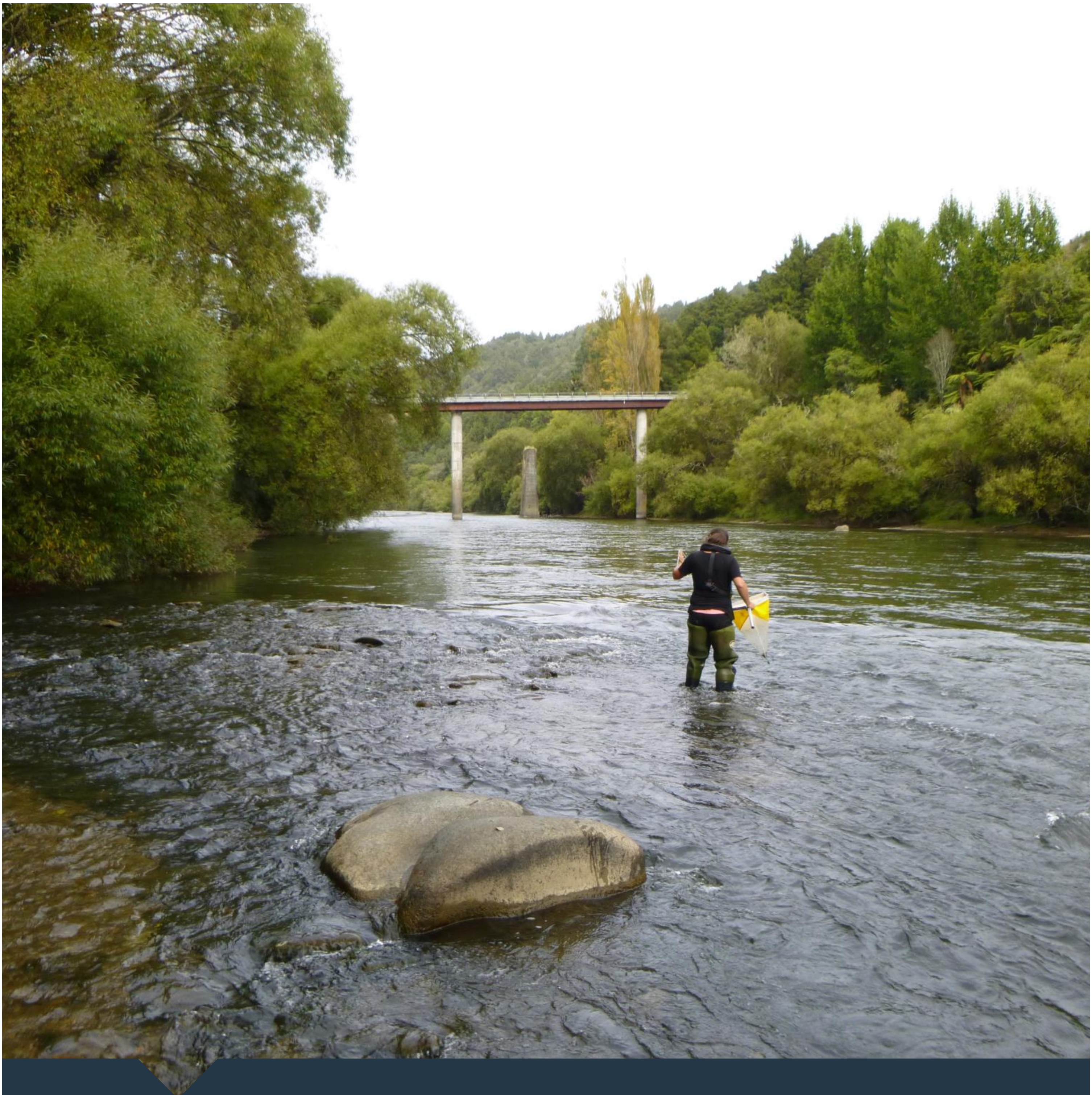

Lake Horowhenua Groundwater Model

October 2021

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Executive Summary

This report documents the outputs from the steady state model of the Horowhenua FMU area. The model provides a good representation of the conceptual understanding of the Horowhenua area, and accurately simulates the Lake Horowhenua water balance. In that sense, it helps to demonstrate that the conceptual model is a valid representation of the patterns of groundwater movements in the area.

Values of hydraulic conductivity are not particularly well constrained in the model and one recommendation is that whilst some aquifer parameter data is available, it is of relatively poor quality and frequently represents the outcome from step test (i.e. short term, localised) analysis. Undertaking two or three well controlled, longer term pumping tests in the area would help to constrain aquifer parameters. These should be completed in both deeper and shallower strata close to Lake Horowhenua. It would be particularly helpful to use this testing to verify the modelled presence of higher conductivity strata around the south-east of the lake, and between Lake Waiwiri and Lake Horowhenua.

Development of a steady state model provides a helpful starting point for a modelling exercise but one drawback of a steady state model is that they are calibrated to estimates of average groundwater levels and average flows, which are not necessarily based on consistent datasets. Losses from the Ōhau River are a key component of the model, and they are generally poorly constrained for average flow rates, although they are better constrained at low flows where a number of gauging surveys have been carried out. As a result, those losses may not be representative of average groundwater levels. Some further work to help refine these losses at a range of flows would help to reduce the uncertainty of any model predictions.

Development of a transient model that represents changes in groundwater levels and flows through time will also help to resolve this issue, as each dataset will be consistent in time and space.

The particle tracking exercise indicates that travel times from the Ōhau River to Lake Horowhenua are likely to be less than 10 years in shallow strata, although longer times are likely in deeper strata. Based on the model outputs, travel times to Lake Horowhenua in shallower strata within the Arawhata Drain catchment may be within the order of 5 years. However, there is considerable uncertainty around these estimates and development of a transient model would help to reduce this uncertainty.

A summary of the key recommendations is provided below:

- Further information regarding drains, their depths and their connection to existing surface waterways is required. This is especially so around the Arawhata Drain.

- Shallow groundwater in the Arawhata Drain area is likely to be affected by evapotranspiration effects, which is not currently included in the model. Simulation of this effect is likely to be required in order to better match groundwater levels around the lake.
- Two or three well controlled, longer term pumping tests would help to constrain aquifer parameters. These should be completed in both deeper and shallower strata close to Lake Horowhenua and between Lake Horowhenua and Lake Waiwiri.
- Further work to help refine losses from the Ōhau River upstream of Hoggs Road at a range of flows would help to reduce the uncertainty of any model predictions. This could include undertaking a pumping test to help constrain stream bed conductance in the reach between Muhunoa Road and SH1, and along the upstream reach between the Rongomatane gauging station and Kimberley Road. Groundwater level monitoring in this area would also help to reduce modelled uncertainty regarding the loss from the river in this reach.
- The structure of the Levin fault is likely to have a strong impact of groundwater flows in the area, which are complex. Some additional information on the structure of the basement high around the lake may be beneficial to help reduce uncertainties in future predictions using the model.
- Running the model as a transient groundwater model would help to reduce uncertainties that are likely to be present, particularly if the model is used to investigate travel times and contaminant transport towards Lake Horowhenua and Lake Waiwiri.

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1.0 Introduction

1.1 Background

Lake Horowhenua is a shallow coastal lake located to the west of Levin. The lake has historically suffered from water quality issues which have arisen due to a variety of different factors, including landuse within the lake catchment and construction of a weir across the lake outlet.

Variations in the water quality within the lake are driven by changes in the nutrient flux into the lake and by ecological processes within the lake. In turn, the nutrient flux into the lake is dependent on surface water and groundwater inflows into the lake. Estimates of the lake water balance are not well constrained, with estimates of the groundwater component of inflows ranging from 30% to 60% of the overall lake water balance.

In recent years a significant amount of information regarding the surface water and groundwater fluxes into the lake has been collected including:

- Groundwater level data
- Surface water flow data for many of the streams that feed into the lake
- Improved ground surface data via LiDAR
- Improved aquifer parameter data through data from pumping tests
- Additional water quality data for surface water inflows.

However some information gaps still exist, particularly including information around groundwater quality and accurate information on the distribution of different land uses in the catchment (together with historical changes). Furthermore, there is some uncertainty regarding the conceptual model of groundwater flow in the area around the lake, including the extent of the Poroutawhao High and the source(s) of groundwater in the area.

The issues around groundwater allocation and surface water/groundwater interaction are best addressed through a numerical groundwater model, which will allow a better understanding of the interaction between the different components of the groundwater and surface water systems. Whilst a model was prepared some years ago (in 2005), there is considerably more information available now which justifies the development of a new modelling tool.

1.2 Purpose of this Model

The key purpose of the model is to help refine the water balance for Lake Horowhenua and to use the model to determine the groundwater catchment to the lake. In this respect the model will be used to test the existing conceptual model of groundwater flow in the area and answer questions such as:

- The extent to which seepage from the Ōhau River forms a source of water to Lake Horowhenua and Lake Waiwiri
- The hydraulic connection, if any, between Lake Horowhenua and Lake Waiwiri
- The impact of the Levin Fault on groundwater flow.

In addition, the model will be used to help focus further data collection to areas where limited data is available, but which have a strong influence on the lake water balance. Note that Lake Waiwiri has previously been referred to as Lake Papaitonga and is named as such on some maps.

2.0 Conceptual Model

The study area is bounded by the Manawatū River in the north and the Manakau and Waikawa Streams in the south and extends from the coast to the Tararua Range foothills to the east. A map showing the general study area is provided in Figure 1.

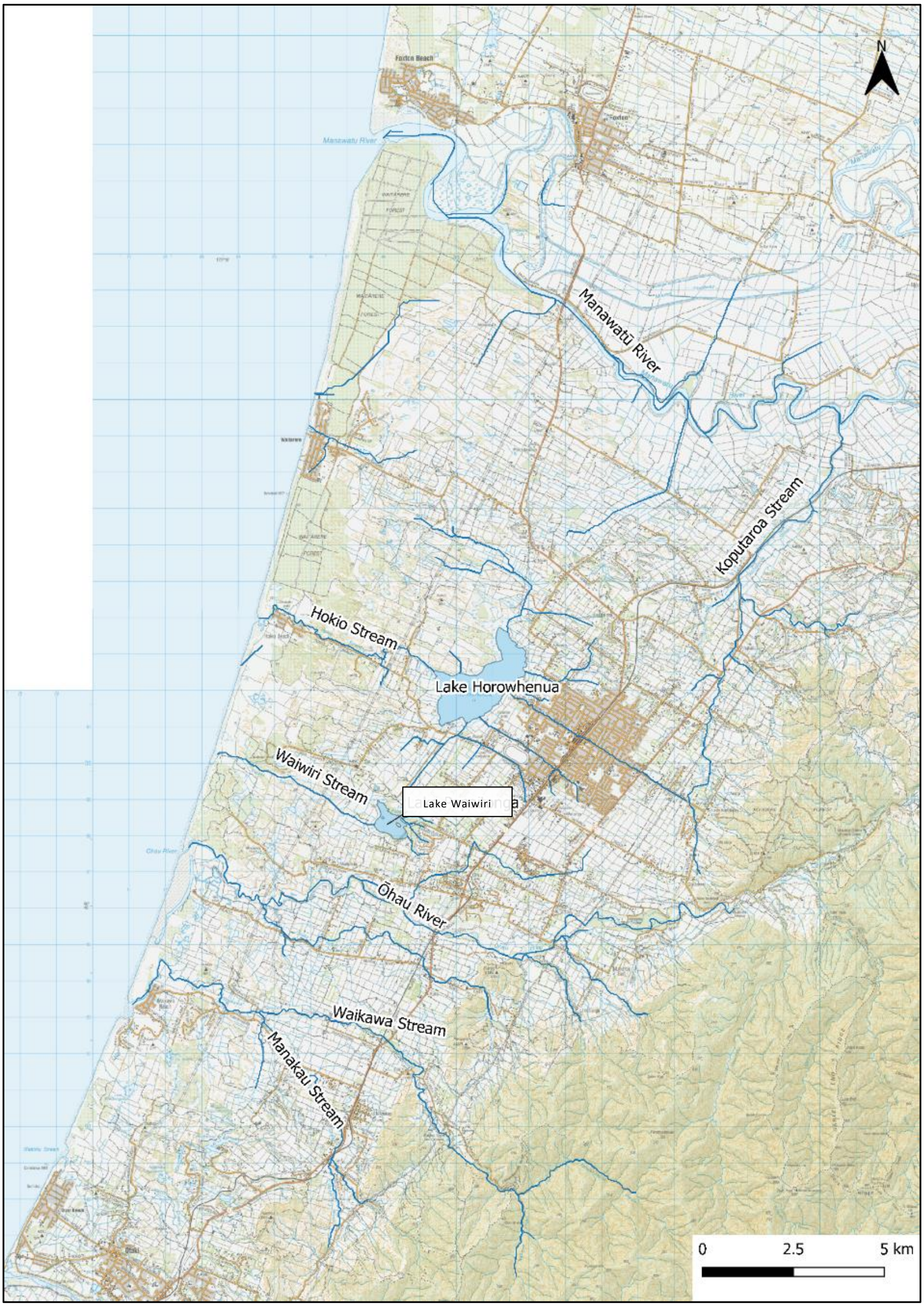

Figure 1: Horowhenua model study area

2.1 Geology

The geology of the Lake Horowhenua area is complex, with significant uncertainties. The Tararua range consists of ‘greywacke’ basement rock (Torlesse Supergroup), while the plains consist of young (Pleistocene to Holocene) alluvial, beach and dune deposits (Begg and Johnston, 2000). The relevant aspects of the geology of the area are discussed in more detail below.

2.1.1 Structure

The study area contains several significant geological structures (as shown in Figure 2). Major active faults, such as the Northern Ohariu Fault, control the western rangefront of the Tararua Range, while another significant fault, the Poroutawhao/Levin Fault, exists adjacent to the western side of Lake Horowhenua. The Poroutawhao Fault is inferred to be a blind thrust fault that may be similarly oriented to the Mt Stewart Fault to the north of the Manawatu River and is related to the Poroutawhao High (Litchfield et al., 2013).

The Poroutawhao High is an area of elevated greywacke basement that is not exposed at the surface but is shown from boreholes to reach to within ~20 m of the surface, west of Lake Horowhenua. The geometry of the Poroutawhao High is poorly understood due to there being few deep (>200 m) boreholes in the area, however it likely has a steeply dipping eastern side, due to uplift along the Poroutawhao Fault, and boreholes show that the western side is also reasonably steep-sided, though this is poorly constrained. The along-strike (i.e. NE-SW) geometry is also poorly constrained, however it may be similar in shape to Kāpati Island (White et al., 2010). Active folds are present west of the Tararua Range and northeast of Lake Horowhenua, these include the Levin Anticline, Koputaroa Syncline and the Shannon Anticline.

