outside of the growing residential and rural resident zones at Lake Hāwea and Hāwea Flat. Irrigation continues to transition to more efficient spray methods, though a few pockets of border dyke and flood irrigation remain.

3.1.2 Mixed Land Uses, Water Requirements & Conflicts

There are signs of increasing competition for groundwater rights arising from the closure of four groundwater allocation zones. The lake fed irrigation supply is at full capacity and the shortfall is being made up by groundwater supplies on an individual basis. The Lake Hāwea township is fully reticulated with pressurised groundwater pumped from the aquifer directly adjacent to Lake Hāwea. In contrast, the rural residential community of Hāwea Flat obtains water supplies exclusively from individual water bores drawing on the Hāwea Flat Aquifer. Contact Energy manages Lake Hāwea as a nationally significant, renewable energy storage for downstream hydroelectricity generation.

These juxtapositions of land use, water and the requirements held for each holds sources of potential conflict(s). For example, generalised groundwater level decline or bore to bore drawdown effects could cause individual bores in Hāwea Flat locality to fail. From another perspective, the presence of unmonitored individual water supplies alongside substantial grazing and forage crop operations raises the potential for reverse sensitivity constraints on the farming community. Contact Energy may continue to operate Lake Hāwea within the operating range mandated by operative consent conditions, however and changes to the lake storage patterns could result in Hāwea Flat residents and irrigators experiencing periods of compromised water supply security.

3.1.3 Lake Level Effects and Indicated Connectedness of Aquifers

Lake storage manipulation by the hydroelectric operator under the current pattern of operation could have the effect of delivering low groundwater levels in early summer, but these should improve by late summer provided the approximate 75-day lag in peaks and troughs continues to be the case. The ability to recognise and track the movement of the annual lake level wave through Hāwea Flat and High Terrace aquifers is a significant pointer to a higher degree of connectedness than was earlier considered to be the case. Such recognition of interconnection detracts from the Lakeside – Hillside groundwater management zonation adopted by ORC. The zonation should be further tested with the transient flow model.

3.1.4 Land Surface Recharge Modelling & Water Budget

We have improved the understanding of range-front recharge from losing creeks. We were also able to extend the Rushton land surface recharge model to cover the last ten years. We note that the overall trends in rainfall and rainfall recharge are generally reflected in the groundwater levels. We can introduce irrigation take records to recharge modelling, which should allow the addition of irrigation land recharge to the water budget. The lake contribution to the water budget of the Hāwea Flat and High Terrace aquifers is highly uncertain, so we recommend improving inflow estimates where possible to minimize the uncertainty of the overall water budget.

3.1.5 Subsequent Current State Comments

Irrigation trends and actual water meter data were used to quantify rates of groundwater and water race usage, which clarified the current state as to volumes of water used for consented irrigation and public water supply. Reasonably good metering data were available for the years 2015 to 2020. A special sub-project was initiated that provided cleaned and in-filled water data for this purpose.

While the “lake wave” was recognised at the time of the March 2022, Current State Report, the unique lake interface had not been fully appreciated. The revised conceptual model and adjusted groundwater model boundary configuration addressed these issues while providing a coherent explanation of the “lake wave” phenomenon.

The revised groundwater model boundary at the Lake Hāwea interface provided a better means of simulating recharge of the Hāwea Flat Aquifer from Lake Hāwea for the betterment of the MODFLOW model’s predictive power. The model implementation, including the revised lake interface boundary condition set-up was further optimised. The optimisation allowed the final model realisation to reproduce the recorded “lake wave’ effects on monitoring bore locations throughout the groundwater system.

Improvements to the quantification of water use rates and volumes allowed the modelling of recharge rates to be more precisely and accurately realised. Land Surface Recharge under irrigated areas was modelled and rates of spray or border irrigation application were determined from analysis of water take meter data. The meteoric and applied irrigation soil-water inputs were the subject of lumped parameter water balance modelling on a daily total basis. An important development was the ability to examine long period (1950 – 2020) and shorter period water balance modelling intervals. Longer period modelling employed a global re-analysis of meteorological data (ERA5-Land) while the shorter (2012 – 2021) had the advantage of using actual measured meteorological and water resource data, mostly obtained from ORC and NIWA. Range-front or hillside creek recharge has already been described under New Scientific Insights, Section 2.4 “Hill Creek Catchment Inflows”.

3.2 Model Conceptualisation and Construction

3.2.1 Hosting Geological Materials

This section shows how relevant hydrogeological / hydrological data have been evaluated and translated into a numerical representation of the key aspects of the Hāwea basin hydrological system. The Hāwea groundwater basin is primarily hosted by Late Pleistocene glacial or fluvial deposits lying atop Mesozoic schist and semi-schist. The Hāwea Glaciation was very influential in landscape formation of the Wānaka – Hāwea valleys, leaving glacial till, eskers, meltwater deposits and fluvial outwash of glacial debris following the collapse of the Hāwea Glacier from 18,000 to 14,000 years before present. A terminal moraine is prominent along the Lake Hāwea foreshore, correlated with the last glacial advance and its waning.

The main Hāwea Basin, including the Te Awa Aquifer, Hāwea Flat Aquifer, High Terrace Aquifer and Maungawera Flat Aquifer, lies between the Mt Maude Range and Grandview Range. Hydraulically, the aquifers of the main basin are fed by Lake Hāwea at a mean elevation of 342.02 m msl and discharges into the Clutha River / Mata Au at river levels between 280 m and 244 m AMSL. The Hāwea River is transitional between being a recharge source or discharge receptor along its 14 km course between lake and Clutha River / Mata Au. A basin offshoot aquifer named Maungawera Valley Aquifer is located to the west and enters the main basin at Maungawera Flat. The Sandy Point Aquifer joins with the southeast flank of the High Terrace Aquifer at Lagoon Valley.

The aquifers of the Hāwea Basin are generally highly permeable with high transmissivity, hydraulic conductivity, and drainable porosity consistent with the predominant material sandy, cobbly gravel. There is little known stratification within the sedimentary pile, except for the Hāwea Terminal Moraine where the MODFLOW model needed to implement a three-layer configuration with a General Head Boundary to simulate the unique lake interface. Unifying features of the main basin are high transmissivity, moderate saturated thickness, and high groundwater flow rates between surface water recharge sites (e.g., Lake Hāwea) and down-gradient discharge zones (e.g., Clutha River / Mata Au).

Three relevant zones of contrasting permeability are known:

- Q2[1] glacial till at the Hāwea Terminal Moraine along the lake foreshore,
- Q4 glacial till at the southern backdrop of Hāwea Flat against the High Terrace Aquifer, and
- Q_4 glacial till between the Te Awa and Maungawera aquifers north of Camphill Road.

These zones of glacial till contain a mix of glacial debris (sand, gravel, cobbles and even boulders) but are characterized by silt and clay fine matrix that is hydrologically distinct from clean sandy gravels, cobbles, or boulders

[1] Q2 or Q4 refer to the Quaternary age in relation to the New Zealand Oxygen Isotope (IO) stages and correlate with glacial or interglacial stages. Q2 relates to 13,000 to 32,000 years before present (late Otira Glacial), while Q4 relates to 32,000 to 75,000 (Otiran Glacial)

(see Figure 8). Consequently, the glacial till is generally of low permeability and where extensive bodies of till exist, groundwater flow is to some extent diminished or blocked. One result of the presence of bodies of glacial till is the relationship between Lake Hāwea and the Hāwea Flat Aquifer. Under current hydraulic gradients the Lake Hāwea interface provides a substantial inflow of lake water to groundwater flowing generally southwest to leave the system at Hāwea River, Clutha River / Mata Au, wetlands, or wells. The lake interaction is sufficiently strong that a lake wave in groundwater levels is recognizable in time series monitoring, first noted by Wilson (2012).

3.2.2 Aquifer Types and Geometry

The Hāwea Basin aquifers are also unconfined, having a free water table. The depth of the water table is generally moderately deep and very deep across the main basin. The time-series fluctuations of the water table are generally due to the influence of surface water boundaries, land surface recharge, or groundwater pumping. Notably, Lake Hāwea has a very significant influence on the water table level, more so than other recharge sources and extraction of groundwater.

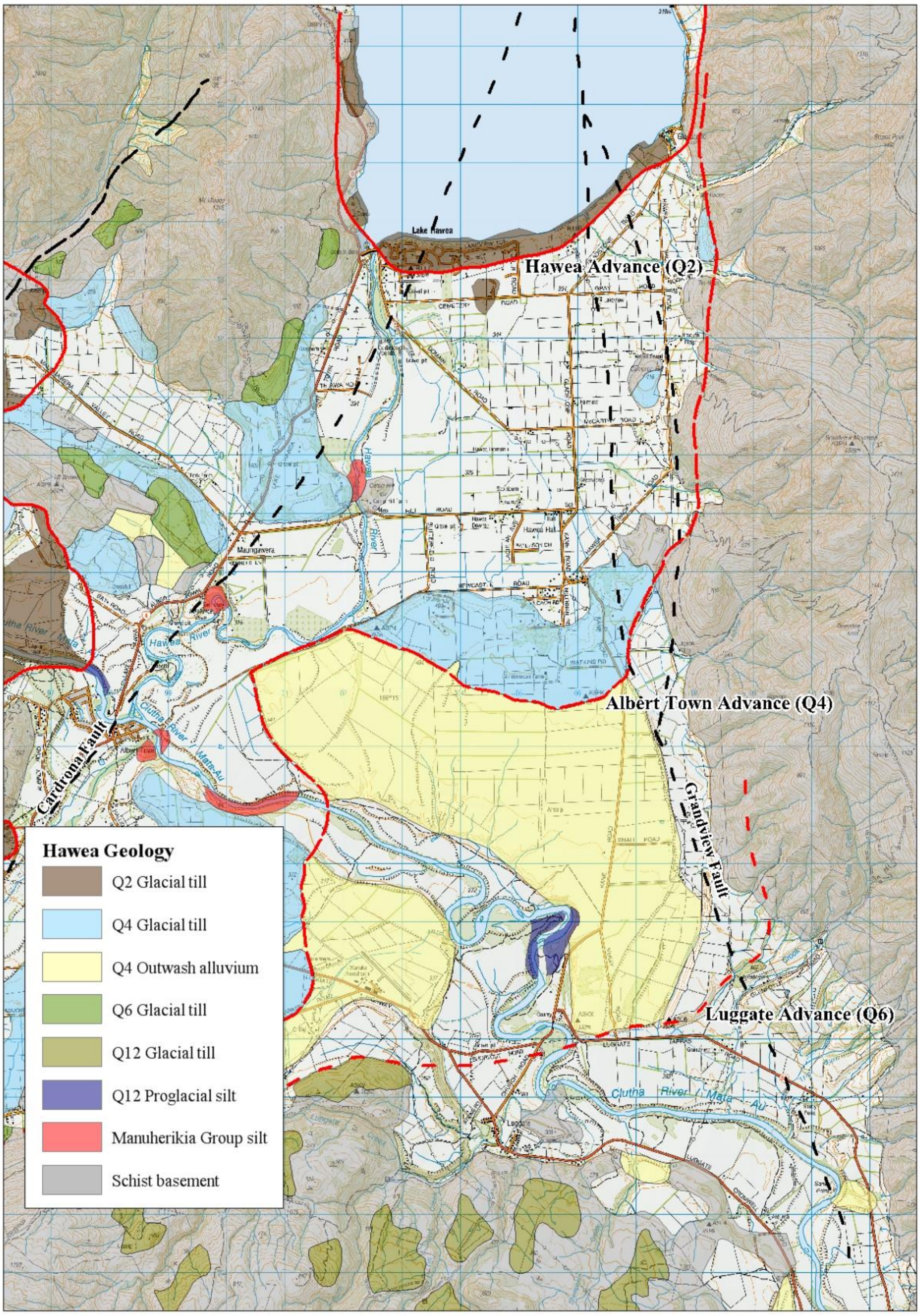

Figure 8: Geology of the Hāwea Basin focusing on geological materials of significance to groundwater resources

On the basis of geological and hydrology criteria, the Hāwea Basin may be divided into several basic aquifers or model domains. The principal aquifers are summarised as follows.

- Hāwea Flat Aquifer,
- (High) Terrace Aquifer,
- Riparian aquifers: Te Awa, Maungawera Flat and Riverside fringing Hāwea and Clutha rivers, and
- Peripheral groundwater areas: Maungawera Valley, Sandy Flat and Camphill Moraine.

The model domains paraphrased as per the above aquifers are mapped across the Hāwea Basin in Figure 9.

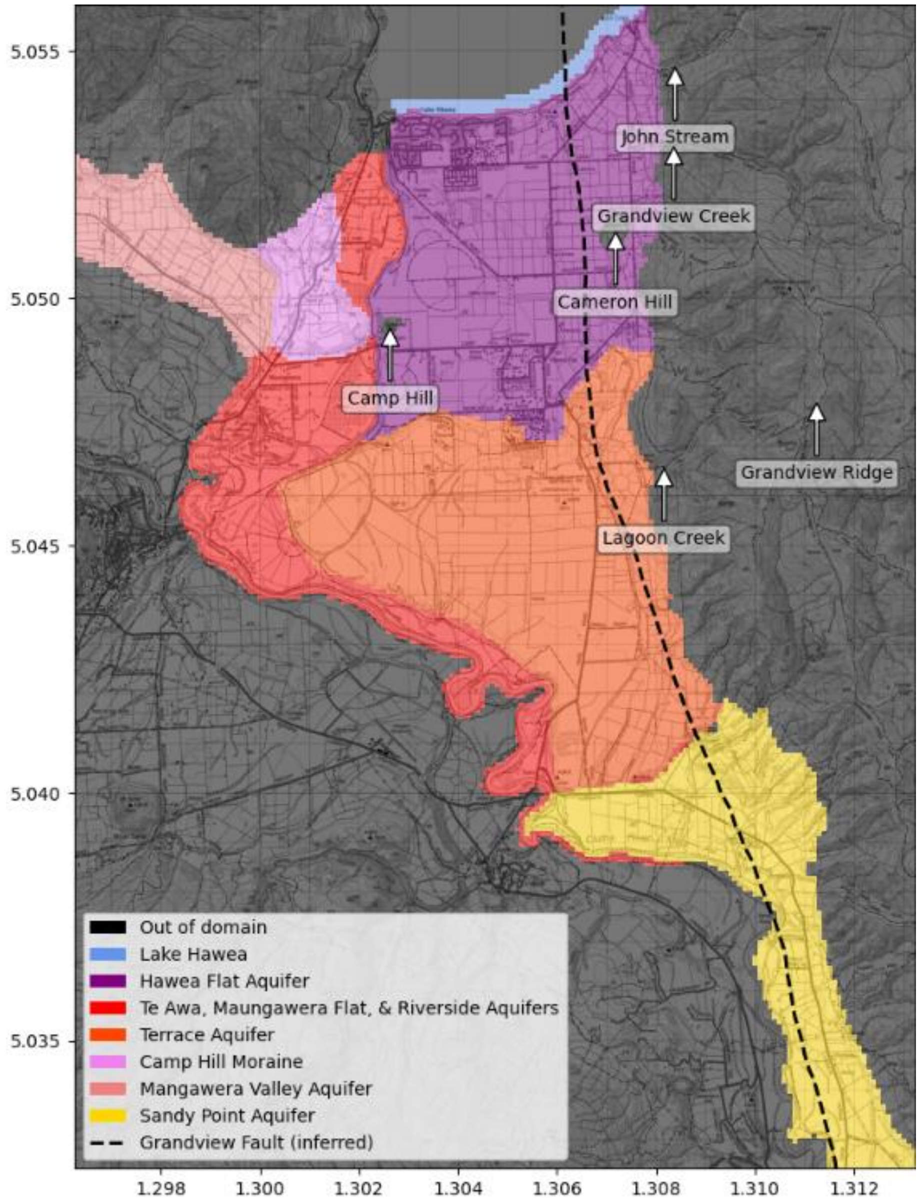

Figure 9: Mapping of model domains based on basic aquifer delineation of the Hāwea Basin

The depth of the aquifer in the Hāwea Flat Aquifer is generally in the 25 to 35 m below ground level (BGL) range. However, due to the significant increase in the height of the High Terrace, the depth of the outwash sandy gravel is in the order of 100 m BGL. The depth of permeable materials in the other aquifers is similar to the Hāwea Flat Aquifer, although the western-most part of the Maungawera Valley Aquifer has reported depths up to 60 m BGL, into a localized semi-confined aquifer.

A full description of the model structural conceptualisation and implementation is available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst#model-structure

3.2.3 Principal Flow Boundaries

The Hāwea Basin has hydrological boundaries as described above and these translate into model boundary conditions. A full description of these model boundary conditions, plots of time series and location data, as well as the methodology used are provided in https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst#model-boundary-conditions. These are summarised below in Table 2.

Table 2: Hāwea Basin Hydrological Boundaries and MODFLOW Boundary Condition Equivalents

Hydrological Boundary Type	MODFLOW Boundary Condition	Additional Information	Link to methodology In GitHub repo
Lake Interface	General Head Boundary (GHB)	Plus 3-layer implementation to simulate till bund effect. Lake levels from 1950 to 2021.	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst#lake-hawea
Hāwea River Interface	Stream Boundary (STR)	River flow and stage data at Camphill from 1968	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst#major-rivers-hawea-river-and-clutha-river
Clutha River / Mata Au	Stream Boundary (STR)	River stage at U/S Cardrona Confluence	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst#major-rivers-hawea-river-and-clutha-river
Hillside Creeks – Grandview Creek & John Creek	Stream Boundary (STR)	Synthesised flow information from 1978 to 2020	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst#hillside-stream-inflows-hillside-inflows
Hillside Creeks – Smaller	Well Package (WEL)	Nine WEL cell injection at the basement – aquifer interface. Synthesised Flow data from 1978 to 2020.	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst#hillside-stream-inflows-hillside-inflows
Land Surface Recharge (Dryland or Irrigated Pasture)	Recharge Property (RCH)	Pre-modelling recharge model developed (Rushton) based on PAW, PRAW, Rainfall, Potential Evapotranspiration (PET) from ERA5-land (1950-2020) and NIWA climate Station (2012-21)	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_build/README.rst#land-surface-recharge-lsr

4. CALIBRATION & OPTIMISATION

4.1 Parameterisation

4.1.1 Spatial Parameters

Hydraulic conductivity (k_h) and specific yield (S_y) were parameterised using pilot points in two discrete zones; one for the high terrace and another for the rest of the model (see Figure 10). We chose to divide the model into two zones because it would be reasonable to assume that the significantly older high terrace sediments could have different hydraulic properties to the younger sediments in the rest of the model. In addition, this sharp parameter change could allow for the impacts of the Q4 Albert Town Advance moraine which we did not explicitly represent in the model. Pilot points extend beyond the active model domain to allow interpolated values to be calculated at the boundary of the active model domain. Note that specific storage, and parameters for the moraine zones are described in other parameters below. The interpolated parameters apply to all layers in the model (inc. the layer pinch out zone) except in the moraine zone where these parameters apply to only layer 2 (the bottom layer recalling that layering follows Python indexing format layer 0 = top layer). These parameters do not apply to the lake zone or the lake bar zone.

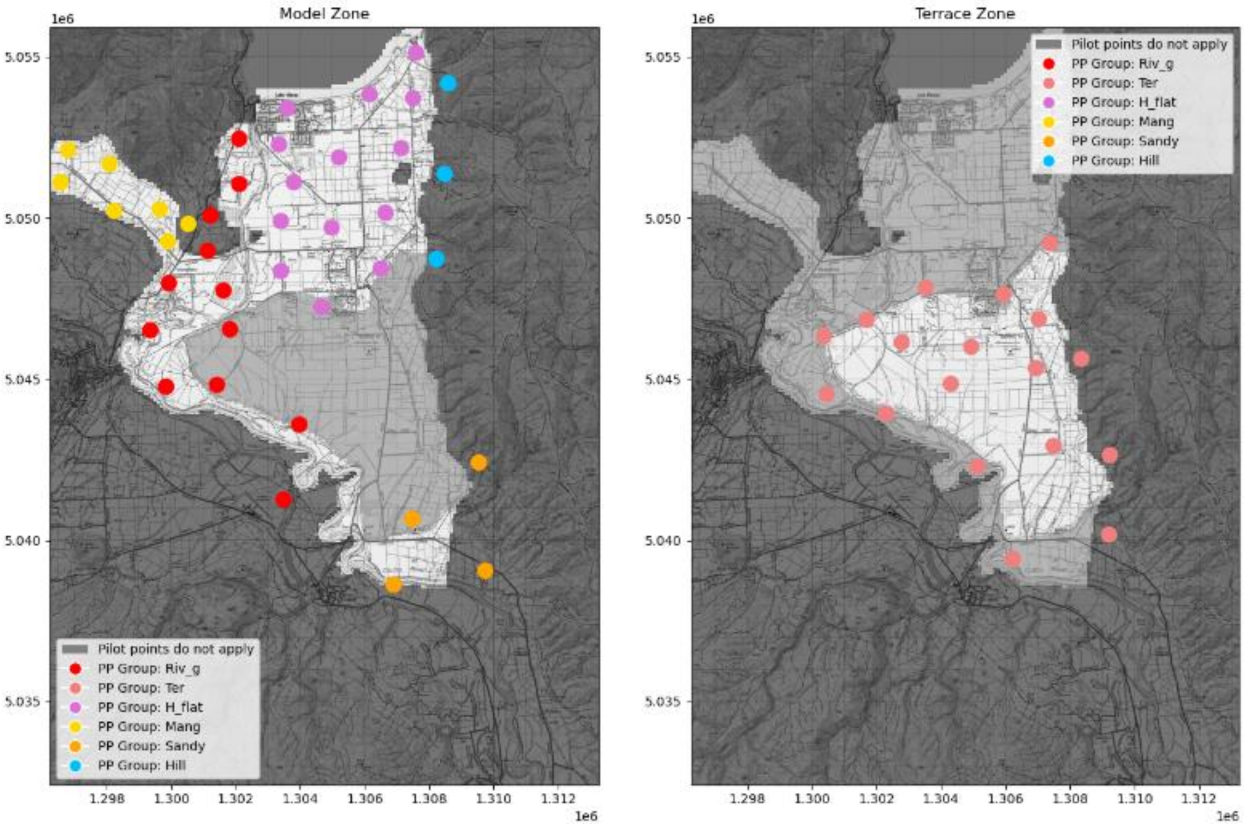

Figure 10: Spatial parameters for hydraulic conductivity (k_h) and specific yield (S_y) in the model domain.

We initially parameterised the model as a relatively homogeneous system. We considered leveraging the parameters generated by Wilson et al. (2012) but decided against is as it could introduce bias from the previous model. Parameter ranges and initial values are defined in the Table below.

Table 3 Spatial parameter bounds and initial values.

Parameter group	Initial	Min	Max
Main Kh	3e2	1e-2	1e4
Terrace Kh	5e1		
Main Sy	1e-2	1e-4	3e-1
Terrace Sy			

Wilson (2012) assessed the annual lake fluctuation in Lake Hāwea using the Jacob tidal equation. They found values of specific yield = 0.012 and a transmissivity estimate of 1,300 m^2/d. We used the specific yield value to set the initial values for the specific yield. The tidal estimates of transmissivity do not include the complex three-dimensional structure which almost certainly limits the transmissivity. We therefore set the initial value to a higher value than the tidal estimate. We set the upper bound based on the highest recorded transmissivity from pump tests, though as noted in Wilson (2012) these tests are somewhat suspect. We set the lower bound at an arbitrary, but very low value allowing k_h to span six orders of magnitude.

4.1.2 Other (Non-Spatial) Parameters

A number of other parameters (see Figure 11) were included in the model. These parameters are listed in the Table 4. Recall layering follows Python indexing format e.g., layer 0 = top layer.

Table 4: List of Initial Non-Spatial Parameters and Multipliers

Parameter type	Package	Name	Initial	Min	Max	Applies to
Hillside inflow multiplier	Wel	hill_se	1	0.8	1.2	see figure below
Hillside inflow multiplier	Wel	hill_main	1	0.8	1.2	
Hillside inflow multiplier	Wel	hill_mang	1	0.8	1.2	
Recharge Multiplier	Rch	rch_all	1	0.5	1.2	full model domain
Race loss multiplier	Wel	race_all	1	0.8	1.2	
River Conductance	Riv	riv_h1	1000	100	10000	see figure below
River Conductance	Riv	riv_h2	1000	100	10000	
River Conductance	Riv	riv_h3	1000	100	10000	
River Conductance	Riv	riv_c1	1000	100	10000	
River Conductance	Riv	riv_gview	100	50	5000	
River Conductance	Riv	riv_john	100	50	5000	
Conductivity	Upw	kh_mor_l0	300	0.001	1000	moraine zone layer 0
Specific Yield	Upw	sy_sy_mor_l0	0.01	0.0001	0.3	&
Specific Storage	Upw	sy_ss_mor_l0	0.0001	0.000001	0.001	lake bar layer 0
Conductivity	Upw	kh_mor_l1	0.0001	0.0000001	1	moraine zone layer 0
Specific Yield	Upw	sy_sy_mor_l1	0.001	0.0001	0.3	&
Specific Storage	Upw	sy_ss_mor_l1	0.0001	0.000001	0.001	lake bar layers 1 & 2

Specific Storage	Upw	sy_ss_rest	0.0001	0.000001	0.001	area of pilot points
Conductivity	Upw	kh_lake	300	0.001	1000	lake zone all layers

We set the initial parameters and ranges for the multipliers (hill_se, hill_main, hill_mang, rch_all, race_all) to allow a 20% change around the predicted in the inflow values. The initial values for the Hāwea and Clutha River conductance (riv_h1, riv_h2, riv_h3, riv_c1) were roughly pulled from the model developed in Wilson (2012). The initial values for the smaller river conductance (riv_gview, riv_john) were set as an order of magnitude lower than the Hāwea and Clutha River conductance (see Figure 11). The ranges for the river conductance are somewhat arbitrary but act to allow the model to explore a range of values. The initial and ranges of k_h_lake, and k_h_mor_l0 were set to the values used for the main pilot points. The specific storage values (sy_ss_rest, sy_ss_mor_l0, sy_ss_mor_l1) were set to typical specific storage values. The specific yield parameters were set to the range used for the main pilot points. The initial value for sy_sy_mor_l0 was set to the starting pilot point values while the initial value for sy_sy_mor_l1 was set an order of magnitude lower. kh_mor_l1 (the moraine low conductivity unit) was set to the typical values for glacial till. Additional information is available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/model_parameterisation/README.rst

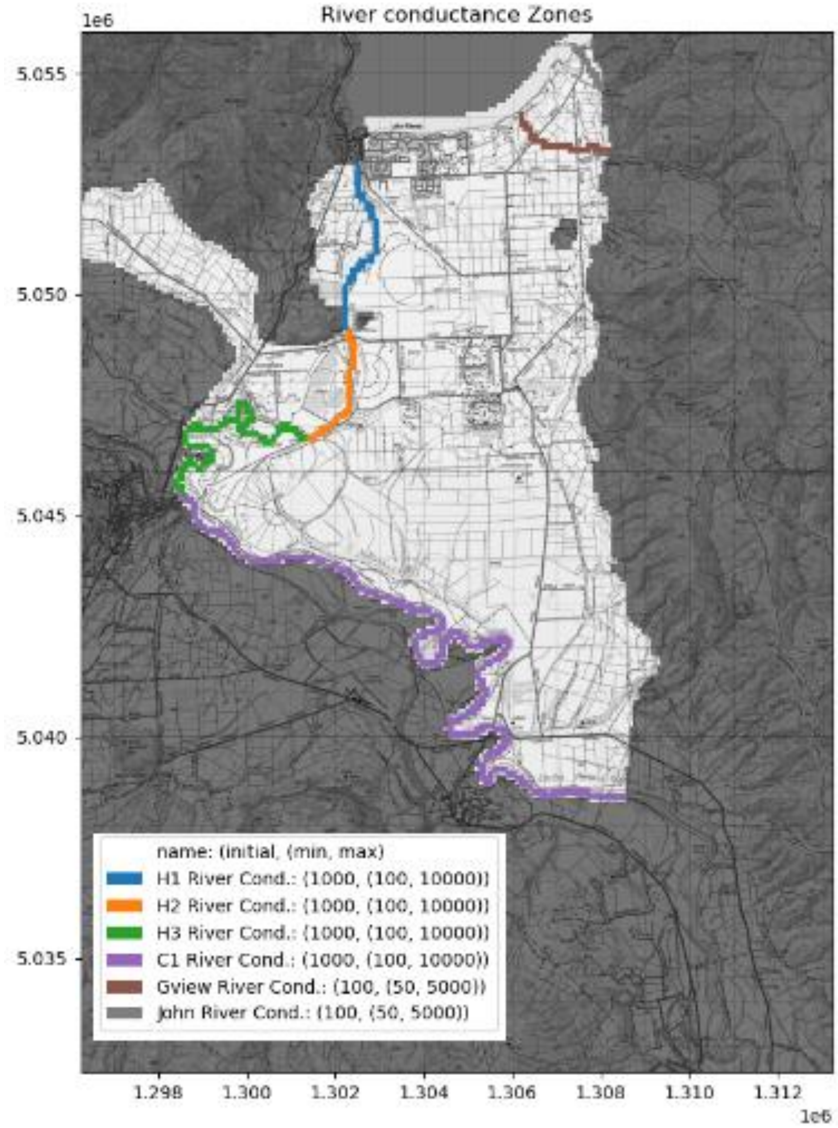

Figure 11: Location of river conductance parameter groups (reaches)

4.2 Calibration / Optimisation

The model was optimised via PEST which is a model calibration and optimisation package. The interface to the model was handled via flopy which is a Python package for working with MODFLOW models and pyemu which is a Python package for working with PEST models. Further details on the optimisation setup and methodology are available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/optimisation/README.rst

A significant part of the optimisation process was formed around dealing with the lake interface and three-dimensional aspects needed to better simulate the lake – aquifer interaction. A significant number of model optimisations were performed on a simplified 1 layer (similar to Wilson et al., 2012). These models were unable to reproduce the observed groundwater level variations, particularly at the bore G40/0415. Based on this incompatibility we rejected the hypothesis that the Lake Hāwea – Hāwea Flat Aquifer interface could be modelled without a complex 3D structure. Additional information on this process is available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/optimisation/README.rst#layer-model-2d-optimisation-results

We also produced a hypothesis testing model optimisation which attempted to fit the observed groundwater levels on and south of the High Terrace in isolation from the rest of the system. We were not able to reproduce the groundwater levels and therefore we rejected the hypothesis that the High Terrace is disconnected from the remainder of the aquifer system. Further details on this process is available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/optimisation/README.rst#terrace-only-model-2d-optimisation-results

Finally, with the advent of the complex 3D model structure, a model realisation was found to reproduce high frequency groundwater levels in the vicinity of the lake interface in the Hāwea Flat Aquifer (Figure 12 and Figure 13) and across most of the rest of the system (labelled 3d_v1d). A full discussion of the optimisation results for 3d_v1d is available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/optimisation/README.rst#d-v1d-final-model. The model structures labelled 3d_v1a and 3d_v1b were created to test the impact variable elevations of the low conductivity moraine sediments at 335 m msl and 333 m msl. Both of these models achieved similar results suggesting that the available data is unlikely to significantly constrain the elevation of the low conductivity sediments. The difference between 3d_v1a and 3d_v1d is simply a change in the optimisation objective function.

Unfortunately, despite this model's good performance throughout most of the Hāwea Flat Aquifer, the model did a very poor job of reproducing (mostly single value) groundwater levels east of the Grandview Fault. The model was considered to be unsuitable in this area and we have outlined an alternate allocation approach for the groundwater east of the Grandview Fault. This result was expected, the groundwater structure (e.g., the location of basement rock) is very uncertain and there is minimal data to inform the optimisation.

Full details of optimisation and all results are available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/optimisation/README.rst.

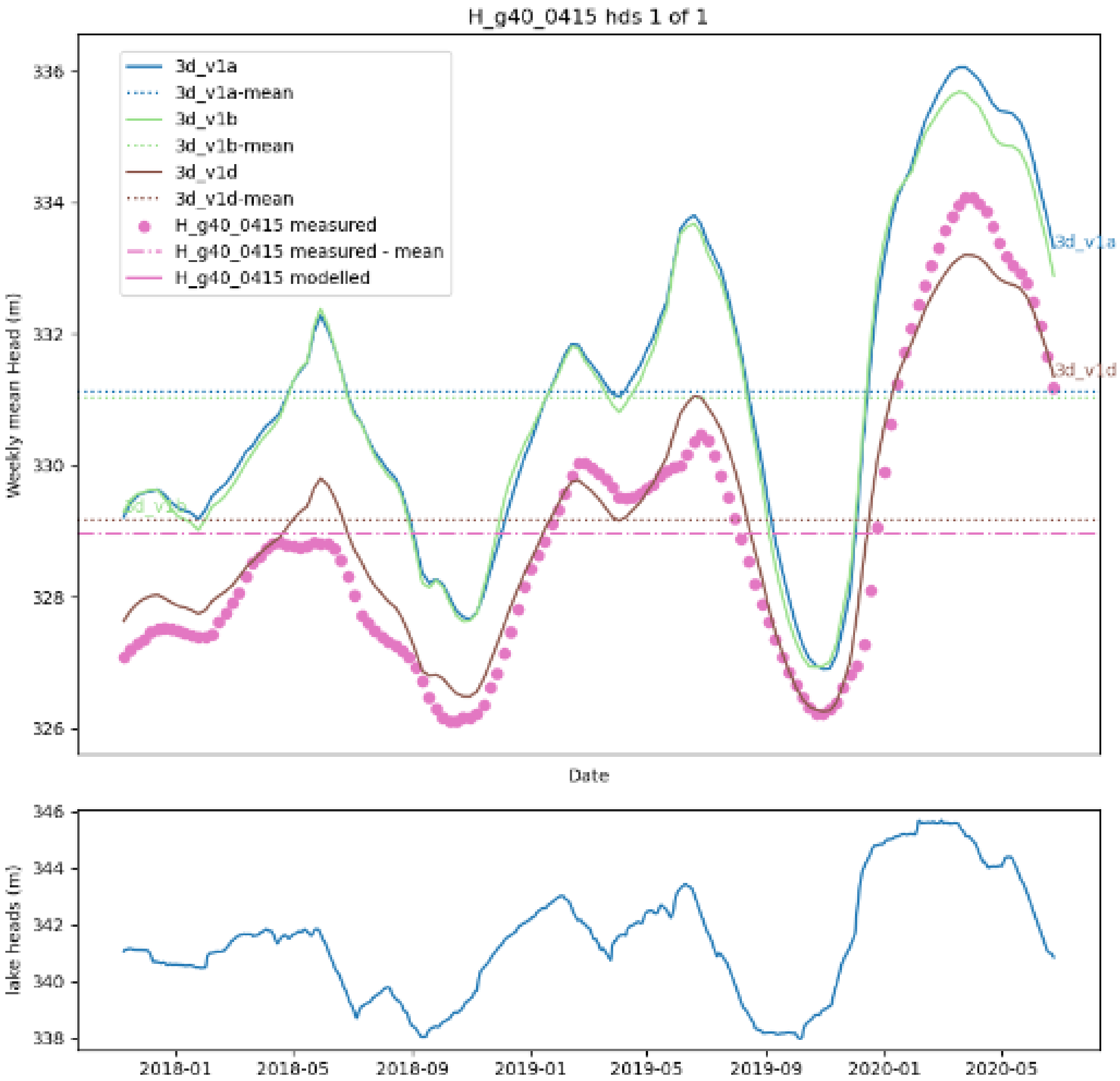

Figure 12: Comparison of measured high frequency level data at bore G40/0415 and the ultimately model realization 3d_v1d.

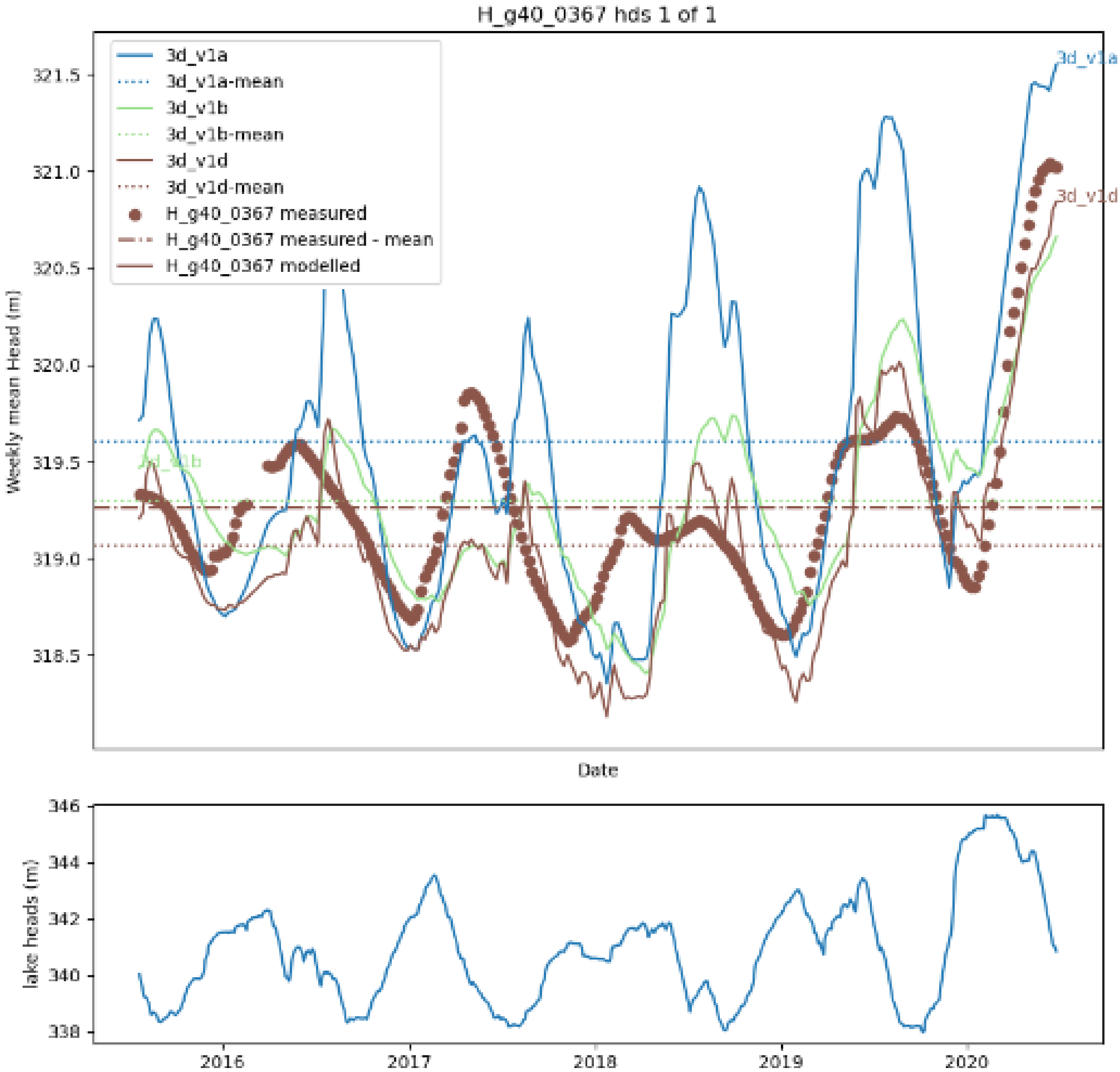

Figure 13: Comparison of measured high frequency level data at bore G40/0367 and the ultimately model realization 3d_v1d.

4.3 Steady State Water Balance

To provide information on the steady state water balance for the 3D_v1d model, Table 5 lists the principal groupings of groundwater fluxes. Note that breaking the model boundary conditions budget down to the individual (e.g., hillside inflow vs abstraction) components introduces some dependencies due to double counting (e.g., where multiple boundary conditions exist in a single cell).

Table 5: Water Balance of the Hāwea Basin Steady State Model listing Main Groups of Fluxes

Boundary Condition	Package	Steady State Inflow, into model (m^3/d)	Steady State outflow Out of model (m^3/d)
Lake	**GHB**	**110,385**	
Recharge	**RCH**	**36,216**	
All STR packages	**STR**		**154,145**
- Hawea1_flux			96,472
- Hawea2_flux	STR	10,649	
- Hawea3_flux	STR	5,536	
- Grandview_flux	STR	3,100	
- John_flux	STR	1,500	
- Clutha1_flux			78,459
All WEL package	**WEL**	**7,544**	
- Race_flux	WEL	4,606	
- hill_maungawera_flux	WEL	850	
- hill_flat_west_flux	WEL	260	
- hill_flat_east_flux	WEL	1,538	
- hill_terrace_east_flux	WEL	3,358	
- hill_south_east_flux	WEL	6,083	
- Abstraction_flux			-7,365
Totals		**154145**	**154145**
Discrepancy		**0.3**	

The modelled fluxes could not be readily compared with measured fluxes since in the case of the Hāwea Basin very few measured fluxes are available, and even fewer that relate to periods extending over many years. Recharge and groundwater abstraction are two of the few fluxes that can be readily estimated from a combination of measurements.

5. SCENARIO MODELLING

Scenario modelling was undertaken to evaluate the response of the hydrological system to pumping stresses. Full details on the methodology and an extensive set of results for the scenarios are available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/Scenarios/README.rst. The model scenarios and key questions are presented in Table 6 below.

Table 6 Model scenarios, key questions and cross references

Scenario Type	Key Questions	Section Link	Link to Github Repo section
Model information Scenarios	How does the model behave, and what impacts groundwater levels?	Not included	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/Scenarios/README.rst#model-information-scenarios
Low lake scenarios	What happens if the management of Lake Hāwea changes significantly?	5.5	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/Scenarios/README.rst#low-lake-hawea-level-scenarios
MT3D indicator scenarios	Where is the water sourced from?	5.3	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/Scenarios/README.rst#id5
Allocation Scenarios	What is a sustainable level of abstraction?	5.4	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/Scenarios/README.rst#id8
Wetland setback scenarios	Where, and to what extent, does abstraction impact significant wetlands?	5.4.9	https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/Scenarios/README.rst#wetland-setback-scenarios

5.1 Overview of Scenario Results and Implications

The table below presents an overview of the key findings of Section 5, the areas they impact and links to the sections. This is provided to better allow users of this report find the relevant information.

