Hawke's Bay 3D Aquifer Mapping Project:

Ruataniwha Plains data and model inventory

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EXECUTIVE SUMMARY

This report details datasets and models available to assist with hydrogeological interpretations of collected SkyTEM data in the Ruataniwha Plains as part of the Hawke's Bay 3D Aquifer Mapping Project (3DAMP).

3DAMP is a three-year initiative (2019–2022) jointly funded by the Provincial Growth Fund, Hawke's Bay Regional Council and GNS Science. The project applies the geophysical SkyTEM technology to improve mapping and modelling of groundwater resources within the Heretaunga Plains, Ruataniwha Plains and Poukawa and Otane basins with SkyTEM data collected in those areas in early 2020.

Using the SkyTEM data, resistivity models were previously developed for the Ruataniwha Plains. This report describes information available to assist with the hydrogeological interpretation of these resistivity models. It summarises major geological and hydrogeological investigations previously undertaken in the area and presents surface, geological, geophysical, hydrogeological and offshore datasets of relevance. The boundary of the Ruataniwha Plains SkyTEM survey area was used to limit the extents of most datasets discussed in this report and presented in the included GIS figures.

A combination of different software packages were used to import and manipulate the data. Key information of relevance to hydrogeological interpretations of the SkyTEM-derived resistivity models is summarised, and unique digital datasets developed as part of this report are supplied, including:

- Detailed digitisation of a selection of lithological logs.
- Quality-checked and quality-coded lithological logs.
- 2D interpretation grids from seismic reflection data.
- Quality-checked water supply intervals, identified from bore construction data and lithologies.
- Re-modelling of GNS Science ground-based electromagnetic data.

This report will be utilized by subsequent reports within the 3DAMP project that deal with hydrogeological interpretation of the collected SkyTEM data within the Ruataniwha Plains.

1.0 INTRODUCTION

This report focuses on describing information and datasets available to assist with hydrogeological interpretations of collected SkyTEM data in the Ruataniwha Plains (Figure 1.1) as part of the Hawke’s Bay 3D Aquifer Mapping Project (3DAMP).

3DAMP is a three-year initiative (2019–2022) jointly funded by the Provincial Growth Fund (PGF), Hawke’s Bay Regional Council (HBRC) and GNS Science’s (GNS) Groundwater Strategic Science Investment Fund (SSIF) research programme. The project applies SkyTEM technology to improve mapping and modelling of groundwater resources within the Heretaunga Plains, Ruataniwha Plains and Poukawa and Ōtāne basins. 3DAMP involves collaboration between HBRC, GNS and the Aarhus University HydroGeophysics Group (HGG).

SkyTEM is an airborne geophysical technique that uses electromagnetic waves to investigate the shallow (up to 500 m depth) resistivity structure of the earth. SkyTEM data were collected in the Hawke’s Bay region during January/February 2020 (SkyTEM Australia Pty Ltd 2020). Using these data, resistivity models were developed for the Ruataniwha Plains by Rawlinson et al. (2022).

The objective of this report is to compile, quality-check and present datasets, including expert knowledge, of value for hydrogeological interpretation of the previously developed SkyTEM-derived resistivity models of the Ruataniwha Plains. Hydrogeological interpretation of these resistivity models will be described in subsequent reports.

1.1 Location and Method

The area of interest for this data inventory report is the area of the Ruataniwha Plains 2020 SkyTEM survey (Figure 1.1). This area was defined by extending a 300 m horizontal buffer around the SkyTEM-derived 1D resistivity model locations developed by Rawlinson et al. (2022). The Ruataniwha Plains is an infilled basin, which is part of the upper Tukituki River catchment in the Central Hawke’s Bay area. The boundary of the Ruataniwha Plains SkyTEM survey area was used to limit the extents of most datasets discussed in this report.

A combination of software packages was used to import and manipulate the data, including:

- ArcMap for 1D, 2D and 2.5D vector and raster data visualisation and analysis.
- Aarhus SPIA for processing ground-based electromagnetic data (GroundTEM).
- Paradigm for seismic data interpretation.
- WellCAD for compilation of geological and geophysical data from research wells.
- Bespoke Python scripts for data manipulation.

The datasets have been compiled using the New Zealand Transverse Mercator spatial reference system (NZTM GD2000) and the NZ Vertical Datum 2016. Where relevant, data have been formatted with consideration of the software to be used for future hydrogeological interpretation studies, such as Geoscene3D software.

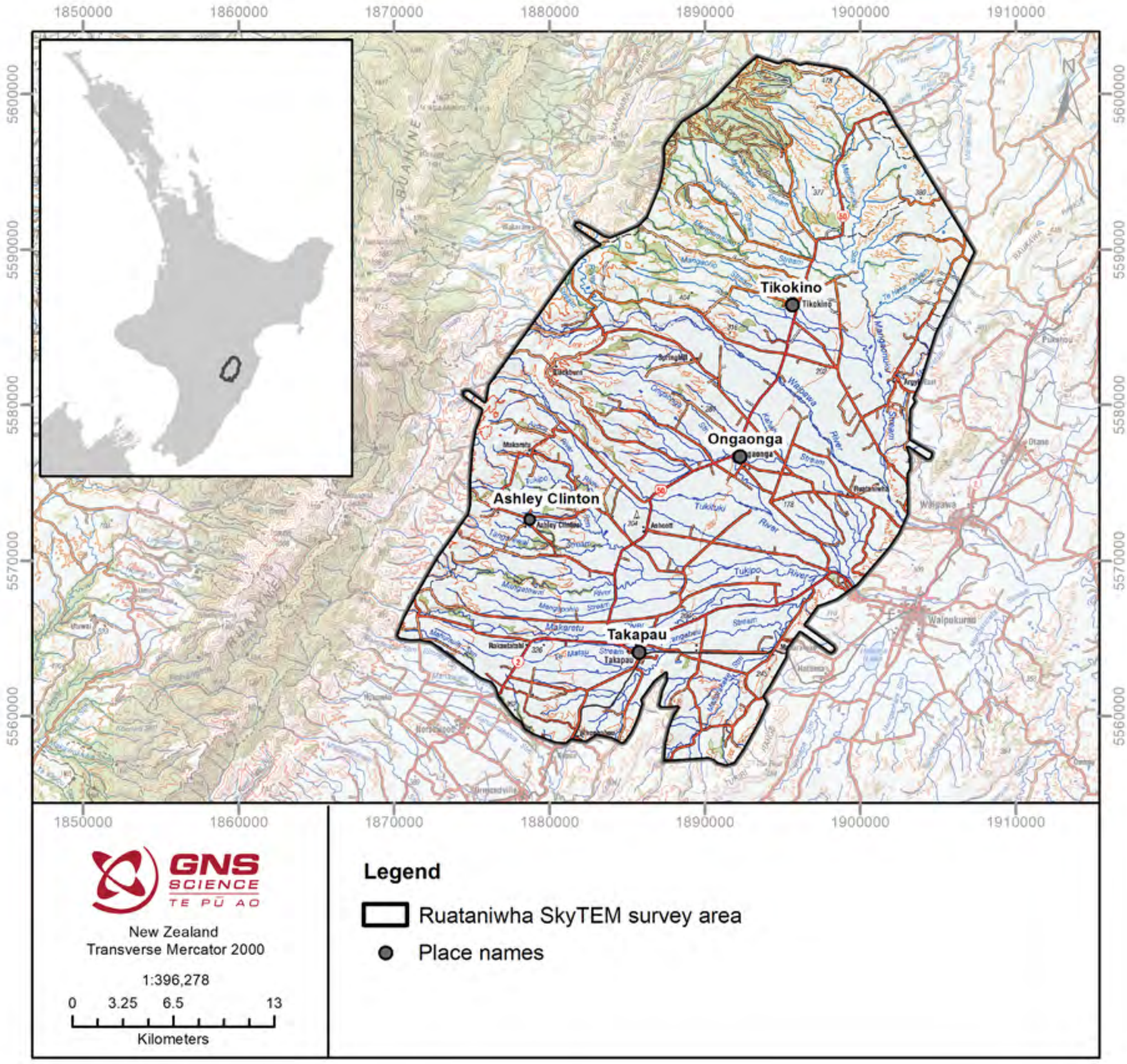

Figure 1.1 Location map of the Ruataniwha Plains showing the extent of the SkyTEM survey area (Ruataniwha SkyTEM survey area).

1.2 Report Outline

Section 2.0 briefly describes investigations that have contributed to the conceptual understanding of the Ruataniwha Plains aquifer system. Section 3.0 describes the surface, geological, geophysical and hydrogeological datasets of relevance. Section 4.0 summarises key information of relevance to hydrogeological interpretations of the SkyTEM-derived resistivity models.

Datasets that were newly digitised or created as part of this project have been provided as digital attachments and are described in the appendices.

2.0 MAJOR STUDIES CONTRIBUTING TO THE CONCEPTUAL UNDERSTANDING OF THE RUATANIWHA PLAINS AQUIFER SYSTEM

Harper (2018) provided an in-depth review of the geological and hydrogeological conditions in the Ruataniwha Basin as well as a summary of geological and hydrogeological models developed for the area. In addition, Harper (2018) developed an updated geological model that is currently utilised in the most recent, and still on-going, numerical groundwater model development for the area.

Major geological and hydrogeological studies, including early investigations between the 1800s and 2000, are described by Harper (2018) and will not be detailed in this current report.

This section explores major hydrogeological studies for the Ruataniwha SkyTEM survey area that have been only peripherally, or not at all, addressed in Harper (2018), either due to being published after the review report or because they were beyond the scope of the report at the time.

2.1 Geological and Hydrogeological Investigations 2002

Brown (2002) summarised the geological and hydrogeological conditions in the Ruataniwha Plains and described the results of a 2001 drilling project of eight groundwater exploration wells at six different sites in the Ruataniwha Plains. The report was never published, and only two of the three appendices could be sourced. Nevertheless, the study provides a useful resource for the geological and hydrogeological interpretation of the resistivity data.

The objective of Brown's (2002) project was "to improve the knowledge of the hydrogeology of the gravel aquifers within the Late Quaternary deposits (last one million years) infilling the Ruataniwha Basin". The results were expected to feed into the development and calibration of a groundwater flow model for the Ruataniwha Plains.

The depths of the wells drilled as part of that project vary between 5.3 and 148.5 m, and all drilled bores were logged with the aim to identify lithostratigraphical and hydrogeological units (aquifers, aquitards and aquicludes). Pollen analyses to determine depositional environments and ages of the deposits were conducted on any carbonaceous material drilled. Fossilised shells that were found in wells drilled in the southeast of the plains were collected for paleontological investigations. The results of the paleontological investigations were supposed to be provided in Appendix 3 of the Brown (2002) report; however, no copy of this appendix has been found as of yet. The report identified the lithostratigraphical and hydrogeological units at each drilled well and a summary overview of these is provided in Section 3.2.3.2.

Investigations in the Brown (2002) report included which geological units at what depth could be the hydrogeological basement in the Ruataniwha Plains. The report noted that the hydrogeological basement would be dependent on the following parameters: "location of the drilling site, the availability of sustainable groundwater yield, drilling capability, and the return on capital invested in finding and utilising the water supply" and suggested the following possibilities for the Ruataniwha Plains:

- The base of the gravel aquifers.
- The base of geological formations that have the potential to host aquifers (Te Onepu Limestone).
- The base of geological formations that host high yielding aquifers connected to groundwater recharge sources (Salisbury Gravel).

- The base of geological formations hosting aquifers that can be drilled by available water well drilling equipment (Te Onepu Limestone in the southern and Salisbury Gravel in the northern Ruataniwha Plains).
- The base of geological formations hosting aquifers where the water abstraction and use is profitable, for example to produce a specific crop.
- The top of greywacke basement.

2.2 Groundwater-Surface Water Interaction Investigations 2009

Two larger studies focussing on groundwater-surface water interaction in the Ruataniwha Plains were conducted by GNS Science (Meilhac et al. 2009; Undereiner et al. 2009) as part of a 2008–2009 GNS Science Groundwater Capability Fund Project collaboration with HBRC. The studies aimed to improve the understanding around groundwater-surface water interaction in the vicinity of the Waipawa River (Figure 2.1) to enable better modelling, water budgeting, and management of the water resources. The areas of interest for both studies were located between SH50 and the Rakawa Ranges and included catchment areas of the Waipawa and Tukituki rivers and the Mangaonuku and Kahakahakuri streams.