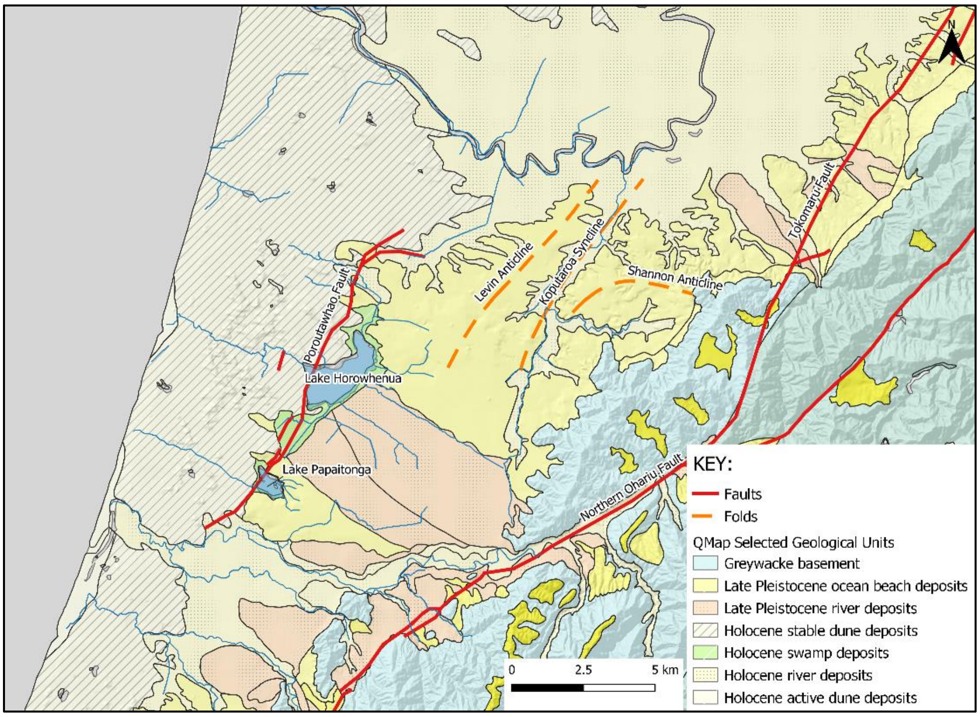

Figure 2: Geological map of the model area (after Begg and Johnston, 2000)

2.1.2 Lithology

The Torlesse Supergroup is the geological basement of the area, and predominantly comprises highly indurated interbedded sandstone and mudstone of Mesozoic (late Triassic to early Cretaceous) age. The Torlesse Supergroup is colloquially known as "greywacke", and it tends to be highly deformed and fractured. In the model area, the Poroutawhao High consists of greywacke, as described above, as well as the foothills of the Tararua Range immediately outside the model boundary to the east. Most of the alluvial sediments in the model area were derived from erosion of the adjacent greywacke ranges. Although the greywacke is likely to be highly fractured, for the purposes of this model it is considered the hydrogeological basement and is assumed to be impermeable, due its expected very low hydraulic conductivity in comparison to the overlying sediments.

The sediments above the basement consist of alluvial, beach and dune deposits of Pleistocene to Holocene age. The area between the Tararua Range and lakes Horowhenua and Waiwiri consists of a remnant elevated Pleistocene alluvial fan derived from the Ōhau River, flanked by partially dissected marine terraces on either side, dominantly comprised of marine sand. Fine-grained swamp deposits are found near lakes Horowhenua and Waiwiri, while the area between these lakes and the coast is dominated by Holocene dune sand deposits. Young (Holocene) gravels are found in valleys near major rivers that drain the Tararua Ranges, such as the Ōhau and Waikawa Rivers. Borelogs show that there is some lithological variability in the units described above, for example silt and/or clay horizons are common in both the alluvial gravel and marine sand deposits.

Figure 3 illustrates the geology in the area based on the lithology observed in bores in the area.

For the purposes of groundwater modelling, the Poroutawhao High was modelled using Leapfrog software. The geometry of the Poroutawhao High was estimated based on the depth to bedrock encountered in bores in the area and the simplified location and orientation of the Poroutawhao Fault. Structure contours were drawn to be consistent with the aforementioned information, and with expert geological judgement as to the likely geometry of the basement high. The contours and borehole information were then used as inputs for the Leapfrog model. Manual polyline adjustments were used to ensure that the model did not project the bedrock Poroutawhao High as extending above the ground surface. Figure 4 shows an image of the resulting three-dimensional modelled geometry of the basement. Note that this is constrained by the available borehole log data, however, where that data is not available there are uncertainties in our interpretation of the shape of the Poroutawhao High structure.

Figure 3: Oblique Leapfrog image looking east towards the Tararua Ranges, with 3x vertical exaggeration, showing observed lithologies in bores in the area. Lake Horowhenua is in the centre left of the image.

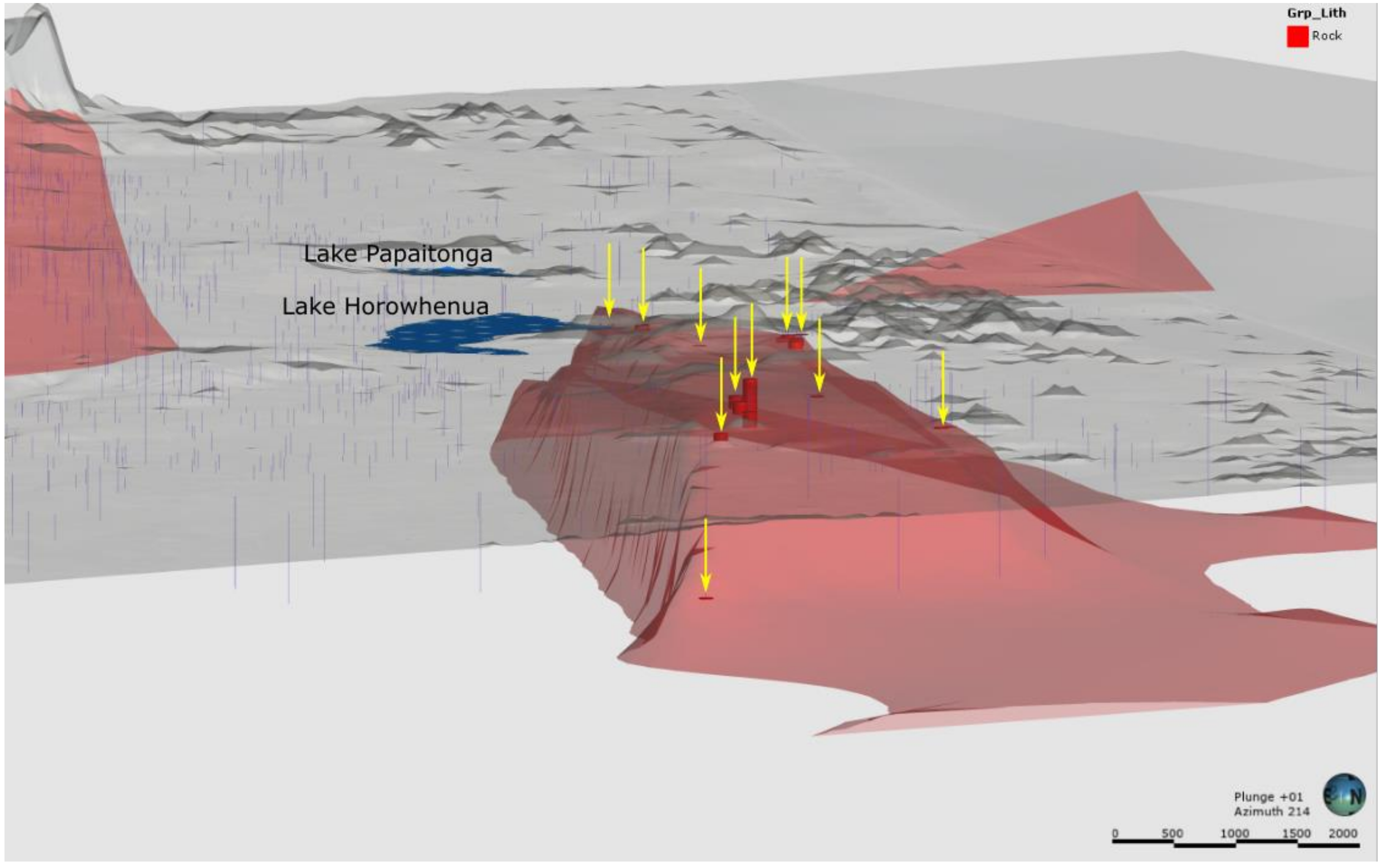

Figure 4: Oblique Leapfrog image looking southwest with 5x vertical exaggeration, showing borehole traces (purple), observed rock in boreholes (dark red) and modelled Poroutawhao basement high (light red). Yellow arrows highlight where rock has been encountered in boreholes.

2.2 Hydrogeology

2.2.1 Groundwater Flow Patterns

The conceptual hydrogeological setting for the study area is relatively well established and largely governed by the geology of the area described above.

The groundwater in the area is recharged via both rainfall (less evapotranspiration) and seepage loss from rivers in the east of the area as they emerge from the Tararua Ranges, principally the Ōhau River. Groundwater flows westwards towards the coast and in the east of the area, close to the foot of the Tararua Ranges, the vertical hydraulic gradient is downwards. However, as westward flowing groundwater approaches the low permeability basement of the Poroutawhao High it is forced upwards, resulting in the increasing groundwater pressures with depth (i.e. an upwards vertical gradient) observed in bores around Levin township. As deep groundwater is forced upwards it discharges into the shallow strata, which subsequently discharges into the lakes and the spring fed streams that flow into the lakes.

As noted in Section 2.1.1 above there is some uncertainty about the geometry of the Poroutawhao High, particularly how far it extends in a northeast – southwest direction. This introduces some uncertainty to our conceptual hydrogeological understanding, because there is an unknown proportion of groundwater that may exit the groundwater catchment for the lakes as throughflow to the west.

Figure 5 shows a generalised conceptual cross section from the Tararua Range to the coast through Lake Horowhenua, illustrating the groundwater flow pattern described above.

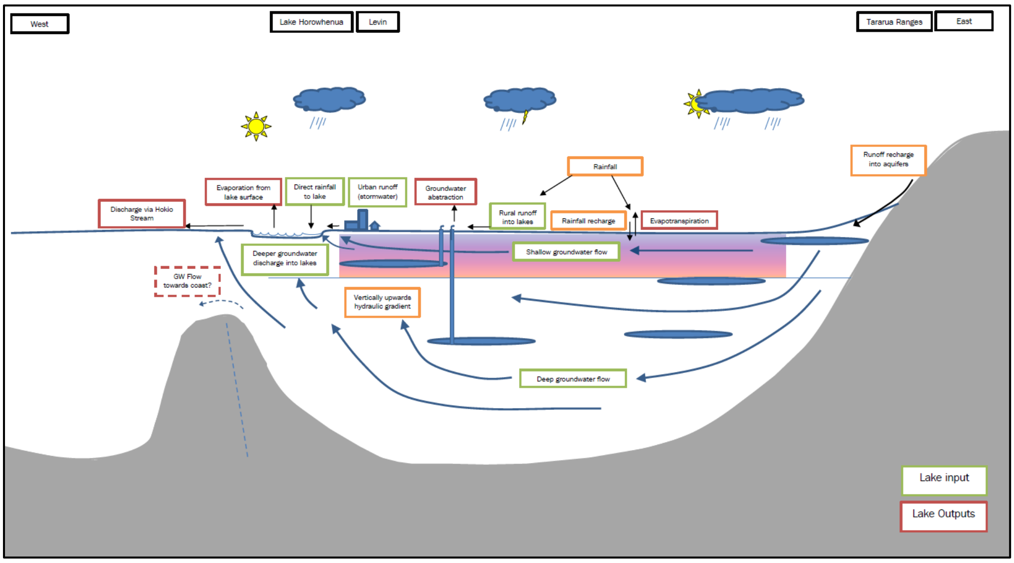

Figure 5: Conceptual cross section (blue ovals represent silty lenses within the strata)

2.2.2 Aquifer Properties

Available aquifer test data indicate that there are some general trends regarding the relationship between aquifer transmissivity and lithology. The most transmissive wells in the area generally abstract from Holocene gravel deposits, such as those near the Ōhau River, although in some cases the aquifer test analysis used to determine the transmissivity values does not accurately account for stream depletion effects, resulting in overestimates of transmissivity.

Wells that abstract from the older alluvial deposits east of Lake Horowhenua indicate that these deposits are less transmissive than the Holocene alluvial deposits, but generally still have a moderate to high transmissivity. The wells that abstract from the Pleistocene marine sands, and from the Holocene dune sands between the lakes and the coast indicate that these deposits are of moderate transmissivity.

Figure 6 shows the distribution of transmissivity in bores in the area.

Figure 6: Map showing the transmissivity of bores in the area

2.2.3 Groundwater Levels

Groundwater levels are monitored at a variety of locations throughout the area, The majority of the sites are monitored at a monthly interval, but there are three sites where continuous measurements are made (Kuku Beach, Butlers and Waitere).

Most of the bores are less than 40 m deep, with a few bores that extend beyond that depth (Figure 7).

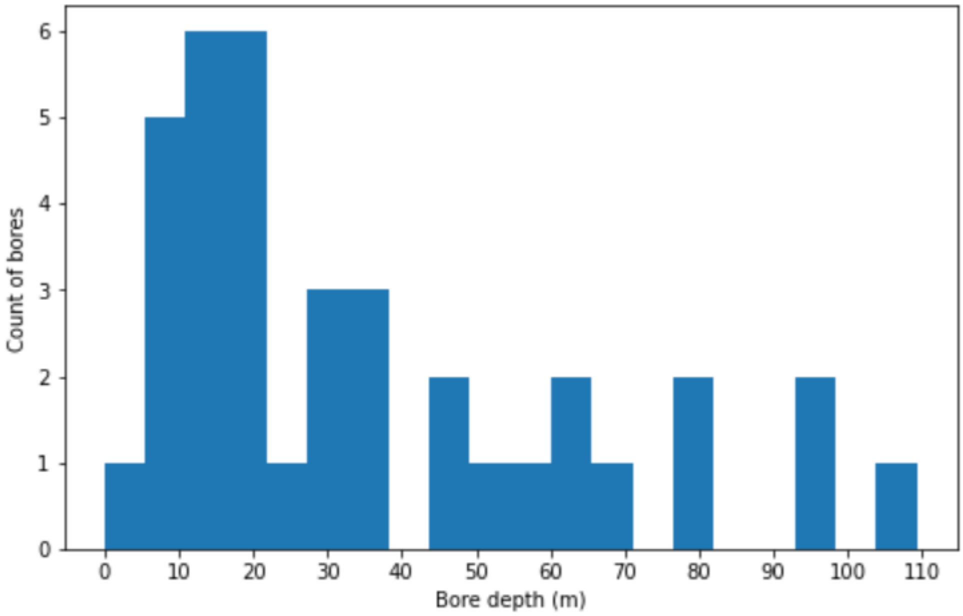

Figure 7: Histogram of bore depths

Groundwater levels are variable across the area, with deeper groundwater levels (in terms of depth below ground surface) typically occurring in bores located closer to the Tararua Ranges and shallower groundwater levels generally occurring closer to the coast. However, shallow groundwater levels are also observed in bores located close to Lake Horowhenua, and also in bores located close to the Ōhau River. A map showing the location of the monitoring bores in the area together with the median depth to groundwater is shown in Figure 8.