Result/Implication	Area of impact	Relevance	Section link
Combine previous Hāwea Flat – Hill and Hāwea Flat – Lake zones into one Hāwea Flat zone	Lake Hāwea to Hāwea Flat	Allocation zones	5.2.1
New Grandview allocation zone to the East of the Hāwea Flat zone	Lake Hāwea to Hāwea Flat East of inferred Grandview fault location	Allocation zone	5.2.2
Water users in the mapped Grandview Zone can be considered in the Hāwea Flat zone if they can prove a groundwater connection to Lake Hāwea		Allocation zone	5.2.2
We suggest a zero-allocation zone for The Camp Hill Moraine, permitted activities are likely consistent with maintaining sustainable groundwater management objectives	Camp Hill moraine	Allocation zones and allocation	5.2.4 and 5.4.12
Other allocation zones are consistent with those in Wilson, 2012 (current practice)	High Terrace, Maungawera Flat, Te Awa, Sandy point, Maungawera Valley	Allocation zone	5.2.3, 5.2.4, and 5.2.5

Our key threshold for evaluating sustainable groundwater use is 1 or more adequate penetration levels defied as 3x the seasonal groundwater level variation below the mean.	Full domain	Allocation	5.4.3
A guide to understanding the model results	Full domain	Model results	5.4.4
A summary of current usage and allocation	Full domain	Allocation	5.4.5
Current usage and current allocation are likely consistent with maintaining bore reliability	Hāwea Flat	Allocation	5.4.6
	Terrace – Hill		5.4.8
	Terrace – River		5.4.8
	Maungawera Flat		5.4.11
	Te Awa		5.4.11
Current usage is consistent with maintaining bore reliability, but a reduction to 60-70% of the current allocation is required to maintain bore reliability in the Maungawera Valley	Maungawera Valley	Allocation	5.4.10
Out of an abundance of caution we would recommend reducing the allocation limit in the sandy point aquifer in line with the new, lower, estimate of mean annual LSR. Note that the current allocation limit is more than an order of magnitude greater than the allocation in this zone.	Sandy Point	Allocation	5.4.13 and 5.4.5
We have identified areas where groundwater abstraction may impact sensitive wetlands, note these zones do not preclude cumulative impacts from abstraction outside the zones.	Butterfield Wetland and Campbells Wetland	Significant Wetlands	5.4.9 and 5.2.3
Groundwater levels are highly connected to Lake Hāwea water levels and there is likely an elevation below which the aquifer will become disconnected to the lake. The exact elevation is unknown, but it is likely between 227 to 337 m msl.	Primarily Lake Hāwea to Hāwea Flat, but it also impacts the full aquifer system except the Grandview, Sandy Point, and Maungawera valley zones.	Lake Hāwea – groundwater relationship	5.5 and 2.1

5.2 Allocation Zones

Wilson (2012) introduced a delineation of the allocation zones to be followed in observing allocation limits. The Regional Plan: Water for Otago includes the ability to set groundwater allocation limits (caps) that apply to restricted discretionary or discretionary groundwater take applications within declared aquifers by plan change. Such plan changes have been undertaken for Clutha / Mata Au catchment, such as the Cromwell Terrace Aquifer by Plan Change 4C which sets the allocation limit at 4 million cubic metres per annum, which is higher than the default 50% of mean annual recharge. Wilson (2012) used a mixture of caps set at 50% of mean annual recharge, or tailored caps that employed the steady state MOFLOW model developed by Wilson to set a groundwater take limit with expert judgement.

One of the tasks of this study is to review the Wilson (2012) allocation zones, and set new ones if the conceptualisation, modelling, and expert analysis support it. Figure 14 maps the allocation zones used by ORC from the Wilson (2012) report (Figure 14A), alongside the suggested allocation zones that we employed in our groundwater modelling assessment (Figure 14B).

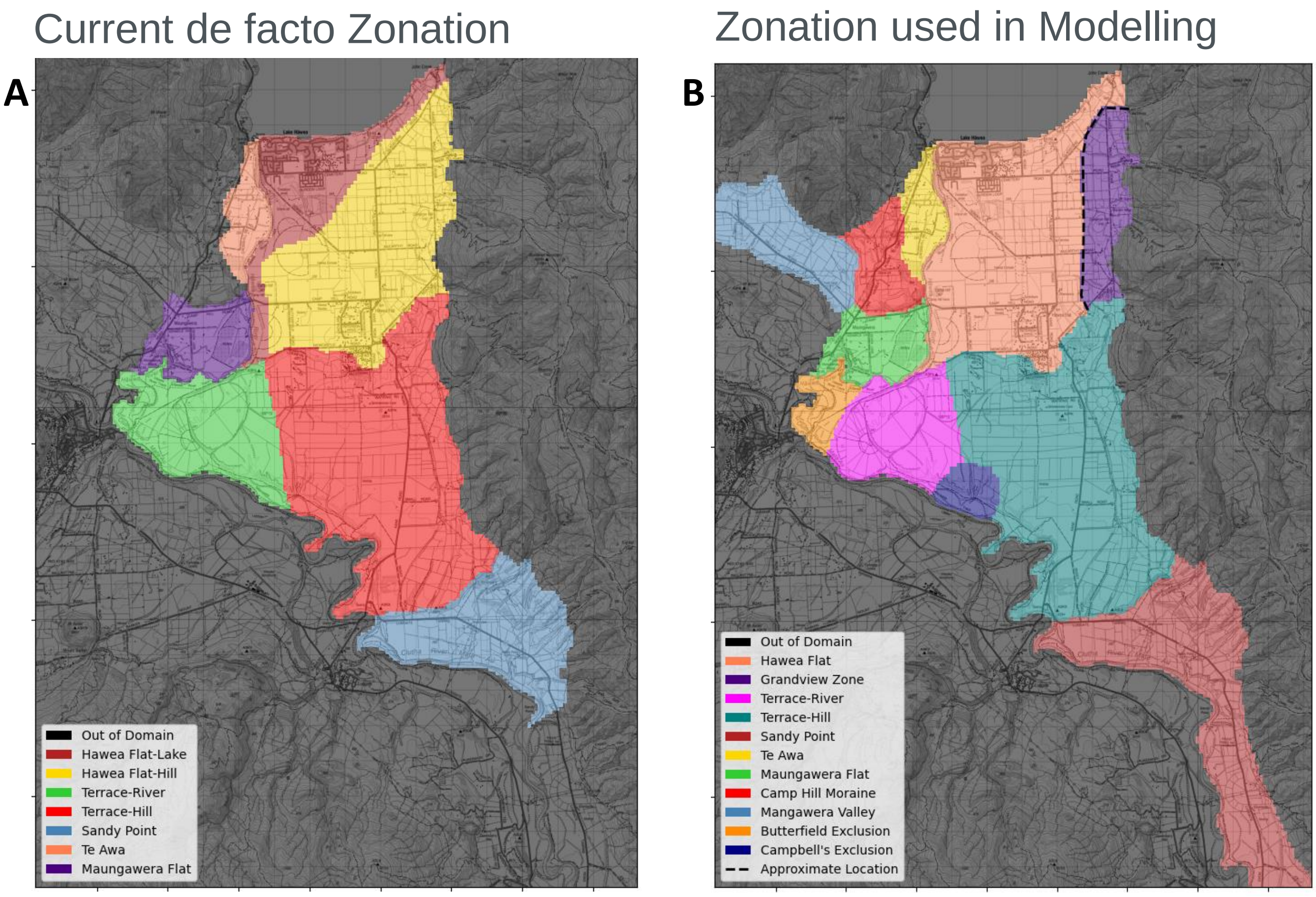

Figure 14: Current (A) and suggested future Hāwea Basin allocation zone mapping (B) used in subsequent modelling assessment

5.2.1 Hāwea Flat Aquifer allocation zonation

Previously, ORC had been managing The Hāwea Flat Aquifer as two allocation zones; Lakeside and Hillside. Wilson (2012) might have recommended the Hāwea Flat Aquifer was allocated as one allocation zone except for the concern that the east of the aquifer was cut off from the lake recharge. The Hāwea Flat aquifer was split into a Lakeside Zone and Hillside Zone. The Lakeside Zone clearly received significant inflows from Lake Hāwea. It was unclear whether the Hillside Zone received any Lake Hāwea water and it may have been more vulnerable to groundwater level declines.

This zone division reportedly led to a complicated management of groundwater in the Hāwea Flat part of the groundwater system. An example was the installation of two large capacity irrigation wells in 2013 separated by 270 m and intended to pump in concert for the irrigation of a block of pasture in the centre of Hāwea Flat. However, the zone boundary between Lakeside and Hillside domains fell between the two bores, necessitating extraordinary processing of the groundwater take application. In addition, the exceedance of the allocation cap of the Hillside Domain in the intervening period led to a small number of consent applications processed in non-complying status.

Our modelling and the analysis of newly available transient water levels, particularly at G40/0415 (Gladstone & Cemetery roads) and G40/0367 (Loach Road, Hāwea Flat Locality) provides significant evidence that most of the Hāwea Flat aquifer is connected to Lake Hāwea. Therefore, we feel quite confident in suggesting that the Hāwea Flat Aquifer zones be combined into one single zone. Note there are still uncertainty to the east of the inferred Grandview Fault, see section 5.2.2 for further details.

5.2.2 Grandview allocation zone

The principal area of uncertainty lies between Hāwea Back Road and Timaru Creek Road, essentially the eastern edge of the Hāwea Flat Aquifer north of Hospital Creek. This area is bisected by the Grandview Fault, a buried Holocene reverse (thrust) fault comprising a range-bounding rupture defining the Grandview Range. Its trace is uncertain and is therefore inferred, potentially lifting the base of the basement beneath the cover sediments. Upthrust basement blocks, perhaps on the upthrust side of Grandview Fault, are inferred at Cameron Hill and a lower mound at Nook Road. This study has identified a potential special groundwater allocation area along the Grandview Range flank of the Hāwea Flat Aquifer. Because this area is conceptually disconnected from the Lake Hāwea recharge it requires a far more conservative allocation approach which is further discussed in Section 5.4.7. The boundary of this allocation zone is explicitly where the groundwater system is disconnected from Lake Hāwea; however, the spatial location of this divide is only approximated at the inferred location of the Grandview Fault. This issue could be addressed by providing a regional plan pathway for groundwater take applications within the mapped Grandview allocation zone to be included in the Hāwea Flat allocation zone if it can be demonstrated that the take has access to lake recharge via the groundwater system[2] and the take has adequate freeboard to accommodate water table decline[3]. This would address the possible challenges of enforcing a zone with an approximate boundary.

5.2.3 Terrace Aquifer allocation zonation

Formerly referred to as the High Terrace Aquifer, the Terrace Aquifer is distinct for several reasons –

- The northern edge of the aquifer is defined by glacial till that is interpreted to be low permeability,
- The Terrace is a distinctly higher elevation feature, approximately 60 m higher than Hāwea Flat,
- The elevation of basement is similar to Hāwea Flat Aquifer, meaning depths to basement are up to 115 m below ground level (BGL),
- The depth to water is often as deep as 95 m BGL, implying high aquifer permeability (confirmed by a single pumping test result), and
- The Terrace aquifer has few bores and only three groundwater takes that are not river-adjacent takes locations.

The western parts of the Terrace Aquifer are recharged primarily by Hāwea River losses originating from the riverbed downstream of Camphill Road (see Figure 16B), while eastern flank of the aquifer is primarily replenished by hillside creek losses and land surface recharge, substantially bolstered by irrigation applied to pasture in recent years. Consequently, a Terrace – Riverside zone is defined in relation to this study and the remainder is delineated as a hillside zone (as was the case in Wilson, 2012). In addition, to the riverside and hillside zonation, allocation (exclusion) zones are defined around the Butterfield and Campbell Wetlands, which are shown in Figure 14B.

5.2.4 Westside Aquifers

Te Awa, Camphill Moraine, Maungawera Flat and Maungawera Valley are found on the west side of the Hāwea River, but form part of the basin groundwater system. The Camphill Moraine is considered to be a largely non-productive area of the basin, being correlated with glacial till composition. While small capacity domestic or stock water bores may be feasible in the moraine, consented groundwater takes for irrigation or industrial purposes are unlikely to be viable due to low permeability and storage.

Te Awa and Maungawera aquifer both fringe the Hāwea River and are also currently served by the westside branch of the Hāwea Irrigation Scheme, sourced from Lake Hāwea at the Hāwea Dam. Land surface recharge, race losses, and hillside creek inflows, are considered the primary water sources of the underlying aquifer. The Maungawera Valley has land surface recharge and hillside creek inflows only. The transition from the Maungawera Valley and Maungawera Flat zones is found at a distinct narrowing in the groundwater system by the combined pinching of the Camphill Moraine and the basement schist near State Highway 6.

5.2.5 Sandy Point

The Sandy Point Aquifer is a largely under characterised part of the Hāwea Basin. Little additional information was obtained for Sandy Point than was available at the time of preparing the Wilson (2012) report. For the purposes of MODFLOW modelling, the Sandy Point Aquifer was truncated at Crook Burn. Lagoon Creek, Crook Burn, Trig Burn and many other smaller hillside catchments contribute hillside flow losses to the Sandy Point Aquifer.

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[2] This might be provided by demonstrating that the site of groundwater bore recorded lake wave level fluctuations meaning that it was not cut off.

[3] Drilling and bore construction information could be provided demonstrating full penetration of the aquifer, along with pumping test and drawdown assessments.

5.3 Water Sources & Pathways

The first model questions posed related to the source and fate of water moving through the Hāwea Basin groundwater system:

- Which parts of the recharge zones provide most of the water in other parts of the basin's groundwater?
- What pathways does the lake recharge water take?
- How do the Hillside (Grandview and John Creek) injections plus the middle Hāwea River influence the composition of down-gradient groundwater?

The MODFLOW and MT3D-usgs simulations were employed to generate source intensity plots across the Hāwea Basin. MT3D (Mass Transport in 3 Dimensions) tracked the path taken by groundwater originating at individual or groups of source boundaries. Figure 15 (LSR and smaller hillside creeks). Figure 16A (Lake Hāwea) and Figure 16B (Hāwea River, Grandview and John creeks) map the extent of the main sources and the aquifer areas they influenced.

The following discussion references the new allocation zones defined in Section 5.2, but also serves as further justification for the zone delineation. We recognise this is recursive, but without zone labels it is very difficult to discuss the results. The groundwater in Hāwea Flat zone is primarily sourced from Lake Hāwea, but some areas, particularly near the eastern edge of Hāwea Flat have a significant component of LSR and hillside creek losses. The Grandview zone is primarily composed of hillside creek losses and LSR. Te Awa and Maungawera Flat zones are modelled as receiving most of their water from Lake Hāwea, which may or may not be the case; there was very little information to constrain the model in these areas. The other key observation from these results is the large swath of the High Terrace which is fed by Hāwea River losses near the West end of Newcastle Road. These results are the basis for dividing the High Terrace into its two component allocation zones.

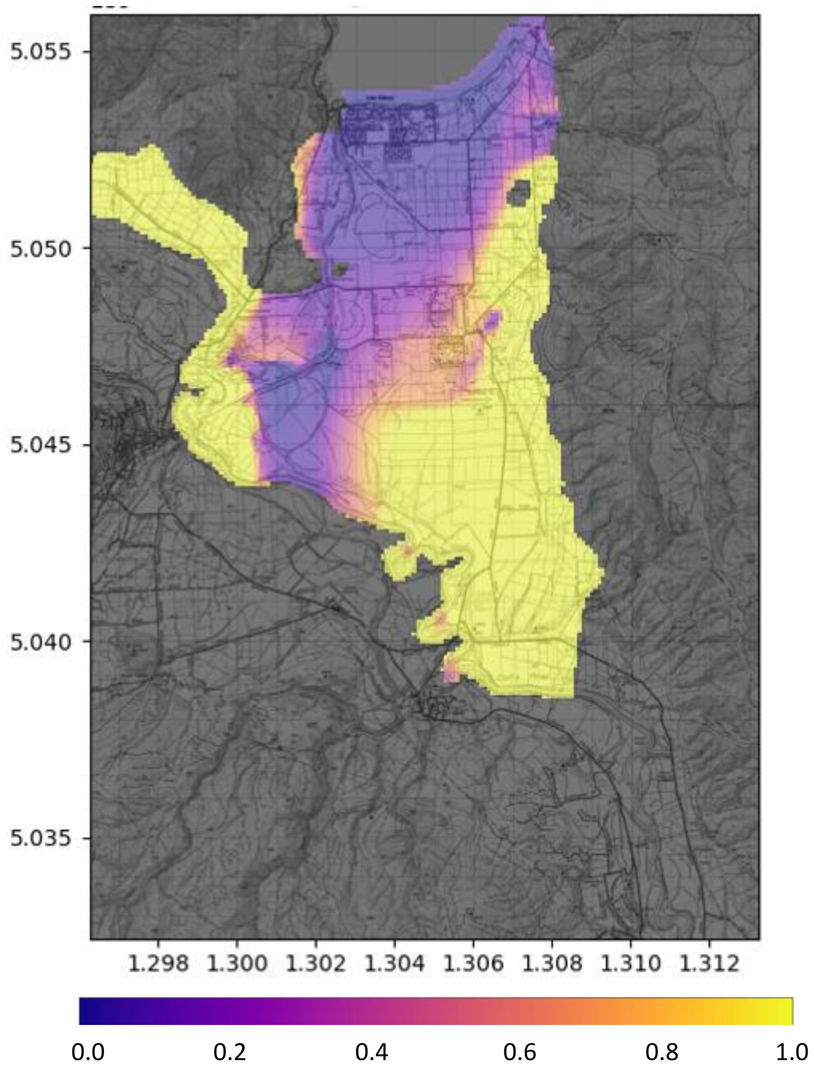


Figure 15: MODFLOW / MT3D source delineation of Land Surface Recharge and Small Hillside creek inflow

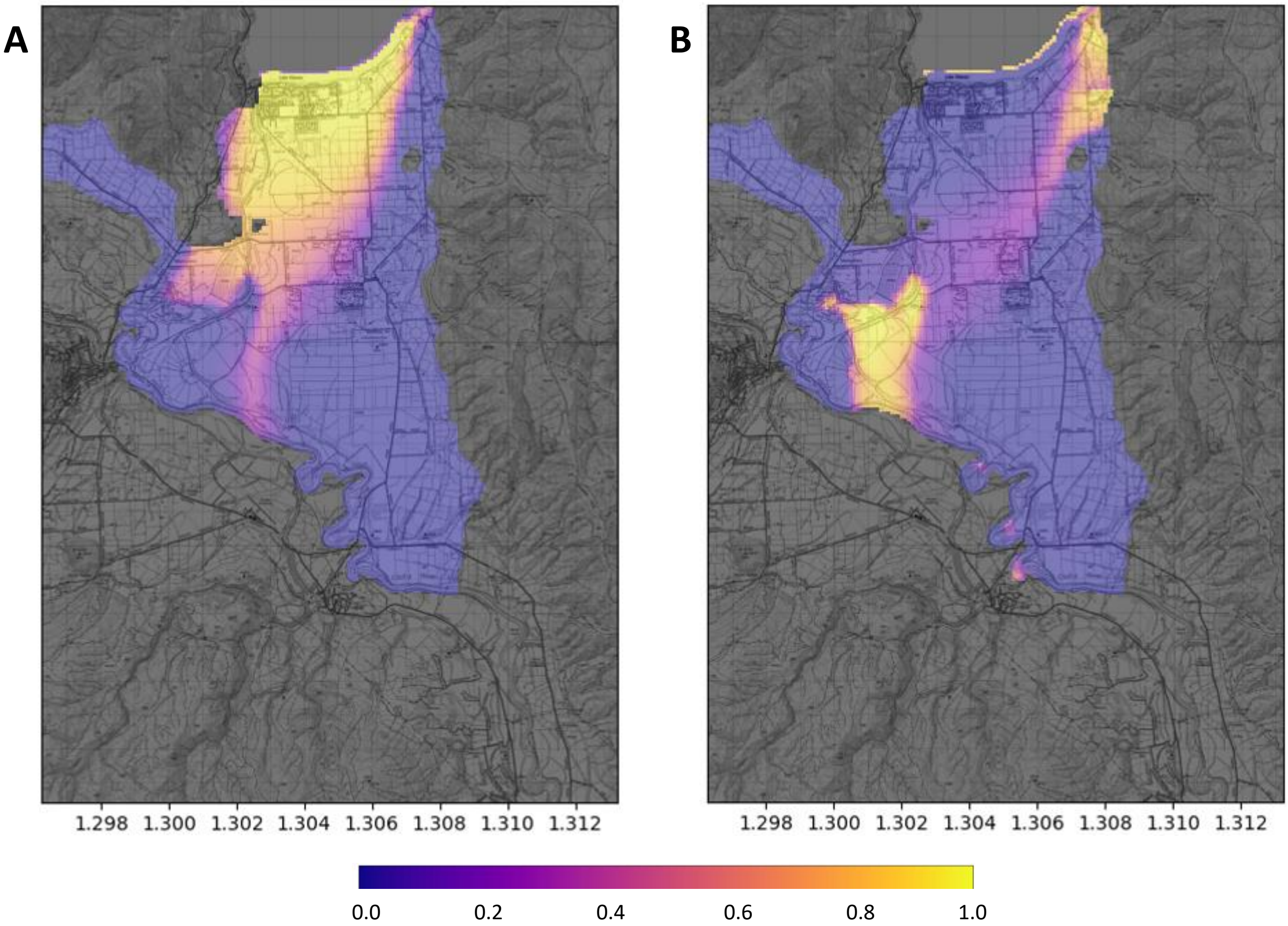


Figure 16: MODFLOW / MT3D source delineation of Lake Recharge (A), and Hāwea River, Grandview & John Creeks (B).

The modelled water source is not the only water source impacting the groundwater level variation. Pressure propagation can induce changes in water levels without changes in water sources; however, it is a good indication of the primary influences on that area of the groundwater system. For instance, the Hāwea Flat Aquifer is somewhat dependent on the losses of Lake Hāwea, John Creek, Grandview Creek and several smaller creek originating from the Grandview Range (see Figure 16 A and B). Without the lake in particular, groundwater levels would be significantly lower than recorded in recent years, and current intensities of irrigation groundwater pumping would exacerbate low groundwater levels. Similarly, it would be fair to say that there is a similar dependence on land surface recharge and hillside creek inflows in the peripheral aquifers such as Maungawera Valley, Maungawera Flat and Sandy Point (Figure 15). The Terrace Aquifer is also significantly fed by land surface recharge and hillside creek inflow in the west. For a detailed analysis of the impacts of different boundary conditions on different areas of the model please see: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/blob/main/Scenarios/README.rst#boundary-condition-sensitivity

This zonation assists with aquifer delineation and throws light onto the groundwater allocation zonation for potential future groundwater management.

5.4 Extraction Modelling Scenarios to Guide Allocation Setting

5.4.1 Introduction to Approach

Our scenario modelling used a number of long-term (1980 – 2020) transient simulations to better characterise the variance from natural weather patterns. These scenarios are defined in Table 7 below and further information is available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/Scenarios#id8

Table 7 Summary of modelling scenarios

Scenario Name	Abstraction scenario	LSR Scenario	Other comments
optimised	optimisation period	Optimisation period	Final optimised model
long_current	extended_pump: ISO weekly mean* pumping	Irrigated recharge 1980-2020	
long_nat	None	Dryland recharge 1980-2020	Race losses still included
no_pumping	None	Irrigated recharge 1980-2020	
full_allocation	extended_full_allo: Maximum daily allocation times the min/max-normalised historical pumping record	Irrigated recharge 1980-2020	Representation of current allocation
max_allocation_on_pump_curve (MAPC)	extended_max_allo_pc: Maximum daily allocation applied to typological pump curve (MAPC). Representation of current allocation	Irrigated recharge 1980-2020	Alternative representation of current allocation
{zone} MAPC + {rate}	MAPC for the full model with an additional {rate} m^3/day applied to the gridded abstraction wells in the {zone}. An increased allocation scenario.	Irrigated recharge 1980-2020	For more details about the grid_pump wells see: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/Scenarios#additional-abstraction-grid-pump
reduction _ {faction}	MAPC for the full model, but wells in the Maungawera Valley allocation zone are multiplied by {fraction} e.g. 0.9 = 90% of maximum allocation on pumping curve for the Maungawera valley	Irrigated recharge 1980-2020	Only applies to the Maungawera Valley allocation zone
max_allocation	extended_max_allo: Maximum daily allocation applied to every day of the year	Irrigated recharge 1980-2020	This is not considered to be a realistic scenario because water demand is much lower in winter than in summer but is included for completeness

* ISO weekly mean abstraction: the mean of abstraction for each week of the year (1-52) for example the ISO weekly mean for week one is the mean of all abstraction occurring in the first week of Jan across all years (e.g. mean of week 1, 2015; week 1, 2016; …; etc.)

The typological pumping was created to simulate the normal intra-annular use of the groundwater resource. It ranges from 0 (no water taken) to 1 (maximum daily rate taken) and is based on the normalised historical abstraction data (Figure 17). The integral of the pumping curve is c. 135, so in allocation scenarios based on the typological pumping curve the annual allocation is defined as 135 x maximum daily rate. Further details on the development of this typological pumping curve can be found at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/Scenarios#development-of-the-pumping-curve

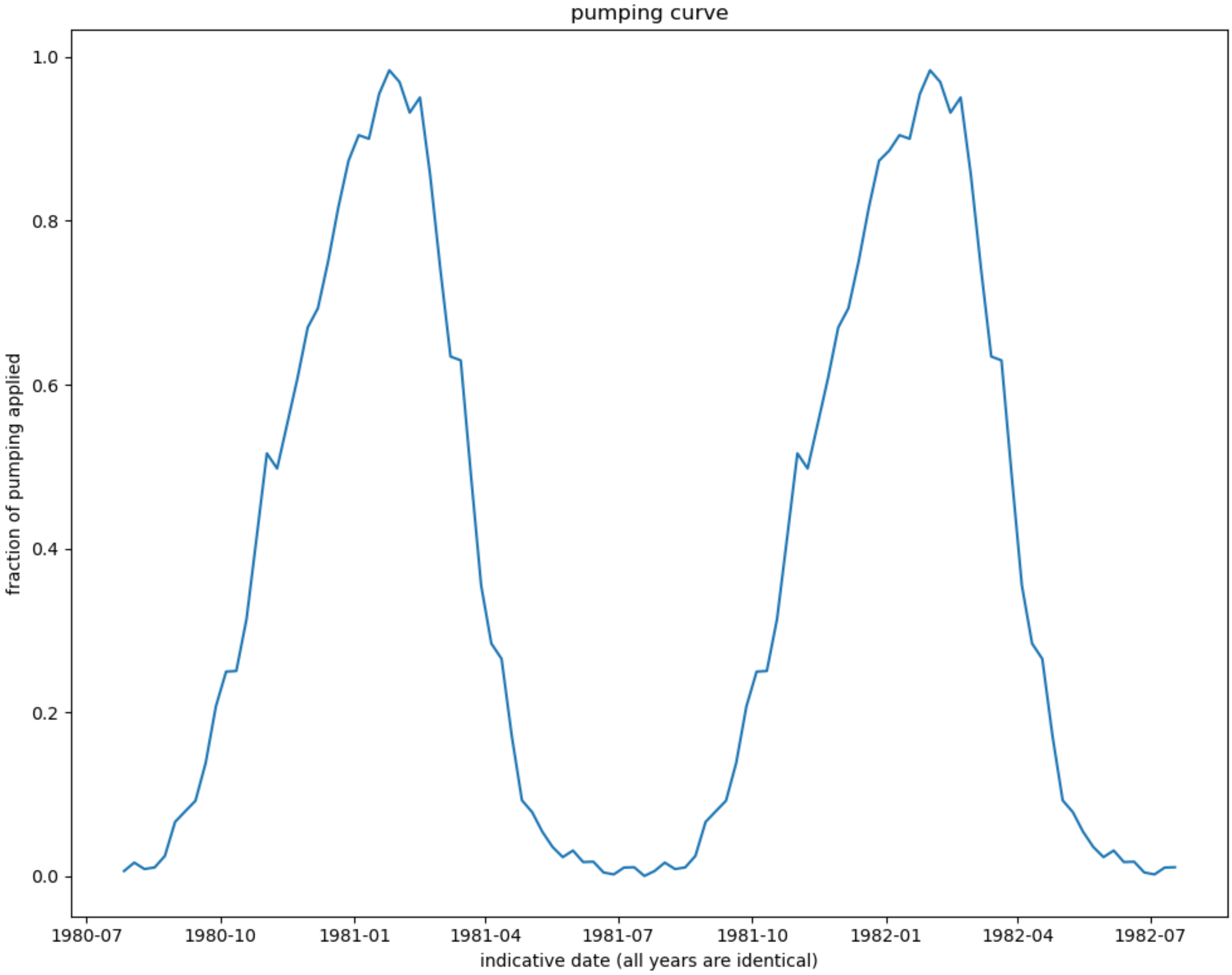


Figure 17: Typological curve of irrigation bore pumping rate based on position along the time continuum for two indicative seasons.

5.4.2 Full List of Zone-specific Scenarios Run.

A full list of all zone specific scenarios is provided below in Table 8. Full outputs for all of the aforementioned scenarios (at a number of indicative well locations) are available in the Github Repo, and are best accessed via: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/Scenarios#zone-specific-scenario-methods-and-results

Table 8 A summary of zone specific modelling scenarios

Scenario Name	**Applicable Zone**	**Pumping Increase (+) / Decrease(-) m³/d**	**Percent Increase (+) / Decrease (-)**
Hawea Flat MAPC + 3424 m^3/day	Hawea Flat	3424	0.05
Hawea Flat MAPC + 6847 m^3/day	Hawea Flat	6847	0.1
Hawea Flat MAPC + 13694 m^3/day	Hawea Flat	13694	0.2
Hawea Flat MAPC + 20542 m^3/day	Hawea Flat	20542	0.3
Hawea Flat MAPC + 34236 m^3/day	Hawea Flat	34236	0.5
Hawea Flat MAPC + 51354 m^3/day	Hawea Flat	51354	0.75

Hawea Flat MAPC + 68472 m^3/day	Hawea Flat	68472	1
Hawea Flat MAPC + 102708 m^3/day	Hawea Flat	102708	1.5
Maungawera Flat MAPC + 500 m^3/day	Maungawera Flat	500	
Maungawera Flat MAPC + 1000 m^3/day	Maungawera Flat	1000	
Maungawera Flat MAPC + 2500 m^3/day	Maungawera Flat	2500	
Maungawera Flat MAPC + 5000 m^3/day	Maungawera Flat	5000	
Maungawera Flat MAPC + 7500 m^3/day	Maungawera Flat	7500	
Maungawera Flat MAPC + 10000 m^3/day	Maungawera Flat	10000	
reduction_0.5	Maungawera Valley	-2348	-0.5
reduction_0.6	Maungawera Valley	-1878	-0.4
reduction_0.7	Maungawera Valley	-1408	-0.3
reduction_0.8	Maungawera Valley	-939	-0.2
reduction_0.85	Maungawera Valley	-704	-0.15
reduction_0.9	Maungawera Valley	-469	-0.1
reduction_0.95	Maungawera Valley	-234	-0.05
Te Awa MAPC + 500 m^3/day	Te Awa	500	
Te Awa MAPC + 1000 m^3/day	Te Awa	1000	
Te Awa MAPC + 2500 m^3/day	Te Awa	2500	
Te Awa MAPC + 5000 m^3/day	Te Awa	5000	
Te Awa MAPC + 7500 m^3/day	Te Awa	7500	
Te Awa MAPC + 10000 m^3/day	Te Awa	10000	
Terrace-Hill MAPC + 135 m^3/day	Terrace-Hill	135	0.1
Terrace-Hill MAPC + 336 m^3/day	Terrace-Hill	336	0.25
Terrace-Hill MAPC + 673 m^3/day	Terrace-Hill	673	0.5
Terrace-Hill MAPC + 1346 m^3/day	Terrace-Hill	1346	1
Terrace-Hill MAPC + 2019 m^3/day	Terrace-Hill	2019	1.5
Terrace-River MAPC + 1011 m^3/day	Terrace-River	1011	0.1
Terrace-River MAPC + 2527 m^3/day	Terrace-River	2527	0.25
Terrace-River MAPC + 5054 m^3/day	Terrace-River	5054	0.5
Terrace-River MAPC + 10109 m^3/day	Terrace-River	10109	1
Terrace-River MAPC + 15164 m^3/day	Terrace-River	15164	1.5

5.4.3 Definition of Adequate Penetration

Consideration of whether existing wells have been drilled to a suitable depth is an important component of groundwater resource limit setting to provide an appropriate degree of protection for existing groundwater users. The concept of "adequate penetration" was developed to address this.

There is a need to define adequate penetration of the aquifer by individual bores in a way that relates to the annual groundwater fluctuation. The majority of bores in the Hāwea Basin do not fully penetrate the aquifer in their location. Instead, most bores are drilled and built so that the intake screen of the bore is sufficiently submerged to provide for the effects of self-induced water level variation, competitive bore-to-bore water level variations and natural variation in the water table, without necessarily extending to the base of the aquifer. These assessments are made somewhat empirically by drilling contractors, based on past operational experience and some degree of conservativism.

This study defines adequate penetration as three times the seasonal level variation below the mean groundwater elevation. An example of the adequate penetration threshold is given below -

Average seasonal range in monitoring wells = 3 m, and 3 x 3 = 9 m.

Mean groundwater level in a given location = 330 m AMSL
(330 m – 9 m = 321 m)

So, adequate penetration depth = 321 m AMSL

This measure of adequate penetration is used to assess the impact of various groundwater extraction scenarios. The basic questions are –

- Whether the modelled water levels fall below the adequate penetration elevation
- If the water level does fall below this threshold, how probable or frequent is the breach?

The adequate penetration levels are calculated relative to groundwater levels modelled under one or more scenarios (in our case long_current and long_nat). This approach removes any potential bias of comparing modelled scenarios to the adequate penetration, as any model bias is included in both the scenario model results and the calculated adequate penetration. However, care should be take comparing these calculated adequate penetration levels to measured groundwater data as model bias could impact the comparison. The adequate penetration groundwater elevations were calculated for each of the groundwater monitoring bores used in calibration and optimisation, plus the sector virtual wells (see below) used in assessing groundwater allocation.

5.4.4 Interpretation of results

Over the course of the modelling process, we produced results at a number of indicator wells spread across the model domain. The most useful figures are labelled as "quantile plots", which show the modelled heads against the modelled time series dataset quantile. An example of a quantile plot (Figure 18) plots the calculated percentile of the model heads at the indicator well over the modelled time series. In Figure 18 the rightmost dotted line (10% on X axis, 342.5 m on Y axis) on the long current line indicates that model heads for the long_current scenario at the upper Maungawera indicator well are less than or equal to 342.5 m msl for 10% of the modelled time period. Because the long_current scenario provides a reasonable sample of the historical record we can infer that if the future record is similar to the historical record (e.g. weather/climate) and the boundary conditions (e.g. lake stage) are similar to the long_current scenario then there is a 10% chance that the model heads at the upper Maungawera indicator well will be less than or equal to the modelled value (342.5 m msl). Note that this does not account for potential biases in the model results. More details on the standard modelled scenario results, including the location of all indicator wells, are available at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/Scenarios#standard-scenario-outputs

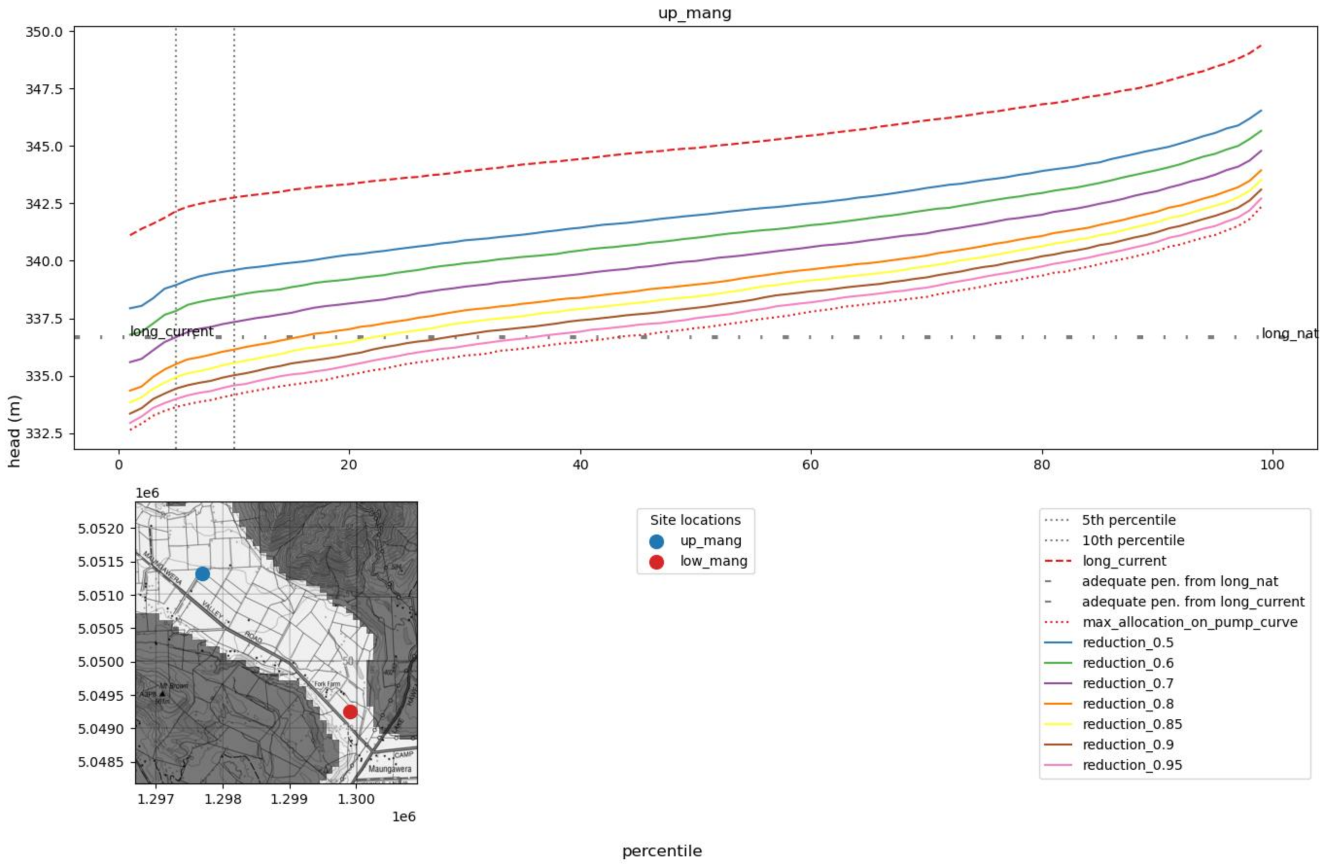


Figure 18 An example set of results to discuss the correct interpretation of the modelling results. Details on these scenarios are available in section 5.4.10.

5.4.5 Current usage and allocation

Table 9 below summarises the current usage, allocation, and any existing caps for the allocation zones presented in Section 5.2. Note that these allocation and usage estimates exclude the usage and allocation associated with the river proximal bores on the basis that these wells are more akin to surface water takes than groundwater takes.

Table 9 Summary of allocation zones and usage

Allocation Zone	Maximum daily usage m^3/day	Annual average usage m^3/yr	Maximum allocated daily rate m^3/day	Annual allocation (135 x daily rate) m^3/yr*	Annual usage as a percent of allocation	Existing allocation limit
Hāwea Flat	18,509	2,446,783	68,472	9,247,500	26.5%	8,680,000
Grandview Zone	0	0	0	0	n/a	n/a
Terrace – River	2,387	303,554	10,136	c	22.2%	1,560,000
Terrace – Hill	174	45,314	1,346	181,710	24.9%	410,000
Sandy Point	56	13,233	233	31,455	42.1%	860,000
Te Awa	0	0	0	0	n/a	297,000
Maungawera Flat	0	0	0	0	n/a	570,000
Camp Hill Moraine	0	0	0	0	n/a	n/a
Maungawera Valley	1,200	130,305	4,696	675,000	19.3%	1,210,000
Butterfield Exclusion	0	0	0	0	n/a	n/a
Campbell's Exclusion	0	0	0	0	n/a	n/a

* The current annual allocation is difficult to calculate as the analysis in Kitteridge (2022) focused on providing daily usage data and daily maximum allocated rates. In the absence of a detailed analysis of current consents we use the 135 times the maximum daily rate that was established in our typological pumping curve.

5.4.6 Hāwea Flat Allocation Zone

The full suite of relevant allocation scenarios for bore G40/0367 in Loach Road, Hāwea Flat are presented in Figure 19. We have included this figure because it was one of the most sensitive indicator wells, but plots were generated at all high frequency monitoring bores and indicator wells. These figures are accessible in the Github Repo and are best accessed via: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/Scenarios#zone-specific-scenario-methods-and-results

Figure 19 suggests that if all users were to take water at their maximum allocated rate (max_allo_on_pumping_curve), bores in and around the Hāwea Flat would likely see water levels below the adequate penetration level for approximately 5% of the time. The maximum allocation scenario would represent a 377% increase in the rate of abstraction as presently groundwater users are taking 27% of their annual rate on average. Consent allocations typically apply for more water than they would use in an average year to maintain water availability in dry years, but this does leave a significant amount of abstraction available under the current consents that might be used, for instance with changing land use.

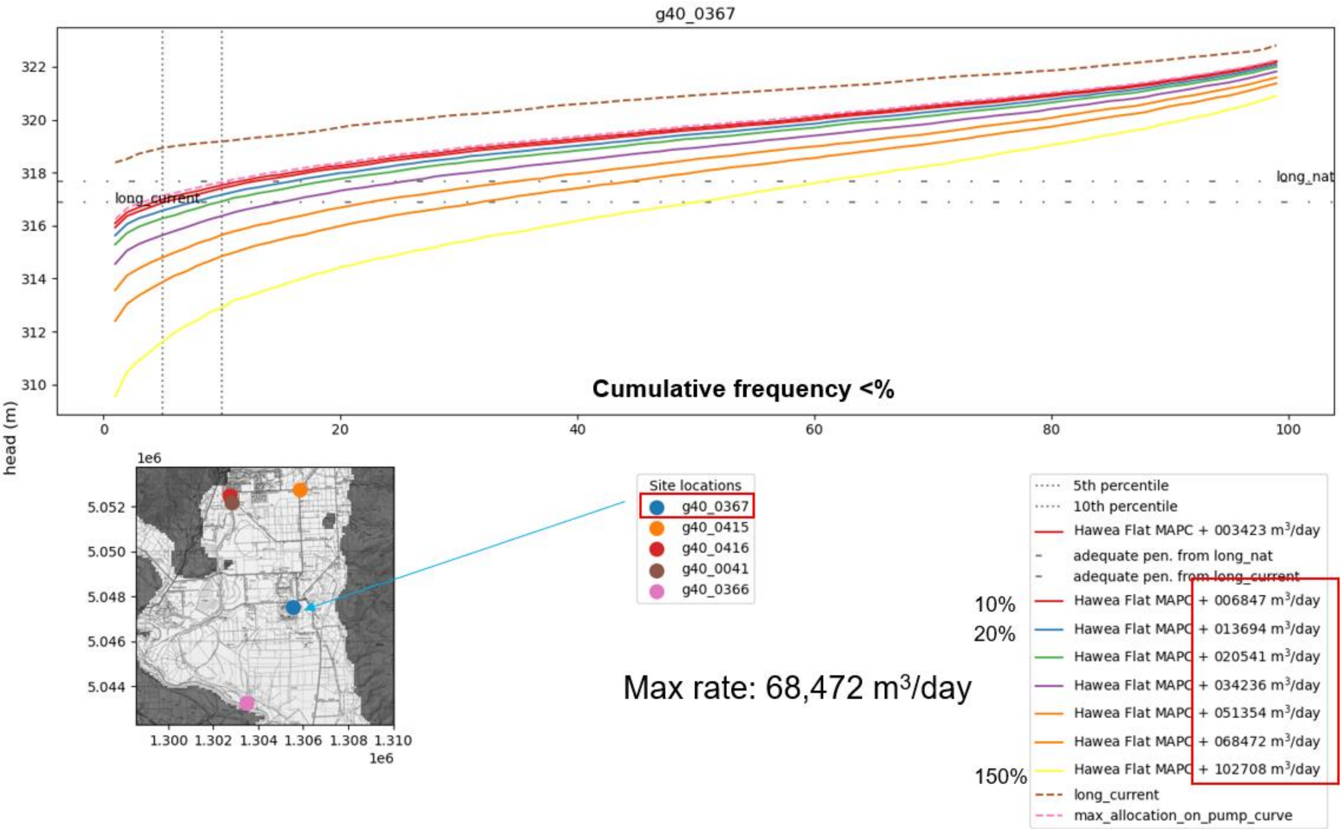


Figure 19: Long-current, MAPC and 10% to 150% of consented allocation pumping scenarios against Adequate Penetration levels of AP under natural and AP under current conditions of groundwater usage

Anecdotal information gleaned from newspaper reports and statements made to the regional council suggest the following –

- Low groundwater levels in the spring of 2008 led to complaints beginning in mid-September of a small number of bore failures in eastern end of Camphill Road, Hāwea Flat,
- The affected bores were all understood to be comparatively shallow and not adequately penetrating.