The studies used different combinations of methods to determine groundwater-surface water interaction in the areas of interest. These methods included the development of a potentiometric surface from shallow bores surveyed in April 2009 (Figure 2.2), geophysical measurements, river gaugings, small scale heat tracer experiments, and larger scale water budgets and lithological modelling. For example, NanoTEM and TEM geophysical measurements were used to map shallow aquifers along the Waipawa River and comparisons with lithological log data demonstrated that materials with lower clay content, i.e. higher permeable layers, exhibited higher resistivity (Figure 2.3). Comparison of these resistivity models with aquifer test data showed a strong (R^2=0.96) linear correlation between resistivity (r) and hydraulic conductivity (K) ($K = 0.0012r - 0.1895$), which was used to estimate approximate hydraulic conductivities across the TEM survey transects (Figure 2.4). Undereiner et al. (2009) mapped the top and bottom contours of a shallow and a deep aquifer in their study area using a 3D model of gravel deposits developed from lithological bore logs (Figure 2.5 and Figure 2.6).

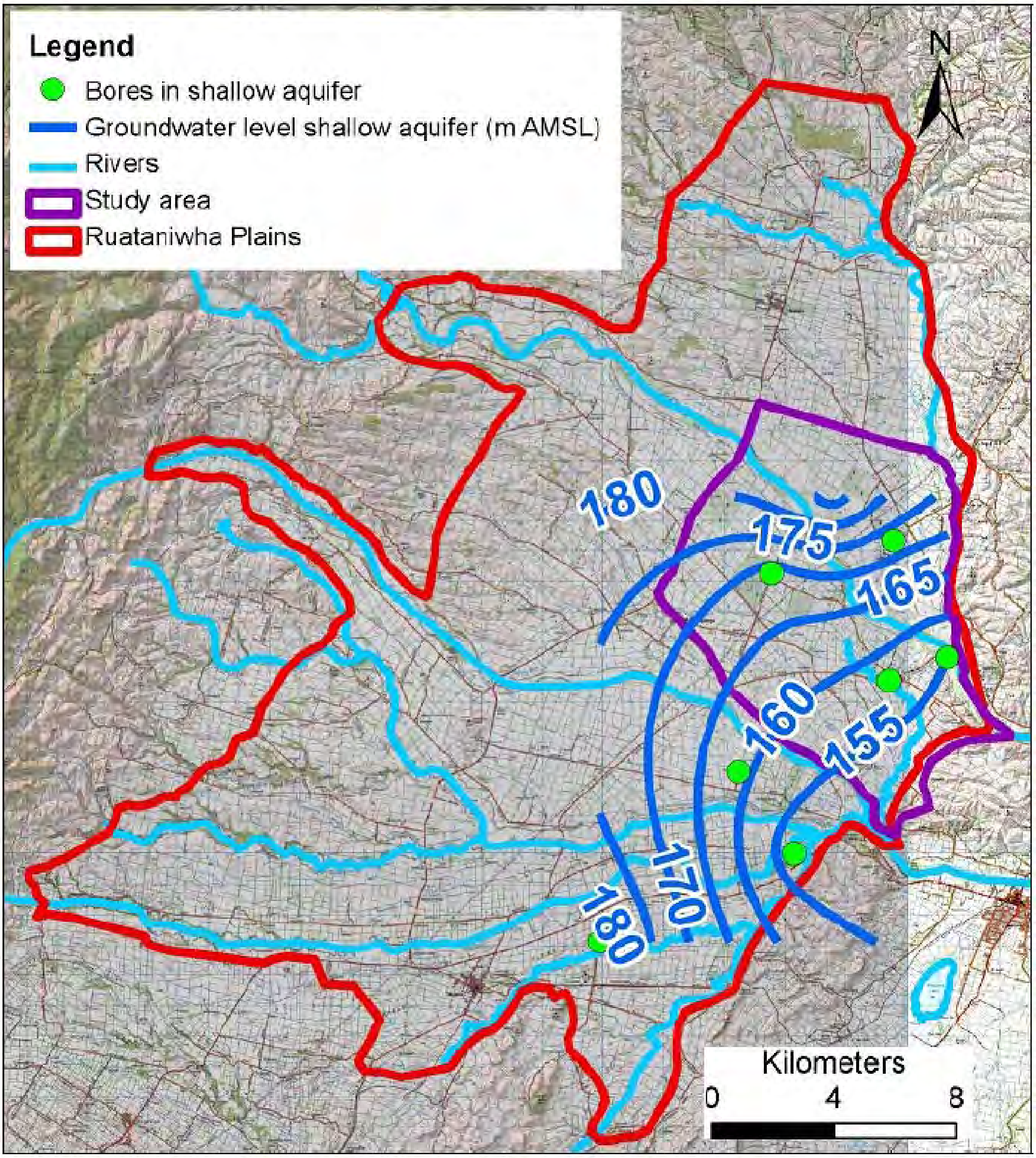

Figure 2.1 General location of the 2009 study area (purple) in the Ruataniwha Plains (red). Larger scale groundwater contours of the shallow aquifer are shown in dark blue. Figure from Undereiner et al. (2009). Higher resolution groundwater level contours are shown in Figure 2.2.

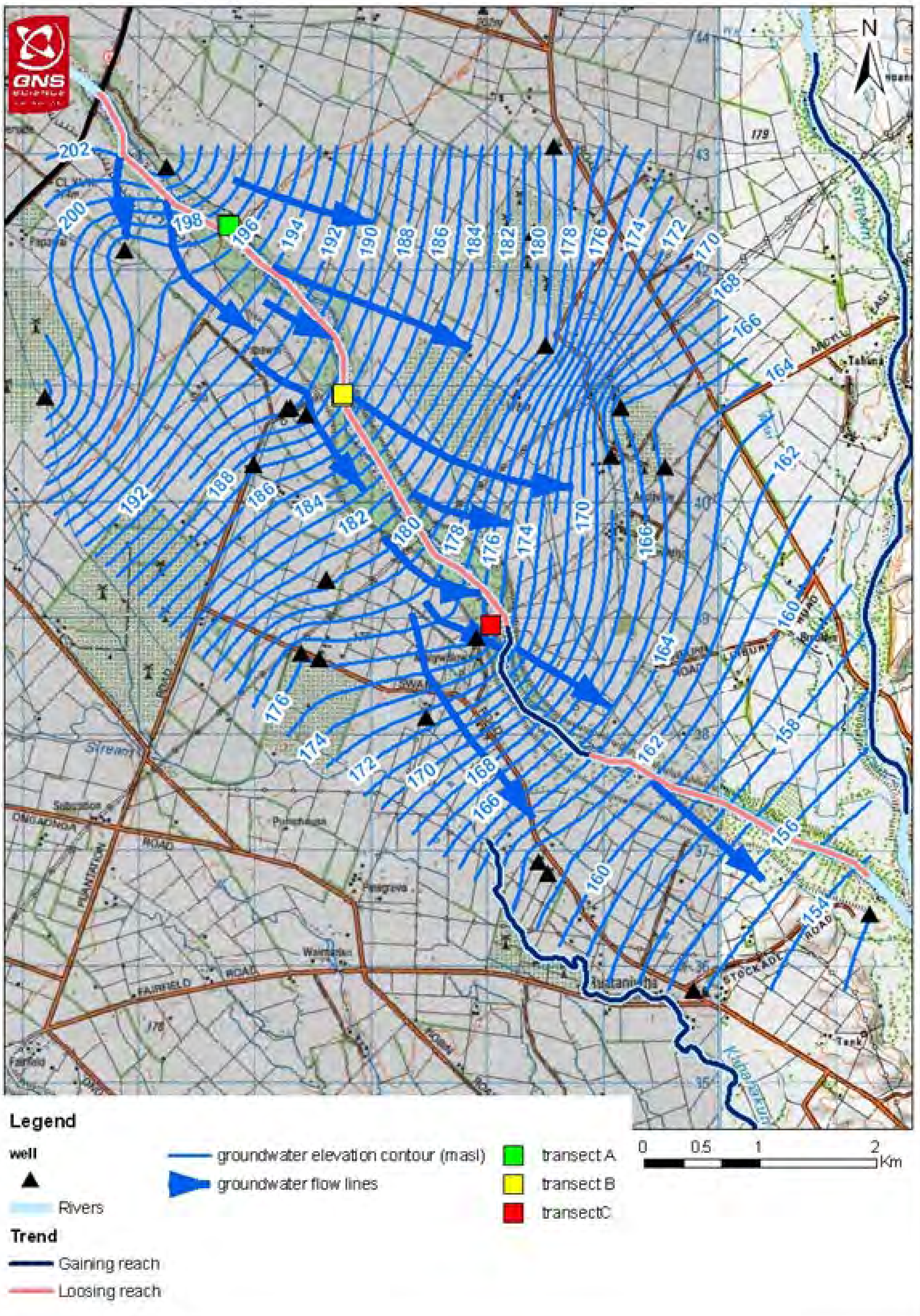

Figure 2.2 Potentiometric surface along the Waipawa River estimated from shallow bores surveyed in April 2009 (figure from Meilhac et al. (2009)).

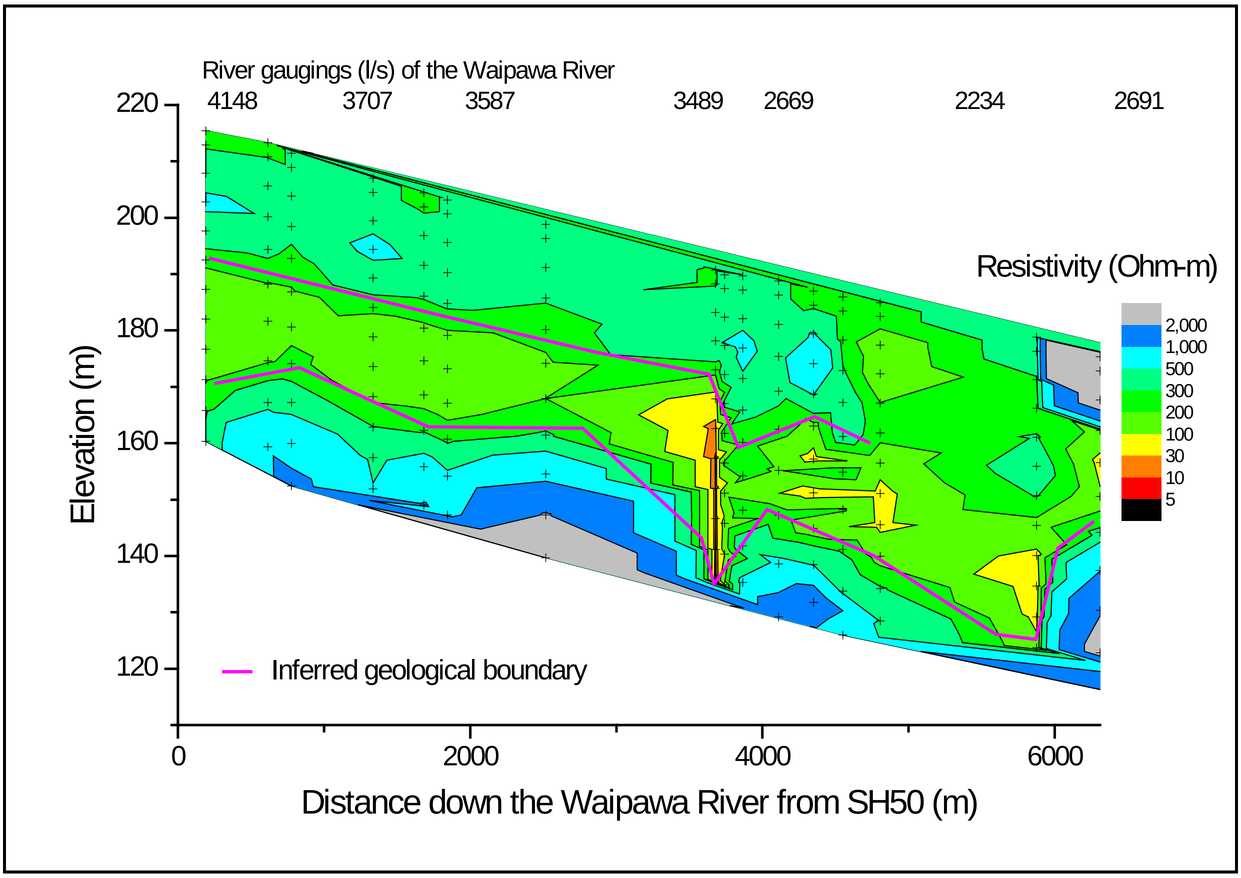

Figure 2.3 Profile along the Waipawa River showing NanoTEM resistivities (figure from Meilhac et al. (2009)).