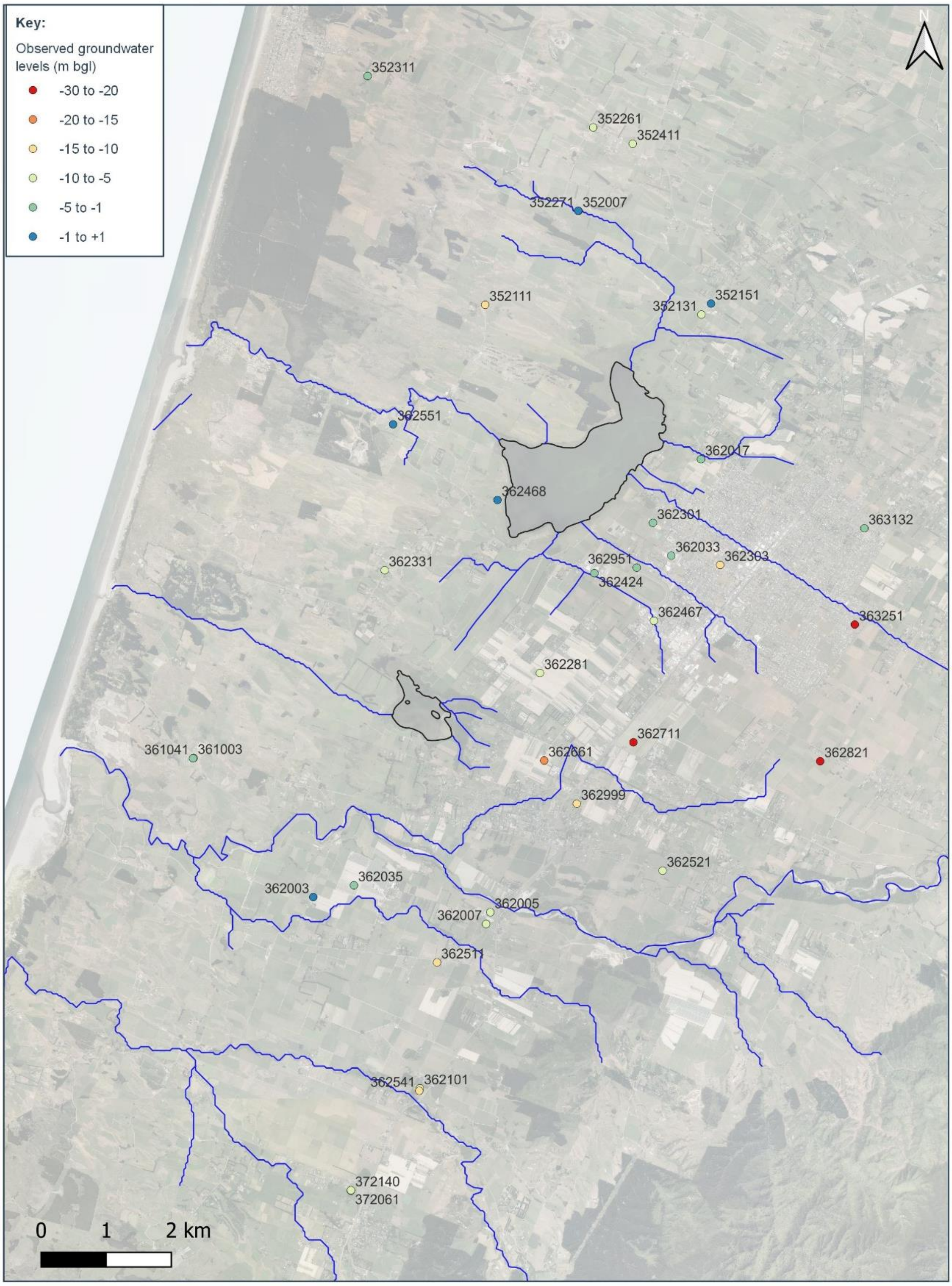

Figure 8: Location of groundwater monitoring bores and observed median depth to water

Groundwater level hydrographs are available for all the bores shown in Figure 7, although the length of the timeseries available for each bore varies. However, typical long term groundwater levels for bores in the area show around 2 to 3 m of seasonal variation, and long term trends do not appear to be present in the data. An example of groundwater level timeseries are provided for two bores in Figure 9:

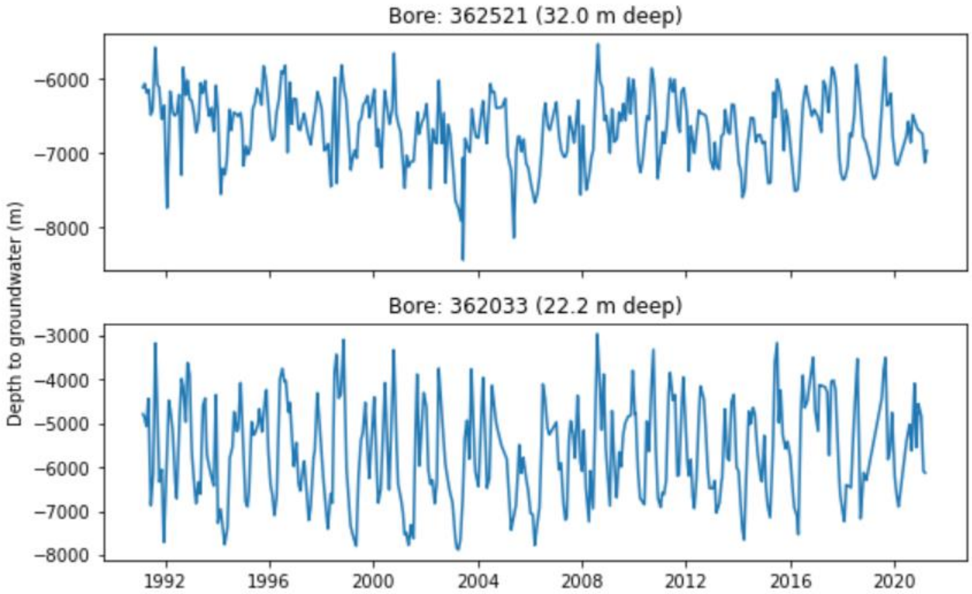

Figure 9: Typical groundwater level timeseries

2.3 Groundwater – Surface Water Interaction

2.3.1 Ōhau River

There is considerable groundwater and surface water interaction in the area, particularly between the Ōhau River and underlying groundwater, as well as between Lake Horowhenua and local groundwater. Additional groundwater and surface water interaction occurs further south in the Manakau and Waikawa catchments, but given the focus of this report on Lake Horowhenua, that is not described here.

Table 1 presents a summary of available flow gauging data along the Ōhau River from the point where it exits the Tararua Range to the most downstream gauging site at Haines Ford.

Table 1: Summary of Ōhau River flow recorder data

River/Stream	Gauging Site	Median Flow L/s[1]	Maximum Flow L/s[1]	Number of measurements	Period of Measurements
Ōhau River	Rongomatane	4,063	110,954	3,578	July 1978 – May 2021
Ōhau River	Haines Ford	5,432	366,269	1,960	Dec 2015 – May 2021

Notes:

1. As mean daily flow.

A gain in flow can occur where groundwater discharges to a surface water way or a loss in surface water flow can occur where surface water seeps through the stream bed into groundwater where there is a downward hydraulic gradient and the stream bed is sufficiently permeable.

Flow gauging data from surveys undertaken along the length of a river can be used to determine whether a particular reach of the river gains or losses. Using the available flow gauging data and previous literature, a plot showing the main gaining and losing reaches of the Ōhau River is shown in Figure 10.

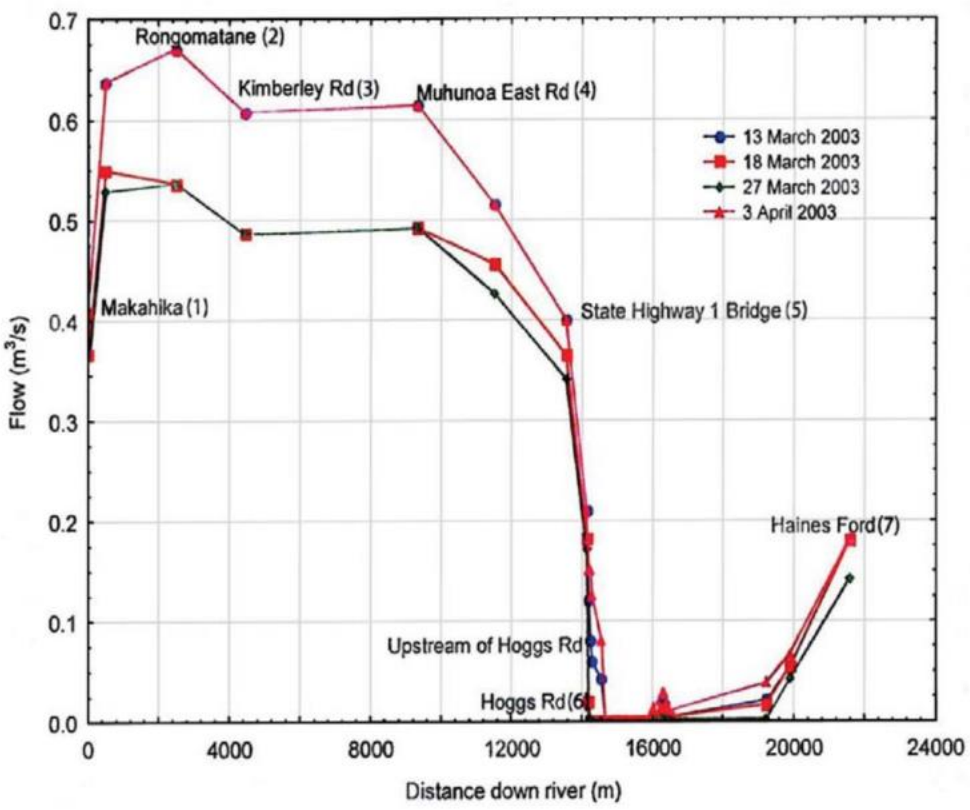

Figure 10: Ōhau River gaining and losing reaches

According to that data and the data shown in Table 1, the major losing reaches on the Ōhau River occur where the river exits the Tararua Ranges onto the alluvial plains and through the middle reaches of the river across the plains to approximately Hoggs Road. The lower section of the Ōhau River, downstream of Haines Ford is a gaining reach, which is implies that groundwater discharges into the river in that area. Based on concurrent low flow surveys, the total loss along the Ōhau River has been measured as around 600 L/s between the Rongomatane monitoring site and Hoggs Road. Downstream of Hoggs Road, the river gained around 200 L/s at the time of the low flow survey.

These estimated losses are important because the Ōhau River represents an important part of the water balance for the catchment and is likely to represent a source of water to Lake Horowhenua, discussed below.

2.3.2 Lake Horowhenua

Figure 11 shows the main surface water inflows to Lake Horowhenua and Table 2 summarises the flow data available for those sites. Lake Horowhenua has a single outlet, via Hokio Stream and lake levels are controlled by a weir at the Hokio Stream outlet.

Figure 11: Lake Horowhenua surface water inflows and outflows

Table 2: Summary of flow gauging data

Gauging Site	Median Flow (L/s)[1]	Maximum Flow (L/s)[1]	Number of measurements	Date Range
Arawhata Drain at Hokio Beach Road	217	2,654	1,365	July 2017 – May 2021
Lake Horowhenua inflow at Lindsay Road	48	852	515	Oct 2019 – May 2021
Patiki Stream at Kawiu Road	38.5	661	545	Oct 2019 – May 2021
Hokio at Lake Horowhenua	906	10,403	2,839	May 2013 – May 2021

Notes:
1. *As mean daily flow.*

A plot showing the long term surface water flow in the Arawhata Stream at Hokio Beach Road (just upstream of its discharge point into the lake) is shown in Figure 12. Flows in the Arawhata vary from around 100 L/s to more than 1,000 L/s, with a median flow of around 200 L/s. Seasonal effects in the flow rate are clearly evident in the plot with typically higher flows in winter and lower flows in summer, corresponding to times of higher and lower groundwater levels. This implies that flows in the Arawhata Stream are dominantly derived from groundwater seepage into the stream, with limited contributions from surface water runoff.

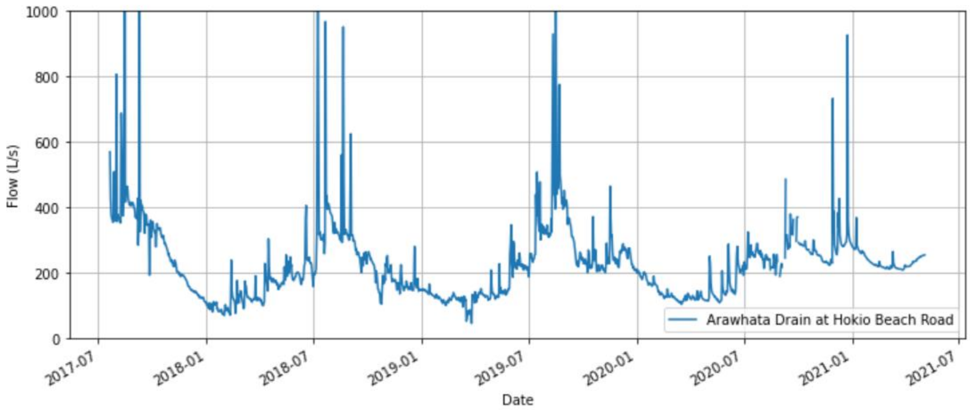

Figure 12: Flows in the Arawhata Drain at Hokio Beach Road

Similar seasonal patterns are evident in data from another recorder site in the inflow at Lindsay Road. However, the data from the Patiki Stream recorder at Kawiu Road appears to show the opposite seasonal pattern, with lower flows in winter (although the record is only available across one season) (Figure 13). Both these sites show a more 'flashy' response to rainfall events with rapid increases in in flow compared to flows in the Arawhata Stream. Both these sites also show a clear baseflow component, but it is evident that these catchments behave differently to the Arawhata and flows in these streams may be less dominated by groundwater seepage.

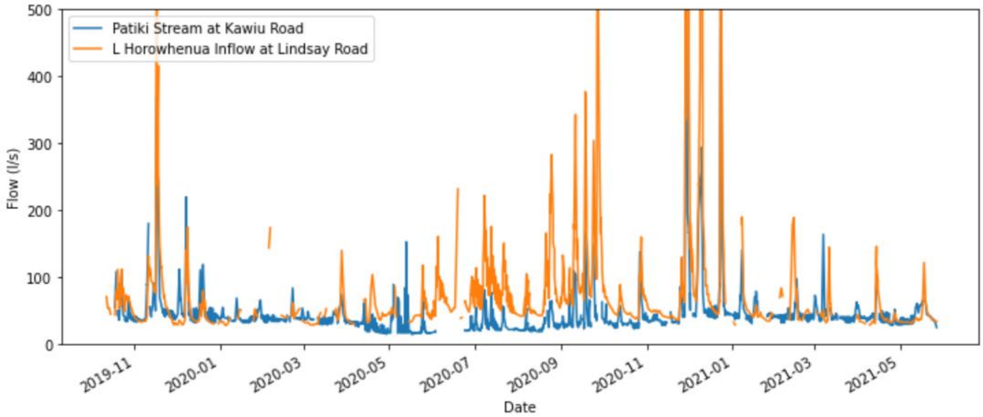

Figure 13: Flows in Patiki Stream and at Lindsay Road

Flows in Hokio Stream at the Lake Horowhenua outlet are shown in Figure 14, together with the flows in the Arawhata Stream. A seasonal pattern is to some extent evident, although higher flows also occur in summer as well as winter. Flows in the Hokio Stream at Lake Horowhenua are influenced by the presence of the weir across the outlet from the lake, which will affect the relationship between groundwater levels and flows in the stream. However, the general seasonal pattern is likely to reflect some groundwater input to the lake and some relationship between the flows in the Hokio Stream and in the Arawhata Stream is clear where data is available. Median flows in Hokio Stream are around 800-900 L/s, which is notably higher than the sum of measured surface water flows into the lake (as also indicated by the data in Table 2).