Unfortunately, the period pre-dates the installation of groundwater monitoring in the Hāwea Basin or comprehensive water metering. Measured quarterly groundwater level measurements in the NGMP monitoring bore in Camphill Road inside the rural residential settlement measured the lowest level at this time for the period 1997 to 2020. Lake Hāwea had also dipped its lowest level in the same period of 338.1 m, barely above the consent minimum.

Bore failures have been experienced in the basin, but probably not of fully or adequately penetrating bores since lake levels stabilized within the 1980s. This is broadly consistent with the comparison of the long-term response to abstraction at current rates of actual usage versus the maximum allocation rates allowed under issued consents.

These model results overall suggest that additional allocation granted in the Hāwea Flat allocation is likely to lead to a reduction in reliability for existing groundwater users. The additional allocation scenarios presented in Figure 19 provide ORC with additional information on the likely impacts of issuing allocation beyond current allocated levels.

5.4.7 Grandview Allocation Zone

The chief difficulty in making a more certain statement on the ability and magnitude of water that could be sustainably allocated to groundwater abstraction in the Grandview special zone is the overall lack of data on aquifer geometry, groundwater levels or aquifer properties. Groundwater information is incomplete, but current indications are concerning. The principal concerns relate to the uncertain aftermaths of movement on the Grandview Fault and the presence of basement outcrops and aquifer shallowing potentially cutting the zone off from useful hydraulic communication with the rest of the Hāwea Flat Aquifer. This study notes that there is currently no bore allocated with groundwater in the zone.

In the absence of bespoke groundwater information, the standard process for establishing a sustainable allocation is to set an allocation limit of up to 50% of land surface recharge, which would be up to 787,000 m^3/year. However, local complex geology related to the Grandview Fault could produce local areas of more significant impact. Another option is to set a zero-groundwater allocation while allowing permitted activity groundwater use to continue. Regardless, any groundwater in the Grandview allocation zone eventually recharges the main Hāwea Flat aquifer. Therefore, any water allocated to the Grandview allocation zone would need to be removed from allocation limits for the adjoining Hāwea Flat zone to prevent impacts in the Hāwea Flat allocation zone.

5.4.8 Terrace – Hill Zone and Terrace – River Zone

Terrace – Hill zone

The Terrace – Hill zone supplies a small quantity of consented stock water, domestic and irrigation abstraction. As is the case for the Hāwea Flat Allocation Zone, we have included the results for the southern portion of the High Terrace (Figure 20), because it was one of the most sensitive indicator wells, but plots were generated at all high frequency bores and indicator wells. These figures are accessible in the Github Repo and are best accessed via: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/Scenarios#zone-specific-scenario-methods-and-results

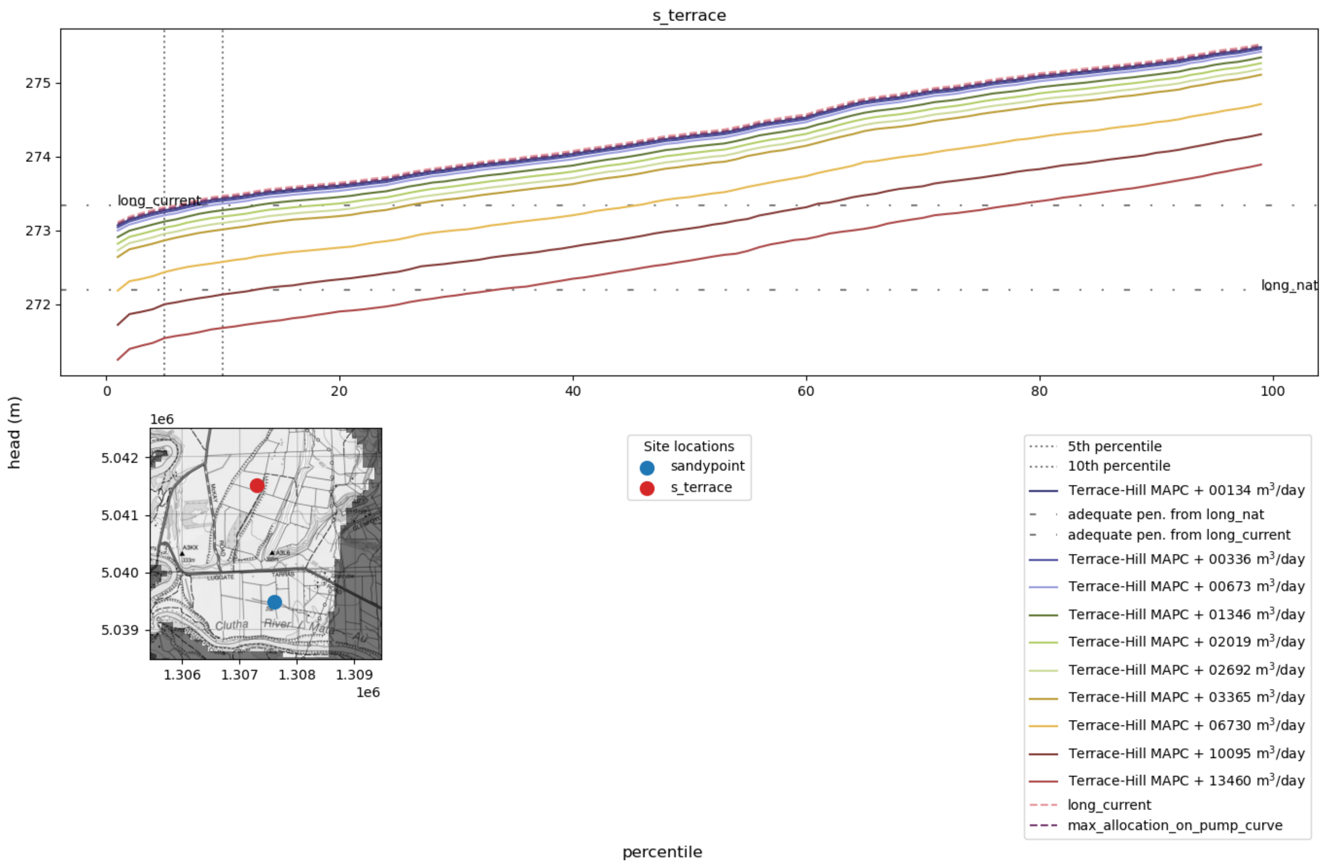


Figure 20: Modelled impacts of abstraction for the s_terrace synthetic monitoring point

The Terrace - Hill zone is a lightly exploited and potentially unattractive zone for groundwater abstraction for irrigation, and the transient modelling does not paint a more favourable picture. The results suggest that even relatively modest increases could see reduced reliability relative to the long_current scenario. It is worth noting that the adequate penetration level for the long_current scenario is actually higher than that of the long_nat scenario. This is due to the prevalence of Hāwea river sourced irrigation increasing the LSR without much additional pumping. The size of this impact varies across the High Terrace; however, it does raise an interesting question for decision makers: currently, light groundwater usage appears to lie on the cusp of exceeding thresholds for adequate reliability if that adequate reliability is defined from the long_current scenario, but if the adequate reliability is defined from the long_nat scenario an additional 2019 m^3/d (1.5x the current allocation) may be available before reliability begins to be impacted. The size of the increase represents a stress to the hydrological system outside of the optimisation conditions which will likely increase the uncertainty of the prediction. The existing allocation cap of 410,000 m^3/yr is similar to the allocation cap we recommend above 454,275 m^3/yr (current consents and additional maximum rate of 2019 m^3/d multiplied by 135 days), so this work further supports the allocation limits recommended by Wilson, 2012.

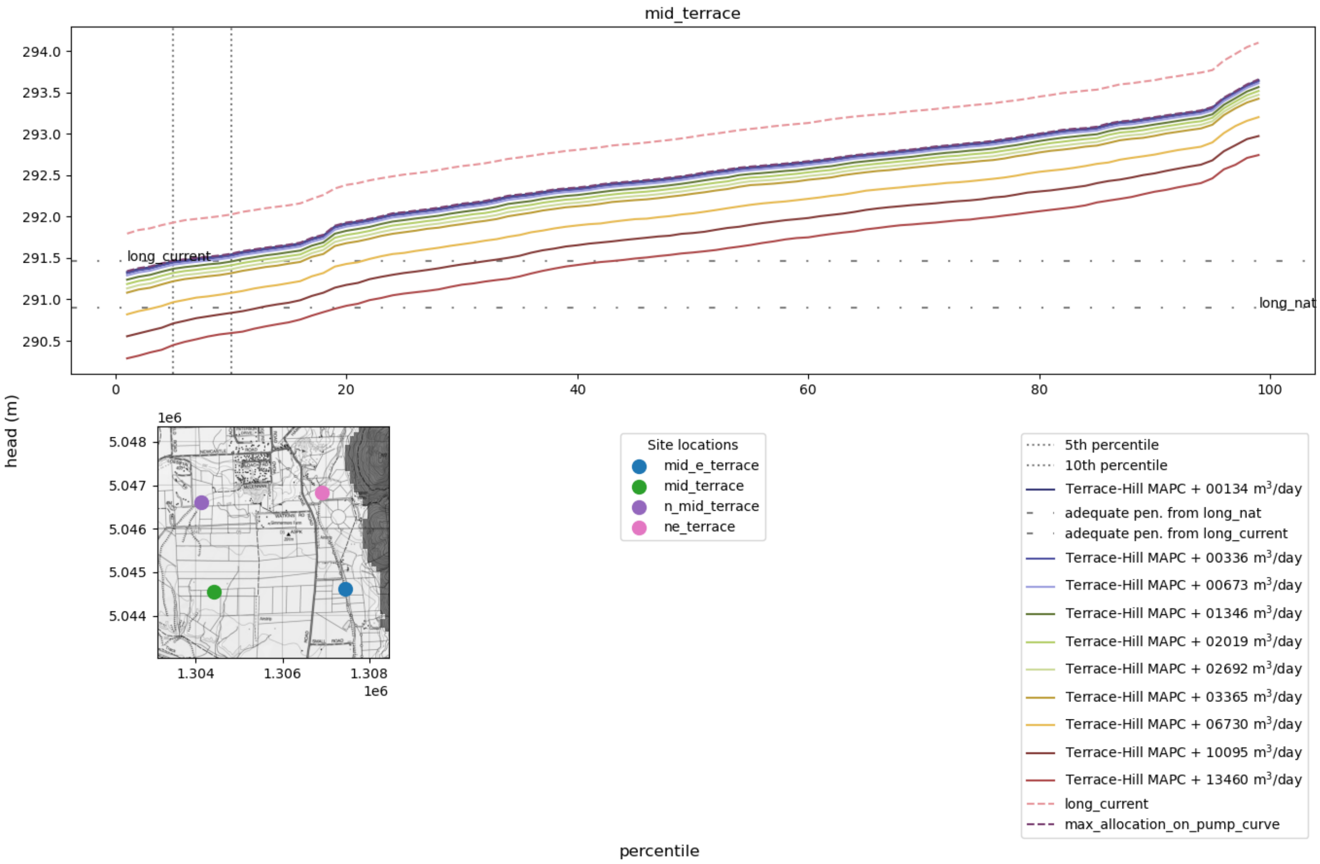


Figure 21: Impacts of additional abstraction in the Terrace - Hill Zone at the mid_terrace synthetic monitoring point

Terrace – River Zone

The Terrace – River Zone has a small number of consented takes, with a major abstraction bore on the sub-terrace on the southwest portion of the zone. The transition to maximum daily allocation on the typological pumping curve (MAPC) has minimal impacts on the Terrace – River levels except near the sub-terrace monitoring point. This point is very close to the main abstraction bore in the area and so these impacts are likely local effects. Model results for some of the Terrace – River Zone monitoring points also demonstrate impacts where the long_current adequate penetration level is inflated relative to the long_nat adequate penetration level.

Based on our modelling, a 100 percent increase in abstraction over the MAPC likely would not yield significant reliability changes relative to the lowest adequate penetration level (long_current in some bores and long_nat in others). However, the division between the Terrace – River Zone and the Terrace – Hill Zone is not a groundwater flow boundary. Therefore, abstraction in one zone can impact water levels in the other, particularly when that abstraction is near to the boundary between the two zones; this effect is demonstrated in Figure 21 and Figure 22. The division is to ensure that abstraction is appropriately distributed across the High Terrace and particularly to avoid local over allocation near the base of the Grandview Range. Any decisions to adjust the allocation limits in either of the Terrace Zones should consider the impacts on the other zones. If the full allocation in the Terrace – Hill Zone was granted as well as additional allocation in the Terrace - River Zone, the centre of the High Terrace could see groundwater levels drop below even the long_nat adequate penetration level. In the event that an increase in groundwater allocation is the preferred option for this zone, a more modest increase of 25% would provide a more conservative approach to address this eventuality. This approach would yield an allocation cap of 1,710,500 m^3/yr and a maximum daily take of 12,700 m^3/day, which is a modest 10% increase on the allocation limit suggested by Wilson (2012).

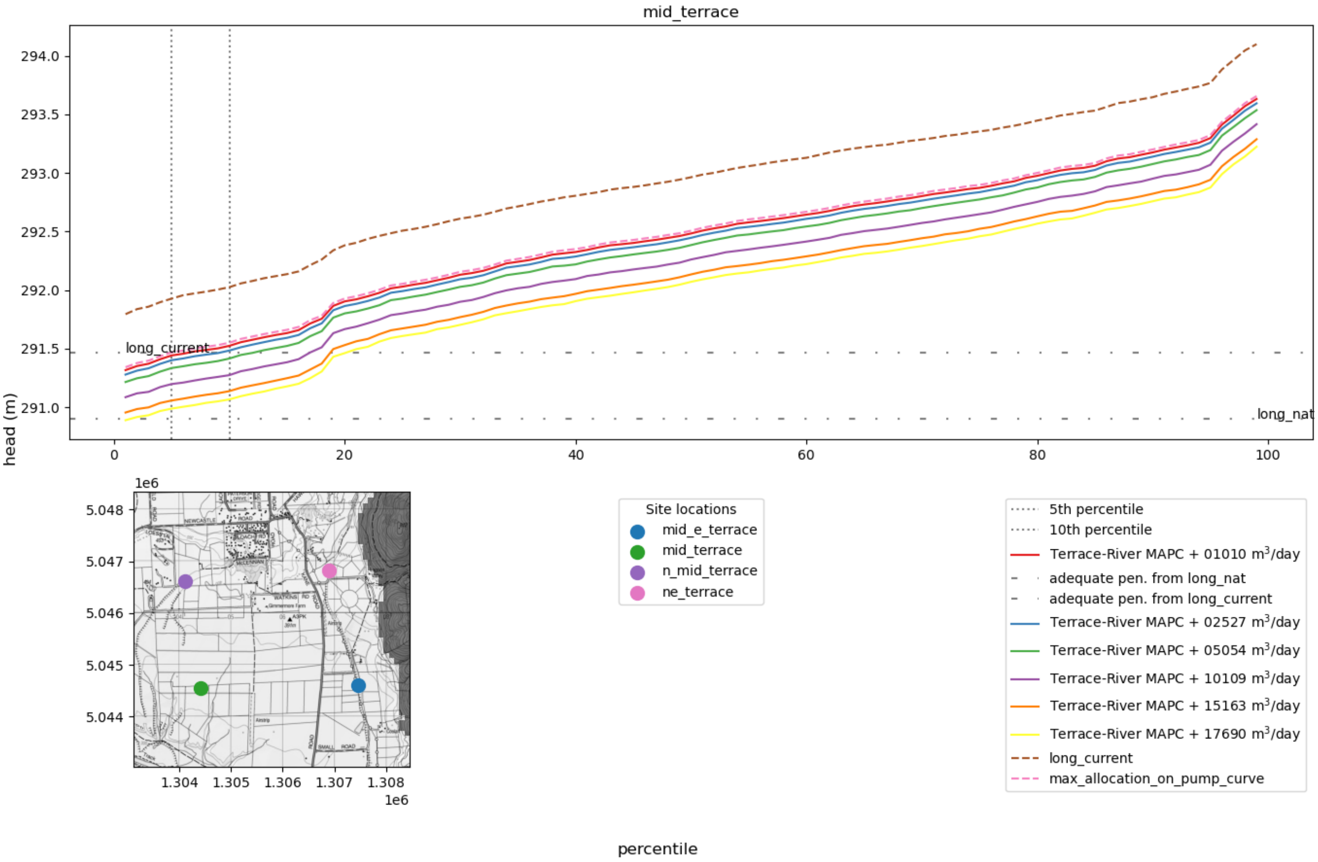


Figure 22: Impacts of additional abstraction in the Terrace – River Zone at the mid_terrace synthetic monitoring point

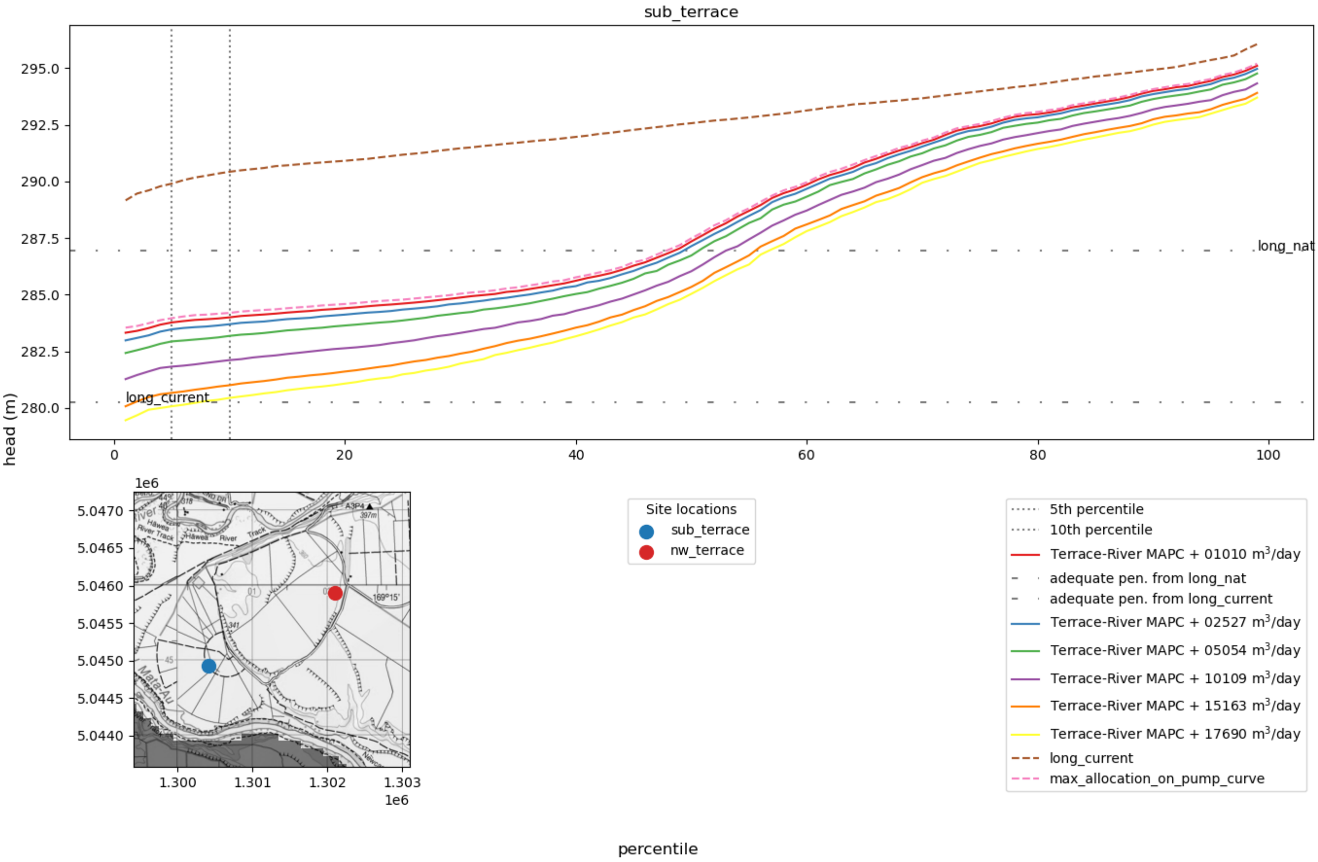


Figure 23: Impacts of additional abstraction at the sub_terrace synthetic monitoring point

5.4.9 Wetlands Setback Zones

One key interest for this study was the potential for groundwater abstraction to impact either of the significant wetlands in the Hāwea area. The effects of groundwater abstraction on a water body are typically considered in terms of direct effects and cumulative effects. Direct effects are normally managed under consenting or renewal processes for individual consents via a requirement for groundwater water take applications to include an assessment of the abstraction on surface water bodies and existing groundwater water users. Cumulative effects are normally managed via allocation limits within a given area. The purpose of the modelling presented here is to address the latter and not the former. To accomplish this, we undertook a specific modelling investigation of the cumulative impacts of pumping under different model parameterisations. Full details and results for this work are available in the Github Repo at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/Scenarios#wetland-setback-scenarios

Through a mixture of quantitative and qualitative assessments of a significant number of model results we identified two zones where cumulative groundwater takes are likely to have the greatest impact on these significant wetlands. We have labelled them as exclusion zones where, if adopted, no groundwater abstraction would take place. Figure 24 maps the location and extents of the potential allocation zones for exclusion (or significant limitation) of groundwater abstraction around the respective wetland areas. Note that this assessment was primarily focused on the peak depletion of single abstraction points. Significant cumulative abstraction outside of these exclusion zones could still have impacts on the wetlands.

Presently there is no consented activity within these zones. The nearest significant abstractions are the large gallery wells near the Clutha River, which are unlikely to impact the wetland because the majority of their water is likely sourced directly from the Clutha River. The Butterfield exclusion contains no known wells, while the Campbell's exclusion contains seven possible wells, which would need further review. At least one of the wells is a monitoring bore (G40/0366) and all but one of the remaining wells are within 50 m of the Clutha River. The final well (G40/0422) has a listed activity usage as irrigation, is within 100 m of the Campbell's wetland and is closer than that of G40/0366, which, through concurrent monitoring, has been shown to have identical water levels to the Campbell's wetland. Therefore, we believe that abstraction at G40/0422 is likely to negatively impact Campbell's wetland.

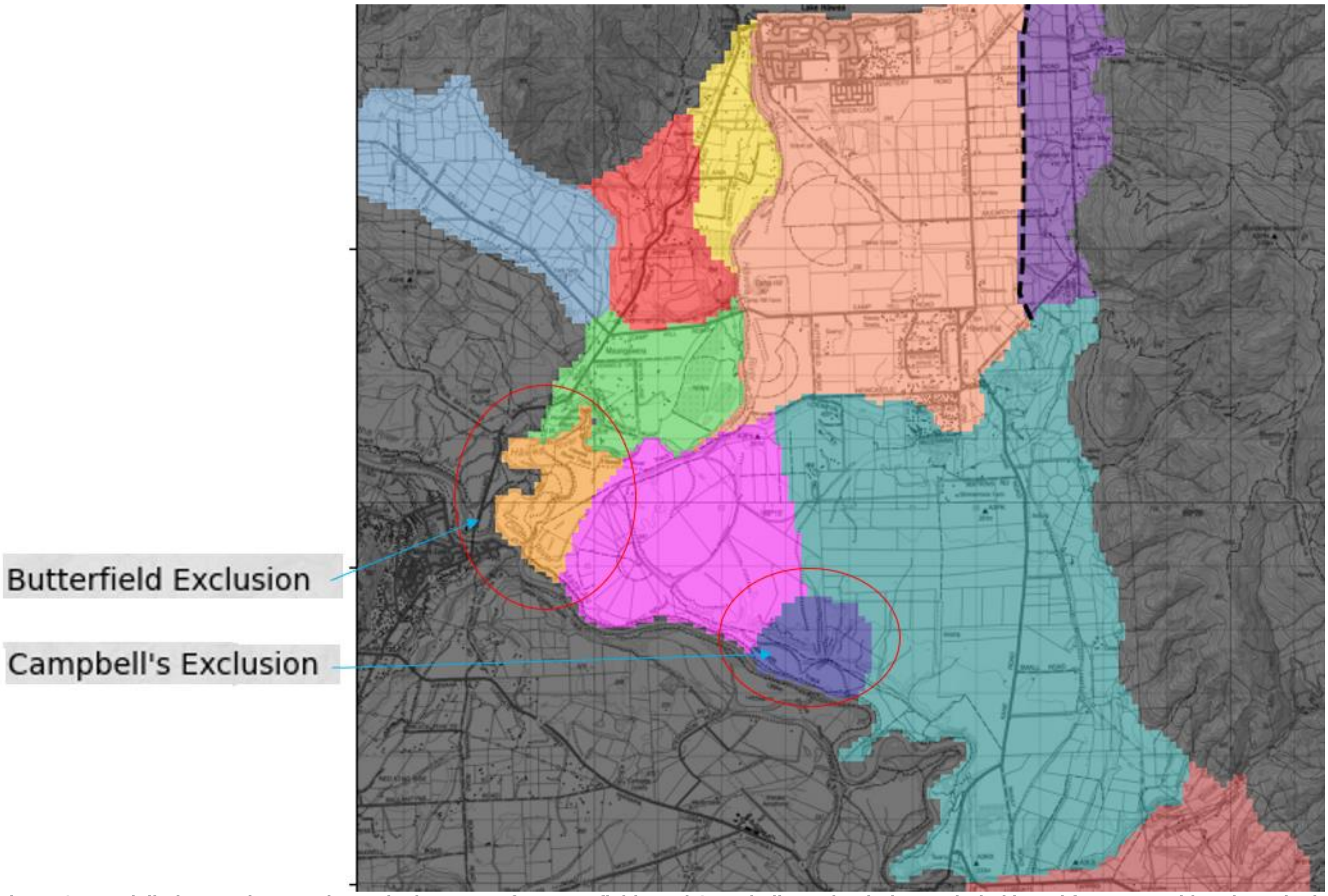


Figure 24: Modelled groundwater take exclusion zones for Butterfields and Campbells wetlands (zone circled in red for geographic orientation).

5.4.10 Maungawera Valley Zone

The Maungawera Valley Zone has been considered to be fully allocated at 1.2 million cubic metres of groundwater per year (via ORC webmap). Our analysis of groundwater users suggests the allocation is closer to 675,000 m^3/yr. It is unclear where this discrepancy originates, but we suspect that bores near Lake Wānaka or in the adjacent Quartz Creek zone may account for the difference between the ORC webmap and our allocation analysis. Regardless, current usage only amounts to 11 – 19% of the allocation total within the valley, suggesting the some or all groundwater users make light or only occasionally use of the groundwater they hold consent for.

Model assessment suggests that while the Long_current level of usage is consistent with keeping groundwater levels above the thresholds for adequately penetrating bores, groundwater abstraction at maximum allocation on the pumping curve (MAPC) would result in these thresholds being significantly exceeded. Figure 25 and Figure 26 illustrate the results of pumping scenarios of the Maungawera Valley at the Lower Maungawera (*low_mang*) and Upper Maungawera (*up_mang*) virtual monitoring sites. It was clear during the scenario modelling process that the Maungawera Valley Zone could not sustain additional pumping to the MAPC scenario, so instead reductions to the MAPC pumping rates were tested.

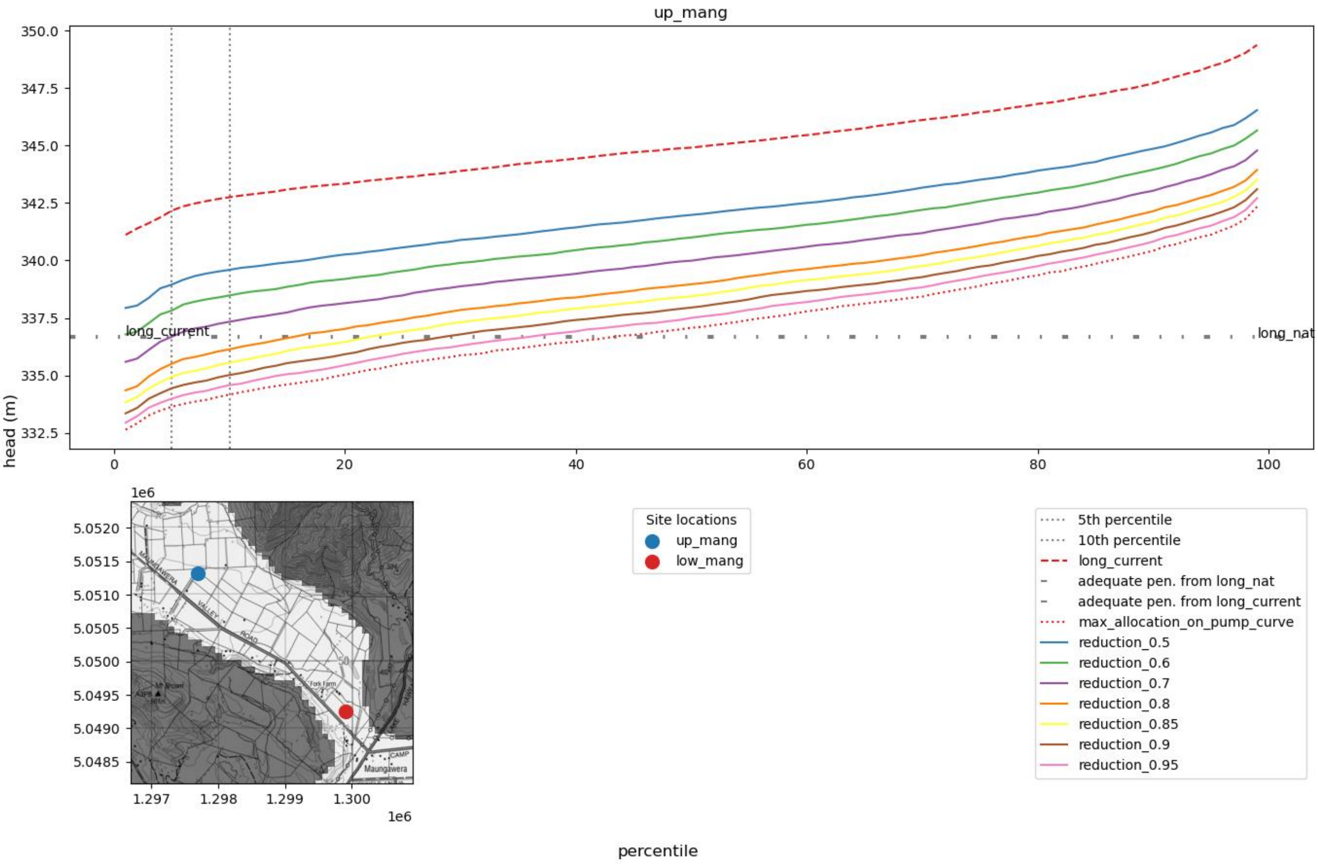


Figure 25 Results at the upper Maungawera synthetic monitoring point

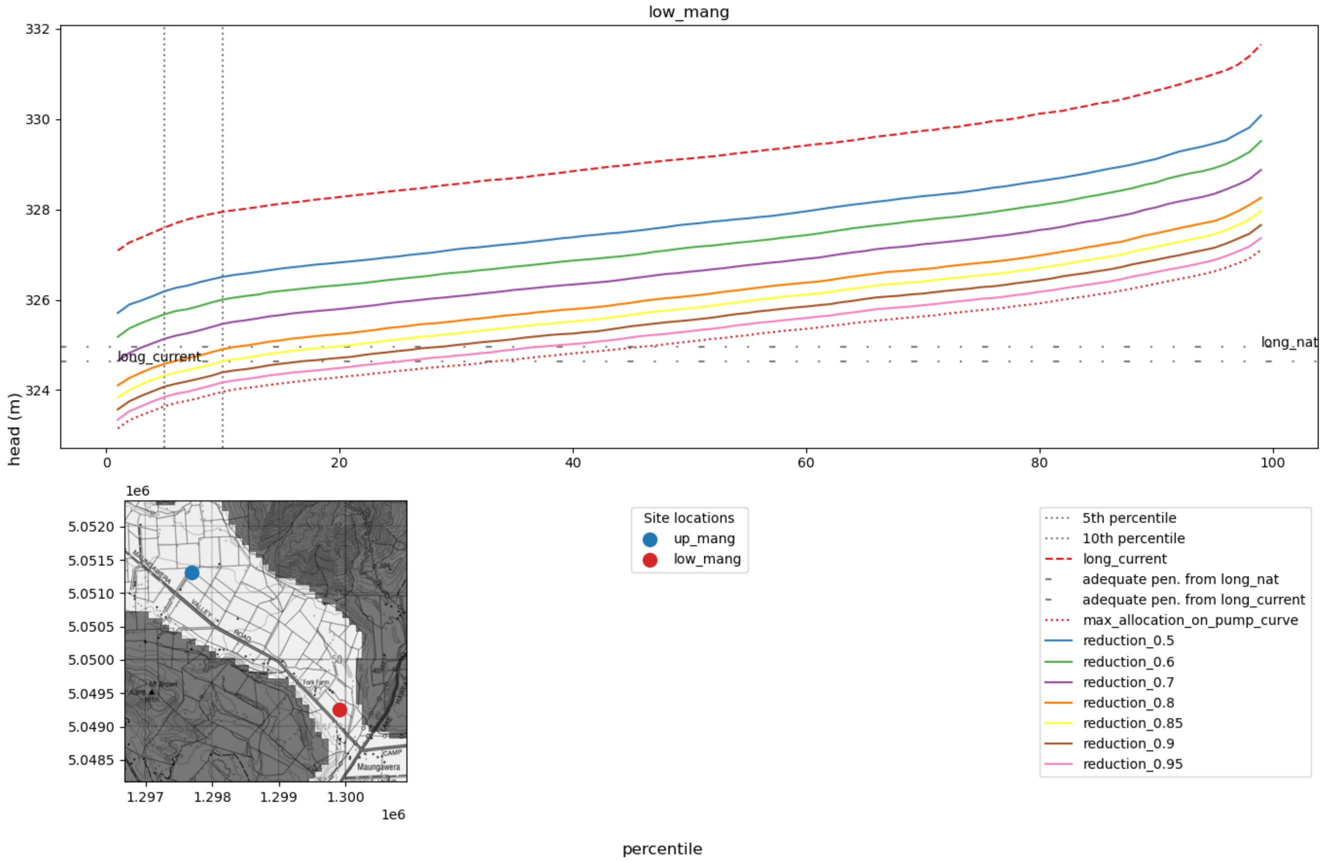


Figure 26: Results at the Lower Maungawera indicator bore

The modelling results suggest that under the maximum allocation scenario the adequate penetration threshold would be exceeded 40-50% of the time. In order to reduce the frequency of exceedance to 5% of the time or lower, a reduction to 70% of the current groundwater allocation would be necessary. A reduction to 60% of the current groundwater allocation would yield minimal exceedances. Note that a reduction to 60% corresponds to a maximum allocated daily rate of c. 2,800 m^3/day and a reduction to 70% yields c. 3,300 m^3/day. This is far greater than the maximum daily usage recorded between 2015 and 2020 (1,200 m^3/day). This suggests that there is capacity for the current activities, even with a significant reduction in allocation. However, if water use should intensify, groundwater reliability could become problematic. Regardless, the Maungawera Valley is clearly an area with the potential for groundwater management problems. We would suggest additional monitoring (e.g. a high frequency bore in the lower Maungawera Valley), so that additional data can be captured to better understand potential issues before they arise.

5.4.11 Maungawera Flat and Te Awa Zones

Both the Maungawera Flat and Te Awa zones are adjacent to the Hāwea river, have no consented groundwater takes and have very minimal groundwater level information. Our modelling shows both zones could have significantly higher groundwater usage before impacting the reliability of supply (see Figure 27 as an example). In both cases we believe that these results indicate that the model is sourcing much of this additional water by depleting the Hāwea River. Given the minimal information constraining the model in these zones a conservative approach to allocation setting in these areas would be to maintain the current allocation caps (297,000 and 570,000 m^3/year for the Te Awa and Maungawera Zones, respectively). Should demand in these zones increase, additional monitoring will be necessary to better constrain the availability of Hāwea River sourced water in these zones.

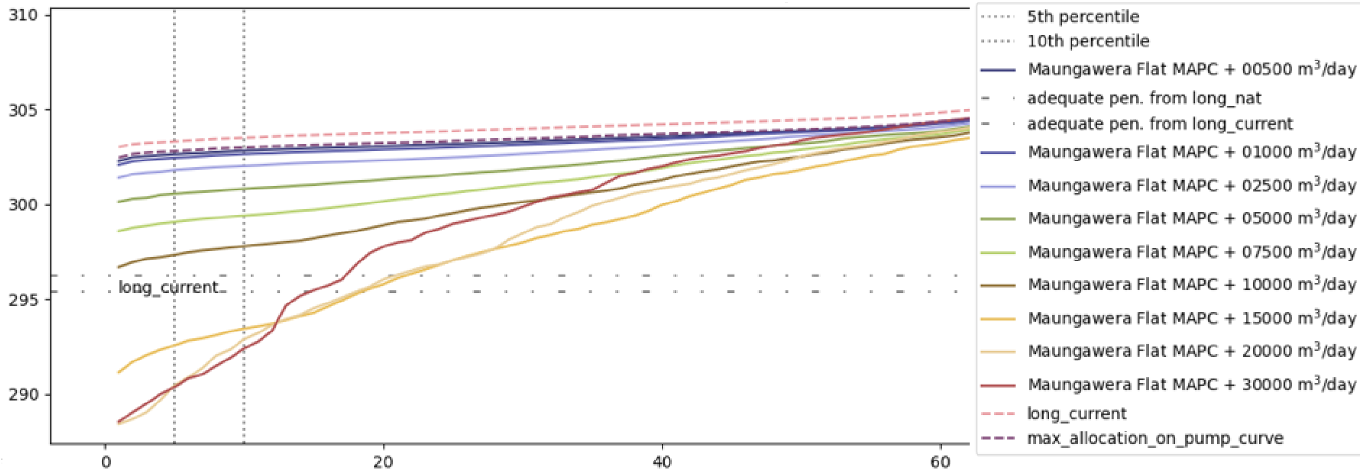


Figure 27: Modelled groundwater elevation (m AMSL, y axis) and occurrence (x axis) for current usage, MAPC and additional groundwater pumping.

5.4.12 Camphill Moraine Zone

The Camphill Moraine has been previously discussed. It is thought to have utility as a groundwater resource for small (permitted activity level) groundwater takes such as domestic supplies, stock water, etc. The glacial till has a haphazard pattern of moderate permeability lenses amongst a low permeability groundmass. Accordingly, this study carried out no modelling assessment into groundwater allocation and instead suggests that the most conservative approach would be to assign the zone an allocation limit of zero while retaining any permitted activity takes.

5.4.13 Sandy Point Zone

The Sandy Point Zone has a large near-river groundwater take, but minor current groundwater usage of 56 m^3/d and 13,233 m^3/year. The groundwater take allocation cap is currently 860,000 m^3/year on the basis of recharge estimation (Wilson, 2012). This study found that the 50% of mean LSR limit falls at 13,211 m^3/d, 660,570 m^3/year. This is more than an order of magnitude beyond the current allocation (excluding near river takes). A conservative approach would be to adopt a new lower limit (e.g. cap at 660,570 m^3/year). There is presently very little demand for groundwater in this zone but should demand increase there is insufficient data to further assess the sustainable level of groundwater abstraction. Any further analysis would require a monitoring programme to provide a basis for future review. Note our LSR limit excludes hillside creek inflows which are likely to be a significant contribution to the water budget.

5.5 Lake Levels Modelling Assessment

A key outcome of the new modelling work is a far better understanding of the interactions between changes in the Lake Hāwea water levels and the groundwater system as a whole. Section 2.1 outlines the existence of an invert below which the groundwater levels relative to the Lake Hāwea levels become significantly different to the relationship that has been observed historically. The exact structure and level of this invert is unknown, but for the purpose of modelling we assumed a flat invert at 335 m msl. Further information on the invert can be found in the Github repo at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/model_build#multi-layer-3d-model-structure

We modelled a number of different lake level patterns above and below the invert level. The methodology for developing these scenarios is available in the Github Repo at: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/Scenarios#lake-hawea-levels-for-low-lake-scenarios. The full list of the scenarios run and the results (across all indicator wells) are also available in the Github Repo, and are best accessed via: https://github.com/Komanawa-Solutions-Ltd/Z22031HAW_hawea-model/tree/main/Scenarios#low-lake-hawea-level-scenarios.

In this report we will focus on the “lake_drop” scenarios where the lake levels rapidly drop below the assumed invert and remain there for several years. This scenario is not likely but serves to demonstrate the relationship between Lake Hāwea and the groundwater system. The two assessment locations we have included below coincide with monitoring bore G40/0415 at the corner of Gladstone and Cemetery roads, and G40/0367 at Loach Road, Hāwea

Flat. Figure 28 illustrates the long period and substantial decline in Hāwea Flat groundwater levels arising from the modelled long-term drop in lake level as described.

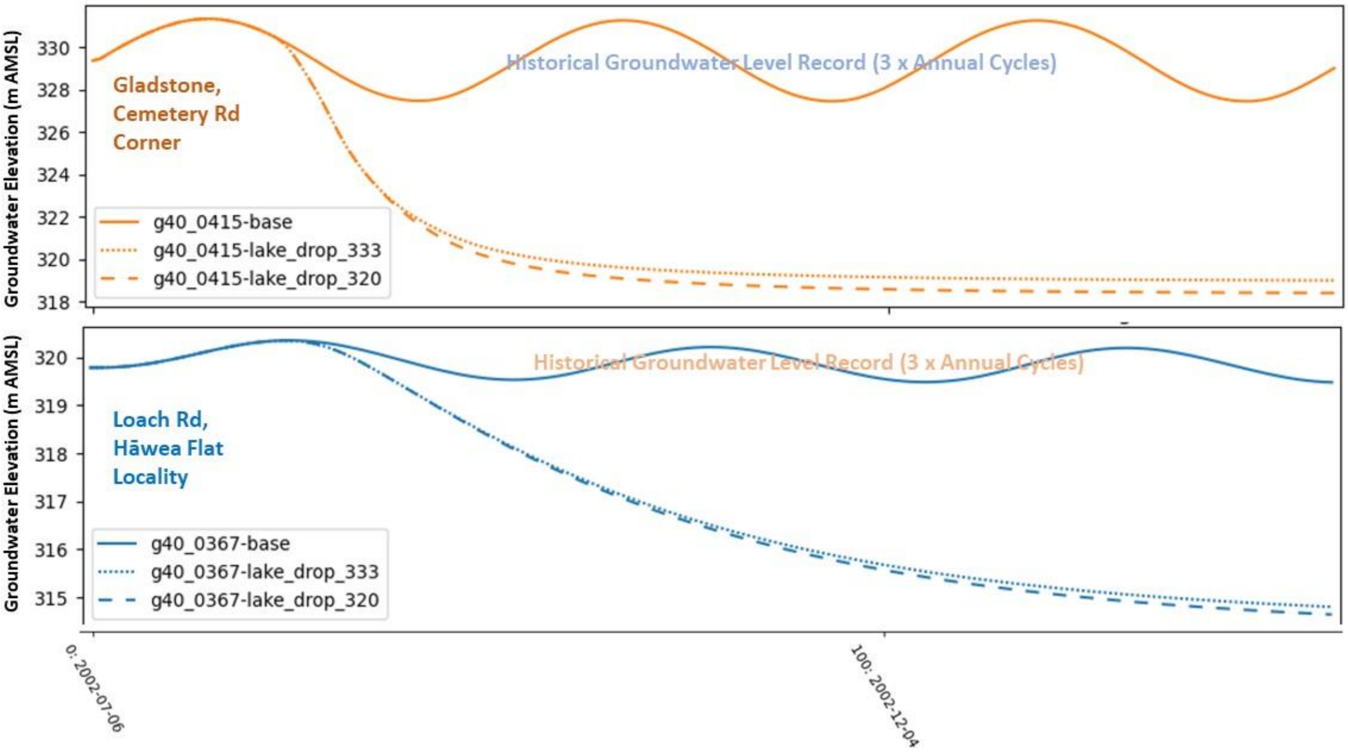


Figure 28: Simulated groundwater level drops arising from lake level dropping to 333 m msl and 320m msl at monitoring bores G40/0415 and G40/0367.