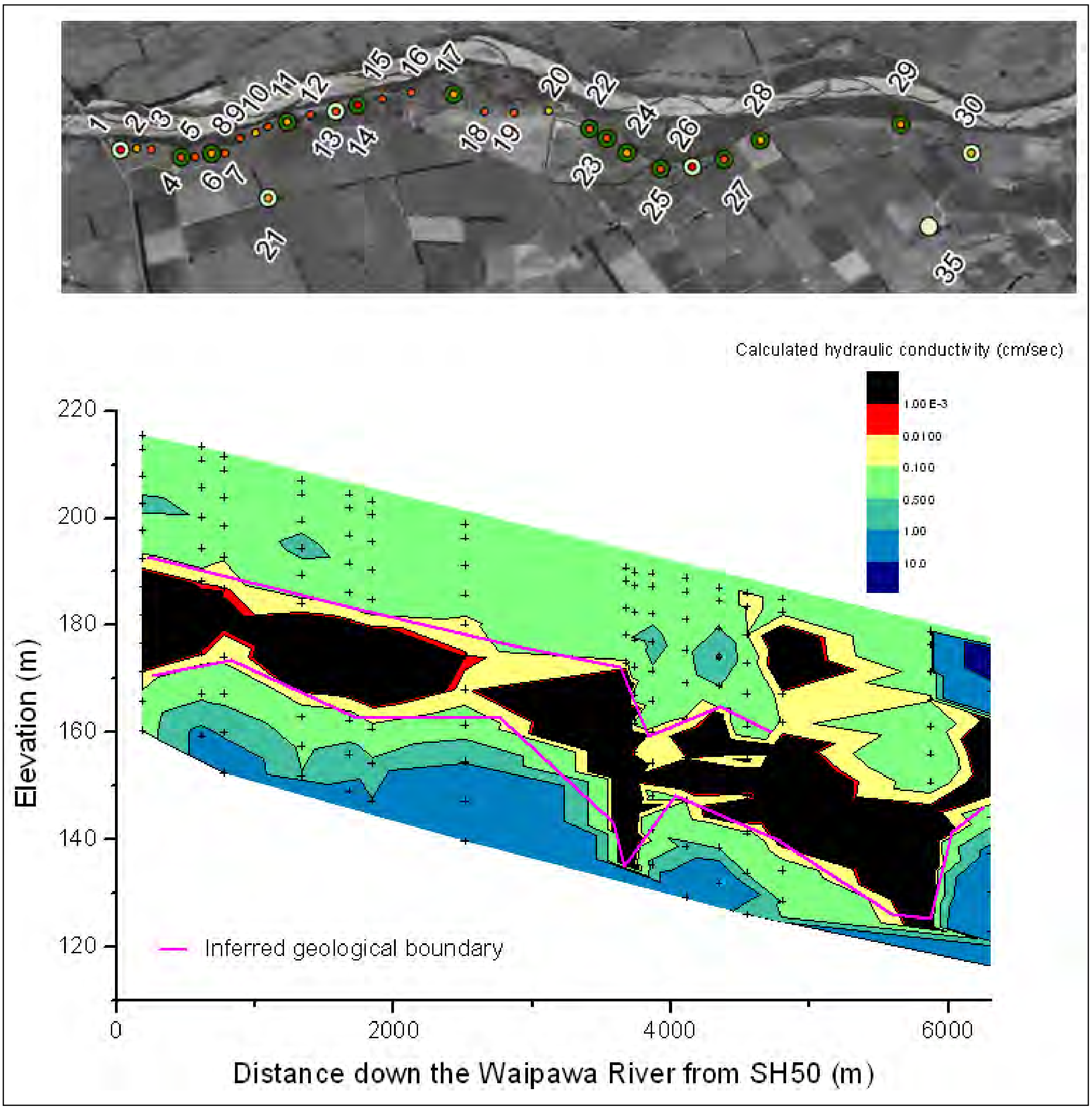

Figure 2.4 Profile along the Waipawa River showing inferred hydraulic conductivities (figure from Meilhac et al. (2009)).

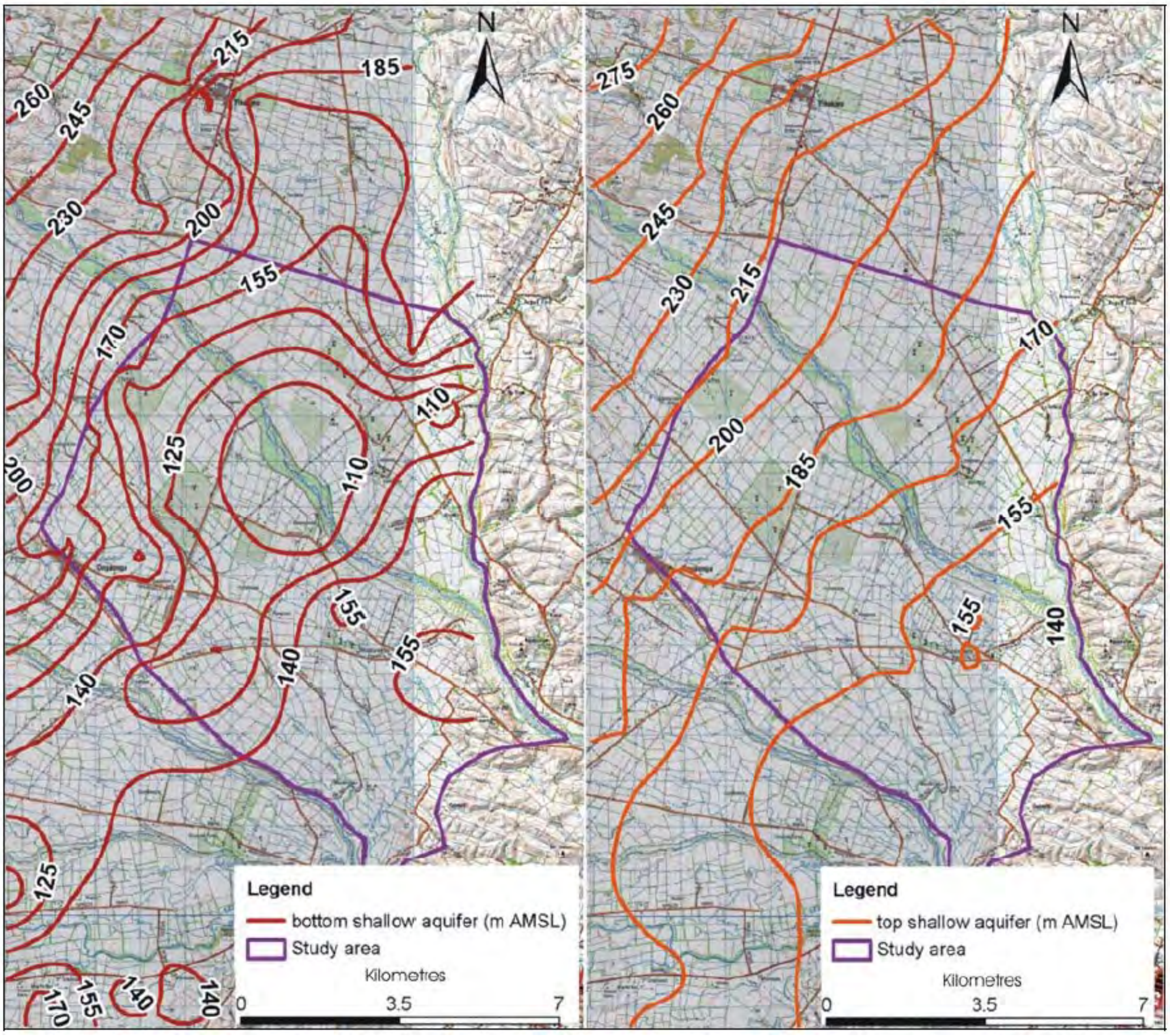

Figure 2.5 Contours of the bottom (left) and top (right) of the shallow aquifer modelled (figure from Undereiner et al. (2009)).

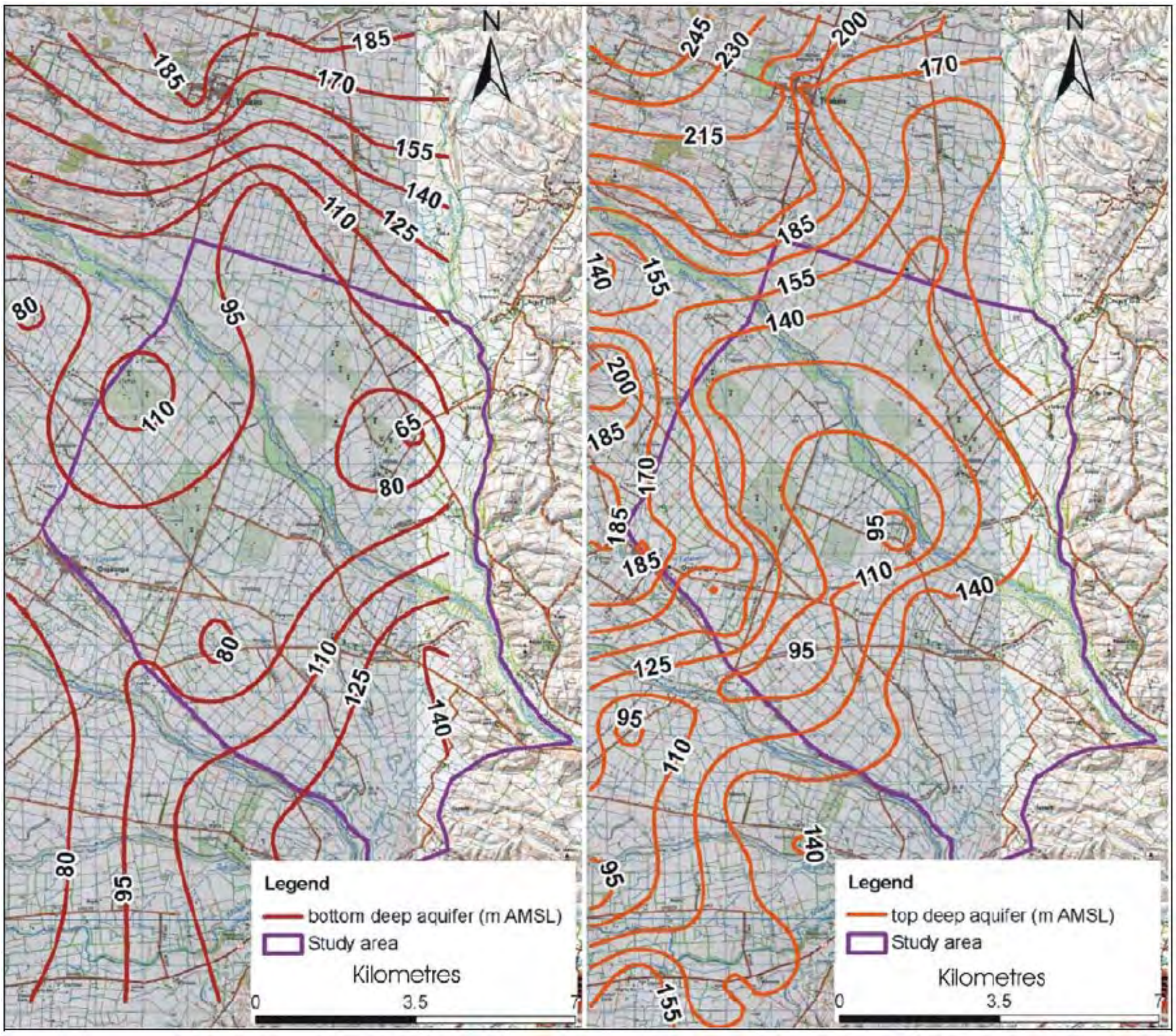

Figure 2.6 Contours of the bottom (left) and top (right) of the deep aquifer modelled by (figure from Undereiner et al. (2009)).

2.3 Conceptual Understanding of Groundwater Flow Patterns in the Ruataniwha Plains 2012

Work undertaken by Morgenstern et al. (2012) was aimed at improving the conceptual understanding of groundwater flow patterns in the Ruataniwha Basin and to provide data for the calibration of a numerical groundwater flow model.

As part of the project, Morgenstern et al. (2012) collected and analysed hydrochemistry, dissolved gases, and age tracer samples from groundwater bores in the Ruataniwha Plains. Age tracers were not only analysed to derive groundwater age (mean residence time (MRT)[1]; Figure 2.7); but also, to interpret groundwater recharge rates and sources, and changes in sources; as well as to investigate potential homogeneity or heterogeneity of the aquifers.