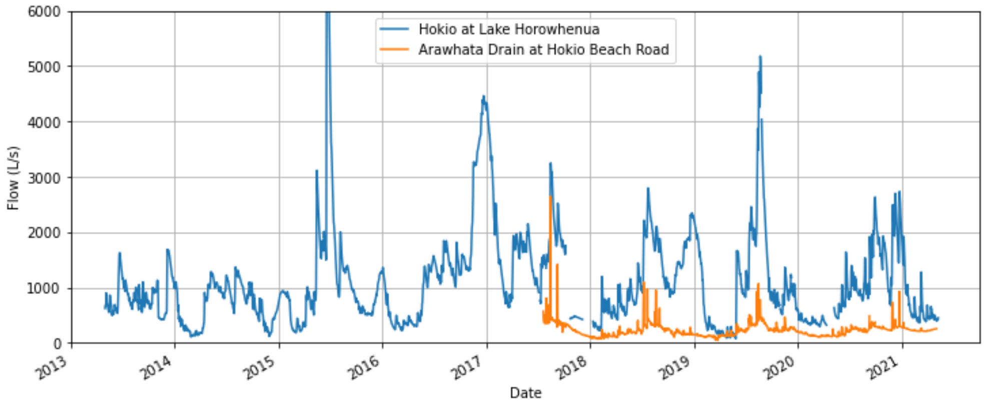

Figure 14: Flows in Hokio Stream at Lake Horowhenua

2.4 Lake Horowhenua Water Balance

A summary of the components of the Lake Horowhenua water balance is provided in Table 3. There are uncertainties within the values provided in Table 3, particularly with respect to groundwater inputs to the lake which cannot be measured directly. In Table 3, the groundwater component is calculated as the difference between the sum of inflows and the outflow from Hokio Stream. Surface water inflows/outflows are based on the median value of measured flows.

Table 3: Lake Horowhenua estimated water balance (L/s)

Component	Inflows	Outflows
Rainfall	107	
Arawhata Stream flow in	217	
Patiki Stream flow in	38.5	
Inflow at Lindsay Road	48	
Queen Street Drain	29[1]	
Heatherlea Swamp at Kawiu Road	12[1]	
Groundwater inflow	531.2[2,3]	
Hokio Stream flow out		906
Evaporation		76.7
Groundwater flow out		?[2]
Total	982.7	982.7

Notes:

1. *Flows in these surface waterways are based on the median of gauging runs between 1975 and 2018*
2. *Calculated as the balance of outflows and gauged inflows. Any groundwater inflow greater than this number would be balanced by an outflow from the western side of the lake into groundwater, currently shown as a "?" in the water balance. Other seeps and any drain discharge into the lake which is not gauged is part of this number. Additional inflows to the streams downstream of the gauging point are also counted as groundwater inflow in Table 3.*
3. *There are some other inflows which are not listed in the table above, including the Makomako Drain, inflows at Bruce Road, and Inflows at Hokio Sand Road. Gauging of these flows amount to a few L/s and their contribution is included in the Groundwater inflow component.*

Based on the water balance for Lake Horowhenua in Table 3, groundwater inflows are likely to make up around 54% of the total water balance on average. Seasonally, the proportion is likely to vary, but it also worth noting that the majority of the flow in the Arawhata Stream is derived from groundwater discharge, in which case the effective dependence of the lake on groundwater discharge is more than 54%. However it is also worth highlighting that in Table 3, not all the gauging locations are directly adjacent to the lake, for example the Patiki Stream and Heatherlea Swamp at Kawiu Road are both gauged upstream of the lake. Additional groundwater inflows to the stream may occur downstream of the gauging locations, but in Table 3, these are counted as part of the 'direct groundwater inflow' water balance component.

3.0 Model Structure And Design

The groundwater model developed for this project seeks to replicate the general conceptual setting discussed above and the following sections describe how the model represents the key conceptual features and understanding of the Horowhenua groundwater system.

3.1 Model Boundary

A map showing the model boundary is provided in Figure 15. The model is a roughly rectangular shape, orientated so the south-eastern boundary is parallel to the coast. The four outer boundaries were based on the following information.

- The eastern, inland boundary represents the geological boundary between quaternary gravels that make up the plains and basement strata that make up the foothills of the Tararua Range. This boundary is represented as a no flow boundary.
- The western boundary is the coast, although the model extends offshore to a distance of around 1 km from the coast. This extension beyond the coastal boundary was considered necessary to represent the expected offshore discharge from deeper strata. The coastal boundary is represented by a general head boundary in all layers.
- The northern boundary is approximately parallel to and extends north- of the Manawatu River. The model boundary line is approximately perpendicular to expected groundwater contours such that groundwater flow across the boundary is expected to be limited. The northern extent of the model therefore expected to help limit boundary effects that could occur if the model boundary were set along the line of the river, particularly in shallower strata.
- The southern model boundary is coincident with the southern boundary of the Horizons Region and follows the catchment boundary. In general, limited groundwater flow is expected across this area and this boundary is set as a no flow boundary.

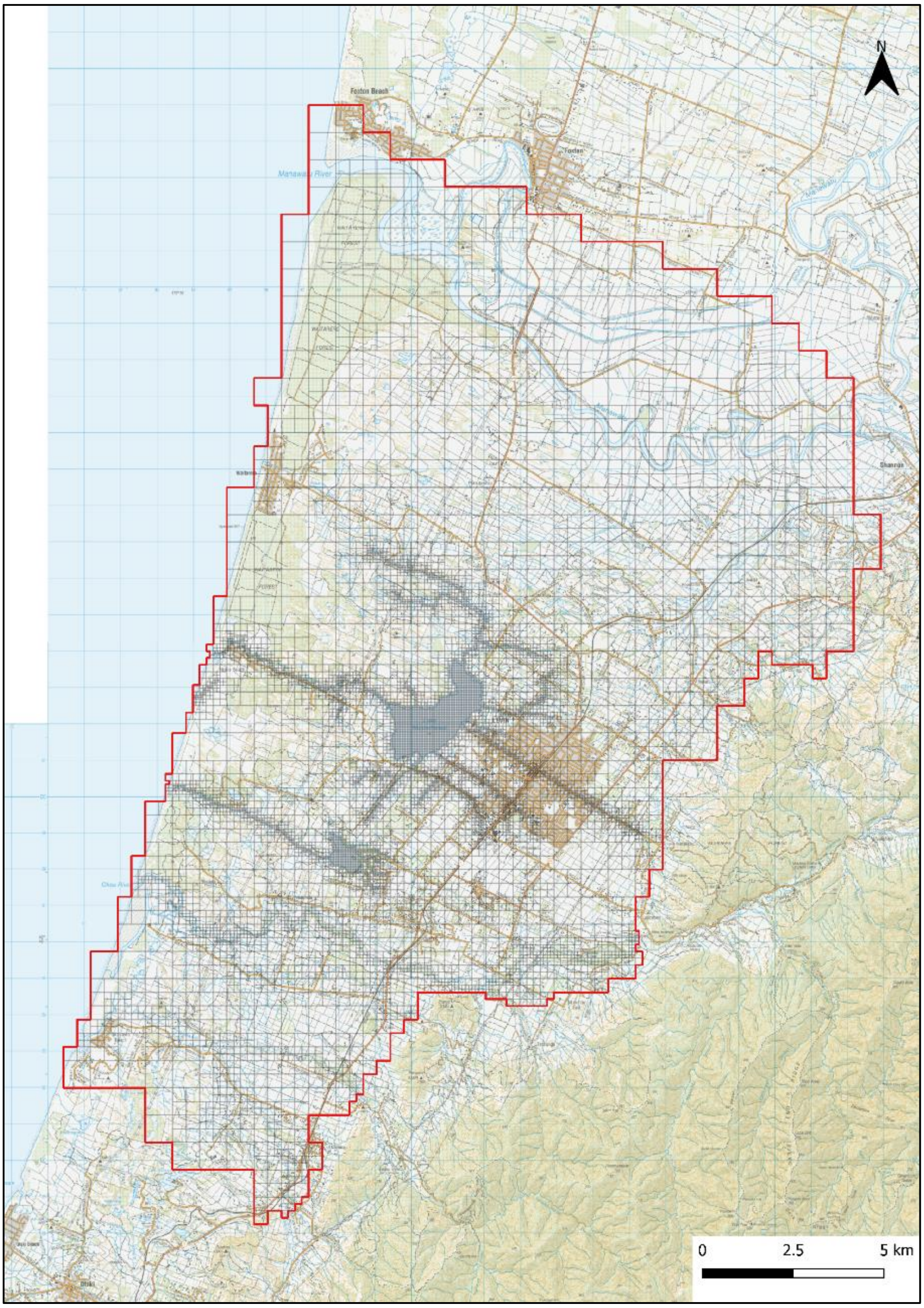

Figure 15: Map showing the model grid and boundary (red)

3.2 Model Layers

The groundwater system in the Horowhenua can be considered in general to behave as a single anisotropic aquifer. This system is represented in this model through seven layers, to allow for some variation in hydrogeological properties at different depths, with the top layer 10 m thick and deeper layers set to 20 m thick, except for layers 5, 6 and 7, which are 40 m thick. The total model thickness is therefore 190 m. While deeper alluvial deposits are expected to be present, this thickness is considered sufficient to represent the majority of groundwater flow in the plains that is likely to be impacted via land use activities and covers the depth of almost all abstraction bores in the area.

The surface elevation of the model is based on the LiDAR data for the area.

3.3 Model Discretization

Spatially, the model is discretised using an unstructured quadtree grid, shown in Figure 15. An unstructured grid allows coarser cells sizes (up to 750 m) in areas away from points of interest (for example around eastern model boundary) but much finer grid sizes in areas of interest, for example around Lake Horowhenua and along key river reaches such as the Ōhau River. Unstructured grids provide a balance between ensuring sufficient detail for the purposes of the model and allowing reasonable model run times so that model calibration was not unduly constrained.

The model was run using the USGS MODFLOW 6 code, which enables the use of an unstructured grid.

3.4 Temporal Settings

The model has been set-up as a steady state model, with a single stress period. A transient model would provide increased certainty with respect to the model parameters (because it can be calibrated against more detailed information) however a transient model is considerably more time consuming to develop and was outside the scope of the purpose of this initial modelling work. A steady state model is expected to be sufficient at this point in time, and further development can occur. The model could be adapted to run as a transient model later if required using the steady state model as a basis for different transient scenarios, with further calibration.

3.5 Model Recharge

Recharge was modelled using a simple lumped parameter model that approximates water movement in the vadose zone called LUMPREM2 (John Doherty, Watermark Numerical Computing, 2021). This model takes a simple bucket-based approach to simulating recharge and uses crop factor, soil, rainfall, and evapotranspiration inputs to calculates total recharge to groundwater over specific time periods. For this assessment, average daily recharge was calculated over the period 1 January 1972 – 1 June 2021, based on available climate data, and used as a steady-state input into MODFLOW.

Rainfall and evapotranspiration input data was obtained from the virtual climate station network (VCSN) provided by NIWA. The data was checked against rainfall and evapotranspiration from actual climate stations in the area and considered suitable for use.

Crop factors were derived from AgriBase land use classifications (provided by Horizons). Hydraulic conductivity and profile available water (PAW) values were estimated using the fundamental soils layer (FSL, Landcare Research). Irrigated land areas (2020) were obtained from Aqualinc Research Limited. All irrigated areas were assumed to begin irrigation when the soil moisture store fell below 50% of capacity. Additional details on LUMPREM2 model inputs are provided in Appendix A.

The average daily recharge results of running the LUMPREM2 model on each grid cell are shown in **Error! Reference source not found.**6. Most of the model area h as average recharge values ranging between 1 and 2 mm/day, while irrigated areas of high permeability have recharge values between 5 and 10 mm/day.

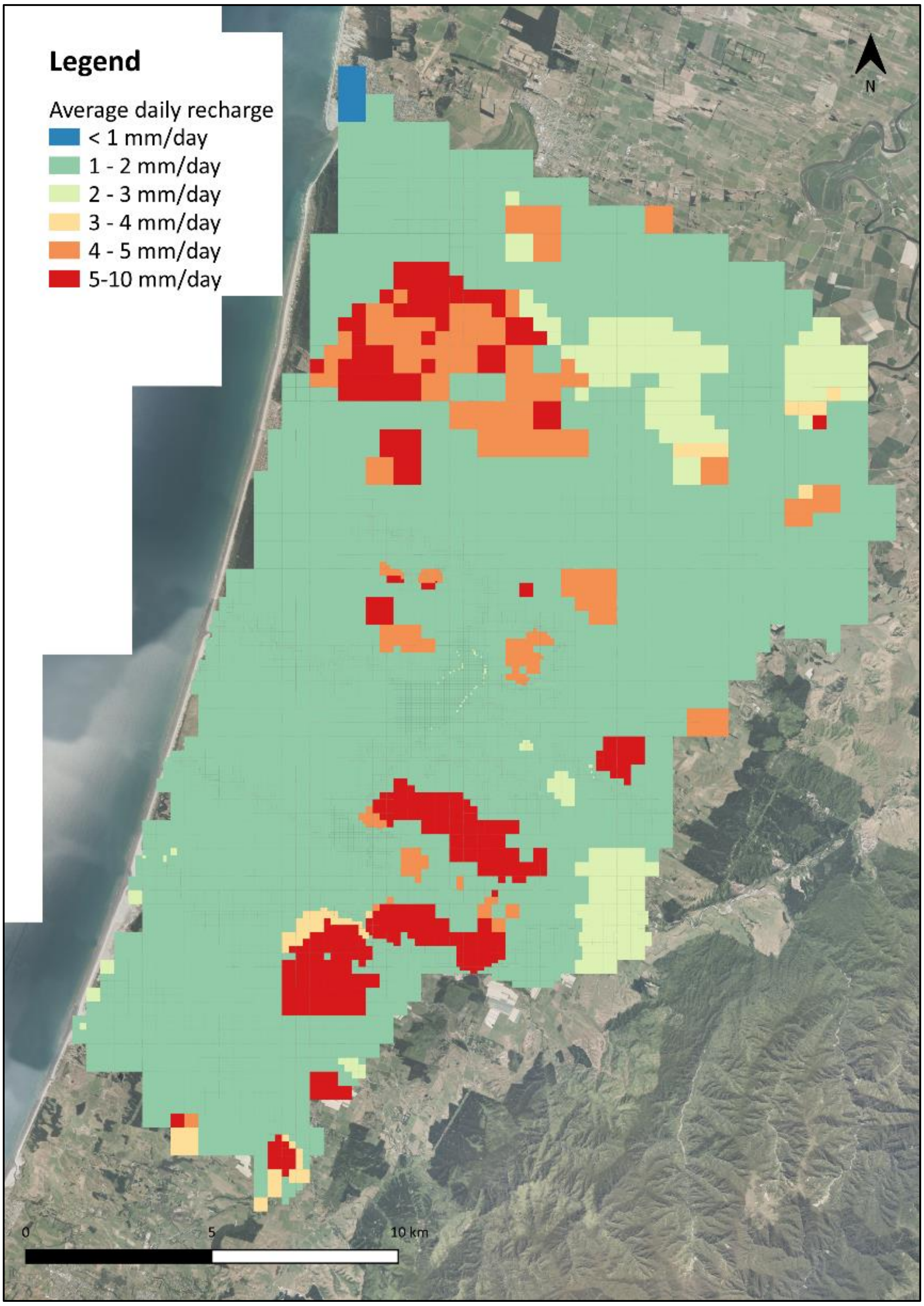

Figure 16: Simulated recharge to the model

3.6 Model Boundary Conditions

3.6.1 Surface Water Boundaries

A number of boundary conditions were defined in the model to represent surface water features including the Ōhau River, the Manakau and Waikawa Rivers, and the Manawatu River, as well as the streams around Lakes Horowhenua and Waiwiri. A map showing the location of surface water boundaries in the model is provided in Figure 17. Lakes Horowhenua and Waiwiri were explicitly represented in the model as lakes.