Closer to the lake in G40/0415, the overall decline was indicated from modelling to be about 11 m. Further down down-gradient in the Hāwea Flat locality, the overall declines are up to 5 m and the full effect of the decline is shown numerically to be lagged by up to two years. There is little difference in the two simulated lake level declines (to 333 m or 320 m AMSL) provided the lake level is beneath the inferred berm invert level. Such declines would cause significant decreases in bore reliability in the Hāwea Flat Aquifer. Bores in the Hāwea Basin historically have been subject to 2.5 m to 3.0 m of groundwater level variation. Declines to more than 5 m, reaching 11 m in places, would lead to the failure of many bores, especially those installed for domestic or stock water utilisation since these are usually not taken to the base of the aquifer. The plots also suggest that the magnitude of lake level decline is immaterial, as long as it is lower than the invert. Further work is required to determine the invert level of the inferred low permeability feature described above.

6. MODEL LIMITATIONS AND RECOMMENDED ADDITIONAL DATA

6.1 Model limitations

There are a number of limitations to this model and the model optimisation. The main limitations are:

- A non-unique model structure: Because the complex structure in the moraine zone is not well constrained by the data we have assumed a very simple model structure that almost certainly introduces structural error. It is likely that some of the parameters in the model are compensating for this model structural error, which may have flow on effects, particularly for scenarios that are well outside the model optimisation conditions.
- A non-unique parameterisation: the PEST optimisation process is a poorly posed problem (that is there is not enough observations to calculate a unique solution to the model parameters). This means that there are multiple solutions to the model parameters that represent a good fit to the observations. This model has not undergone a parameter uncertainty process so we cannot predict the likely range or implications of the parameter uncertainty. In addition, the uncertainty of the model parameters is compounded by the uncertainty in the model structure. There are likely many other model structure/parameter sets that would fit the observations as well as this model.
- Area to the east of Grandview Fault: The model has persistent dry cells to the east of the inferred location of the Grandview Fault. This is likely due a combination of model structural and parameterisation errors. The results from this area should not be used and there is currently insufficient data to produce a trustworthy model in this area.
- Limited data for hillside streams: The hillside streams are a major source of water to the Hāwea aquifer systems, but we only have observations from two gauging sites for a limited period of time. We estimated the inflows from a correlation with the Lindis River; however, both of the gauged streams are of similar size so the correlation may not hold for the smaller hillside streams.
- Piezometric survey date: the only piezometric survey conducted for the Hāwea aquifer system was conducted in Sept of 2011. This survey was conducted outside our optimisation period (we did not have adequate abstraction information to conduct the model optimisation during 2011). A significant portion of the model domain therefore does not have any observations taken during the optimisation period, which adds another source of uncertainty to these areas of the model.
- Parameterisation near Butterfield Reserve: Butterfield Reserve is a sensitive wetland in an old oxbow of the Hāwea River. The final parameterisation in this area is for a very low hydraulic conductivity which likely underestimates the degree of connectivity between Butterfield Reserve and the Hāwea River. Model results here should be used with caution.

6.2 Additional Data

Over the course of our optimisation process we identified a number of additional data sources that would be useful. We have listed them here, with a discussion of why the information would be useful, but we have not included any feasibility assessments or costings to acquire these data sources. We recognise that some of these data sources may not be feasible but we have included them here so that decision makers can consider their relative value. We have not ranked these additional data sources in any way as any prioritisation is an intersection of priories (which we cannot address) and scientific merit.

- **A high frequency groundwater record near the Northeast Corner of the Hāwea Flat aquifer:** One of the key model predictions for the complex moraine structure is that groundwater levels (impacted by the lake) should be elevated in and around the Grandview/John Creek alluvial fans. Testing this prediction would require a high frequency groundwater level record in this area of at least a couple of years in length. The exact location of such a bore would need more detailed consideration.
- **A high frequency groundwater record near the exit of the Maungawera Valley:** The Maungawera Valley has a relative paucity of data which makes predictions regarding the sustainable use of groundwater uncertain. A high frequency monitoring bore near the exit of the valley (e.g. up valley of the Maungawera Valley Road and Lake Hāwea Albert Town Road intersection) would act as an integrator for the up valley groundwater system and would provide significantly more information about the local groundwater system. The exact location of such a bore would need more detailed consideration.
- **A high frequency bore near the Hāwea domain and/or Butterfield Road:** Water from Lake Hāwea can flow either toward Hāwea Flat township or it can flow back towards the Hāwea River. Understanding the piezometric surface in the aforementioned area would help constrain that flow. The exact location of such a bore would need more detailed consideration.

- **A detailed investigation of moraine structure:** As mentioned multiple times within this report, the moraine structure is not well constrained by the data. A detailed investigation of the moraine structure would help constrain the model structure and reduce the uncertainty in the model predictions. The method of investigation would need significant consideration and would likely require a combination of geophysical and drilling investigations.
- **An investigation of structure to West of Hāwea flat Township:** As discussed above, glacial geomorphology suggests that there could be a low permeability structure to the west of Hāwea Flat township associated with a potential lateral moraine of the Albert Town advance. Further investigation of this possible structure would help constrain our understanding of the groundwater system in this area.
- **Multiple concurrent gauging of multiple hillside streams:** The hillside streams are a major source of water to the Hāwea aquifer system. However, we only have observations from two gauging sites for a limited period of time. We estimated the inflows from a correlation with the Lindis River; however, both of the gauged streams are of similar size so the correlation may not hold for the smaller hillside streams. Multiple concurrent gaugings (at high and low flows) of multiple hillside streams (both large and small catchment areas would help constrain the predictions of inflows from the hillside streams.
- **Additional Piezometric surveys:** At present the only piezometric survey completed in the Hāwea region was conducted in Sept of 2011. This survey was conducted we had adequate abstraction information and so we had to transpose these groundwater head targets to dates inside the optimisation period, which adds uncertainty to the targets and therefore the model. One or more additional piezometric surveys (e.g. at high and low water levels) would help constrain the model predictions in the areas that are only informed by the piezometric survey.
- **Model parameter / structural uncertainty analysis:** In the absence of additional data collection more information about the uncertainty of the model predictions could be obtained by conducting a parameter / structural uncertainty analysis. Given the significant structural uncertainty in the moraine zone we would recommend calibrating and conducting parameter uncertainty analysis on many different model structures. This would be a significant undertaking but could easily build on the work and data analysis from this project and contained within the Github Repo.

7. CONCLUSIONS AND IMPLICATIONS

This study has provided a contemporary review of the Wilson (2012) model and groundwater allocation study. The Wilson study has been the foundation for managing the basin's water resources as the various strengthening plan changes to the Regional Plan: Water had come into operation since 2012. This study has provided additional insight into the nature and responses of the groundwater resource available in the Hāwea Basin. It has also reviewed the current allocation limits and assessed the levels of abstraction that are consistent with maintaining current reliability of existing water supply wells. The key conclusions of this report are:

1. A review of the groundwater allocation zones suggests the following changes would provide an improved basis for groundwater resource management,
    1.1. Combine the current Hāwea Flat – Hill and Hāwea Flat – Lake zones into one Hāwea Flat zone as most of the zone shows evidence of a connection with Lake Hāwea.
    1.2. Create a new allocation zone (Grandview Zone) to the east of the inferred Grandview Fault as basement rock in this area may be up-thrust and cause a disconnect from this portion of the aquifer and Lake Hāwea. We note that the location of this zone boundary is uncertain and suggest possible methods for water users to prove they are actually within the Hāwea Flat allocation zone. Specifically, we suggest that groundwater take applications within the mapped Grandview allocation zone to be within included in the Hāwea Flat allocation zone if it can be demonstrated that the take has access to lake recharge via the groundwater system and the take has adequate freeboard to accommodate water table decline
    1.3. Identified areas, which adopted as exclusion zones for groundwater abstraction, should limit the impacts on the Butterfield and Campbell's Wetlands
2. The distinction between river proximal galleries and true groundwater abstraction should be better constrained. If all the river proximal bores in the Hāwea domain were to transition into the centre of the aquifer there would likely be significant groundwater impacts.
3. Groundwater abstraction at current use levels is very likely to be sustainable assuming future climate and Lake Hāwea management do not change significantly from the historical record (1980-2020).
4. If water users were to take their full allocation, groundwater levels in some areas would fall significantly but in most of the basin this decrease in groundwater levels is unlikely to cause problems with reliability.
5. An exception to the above is the Maungawera Valley, where water users taking their full allocation could lead to reliability issues 40-50% of the time. We note that the Maungawera Valley has very low actual usage relative to consented allocation (11-19%) and current usage is unlikely to cause reliability concerns. Model results indicate that a reduction from the current allocation to 60-70% of the current allocation would be consistent with reliability issues occurring 5% of the time or less.
6. Modelling estimates suggest that, apart from the Maungawera valley, current allocation limits are broadly consistent with minimising groundwater reliability issues for existing users under the assumption that wells adequately penetrate the aquifer.
7. This study offers a significantly improved understanding of the interactions between Lake Hāwea water levels and the groundwater system:
    7.1. There is strong evidence that the seasonal variation in Lake Hāwea water levels propagates through the groundwater system as far as the Clutha River.
    7.2. This study identified the likely existence of band of low conductivity sediment that causes a sharp groundwater gradient between Lake Hāwea and the groundwater system (analogous with an underground waterfall). The elevation of these sediments is unknown, but this study suggests that the top of the sediments probably occurs between 327 – 337 m msl.
    7.3. Should the Lake Hāwea levels become lower than the top of the low conductivity sediments, the groundwater system would become disconnected from Lake Hāwea. If this happened for an extended period of time, groundwater levels could potentially fall by up to 11 m causing widespread bore failures.

8. The new Hāwea model has been rigorously documented and is hosted within a Github repository allowing easier future access.

8. REFERENCES

Edkins, R. 2012. Lake Hāwea Public Water Supply – Aquifer testing and well field design. Aqualinc Research report No. C11036/2, prepared for Queenstown Lakes District Council, February 2012, Christchurch. 56 pages including appendices.

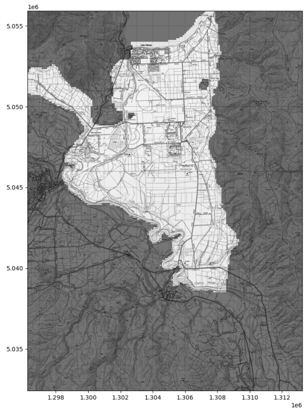
Kitteridge, 2022. Hawea Water Usage Processing, Hawea Groundwater modelling project, Report 1052-08-01 R1

Rushton, K R; Eilers, V H M; and Carter, R C. 2006. Improved soil moisture balance methodology for recharge estimation. Journal of Hydrology, Volume 318, Issues 1–4, 1 March 2006, Pages 379-399.

Wilson, S. 2012. Hāwea Basin Groundwater Review. Prepared by Resource Science Unit of Otago Regional Council, June 2012, Dunedin. 69 pages.

9. APPENDIX 1

Hawea Transient groundwater model (Hawea Model)



Author: Matt Dumont

Date: 2021-11-02

Version: 1.0.0

Status: Draft

KSL project: Z22031HAW_hawea-model

Purpose: This document describes the Hawea Model repo

The Hawea model domain; the inactive portions of the model are coloured dark grey. The model domain is a 3D model of the Hawea aquifer systems including the Maungawera Valley. The model domain is bounded by Lake Hawea to the North, the Clutha River to the South, and the hillslopes to the East and West. The model domain is 17 km by 23.5 km. The model cell spacing is 100 m and the model is on a regular North-South grid. The model is loosely based on the 2D model of the Hawea aquifer system developed by Wilson et al, (2011).

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Table of Contents

Modelling methodology and results

Rather than a traditional model report this repository serves as the detailed documentation of the modelling process. The final report with the interpretation of the modelling process and results is available in the repo here. The modelling process was broadly undertaken in the following steps; each step has its own readme document detailing its methodology and, where applicable, the results of the step:

1. Model build: build the model structure and boundary conditions
2. Model targets: define the model targets and objective function
3. Model Parameterisation: define the initial model parameters and parameterisation
4. Model Optimisation and limitations: optimise the model to the available data
5. Model Scenarios: run a series of scenarios to better understand the model behaviour and to predict the systems response to changing conditions

Modelling Software

Most of the model was produced using open source Python packages and the MODFLOW suite. Specifically the model was built using MODFLOW NWT, optimised using PEST, and scenarios were run in MT3DMS-usgs.

Python Environment

This model was developed in Python on linux (ubuntu 20.04). The Python environment was created using the Anaconda package manager. The environment was created using the following command:

```
conda create -c conda-forge --name hawea python numpy pandas pytables openpyxl matplotlib scipy netcdf4 psutil geopandas flopy pysheds scikit-learn py7zr
conda activate hawea
pip install pyemu
pip install ppscore
pip install tabulate
pip install fpdf
pip install pdfkit
```

In addition to the creation code above, the repo environment was exported in:

- environment.yml
- environment.txt

Github repo structure

The full modelling process for the Hawea model was undertaken within this Github repo. The only exceptions are several large datasets (LIDAR/DEMs) which were simplified (code in repo) and then the simplified product was saved in the Github repo. This means that no external datasets are necessary to completely recreate the Hawea model and the full methodology is present in this repo.

Comment keyword standards:

We have used a number of keywords (case insensitive) to support identifying important comments within the text. These are:

- TODO: A comment that identifies a task that needs to be completed
- FIXME: A comment that identifies a problem that needs to be fixed
- KEYNOTE: A comment that identifies a key assumption or point of interest
- OPEN SOURCE IMPROVE: A comment that identifies a potential improvement to existing open source code repos

At this point only KEYNOTE and OPEN SOURCE IMPROVE should remain in the repo, however it is possible that some TODOs and FIXMEs will remain accidentally. Note that these have been dealt with, but were accidentally not removed from the code. Many IDEs have a search function that can be used to find these keywords, which we encourage you to use.

Repo index

Below is a rough guide to the repo structure. Not every file in the repo is described. Often the best way to find out what information a file contains is to look through the appropriate Python function and read the docstrings. The repo has been documented to a reasonable extent, but there is still some work that could be done to make the repo more user friendly. If you have any questions please contact Matt Dumont (matt@komanawa.com)

- README.rst: This document
- project_base.py: A script to set up the project environment and manage paths
- scott_model: A copy of the original 2D model of the Hawea aquifer system developed by Wilson et al, (2011)
- **model_build: model build process and datasets**
    - README.rst: a readme file for the model build
    - base_data: raw input data for the model build

    - processed_input_data: processed data for the model build that was built by the scripts in this folder from the raw data in the base_data folder
    - project_model_tools.py: a script to define the model tools instance, and the model structure
    - get_boundary_condition_data.py: a script to get the boundary condition data
    - **supporting_data_analysis: scripts to support creating the boundary condition data and structure**
        - all_wells.py: a script to get all the well location data
        - base_concept_diagram.py: a script to build a base concept diagram of the 3D model structure
        - compare_met_era5land.py: compare precipitation and PET between the available met station and the ERA5-land data
        - explore_structure.py:
        - get_era_5_land.py: script to get ERA5-land data
        - get_pumping_data.py: get and process historical pumping data
        - hillside_inflows.py: model and process estimates from the hillside inflows
        - irrigation_race_losses.py: get and process the historical race loss data
        - lake_data.py: get and process the historical lake data
        - map_flowmeter_to_wells.py: a process to map the flowmeter data to the most likely well
        - plot_borelogs.py: a process to plot the borelogs in the model
        - recharge_model.py: develop and create LSR estimates from met and ERA5-land data
        - river_data.py: : a process to get and process the river data
    - modflow_model.py: a script to build a MODFLOW model instance
    - utils.py: a script to define some utility functions
    - zones.py: a script to define indicative model zones
- **model_parameterisation: model parameterisation and implementation**

    - README.rst: a readme file for the model parameterisation
    - base_data: raw input data for the model parameterisation
    - processed_data: processed data for the model parameterisation that was built by the scripts in this folder from the raw data in the base_data folder
    - static_params.py: a script to define the static model parameters
    - pilot_points.py: a script to create, define, and interpolate pilot points for kh and sy
    - inital_parametersiation.py: a script to define the initial model parameters (before optimisation)
    - plot_parameter_names.py: a script to plot the parameter names generates parameter_map.png
    - optimised_parameterisation.py: a script to easily access optimised parameter sets
    - **optimised_parameter_sets: optimised parameter sets**
        - 3d_v1a_opt.par: optimised parameter set for the 3D model version 1a
        - 3d_v1b_opt.par: optimised parameter set for the 3D model version 1b
        - 3d_v1d_opt.par: optimised parameter set for the 3D model version 1d
    - parameter_map.png: a map of the model parameters
- **targets_and_sensitive_sites: target development and data**
    - README.rst : readme document detailing the methods and data used to develop the targets
    - model_output.py: script to extract consistent model outputs and plots
    - get_raw_target_data.py: ingest raw target data
    - get_indicative_times.py: get indicative times for the targets that fall outside of the optimisation period
    - head_targets.py: definition of the head targets
    - riv_gain_loss_targets.py: definition of the river gain and loss targets
    - senstive_sites.py: identification of sensitive sites
    - target_structure_checks.py: checks to ensure that the targets and the model structure were not mutually exclusive
    - base_data: base input data for the targets
    - processed_data: processed target data, this was developed from the raw data in the base_data folder
- **optimisation: optimisation code and results**
    - README.rst: readme document detailing the optimisation process and methodology
    - **PEST optimisation build, run, and post processing scripts**
        - build_optimisation.py: script and functions to build the PEST files
        - a_build_run_optimisation_version.py: build and run a PEST optimisation
        - run_opt_step_models.py: run the step models from a PEST optimisation
        - manual_optimisations: manual optimisations that were run, in the end these never contributed more than some information to the modeller

    - model_utils_for_forward_run.py: functions to build and run a model from PEST parameter files
    - compare_parameterisations.py: script to compare parameters across multiple parameter files
    - hawea_plot_optimisation.py: script to plot the optimisation results
    - plot_multiple_high_freq.py: script to plot multiple high frequency observations for given PEST obs files
  - **Manage optimisation period:**
    - determine_opt_start.py: script to determine the start and end of the optimisation period
    - optimisation_period.py: script to manage and hold the information about the optimisation period
  - **Optimisation Results**
    - **optimisation_results: results for the optimisation holding all of the pest input and output files**
      - 3d_v1a: optimisation results for the 3D model version 1a
      - 3d_v1b: optimisation results for the 3D model version 1b
      - 3d_v1d: optimisation results for the 3D model version 1d (final model)
    - **final_opt_models: the final optimised model files**
      - 3d_v1a: final optimised model files for the 3D model version 1a
      - 3d_v1b: final optimised model files for the 3D model version 1b
      - 3d_v1d: final optimised model files for the 3D model version 1d (final model)
      - compress_uncompress_model.py: utilities to compress and uncompress the model files so they could be included in the Git repo (50mb limit)
  - **Computational support files**
    - compile_pest: compile PEST for linux
    - pest_run_data: static data needed by PEST to run the model
    - git_setup.sh: script to setup the Git repo for the optimisation on a machine
  - **Model overview**
    - pre_optimisation_overview.py: make pre optimisation overview plots
    - make_preopt_slideshow.py: make a pre optimisation slideshow
    - pre_optimisation_plots_png: pre optimisation plots of boundary conditions, targets, parameterisation, and other supporting work, many of these figures are referenced in the various readme.rst files
    - make_opt_presentation.py: make a presentation of the optimisation results for a meeting
- **quartz_creek_lsr: modelling of LSR for the Quartz Creek area see the Scenarios readme for more information**
  - ` results <quartz_creek_lsr/results>`_: results from the LSR modelling
  - ` model_qtz_ck_lsr.py <quartz_creek_lsr/model_qtz_ck_lsr.py>`_: script for LSR modelling
- **Scenarios: scenario modelling code and results**

- README.rst: document describing the scenario modelling methods and results
- Scenario development and supporting scripts - scen_period.py: script to handle the scenario period - boundary_condition_plots: plots of the scenarios boundary conditions - base_data: base input data for the scenarios - processed_input_data: processed input data for the scenarios, these files were all developed from the base data - boundary_conditions.py: develop the input boundary conditions for the scenarios - supporting_data_analysis: additional data analysis scripts to support creating boundary conditions - scenario_outputs.py: script to make consistent scenario outputs - run_flow_scenario.py: script to run a flow scenario - run_scenario.py: script to run a scenario (in multiprocessing)
- **Model information and MT3D indicator modelling**
    - run_mt3d_scenario.py: script to support running MT3D
    - mt3d_indicator_scens.py: script to run MT3D indicator scenarios
    - compare_boundary_sensitivity.py: compare the results of the boundary condition sensitivity analysis
    - model_info_scenarios.py: script to run model information scenarios
    - **model_info_scen_results: model results and plots for model information scenarios**
        - 0_results: plots for model information scenarios
        - {scenario name}: Model results for model information scenarios: input and output data for the scenario
    - mt3d_indicator_scenarios: model results and plots for the MT3D scenarios
- **Low Lake Hawea level scenarios**
    - low_lake_scenario_data.py: script to develop typological lake levels and perturbations
    - low_lake_scenarios.py: script to run low lake scenarios
    - compare_low_lake.py: script to compare low lake scenarios
    - **low_lake_scenarios: model results and plots for low lake scenarios**
        - 0_results: plots for low lake scenarios
        - {scenario name}: Model results for low lake scenarios: input and output data for the lake scenario
- **Allocation modelling**
    - allocation_zones.py: get and plot allocation zones
    - allo_rch_hillside.py: scripts to get and compare the allocation, hillside recharge, and LSR for each zone
    - allocation_scenarios.py: script to develop all allocation scenarios and to run the non-gridded allocation scenarios
    - run_grid_allocation.py: script to run the gridded allocation scenarios
    - compare_allocation_scens.py: script to compare allocation scenarios
    - allocation_scenarios: model results for allocation scenarios
    - **allocation_results: plots of allocation results**
        - old_allo_zones.png: figure of the old allocation zones (Wilson et al., 2012)
        - new_allo_zones.png: figure of the new allocation zones
        - Hawea Flat_results: results for the gridded Hawea Flat allocation scenarios

            - Maungawera Flat_results: results for the gridded Maungawera Flat allocation scenarios
            - Terrace-Hill_results: results for the gridded Terrace-Hill allocation scenarios
            - nat_current_full: results for the naturalised, current allocation, and full allocation scenarios
            - Te Awa_results: results for the gridded Te Awa allocation scenarios
            - Terrace-River_results: results for the gridded Terrace-River allocation scenarios
            - mangawera_valley: results for the Maungawera Valley allocation reduction scenarios
            - allo_zone_rch: results comparing LSR, hillside inflows, and allocation for each zone
            - example_quantile_plots: example quantile plots for the allocation scenarios to support presentations
    - **Wetland Setback Modelling**
        - wetland_setback_campbells: wetland setback modelling for Campbells wetland scripts and results
        - wetland_setback_butterfield: wetland setback modelling for Butterfield wetland scripts and results
- support_figures: supporting figures for this and other README.rst documents
- dummy_packages: dummy packages for the proprietary packages used in the model, these packages have some, but not all of functionality of the original packages

Supporting data index

This repository contains all of the input and processed data needed to build and run the model. There are two exceptions to this; the 1 m LIDAR dem for the Clutha and Hawea rivers and the 15 m DEM used for the model top. Both DEMs are too large to store in the repo, so they have been simplified and the simplified versions are stored in the repo. There are a number of directories in the repo that contain the input and processed data each of these directories contains a readme.rst file that briefly describes the data in the directory. The directories are:

- model_build/base_data: contains the base data used to build the model
- model_build/processed_input_data: contains the processed data used to build the model
- model_parameterisation/base_data: contains the base data used to parameterise the model
- model_parameterisation/processed_data: contains the processed data used to parameterise the model
- Scenarios/wetland_setback_butterfield/base_input_data: contains the base data used to run the butterfield wetland setback scenario
- Scenarios/wetland_setback_butterfield/processed_input_data: contains the processed data used to run the butterfield wetland setback scenario
- Scenarios/base_data: contains the base data used to run the scenarios
- Scenarios/processed_input_data: contains the processed data used to run the scenarios
- Scenarios/wetland_setback_campbells/base_input_data: contains the base data used to run the campbells wetland setback scenario

- Scenarios/wetland_setback_campbells/processed_input_data: contains the processed data used to run the campbells wetland setback scenario
- targets_and_sensitive_sites/base_data: contains the base data used to define the model targets and objective function
- targets_and_sensitive_sites/processed_data: contains the processed data used to define the model targets and objective function

Proprietary packages

For the most part we relied on open source packages to create the Hawea model, but we did use some proprietary in house packages. These packages are not included in this repository, but we have included dummy packages that contain the same structure as the original packages and replicates some of the functionality. These dummy packages are located in the dummy_packages folder in the model repo and the python scripts have all been adjusted to load the dummy package version if the original version is not available.

Additionally, to ensure future use of this model we have included outputs of the data which necessitated the use of the proprietary packages. These outputs are located in the *processed_input_data* folders. The functions that use these packages to develop the outputs tend to follow are "recalc" structure, that is:

```
def get_data(*args, **kwargs, recalc=False):
    save_path = processed_data_dir.joinpath('data.csv') # path in the processed data folder where the outputs are saved
    if save_path.exists() and not recalc:
        # read the data from the saved path and return it
        # sometimes additional processing (e.g. other args) is done after loading the data
        return pd.read_csv(save_path)
    else:
        # the process by which the data was generated
        outdata = None
        # save the data to the save_path
        outdata.to_csv(save_path)
        return outdata
```

This structure allows the user to run the model without the proprietary packages, but also allows the user to see the full methodology used to generate the outputs. This also keeps the links between the data generation and the data use (e.g. in a model) explicit. This prevents the 'black box' problem that can occur when the data is generated by a different process and then ingested into the model.

Excluding a full model re-build, these proprietary packages should not be needed; however, if the user wishes to run the model with the proprietary packages or to generate a next generation with the proprietary packages they are encouraged to contact the author of this model: matt@komanawa.com

The proprietary packages used in this model are:

- **Dummy packages provided:**
    - **from model_tools.time_discretization import TimeDis**
        - mange the human time to model time
    - **from model_tools.regular_modeltools import ModelTools_RegularGrid**
        - manage the model structure and real world coordinates to model coordinates
- **No Dummy packages provided**
    - **from rushton_model.rushton import Rushton**
        - land surface recharge model
    - **from run_managers.beopest_manager import BeopestManager**
        - Manage Beopest across multiple linux machines

- **from run_managers.ssh_distributor import SshDist**
    - Distribute a list of model runs across linux machines
- **from model_tools.util_functions.list_file_utils import ListSolverInfo**
    - extract solver information from the list file
- **from model_tools.plot_borelogs import plot_borelogs, plot_single_log, make_single_log_handles**
    - plot bore logs
- **from model_tools.model_plotting import plot_spd, first, last, FakePath**
    - plot model results
- **from model_tools.plot_optimisation import plot_optimisation_and_extract_info**
    - plot optimisation results

Dead links

We have made a substantial effort to ensure that all links in the model are valid. However, there are likely some links that return a 404 error. If you come across this, then please contact the author of this model: Matt@komanawa.com so that he can fix the links. Typically the links are relative to the repository. if the link is broken you can likely infer the correct location by looking at the link and the repo structure.

Branches and releases

The process of the model optimisation required multiple structural changes to the model as well as changes to the objective function to attain a satisfactory history match. These different structures and changes were all set up as unique branches within the repo. For more information on branches see github's explanation of branches. At the end of the calibration process there were 24 unique branches, most of which were abandoned. These branches were issued as pre-production releases (More information about releases). Only the key structures were retained and the "final" model was merged back to the main branch.

Active Branches

Main (3d_v1d)

- The 'final' optimised model.
- Contains 3D structure around the Lake Hawea Moraine
- Best fits for the high frequency targets.
- Bund elevation set to 335 msl
- NGMP well head observations removed from objective function as there is significant tension between these records and the high frequency observations. The NGMP wells are pumped irrigation bores and the primary purpose for sampling was water quality monitoring.

3d_v1a

- Identical to "Main (3d_v1d)" except that the NGMP wells were included in the objective function
- decent history matching; however "Main (3d_v1d)" provides better results
- retained as active branch for comparison to "3d_v1b"

3d_v1b

- Identical to “3d_v1a” except that the bund elevation was set to 333 MSL.
- history matching results were similar to “3d_v1a” suggesting that the bund elevation is largely non-unique
- retained to demonstrate the non-uniqueness of the 3D structure

terrace_only

- This model structure only includes the High Terrace (south of Hawea Flat) to the Clutha river
- this optimisation was undertaken to see if the High Terrace could be history matched (within the accepted parameter ranges) in isolation from the rest of the Hawea aquifer system.
- History matching was not achieved.

previous branches (releases)

There are many previous branches that were issued as pre releases and then deleted (effectively archived). There should be no reason for other users to delve into these previous branches as they ended up with unsatisfactory history matching; however, they are available and briefly described below (working notes) for completeness.

1. Main (before 2/11/22) The main build branch. First structural version
2. Structure v2, Changes:
    - Increase parameterisation via pilot points to Maungawera
    - Add recharge multiplier pilot points across model (NI)
    - Remove sandy point from model
    - abandoned but retained
3. Structure v3,Changes:
    - Set ss=sy
    - Set the model to confined to reduce computational burden
    - This helped but the model preformed poorly,
    - Error did not reduce saturated thickness.
    - abandoned and deleted
4. Structure_v4:
    - From structure v2
    - Add new mean annual head targets from regular
    - Increase steps to 7 in transient
    - Expand hillside streams to all adjacent cells (up to 9 cells per hill)
    - Optimisation never run here, just saved to version structural changes
5. Structure_v5
    - From structure_v4
    - Remove near river pumping wells.
6. Structure_v6
    - From structure 5

- Add a 1m confined layer below the bottom of layer 1 (may improve stability)

7. Structure_v6a
    - From v6, but set ss to sy
8. Structure_v7 (built but not run)
    - From structure 5
    - Reduce thickness to reasonable pumped thickness and then Maximum 30m sat thickness
    - Set ss = sy
    - run as a confined model
9. Structure_v8
    - From structure_v6a
    - increase initial conductivity (to 50, 100 and 70 was too unstable)
    - rch multiplier only by irrigated not irrigated bounds of multiplier 0.5-1.2
10. Structure_v9
    - Fix river targets (they were backwards!)
    - Implement grandview and john creek (+Hawea and Clutha) as str package
    - Lake stage vs g40_0415
    - Looks fine, honestly the fact that them model isn't matching it suggests some sort of structural error. Reworked transport in grandview stream?/ water through grandview stream??? Likely the problem google maps shows water in grandview to the lake (and in john creek (to the north), all other creeks are probably fine.
    - Lower basement around g40_0366
11. Structure_v10
    - Set weight of regular year targets to 0
    - set each of the 'h_hf' targets equal weights despite different data lengths
    - look/lower basement in dry cells near model boundaries
    - NE hillside area (done)
    - Near clutha river (done)
    - I think I need some more pilot points
    - Near pt 402 on camp hill moraine (move Maungawera south?) () and another in the moraine (to interpolate with other river group
    - To stop dry cells south of camp hill moraine
    - Significant number in the hillslope area just off the bounds to allow conductivity to fall there if needed for stability. And to manage the change in geologic setting near hillslope
    - Adjust some locations based on the new pilot point locations
    - New rivergroup south of Maungawera valley entrance to allow for the difference between the two settings
    - Additional point in the middle of the terrace to manage near hillside environment.
    - Try lowering hillside conductance → set to 100 vs 1000 for Hawea/Clutha, which means much of the peak flow does does not make it into the model.
12. Structure_v11
    - Move to 1 global recharge modifier (done)

- Much higher initial kh (lake=5, rest = 300) (in progress
- Lower sy, and lower sy bounds
- Change weights (lower low frequency targets)
- Bit of a hail mary before the weekend
- retired (even though I'm happy with the parameterisation. If I want to change back to vll parameters do it from v12

13. Structure_v12
    - Increase kh/sy parameterisation in the near lake environment
14. p_lake
    - As per structure_v11 but with a single additive parameter for lake heads (e.g. lake hds = lake hds + mod
    - A test to see if the lake levels problems are sorted everything else works great?
    - Note the parameter is offset by 100m as pyemu has bugs!
15. lake_bar
    - Add a 1 cell thick barrier for kh
    - Remove additional v12 parameterisation
16. cond_int
    - Try to fit the heads by simply setting lake conductance (1 cell width lake)
17. 3d_v1
    - Address the 3D moraine issues in structure
    - 3 layers the bottom two pinch out against the bottom of the model.
    - well management
    - target management
    - other structural pieces
    - Add abrupt parameter change at terrace interface
    - Remove from dam to "dam control" road from model (e.g. no flow)
    - Re-run pre_optimisation_overview.py
    - remove the slope fixer on the east side
    - remove additional parameterization of v12
18. 3d_v2
    - As per v1 but fully confined (to increase stability)
    - Ss[0] = sy[0]
    - Initial parameters do not manage the drop quite so well. This may really need the unconfined aspects of the model.
    - Bit of a hail mary over xmas. Really need the unconfined action to make the 'waterfall happen'
19. 3d_v1c
    - As 3d_v1a but with top of bund set to 337
    - great difficulty getting this to converge
    - abandoned

20. 3d_v4

    - As 3d_v1a, but top of bund is set to 340m MSL instead of 335
    - Difficult to get model to converge
    - abandoned

21. 3d_v5

    - As 3d_v1a, but top of bund is parameterised
    - Largely unstable

References

- Wilson, J., 2012. Hawea Basin Groundwater Review. prepared by Resouce Science Unit of Otago Regional Council, June 2012, Dunedin.

Hawea Transient groundwater model (Hawea Model) build methods and results

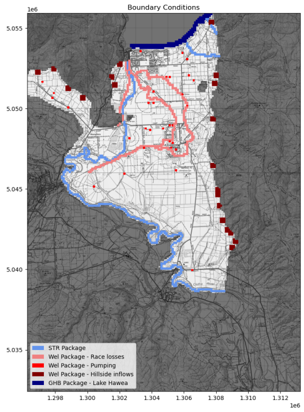


Figure: Overview of model boundary conditions

Author:	Matt Dumont
Date:	2021-11-02
Version:	1.0.0
Status:	Draft
KSL project:	Z22031HAW_hawea-model
Purpose:	This document provides the methodology and results for the model build process

Index

Table of Contents

Module Index

- README.rst: this document
- base_data: raw input data for the model build

- processed_input_data: processed data for the model build that was built by the scripts in this folder from the raw data in the base_data folder
- project_model_tools.py: a script to define the model tools instance, and the model structure
- get_boundary_condition_data.py: a script to get the boundary condition data
- **supporting_data_analysis: scripts to support creating the boundary condition data and structure**
    - all_wells.py: a script to get all the well location data
    - base_concept_diagram.py: a script to build a base concept diagram of the 3D model structure
    - compare_met_era5land.py: compare precipitation and PET between the available met station and the ERA5-land data
    - explore_structure.py:
    - get_era_5_land.py: script to get ERA5-land data
    - get_pumping_data.py: get and process historical pumping data
    - hillside_inflows.py: model and process estimates from the hillside inflows
    - irrigation_race_losses.py: get and process the historical race loss data
    - lake_data.py: get and process the historical lake data
    - map_flowmeter_to_wells.py: a process to map the flowmeter data to the most likely well
    - plot_borelogs.py: a process to plot the borelogs in the model
    - recharge_model.py: develop and create LSR estimates from met and ERA5-land data
    - river_data.py: : a process to get and process the river data
- modflow_model.py: a script to build a MODFLOW model instance
- utils.py: a script to define some utility functions
- zones.py: a script to define indicative model zones

Model boundaries

The model domain (see figure below) was initially defined to include the following aquifers:

- **The main Hawea flat aquifer** stretching from Lake Hawea in the North to the base of the High Terrace in the South. This aquifer is bounded by the Hawea River on the West and the Grandview Ridge on the East
- **The High Terrace aquifer** stretching from the base of the High Terrace in the North to Clutha River in the South. This aquifer is also bounded by the Hawea River on the West and the Grandview Ridge on the East
- **Aquifers near the Hawea river** including Te Awa, Maungawera Flat, and river adjacent aquifers to the south of Maungawera flat and East of the High terrace.
- **The Maungawera Valley aquifer** including the Maungawera Valley aquifer from the approximate Hawea River/ Lake Wanaka flow divide in the Northwest to the Maungawera Flat aquifer
- **The Sandy Point Aquifer** which is to the East of the Clutha River to the South of the High Terrace aquifer. This aquifer is also bounded by the Grandview Ridge on the East

During the model build the steep topography of the Sandy Point aquifer caused model convergence issues. The Sandy Point has minimal data available (only one historical groundwater measurement). Therefore we resolved the convergence issue by removing the Sandy Point aquifer from the model domain. We still produced estimates of land surface recharge (LSR) and Hillside inflows to this aquifer, which were used to inform groundwater allocation decisions.

The boundaries of the model domain were all defined by no-flow boundary conditions. In addition, at the Lake Hawea Dam, Camp Hill, and Cameron Hill bedrock is exposed. Therefore these outcrops were also defined as no-flow boundaries. Finally, the Camp Hill Medial Moraine, located between Te Awa and the Maungawera Flat aquifers, is comprised of poorly sorted and unworked moraine sediments. While there are a few domestic supply bores in this area, the groundwater system is likely minimal, particularly in comparison with the other outwash dominated aquifers. We therefore chose to define this area as a no-flow boundary.

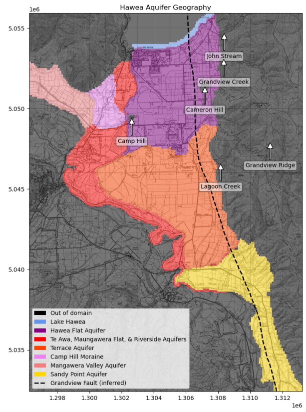


Figure: Map of the model domain with key features labelled

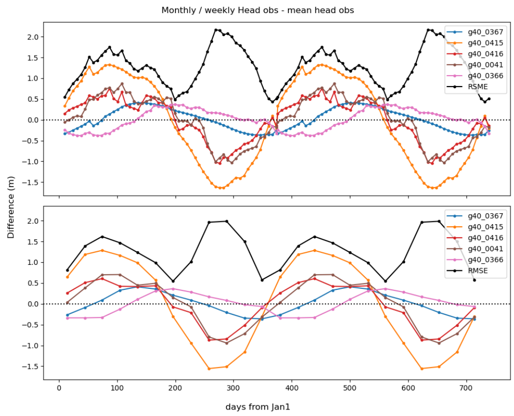
Model Time period

This model is a transient groundwater model with the first period defined as a steady state period. For the purposes of boundary conditions we defined two time periods for the model:

- **Optimisation period: 2015-07-18 to 2020-06-27:**
    - the period where we have the most data available across boundary conditions, observations (targets).
    - we defined the start year of the optimisation period to 2015 as this was the first year that we had reliable groundwater abstraction data were available.
    - weekly MODFLOW stress periods were used.
- **Scenario Period: 1980-07-18 to 2020-12-01**
    - the period where we have reasonable data available across boundary conditions, but minimal observations (targets)
    - weekly MODFLOW stress periods were used.

Model Starting heads

The challenge of defining starting heads for a transient groundwater model is that any choice of starting heads can then impact the subsequent model results. For this model we chose to use the top of cell as the starting heads and then run a steady state model period. To identify the best month to transition between the steady state model and the transient model we calculate the difference between the monthly and weekly high frequency data (see target readme for more details). and the mean of the full dataset. The results are shown in the figure below, but there were obvious local minimums in the RMSE at 200 and 365 days from January 1 or approximately start of January and mid July. We chose a start date of in mid July (2015-07-18) as this will minimize the variability in heads associated with the irrigation season.



Model Structure

The model structure was initially created as a 1 layer model, but during the course of the optimisation it became clear that the model could not reproduce the data without additional structure and layering. For more information on the optimisation process see the optimisation readme.

1 layer model structure

The 1 layer model was largely based on Wilson et al. (2012). The model top was defined based on a 15 m DEM (from NZWaM - Hydro), and the model bottom was initially set from the model bottom used in Wilson et al. (2012). The model bottom and top were then adjusted as follows:

- All cells with stream package cells with the stream rbot parameter below the model bottom were set as 0.5 m below rbot.
- A number of cells which routinely caused dry cells (and instability in the model) had the bottom gradient reduced
- The model top was adjusted so that the tops were always at least 0.5 m above the rbot of the stream package cells.
- There were a number of cells near the Clutha River that caused dry cells due to the incised nature of the river. For these cells the bottom was set to the bottom of the nearby river cells
- The model bottom was adjusted to ensure that the model thickness was at least 2 m

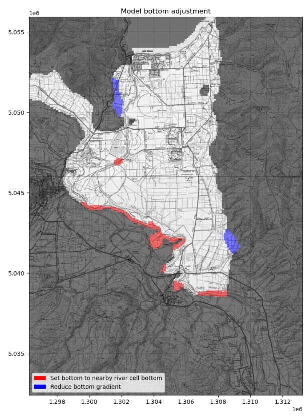


Figure: location where the gradient of the bottom or the absolute bottom elevations were reduced

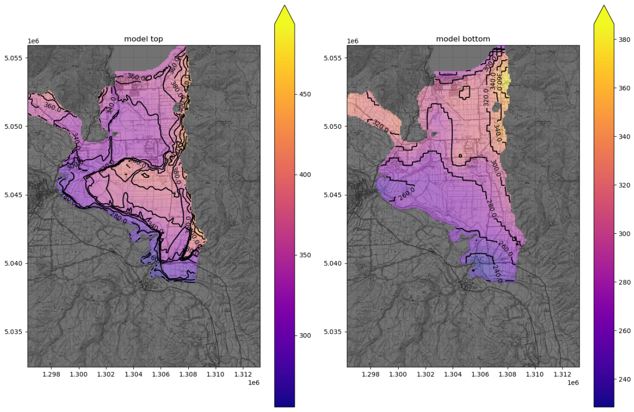


Figure: Model top and bottom

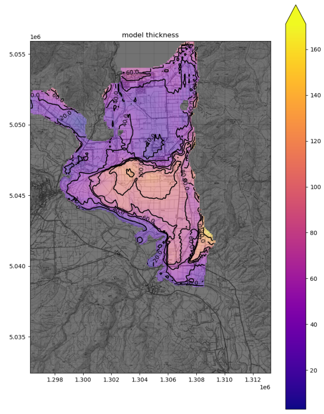


Figure: Model thickness

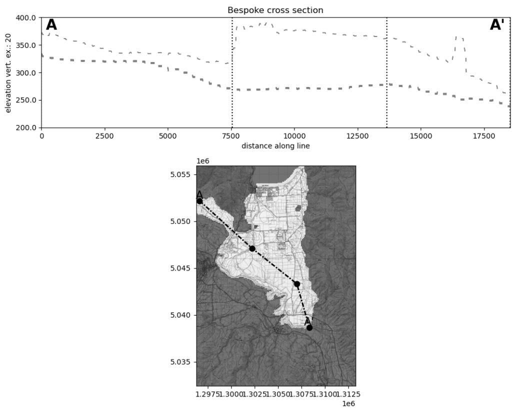


Figure: Example model cross-section 1

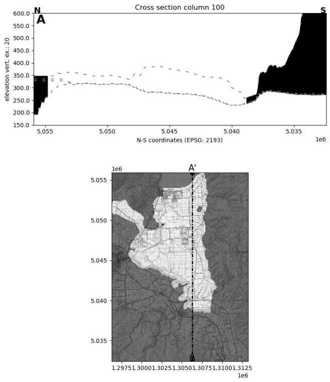


Figure: Example model cross-section 2

multi-layer (3d) model structure

The multi-layer model structure that was created better represents the complex geology in and around the Southern edge of Lake Hawea. There is likely to be other areas of the model domain that have more complex geology; however, excluding the structure at the Lake Hawea moraine precluded our model from fitting the observed data. For more information on the optimisation process see the optimisation readme.