[1] The average age of the groundwater from different flow lines, with the age being the time that has elapsed since the water entered the groundwater system.

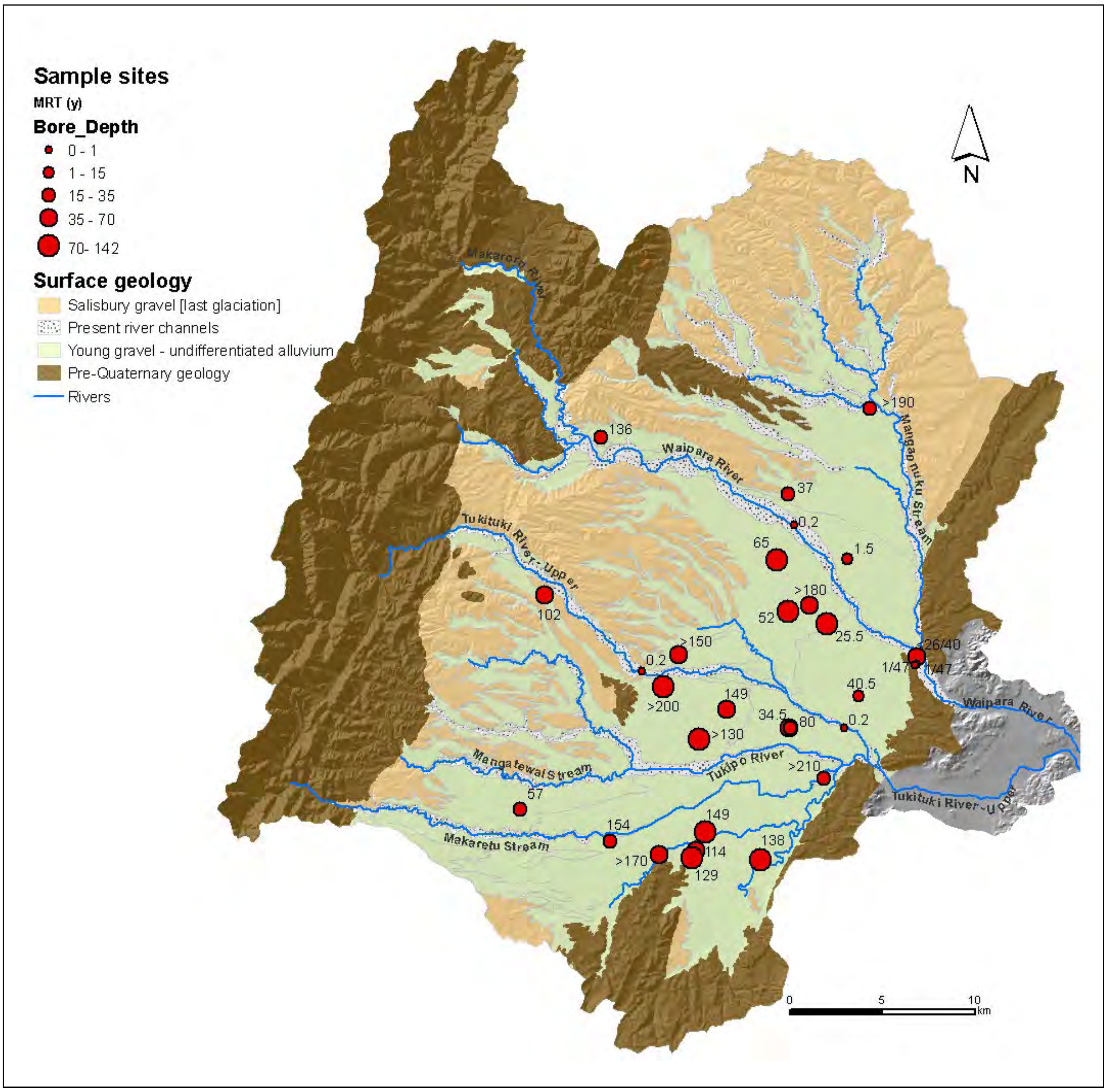

Figure 2.7 Groundwater ages and depths of bores in the Ruataniwha Plains. Figure from Morgenstern et al. (2012).

Most groundwater samples contained relatively old water, with MRTs >25 years, and only one well (3076) had younger water, which the authors suggested was due to a connection of the well to the river via paleo river channels that provided a fast flow path. The wells with the older groundwater ages are likely not linked directly to any surface water sources. Geological units with a low permeability in the SE of the basin were linked by Morgenstern et al. (2012) to old groundwater (>100 years) in the area that indicates “slow movement of groundwater and slow recharge, consistent with the geology of the area.”

Morgenstern et al. (2012) also investigated the relationship between groundwater age vs depth (Figure 2.8) to identify the recharge rate in the basin and noted that upwelling effects, which reflect “the closed nature of the basin”, may result in a shift of those MRT values that are affected by upwelling to the right in Figure 2.8. Because of this shift, Morgenstern et al. (2012) do not use those ‘shifted’ datapoints to derive the average age-depth relationship (black line in Figure 2.8), or the average recharge rate in the basin, which is estimated at 0.19 m/year using the average vertical flow velocity. This recharge rate is not only averaged across the entire basin, but also over the last 100 years, as a range of groundwater ages up to and including 100 years were measured in the sampled wells across the basin. The orange line in Figure 2.8 indicates "the excellent age-depth relationship" that Morgenstern et al. (2012) found for four wells in the vicinity of the lower Waipawa River (downstream of a losing reach of the river) indicating that there is no upwelling of deep groundwater in this area. The estimated recharge rate of 0.41 m/year in that area is more than double the average recharge rate in the basin, which suggests that the groundwater here is recharged not just by rain but also by river recharge.

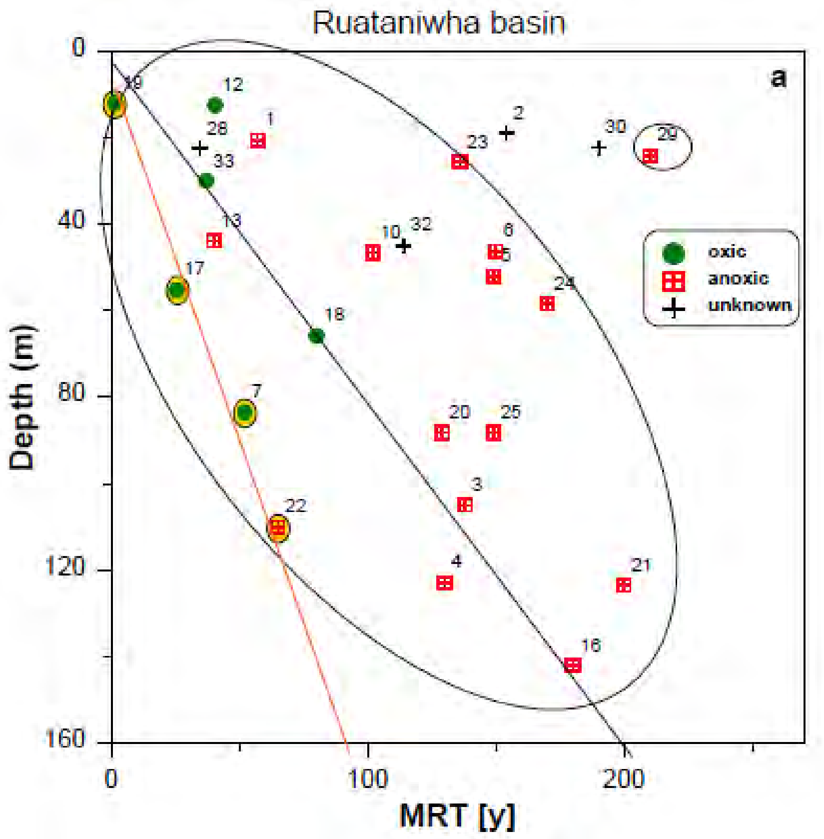

Figure 2.8 Groundwater age vs depth for the Ruataniwha Basin. The black line indicates the general age-depth relationship. The orange line indicates the near perfect age-depth relationship of wells in the vicinity of the lower Waipawa River (downstream of a losing reach of the river). Figure from Morgenstern et al. (2012) (labels refer to ID numbers in tables in Morgenstern et al. (2012)).

To help identify the recharge sources of the groundwater samples, water isotopes (^{18}O and ^{2}H) and dissolved gases (Ar and N2) were analysed and investigated together with the hydrochemistry of the water samples. River recharge signatures were found only in wells located near the lower reaches of larger rivers, like the Waipawa and Tukituki rivers, downstream of losing reaches. This is consistent with the interpretations of the age-depth relationship of the sampled groundwaters in the vicinity of the Waipawa River (see above), and indicates "gravel deposits connecting the present river bed to the deep groundwater flow system along these rivers" (Morgenstern et al. 2012). Oxic groundwater, which Morgenstern et al. (2012) associated with clean gravel aquifers without any organic matter present, was only found in wells close to the Waipawa River.

In the vicinity of a gaining reach of the Waipawa River in the east, near the exit of the river out of the basin, one well (4694) shows a very clear river recharge signature, and springs in this area exhibit "a mixture of rain and river recharge" (Morgenstern et al. 2012). Morgenstern et al. (2012) infer that this is likely because "groundwater in this area is river water that was lost from the river further upstream and is upwelling back to the surface at the end of the basin."

Rain recharge signatures were found in the southern part of the basin close to smaller rivers and streams, suggesting limited or no connection between surface water and the deeper groundwater in this area.

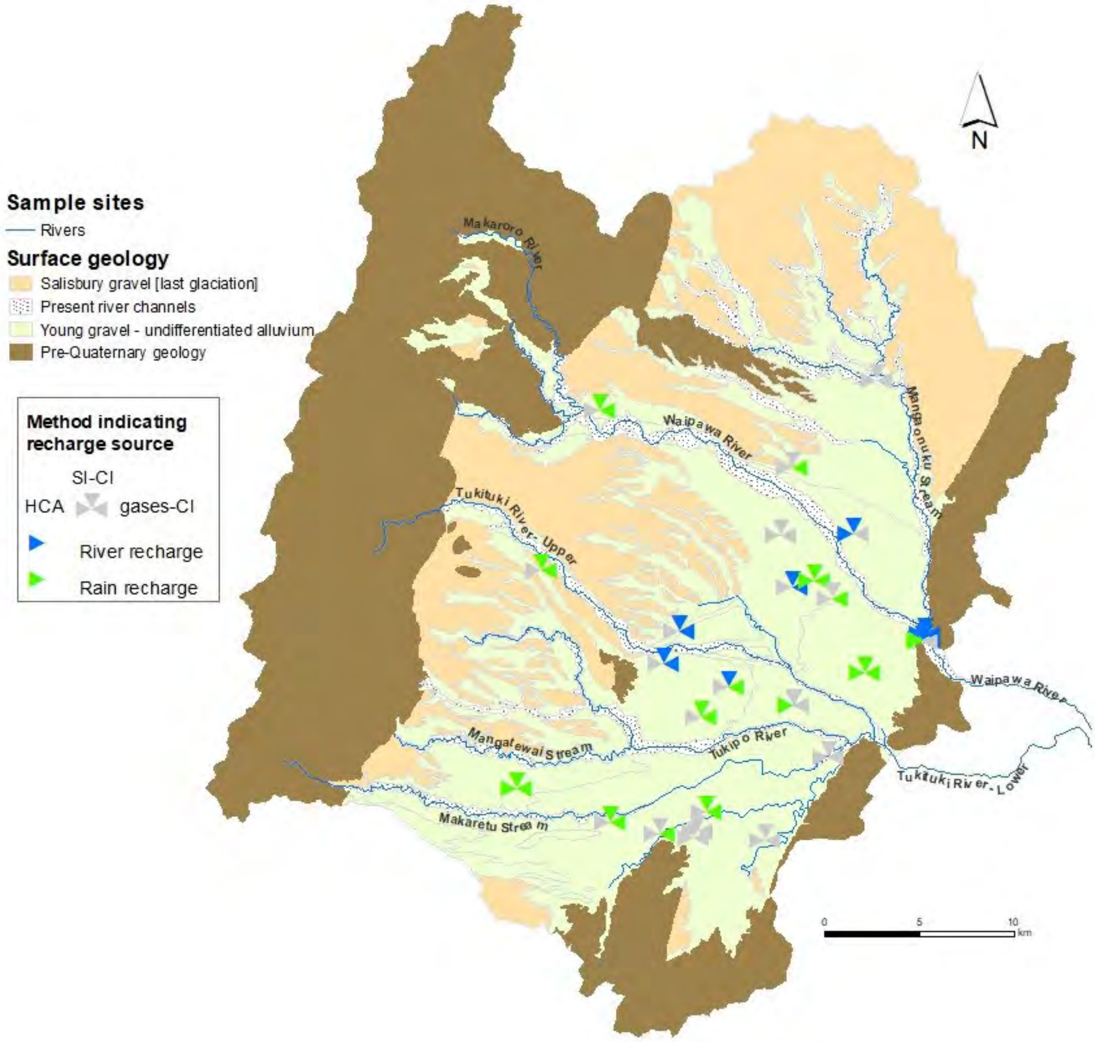

Figure 2.9 Recharge patterns in the Ruataniwha Plains. The direction of the triangle indicates the method used to identify the recharge source: left – hierarchical cluster analysis; top – stable isotopes and Cl; right – Ar-N2-Cl. Figure from Morgenstern et al. (2012).