Figure 17: Surface water boundaries: The coastal general head boundary is red and stream cells are blue. The two lakes (Horowhenua and Waiwiri) can be seen in the approximate centre of the model area.

All stream and rivers were simulated using the MODFLOW surface water routing package (SFR). The stream package is more complex than the river package because it accounts for stream flow volumes and allows water to be routed down a defined stream network. It also allows surface water takes to be simulated as diversions from the stream network. Losses from the stream network to groundwater are constrained by the available flow in the stream (i.e. no losses occur if there is no flow in the stream). The stream package is therefore much better suited to model the pattern of flows along the major rivers.

Flows in the modelled rivers were added to the most upstream reach based on observed flows at respective recorder locations. The main river where flows were added is the Ōhau River, where there are substantial flows in the river at the point where it enters the model domain and the input flow to the Ōhau River is based on the median flow from the Rongomatane gauging station. The Manawatu River also has substantial flows where it enters the model domain, although the Manawatu River is not thought to lose substantial flow to groundwater in the reach that coincides with the model domain.

Stream flows in the Ōhau River were calibrated to observed losses and gains from the river based on gauging runs. These appear to indicate that there is around 600 L/s of flow loss between the Rongomatane gauging station and Hoggs Road, with around 250 L/s of flow gain between Hoggs Road and Haines Ford. The model was not calibrated to flows along the Manawatu River as these were not expected to have substantial impacts on the Lake Horowhenua area.

Stage elevations were defined for the rivers based on LiDAR data, using the minimum elevation in a cell. Detailed data on the stream cross sections are not generally available in the area and the stage was set as a constant in the model, which is reasonable for a steady state model. However, if the model is used as a transient model, dynamic calculation of stream stage will likely be required.

In addition to the streams around Lake Horowhenua, additional drains were added into the model around the Arawhata Drain area and to the south west of Lake Horowhenua to control groundwater levels in those areas. The flows in these modelled drain cells were transferred into the stream cells representing the Arawhata Drain and into Lake Horowhenua (via the MODFLOW 6 'MOVER" package). Their effects are therefore included in the lake water balance.

Lake Horowhenua and Waiwiri were represented using the MODFLOW lake ('LAK') package, which allows inflows and outflows (based on the calculated lake stage) from the lakes to be explicitly modelled, including surface water inflows from the streams represented in the model (via the MODFLOW 6 mover package). This approach allows the water budget for the lakes to be modelled more accurately.

3.6.2 Groundwater Abstraction

Groundwater abstractions were included in the model at the locations corresponding to currently consented groundwater abstraction bores. Actual use data was available for some bores in the area, and this data was used to set the abstraction rates where it was available, based on the average abstraction rate.

Where actual use data was not available, the use for a particular bore was estimated based on the use from other consents for a similar purpose i.e. the average use (as a proportion of the annual volume) was calculated for agricultural consents, industrial consents and others, and this proportion was applied to consents where no actual use data was available.

4.0 Model Calibration

4.1 Model Parameterisation

4.1.1 Hydraulic Conductivity

There are a number of different approaches to estimating the hydraulic conductivity across a model area, including:

- defining zones where values of hydraulic conductivity are typically set to a single value, or
- using pilot points where the hydraulic conductivity at those points is varied during the model calibration process. The point estimates are then spatially interpolated to generate a hydraulic conductivity field across the model area.

A pilot point approach was employed for the Horowhenua model and a plot showing the location of pilot points used to generate the hydraulic conductivity field is shown in Figure 18. The main benefit of using pilot points is that they do not require artificial zone boundaries to be set within the model area which are not generally present, or geologically defined, Horowhenua area. Pilot points can also allow for a smoother variation in the hydraulic conductivity field compared to a zonal approach. The initial values for the pilot points were based on the results of aquifer tests in the general area surrounding each point and where no data was available, an initial value of 20 m/d was used. A plot of the calibrated hydraulic conductivity field for each model layer is shown in Figure 19. Note that the same set of pilot points was used for each model layer.

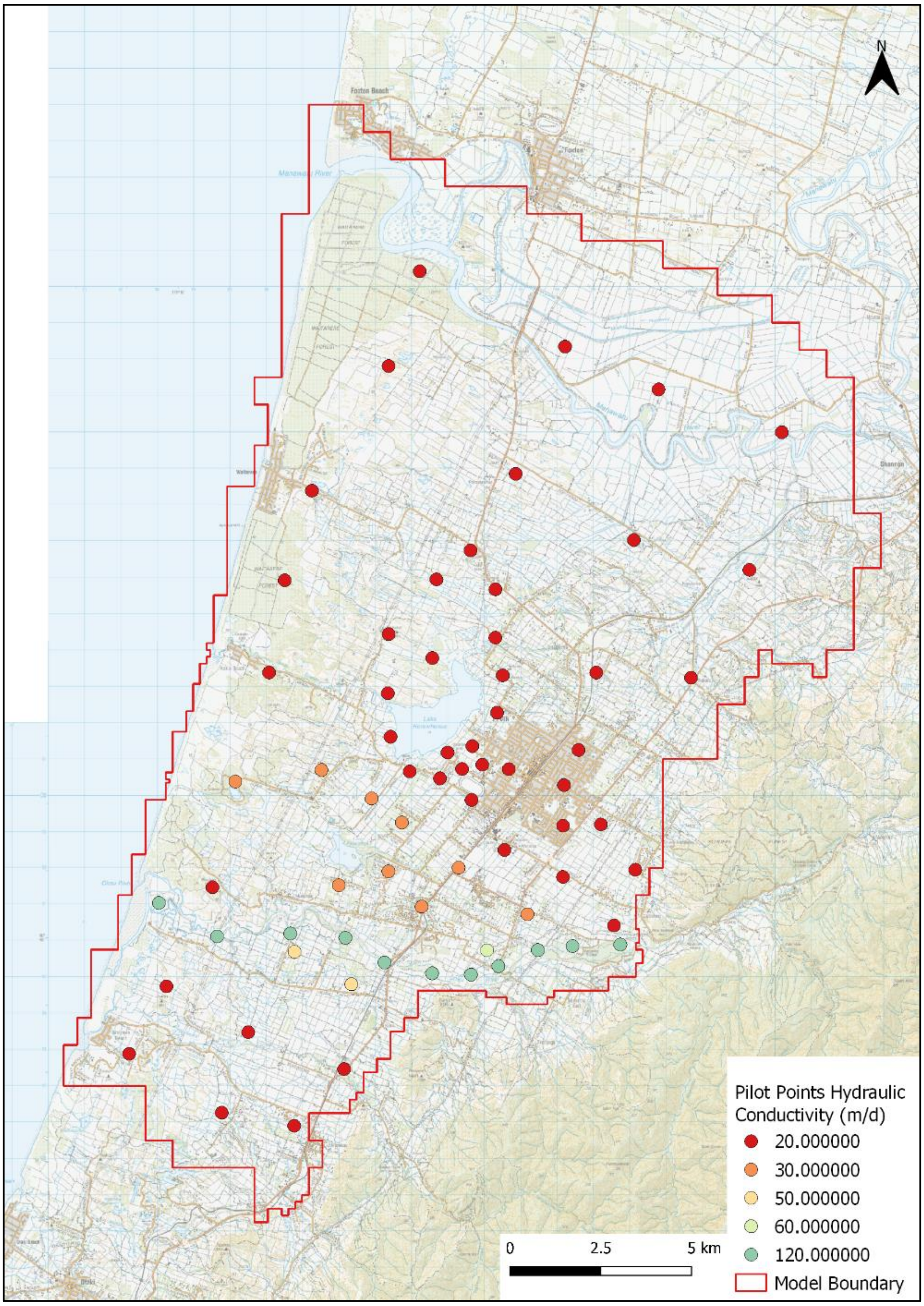

Figure 18: Pilot point locations with initial values for hydraulic conductivity.

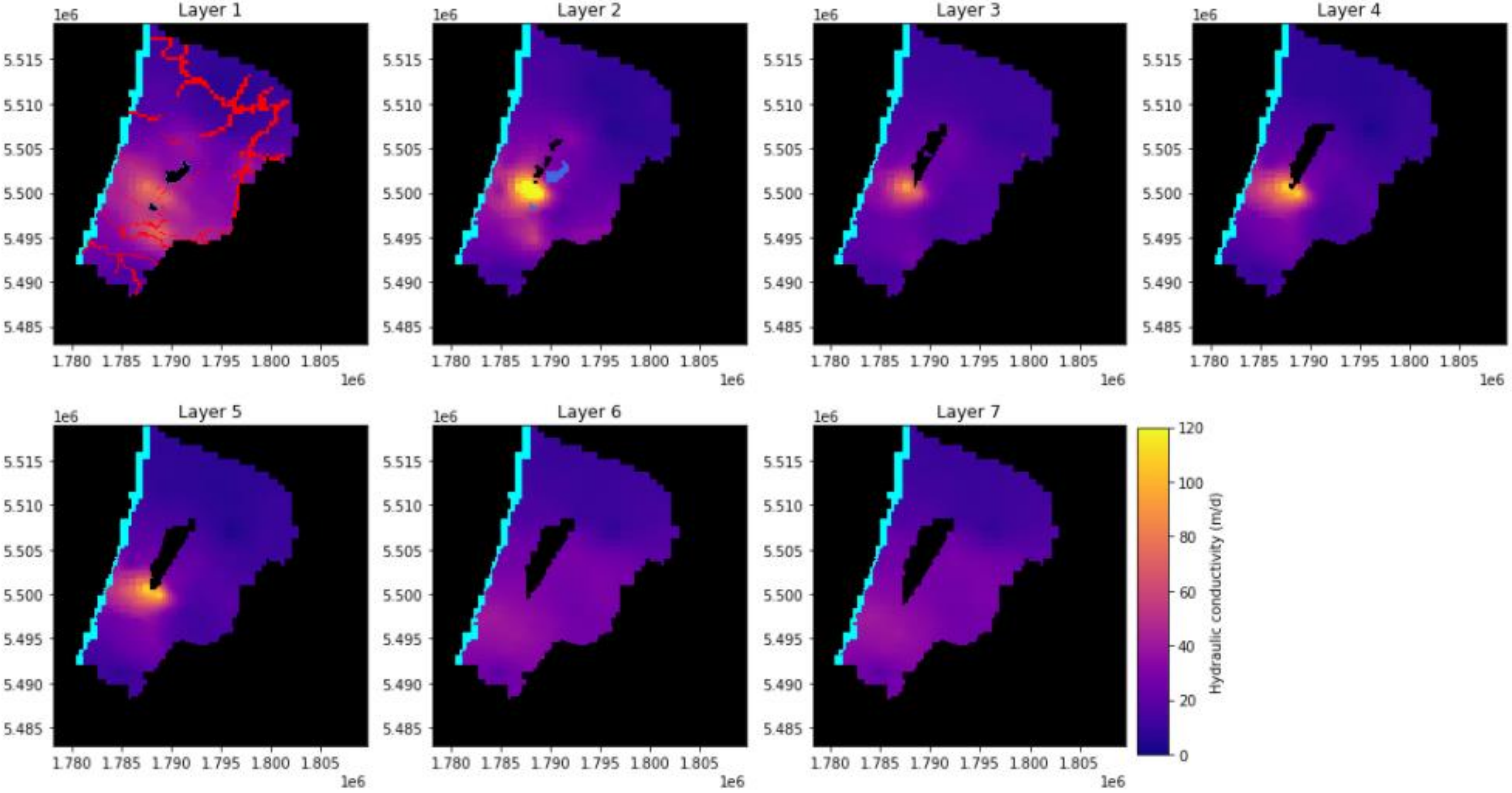

Figure 19: Calibrated hydraulic conductivity fields (the central black zone in each model layer represents the Poroutawhao basement high)

Note that hydraulic conductivity values were varied separately for each model layer. It was originally intended that each layer would have the same hydraulic conductivity distribution, but it was found that this approach made calibration very difficult, and therefore conductivity within each layer was allowed to vary separately. This has resulted in widely varying hydraulic conductivities between each layer and further model refinement could simplify the calibrated distribution.

However, generally the distribution of hydraulic conductivity shown in Figure 19 fits with the conceptual model and observed data, which indicate generally lower values of hydraulic conductivity to the north of Lake Horowhenua, compared to south of the lake, together with an area of higher hydraulic conductivity between Lakes Horowhenua and Waiwiri. These higher values were found to be necessary to achieve reasonable heads around Lake Horowhenua, but we note that this is likely to have been strongly influenced by the shape of the Poroutawhao basement high, which is not particularly well constrained.

The hydraulic conductivity field shown in Figure 19 represents a set of hydraulic conductivity values that fit the observed groundwater levels, surface water flows and lake levels. This does not mean that it is the 'true' distribution of hydraulic conductivity in the area.

Tikhonov regularisation was also during the calibration process with PEST employed so that the preferred difference between adjacent pilot point values was set to 0, unless the model could not be calibrated without the difference.

4.1.2 Boundary Conductance

The conductance of the different model boundaries was also varied during model calibration and a plot showing the final values of conductance as applied to the model streams and general head boundaries is shown in Figure 20.

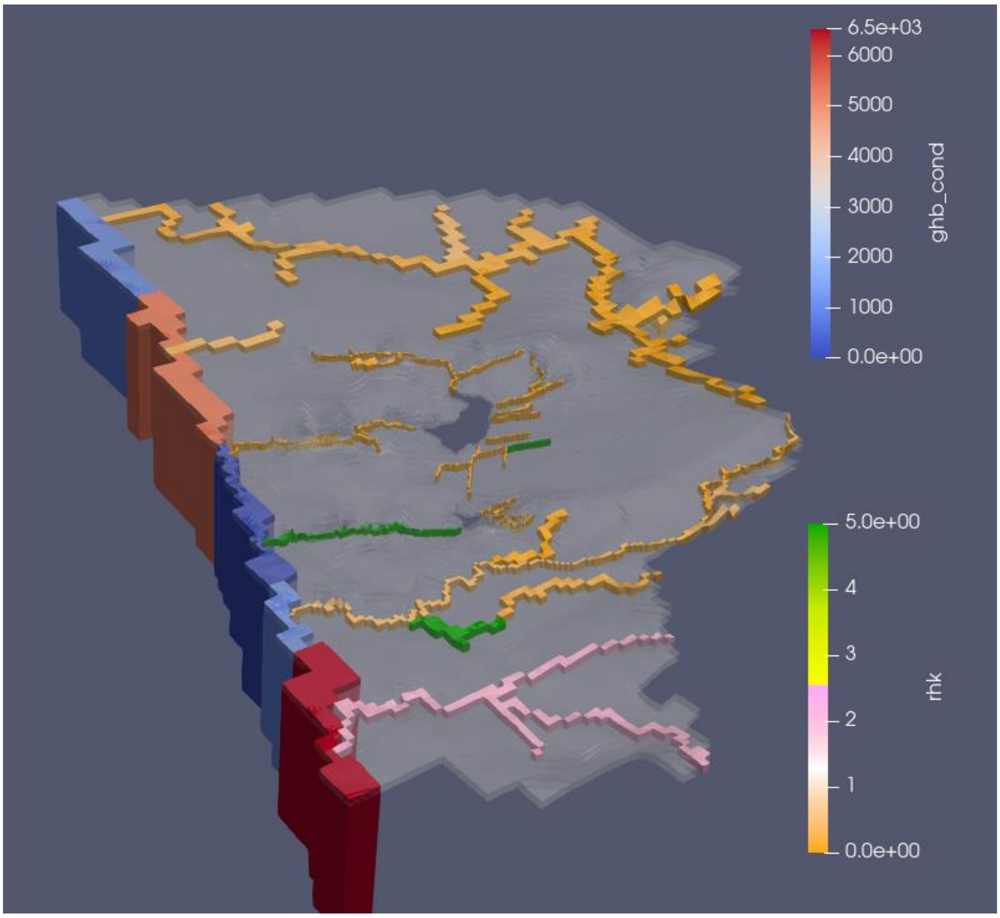

Figure 20: Boundary conductances (ghb = general head boundaries, rhk = river hydraulic conductivity)

4.2 Model Calibration Targets

A number of numeric targets were employed during calibration of the model pertaining to both groundwater levels observed in bores and flow rates in surface waterways. Table 4 summarises the model calibration targets.