Lake Hawea Moraine Conceptual Model

In the 1 layer model structure the Lake Hawea moraine was represented as a single layer and its impact on the groundwater system was parameterised as a single parameter -- hydraulic conductivity. However, in reality the Lake Hawea moraine is a complex geological structure. From a groundwater perspective the key observations that precluded the 1 layer model from fitting the data were the high frequency measurements at well G40/0415 (roughly at the intersection of Cemetery Road and Gladstone Road). These observations showed that the groundwater levels in this well are highly correlated with the lake levels, but with approximately 10 m of vertical displacement. We developed and fitted a very simple numerical model to the groundwater levels at G40/0415 to better understand the relationship between the lake levels and the groundwater levels in this well. The model parameterised the groundwater levels as:

$$h_{gw}(t) = \sum_{n=t+l}^{t+l+s}h_{lake mod(n)} / s$$

$$h_{lake mod}(t) = ((h_{lake}(t) - h_{lakeMean}) * a) + h_{lakeMean} + \Delta_{h}$$

where:

- h_{gw} is the groundwater level,
- h_{lake} is the lake level,
- t is the time (day),
- l is the lag parameter (days),
- s is the number of days to smooth the lake levels,
- $h_{lakeMean}$ is the mean lake level,
- Δ_{h} is the vertical step parameter,
- a is the lake level amplitude modifier,

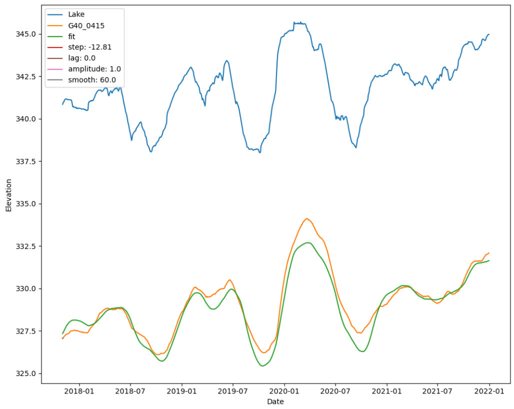


Figure: results of the simple fit to Lake Hawea levels

The simple numerical model provides a good fit to the groundwater levels at G40/0415 with a step change of 12.81 m and a 60 day smoothing period.

With the 1D model we were unable to fit the water levels at G40/0415. We could either fit the shape of the groundwater levels but there was substantial bias in the mean groundwater level (too high) or we could fit the mean groundwater level but the shape of the groundwater levels was lost.

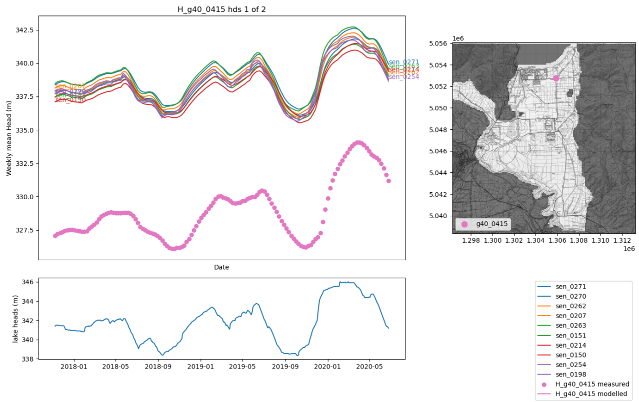


Figure: the results of the 1 layer model which fit the shape of the groundwater levels, but not the mean

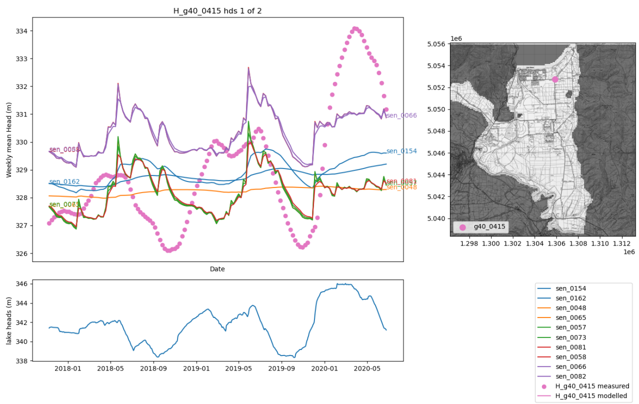


Figure: the results of the 1 layer model which fit the mean of the groundwater levels, but not the shape

We do not have other high frequency observations of groundwater levels near the Lake Hawea moraine. However, we do have a number of static water levels that were measured shortly after drilling the bore. These water levels, relative to the lake level at the time of measurement are shown in the figure below. This figure shows a constant vertical offset between the groundwater levels and the lake levels of approximately 10 m. Some of these boreholes are located in the moraine less than 200 m from the lake. Many of the water supply wells near the lake (within the mapped moraine) are relatively deep (e.g. 50+ m).

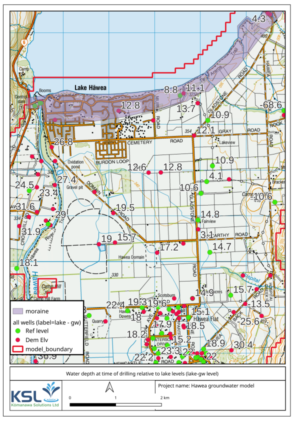


Figure: all groundwater levels relative to the Lake Hawea level on the sampling date (positive values are groundwater levels below the lake)

Several of the bores have recorded bore logs which are shown in the figure below. Drillers logs can be imprecise; however, the logs demonstrate lower conductivity sediments overlying more conductive sediments at ~ 320 m msl. This elevation is also typically where drilling stopped, suggesting they had finally found conductive material. Some logs also show more conductive sediments overlying the less conductive sediments, but this is spatially variable.

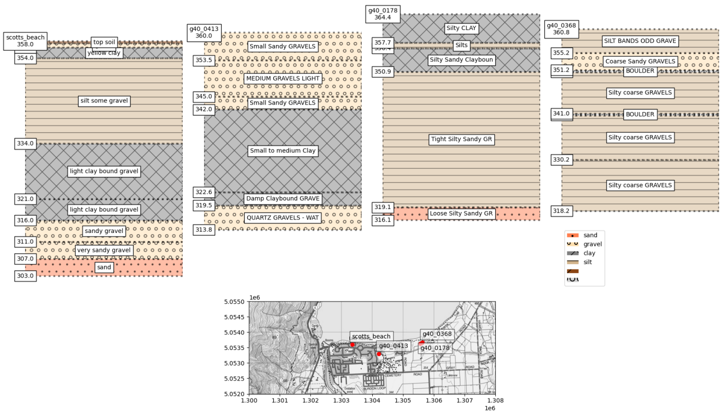


Figure: bore logs from the Lake Hawea Moraine

The Quaternary geological history of the Lake Hawea area is made up of a number of glacial advances and retreats described below and show in the figure below.

1. After the Q6 Luggate Advance relatively conductive glacial out-wash filled the basin and deposited the sediments of the high terrace
2. The Q4 Albert Town Advance scoured many of the previous sediments and deposited relatively impermeable, glacial moraine at the Camp Hill Moraine and the moraine at the northern base of the High Terrace.
3. The subsequent Q3 retreat meant relatively conductive outwash sediments were deposited between the High Terrace and Lake Hawea.
4. The Q2 Hawea Advance scoured the previous sediments (producing Lake Hawea) and deposited a relatively impermeable moraine at the southern edge of Lake Hawea.

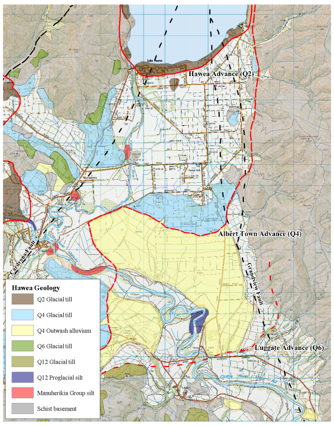


Figure: Quaternary geological history of the Lake Hawea area from Wilson(2012)

Based on the borelog information, the geological history of the area, and the groundwater levels we propose a conceptual model of the Lake Hawea Moraine. The conceptual model is shown in the figures and described below:

1. During the Q2 Hawea Advance the glacier did not fully scour the previous outwash sediments and the new Lake Hawea moraine was deposited on a thin wedge of Q3+ outwash.
2. The moraine forms a relatively impermeable barrier to groundwater flow from Lake Hawea to the Hawea Flat aquifer system.
3. During and after the Q2 Lake Hawea Advance the moraine was locally reworked and eroded by some combination of the Hawea river, Grandview and John Creek periglacial activity (e.g. local reworking of the moraine by surface water on the top of the glacier). Regardless, this reworking produced a locally continuous cap of relatively conductive material on top of the moraine.
4. After the completion of the Lake Hawea dam in the 1950s the Lake Hawea level was raised by approximately 20 m, which allowed Lake Hawea water to seep through the permeable cap of the moraine and into the Hawea Flat aquifer system. This is anecdotally supported by reports of relatively low groundwater levels prior to the completion of the dam.
5. The permeable cap of the moraine is relatively thin and is almost certainly not continuous across the moraine. This forms a small, possibly perched, aquifer system on top of the previous moraine. This aquifer system then effectively spills over the moraine into the Hawea Flat aquifer system with very steep localised groundwater gradients.
6. The Hawea Flat aquifer system is a relatively conductive system and has relatively low groundwater gradients. Locally, where the Lake Hawea moraine overlies more conductive material, groundwater will flow from this conceptual pour point back towards Lake Hawea, providing the groundwater in the aforementioned groundwater bores (Scott's Beach, G40/0413, G40/0368, G40/0178)

The main significance of this conceptual model is that at some point the groundwater system could become disconnected from Lake Hawea. If this were to happen then groundwater levels could significantly decline in the Hawea Flat aquifer. More details on these scenarios are discussed in the scenarios readme file..

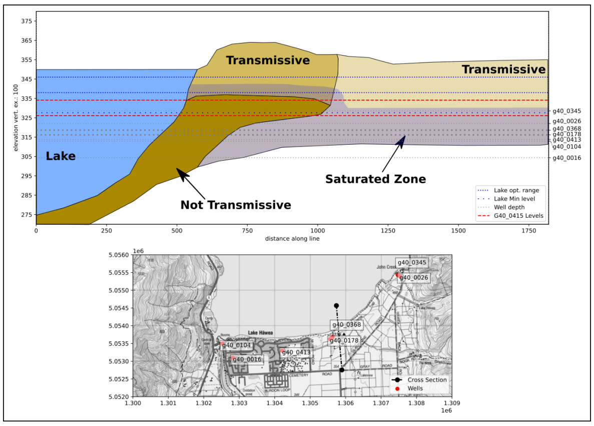


Figure: conceptual model of the Lake Hawea Moraine (across the moraine)

The location and elevation of the conceptual pour point is fundamentally unknown. If we assume a perched aquifer (rather than a local penetration, discussed below) then, based on groundwater levels, and the bore logs, we can estimate the bottom elevation of the impermeable moraine to be approximately 320 m msl. The top of the impermeable moraine is likely is more difficult to estimate. Based on the behaviour of the water levels in G40/0415, we can suggest it is likely below the typical minimum operating level of Lake Hawea (338 m msl). The observed water levels in G40/0415 do not become disconnected (e.g. variations in Lake levels which are not seen in the measured bore levels) and the rise and fall of the groundwater levels are relatively symmetrical. If the lake was disconnected we would expect to see a period of groundwater decline with a sudden increase in groundwater levels (as the lake became re-connected to the groundwater system). There is some anecdotal evidence that the groundwater levels in the Hawea Flat aquifer system have declined significantly when the lake levels reached their historical minimum (327.6 m msl in 1976 & 1977). We could interpret this as evidence of a lake disconnect, suggesting that the top of the moraine is likely above 327.6 m msl, but there are not sufficient records from this event to be certain.

It is also possible that the moraine is not continuous across the Lake Hawea foreshore, but is instead locally penetrated by a paleo-channel of either the Hawea River, John Creek, or Grandview Creek. If this is the case the penetration would likely be within the spatial extent of the Grandview Creek and John Creek alluvial fans. The response of the groundwater system to a local penetration of the moraine is likely to be dependent on the shape of the paleo-channel. The response would likely be non-linear as the transmissivity of the paleo channel would decline rapidly with decreasing water levels This scenario is fundamentally uncertain and very difficult to include in a groundwater model without additional information. Therefore we chose to assume a perched aquifer for the conceptual model used in the multi-layer model structural design.

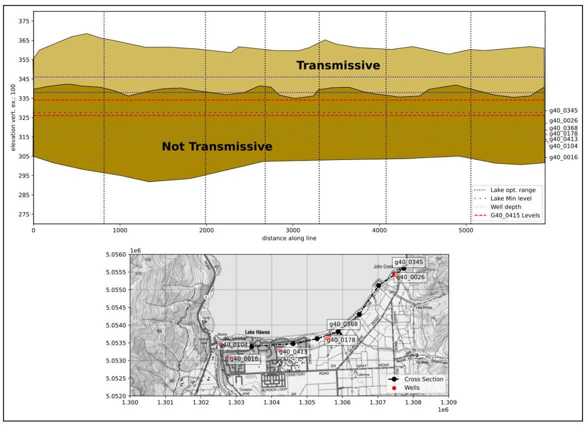


Figure: indicative conceptual model of the Lake Hawea Moraine (along the moraine) assuming a perched aquifer

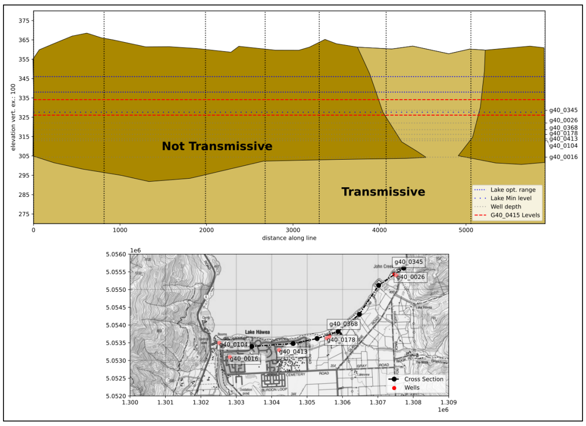


Figure: indicative conceptual model of the Lake Hawea Moraine (along the moraine) assuming local penetration of the moraine with a paleo-channel

Implementation of the Lake Hawea Moraine Conceptual Model into the groundwater model

We implemented a very simple version of the conceptual model described above, assuming a perched aquifer system. We:

1. implemented a 3 layer system. Layer number follows Python indexing (i.e. layer 0 is the top layer)
2. defined four new zones for the model (see figure below)
    1. The moraine zone: Layer 0 represents the permeable cap of the moraine, layer 1 represents the impermeable moraine, and layer 2 represents the conductive out-wash left by the Q4+ glaciations of the main Hawea Flat aquifer system.
    2. The Lake bar: This zone does not occur in layer 0, but in layer 1 and 2 it represents the impermeable material that separates Lake Hawea from the Hawea Flat aquifer system.
    3. The Lake: This zone occurs in layer 0, 1, 2; it is conductive material and contains GHB boundary conditions (see more below)
    4. The Layer pinch out area: This zone occurs in layer 0, 1, 2 and is used to pinch out the three layer system so that for the rest of the model domain, layer 0 is the main aquifer system (e.g. like the 1 layer model) layers 1 and 2 consist of 1 m thick layers
3. set the top of layer 2 (bottom of the moraine) to be 328 m msl.
4. set top of layer 1 (top of the moraine) to be 335 m msl. note in some of the branches of this repo we used different "bund_top" elevations. the layer 1 elevation is always specified in model_build.project_model_tools.bund_top object

Several cross sections are presented below; additional crossections and spatial figures about the multi layer model structure are available in the support figures folder.

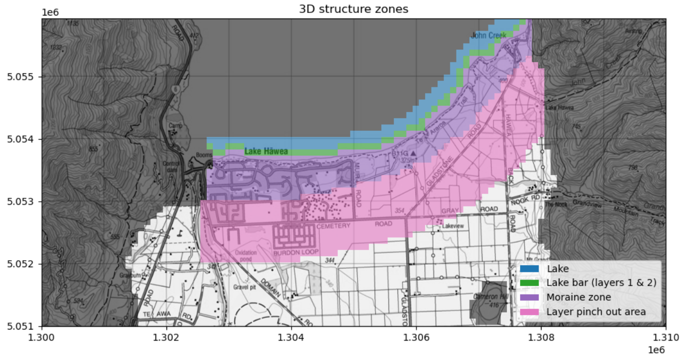


Figure: 3D spatial view of the multi-layer model structure zones

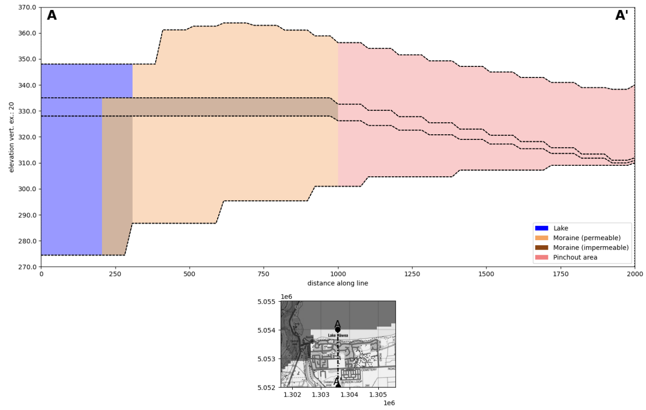


Figure: 3D cross section view 2 of the multi-layer model

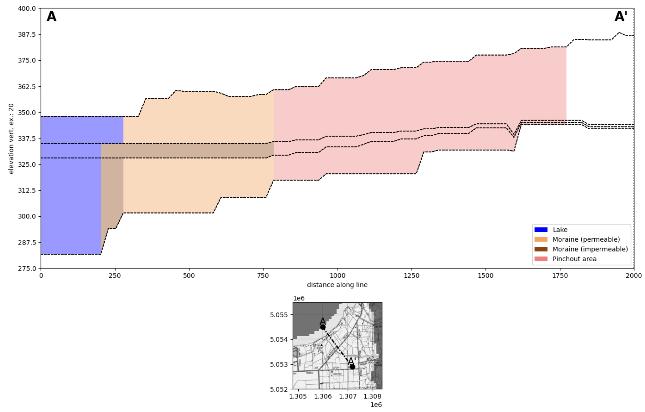


Figure: 3D cross section view 6 of the multi-layer model

Model boundary conditions

Land surface recharge (LSR)

LSR model

We chose to use the Rushton model to estimate LSR. The Rushton model is simple, easy to implement, and has been used in a number of other studies. In general the Rushton model uses the following methods to estimate soil moisture balance:

1. **Calculation of infiltration to the soil zone (In), and near surface soil storage for the end of the current day**

    (SOILSTOR). Note that Infiltration (In) as specified by the Rushton algorithms is not just infiltration (Rainfall-Runoff). It also includes SOILSTOR from the previous day.

2. **Estimation of Actual ET**

    The spreadsheet calculates TAW and RAW from field capacity, wilting point, and rooting depth data. Typical values for field capacity and wilting point are given in Table 19 of Allen et al. (1998). Rooting Depth changes with the season, and is typically 0.5-1m for grass (Table 22 of Allen et al.,1998) A depletion Factor, p, needs to be estimated for the calculation of RAW. p is the average fraction of TAW that can be depleted from the root zone before moisture stress (reduction in ET) For NZ conditions p should be around 0.4-0.6, typically 0.5 for grass. See Table 22 of Allen et al. (1998) for more values Fracstor (near surface soil retention) needs to be estimated. Typical values are 0 for a coarse sandy soil, 0.4 for a sandy loam, 0.75 for a clay loam (Rushton, 2006, pg 388)

3. **Calculation of Soil Moisture Deficit and recharge.**

    Note that the Soil Moisture Deficit equation, section (d) of Rushton, is ambiguous. SURFSTOR for this equation should be for the end of the current day, as calculated in section (b). The three steps outlined above partition near surface soil storage between near surface soil storage for the following day, AET, and the soil moisture deficit/reservoir respectively

Groundwater recharge occurs only when the soil moisture deficit is negative, i.e. there is surplus water in the soil moisture reservoir.

We also added an irrigation component to the Rushton model as follows:

1. Natural irrigation demand (before irrigation is applied) is calculated to reach the target value (taw * self.irrig_targ) if Irrigate (bool parameter):

    1. define the irrigation index (those cells with soil moisture < trig (taw* irrig_trig) AND which have not been irrigated more recently than the minimum number of days between irrigation (min_irrig_return))
    2. calculate used irrigation demand * if date is not in the irrigation days (between irrig start and stop) then use demand = 0 * else use demand = max(max_irrigation applied, irrigation demand + irrigation inefficiency)
    3. irrigate from the scheme (irrig_available)
    4. where excess demand remains irrigate from storage
    5. where excess water from the scheme is available add it to storage up to maximum storage
    6. add irrigation water to use_rain and recalculate the soil moisture balance note that irrigation will only be allowed to runoff if allow_irrigation_to_runoff = True
    7. calculate remaining irrigation demand (after irrigation is applied)

2. next day

LSR model inputs -> Precip and PET

We used two sets of inputs for meteorological data to estimate LSR:

- **ERA5-land**: a global reanalysis dataset of meteorological data (1950 - 2020) accessed here
- **Met station data**: Hawea met station data provided by ORC (2012-2021)

We chose to use these two datasets as the met station data is measured data and is therefore more accurate and covers the full optimisation period. For the longer scenario period we relied on the ERA5-land data as it is an available, well documented and validated reanalysis that is available for the full scenario period.

LSR model inputs -> Irrigated area and efficiency

The Rushton model accounts requires irrigation efficiency and irrigation area to be specified. The irrigation area is from MFE's national irrigated land spatial dataset. The irrigation efficiency, triggers, return frequencies and application rates are all specified in the recharge modelling script and are largely informed from McIndoe (2002)

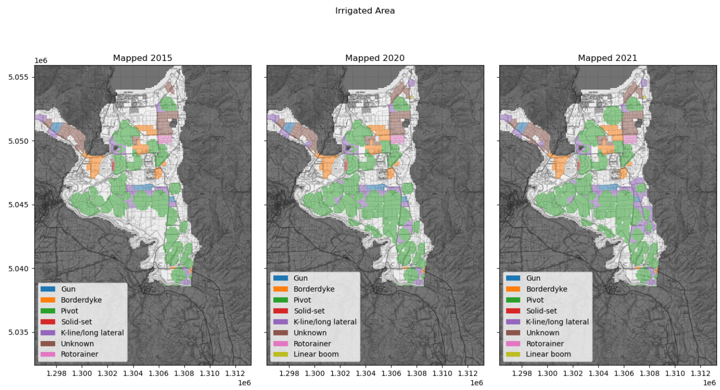


Figure: irrigated area and irrigation types

Correcting ERA5-land data

Unsurprisingly, the ERA5-Land has biases and unit conversion issues. We corrected the ERA5-land data by simple multi-linear regression. For the PET we used the daily ERA5-land PET and the season as the predictor variables and daily met PET. For the precipitation we used the weekly mean ERA5-land precipitation as the predictor variable and the weekly mean met precipitation as the dependent variable. The results of the regression are shown in the figure below.

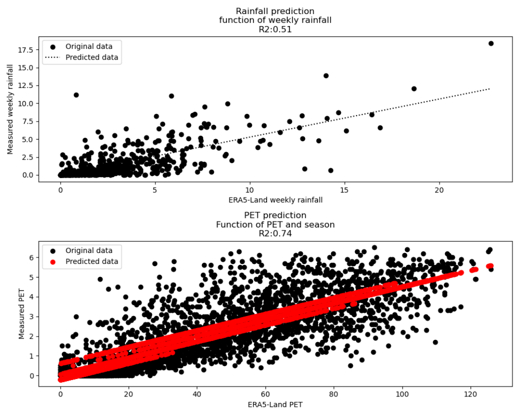


Figure: Era5-land vs met data and regressions

Met station based LSR

The weekly mean met station based recharge and spatial mean recharge are presented in the figures below.

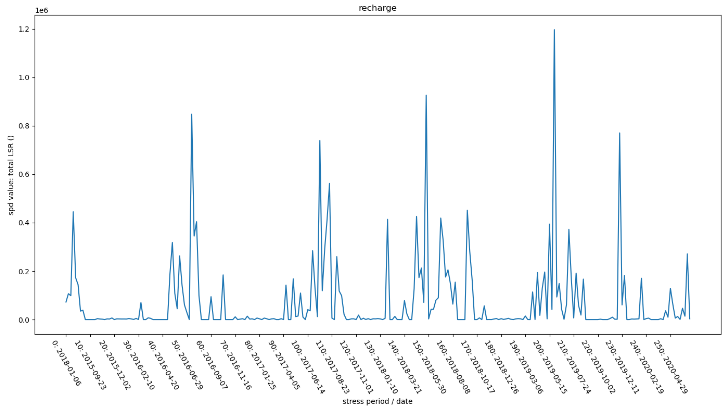


Figure: Weekly mean met data recharge

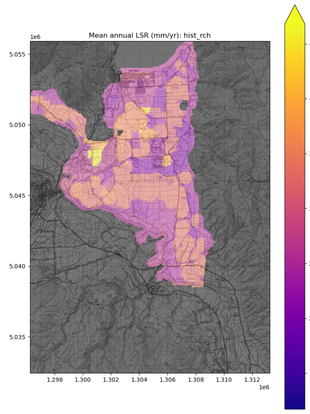


Figure: spatial variation of mean met data recharge

Correcting ERA5-land based LSR

The ERA5-land based recharge was biased relative to the met station based recharge despite the corrections applied to the meteorological data. We corrected the ERA5-land based recharge by two simple multilinear regressions one for irrigated sites and another for dryland sites based on the weekly mean LSR. The regressions and the results are shown in the figures below.

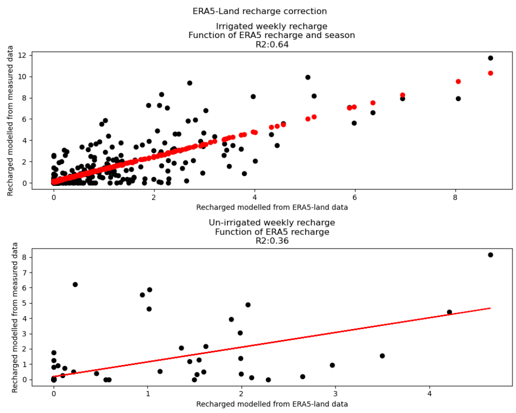


Figure: regressions for ERA5-land and metdata recharge

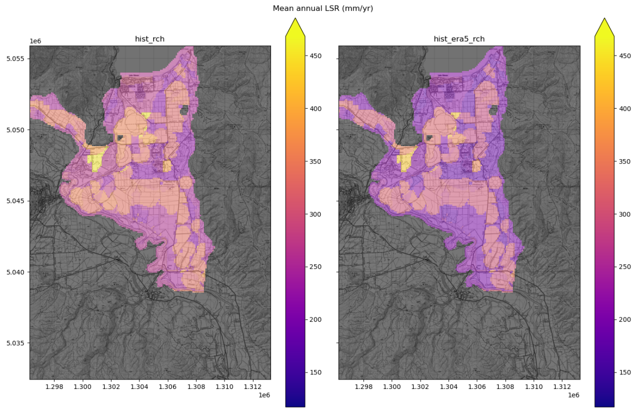


Figure: comparison for the spatially distributed mean recharge, Note that hist_rch is the metdata based recharge and hist_era5_rch is the same period, but using the ERA5-land data

While the regressions are not perfect, they do improve the large scale bias between the ERA5-land based recharge and the met station based recharge. We use the met station based recharge for the optimisation and the ERA5-land based recharge for the scenarios. While this does introduce some bias in our scenarios we analyse the results of the scenarios relative to the optimisation period run with the ERA5-land based recharge, which should mitigate the bias.

Generating a Long record of LSR

The advantage of using the ERA5-land data is that it is available for the full scenario period. We generated several long records of LSR for the full scenario period. The records are defined as follows and are show in the figure below.

- **dryland_rch**: recharge calculated from ERA5-land assuming this is no irrigation in the catchment (e.g. no irrigation losses)
- **irr_rch**: recharge calculated from ERA5-land assuming that irrigation in the catchment maintains the spatial coverage from 2021, but all irrigation is applied via pivot irrigators (e.g. 85% irrigation efficiency)
- **hist_rch**: recharge calculated from the met station data for the optimisation period (2015-2020)
- **hist_era5_rch**: recharge calculated from ERA5-land for the optimisation period (2015-2020)

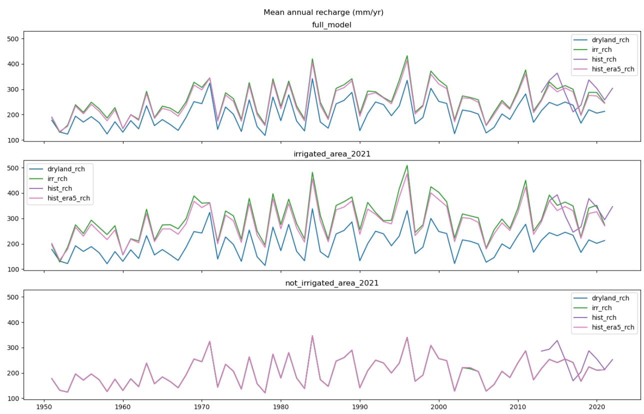


Figure: comparison of the temporal recharge

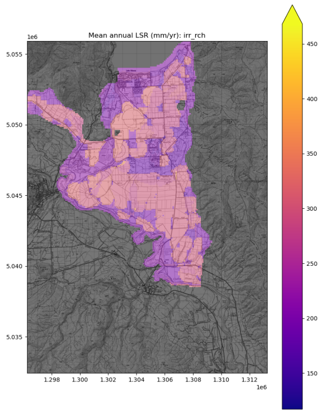


Figure: spatially distributed mean recharge for the irr_rch scenario

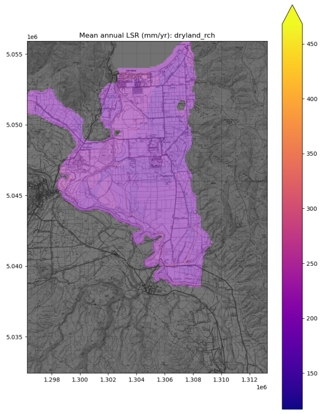


Figure: spatially distributed mean recharge for the dryland_rch scenario

Groundwater Abstraction (pumping)

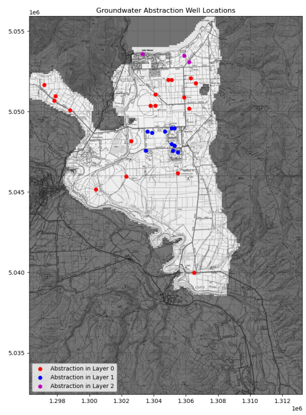


Figure: Groundwater abstraction locations

Groundwater abstraction was defined from the ORC usage data. The water use data was provided by the ORC and further interpreted in Kitteridge (2022). Good metering data is available from 2015 to 2020. The linkage between water metering data and the water abstraction point is complex with multiple abstraction points using 1 meter and multiple meters service 1 abstraction point. Where possible we matched the abstraction to the metering data, and where this was not possible we simply used the location data associated with the meter for the groundwater abstraction points.

The layering of the model is sufficiently simple that we made simple assumptions to define the layer for the abstraction points. In general all abstraction points were assumed to be in the top layer with the following exceptions:

- The abstraction points within the moraine and the layer pinch out zone (see multi-layer (3D) model structure above) were assumed to be in layer 2 (recalling that layers follow Python indexing standards and layer 0 is the top layer). This prevented any abstraction to be misplaced into low conductivity units or in cells that may become dry (i.e. while layer 1 and 2 are being pinched out).
- A number of abstraction bores in and around the Hawea Flat township were placed in layer 1 (the middle layer) as the top model cell would become dry during some periods. This is likely due to model structural error (there are no reports of these bores routinely going dry) and is a limitation of the model. By placing the bores in layer 1 we ensure that the abstraction occurs and is consistent with the model water balance.

The abstraction points included within the model and the temporal variation in groundwater abstraction are shown in the figures below.

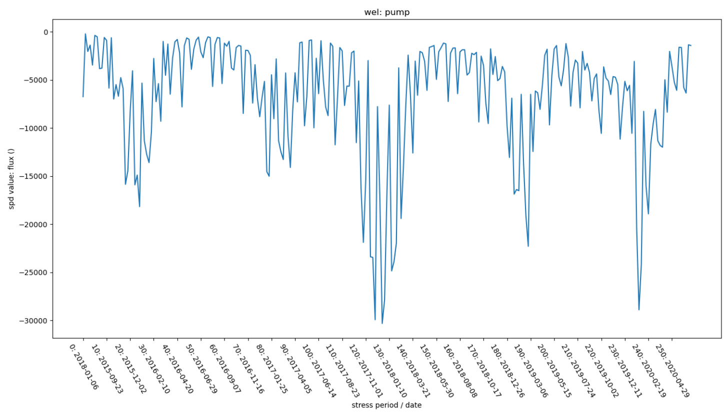


Figure: Total model groundwater abstraction (m/day)

Near river bores

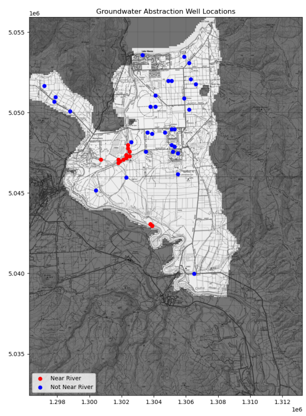


Figure: Groundwater abstraction locations including the abstraction near the Hawea and Clutha Rivers

The bulk of the "groundwater" abstraction in the model domain comes from two locations adjacent to the Hawea and Clutha Rivers. These abstraction bores occur in river proximal gravels which likely have a significantly higher hydraulic conductivity than the rest of the aquifer system. We initially attempted to include these bores in the model, but our model structure was not sufficiently resolved to include this river proximal aquifer. The very high localised abstraction caused dry cells and significant model instability. We therefore considered these river proximal wells as surface water abstraction (e.g. via a gallery) and removed these abstraction points from the model. We did use the river proximal abstraction data to adjust our river gain and loss targets and therefore conserve the water budget.

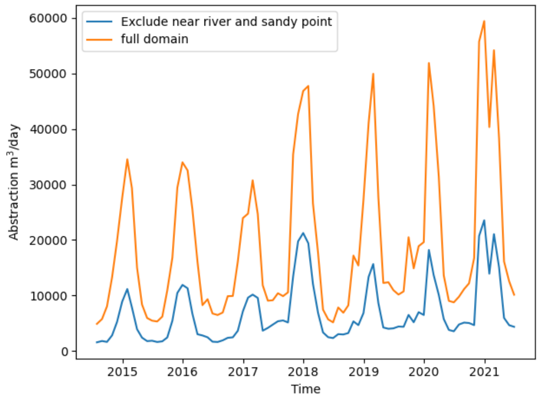


Figure: Comparisons of abstraction including and excluding the near river bores

Major Rivers (Hawea river and Clutha River)

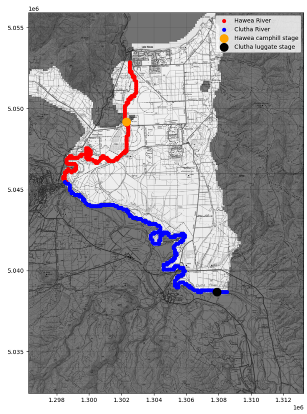
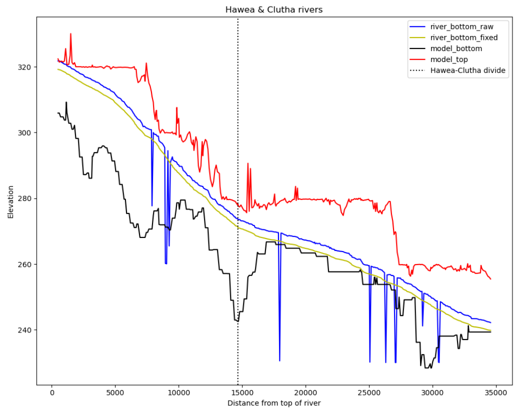


Figure: Major Rivers and Stage monitoring locations

The Hawea and Clutha rivers were included in the model using the stream boundary condition package.. The stream boundary condition package models both stream flow and surface-ground water interactions. While the package allows for modelling of stream stage, for this model we specified the stream stage. The package requires the following inputs:

- Stream location and riverbed elevation
- Stream stage
- Stream flow (at the top segment of each stream)
- The stream bed conductance factor

We defined the stream location with a carefully drawn line along the riverbed informed by a LiDAR dataset provided by Otago Regional Council. The raw riverbed elevation was defined as the minimum LiDAR elevation in each river model cell. This left a river profile that was not consistently decreasing downstream. To correct this we used a rolling mean to define the river bed elevation. Finally we inset the river bottom by 2.5 m so that the riverbed elevation was always below the river stage.



river bed elevations

The streambed conductance factor was a parameter in the model inversion. See the model parameterisation readme for more information The steam flow did not need to be particularly precise as the river would never come close to losing all of its water to the aquifer system. Therefore we set the Hawea River flow to the historical flow measured at Camp Hill. The Clutha River flow was arbitrarily set to 10 * the Hawea River flow. We prescribed the river stage for both the Hawea and Clutha rivers by interpolating historical river stage data at Camp Hill (Hawea River) and at a point on the Clutha River 200 m downstream of Luggate Confluence. The Clutha stage data did not cover the full optimisation period; therefore, we used the ISO-weekly mean river stage for the missing data. The Hawea River stage data was temporally complete. To interpolate the river stage spatially we simply applied the stage measured at Camphill relative to the riverbed elevation to the riverbed elevation in all other Hawea River model cells. The same approach was used for the Clutha River; however where the Clutha River joined the Hawea River there was an offset. To avoid this offset causing model convergence issues we linearly interpolated the stage at the end of the Hawea River to the stage on the Clutha River 200 m downstream of Luggate Confluence. The river stages generated this way do not cover the full scenario period. Therefore we used the ISO-weekly mean river stage for the scenario period.

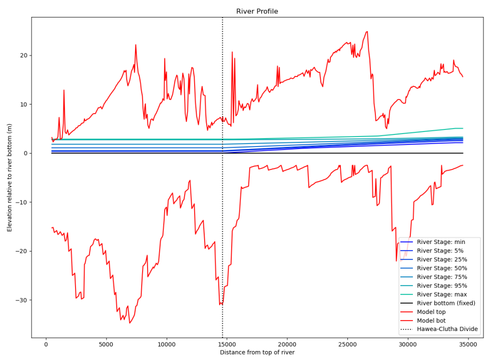


Figure: river stage relative to riverbed elevation

Lake Hawea

Lake Hawea was modelled with the General Head Boundary Package, which allows for time variant heads to be set. The package requires the following inputs:

- Location
- Head
- Conductance

For this model the lake locations were defined as all layers where the model cells that intersected the lake polygon. The lake conductance was set to a very high value (1e10) so that the only parameter defining the lake - model interaction was the cell's hydraulic properties (e.g. hydraulic conductivity). The lake head was set based on the historical lake stage measured at the dam. The historical lake stage covered both the full optimisation period and the full scenario period.

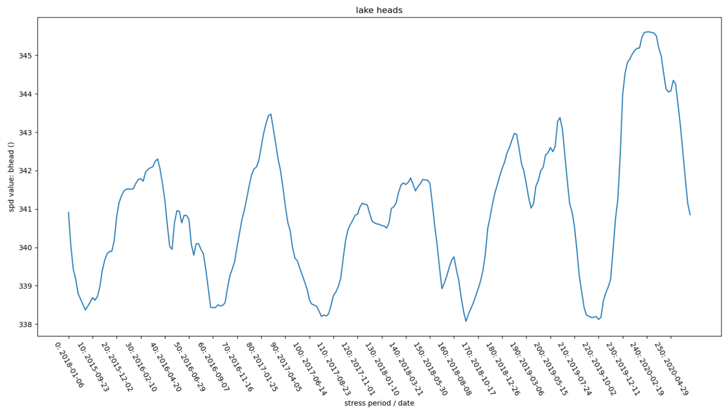


Figure: Lake levels for the optimisation period

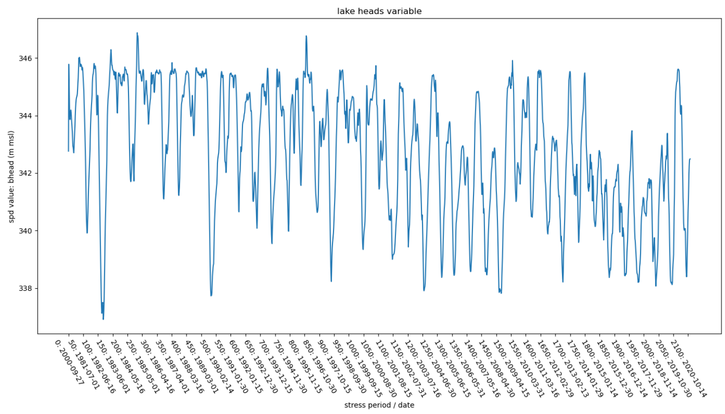


Figure: Lake levels for the Scenario period

Irrigation Supply Race Losses (race losses)

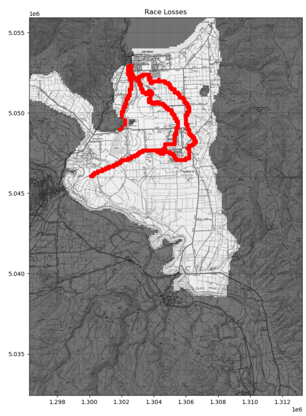


Figure: Race boundary condition locations

There are a number of irrigation supply races across the model domain. Estimates of race water losses are uncertain, however McIndoe (2002) suggests that approximately 10% of the race flows are lost to groundwater. We have access to records of daily race takes from the Hawea Irrigation Co. from 2012-01-01 to 2021-12-31, which covers the full optimisation period. For the scenario period we simply used the ISO weekly mean race losses.

Race losses were implemented as well boundary conditions using the Wel package. Well boundary conditions were placed in every model cell that intersected the race shapefiles and the flux was specified as 10% of the daily race flows spread evenly across every 'race' boundary condition.