The analysis of the hydrochemistry samples showed high variability in space and time consistent with the complicated hydrogeological setting of the Ruataniwha Basin, which consists of multi-layered aquifer systems in different lithologic strata and pockets of gravels. Some deep wells also showed alternating hydrochemistry concentrations over time, which Morgenstern et al. (2012) suggested indicated “that pockets of water with different hydrochemistry exist in close proximity”. They suggest that theses alternating hydrochemistry concentrations may be due to seasonal changes in recharge and groundwater abstraction that are noticeable in wells intersecting these pockets. However, there generally appeared to be a consistent relationship between hydrochemistry and groundwater age, indicating that “despite the complex structure of the groundwater system with localised heterogeneity at basin-wide scale, groundwater in the basin overall has a homogeneous flow pattern” — (Morgenstern et al. 2012).

2.4 Review of Existing Geological and Hydrogeological Models and New Model Development 2018

Harper (2018) reviewed the geological and hydrogeological data and models available in the Ruataniwha Plains as part of a groundwater and surface water modelling initiative “to assess the long-term and cumulative effects of increased allocation and the effectiveness of proposed mitigation schemes”. As part of this work, the author developed an updated lithostratigraphic 3D model with the purpose to assess the suitability of the existing groundwater flow model or provide the basis for a new groundwater flow model.

The geological and hydrogeological models reviewed by Harper (2018) were:

- The conceptual hydrogeological model developed by Pattle Delamore Partners (PDP) (1999).
- The geological model developed by Francis (2001).
- The numerical groundwater model by Murray (2002a; 2002b).
- The numerical groundwater model by Phreatos Groundwater Research and Consulting (2003).
- The numerical groundwater model by Baalousha (2008).

Subsequently, Harper (2018) developed four 3D (hydro) geological and lithological models using Leapfrog and Rockware Software:

1. Hydrogeological model from cross-sections and geological maps by PDP (1999).
2. Geological model from cross-sections, contour maps and geological maps by Francis (2001).
3. A hybrid geological model that combined the PDP (1999) and Francis (2001) (hydro) geological models by identifying similarities between the layers in these models and grouping them into common layers (Figure 2.10), as well as incorporating additional information from the most recent geological map (Lee et al. 2011).
4. A lithological model developed using well logs (with extents limited based on model units within the hybrid geological model).

The development of models 1 and 2 provided a 3D model basis to better explore the differences between the two main existing conceptual models of the area. These were then utilised to develop model 3 as a synthesis of the existing information. Model 4 was then developed only within certain model units of the hybrid geological model. Table 2.1 provides a correlation of the map and model layers between Francis (2001), PDP (1999), Harper’s (2018) hybrid model, the Brown (2002) bore logs, and the stratigraphic units in the most recent geological map (QMAP; Lee et al. 2011).

Models 1, 2 and 3 were developed in the Leapfrog Geo 3D modelling software at an XY resolution of not coarser than 100 m. The data used in these models were the geological interpretations, cross-sections and maps from PDP 1999 and Francis 2001; a DTM that was developed by combining LiDAR data, where available, with a LINZ 8 m DEM; QMAP surface geological data (Lee et al. 2011) and well log data (Harper 2018).

Model 4 was built at an XYZ resolution of 250x250x2 m using Rockware 2015 software and 640 bore logs from the HBRC wells database (WellStor). It was then imported into Leapfrog Geo 3D modelling software to limit the extents based on Model 3. The lateral model boundary was set to the extent of Quaternary deposits mapped at the ground surface in the

Ruataniwha Basin. To identify the lithological units, the primary lithology field of the logs was simplified into 12 main lithological units. Harper (2018) used these logs in addition to QMAP data, petroleum well logs, and data and surfaces from previously developed geological and hydrogeological models to build the lithological model. A boundary filter was used to remove any wells deeper than the base of Kidnappers Group (as per the surfaces defined in the hybrid geological model (Model 3)).

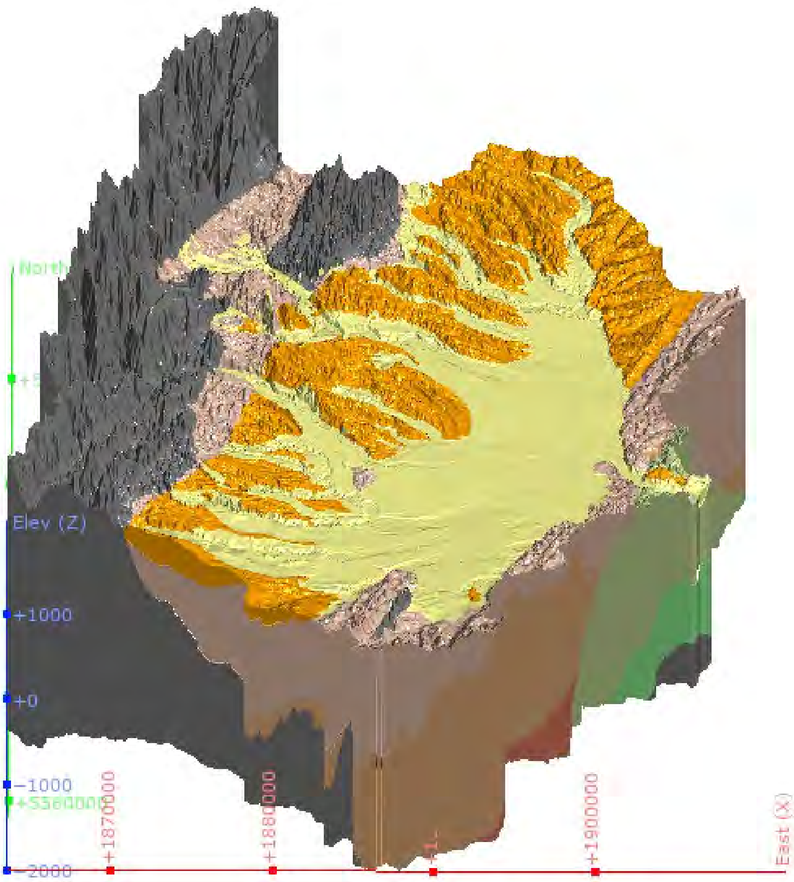

Figure 2.10 Hybrid geological model (Model 3) for the Ruataniwha Plains developed by Harper (2018). View towards the north. Units from youngest to oldest: light yellow = Young gravels; orange = Kidnappers Group; light pink = Mangaheia Group; brown = Tolaga Group; red = Mangatu Group; olive green = Tinui Group; green = Mangapurupuru Group; dark grey = Torlesse Terrane basement.

Harper (2018) also investigated the use of the lithologic data to delineate hydrofacies units[2], and noted that, “unlike the Heretaunga Plains where a clear distinction can be made between confining and aquifer sediments, there are no clear patterns within the lithologies to greatly assist with delineation of hydrofacies”. This is due to the gravel prevalence in the aquifer and the confining units in the Ruataniwha Plains, resulting in it being “almost impossible to distinguish independently from lithological or geological data alone” (Harper 2018).

[2] A hydrofacies unit is a homogeneous sedimentological unit or a homogeneous but not necessarily isotropic hydrogeological unit formed under characteristic conditions which lead to characteristic hydraulic properties. Understanding hydrofacies units can be useful to understand hydrogeological characteristics, particularly where lithological units may be rapidly varying and highly heterogeneous.

Additional summary information provided by Harper (2018) includes:

- The main groundwater system is formed within alluvial sediments deposited during the Quaternary period.
- “The depth of these alluvial sediments beneath the Ruataniwha Plains vary between studies but broadly range between 150–250 metres. Typically, the model developed by Francis (2001) indicates a greater thickness of alluvial sediments compared with PDP (1999).”
- “Wells drilled for groundwater are predominantly screened to the upper 50 metres (66%) and therefore, generally describe the shallow part of the aquifer system. There are only 16 wells greater than 150 metres.”
- “In general, Late Quaternary gravels form the more permeable groundwater pathways within the Quaternary strata and are characterised by unconsolidated gravel, clay, silt and volcanic ash forming near-surface deposits over much of the plains and on alluvial terraces to the north, west and south of the plains. Thickness of these deposits is greater to the east of Highway 50 than to the west.”
- “In the central plains area, within the Waipawa River Catchment, the aquifer system is characterised by a shallow zone of relatively loose unconfined gravels. Baalousha (2010) characterised this zone with higher calibrated hydraulic conductivities. Toward the south between Makaretu and Tukituki Rivers, a sequence of clay bound gravels form an aquitard over the main productive aquifer within the Late Quaternary deposits (PDP, 1999). This aquitard is up to 80 metres thick in this area and thins to the north.”
- “Beneath the Quaternary alluvium lie a considerable thickness of Pliocene-Pleistocene marine sediments. These consist principally of mudstone, sandstone, conglomerates and limestone, which may contain deeper aquifer sources and interact with some of the younger alluvial aquifer formations. Petroleum exploration indicates limestone formations beneath the plains contain fresh water and are highly porous. Some of these formations can be encountered at shallow depths on the edge of the plains near Limestone surface outcrops.”
- “PDP (1999) delineate the Quaternary deposits into five hydrogeological units based primarily on lithological characteristics. Francis (2001) delineate the Quaternary deposits into Salisbury Gravel and Late Quaternary deposits (referred to as young gravels).”
- “Lithological markers used in the studies to delineate model units are not clearly identifiable from the well logs, particularly within the Quaternary sediments.”
- “The Upokororo formation, Ancient terrace deposits and possibly Old Terrace deposits (PDP, 1999) are approximately equivalent to Salisbury Gravel (Francis, 2001) and crop out broadly where Lee et al, 2011 define Kidnapper Group and middle Quaternary deposits. These deposits are considered significantly more compacted and cemented than the younger terraces. Few wells are drilled to these older sediments.”
- “The Recent Terrace Group and possibly Old Terrace deposits (PDP, 1999) are approximately equivalent to the young gravels (Francis, 2001) and form the main producing aquifers in the area. These deposits are not considered cemented.”
- “Clear hydrogeological layers could not be identified from the lithological model. In the alluvial sediments of the Ruataniwha Basin both the confining and aquifer material are composed of similar lithologies. Lithological modelling further highlighted the heterogeneity in the system and the difficulty of using well log data to build a hydrofacies model.”

- "Recent numerical groundwater studies adopt the conceptualisation presented by Francis (2001) and divide the Ruataniwha Plains aquifer system into two layers under the premise, the units are geologically distinct and therefore hydrogeologically distinct. The seismic interpretations are not available for these cross sections and therefore it is difficult to evaluate the replicability of these boundaries."
- "The lithological data used to delineate model units such as in PDP (1999) is of variable quality, and at times contradictory, and therefore interpretations, require a considerable amount of judgement. Lithological and geological descriptions, although useful, are generally poor indicators for hydrofacies modelling, especially in complex, heterogeneous alluvial systems. As such, there exists large uncertainty regarding the hydrogeological structure of the alluvial sediments beneath the Ruataniwha Basin."

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Table 2.1 Summary of relationships between different geological models and maps relevant for the Ruataniwha Plains.