Groundwater level calibration targets are based on the median observed groundwater level in bores with a timeseries of data available. Some bores were excluded from this dataset where they represented shallow bores in model layer 1 (for example bores located in the dune sands to the west of the lakes). These model layers typically fell dry (i.e. modelled groundwater levels were below the base of the modelled layer) and the model was not able to represent groundwater levels at those points. Selection of calibration points was also focussed towards bores around Lake Horowhenua, as that is a key focus of this modelling exercise.

Surface water flow calibration data included data from flow recorders around Lake Horowhenua and the Ōhau River, where the median flow rates were used as calibration guide. In addition, data from gauging surveys along the Ōhau River was used to provide calibration guides regarding flow losses along the river (although this was not given a high weighting), as well as data from gauging surveys around Lake Horowhenua.

Table 4: Calibration targets

Calibration Point	Type	Target
GW discharge to Lake Horowhenua	Flow (L/s)	-503.472
Arawhata at Hokio Beach Road	Flow (L/s)	-217
Culvert d/s of Queen St	Flow (L/s)	-5
Heatherlea Swamp inflow	Flow (L/s)	-12
Hokio Stream at Lake Horowhenua	Flow (L/s)	-906
Inflow at Lindsay Road	Flow (L/s)	-48
Makomako Drain	Flow (L/s)	0
Ōhau at Mahunoa Road	Flow (L/s)	-3,963
Ōhau at SH1	Flow (L/s)	-3,863
Ōhau at Hoggs Road	Flow (L/s)	-3,813
Ōhau at Soldier Road1	Flow (L/s)	-3,463
Ōhau at Soldiers Road2	Flow (L/s)	-3,363
Ōhau at Haines Ford	Flow (L/s)	-3,713
Patiki Stream at Kawiu Rd	Flow (L/s)	-38.5
Queen St Drain	Flow (L/s)	-29
Waiwiri at Beach	Flow (L/s)	-184.5
Waiwiri at Lake Waiwiri	Flow (L/s)	-17.5
352007 (Layer 2)	Heads (m above sea level)	13.5
352131 (Layer 5)	Heads (m above sea level)	14.6
352151 (Layer 3)	Heads (m above sea level)	14.8
352261 (Layer 2)	Heads (m above sea level)	18.4
352311 (Layer 5)	Heads (m above sea level)	6.2
361003 (Layer 1)	Heads (m above sea level)	5.7
361041 (Layer 3)	Heads (m above sea level)	5.5

Table 4: Calibration targets

Calibration Point	Type	Target
362003 (Layer 2)	Heads (m above sea level)	10.0
362005 (Layer 1)	Heads (m above sea level)	20.0
362007 (Layer 1)	Heads (m above sea level)	19.4
362017 (Layer 4)	Heads (m above sea level)	16.0
362033 (Layer 2)	Heads (m above sea level)	16.6
362035 (Layer 2)	Heads (m above sea level)	13.6
362101 (Layer 2)	Heads (m above sea level)	21.6
362281 (Layer 1)	Heads (m above sea level)	14.8
362301 (Layer 4)	Heads (m above sea level)	15.4
362303 (Layer 5)	Heads (m above sea level)	20.9
362331 (Layer 2)	Heads (m above sea level)	11.0
362424 (Layer 2)	Heads (m above sea level)	11.8
362467 (Layer 1)	Heads (m above sea level)	23.1
362468 (Layer 1)	Heads (m above sea level)	9.5
362511 (Layer 2)	Heads (m above sea level)	14.1
362521 (Layer 2)	Heads (m above sea level)	44.8
362541 (Layer 2)	Heads (m above sea level)	27.2
362551 (Layer 3)	Heads (m above sea level)	9.6
362661 (Layer 3)	Heads (m above sea level)	22.3
362711 (Layer 5)	Heads (m above sea level)	19.1
362821 (Layer 4)	Heads (m above sea level)	37.8
362951 (Layer 4)	Heads (m above sea level)	15.9
362999 (Layer 2)	Heads (m above sea level)	33.0
363132 (Layer 1)	Heads (m above sea level)	36.7
363251 (Layer 2)	Heads (m above sea level)	27.0
372061 (Layer 2)	Heads (m above sea level)	21.9
372140 (Layer 2)	Heads (m above sea level)	21.9

5.0 Model Results

Plots showing the model results in terms of groundwater levels and water balances are provided in the following section.

5.1 Overall Model Water Balance

Table 5 illustrates the overall model water balance.

Table 5: Overall model water balance

Component	Inflow (m^3/day) (L/s)	Outflow (m^3/day) (L/s)
Rainfall recharge	808,564.2 (9,358)	
Stream leakage	68,361.69 (791)	538,731.5 (6,235.3)[1]
Lake	0	40,0150 (464)
Abstraction		4,391 (50)
General head boundary		293,652.7 (3,398)
Total	876,925.9	876,925.7

Notes
1. *This includes drain outflows from the model*

The majority of recharge to the modelled groundwater system occurs via rainfall infiltration, with a much smaller proportion of seepage from the rivers, which is predominantly sourced from the Ōhau River, with a lesser proportion of seepage from the other rivers in the model area.

The majority of groundwater discharge is to the modelled rivers and streams, including the Ōhau River, the streams flowing to Lake Horowhenua and the tributaries leading to the Manawatu River. However, groundwater discharge to the coast is also an important part of the water balance. Note that this is largely unmonitored.

5.2 Groundwater Levels

Figure 21 shows plots of the modelled groundwater levels in each model layer. These generally represent the observed pattern of groundwater levels in the area, with a predominant north-westerly flow direction from the Tararua Range towards the coast.

The contours shown for layer 1 are complex, which reflect, in part, the occurrence of dry cells in layer 1 close to the Tararua Range, and also on the western side of the Levin Fault, where modelled groundwater levels in the dune sands are below the base of layer 1.

In both layer 1 and 2, and to a lesser extent, layer 3, the effects of the Ōhau River and other streams such as the Waikawa and Manakau are evident in the shapes of the contours, which is a result of the seepage from, and groundwater discharge to, those surface waterways. The effects of surface waterways are less pronounced in the deeper layers due to the vertical permeability of the strata, which restricts any direct connection between layer 4 to 7 and surface waterways.

The modelled groundwater contours clearly illustrate the effect of modelled seepage from the Ōhau River in its upper reaches. Based on the model, seepage from the Ōhau River is a significant source of groundwater recharge to the Lake Horowhenua area, as well as to Lake Waiwiri.

During the development of the model scope, one question that arose was in regard to any hydraulic connection between Lake Horowehenua and Lake Waiwiri. Both lakes are hydraulically connected to the shallow groundwater system, but based on the results of this groundwater model, no obvious hydraulic gradient is present; indeed the model suggests that there is a slight groundwater divide between the two lakes, although this represents average conditions.

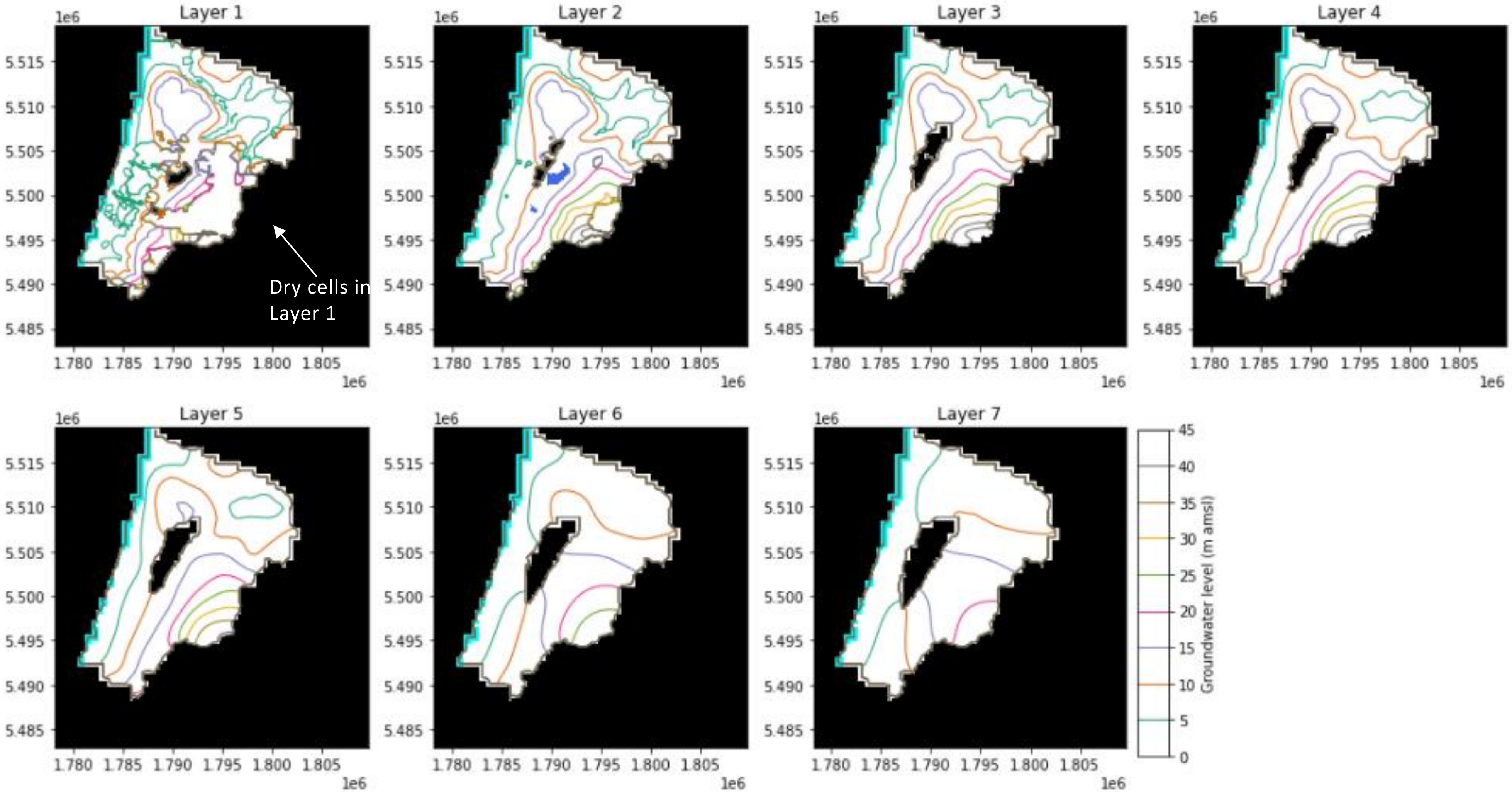

Figure 21: Simulated groundwater levels in each model layer

Figure 22 shows a plot comparing modelled (y axis) and observed groundwater (x axis) levels at each of the 33 groundwater level monitoring points. The red line shows where the points would lie if the modelled and observed groundwater levels matched exactly.

In general, the modelled groundwater levels match the observed groundwater levels, although there are areas where the model both underestimates and overestimates observed groundwater levels. These areas are shown in Figure 23.