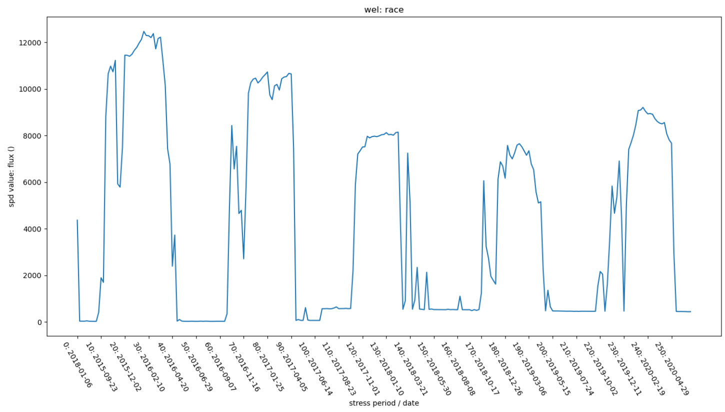


Figure: race losses (m/day) during the optimisation period

Hillside stream inflows (hillside inflows)

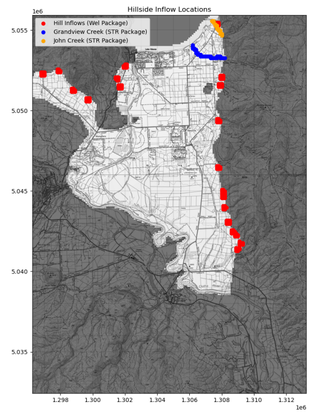


Figure: Hillside inflow locations

Method to estimate hillside inflows

There is has been rather minimal gauging data for the various hillside creeks that flow into the model domain, but it likely that these creeks contribute significantly to the groundwater budget. Recorders were put into Grandview and Lagoon Creek during the winter of 2017, so we have a daily data flow record for the period 2017-08-21 to 2021-02-09. This period is insufficient for even the optimisation period, let alone the scenario period. In addition there are another 19 hillside creeks that have not been gauged. We chose to estimate the hillside inflows based on the long term record of nearby Lindis River. The Lindis River is a much larger river that drains the mountains to the east of Lake Hawea. While the Lindis River catchment is much larger than the hillside inflows, it drains areas with similar geography and climate and has a historical high frequency gauging record at Lindis Peak starting in 1976-09-23. To estimate the hillside inflows we used the following methodology:

1. We estimated the catchment area (CA) for each of the hillside catchments that flow into the model domain using pysheds

2. We manually estimated the Lindis River Catchment above the Lindis Peak recorder (by drawing a shapefile). Note we did not use pysheds here as the lower gradient topography in the Lindis River created complications with the precision of the available DEM

3. We normalised the daily flows of the Lindis River, Lagoon Creek, and Grandview Creek to their respective catchment areas

4. We calculated the mean annual low flow (MALF) normalised to the catchment area for each of the hillside creeks and the Lindis River

5. We then conducted a logarithmic regression of the MALF/CA against catchment area (see figure below). Note that our regression predicted a MALF of zero at a catchment area of 0.14 km^2, which is consistent with the behaviour we would likely expect.

6. We then conducted a multiple linear regression of daily flows of the hillside creeks against the independent variables of Lindis River Flow/CA and the predicted MALF/CA. (see figure below) The Root Mean Squared errors for the daily and monthly flows at Lagoon Creek and Grandview Creek are shown in the table below.

7. We then used both of these regressions to predict the daily flows of the hillside creeks for the period of 1976-09-23 to 2021-06-30. Where the prediction was negative we set the flow to zero.

8. Finally, to reduce the impact of very high flows (where overland flow may not be inconsequential) we set any daily flows greater than the 98th percentile of the daily flows to the 98th percentile.

This methodology certainly has its limitations. Regression scores are not as high as we would like, but given the minimal data this was one of the very few options available. Other options could be based on rainfall-runoff modelling, but this would be very complex, and would introduce additional biases associated with the meteorological data and other modelling parameters. The root mean squared error of the daily flows at Lagoon Creek and Grandview Creek are presented in the table below. Note that the monthly mean flows are much better predicted than the daily flows. Given these RSME values we would consider our predictions to be good enough for the modelling process. In addition, we added a parameterised multiplier to the hillside inflows during our model inversion.

Creek	rsme_daily (m3/s)	rsme_monthly(m3/s)
Grandview	0.057	0.036
Lagoon	0.024	0.014

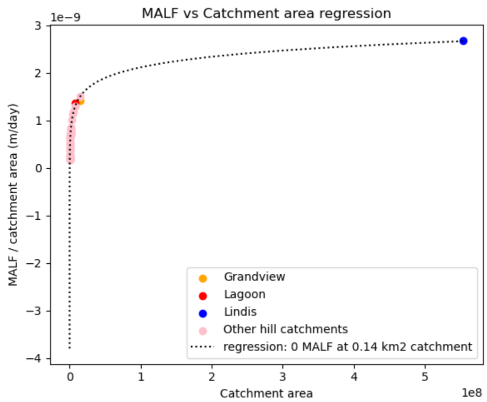


Figure: The relationship used to predict the catchment area normalised MALFs

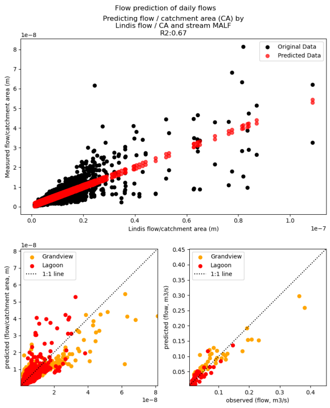


Figure: The relationship used to predict daily hillside creek flows

Large Hillside Inflows (Grandview and John Creek) implementation

Both John Creek and Grandview Creek can have significant flows, flow directly into Lake Hawea, and sometimes do not lose all of their water to groundwater. Therefore we implemented these using the stream boundary condition package.. This allowed the model to partition the groundwater losses across the length of the stream. The stream bottom was set to 2 m below the model top. The stream bottoms were then adjusted so that they were continuously decreasing downstream. The conductance factor was parameterised. The stream flow at the top of the stream was set using the inflow estimates described above and the stream stage was set at the smoothed model top (i.e. 2 m above the stream bottom).

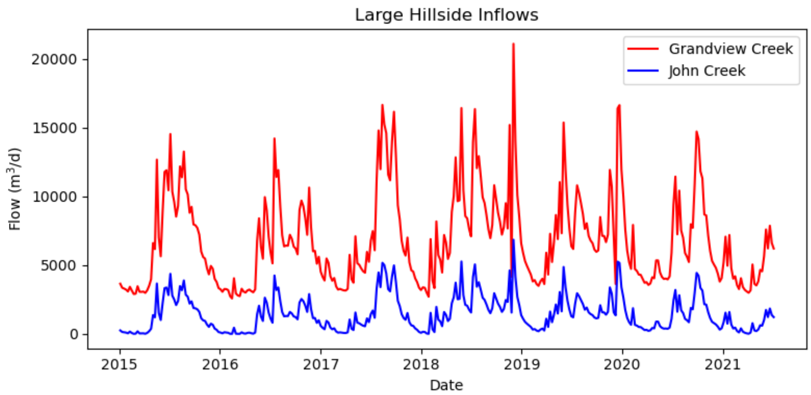


Figure: Large hillside inflows rates

Smaller Hillside inflows (other hillside inflows) implementation

All of the smaller inflows were implemented using the Well package. A series of 9 well boundary conditions were placed, centered on model cells that intersected the hillside inflow shapefiles. The flux was set to the daily hillside inflow estimate divided by 9 and spread evenly across the 9 well boundary conditions.

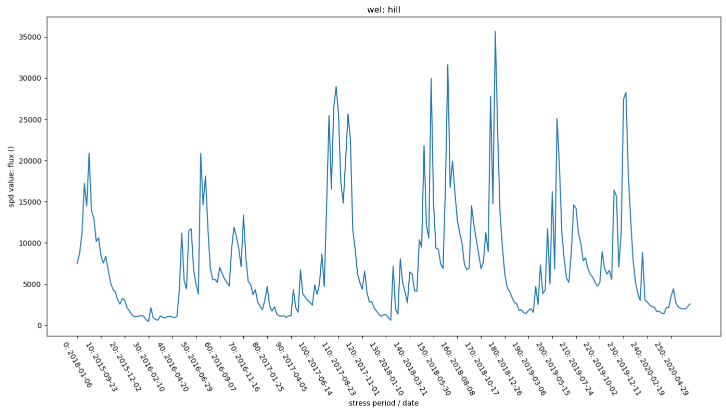


Figure: Total inflow for the smaller hillside catchments (m/day)

Model Zones

A number of model zones were generated to more easily visualise the model results. The generated zones are shown below.

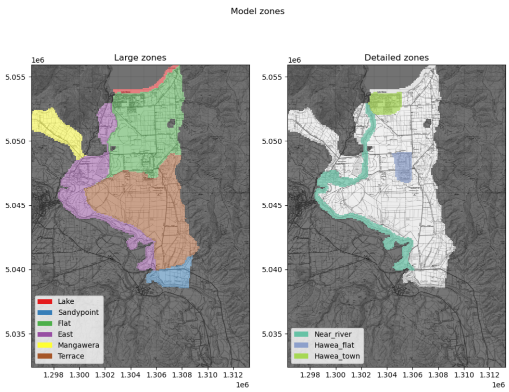


Figure: helpful model zones

References

- Wilson, J., 2012. Hawea Basin Groundwater Review. prepared by Resouce Science Unit of Otago Regional Council, June 2012, Dunedin.
- McIndoe, I., 2002. Efficient and reasonable use of water for irrigation.
- Rushton, K.R., Eilers, V.H.M., Carter, R.C., 2006. Improved soil moisture balance methodology for recharge estimation. Journal of Hydrology 318, 379-399.

Hawea Transient groundwater model (Hawea Model) parameterization

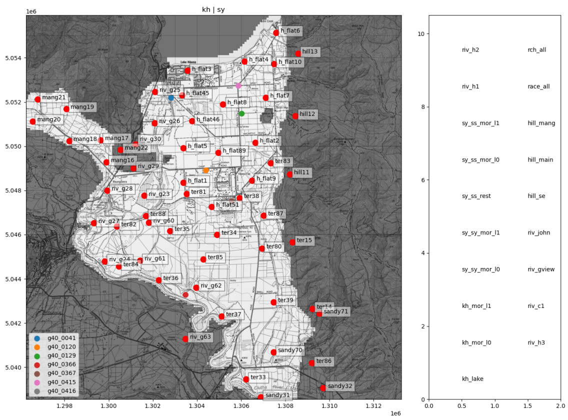


Figure: All Hawea Model parameters and their location in the model domain.

Author:	Matt Dumont
Date:	2021-11-02
Version:	1.0.0
Status:	Draft
KSL project:	Z22031HAW_hawea-model
Purpose:	This document describes the development of model parameters

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Table of Contents

Module Index

- README.rst: this document
- base_data: raw input data for the model parameterisation
- processed_data: processed data for the model parameterisation that was built by the scripts in this folder from the raw data in the base_data folder
- static_params.py: a script to define the static model parameters
- pilot_points.py: a script to create, define, and interpolate pilot points for kh and sy

- inital_parametersiation.py: a script to define the initial model parameters (before optimisation)
- plot_parameter_names.py: a script to plot the parameter names generates parameter_map.png
- optimised_parameterisation.py: a script to easily access optimised parameter sets
- **optimised_parameter_sets: optimised parameter sets**
    - 3d_v1a_opt.par: optimised parameter set for the 3D model version 1a
    - 3d_v1b_opt.par: optimised parameter set for the 3D model version 1b
    - 3d_v1d_opt.par: optimised parameter set for the 3D model version 1d
- parameter_map.png: a map of the model parameters

Static parameters

There are four static parameters in the model. They are:

Parameter Name	Parameter type	Value	Comment
lake_ss	specific storage in the lake zone	1e-10	Minimal storage in the lake zone
lake_sy	specific yield in the lake zone	1e-10	
vka	vertical conductivity	1	Set to 1 as we are not modelling vertical gradients (no z data for targets)
lake_conduct	lake conductance	1e10	Set high so that lake hydraulic conductivity is the only parameter bounding the lake-groundwater interaction

Spatial parameters

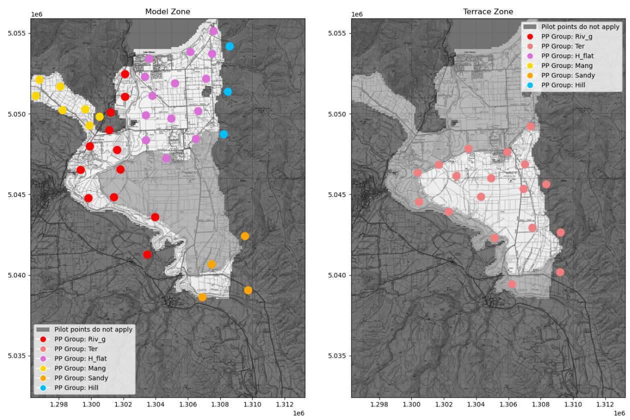

Figure: Spatial parameters for hydraulic conductivity (kh) and specific yield (sy) in the model domain.

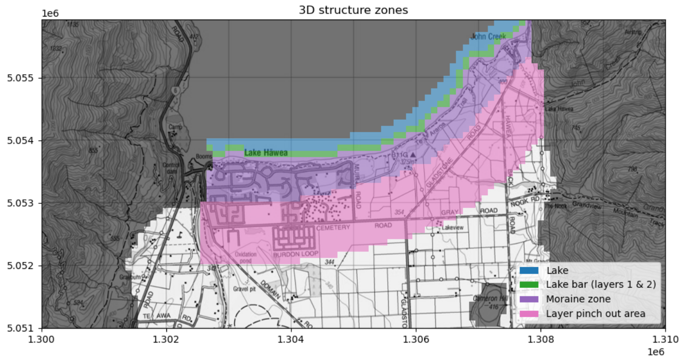

Figure: 3D spatial view of the multi-layer model structure zones

Hydraulic conductivity (kh) and specific yield (sy) were parameterised using pilot points in two discrete zones; one for the high terrace and another for the rest of the model. We chose to divide the model into two zones because it would be reasonable that the significantly older high terrace sediments could have different hydraulic properties to the younger sediments in the rest of the model. In addition this sharp parameter change could allow for the impacts of the Q4 Albert Town Advance moraine which we did not explicitly represent in the model. Pilot points extend beyond the active model domain to allow interpolated values to be calculated at the boundary of the active model domain. Note that specific storage, and parameters for the moraine zones are described in *other parameters* below. The interpolated parameters apply to all layers in the model (inc. the layer pinch out zone) except in the moraine zone where these parameters apply to only layer 2 (the bottom layer recalling that layering follows python indexing format layer 0 = top layer). These parameters do not apply to the lake zone or the lake bar zone.

We initially parameterised the model as a relatively homogeneous system. We considered leveraging the parameters generated by Wilson et al. (2012), but decided against is as it could introduce bias from the previous model. Parameter ranges and initial values are defined in the table below.

Parameter group	Initial	Min	Max
Main Kh	3e2	1e-2	1e4
Terrace Kh	5e1		
Main Sy	1e-2	1e-4	3e-1
Terrace Sy			

Wilson et al. (2012) assessed the annual lake fluctuation in Lake Hawea using the Jacob tidal equation. They found values of specific yield = 0.012 and a transmissivity estimate of 1300 m^2/d. We used the specific yield value to set the initial values for the specific yield. The tidal estimates of transmissivity do not include the complex three dimensional structure which almost certainly limits the transmissivity. We therefore set the initial value to a higher value than the tidal estimate. We set the upper bound based on the highest recorded transmissivity from pump tests, though as noted in Wilson et al. (2012) these tests are somewhat suspect. We set the lower bound at an arbitrary, but very low value allowing kh to span six orders of magnitude.

Interpolating spatial parameters

We interpolated the pilot points to continuous values using Radial basis function (RBF) interpolation with a multiquadric kernel. The RBF interpolation was performed using the *scipy.interpolate.Rbf* function. The RBF interpolation was preformed on log (base 10) transformed values. An example of the RBF interpolation is shown below.

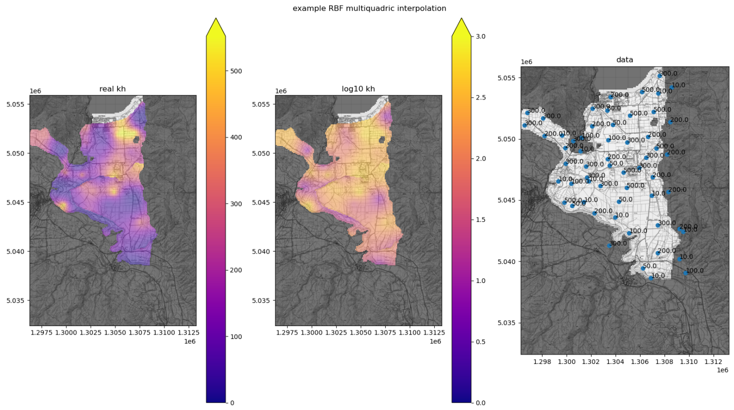

Figure: Example of the RBF interpolation of the spatial parameters. The interpolated values are shown for the bottom layer of the model.

Other parameters

A number of other parameters were included in the model. These parameters are listed in the table below. Recall layering follows Python indexing format e.g. layer 0 = top layer.

Parameter type	Package	Name	Initial	Min	Max	Applies to
Hillside inflow multiplier	Wel	hill_se	1	0.8	1.2	see figure below
Hillside inflow multiplier	Wel	hill_main	1	0.8	1.2	
Hillside inflow multiplier	Wel	hill_mang	1	0.8	1.2	
Recharge Multiplier	Rch	rch_all	1	0.5	1.2	full model domain
Race loss multiplier	Wel	race_all	1	0.8	1.2	
River Conductance	Riv	riv_h1	1000	100	10000	see figure below
River Conductance	Riv	riv_h2	1000	100	10000	
River Conductance	Riv	riv_h3	1000	100	10000	
River Conductance	Riv	riv_c1	1000	100	10000	
River Conductance	Riv	riv_gview	100	50	5000	
River Conductance	Riv	riv_john	100	50	5000	
Conductivity	Upw	kh_mor_l0	300	0.001	1000	moraine zone layer 0
Specific Yield	Upw	sy_sy_mor_l0	0.01	0.0001	0.3	& lake bar layer 0
Specific Storage	Upw	sy_ss_mor_l0	0.0001	0.000001	0.001	

Conductivity	Upw	kh_mor_l1	0.0001	0.0000001	1	moraine zone layer 0
Specific Yield	Upw	sy_sy_mor_l1	0.001	0.0001	0.3	& lake bar layers 1 & 2
Specific Storage	Upw	sy_ss_mor_l1	0.0001	0.000001	0.001	
Specific Storage	Upw	sy_ss_rest	0.0001	0.000001	0.001	area of pilot points
Conductivity	Upw	kh_lake	300	0.001	1000	lake zone all layers

We set the initial parameters and ranges for the multipliers (hill_se, hill_main, hill_mang, rch_all, race_all) to allow a 20% change around the predicted in the inflow values. The initial values for the Hawea and Clutha River conductance (riv_h1, riv_h2, riv_h3, riv_c1) were roughly pulled from the model developed in Wilson et al. (2012). The initial values for the smaller river conductance (riv_gview, riv_john) were set as an order of magnitude lower than the Hawea and Clutha River conductance. The ranges for the river conductance are somewhat arbitrary but act to allow the model to explore a range of values. The initial and ranges of kh_lake, and kh_mor_l0 were set to the values used for the main pilot points. The specific storage values (sy_ss_rest, sy_ss_mor_l0, sy_ss_mor_l1) were set to typical specific storage values. The specific yield parameters were set to the range used for the main pilot points. The initial value for sy_sy_mor_l0 was set to the starting pilot point values while the initial value for sy_sy_mor_l1 was set an order of magnitude lower. kh_mor_l1 (the moraine low conductivity unit) was set to the typical values for glacial till.

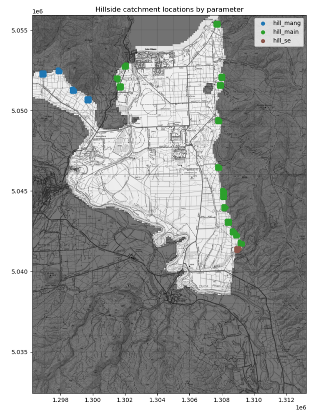

Figure: Spatial location of the hillside inflow multiplier parameters.

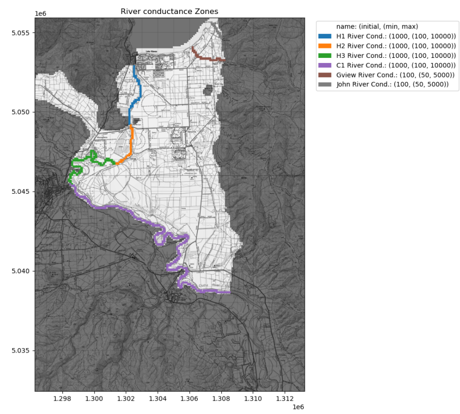

Figure: Spatial location of the river conductance parameters.

References

- Wilson, J., 2012. Hawea Basin Groundwater Review. prepared by Resouce Science Unit of Otago Regional Council, June 2012, Dunedin.

Hawea Transient groundwater model (Hawea Model) Targets and Sensitive sites

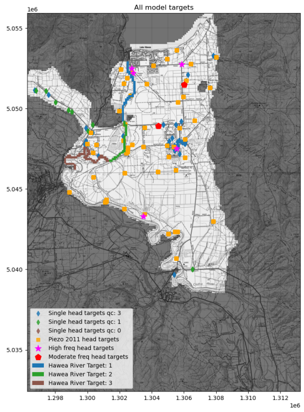

Figure: All Hawea Model targets

Author: Matt Dumont

Date: 2021-11-02

Version: 1.0.0

Status: Draft

KSL project: Z22031HAW_hawea-model

Purpose: This document describes the development of model targets and the identification of sensitive sites

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Module Index

- README.rst : readme document detailing the methods and data used to develop the targets
- model_output.py: script to extract consistent model outputs and plots
- get_raw_target_data.py: ingest raw target data
- get_indicative_times.py: get indicative times for the targets that fall outside of the optimisation period
- head_targets.py: definition of the head targets
- riv_gain_loss_targets.py: definition of the river gain and loss targets
- senstive_sites.py: identification of sensitive sites
- target_structure_checks.py: checks to ensure that the targets and the model structure were not mutually exclusive
- base_data: base input data for the targets
- processed_data: processed target data, this was developed from the raw data in the base_data folder

Groundwater head targets

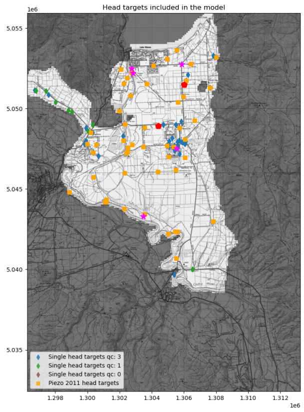


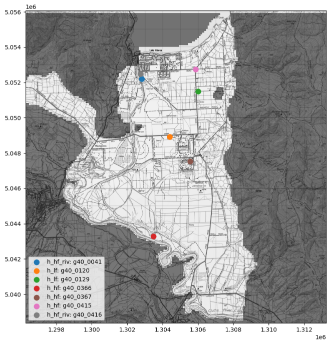
Figure: Spatial distribution of groundwater head targets

High and moderate frequency targets

High and moderate frequency targets were provided by Otago Regional Council (ORC) and included the following wells. Note that in the code these targets are often referred to as "regular" targets:

Well name	Group	Description
G40/0041	h_hf_riv	High frequency loggers installed after 2014, near Hawea river
G40/0416	h_hf_riv	High frequency loggers installed after 2014, near Hawea river
G40/0366	h_hf	High frequency loggers installed after 2014
G40/0367	h_hf	High frequency loggers installed after 2014

G40/0415	h_hf	High frequency loggers installed after 2014
G40/0120	h_lf	NGMP wells, which have a longer record than the others, but less frequent sampling
G40/0129	h_lf	NGMP wells, which have a longer record than the others, but less frequent sampling



Targets from the 2011 Piezometric Survey

The 2011 piezometric survey was conducted on 21-sept-2011 and is detailed in Wilson et al., (2012). The survey provides a significant spatial distribution of targets across the model domain and is highly reliable. These targets make up much of the information used to constrain the model in the optimisation away from the high frequency targets.

Single targets

Often when drillers are installing wells, they will take a single, static water level measurement at the time of installation. This information is less reliable than a piezometric survey, but it is still useful to constrain areas of the model where there is little other information. There is often missing information for these records, as such we created four quality categories for these targets:

- 0: no date data for the depth to water field -- Not included in the model
- 1: no elevation data present (read from DEM) -- Only included in the model in the Sandy Point and Maungawera Valley, where there is a relative dearth of other information.
- 2: no depth data for the well -- No wells matched this category
- 3: as good as it gets -- included in all parts of the model

River gain and loss targets

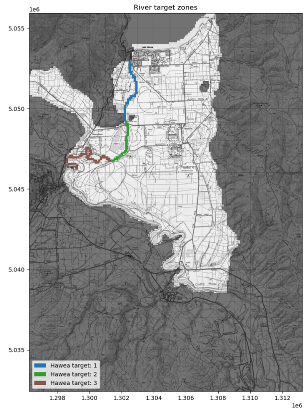


Figure: Spatial distribution of river gain/loss targets

Measured data

Two sets of four concurrent river gaugings on the Hawea River were used to develop the river gain/loss targets. The first set of gaugings were taken on 2017-09-29 and the second set were taken in on 2018-02-07. These targets are inherently uncertain as the gauging error is typically >= 10% of the river discharge and in braided river systems such as the Hawea River, the river discharge can vary significantly over short distances as water travels in and out of the river proximal and riverbed gravels. Nevertheless, the river gain/loss targets are the only measured constraint on the model and are therefore used in the optimisation.

Expert judgement

In addition to the measured datasets described above, the expert judgement of the Hawea River is that it is largely a gaining reach from the Hawea Dam to Camp Hill. After Camp Hill, the river loses a significant amount of water as the river turns west against the high terrace. The lower reaches are gaining and losing until it reaches the Clutha River. The Clutha River is exclusively thought of as a losing reach. This expert judgement is in agreement with the measured data and while it is not explicitly included within the model optimisation targets, it was used to qualitatively assess the performance of the model.

Managing targets outside of the optimisation period

Many of the targets used in the model fall outside of the optimisation period. If we only included information from within the optimisation period we would be left with only the "regular" high and moderate frequency targets -- that is seven spatial targets across the model domain and no targets in the Maungawera Valley. Therefore we needed to apply the targets out of the optimisation period to the most appropriate time within the optimisation period. This is done by:

1. Calculating the last 12 months normalised average recharge and hillslope inflow for each month in the scenario period (1980-07-18 to 2020-12-01). Any targets outside of this period were excluded from the model. The choice to use the last 12 months was based off of the annual cycle, and confirmed by calculating the predictive power of multiple different time periods (e.g. 6 months, etc.). The annual data provided the best predictive power.
2. The target dates outside of the optimisation period were then assigned to the month within the optimisation period that was the closest (cartesian distance of the normalised 12 previous month recharge and hillslope inflows) to the target date and had the closest normalised recharge and hillslope. Targets were allowed to shift up to 1 month (e.g. a target measured in September could was assigned to the closest August, September or October month). This was done to maintain any seasonal effects while allowing a larger potential pool of matches.
3. Targets which were temporally shifted in this way were assigned to all stress periods in the month.

The following figures show the results of this process. Figures of each target month are available here

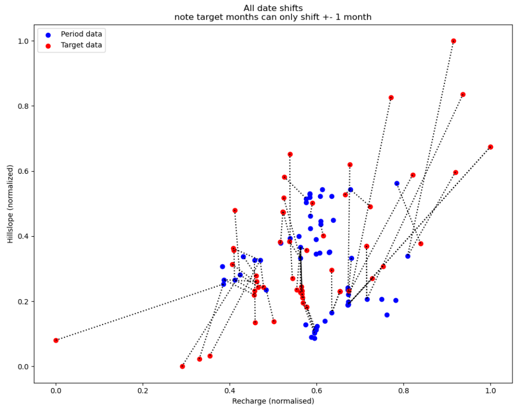


Figure: Target period shifts for all targets

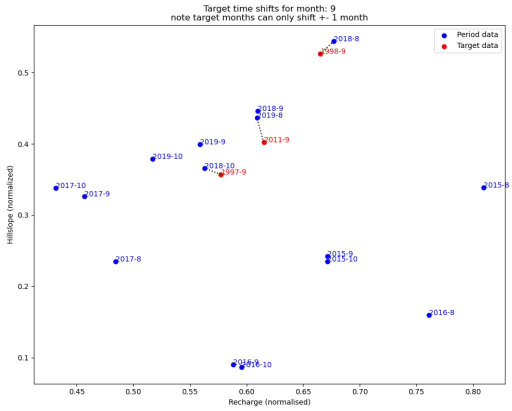


Figure: Target period shifts for the targets measured in September, recall that the 2011-9 targets include the piezometric study

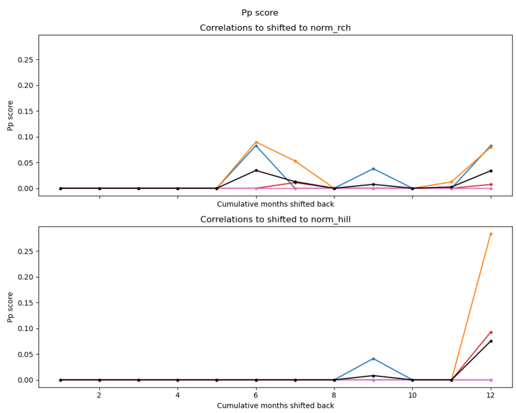


Figure: The predictive power score of different monthly aggregations of the normalised recharge and hillslope inflows

Temporal distribution of targets

The final temporal distribution of targets in the model is shown in the following figures. Recall that the targets which were measured outside of the optimisation period were assigned an indicative time during the optimisation period.

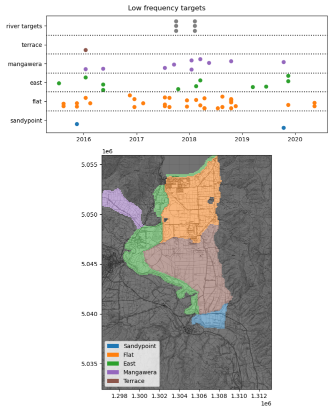


Figure: Temporal distribution of low frequency groundwater head and river gain/loss targets

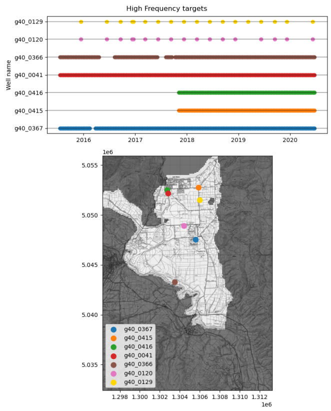


Figure: Temporal distribution of high frequency groundwater head targets

Model Objective Function and target weighting

The objective function is at a high level simply the weighted sum of squared errors between the modelled values and target. The weighting strategy is often adjusted during the course of the model optimisation (for more info on the final weighting scheme see the optimisation readme); however, the initial strategy for the weighting of the targets is described below.

1. **We developed a hierarchy of target groups as follows:**

    1. **h_hf:** High frequency groundwater head targets: these are high quality data with a high temporal resolution and a moderate spatial resolution. They are by far the most important targets within the model.
    2. **h_hf_riv:** High frequency groundwater head targets near the Hawea River: these are high quality data with a high temporal resolution, but they are adjacent to the Hawea River so are more susceptible to structural bias based on our implementation of the Hawea River in the model.
    3. **h_lf:** Moderate frequency groundwater head targets: these targets provide two additional sites with a number of samples across the optimisation period.
    4. **h_piezo:** Scott 2011 piezo survey: these targets provide a significant spatial distribution of targets across the model domain and are highly reliable; however, they fall outside of the optimisation period and therefore likely have some bias.
    5. **h_single_1:** Single targets Q3: generally lower quality targets but they provide some additional data.

6. **h_single_3:** Single Targets Q1: generally very low quality targets, but in areas they are the only data available.
7. **riv:** River targets: useful and the only way to constrain the river gain/loss, but they are not very reliable (as described above).
8. **There were two additional target groups that were never weighted:**

    1. **rwh_hf:** ISO weekly mean for each high frequency target (e.g. for the "typical" water year)
    2. **rwh_hf_riv:** ISO weekly mean for each high frequency near river target (e.g. for the "typical" water year)

2. The initial weights were set so that all targets weights were proportional to their value, that is that the expected value * weight = 1
3. The weights were then adjusted so that single_3 had twice the impact relative to single_1
4. The weights were then normalised so that the total impact of each group was equal regardless of the number of targets within the group.
5. The groups were then manually weighted with a multiplier to adjust the relative impact of each group in accordance with the hierarchy described above. This weight factor was adjusted during the course of the optimisation. For more info on the final weighting scheme see the optimisation readme.

Note that when a target occurred in a dry model cell the modelled value was set to the head value in the cell in the layer below, or if that cell was also dry, the head value in the cell below that. This was done to ensure that the modelled values did not get impacted by the dry cell flag.

Other sensitive sites

There are two sensitive wetlands within the model domain -- Butterfield Reserve and Campbell's Reserve. These wetlands were not included within the model as boundary conditions, but they are indexed here.

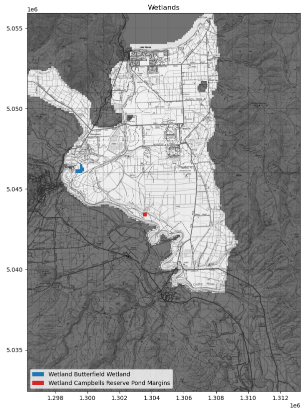


Figure: Wetlands in the Hawea model domain

References

- Wilson, J., 2012. Hawea Basin Groundwater Review. prepared by Resouce Science Unit of Otago Regional Council, June 2012, Dunedin.

Hawea Transient groundwater model (Hawea Model) optimisation and results

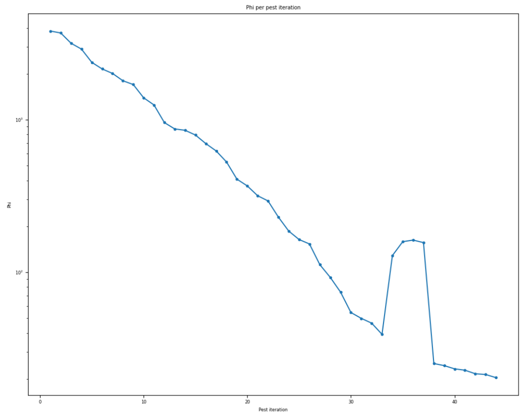


Figure: Model objective function over the optimisation

Author:	Matt Dumont
Date:	2021-11-02
Version:	1.0.0
Status:	Draft
KSL project:	Z22031HAW_hawea-model
Purpose:	This document provides the methodology and results for the model optimisation process and discusses the model limitations

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  - run_opt_step_models.py: run the step models from a PEST optimisation
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- **Computational support files**
  - compile_pest: compile PEST for linux
  - pest_run_data: static data needed by PEST to run the model
  - git_setup.sh: script to setup the Git repo for the optimisation on a machine
- **Model overview**
  - pre_optimisation_overview.py: make pre optimisation overview plots
  - make_preopt_slideshow.py: make a pre optimisation slideshow

- pre_optimisation_plots_png: pre optimisation plots of boundary conditions, targets, parameterisation, and other supporting work, many of these figures are referenced in the various readme.rst files
- make_opt_presentation.py: make a presentation of the optimisation results for a meeting

Optimisation overview

The optimisation process involved changing group weightings, parameter bounds, and the model structure. This chaotic process is typical in model optimisation and is typically very difficult to follow for anyone other than the primary modeller. To try and make this process more transparent and to provide a record of the process, we created a new Git branch for each optimisation version. This allowed us to track the changes to the model and reproduce and archive all of the key input data with any changes. To reduce the size of the Github repo we deleted all of the abandoned branches, but we produced a Github release for each abandoned branch so that the data could be recovered if needed.

Broadly speaking there were 3 main stages to the optimisation process:

1. A 1 layer model (2D)
2. Specific sub model (2D) to test whether or not the terrace observations could be fit by disconnecting the terrace from the main model
3. A 3 layer model (3D)

Optimisation setup / PEST structure

The model was optimised via PEST which is a model calibration and optimisation package. The interface to the model was handled via flopy which is a Python package for working with MODFLOW models and pyemu which is a Python package for working with PEST models. The PEST iterations were run in parallel on a cluster of linux machines using Beopest which is a subpackage of PEST. Beopest was managed via an in house class called BeopestManager. In addition, some manual optimisation was undertaken during the optimisation process to better understand the limits of specific model structures. These manual optimisations were undertaken using another in house class called SshDist. The main optimisation script was a_build_run_optimisation_version.py

The build of the PEST runfile was undertaken in build_optimisation.py. which has a number of component functions:

- raw_pest: - Overarching function to build the PEST runfile (calls the following functions). - Also handles the singular value decomposition (SVD) parameters.
- make_template_and_infiles: - Make the template and infiles for PEST to interact with the model parameter inputs.
- make_ins_and_output_files: - Make an example output files (model outputs) and the PEST instruction files to read the model output data (targets).
- set_control_data: - Set the control data for the PEST runfile.
- set_parameter_data_groups: - Set parameter data groups, limits, transformations, and derivative handling.
- set_obs_data: - Set the observation data, weights, and group weightings.

While the full specification for our PEST optimisation is available in the code the following relevant key parameters are listed below:

- Kh and river conductance parameters were varied on a log transform (*partrans*)
- All other parameters were varied with no transform (*partrans*)
- PEST was run in estimation mode (*pestmode = 'estimation'*)
- PEST allowed model failures in lamda calculation (*lamforgive = 'lamforgive'*)

- PEST allowed model failures in derivative calculation (*derforgive = 'derforgive'*)
- PEST was run with singular value decomposition (*svdmode = 1*)
- The eigenvalue threshold for svd was set to 5e-7 (*svd_dataeigthresh = 5e-7*)

Standard optimisation outputs

For each optimisation version we produced a number of standard outputs that are consistent across each optimisation result. We detail them here so that individuals can have easy access to the key outputs.

The output structure is as follows (links to the files are provided to 3d_v1d which is the final optimised model):

- **Base_Optimisation_plots:**
    - final_opt_model: plots of the final optimised model including the parameterisation, model heads, and the model fits to the observations - cross_sections: plots of heads in model cross sections - spatial_hds: spatial plots of head target residuals - spatial_riv: spatial plots of the river gain and losses - str_flow: plots of the stream flow in the river boundary conditions - Max_heads_(Hawea_aquifer).png: minimum heads across the model time steps - Min_heads_(Hawea_aquifer).png: maximum heads across the model time steps - Range_of_Heads_(Hawea_aquifer).png: range of heads across the model time steps - Steady_state_heads_(Hawea_aquifer).png: plot of the steady state heads (in layer 0 for most of the model, but layer 2 for the moraine areas) - 3d_hds.png: plot of heads in the 3D zone - SS_budget.png: plot of the steady state water budget - all_riv_targets_mes_mod.png: plot of the measured vs modelled river targets - all_riv_targets_residual.png: plot of the river target residuals - all_river_fluxes_hill.png: total river fluxes for each conductance parameter zone for John and Grandview Creek - all_river_fluxes_large.png: total river fluxes for each conductance parameter zone for the Hawea and Clutha rivers - dry_cells_l0.png: number of time steps with dry cells for layer 0 - dry_cells_l1.png: number of time steps with dry cells for layer 1 - dry_cells_l2.png: number of time steps with dry cells for layer 2 - flooded_cells_l0.png: number of time steps with flooded cells for layer 0 - flooded_cells_l1.png: number of time steps with flooded cells for layer 1 - flooded_cells_l2.png: number of time steps with flooded cells for layer 2 - hds_all_mod_v_meas.png: plot of the measured vs modelled heads - hds_all_residual_time.png: plot of the head target residuals - hds_closeup_h_g40_0041.png: plot of measured and modelled heads for well G40/0041 - hds_closeup_h_g40_0120.png: plot of measured and modelled heads for well G40/0120 - hds_closeup_h_g40_0129.png: plot of measured and modelled heads for well G40/0129 - hds_closeup_h_g40_0366.png: plot of measured and modelled heads for well G40/0366 - hds_closeup_h_g40_0367.png: plot of measured and modelled heads for well G40/0367 - hds_closeup_h_g40_0415.png: plot of measured and modelled heads for well G40/0415 - hds_closeup_h_g40_0416.png: plot of measured and modelled heads for well G40/0416 - hds_h_piezo_mod_v_meas.png: plot of measured and modelled heads for the piezo survey - hds_h_piezo_residual_time.png: plot of the piezo survey head residuals - hds_h_single_1_mod_v_meas.png: plot of measured and modelled heads for the single head targets Q1 - hds_h_single_1_residual_time.png: plot of the single head targets Q1 residuals - hds_h_single_3_mod_v_meas.png: plot of measured and modelled heads for the single head targets Q3 - hds_h_single_3_residual_time.png: plot of the single head targets Q3 residuals - hds_normal_year_all.png: plot of the measured and modelled heads for the normal water year (ISO week mean) - hds_normal_year_mod_v_meas.png: plot of the measured vs modelled heads for the normal water year (ISO week mean) - hds_regular_mod_v_meas.png: plot of the measured and modelled heads for the regular observations (e.g. high frequency) - hds_regular_residual_time.png: plot of the regular observation head residuals - hds_regyear_h_g40_0041.png: plot of the regular water year heads (ISO weekly mean) for well, G40/0041 - hds_regyear_h_g40_0366.png: plot

of the regular water year heads (ISO weekly mean) for well, G40/0366 - hds_regyear_h_g40_0367.png: plot of the regular water year heads (ISO weekly mean) for well, G40/0367 - hds_regyear_h_g40_0415.png: plot of the regular water year heads (ISO weekly mean) for well, G40/0415 - hds_regyear_h_g40_0416.png: plot of the regular water year heads (ISO weekly mean) for well, G40/0416 - more_than_50_outers.png: areas in the model that required more than outer 50 iterations to converge - more_than_100_outers.png: areas in the model that required more than outer 100 iterations to converge - more_than_300_outers.png: areas in the model that required more than outer 300 iterations to converge - more_than_500_outers.png: areas in the model that required more than outer 500 iterations to converge - more_than_800_outers.png: areas in the model that required more than outer 800 iterations to converge

- obs_plots: plots of the model objective function and target residuals through the optimisation process (e.g. at each optimisation step))
- regular_hds_closeup: plots of changes in the fit to the regular observations ((e.g. high frequency) through each optimisation step)
- param_plots: plots of parameter values through the optimisation process (e.g. at each optimisation step)
- param_fail_plots: plots of parameter values that failed to converge vs those that did not
- param_sen_plots: plots of parameter sensitivity through the optimisation process (e.g. at each optimisation step)
- parameters_norm_to_bounds.txt: a text file of the parameter values of the final model normalised to the parameter bounds
- parameters_norm_to_bounds_close.txt: as above, but only those that are close to their bounds
- parameter_norm_sy_kh.png: ignore, bug in plot
- jacobian_filled_0_of_1.png: plots of whether or not the Jacobian was filled (red values had model failure)
- hk_values.png: plot of the final hk parameter values at the pilot points
- kh_array.png: plot of the interpolated final kh parameter values
- sy_values.png: plot of the final sy parameter values at the pilot points
- sy_array.png: plot of the interpolated final sy parameter values

1 layer model (2D) optimisation results

With the 2D model we were able to fit many of the targets within the model, but despite numerous (we ran 17 unique optimisations) parameterisations, observation weighting schemes, and change to the model structure we were unable to replicate the water levels at G40/0415. The model could either fit the shape of the groundwater levels but there was substantial bias in the mean groundwater level (too high) or we could fit the mean groundwater level but the shape of the groundwater levels was lost.