Geological Map of New Zealand at 1:250,000 (Heron 2020)*	Harper 2018 Hybrid Geological Model		Francis 2001	PDP 1999	Brown 2002
OIS1 Holocene river deposits	Young gravels		Young gravels	Recent Terrace Aquifer Group: Central Plains Unconfined Aquifer (loose gravel deposits)	Fairfield (Post glacial)
				Recent Terrace Aquifer Group: Tukipo Aquitard** (clay-bound gravels)	
				Recent Terrace Aquifer Group: Recent Terrace (Fairfield terrace – <15 000 years old)***	
OIS2 Late Pleistocene river deposits; OIS3 Late Pleistocene river deposits***				Old Terrace Aquifer Group (Tikokino terrace – ~15 000 years old)	Tikokino (Last glacial maximum) Ongaonga (Last interglacial) Ngaruru (penultimate glacial) Glen Appin (penultimate interglacial)
OIS2 Late Pleistocene river deposits					
OIS6-OIS2 Mid Pleistocene to Late Pleistocene river deposits; Middle Pleistocene river deposits					
					Hugenden (Glacial) Blackburn (Glacial)
Early Quaternary Kidnappers Group	Salisbury Gravel (Kidnappers Group)		Salisbury Gravel (Late Pliocene to Early Pleistocene)	Ancient Terrace Aquifer Group (Ongaonga, Ngaruru, Glen Appin, Hugenden, Blackburn terraces – ~200 000 – 400 000 years old)	Salisbury Gravel Poutaki Pumice Fm***** Potaka Tephra
				Upokororo Formation, Pebbly Hill	
Pliocene Mangaheia Group	Pre-Salisbury Gravel (Pre-Kidnappers Group)	Mangaheia Group	Top Pliocene sandstone and siltstone	Ashley Formation****	Upokororo Fm
			Upper Pliocene limestone		Okauawa Fm
			Upper Pliocene mudstone		Pukeroa Oyster Shellbed
			Te Onepu Limestone		
			Tukituki Sandstone		
			Mid to lower Pliocene mudstone and sandstone		
		Tolaga Group	Miocene mudstone and sandstone		
		Mangatu Group	Whangai Formation		
		Tinui Group			
		Mangapurupuru Group			
Torlesse Composite Terrane	Torlesse (Composite) Terrane			Greywacke	

*Note that QMAP units and units from older models cannot always be directly correlated due to differences in mapped formations and map scales.

**This aquitard is not represented in QMAP as a separate geological unit.

***There is also some overlap with areas that have been mapped as OIS6-OIS2 Mid Pleistocene to Late Pleistocene river deposits and Middle Pleistocene river deposits.

****Noted by Harper (2018) to generally represent pre-Quaternary deposits and is therefore shown to be generally equivalent to pre-Quaternary units in this table. Ashley Formation is included in Kidnappers Group in QMAP, however, according to Grant-Taylor (1978) it appears to be equivalent to Mangaheia Group.

***** “The Salisbury Gravel overlies, is interbedded with and underlies Poutaki Pumiceous Formation.” — Brown (2002).

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2.5 Ruataniwha Aquifer Properties Analysis and Mapping 2018

PDP (2018) aimed to provide aquifer property data, in particular hydraulic conductivity and storage, for the development of a new groundwater flow model for the Ruataniwha Basin.

As part of that work, PDP (2018) reviewed existing pumping test data in the Ruataniwha Basin, reanalysed tests where appropriate to derive additional information, and provided graphs and maps detailing the distribution of observed hydraulic properties in the Basin.

Within the study area, data was available for 83 pumping bores, and tests included constant rate tests as well as step drawdown tests in some cases. The review of the existing pumping test data included a pumping test reliability assessment to indicate the level of confidence in the observed aquifer parameters and detailed the process for selecting bores for reanalysis.

The reliability assessment split the pumping tests into reliable and unreliable tests: Constant rate tests with observation bores at similar depths as the pumping well, and with a noticeable drawdown in these bores, were deemed to be reliable. Any pumping tests that had no observations bores, or that had varying pumping rates (including step tests), significant interference from outside influences (e.g. from neighbouring bores), or unclear drawdown signals, were assessed to be unreliable.

The depth of the bores in the Ruataniwha Basin ranged from <10 m to >150 m. For the review and reanalysis, PDP (2018) split the bores into three categories using the top of the screen where it was available, or the bore depth. The resulting ‘depth’ categories were: 5–40 m, 40–75 m, and >75 m. PDP (2018) acknowledges that these depth intervals “do not necessarily represent geological intervals but are helpful for illustrative purposes. However, these depth intervals are broadly consistent with the ‘Younger Gravels’ and the Salisbury Gravels”.

For the reanalysis of the pumping tests, PDP (2018) uses the Boulton (1973) solution for leaky aquifers, via Hunt's (2012) ‘Function.xls’ Excel spreadsheets. A list of bores that were reanalysed and the original and reanalysed aquifer properties were provided in Appendix A of PDP (2018). Shapefiles of the results were provided to HBRC by the author at the time.

Mapping of the available transmissivity (T) data showed clustering in some places and data gaps in other places across the basin. Transmissivity ranges (<250 m^2/day, 250–1000 m^2/day, 1000–5000 m^2/day and >5000 m^2/day) were defined using all available T values in the Ruataniwha Basin, independent of the depth. Zone polygons for a lower T zone (250–1000 m^2/day) and a higher T zone (>1000 m^2/day) were delineated manually based mainly on the distributions of medium-high confidence parameters (Figure 2.11). PDP (2018) noted higher T values (up to 3,5000 m^2/day) north of the Tukituki River and up to and including the current Waipawa River channel, whereas south of the Tukituki River transmissivity values were generally <1000 m^2/day. The author suggested that this difference may be linked to depositional changes of the Tukituki and Waipawa rivers and that higher T zones are likely reflective of paleochannel gravel deposits. Outside of the high T zone, transmissivities are usually 250–1000 m^2/day, except in the south-western part of the basin, where T values of <250 m^2/day have been observed. Due to the lack of data, a clear zone delineation was not possible for that area. The author recommended that these zones are used for guidance only due to the heterogeneity of the deposits in the basin.

Analysing the T values over screened depths showed that higher transmissivities (>1500 m^2/day) generally appear to occur at depths between 40–60 m. At other depth ranges, transmissivities are generally lower.

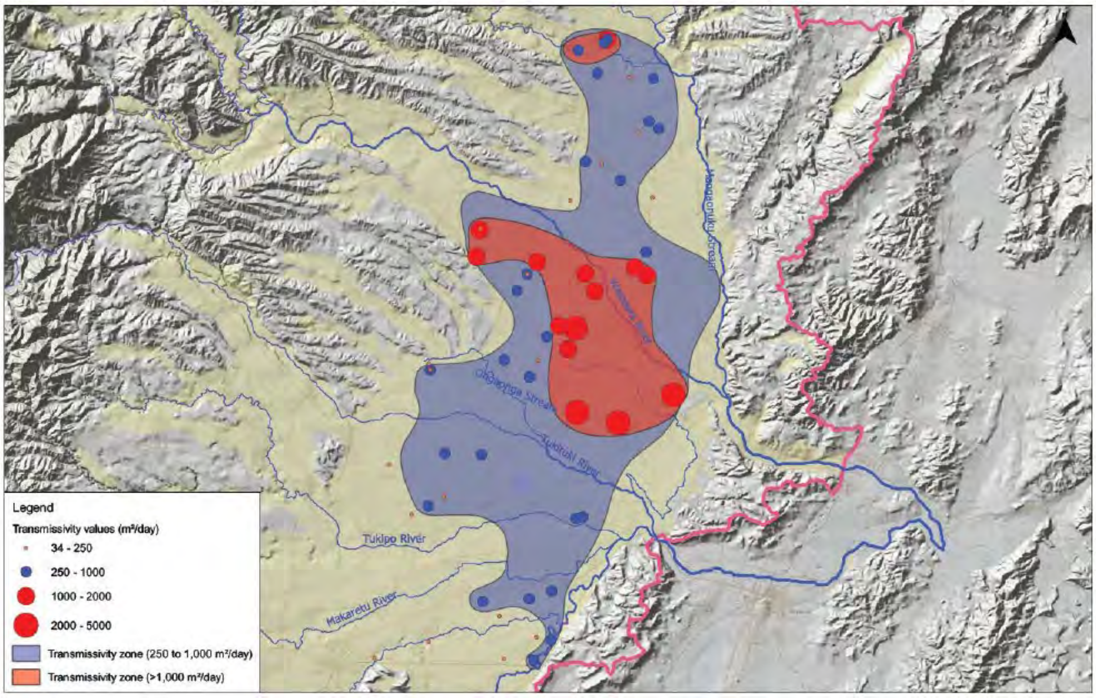

Figure 2.11 Transmissivity data available for the Ruataniwha Plains and manually delineated transmissivity zones. Figure from PDP (2018).

Horizontal hydraulic conductivity (Kh) was calculated by dividing the transmissivity by the screen length plus 4 m (or plus 2 m for screens at the top or bottom of the well). For those bores without screen information (13 bores), the screen length was assumed to be 6 m, which was the most frequent screen length of the bores with a screen record in the dataset. PDP (2018) noted that Kh values are generally an order of magnitude lower than T values, which is due to most of the wells having a 6 m screen length, resulting in a 10 m assumed aquifer thickness. PDP (2018) set Kh zones to be the same as T zones and mapped the results for different depth intervals, did the same as with the transmissivity data. PDP (2018) also calculated 35 vertical hydraulic Conductivity (Kv) values from aquitard conductance from aquifer test data, using the thickness of lower permeability layers from the lithological logs. They note that “the setting of the Ruataniwha Basin indicates that some leakage from shallow strata to deeper strata (or vice versa, where deep groundwater discharges to shallower strata) must occur” and assume the Kv values to be the maximum vertical hydraulic conductivity, with actual values potentially being lower. The area of higher Kv values generally overlaps with the zone of higher T values defined above.

Storativities (S) were plotted by depth slice. Data was checked, and storativity values from the most unreliable tests were disregarded. No patterns of S were noticeable, either laterally throughout the plains nor vertically, via the depth of the top of the screen, which PDP (2018) attributes to the “heterogeneous nature of the aquifer system”.

PDP (2018) concludes “Overall, based on our previous experience and this review, there appear to be no particularly discrete aquifers underlying the Ruataniwha Plains, rather there is a series of discontinuous alluvial deposits which have varying properties dependent upon depth and spatial location. This is consistent with previous studies, including PDP (1999).”

Table 2.2 Lithology for observed transmissivity and horizontal hydraulic conductivity ranges in the Ruataniwha Plains based on Kruseman and Ridder (1994). Table from PDP (2018).

Transmissivity Zone (m^2/day)	Equivalent Hydraulic Conductivity (m/day)	Equivalent Theoretical Strata[1]
<250	<20	Medium to fine sand
250 to 1,000	20 to 70	Sand and gravel mixes
1,000 to 5,000	70 to 350	Gravel
>5,000	>350	Gravel
Notes: 1. Based on estimates from Kruseman and de Ridder		

2.6 Managed Aquifer Recharge Investigation 2019

In 2019, Wallbridge Gilbert Aztec (WGA) conducted a Managed Aquifer Recharge (MAR) pre-feasibility assessment for the Central Hawke's Bay that covered the Ruataniwha SkyTEM survey area (Wallbridge Gilbert Aztec 2019). This assessment is of interest to the Ruataniwha SkyTEM data interpretation, as WGA also investigated lithological and hydrogeological conditions in the survey area and reviewed lithological borelogs and previous geological assessments. A field investigation was also part of the assessment. This section describes some of the findings of the assessment with regard to lithology and hydrology of the study area that may be of interest to the SkyTEM data interpretation, however, it does not represent a full review of the MAR assessment as that is beyond the scope of this work.

Based on bore logs, Wallbridge Gilbert Aztec (2019) identified several 10–15 m thick gravel beds within the Salisbury Gravel on a terrace west of Ongaonga but could not ascertain how connected these gravel beds were. They also describe thick gravel deposits in the Young Gravels unit along the western edges of the Ruataniwha Basin (Waipawa Valley).

Locations with deeper gravel are of particular interest to the pre-feasibility study and Wallbridge Gilbert Aztec (2019) describe "a substantial thickness of gravel mid-basin and north of the Waipawa River, near monitoring well 3076" and recommend that the area of deeper gravel in the central basin north of Waipawa River may be suited to target the confined Salisbury Gravel Aquifer.

Figure 2.12 Outcrop of Salisbury Gravel and overlying ignimbrite beside SH50, north of the Ruataniwha Basin. (Photo from Wallbridge Gilbert Aztec (2019).

The effectivity of MAR can be inhibited by clay layers and clay-bound gravels, and therefore the identification of these layers is important for MAR studies. Wallbridge Gilbert Aztec (2019) particularly note the numerous clay and silt layers and clay-bound gravels in the survey area, especially on the western and southern edges of the basin and underlying the Waipawa River.