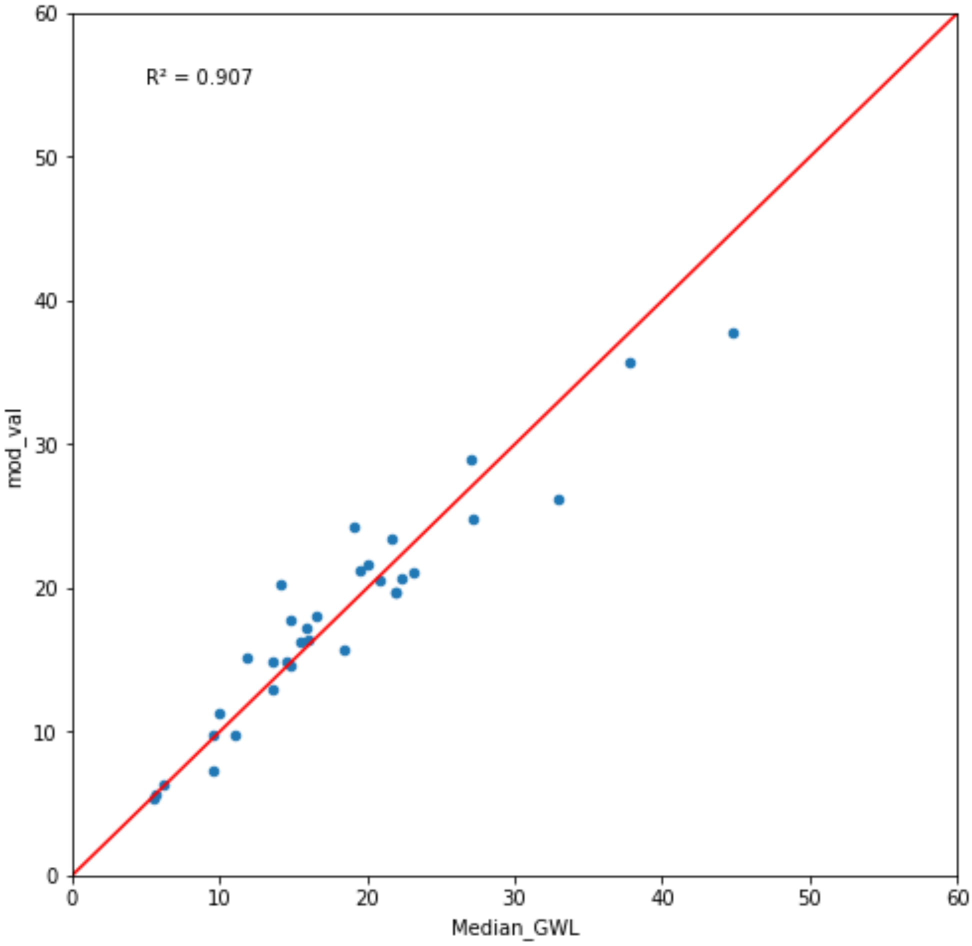

Figure 22: Modelled and observed groundwater levels

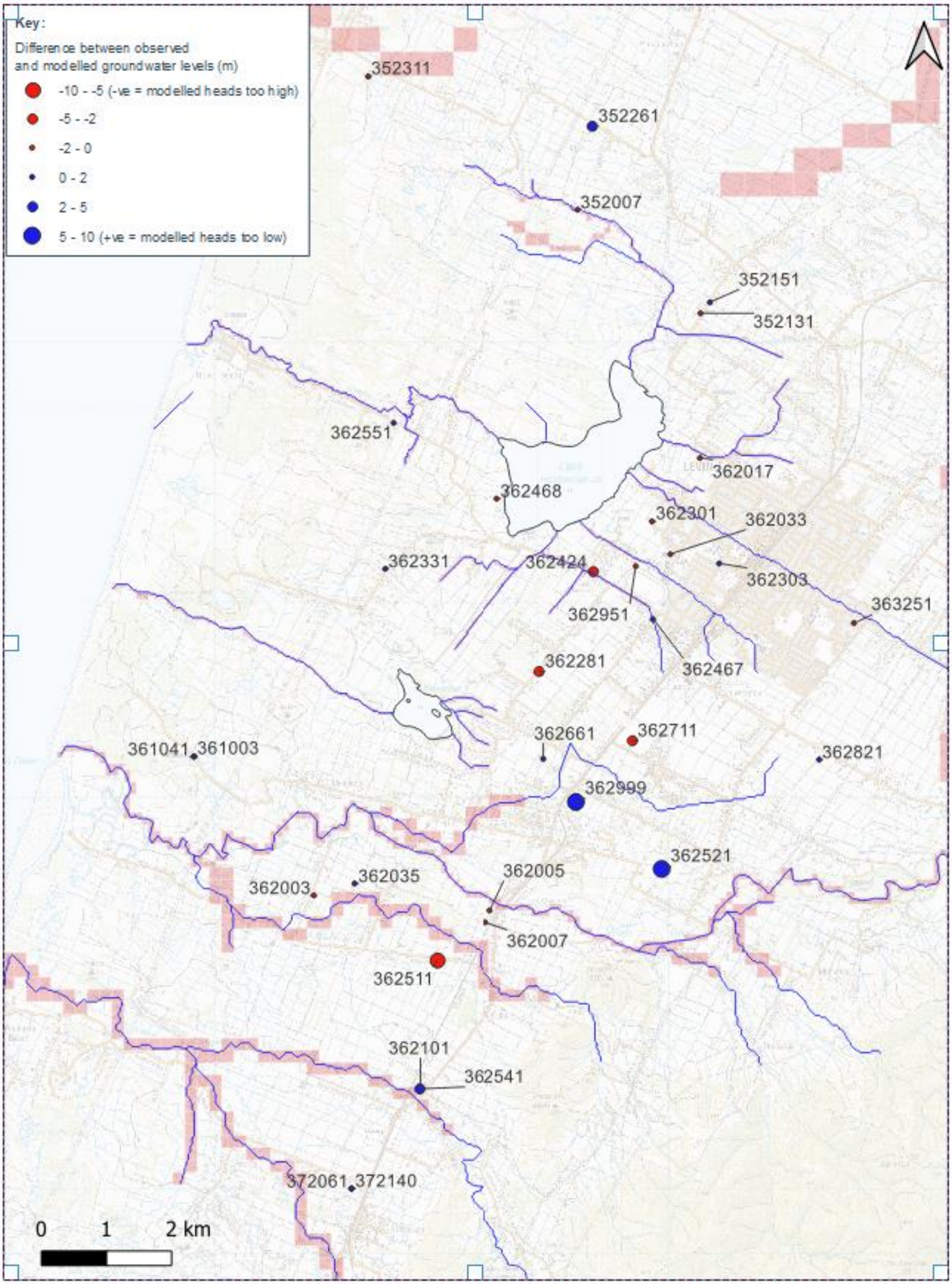

Figure 23: Location of head observation targets and model vs. observed levels

The modelled heads close to Lake Horowhenua are generally very close to the observed levels with one exception (bore 362424). However, heads further away from the lake and between the lake and the Ōhau River are generally too low. This is likely to be related to losses from the Ōhau River, which were calibrated to flow losses observed during low flow surveys. However the model represents median flows and it is likely that greater losses occur from the river at times of higher flows, which would help to resolve these modelled low heads.

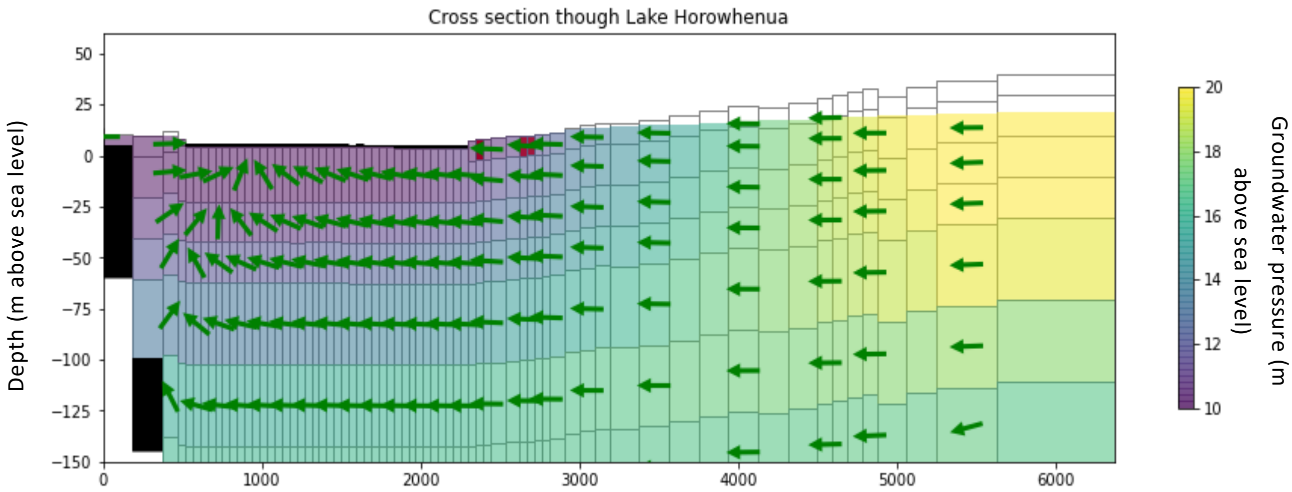

Figure 24: East -west cross section through Lake Horowhenua

Figure 24 shows an east-west cross section through the model from just west of Lake Horowhenua, through the lake and extending towards the Tararua Range in the east. The cross section helps to illustrate how deeper groundwater in the east of the area moves downwards until it encounters the basement high structure caused by the Levin Fault. As deeper groundwater approaches the fault, it is forced upwards and discharges into the lake, as shown by the higher pressures at depth (yellow colours in Figure 24).

5.3 Flows and Lake Water Balances

5.3.1 Ōhau River

Figure 25 shows the modelled seepage losses and gains along the Ōhau River (where Haines Ford is the downstream recorder site). The model simulates the losing reach between the point where the river exits the hills and State Highway 1. Based on gauging surveys, some loss may occur at low flows further downstream of SH1, which is not represented in the model, however it is not clear whether this loss occurs at times of higher flows (rather than the median flows simulated in the model). This aspect of the model could be better investigated via a transient model which simulates changes in flows and water levels through time.

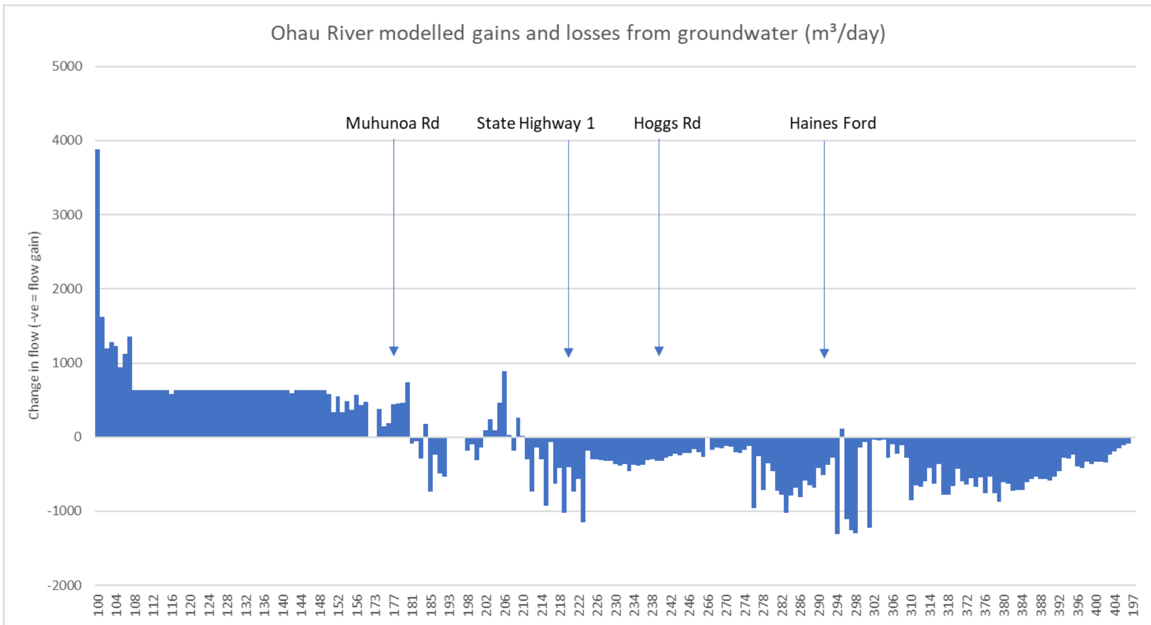

Figure 25: Seepage losses and gains along the Ōhau River

5.3.2 Lake Horowhenua Water Balance

Table 5 shows the observed and modelled water balance for Lake Horowhenua. The model represents the lake water balance closely, which implies that the numerical representation of the conceptual model of groundwater flow around the lake is correct. Based on the results of the model and via some exploration using the model, we do not think that it is possible to match the observed water balance without the presence of the Levin fault close to the surface and just west of Lake Horowhenua. If the fault were not present, groundwater inflows to the lake would be substantially reduced and it is not possible to match outflows from the lake.

Table 6: Lake Horowhenua estimated water balance (L/s)

Component	Inflows	Outflows	Modelled Inflow	Modelled outflow
Rainfall	107		107.0	
Arawhata Stream flow in	217		224	
Patiki Stream flow in	38.5		45.8	
Inflow at Lindsay Road	48		37.15	
Queen Street Drain	29[1]		14.8	
Heatherlea Swamp at Kawiu Road	12[1]		7.3	
Groundwater inflow	531.2[2,3]		570.65[5]	
Hokio Stream flow out		906		930
Evaporation		76.7		76.7
Groundwater flow out		?		0
Total	982.7	982.7	1006.7	1006.7

Notes:

1. *Flows in these surface waterways are based on the median of gauging runs between 1975 and 2018*
2. *Calculated as the balance of outflows and inflows.*
3. *There are some other inflows which are not listed in the table above, including the Makomako Drain, inflows at Bruce Road, and Inflows at Hokio Sand Road. Gauging of these flows amount to a few L/s and their contribution is included in the Groundwater inflow component. This value also allows for additional discharge to surface waterways between the monitoring locations and the lake.*
4. *This value allows for around 90 L/s of groundwater discharge to the lake and nearby streams between the surface water flow gauging locations and the lake.*
5. *Modelled direct groundwater inflow to the lake is around 450 L/s, with the balance of 120 L/s made up from groundwater discharge to streams between the gauging points and the lake and other ungauged discharges, such as drains.*

The model was specifically calibrated to represent the lake water balance as shown above. However, it is important to note that the water balance is a steady state estimate, based on median flows. The model is sensitive to losses from the Ōhau River and how this varies under different flow conditions is not particularly well constrained and as a result there are some uncertainties in the aquifer parameters used to calibrate the model, discussed below.

Lake stage is also calculated as part of the model, which resulted in a stage value for Lake Horowhenua of 7.4 m above sea level. Note that elevations in the model are based on LiDAR data, which indicates a lake stage of 7.35 m asml, so the modelled value is reasonable. We also note that modelled outflows from the lake are sensitive to the estimated invert level of Hokio Stream where it leaves Lake Horowhenua. This is not clearly defined.

5.4 Particle Tracking

To provide an indication of groundwater travel times to Lake Horowhenua from the major sources of water to the lake, a particle tracking exercise model was used. This is based on the model flow field and used the USGS MODPATH 7 code to track particles backwards from Lake Horowhenua to their source. Particles were placed into Layer 2 (i.e. directly beneath the lake)

Particle tracking was based on a porosity value of 0.1 and the result of the particle tracking are shown in Figure 26 and 27.

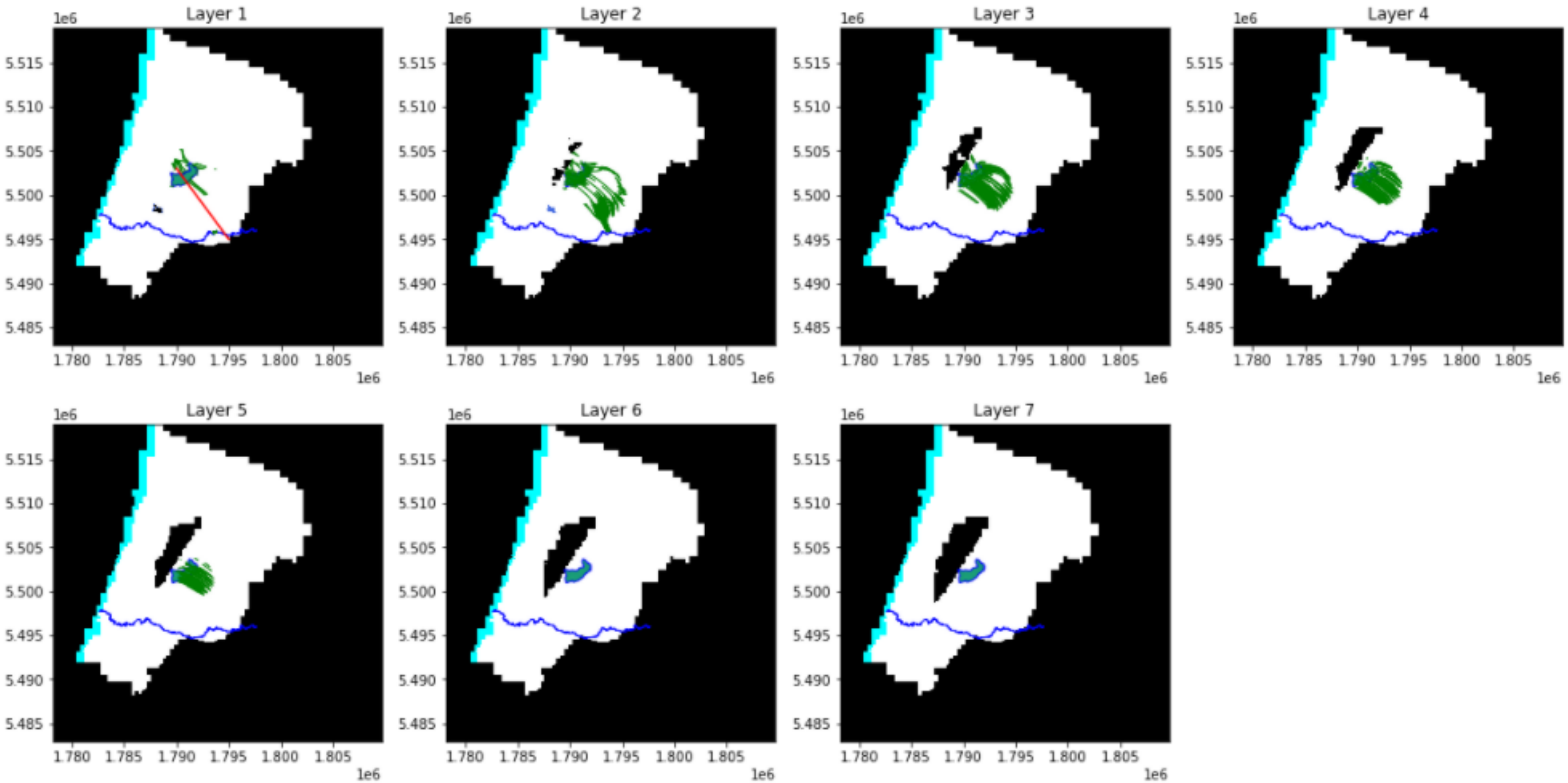

Figure 26: Particle tracks originating from Lake Horowhenua based on 20 years of travel for each model layer. The line of the cross section in Figure 27 is shown as a red line on Layer 1.