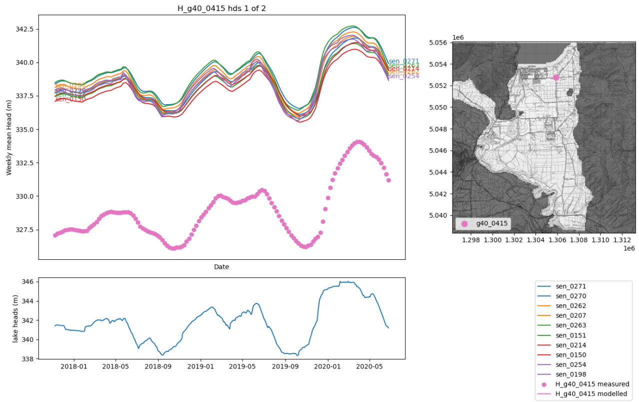

Figure: the results of the 1 layer model which fit the shape of the groundwater levels, but not the mean

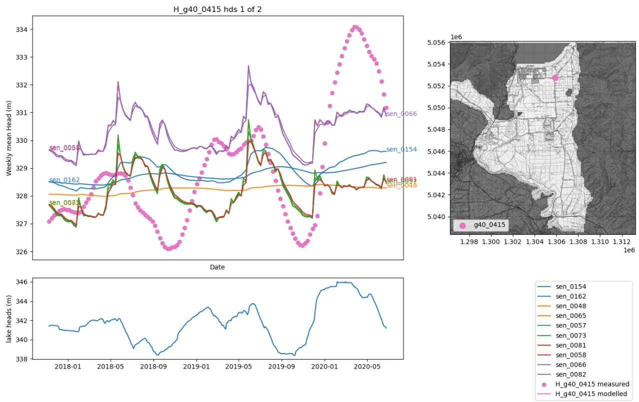

Figure: the results of the 1 layer model which fit the mean of the groundwater levels, but not the shape

We do not have other high frequency observations of groundwater levels near the Lake Hawea moraine. However, we do have a number of static water levels that were measured shortly after drilling the bore. These water levels, relative to the lake level at the time of measurement are shown in the figure below. This figure shows that a constant vertical offset between the groundwater levels and the lake levels of approximately 10 m. Some of these boreholes are located in the moraine less than 200 m from the lake. Many of the water supply wells near the lake (within the mapped moraine) are relatively deep (e.g. 50+ m).

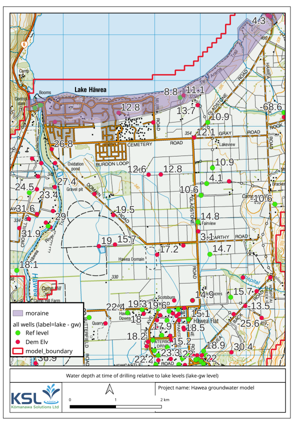

Figure: all groundwater levels relative to the Lake Hawea level on the sampling date (positive values are groundwater levels below the lake)

Because we could not reproduce the groundwater levels at G40/0415, we deemed that the we could reject the hypothesis that a 1 layer model could reproduce the groundwater levels the Hawea system with confidence. This is an essential outcome from the Hawea groundwater model as the complex three dimensional structure has a key implications for the management of the groundwater system; the groundwater system is likely to be either disconnected or have other non-linear responses to Lake Hawea level if the lake falls below a threshold value.

Terrace only model (2D) optimisation results

The terrace only model had 1 target to fit, G40/0366. The model was unable to fit this target. The heads are higher than the measured data, and theape of the curve does not match the observed data. The full model was able to fit this target significantly better. From these data we can reject the hypothesis that the terrace only model can reproduce the observed groundwater levels in G40/0366. This suggests that there is indeed some connection between the High Terrace aquifer and the Hawea Flat aquifer.

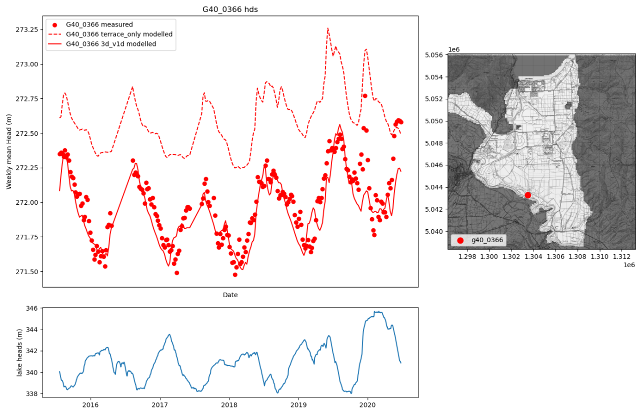

Figure: Comparison of the terrace only model and the 3d_v1a model at the south end of the High Terrace

3 layer model (3D) optimisation results

We produced 3 final 3 layer models. The differences (relative to the final model 3D_v1d) are listed below.

Model | "bund_top"*	NGMP wells included in objective function
3d_v1a | 335m msl	yes
3d_v1b | 333m msl	yes
3d_v1d | 335m msl	no

*the "bund_top" is the elevation of the top of the low conductivity layer in the moraine zone, which is also the threshold value for the non-linear response of the groundwater system to the lake level.

Final observation weightings:

Parameter group	Weighting
'rwh_hf'	0
'rwh_hf_riv'	0
'h_hf'	150
'h_hf_riv'	50
'h_lf'	{0, 10} {v1d, (v1a, v1b)}
'riv'	1e-3
'h_piezo'	10
'h_single_1'	5

'h_single_3'	5

3D_v1d (final model)

The model 3d_v1d is the final model that we used for all of the scenarios. This model did an excellent job reproducing the groundwater levels in our high frequency monitoring points across all of the historical data. The figures for these high frequency observation and a discussion of the results are provided in the *Comparison of 3d_v1a, 3d_v1b, and 3d_v1d* section below. The full set of optimisation plots for this model are available in the 3d_v1d optimisation results plots folder.

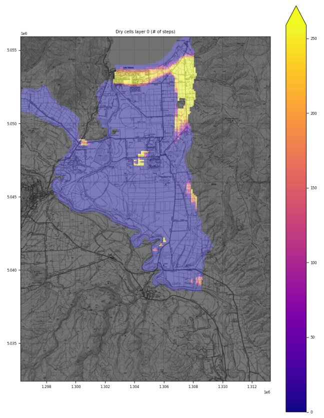

Figure: the number of model stress periods with dry cells in the final model

There are a number of areas in the model with consistent dry cells. There are a number dry cells directly south of the moraine. These are not a concern and are instead simply an artefact of the complex 3D structure in the area. Many more of these persistent dry cells are relatively isolated and occur in areas of steep topographical gradients (e.g. near the Clutha River, Camp Hill Moraine, or just adjacent to the Grandview Ridge). These cells are likely caused by structural error in topographical data and are of little concern.

More concerning are the dry cells in and around the Hawea Flat township. These dry cells are likely caused by the relative thinning of the model in this area, local abstraction and parameter structural errors, and/or a missing structure in the model. It is quite possible that there is a lower conductivity layer to the west of the Hawea Flat township from the Q4 Albert Town Advance. There was not enough information to justify adding this structure to the model, but it may warrant further investigation.

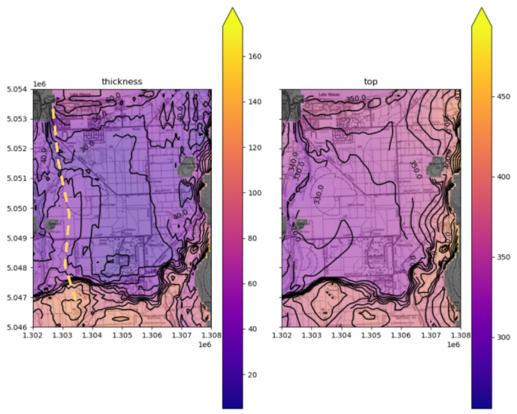

Figure: the possible indicative location (yellow dashed line) of a moraine structure to the east of the Hawea Flat township

Finally the model does a very poor job of reproducing the groundwater levels in the area to the east of the inferred Grandview Fault. There is very limited information in this area (3 single observations) most of which are near boundary conditions (e.g. Grandview Creek), so it is difficult to draw any conclusions about the cause of the poor model performance in this area. Instead, we have to accept that the model is not suitable in this area and the model results should not be used.

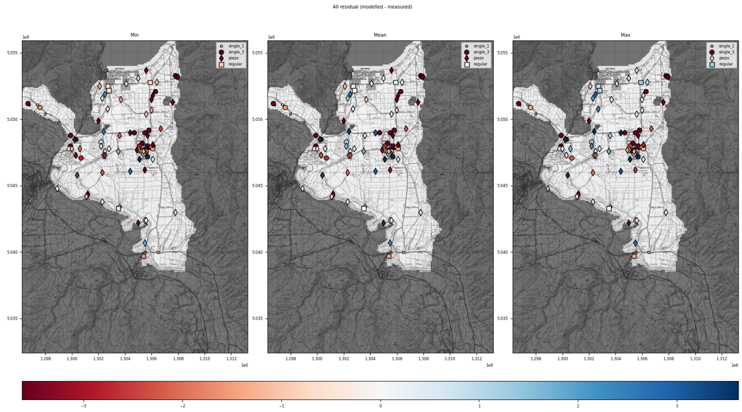

Figure: the groundwater levels residuals plotted spatially for the full model domain. Note that where a target has multiple temporal observations the min, mean and max residuals are shown. The color bar units are m

In general the model does a good job of replicating the groundwater levels across the model domain. There are some areas where the model over or under predicts the groundwater levels. As discussed above the areas to the east of the inferred Grandview Fault are significant under estimates and the model does not preform well in these areas. There are multiple targets in and around the Hawea flat township which are underestimated by the model, but given the close proximity of the high frequency observations at bore G40/0367, we believe that these misfits are most likely due to either poor data quality of the targets or problems arising from applying the historical measured water levels to the time period within the optimisation period. The latter is the most likely as there is a significant amount of abstraction in and around the Hawea Flat Township that may not have been present when the historical water levels were measured.

The two figures below show the modelled groundwater-surface water interaction for the Hawea and Clutha Rivers. While there are some target misfits, the model does a very good job of reproducing the expected interaction between the groundwater and surface water systems. The misfits occur in areas which both lose and gain water across the model period. The model does a good job reproducing the expected behaviour (gain/loss), but underestimates the total losses relative to the measured data. As discussed in the model target readme there is significant uncertainty in the measured gauging, therefore, we feel that the model is performing well in this area. In addition, the model does an excellent job of reproducing the expert judgment of the surface water and groundwater interaction. The Hawea is gaining below the dam to approximately Camp Hill, and then loses a significant amount of water between Camp Hill and sharp westward bend.

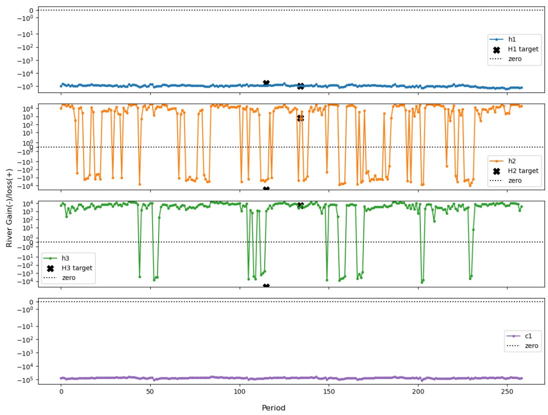

Figure: the river fluxes for the final model at each of the parameter zones

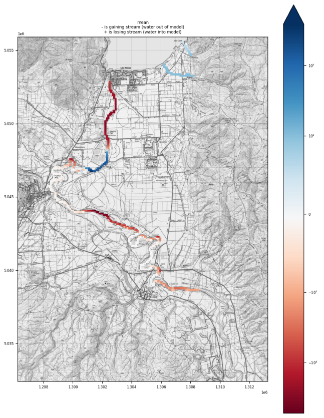

Figure: the mean river fluxes spatially for the final model

The figure below shows the steady state groundwater heads around the moraine zone in all three layers. We don't have any targets to inform this data, but it does produce a key prediction that could be tested in the future. The model predicts that the groundwater levels are significantly higher in the northeastern edge of the moraine and that this is the area which ultimately controls flow between the lake and the groundwater system. This is consistent with either the perched aquifer conceptual model or the local penetration conceptual model (see the Lake Hawea Moraine Conceptual Model section of the model build readme).

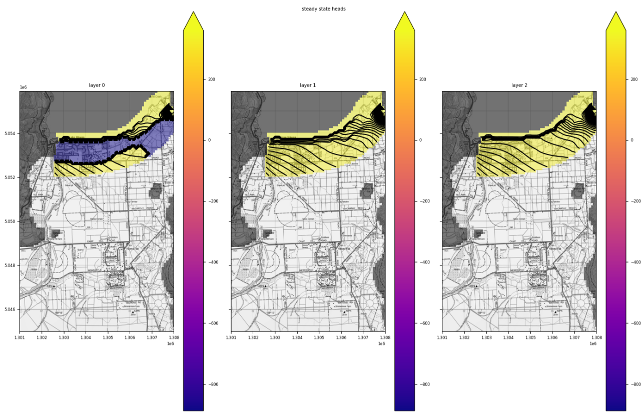

Figure: the steady state groundwater heads around the moraine zone in all three layers

3D_v1a

We will not independently discuss the results for 3d_v1a here, but the full set of optimisation plots for this model are available in the 3d_v1a optimisation results plots folder. A discussion of the differences between the three models is provided below.

3D_v1b

We will not independently discuss the results for 3d_v1a here, but the full set of optimisation plots for this model are available in the 3d_v1b optimisation results plots folder. A discussion of the differences between the three models is provided below.

Comparison of 3d_v1a, 3d_v1b, and 3d_v1d

The figures below show the results for all three of the 3D models for the high frequency groundwater levels.

Fit to higher frequency groundwater levels at G40/0415

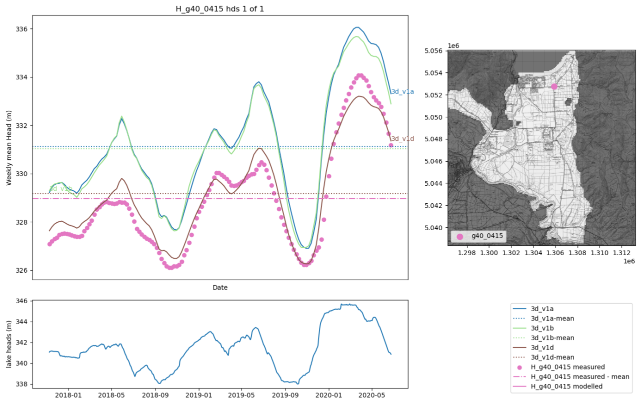

Figure: the groundwater levels for the 3d_v1a/b/d models at bore G40/0415

Fit to higher frequency groundwater levels at G40/0416

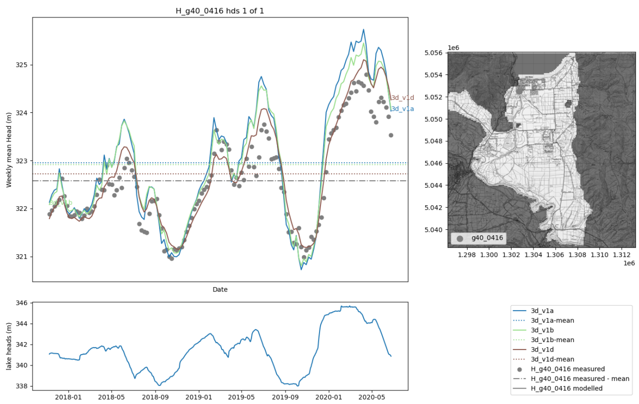

Figure: the groundwater levels for the 3d_v1a/b/d models at bore G40/0416

Fit to higher frequency groundwater levels at G40/0041

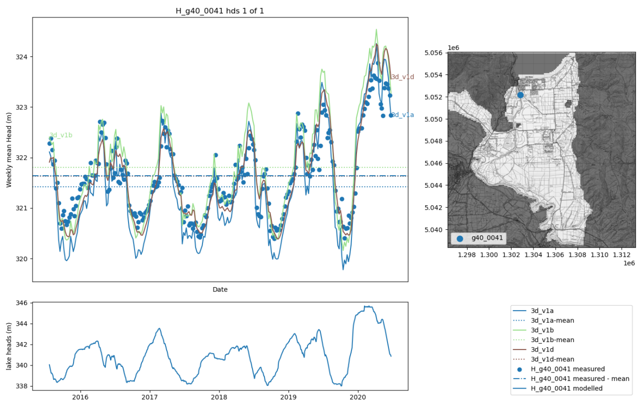

Figure: the groundwater levels for the 3d_v1a/b/d models at bore G40/0041

Fit to higher frequency groundwater levels at G40/0129

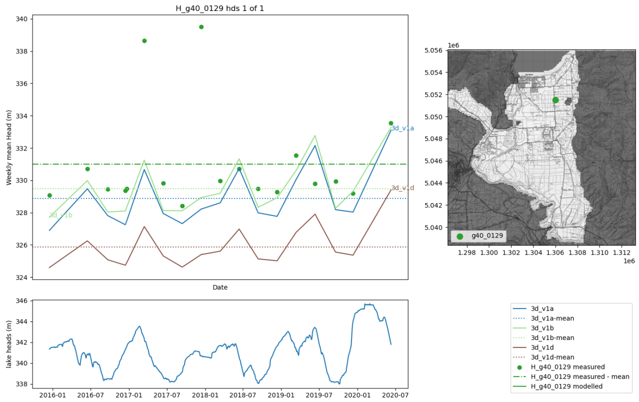

Figure: the groundwater levels for the 3d_v1a/b/d models at bore G40/0129 (NGMP bore)

Fit to higher frequency groundwater levels at G40/0120

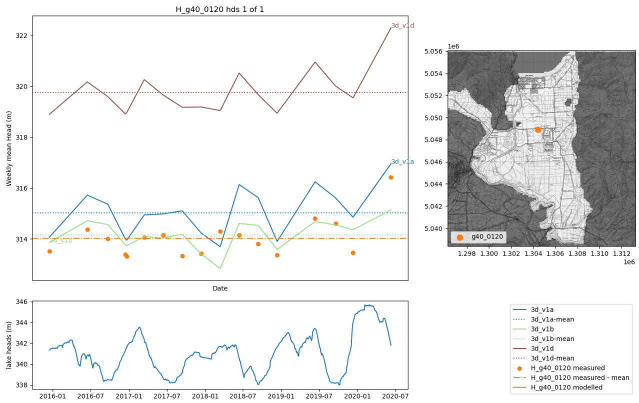

Figure: the groundwater levels for the 3d_v1a/b/d models at bore G40/0120 (NGMP bore)

Fit to higher frequency groundwater levels at G40/0367

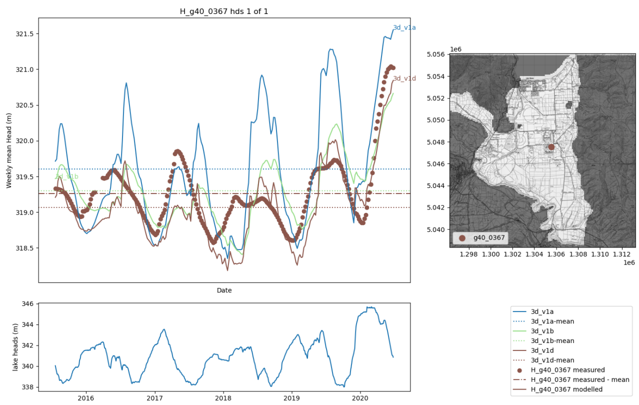

Figure: the groundwater levels for the 3d_v1a/b/d models at bore G40/0367

Fit to higher frequency groundwater levels at G40/0366

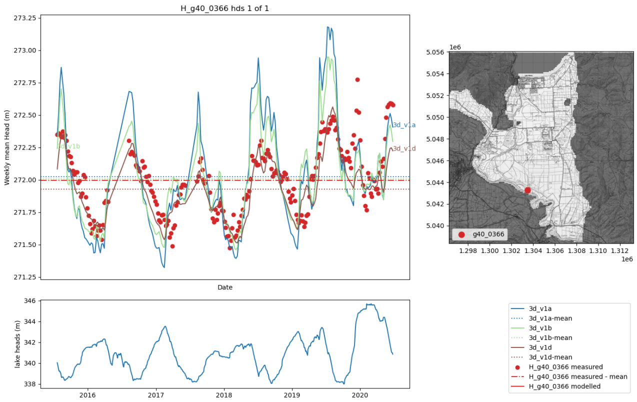

Figure: the groundwater levels for the 3d_v1a/b/d models at bore G40/0366

Discussion and implications

Model versions 3D_v1a, 3D_v1b, and 3D_v1d all do an adequate job of replicating the high frequency groundwater level observations. 3D_v1d does a slightly better job of replicating the high frequency groundwater levels than 3D_v1a and 3D_v1b, but it does this at the expense of the moderate frequency groundwater observations (i.e. the NGMP wells G40/0129 & G40/0120). This prioritisation was intentional as the NGMP bores are designed to monitor contaminants rather than static water levels. These bores are often pumped irrigation bores and structural error in the pumping is likely to impact the observation fits. Therefore we suggest that the 3D_v1d model is the best model for predicting the likely impacts of alternative management conditions.

Model versions 3D_v1a and 3D_v1b produce very similar results. The key outcome of the similar results from the 3d_v1a and 3d_v1b models is that the current observations do not constrain the threshold value, below which the groundwater levels exhibits a non-linear response to the lake level. We discuss plausible ranges for the threshold value in the Lake Hawea Moraine Conceptual Model section of the model build readme, but we are not able to further constrain this range. More discussions of the impacts of this threshold are discussed in the scenarios readme file.. Note that we did attempt to model the threshold value as 337 m msl, but this optimisation did not converge. However, we did not spend a significant amount of resources trying to get this optimisation to converge, so we do not believe that the lack of convergence here indicates that the threshold value cannot be as high as 337 m msl.

Steady State Model Water Budget (3D_v1d)

The table below provides the steady state water budget for the 3D_v1d model. Note that breaking the model boundary conditions budget down to the individual components (e.g. hillside inflow vs abstraction) components which introduces some dependencies due to double counting (e.g. where multiple boundary conditions exist in a single cell). This discrepancy is c. 1700 m^3/d; the discrepancy for the model (e.g. all_well/all_riv) is c. 0.3 m^3/d.

Boundary Condition	Steady State Flux
Lake	110384.9
Recharge	36216.2
Hawea1_flux	-96472.1
Hawea2_flux	10649.3
Hawea3_flux	5536.4
Clutha1_flux	-78458.9
Grandview_flux	3100.0

John_flux	1500.0
all River	-154145.3
Race_flux	4605.7
Abstraction_flux	-7365.3
hill_maungawera_flux	850.2
hill_flat_west_flux	259.8
hill_flat_east_flux	1537.8
hill_terrace_east_flux	3357.6
hill_south_east_flux	6083.2
all well	7544.0
discrepancy	-0.3

Access to final optimised parameter sets and models

The final optimised parameter sets for the 3d_v1a, 3d_v1b, and 3d_v1d models are available in this repository in the optimised_parameter_sets directory and are accessible via Python by the model_parameterisation.optimised_parameterisation.get_3d_v1{a|b|d}_params method. The final models are available in the final_opt_models directory. Due to the limit on file sizes that Github implements, the final models have been compressed and some files have been split into multiple parts with the 7zip library. To uncompress these models you must use the optimisation.final_opt_models.compress_uncompress_model.uncompress_model function.

To uncompress the 3d_v1d model to your downloads folder can use the following code:

```
from optimisation.final_opt_models.compress_uncompress_model import
from project_base import proj_root
from pathlib
# proj_root is the path to the root of the repo
# path to the model in the repo, you can substitute an absolute path
compressed_path = proj_root.joinpath('optimisation/final_opt_models/3d_v1d')
# path to save the uncompressed model to (currently set to 3d_v1d in your downloads folder)
out_path = Path.home().joinpath('Downloads', '3d_v1d')
uncompress_model(compressed_path, out_path)
```

Model limitations

There are a number of limitations to this model and the model optimisation. The main limitations are:

- **A non-unique model structure**: Because the complex structure in the moraine zone is not well constrained by the data we have assumed a very simple model structure that almost certainly introduces structural error. It is likely that some of the parameters in the model are compensating for this model structural error, which may have flow on effects, particularly for scenarios that are well outside the model optimisation conditions.
- **A non-unique parameterisation**: the PEST optimisation process is a poorly posed problem (that is there is not enough observations to calculate a unique solution to the model parameters). This means that there are multiple solutions to the model parameters that represent a good fit to the observations. This model has not undergone a parameter uncertainty process so we cannot predict the likely range or implications of the parameter uncertainty. In addition, the uncertainty of the model parameters is compounded by the uncertainty in the model structure. There are likely many other model structure/parameter sets that would fit the observations as well as this model.

- **Area to the east of grandview fault**: The model has persistent dry cells to the east of the inferred location of the Grandview fault. This is likely due a combination of model structural and parameterisation errors. The results from this area should not be used and there is currently insufficient data to produce a trustworthy model in this area.
- **Limited data for hillside streams**: The hillside streams are a major source of water to the Hawea aquifer systems, but we only have observations from two gauging sites for a limited period of time. We estimated the inflows from a a correlation with the Lindis River; however, both of the gauged streams are of similar size so the correlation may not hold for the smaller hillside streams.
- **Piezometric survey date**: the only piezometric survey conducted for the Hawea aquifer system was conducted in Sept of 2011. This survey was conducted outside our optimisation period (we did not have adequate abstraction information to conduct the model optimisation during 2011). A significant portion of the model domain therefore does not have any observations taken during the optimisation period, which adds another source of uncertainty to these areas of the model.
- **Parameterisation near Butterfield Reserve**: Butterfield Reserve is a sensitive wetland in an old oxbow of the Hawea River. The final parameterisation in this area is for a very low hydraulic conductivity which likely underestimates the degree of connectivity between Butterfield Reserve and the Hawea River. Model results here should be used with caution.

Recommended additional data

Over the course of our optimisation process we identified a number of additional data sources that would be useful. We have listed them here, with a discussion of why the information would be useful, but we have not included any feasibility assessments or costings to acquire these data sources. We recognise that some of these data sources may not be feasible but we have included them here so that decision makers can consider their relative value. We have not ranked these additional data sources in any way as any prioritisation is an intersection of priories (which we cannot address) and scientific merit.

- **A high frequency groundwater record near the Northeast Corner of the Hawea Flat aquifer:** One of the key model predictions for the complex moraine structure is that groundwater levels (impacted by the lake) should be elevated in and around the Grandview/John Creek alluvial fans. Testing this prediction would require a high frequency groundwater level record in this area of at least a couple of years in length. The exact location of such a bore would need more detailed consideration.
- **A high frequency groundwater record near the exit of the Maungawera Valley:** The Maungawera Valley has a relative paucity of data which makes predictions regarding the sustainable use of groundwater uncertain. A high frequency monitoring bore near the exit of the valley (e.g. up valley of the Maungawera Valley Road and Lake Hawea Albert Town Road intersection) would act as an integrator for the up valley groundwater system and would provide significantly more information about the local groundwater system. The exact location of such a bore would need more detailed consideration.
- **A high frequency bore near the Hawea domain and/or Butterfield Road**: Water from Lake Hawea can flow either toward Hawea Flat township or it can flow back towards the Hawea River. Understanding the piezometric surface in the aforementioned area would help constrain that flow. The exact location of such a bore would need more detailed consideration.
- **A detailed investigation of moraine structure**: As mentioned multiple times within this repository, the moraine structure is not well constrained by the data. A detailed investigation of the moraine structure would help constrain the model structure and reduce the uncertainty in the model predictions. The method of investigation would need significant consideration and would likely require a combination of geophysical and drilling investigations.
- **An investigation of structure to West of Hawea flat Township**: As discussed above, glacial geomorphology suggests that there could be a low permeability structure to the west of Hawea Flat township associated with a potential lateral moraine of the Albert Town advance. Further investigation of this possible structure would help constrain our understanding of the groundwater system in this area.

- **multiple concurrent gauging of multiple hillside streams:** As described in the model build readme the hillside streams are a major source of water to the Hawea aquifer system. However, we only have observations from two gauging sites for a limited period of time. We estimated the inflows from a a correlation with the Lindis River; however, both of the gauged streams are of similar size so the correlation may not hold for the smaller hillside streams. Multiple concurrent gaugings (at high and low flows) of multiple hillside streams (both large and small catchment areas would help constrain the predictions of inflows from the hillside streams.
- **Additional Piezometric surveys:** At present the only piezometric survey completed in the Hawea region was conducted in Sept of 2011. This survey was conducted we had adequate abstraction information and so we had to transpose these groundwater head targets to dates inside the optimisation period, which adds error. One or more additional piezometric surveys (e.g. at high and low water levels) would help constrain the model predictions in the areas that are only informed by the piezometric survey.
- **Model parameter / structural uncertainty analysis**: In the absence of additional data collection more information about the uncertainty of the model predictions could be obtained by conducting a parameter / structural uncertainty analysis. Given the significant structural uncertainty in the moraine zone we would recommend calibrating and conducting parameter uncertainty analysis on many different model structures. This would be a significant undertaking, but could easily build on the work and data analysis from this project and contained within this repo.

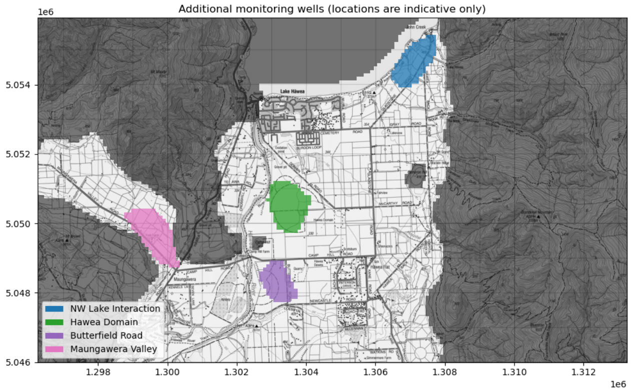

Figure: Areas for possible additional high frequency monitoring bores

Optimisation working notes

These working notes are largely verbatim except that the active branches are elevated above the abandoned branches. The number indicates the order in which the branches were developed.

Active Branches (optimisation versions)

25. Main (3d_v1d)

- The 'final' optimised model
- Contains 3D structure around the Lake Hawea Moraine
- Best fits for the high frequency targets
- Bund elevation set to 335 msl
- NGMP well head observations removed from objective function as there is significant tension between these records and the high frequency observations. The NGMP wells are pumped irrigation bores and the primary purpose for sampling was water quality monitoring

20. 3d_v1a

- Identical to “Main (3d_v1d)” except that the NGMP wells were included in the objective function
- decent history matching; however “Main (3d_v1d)” provides better results
- retained as active branch for comparison to “3d_v1b”

21. 3d_v1b

- Identical to “3d_v1a” except that the bund elevation was set to 333 MSL.
- history matching results were similar to “3d_v1a” suggesting that the bund elevation is largely non-unique
- retained to demonstrate the non-uniqueness of the 3D structure

14. terrace_only

- This model structure only includes the High Terrace (south of Hawea Flat) to the Clutha River
- this optimisation was undertaken to see if the High Terrace could be history matched (within the accepted parameter ranges) in isolation from the rest of the Hawea aquifer system.
- History matching was not achieved

Abandoned branches (releases, optimisation versions)

There are many previous branches that were issued as pre releases and then deleted (effectively archived). There should be no reason for other users to delve into these previous branches as they ended up with unsatisfactory history matching; however they are available and briefly described below (working notes) for completeness.

1. Main (before 2/11/22) The main build branch. First structural version
2. Structure v2, Changes:
    - Increase parameterization via pilot points to Maungawera
    - Add recharge multiplier pilot points across model (NI)
    - Remove sandy point from model
    - abandoned but retained
3. Structure v3,Changes:
    - Set ss=sy
    - Set the model to confined to reduce computational burden
    - This helped but the model preformed poorly,
    - Error did not reduce saturated thickness.
    - abandoned and deleted
4. Structure_v4:
    - From structure v2
    - Add new mean annual head targets from regular
    - Increase steps to 7 in transient
    - Expand hillside streams to all adjacent cells (up to 9 cells per hill)
    - Optimisation never run here, just saved to version structural changes

5. Structure_v5
    - From structure_v4
    - Remove near river pumping wells.
6. Structure_v6
    - From structure 5
    - Add a 1 m confined layer below the bottom of layer 1 (may improve stability)
7. Structure_v6a
    - From v6, but set ss to sy
8. Structure_v7 (built but not run)
    - From structure 5
    - Reduce thickness to reasonable pumped thickness and then maximum 30 m sat thickness
    - Set ss = sy
    - run as a confined model
9. Structure_v8
    - From structure_v6a
    - increase initial conductivity (to 50, 100 and 70 was too unstable)
    - rch multiplier only by irrigated not irrigated bounds of multiplier 0.5-1.2
10. Structure_v9
    - Fix river targets (they were backwards!)
    - Implement Grandview and John Creek (+Hawea and Clutha) as str package
    - Lake stage vs g40_0415
    - Looks fine, honestly the fact that them model isn’t matching it suggests some sort of structural error. Reworked transport in grandview stream?/ water through grandview stream??? Likely the problem google maps shows water in grandview to the lake (and in john creek (to the north), all other creeks are probably fine.
    - Lower basement around g40_0366

11. Structure_v10
    - Set weight of regular year targets to 0
    - set each of the ‘h_hf’ targets equal weights despite different data lengths
    - look/lower basement in dry cells near model boundaries
    - NE hillside area (done)
    - Near Clutha River (done)
    - I think I need some more pilot points
    - Near pt 402 on camp hill moraine (move Maungawera south?) () and another in the moraine (to interpolate with other river group
    - To stop dry cells south of camp hill moraine
    - Significant number in the hillslope area just off the bounds to allow conductivity to fall there if needed for stability. And to manage the change in geologic setting near hillslope
    - Adjust some locations based on the new pilot point locations
    - New rivergroup south of Maungawera valley entrance to allow for the difference between the two settings
    - Additional point in the middle of the terrace to manage near hillside environment.
    - Try lowering hillside conductance → set to 100 vs 1000 for Hawea/Clutha, which means much of the peak flow does does not make it into the model.
12. Structure_v11
    - Move to 1 global recharge modifier (done)
    - Much higher initial kh (lake=5, rest = 300) (in progress
    - Lower sy, and lower sy bounds
    - Change weights (lower low frequency targets)
    - Bit of a hail mary before the weekend
    - retired (even though I’m happy with the parameterisation. If I want to change back to vll parameters do it from v12
13. Structure_v12
    - Increase kh/sy parameterisation in the near lake environment
14. terrace only
    - see above
15. p_lake
    - As per structure_v11 but with a single additive parameter for lake heads (e.g. lake hds = lake hds + mod
    - A test to see if the lake levels problems are sorted everything else works great?
    - Note the parameter is offset by 100 m as pyemu has bugs!
16. lake_bar
    - Add a 1 cell thick barrier for kh
    - Remove additional v12 parameterisation
17. cond_int
    - Try to fit the heads by simply setting lake conductance (1 cell width lake)

18. 3d_v1
    - Address the 3D moraine issues in structure
    - 3 layers the bottom two pinch out against the bottom of the model.
    - well management
    - target management
    - other structural pieces
    - Add abrupt parameter change at terrace interface
    - Remove from dam to “dam control” road from model (e.g. no flow)
    - Re-run pre_optimisation_overview.py
    - remove the slope fixer on the east side
    - remove additional parameterisation of v12
19. 3d_v2
    - As per v1 but fully confined (to increase stability)
    - Ss[0] = sy[0]
    - Initial parameters do not manage the drop quite so well. This may really need the unconfined aspects of the model.
    - Bit of a hail mary over xmas. Really need the unconfined action to make the ‘waterfall happen’
20. 3d_v1a
    - see above
21. 3d_v1b
    - see above
22. 3d_v1c
    - As 3d_v1a but with top of bund set to 337
    - great difficulty getting this to converge
    - abandoned
23. 3d_v4
    - As 3d_v1a, but top of bund is set to 340 m MSL instead of 335
    - Difficult to get model to converge
    - abandoned
24. 3d_v5
    - As 3d_v1a, but top of bund is parameterised
    - Largely unstable
25. 3d_v1d
    - see above

References

- Wilson, J., 2012. Hawea Basin Groundwater Review. prepared by Resource Science Unit of Otago Regional Council, June 2012, Dunedin.

Hawea Transient groundwater model (Hawea Model) scenarios methods and results

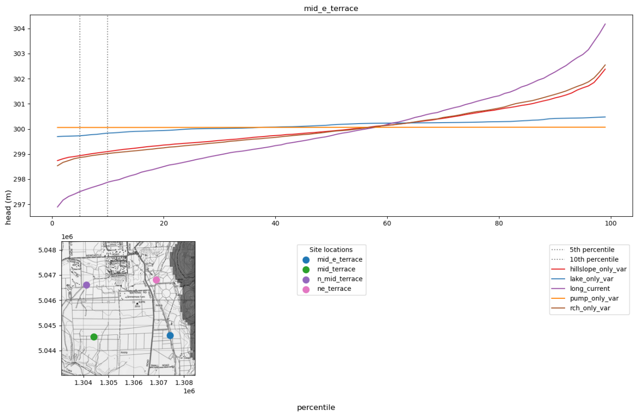

Figure: results of the boundary condition sensitivity analysis at the mid_e_terrace indicator well

Author:	Matt Dumont
Date:	2021-11-02
Version:	1.0.0
Status:	Draft
KSL project:	Z22031HAW_hawea-model
Purpose:	This document provides the methodology and results for the model scenario process

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    - allocation_scenarios.py: script to develop all allocation scenarios and to run the non-gridded allocation scenarios
    - run_grid_allocation.py: script to run the gridded allocation scenarios
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        - new_allo_zones.png: figure of the new allocation zones
        - Hawea Flat_results: results for the gridded Hawea Flat allocation scenarios
        - Maungawera Flat_results: results for the gridded Maungawera Flat allocation scenarios
        - Terrace-Hill_results: results for the gridded Terrace-Hill allocation scenarios
        - nat_current_full: results for the naturalised, current allocation, and full allocation scenarios
        - Te Awa_results: results for the gridded Te Awa allocation scenarios
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- **Wetland Setback Modelling**

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- wetland_setback_butterfield: wetland setback modelling for Butterfield Wetland scripts and results

Scenarios Overview

Scenario Type	Key Questions
Model information Scenarios	How does the model behave, and what impacts groundwater levels?
Low lake scenarios	What happens if the management of Lake Hawea changes significantly?
MT3D indicator scenarios	Where is the water sourced from?
Allocation Scenarios	What is a sustainable level of abstraction?
Wetland setback scenarios	Where, and to what extent, does abstraction impact significant wetlands?

Boundary Conditions Overview

The table below has an overview of the different possible boundary conditions for the model Scenarios. Some of these boundary conditions were defined in the model_build readme and other are defined more fully below. Note that we also used static recharge, hill inflows, lake levels, and river flows for the scenarios. These were simply the steady state component of each boundary condition (i.e. the mean value).

Boundary condition name	Package	Water component	Overview	Reference
dryland_rch	Rch	LSR	scenario period ERA5 dry-land recharge	../model_build readme
irr_rch	Rch	LSR	scenario period ERA5 irrigated recharge	../model_build readme
hist_rch	Rch	LSR	opt period met recharge	../model_build readme
hist_era5_rch	Rch	LSR	opt period ERA5 recharge	../model_build readme
large rivers	Str	Hawea and Clutha R.	ISO weekly mean river flows / stage	../model_build readme

hillside flows	Str/Wel	Hillside inflows	long record of hillside inflows	../model_build readme
race losses	Wel	race losses	ISO weekly mean race losses	../model_build readme
no_pump	Wel	GW abstraction	no abstraction	n/a
pump curve	Wel	GW abstraction	typological annual pumping curve (0-1)	below
static_pump	Wel	GW abstraction	steady state optimisation pumping	below
extended_pump	Wel	GW abstraction	ISO weekly mean pumping	below
extended_full_allo	Wel	GW abstraction	ISO weekly mean of maximum daily allocation normalised to historical pumping record	below
extended_max_allo	Wel	GW abstraction	maximum daily allocation applied to every day of the year	below
extended_max_allo_pc	Wel	GW abstraction	maximum daily allocation applied to pump curve	below
reduced abstraction	Wel	GW abstraction	allocation reduction (fraction of extended_pump)	below
grid_pump	Wel	GW abstraction	gridded abstraction (additional allocation)	below
lake	Ghb	Lake Hawea	long record of Lake Hawea levels	../model_build readme
low lake levels	Ghb	Lake Hawea	typological low Lake Hawea levels	below

Boundary conditions Methodology

The sections below provide additional documentation for the boundary condition options that have not been sufficiently described in the model build readme.

Groundwater abstraction

Development of the pumping curve

In order to apply additional levels of groundwater abstraction in a sensible way that is constant with the annual usage patterns we developed a typological pumping curve. This was developed by analysing the ISO weekly mean pumping data. The ISO weekly data still has some variation so we then applied a centered moving window mean of 9 weeks to smooth the data. The data was then transformed via min/max normalisation to a range of 0-1. For increased abstraction scenarios we could then apply a maximum daily take rate to the pumping curve to get the daily abstraction. For reference the integral of the pumping curve is c. 135 suggesting that on average the annual usage is 135 times the mean annual maximum daily take.

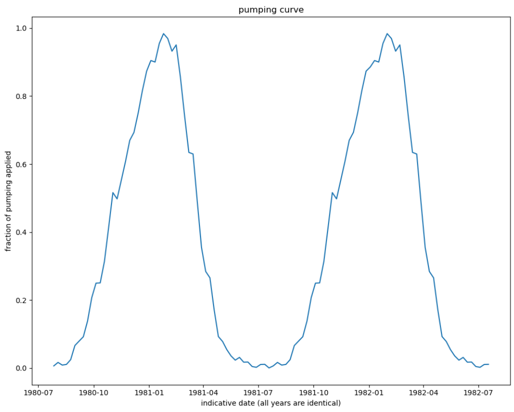

Figure: typological pumping curve

extended_pump

We produced the extended_pump time series to apply the current level of abstraction to the full scenario period. This was done by simply repeating the ISO weekly mean historical pumping data to all weeks of the scenario period.

extended_full_allo

The extended_full_allo pumping record is maximum daily allocation applied to the min/max normalised historical pumping record (2015-2020). This likely underestimates the full allocation scenario as most users do not regularly take their maximum daily usage every year.

extended_max_allo

The extended_max_allo pumping record is maximum daily allocation applied to every day of the year. This is almost certainly not attainable for 2 reasons. 1) no water users are likely to use their allocation every day of the year (e.g. irrigators do not irrigate in winter) and 2) many consents have maximum annual allocations as well as maximum daily allocations; however, analysis of these data were not included in the usage analysis preformed by Kitteridge (2022).

extended_max_allo_pc

The extended_max_allo_pc pumping record is maximum daily allocation applied to the typological pumping curve. This is likely the most realistic scenario of the level of abstraction that could be achieved with the current consented activities.

Additional abstraction (grid_pump)

One of our goals was to explore the impacts of additional water allocation. Introducing new allocation is challenging because the spatial locations of these abstractions are unknowable. To address this we developed a 500 m grid of abstraction points for each of the allocation zones. To assess the impact of additional abstraction we then applied an additional maximum daily take to the typological pumping curve and then evenly distributed this abstraction across the grid points within the allocation zone. This approach will underestimate the local impacts of abstraction, but it should represent the impacts to the allocation zone as a whole. We anticipate that other approaches (e.g. well interference and/or stream depletion assessments) would be used to limit the local impacts of any additional consented abstraction.