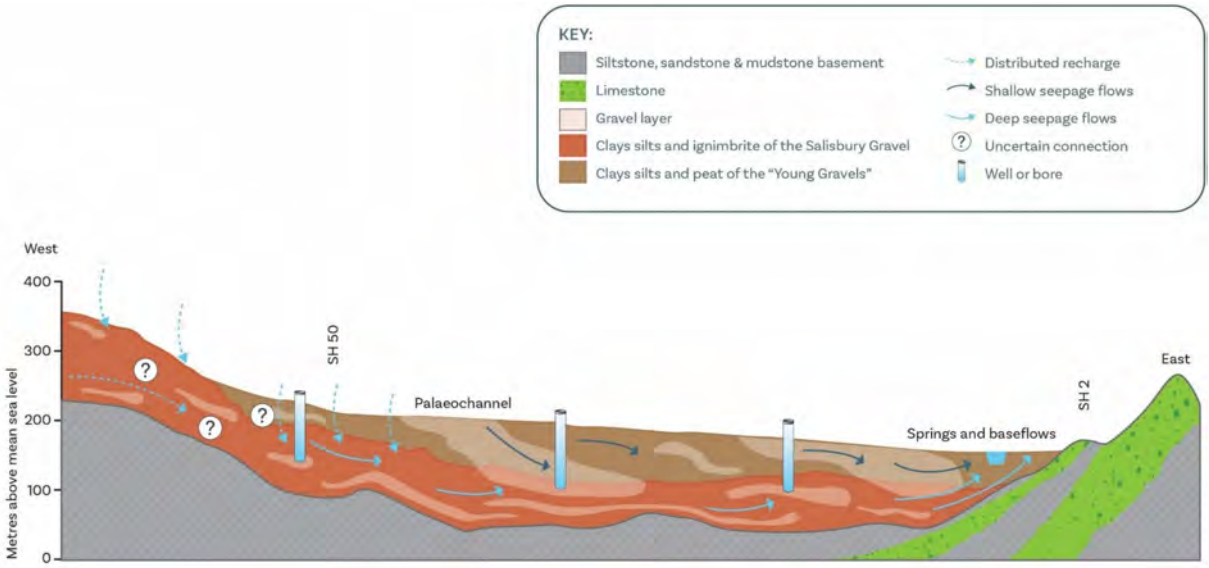

Figure 2.13 Conceptual hydrogeological model NW-SE cross-section north of Ongaonga. Figure from Wallbridge Gilbert Aztec (2019).

2.7 Groundwater Age and Groundwater Recharge Sources 2021

Morgenstern (2021) analysed hydrochemistry, groundwater age and stable isotope data from State of the Environment wells in the Ruataniwha Basin and put these into the context of earlier results analysed by Morgenstern et al. (2012). The aim of both studies was to interpret these data with regard to mean residence times, recharge source and groundwater processes. Data used in the Morgenstern (2021) report was attached to the PDF as an Excel file.

As river recharge has low excess air and low chloride, these were used to identify river versus rain recharge signatures. Four sites in the lower Holocene gravel fan of the Waipawa River (sites 19, 50, 49, 58) and one site in the Holocene gravel of an apparent paleochannel of the Tukituki River (site 6) showed river recharge signatures. Oxic groundwater was present in all the four lower Holocene gravel fan bores, and groundwater ages at these bores increased in the downstream direction (Figure 2.14). All other groundwater samples taken across the basin are, according to the recharge source indicators interpreted by Morgenstern 2021, most likely recharged from local rain.

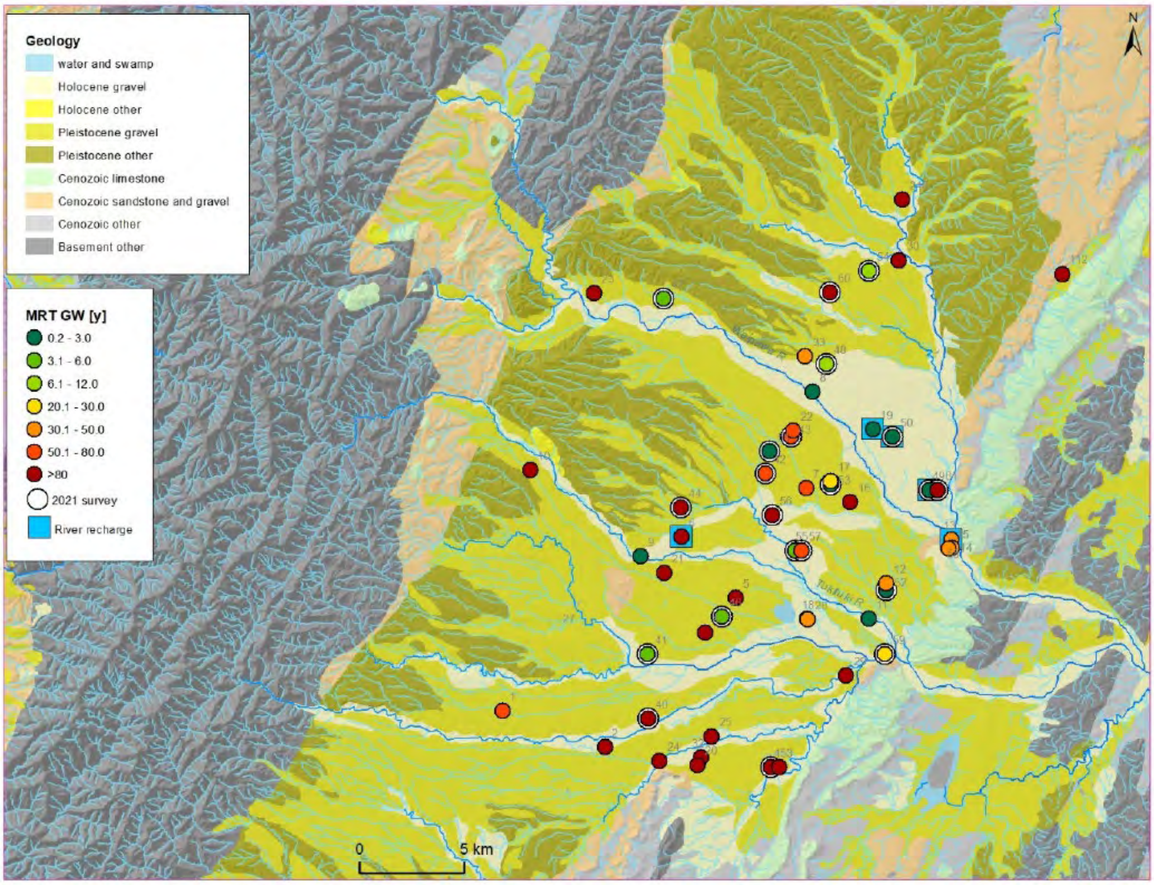

Figure 2.14 Mean residence times of groundwater (groundwater age) from Morgenstern at al. (2012) and Morgenstern (2021). The latter are identified by a double circle. Figure from Morgenstern (2021). The 2021 MRT estimates update the 2012 data where it exists.

While groundwater ages throughout the plains vary, older groundwaters are predominant in the Pleistocene gravels and, in particular, in the south of the plains, “indicating that the groundwater system there is disconnected from the surface.” This is also supported by the “relatively high” nitrate levels in Porangahau Stream and Tukipo River samples that indicate that “nitrate-loads from land-use activities directly discharge into the surface waterways than into the groundwater systems” (Morgenstern 2021).

Young groundwater with high nitrate levels was found in relatively shallow wells (7–26 m deep) in the Pleistocene gravel and in shallow and deeper (up to 79 m deep) wells in the Holocene gravel. This is likely due to higher transmissivity of the Holocene gravels compared to the Pleistocene gravels (Morgenstern 2021).

2.8 On-going Hydrogeological Model Development 2022

Several groundwater flow models have been developed in the past for groundwater management for the Ruataniwha Plains (Murray 2002a; Murray 2002b; Phreatos Groundwater Research and Consulting 2003; Baalousha 2008). These were summarised by Harper (2018).

A new groundwater flow model is currently being built by HBRC, following the development of the latest geological model by Harper (2018). The information on the flow model in this chapter has been summarised from a memo provided by HBRC (Rakowski 2021). As the construction of the flow model is currently in progress, the information presented in this chapter should be treated as preliminary and may have changed by the time the model is finalised.

Model layers for the new groundwater flow model were delineated based on the framework by Francis and refined using preliminary SkyTEM conductivity data provided by SkyTEM Australia (2020). The SkyTEM data was visualised in Leapfrog Geo 3D modelling software and compared to available geological information, like cross-sections from Francis (2001) and the Hybrid model developed by Harper (2018) (Figure 2.15).

Layers defined were:

- L1 Young Gravels
- L2 to account for localised confinement between L1 & L3
- L3 Salisbury Gravel

Pliocene limestone units that have been shown to have aquifer potential will not be represented as a separate layer in the model.

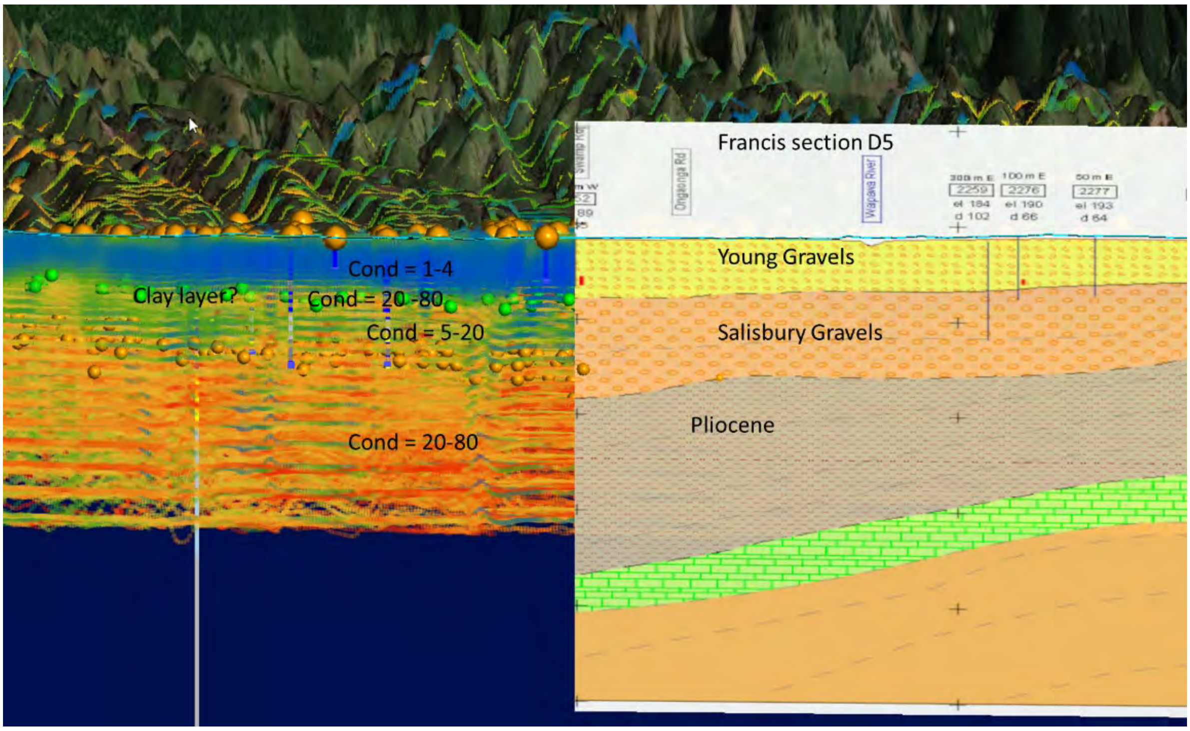

Figure 2.15 Preliminary SkyTEM-derived conductivity (Cond; left) compared with a cross-section from Francis (2001). Harper (2018)'s hybrid model units follow exactly the boundaries of Francis (2001)'s Young and Salisbury Gravels at the locations of cross-sections. Figure from (Rakowski 2021).

The comparisons showed that there is good agreement between the Young Gravels from Francis (2001) and the shallow low conductivity zone (cond. 1–4 mS/m) in the SkyTEM conductivity data. The contact to the underlying Salisbury Gravels is clearly visible in the SkyTEM conductivity data.

A thin higher conductivity zone (20–80 mS/m) between the Young Gravels and Salisbury Gravels may indicated a discontinuous clay layer, which was also found in bore logs.

The base of the Salisbury Gravels is not as distinct, however, Rakowski (2021) found that this unit generally had conductivity values between 5 and 20 mS/m, whereas underlying units had conductivities up to 80 mS/m.