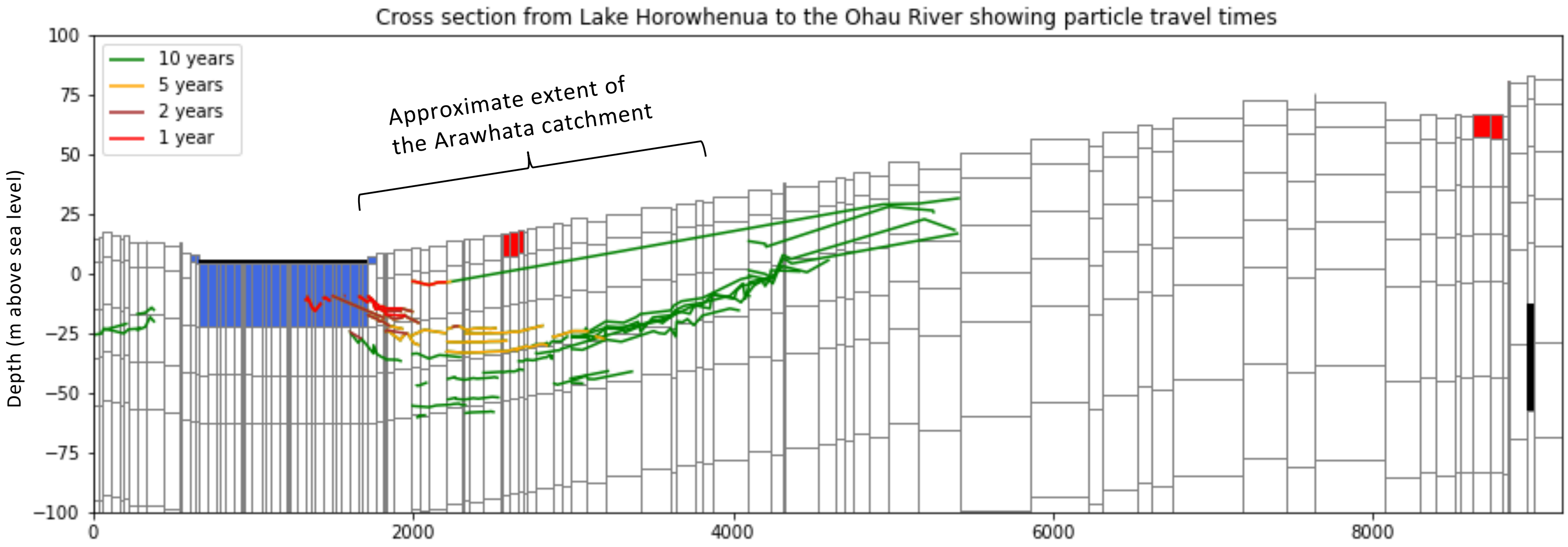

Figure 27: Particle tracks originating from Lake Horowhenua based 10, 5, 2 and 1 year time of travel. This cross section extends in a south-east direction from just north of Lake Horowhenua to the Ōhau River and is shown on Figure 26. Red cells denote the Arawhata Stream and Ōhau River.

The results of the particle tracking indicate that the travel time to Lake Horowhenua from the Ōhau River is likely to be at least 10 years, for particles within layer 1 and 2 and within 5 years for particles within, for example, the Arawhata catchment. However, particles within deeper strata may take much longer to travel to the lake.

These results imply that changes in landuse in the area close to Lake Horowhenua may result in relatively rapid (i.e. within ~5 years) changes to the nutrient load entering the lake. However, changes to landuse in areas further from the lake (i.e. around the base of the Tararua Ranges and close to the Ōhau River) may take much longer. This also implies that if a nutrient load is present within deeper strata, there is likely to be a lag of at least 10 years before it affects the lake.

Although the particle tracking exercise provides some insight into travel times from land areas surrounding to the lake, it is important to highlight that there is likely large error margin in these estimates. As discussed below, values of hydraulic conductivity are not particularly well defined in the model and variations in these values will have a large impact on travel times to the lake. Therefore, the comments above should be viewed with caution at this stage of the modelling exercise.

6.0 Model Sensitivity

The model was calibrated using PEST, which enables the sensitivity of different model outputs (such as groundwater inflow to Lake Horowhenua) to different model parameters to be calculated. For the overall model, the following plot (Figure 28) shows the sensitivity of the model calibration to different parameters:

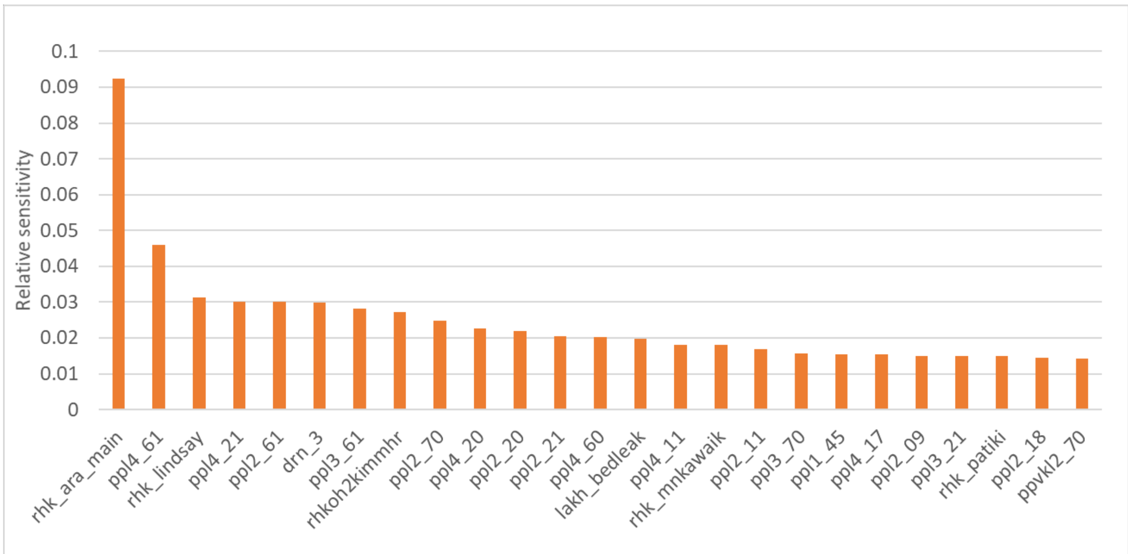

Figure 28: Overall model sensitivity to different parameters

In Figure 28, all the parameter names stating with ‘rhk’ refer to a stream bed conductance parameter, while those starting with ‘pp’ refer to a pilot point location where the value of hydraulic conductivity was varied. The key parameters that this model is most sensitive to are:

- Stream bed conductance along the Arawhata Drain mainstem (‘rhk_ara_main’)
- Hydraulic conductivity between Lake Horowhenua and the coast in layer 4 (‘ppL4_64’)
- Streambed conductance along the Lindsay Road Drain (‘rhk_lindsay’)
- Hydraulic conductivity between Lake Horowhenua and the coast in layer 2, 3 and 4 (‘ppL4_21’, ppL2_61 and ppL3_61)
- Stream bed conductance along the upper part of the Ōhau River (‘rhkoh2kimmhr’).

The model sensitivity to these parameters is not surprising, as discharges into the Arawhata Drain and other streams draining into the lake, as well as groundwater discharges into the lake were key model calibration targets. However, the sensitivity of the model to losses from the upper reaches of the Ōhau River reflects the effect of those losses on groundwater levels between the river and the lakes. These losses are not well defined except at low flows.

During the model calibration, it became apparent that water needed to be diverted away from Lake Horowhenua to ensure that heads (and surface water flows) around the lake could be matched to observed levels. Some of this water is diverted north of the lake in which case flows into the tributaries to the Manawatu River are important controls. Equally, diversion of water between Lakes Waiwiri and Horowhenua towards the coast was required to ensure that heads and flows around the lake were not overestimated.

Difficulties in calibrating the model to observed heads around Lake Horowhenua as well as to surface water flows indicates that groundwater flow around the lake is complex. It is likely that this complexity is strongly influenced by the Poroutawhao basement high and its effects on groundwater flows. It is possible that the sensitivity of the model to stream bed conductance in the tributaries of the Manawatu River is a compensatory effect to uncertainties in the structure of location of the Poroutawhao basement high.

During model calibration with PEST, the hydraulic conductivity at each pilot point is set to a range, with a preferred starting value (i.e. it has an initial uncertainty range). The range was based on the range of hydraulic conductivity values observed in neighbouring bores. As the model is calibrated to observed data, the hydraulic conductivity value at each point may become more constrained, depending on how much the observed data informs the value of that parameter (i.e. it may become less uncertain).

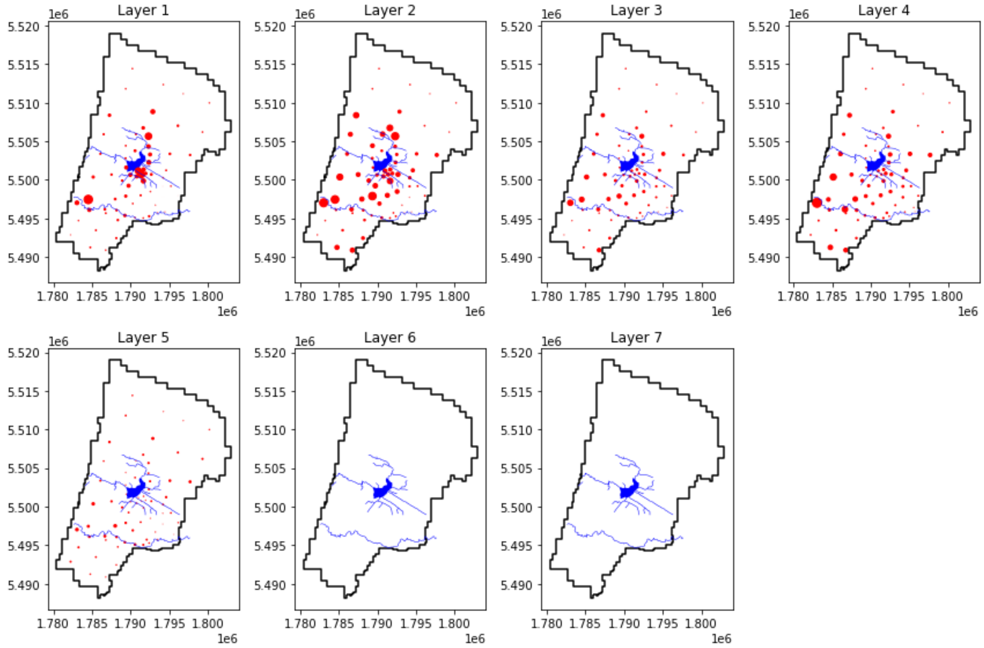

Figure 29: Relative uncertainty reduction in hydraulic conductivity at each pilot point

Figure 29 illustrates the extent to which calibration of model reduced the uncertainty in hydraulic conductivity at each pilot point. The symbol size in Figure 29 relates to the scale of uncertainty reduction at each pilot point, i.e. greater certainty regarding hydraulic conductivity at that point. In relative terms, greater reductions in uncertainty occurred in pilot points in layers 1, 2 and 4, with lesser effects for pilot points in layers 3, 5, 6 and 7. This distribution reflects the depth of observation bores available in the model area. However, the absolute reduction at each point is no more than 6%, meaning that hydraulic conductivity values in the model area are very uncertain.

7.0 Conclusion and Recommendations

7.1 Conclusions

The intended outputs of this modelling exercise included:

- A steady state groundwater model of the Horowhenua FMU area. Calibration will initially focus on observed groundwater levels and stream baseflows into Lake Horowhenua. Groundwater level and flow data for the area south of the Ōhau River will also be included but will be given less weight at this stage of the modelling process;
- A report detailing the model design, sensitivity to different input parameters and uncertainty around the Lake Horowhenua water balance;

- Recommendations around the locations of additional monitoring and/or data collection to reduce the modelled uncertainty around the lake water balance;
- Estimates of travel times to Lake Horowhenua from different parts of the groundwater catchment;
- Recommendations around the next steps for the model to represent transient changes in groundwater flows and further development to represent contaminant transport into Lake Horowhenua.

This report documents the outputs from the steady state model of the Horowhenua FMU area. The model provides a good representation of the conceptual understanding of the Horowhenua area, and accurately simulates the Lake Horowhenua water balance. In that sense, it helps to demonstrate that the conceptual model is a valid representation of the patterns of groundwater movements in the area. In any model, there are trade-offs between simulating both surface water flows as well as groundwater levels within an area, and in this case, greater emphasis was placed on simulating surface water flows.

Nonetheless, the difference between modelled and observed groundwater levels around the lake illustrates two key points with respect for further modelling:

- Further information regarding drains, their depths and their connection to existing surface waterways and/or Lake Horowhenua is required. This is especially so around the Arawhata Drain.
- Losses from the Ōhau River are important and further work to ensure that these are correctly represented is required.

As discussed above, values of hydraulic conductivity are not particularly well constrained in the model and one recommendation is that whilst some aquifer parameter data is available, it is of relatively poor quality and frequently represents the outcome from step test (i.e. short term, localised) analysis. Undertaking two or three well controlled, longer term pumping tests in the area would help to constrain aquifer parameters. These should be completed in both deeper and shallower strata close to Lake Horowhenua. It would be particularly helpful to use this testing to verify the modelled presence of higher conductivity strata around the south-east of the lake, and between Lake Waiwiri and Lake Horowhenua.

Development of a steady state model provides a helpful starting point for a modelling exercise but one drawback of a steady state model is that they are calibrated to estimates of average groundwater levels and average flows, which are not necessarily based on consistent datasets. Losses from the Ōhau River are a key component of the model, and they are generally poorly constrained for average flow rates, although they are better constrained at low flows where a number of gauging surveys have been carried out. As a result, those losses may not be representative of average groundwater levels. Some further work to help refine these losses at a range of flows would help to reduce the uncertainty of any model predictions.

Development of a transient model that represents changes in groundwater levels and flows through time will also help to resolve this issue, as each dataset will be consistent in time and space.

The particle tracking exercise indicates that travel times from the Ōhau River to Lake Horowhenua are likely to be less than 10 years in shallow strata, although longer times are likely in deeper strata. Based on the model outputs, travel times to Lake Horowhenua in shallower strata within the Arawhata Drain catchment may be within the order of 5 years. However, there is considerable uncertainty around these estimates and development of a transient model would help to reduce this uncertainty.

7.2 Recommendations

A summary of the key recommendations is provided below:

- Further information regarding drains, their depths and their connection to existing surface waterways is required. This is especially so around the Arawhata Drain.
- Shallow groundwater in the Arawhata Drain area is likely to be affected by evapotranspiration effects, which is not currently included in the model. Simulation of this effect is likely to be required in order to better match groundwater levels around the lake.
- Two or three well controlled, longer term pumping tests would help to constrain aquifer parameters and possibly help to identify the location of fault if boundary conditions are observed. These should be completed in both deeper and shallower strata close to Lake Horowhenua.
- Further work to help refine losses from the Ōhau River upstream of Hoggs Road at a range of flows would help to reduce the uncertainty of any model predictions. This could include undertaking a pumping test to help constrain stream bed conductance in the reach between Muhunoa Road and SH1, and along the upstream reach between the Rongomatane gauging station and Kimberley Road. Groundwater level monitoring in this area would also help to reduce modelled uncertainty regarding the loss from the river in this reach.
- Running the model as a transient groundwater model would help to reduce uncertainties that are likely to be present, particularly if the model is used to investigate travel times and contaminant transport towards Lake Horowhenua and Lake Waiwiri.

8.0 References

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