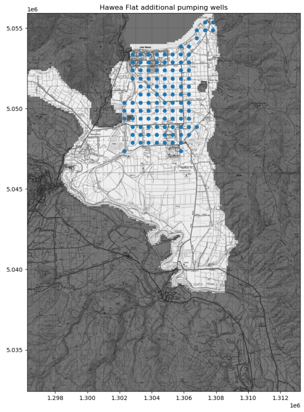

Figure: grid of abstraction points for the Hawea Flat allocation zone

Reduced abstraction (reduced allocation scenarios)

Where we needed to assess the impacts of reduced abstraction (either from the current usage or one of the aforementioned pumping records), we simply applied a percentage reduction to each Wel boundary condition.

Plots of the abstractions

It is beyond the scope of this document to provide and interpret all of the plots of the boundary conditions. However, these plots are all available in the following directories:

- Scenarios/boundary_condition_plots/pumping: full record of the pumping records.
- Scenarios/boundary_condition_plots/pumping_use_allo_difs: comparisons of the different pumping records.

Lake Hawea Levels for low lake scenarios

In order to assess the impacts of heretofore unseen lake levels we developed a typological annual lake level variation. This was done by creating the best fit between the ISO weekly mean lake levels to a modified sin wave function:

$$l = a * sin((t - d) / 52 * 2 \pi) + b$$

where:

- l is the lake level
- a is the amplitude of the lake level variation
- t is the ISO week
- d is the phase shift of the lake level variation
- b is the mean lake level

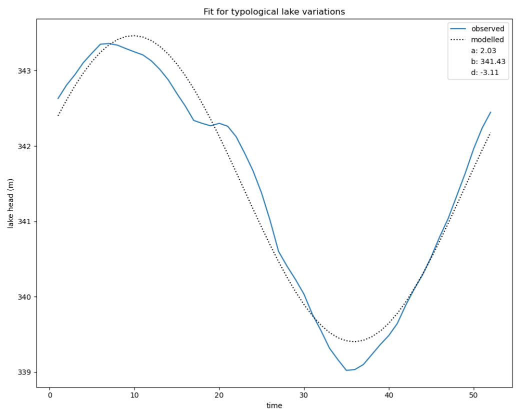

Figure: The fit of the typological lake levels to ISO weekly lake levels for the low lake scenarios

We then used these parameters as a base value for the following equation to perturb the historical lake levels:

Where the lake levels were greater than the annual mean lake level:

$$lh = a_{high} (|sin((t - d) / 52 * 2\pi)|)^{k_{high}} + b_{high}$$

Where the lake levels were less than the annual mean lake level:

$$ll = -a_{low} (|sin((t - d) / 52 * 2\pi)|)^{k_{low}} + b_{high}$$

Where:

- lh is the high lake level
- ll is the low lake level
- a_{high} is the amplitude of the high lake level variation
- a_{low} is the amplitude of the low lake level variation
- b_{high} is the mean lake level for the high lake level variation
- b_{low} is the mean lake level for the low lake level variation
- k_{high} is the width parameter of the high lake level variation
- k_{low} is the width parameter of the low lake level variation
- t is the ISO week
- d is the phase shift of the lake level variation (not modified)

This allows us to modify the lake amplitude, mean, and the width of the sin wave for both the high and low lake levels.

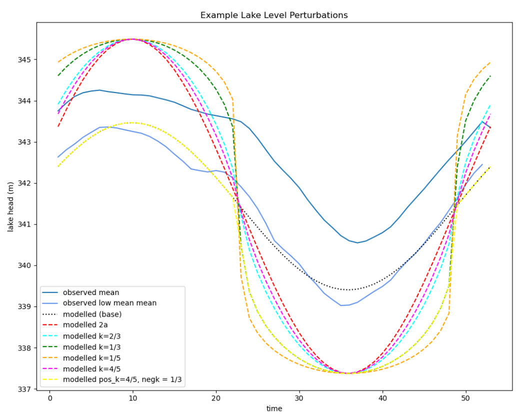

Figure: example of the perturbations to the lake levels for the low lake scenarios

Standard Scenario Outputs

Indicator monitoring points

The Hawea model is a 4 dimensional model (3 spatial dimensions and 1 temporal dimension). In order to visualise the impacts of scenarios we have developed a series of indicator monitoring points. These points are spaced through the model domain and were developed by expert judgement.

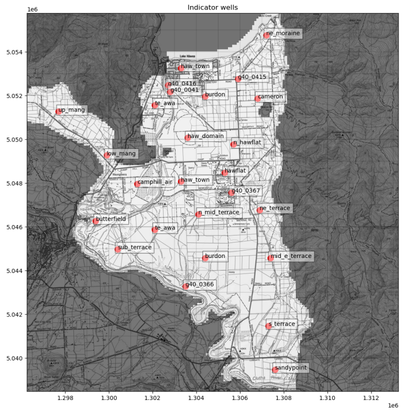

Figure: The indicator monitoring points for the Hawea model

Data outputs

We have developed standard data outputs for the scenarios, they are as follows:

- all_well_output_dataset.csv: model heads at every known well in the model domain.
- converged.txt: text file with a boolean value indicating whether the model converged.
- key_input_data.csv: a record of key input data including recharge, hill inflows, and lake levels.
- output_dataset.csv: the key output data for each time step which is comprised of: - model heads at the indicator monitoring points and at the high frequency monitoring bores. - river gain/losses for each conductance parameter zone. - key extracts from the zone budget.
- zone_budget.csv: the full zone budget.

In addition, some scenarios also contain the following files:

- {}.list: list file from the model runs.
- {}_hds: compressed and split model heads
- plots: plots of the model results (similar to the plots in the Standard optimisation outputs in the model_optimisation)

Figure outputs

The standard output for comparing multiple scenarios is a series of plots including:

- comp_plots: direct comparison of the model results for the full time period
- quantile_plots: comparison of the model quantile data
- qq_plots: comparison of the model quantile to a base model scenario's quantile data

Reading quantile plots

An example of a quantile plot is shown below. This plots the calculated percentile of the model heads at the indicator well. In the figure below the point at (10, 342.5) on the long current line indicates that 10% of the model heads for the long_current scenario at the upper Maungawera indicator well are less than or equal to 342.5 m msl. Because the long_current scenario is a reasonable sample of the historical record we can infer that if the future record is similar to the historical record (e.g. weather/climate) and the boundary conditions are similar to the long_current scenario then there is a 10% chance that the model heads at the upper Maungawera indicator well will be less than or equal to the modelled value (342.5 m msl). Note that this does not account for potential biases in the model results.

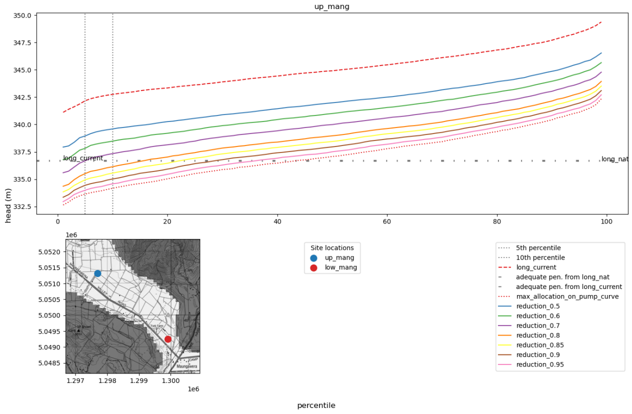

Figure: example of a quantile plot

Reading q-q plots

An example of a quantile-quantile plots is shown below. Note that the data is the same a the example quantile plot described in the *reading quantile plots* section above. This figure compares the quantile data from a base scenario (in this case the long_current scenario) to the quantile data from the scenario of interest. So the point at approximately (10, 60) on the reduction_0.5 line can be interpreted as the modelled 10th percentile heads for the long current scenario (342.5 m msl,from the quantile plot in the section above) would be the 60th percentile heads for the reduction_0.5 scenario. From this if we assume that the long_current scenario is a reasonable representation of the historical record then we can infer that if we transitioned to the reduction_0.5 scenario then we would expect that the current low levels that were experienced 10 percent of the time would now be experienced 60 percent of the time. This addresses the potential bias problems (e.g. if the model over/under estimates the groundwater levels) that are present in the quantile plots, but does make it harder to interpret.

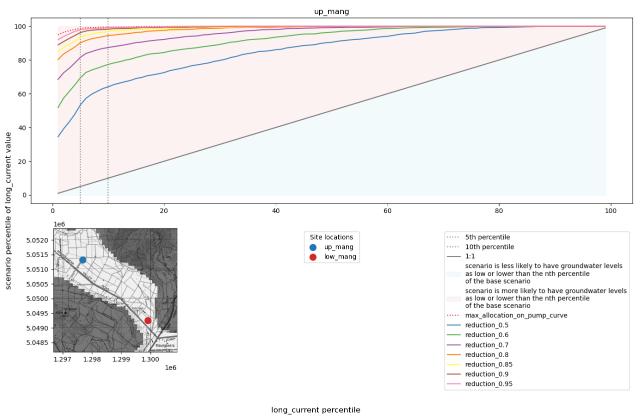

Figure: example of a quantile-quantile plot

Adequate penetration

In addition to the standard outputs we need to estimate an adequate penetration level for each indicator well in the model. The adequate penetration level is the level at which we would expect water supply wells to be screened to maintain reliability. That is if an individual owns a water supply well that is screened above the adequate penetration level then they would expect to have interruptions in their water supply, while if the well is screened below the adequate penetration level then they would expect to have a reliable water supply. The adequate penetration level becomes a key constraint for the model scenarios (e.g. if the model scenario results are lower than the adequate penetration level we would expect significant water supply issues). Adequate penetration levels can be set based on an analysis of current well screens and historical water levels; however, this approach is difficult in the Hawea Area as many bores do not have detailed well construction data. In addition this approach can cause challenges when there are biases in the model results (e.g. if the model over/under estimates the groundwater levels). To address these issues we have calculated the adequate penetration level for a given scenario based on the model results as follows:

$$apl = h_{mean} - 3\sigma$$

where:

- apl is the adequate penetration level
- h_{mean} is the mean of the model heads at the indicator well
- σ is the standard deviation of the model heads at the indicator well

For these models we typically compare results to the adequate penetration level for the long_current scenario and long_nat scenario. The long_current scenario is a reasonable representation of the historical record, while the long_nat scenario is a reasonable representation of the natural record (i.e. no pumping).

Scenario Methods & Results

The following sections describe the methods and results for each scenario set. Note that we typically will only include the results for an individual indicator well. A link to the location for the full sets of model results is provided in the section. We include some discussion and analysis of these results, but our primary discussion is in final report. Regardless, a full discussion of all the results is beyond the scope of this document and this project, but below we provide some example discussion of the results, so that these results could be used to address a future specific question.

Model information scenarios

Scenario Name	Purpose/comment
optimised	Optimised model results
long_current	Long scenario with long_current abstraction and irr_LSR
long_nat	Long current, but with dryland recharge, and no pumping (races left on)
no_pumping	Long current, but with no pumping
hillslope_only_var	What extent does the hillslope inflow variation influence total model variation
lake_only_var	What extent does the Lake Hawea level variation influence total model variation
pump_only_var	What extent does the groundwater abstraction influence total model variation
rch_only_var	What extent does the LSR variation influence total model variation
static_pumping	What variation exists with only pumping held static

Boundary condition sensitivity

To conduct the boundary condition sensitivity we compared the model scenarios where all but one boundary condition was held static to the long current scenario. We could then qualitatively assess the contribution of each boundary condition to the total model variation. An analytical approach is also possible, but we feel it would suffer from false precision, that is that while it would perfectly represent the contribution of each boundary condition to the total model variation the contribution to the experienced real world variation would likely have a significant and unspecified level of error. The results shown in the table below are the results of the qualitative assessment, which we believe should hold true in the real world.

Zone	Recharge	Hill inflows	Lake levels	Pumping
Hawea Flat	Moderate	Low	High	Low
Te Awa	Low	Low	High	N/A
Terrace-River	Moderate	Moderate	Moderate	Localised high
Terrace-Hill	High	High	Moderate	Low
Maungawera Flat	Low	Low	High	N/A
Maungawera Valley	High	High	N/A	Moderate
Sandy Point	High	Moderate	Low	N/A

The figure below provides an example of the results of the boundary condition sensitivity analysis. The full set of results are available at Scenarios/model_info_scen_results/0_results/boundary_sense. In the figure below the pump_only_var scenario has minimal variance across the quantiles relative to the long_current scenario. Conversely, the hillslope_only_var and rch_only_var scenario has a large amount of variance across the quantiles compared to the long_current scenario. This indicates that the hillslope inflows and LSR are a significant contributor to the total water level variation at this indicator well, while the pumping is a relatively minor contributor. Lake levels are minor contributor to the total water level variation at this indicator well, but are still noticeable, particularly at high and low groundwater levels (0-20th and 80-100th percentiles).

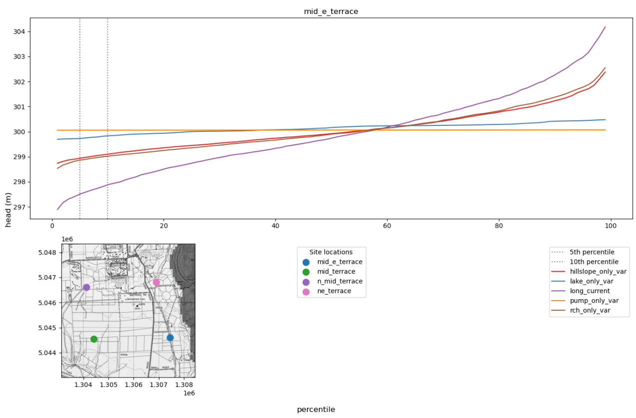

Figure: example results of the boundary condition sensitivity analysis at the mid_e_terrace indicator well

Naturalised vs current without abstraction

These scenarios compare the results of the long_current, long_nat, and no_pump scenarios. In the example figure below the naturalised scenario (long_nat) has a significantly lower mean water level than the no_pump scenario. This is likely because there is significant irrigation on the high terrace, which is not represented in the naturalised scenario. The long_current scenario has a mean water level between the long_nat and no_pump scenarios, which shows that while the current level of abstraction has a significant impact on the water levels, it does not reduce the water levels below the naturalised state. This is consistent with our understanding of the area as the irrigation on the High Terrace is primarily supplied by abstraction from the Hawea River, thus development in this area has shown a net increase in groundwater levels. The full set of results are available at Scenarios/model_info_scen_results/0_results/nat_long_nopump.

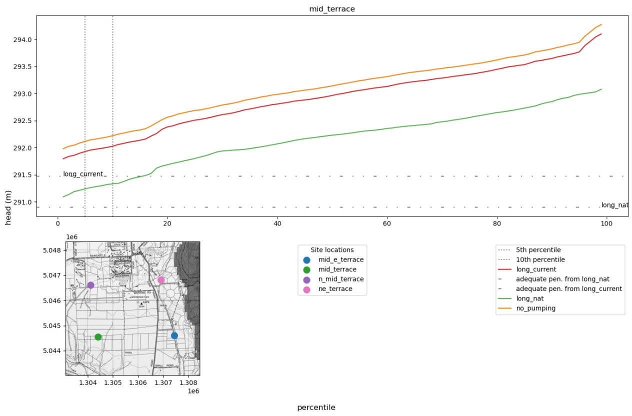

Figure: example results of the comparison of the naturalised, long current, and no abstraction scenarios at the mid_terrace indicator well

Naturalised vs current vs long current

These scenarios compare the results of the long_current, long_nat, and optimised scenarios. We do not include an example figure here as the results are very similar to the naturalised vs current without abstraction scenarios. The full set of results are available at Scenarios/model_info_scen_results/0_results/nat_long_opt.

Naturalised vs current vs long current (opt period only)

These scenarios compare the results of the long_current, long_nat, and optimised scenarios but only for the optimisation period. We do not include an example figure here as the results are very similar to the naturalised vs current without abstraction scenarios. The full set of results are available at Scenarios/model_info_scen_results/0_results/nat_opt_long_opt_per_only.

Low Lake Hawea Level Scenarios

The Low Lake Hawea Level scenarios are designed to test the sensitivity of the model to the Lake Hawea head boundary conditions and to test the impacts of the complex moraine structure specifically. These scenarios involve creating a synthetic lake level boundary conditions and then ascertaining how the model responds to these conditions. The figures below show all of the synthetic lake level scenarios that were tested.

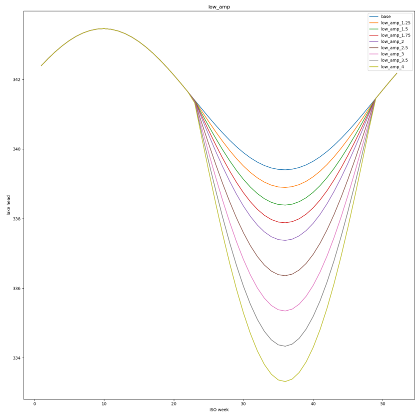

Figure: Lake Hawea head boundary conditions for the low_amp scenarios

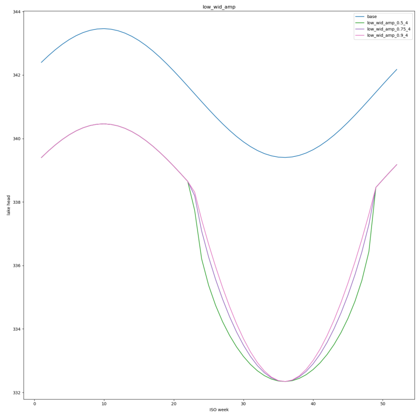

Figure: Lake Hawea head boundary conditions for the low_wid_amp scenarios

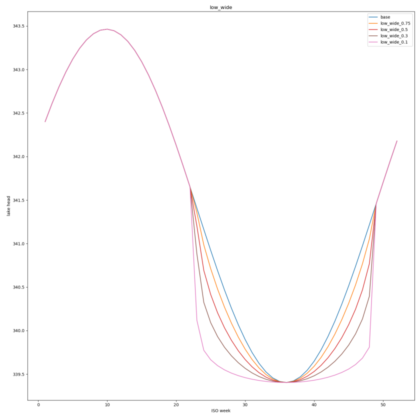

Figure: Lake Hawea head boundary conditions for the low_wide scenarios

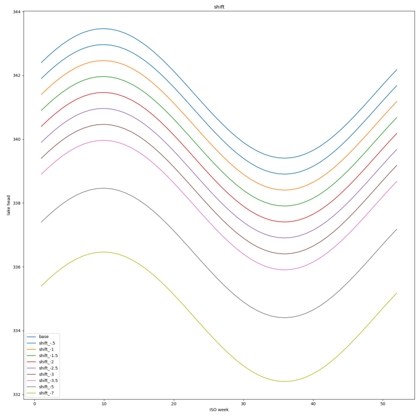

Figure: Lake Hawea head boundary conditions for the shift scenarios

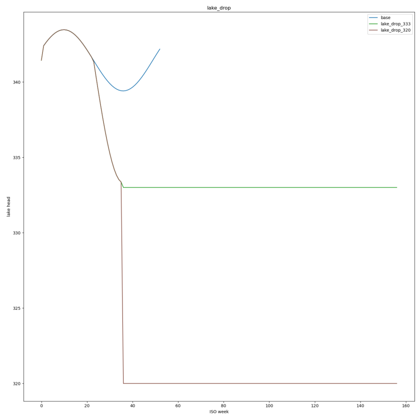

Figure: Lake Hawea head boundary conditions for the lake_drop scenarios.

Methods and results

The synthetic lake levels were created for a three year period. All other boundary conditions were set at the steady state (mean of optimised period) values. The synthetic lake levels were then applied to the model and the results were extracted at the indicator boundary points. Finally we compared these scenarios to the base sin fit to the observed ISO weekly mean lake levels

The sections below show some key figures for the various lake level scenarios. Many more figures for each scenario are available in the low lake level results folder. Scenarios/low_lake_scenarios/0_results/lake_drop/comp_plots/hds_monitoring.png

The changes in lake levels clearly propagate directly to the groundwater levels. However the lake_drop and the low_wide_amp scenarios clearly show the predicted impacts of Lake levels falling below the threshold value.

Lake_drop Scenario results

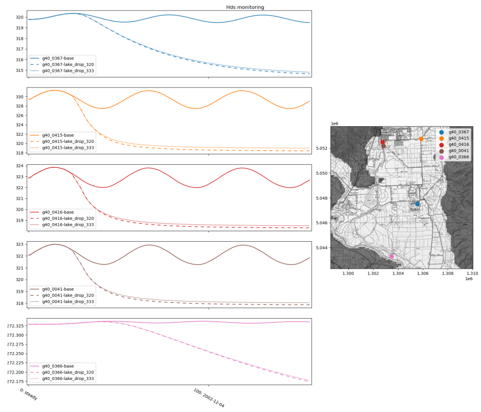

Figure: Responses at the high frequency monitoring bores for the lake drop scenarios.

Low_amp Scenario results

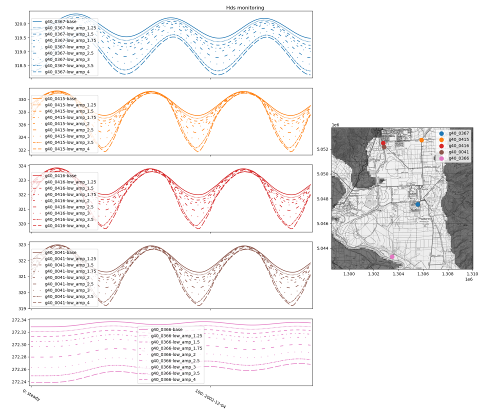

Figure: Responses at the high frequency monitoring bores for the low_amp scenarios.

Low_wid_amp Scenario results

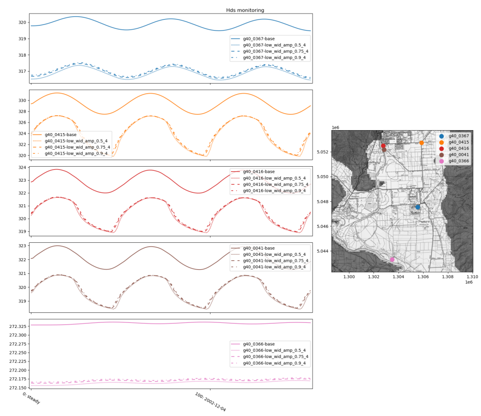

Figure: Responses at the high frequency monitoring bores for the low_wide_amp scenarios.

Low_wide Scenario results

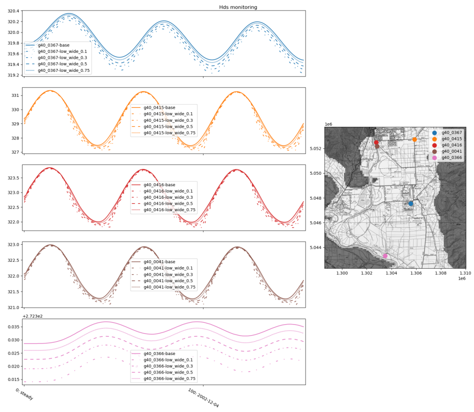

Figure: Responses at the high frequency monitoring bores for the low_wide scenarios.

Shift results

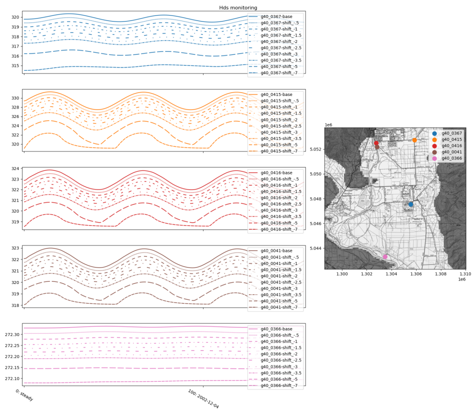

Figure: Responses at the high frequency monitoring bores for the shift scenarios.

MT3D Indicator Scenarios

Scenario name	Boundary condition concentration
all_any	all boundary conditions set to 1 (process check)
all_hill_indicator	all hillside inflows (excluding John and Grandview creeks) set to 1
all_str	all stream boundary conditions set to 1
hill_rch_indicator	all hillside inflows (excluding John and Grandview Creeks) and recharge set to 1
lake_con_indicator	all lake boundary conditions set to 1
not_any	all boundary conditions set to 0 (process check)
not_str	all boundary conditions (except str package)
race_con_indicator	all race cells set to 1
rch_indicator	recharge concentration set to 1

Methods

We ran a steady state model with the mean optimised period boundary conditions and then ran the MT3D model with the concentrations for each boundary condition set to 1 and all others set to 0. The MT3D model was run for an arbitrary period (7.305 E5 years) to ensure the concentrations were at pseudo steady state. The final concentrations for these scenarios were saved and plotted. They are available in the mt3d_indicator_scenarios folder.

Results

Interpretation of these results are relatively trivial a value of 0 means no water in the cell is modelled to originate from the boundary condition, while a value of 1 means all water in the cell originated from the boundary condition. Below we include the figures for the key boundary conditions. These results are useful to determine the relative importance of each boundary condition and help set allocation zone boundaries.

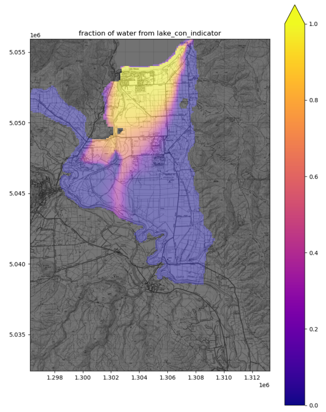

Figure: fraction of the water in the model sourced from Lake Hawea at steady state conditions.

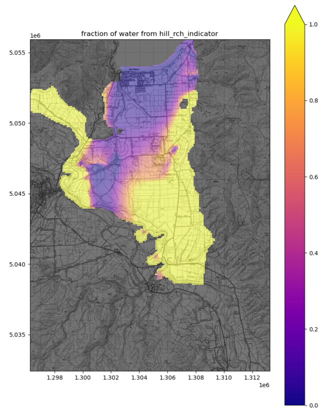

Figure: fraction of the water in the model sourced from hillside inflow or LSR at steady state conditions. Note this excludes John and Grandview Creeks.

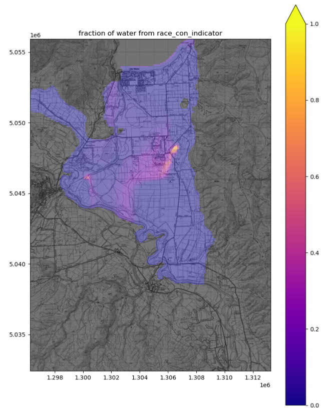

Figure: fraction of the water in the model sourced from water race leakage at steady state conditions.

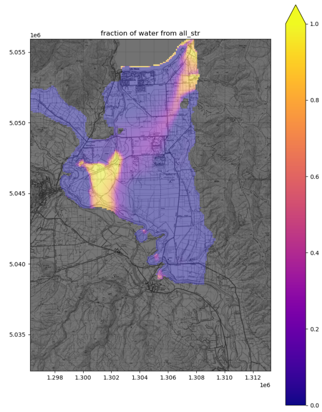

Figure: fraction of the water in the model sourced from the Hawea and Clutha Rivers and John and Grandview Creeks at steady state conditions.

Recommended Allocation Zones

Wilson (2012) recommended a set of allocation zones for the hawea area. These are shown in the figure below.

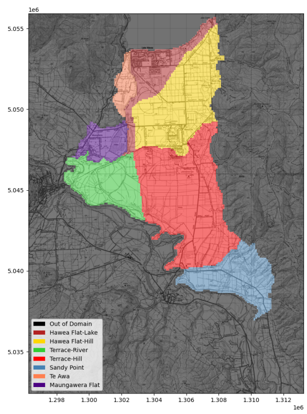

Figure: Allocation zones recommended by Wilson (2012) for the Hawea area. Note the allocation zones are not recommended for the entire model area, only the area of the Hawea Basin Groundwater Review (2012) study.

From the current modelling we have recommended some slight changes to the allocation zones. These are shown in the figure below. The main differences are:

1. The Hawea Flat-hillside and Hawea Flat-lake allocation zones have been rearranged into the Hawea Flat allocation zone and Grandview allocation zone. This is based on the new information that Lake Hawea levels impact the groundwater levels in most of the Hawea Flat area. The Grandview allocation zone is defined as the area to the west of the Hawea Flat allocation zone which is not impacted by Lake Hawea levels. The location of the Grandview-Hawea Flat boundary was approximately defined by the inferred Grandview Fault location. The Grandview Fault is thought to uplift basement rock above the Hawea Flat groundwater levels and therefore prevent the lake levels from impacting the groundwater in this area. Because the location of the Grandview Fault is not well defined we suggest that areas in the Grandview allocation zone could be reassigned to the Hawea Flat allocation zone if further investigation shows that water levels at that location are impacted by the Lake Hawea levels and that it would be reasonable to infer that groundwater flows from the lake to the area of interest.
2. We explicitly included the Camp Hill Moraine, but we suggest that very limited water is likely to be available in this zone.
3. We extend the sandy point zone to the Northern border of the next allocation zone.
4. We explicitly model and include the Maungawera Valley allocation zone, which was not addressed in the Wilson (2012) report.
5. Here we have suggested possible setback areas for the Butterfield and Campbell wetlands, note these location are suggestions however, the actual location of the setback areas requires planning consideration and is beyond the scope of this project. We have provided scientific guidance to support the planning process.

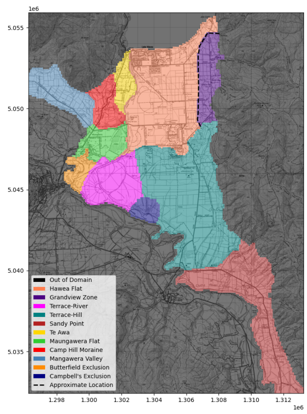

Figure: Recommended allocation zones for the Hawea area from this work.

Allocation Scenarios

Allocation Scenario overview

Scenario Name	Abstraction	LSR	Other comments
optimised	optimisation period	optimisation period	final optimised model
long_current	extended_pump: ISO weekly mean pumping	irr_rch	

long_nat	None	dryland_rch	race losses still included
no_pumping	None	irr_rch	
full_allocation	extended_full_allo: maximum daily allocation multiplied by the min/max normalised to historical pumping record	irr_rch	
max_allocation_on_pump_curve	extended_max_allo_pc: maximum daily allocation applied to pump curve	irr_rch	
{zone} MAPC + {rate} m^3/day	extended_max_allo_pc + {rate} applied to the grid_pump wells for {zone}. Increased allocation scenarios.	irr_rch	
reduction _ {faction}	extended_max_allo_pc, wells in the Maungawera Valley allocation zone are multiplied by {fraction} e.g. .9 = 90% of maximum allocation on pumping curve for the maungawera valley	irr_rch	only for the Maungawera Valley allocation zone
max_allocation	extended_max_allo: maximum daily allocation applied to every day of the year	irr_rch	not realistic

Full List of Zone Specific Scenarios

Scenario Name	Applicable Zone	Pumping Increase (+) / Decrease(-)	Percent Increase (+) / Decrease (-)
Hawea Flat MAPC + 3424 m^3/day	Hawea Flat	3424	0.05
Hawea Flat MAPC + 6847 m^3/day	Hawea Flat	6847	0.1
Hawea Flat MAPC + 13694 m^3/day	Hawea Flat	13694	0.2
Hawea Flat MAPC + 20542 m^3/day	Hawea Flat	20542	0.3
Hawea Flat MAPC + 34236 m^3/day	Hawea Flat	34236	0.5
Hawea Flat MAPC + 51354 m^3/day	Hawea Flat	51354	0.75
Hawea Flat MAPC + 68472 m^3/day	Hawea Flat	68472	1
Hawea Flat MAPC + 102708 m^3/day	Hawea Flat	102708	1.5
Maungawera Flat MAPC + 500 m^3/day	Maungawera Flat	500	
Maungawera Flat MAPC + 1000 m^3/day	Maungawera Flat	1000	

Maungawera Flat MAPC + 2500 m^3/day	Maungawera Flat	2500	
Maungawera Flat MAPC + 5000 m^3/day	Maungawera Flat	5000	
Maungawera Flat MAPC + 7500 m^3/day	Maungawera Flat	7500	
Maungawera Flat MAPC + 10000 m^3/day	Maungawera Flat	10000	
reduction_0.5	Maungawera Valley	-2348	-0.5
reduction_0.6	Maungawera Valley	-1878.4	-0.4
reduction_0.7	Maungawera Valley	-1408.8	-0.3
reduction_0.8	Maungawera Valley	-939.2	-0.2
reduction_0.85	Maungawera Valley	-704.4	-0.15
reduction_0.9	Maungawera Valley	-469.6	-0.1
reduction_0.95	Maungawera Valley	-234.8	-0.05
Te Awa MAPC + 500 m^3/day	Te Awa	500	
Te Awa MAPC + 1000 m^3/day	Te Awa	1000	
Te Awa MAPC + 2500 m^3/day	Te Awa	2500	
Te Awa MAPC + 5000 m^3/day	Te Awa	5000	
Te Awa MAPC + 7500 m^3/day	Te Awa	7500	
Te Awa MAPC + 10000 m^3/day	Te Awa	10000	
Terrace-Hill MAPC + 135 m^3/day	Terrace-Hill	135	0.1
Terrace-Hill MAPC + 336 m^3/day	Terrace-Hill	336	0.25
Terrace-Hill MAPC + 673 m^3/day	Terrace-Hill	673	0.5
Terrace-Hill MAPC + 1346 m^3/day	Terrace-Hill	1346	1
Terrace-Hill MAPC + 2019 m^3/day	Terrace-Hill	2019	1.5

Terrace-River MAPC + 1011 m^3/day	Terrace-River	1011	0.1
Terrace-River MAPC + 2527 m^3/day	Terrace-River	2527	0.25
Terrace-River MAPC + 5054 m^3/day	Terrace-River	5054	0.5
Terrace-River MAPC + 10109 m^3/day	Terrace-River	10109	1
Terrace-River MAPC + 15164 m^3/day	Terrace-River	15164	1.5

Allocation via Zonal recharge

For each of the allocation zones we extracted the range of hillside inflows and LSR. An example figure is shown below. It is a violin plot, so the width of the violin represents the probability of the value occurring. The full results, including tabular results are available in the allo_zone_rch folder.

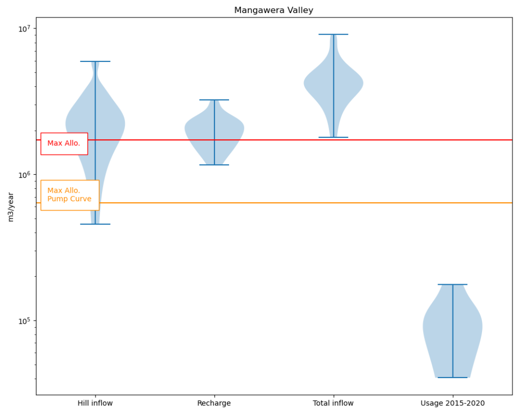

Figure: Example violin plot of the range of hillside inflows and LSR for the Maungawera Valley allocation zone.

Naturalised vs current vs full

In addition to the zonal recharge modelling we also compared the impact of the long current scenario with various full allocation and naturalised scenarios. The full results are available in the nat_current_full folder.

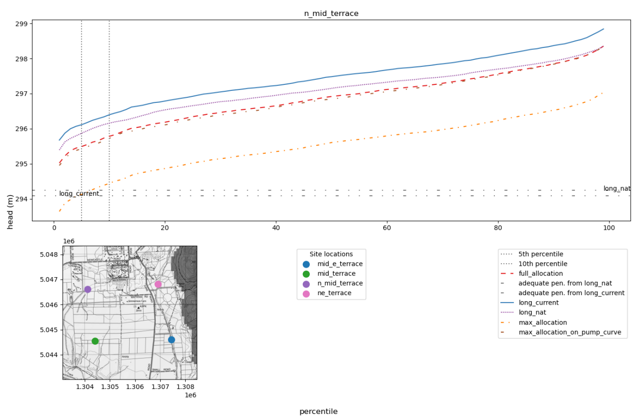

Figure: An example of the comparison between the long_current, naturalised, and various full allocation scenarios.

Zone specific Scenario Methods and Results

We modelled a number of scenarios to determine the impact of potential changes to zonal allocation on the groundwater levels for most allocation zones. An overview of these results are shown in the table below. However, there were some allocation zones that we did not conduct scenario modelling for. These zones and the rational for not modelling them are described below and we suggest any allocation in these zones should be based on the results of the zonal recharge modelling.

- **Grandview Zone:** The model does not provide a good representation of the groundwater levels in this area.
- **Camp Hill Moraine:** We suggest that very limited water is likely to be available in this zone and it was not modelled.
- **Sandy Point:** The model does not provide a good representation of the groundwater levels in this area as there is very limited data available to constrain the model.

Allocation Zone	Scenarios modelled allocation:	Path to results
Hawea Flat	Increases	Scenarios/allocation_results/Hawea Flat_results
mangawera _valley	Decreases	Scenarios/allocation_results/mangawera_valley
Maungawer a Flat	Increases	Scenarios/allocation_results/Maungawera Flat_results
Te Awa	Increases	Scenarios/allocation_results/Te Awa_results
Terrace-Hill	Increases	Scenarios/allocation_results/Terrace-Hill_results
Terrace-Riv er	Increases	Scenarios/allocation_results/Terrace-River_results

Full discussion of potential allocation levels are reserved for the final report. However we want to highlight several key points:

1. Changes in allocation in one zone can impact the groundwater levels in other zones. Therefore, we suggest that allocation in all zones should be considered collectively.
2. These scenarios do not discriminate between groundwater and induced stream depletion. Therefore, we suggest that allocation should be considered in the context of the stream depletion that is acceptable for the Hawea River and Clutha River.
3. Where the results suggest that a significant increase in allocation is possible, particularly where there is limited or no present allocation we suggest a very conservative approach. The lack of current abstraction means that the model has minimal to no information about the impact of abstraction to local groundwater levels. Any increase in allocation in these areas should be phased in over time to allow for monitoring and revised assessment of the impact of the allocation on the groundwater levels.

Quartz Creek Allocation Zone LSR analysis

The Quartz Creek Allocation Zone is a small area to the west of the Maungawera Valley in the catchment and alluvial fan of Quartz Creek. The allocation zone is shown in the figure below. Water in this area drains towards Lake Wanaka and was therefore out of scope of this project. However, we have included the results of LSR modelling for this area in this repository for completeness and because it required minimal additional effort. The LSR results are located in the quartz_creek_lsr/results folder and are shown in the figure below. Note that allocation in some of these areas have the potential to impact the groundwater levels in the Maungawera Valley and therefore should be considered in the context of the Maungawera Valley allocation zone.

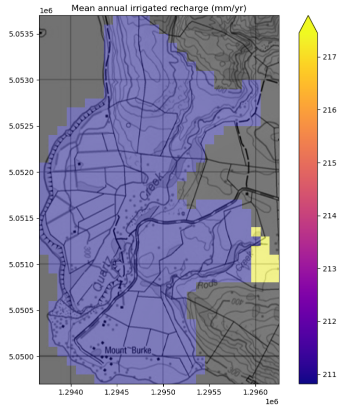

Figure: Locations of the Quartz Creek allocation zone and the LSR results.

Wetland Setback Scenarios

The purpose of the wetland setback modelling was to assess the impact of abstraction on the two sensitive wetland in the Hawea Basin.

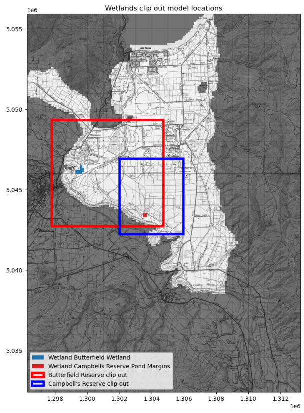

Figure: Locations of the two wetlands in the Hawea Basin and the boundaries for the clip out models.

Methodology

We wanted to examine a larger range of parameters than the optimised model parameter set. Therefore we made two clip out models; one for each wetland. The clip out models were made by clipping out the wetland and an approximately 5 km up gradient buffer. We set the boundary conditions of these models as follows:

- No existing abstraction was included in the model.
- Steady state LSR
- Steady state conditions for the Hawea and Clutha Rivers.
- For the Campbell's wetland model we set the North, East, and West boundaries as constant head boundaries with the head set from the optimised model.

We then created a semi-regular polar grid of test abstraction well locations. To identify the impact of abstraction on the wetland we ran a base scenario (no abstraction) and then ran a series of scenarios. The head difference between the base and new scenarios at the wetland location was extracted. We varied the following parameters:

- pumping rate
- hydraulic conductivity

- specific yield
- river conductance

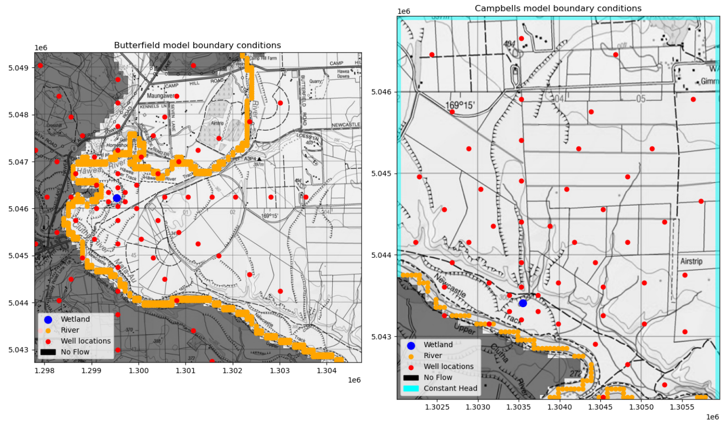

Figure: boundary conditions for the clip out models.

To visualise the results we assigned the head difference at the wetland location to the well location and then interpolated the results for each unique combination of parameters. Finally we qualitatively assessed the various parameterisations to determine an area where abstraction would likely impact the wetland.

Results

The full suite of results are available in:

- Campbell's: Scenarios/wetland_setback_campbells/results
- Butterfield: Scenarios/wetland_setback_butterfield/results

An example of the results for the Campbell's Wetland are shown below. The results for the Butterfield Wetland are similar. This specific example is for a pumping rate of 500 m^3/d, hydraulic conductivity of 0.316 m/d, specific yield of 0.316, and river conductance of 750 m^2/d. This specific example shows that abstraction within 1 km of the wetland is likely to cause c. 0.5 m drawdown at the wetland location. However, abstraction 2 km or further from the wetland is unlikely to cause drawdown at the wetland location. Note that several of the example bore locations were not able to sustain abstraction at this rate. The drawdown at these locations are excluded from the interpolation.

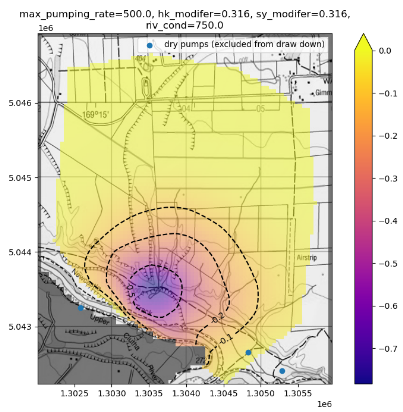

Figure: An example of the wetland setback modelling results for Campbell's Wetland.

References

- Wilson, J., 2012. Hawea Basin Groundwater Review. prepared by Resouce Science Unit of Otago Regional Council, June 2012, Dunedin.

lincolnagritech.co.nz