Due to variability of conductivities across different geological formations, the delineation of model units could not be automated and was performed manually by digitizing a boundary between the Young and Salisbury gravels, and between Salisbury Gravels and lower units (Figure 2.16). The clay layer between Young Gravels and Salisbury Gravels was not digitised as it was discontinuous and relatively thin. Instead, the layer was defined in the groundwater model as a fixed thickness layer with varying parameter values indicating the presence or absence of clay.

The model domain includes the plains and parts of the surrounding hill country. Delineation of the gravel layers within the plains was reasonably straight forward but continuation into the hill country had to be done via manual digitizing of additional data points (Figure 2.17).

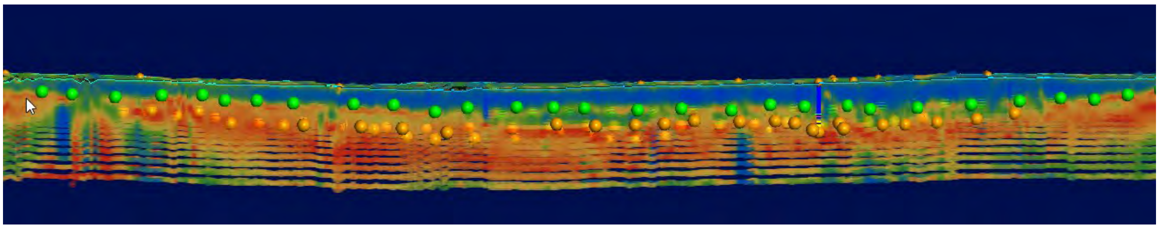

Figure 2.16 Manual Layer Interpretation. Figure from (Rakowski 2021).

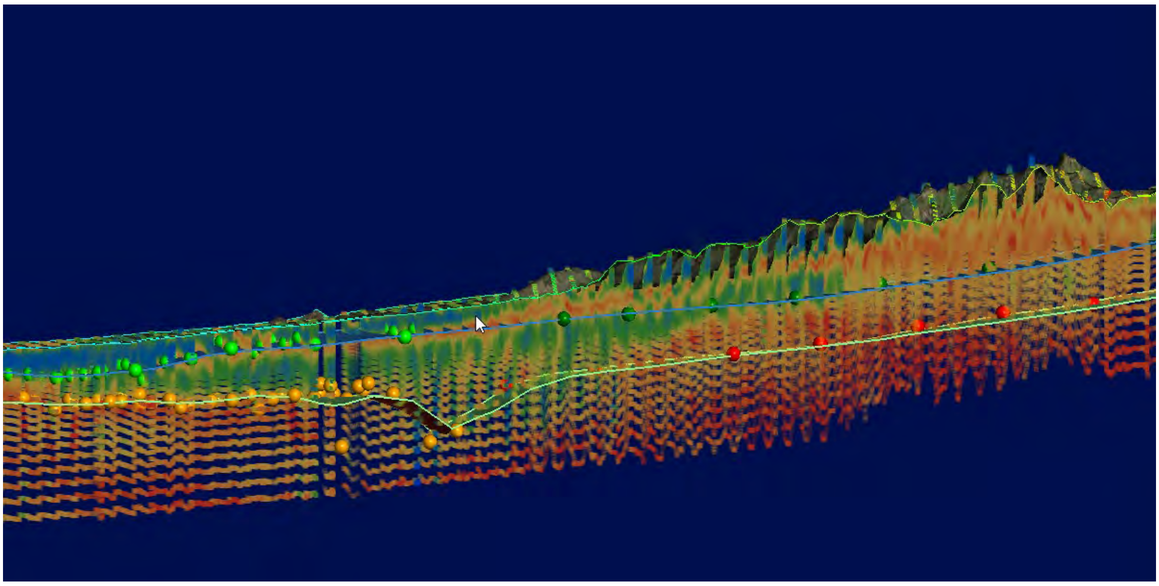

Figure 2.17 Model layers continue smoothly outside of main basin. Light green – interpreted base of young gravels, dark green – model layer continuation outside of basin. Yellow – interpreted base of Salisbury gravels in the main basin, Red – model layer continuation outside of the basin. Figure from (Rakowski 2021).

3.0 DATA INVENTORY

3.1 Surface Data Inventory

3.1.1 Digital Elevation Model

The latest, and highest-resolution, digital elevation model (DEM) that covers most the SkyTEM survey area is a 5 m horizontal resolution DEM provided by HBRC (Farrier 2022), which was generated from 2021 LiDAR data (Farrier 2021). Missing DEM data was supplemented using an older 5 m DEM that combined older LiDAR data with the SRTM v2 data (Farrier 2020). The resulting DEM for the survey area was down-sampled to 10 m resolution (Figure 3.1).

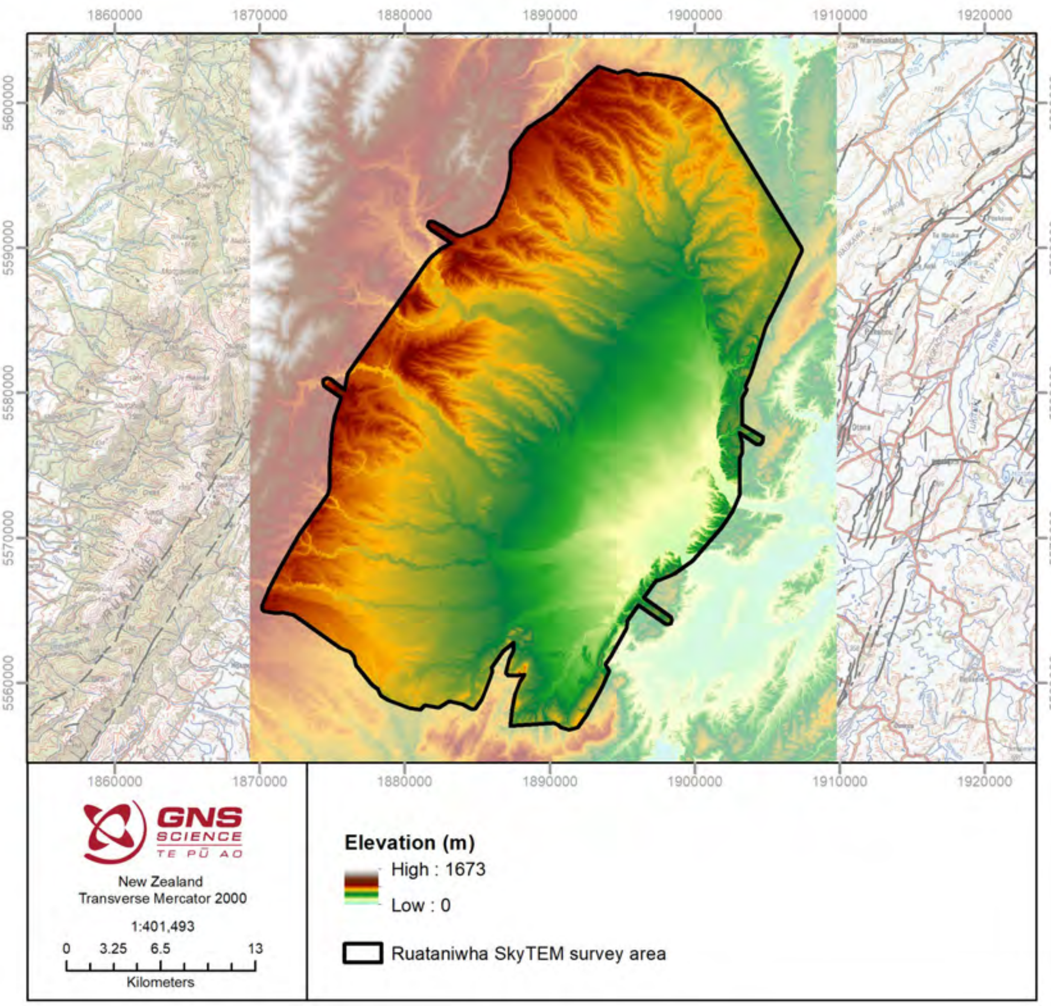

Figure 3.1 Map of the Ruataniwha Plains showing the extents of the digital elevation model and SkyTEM survey area.

3.2 Geological Data Inventory

3.2.1 Surface Geological Maps

There is one published recent geological map and one unpublished pre-2000 geological map available that cover the area of the SkyTEM survey partially or fully:

- Geological map of New Zealand 1:250,000-scale surficial geological map (Heron 2020); Figure 3.2 The attribute data of this map also includes main rock type (Figure 3.3).
- Geological map at the 1:50,000 scale by Brown (1998); Figure 3.4.

The 1:250,000-scale map is available in both vector format and as georeferenced raster images, whereas the 1:50,000 map is only available as a scanned image.

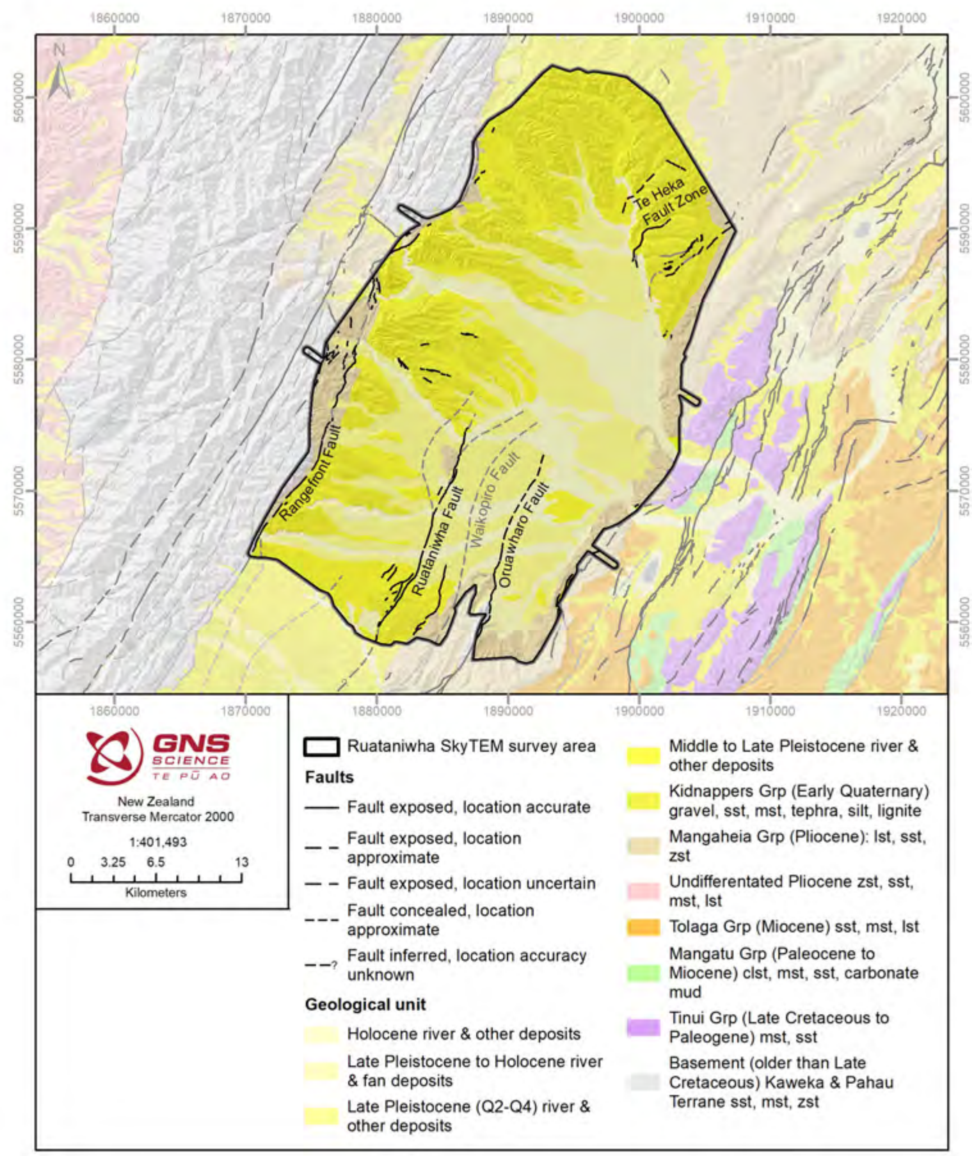

Figure 3.2 1:250,000-scale geological map of New Zealand for the wider survey area (Heron 2020). Active faults are shown in darker colours and inactive faults in lighter grey. The following abbreviations have been used in the legend: sst – sandstone, zst – siltstone, mst – mudstone, clst – claystone and Grp – Group.

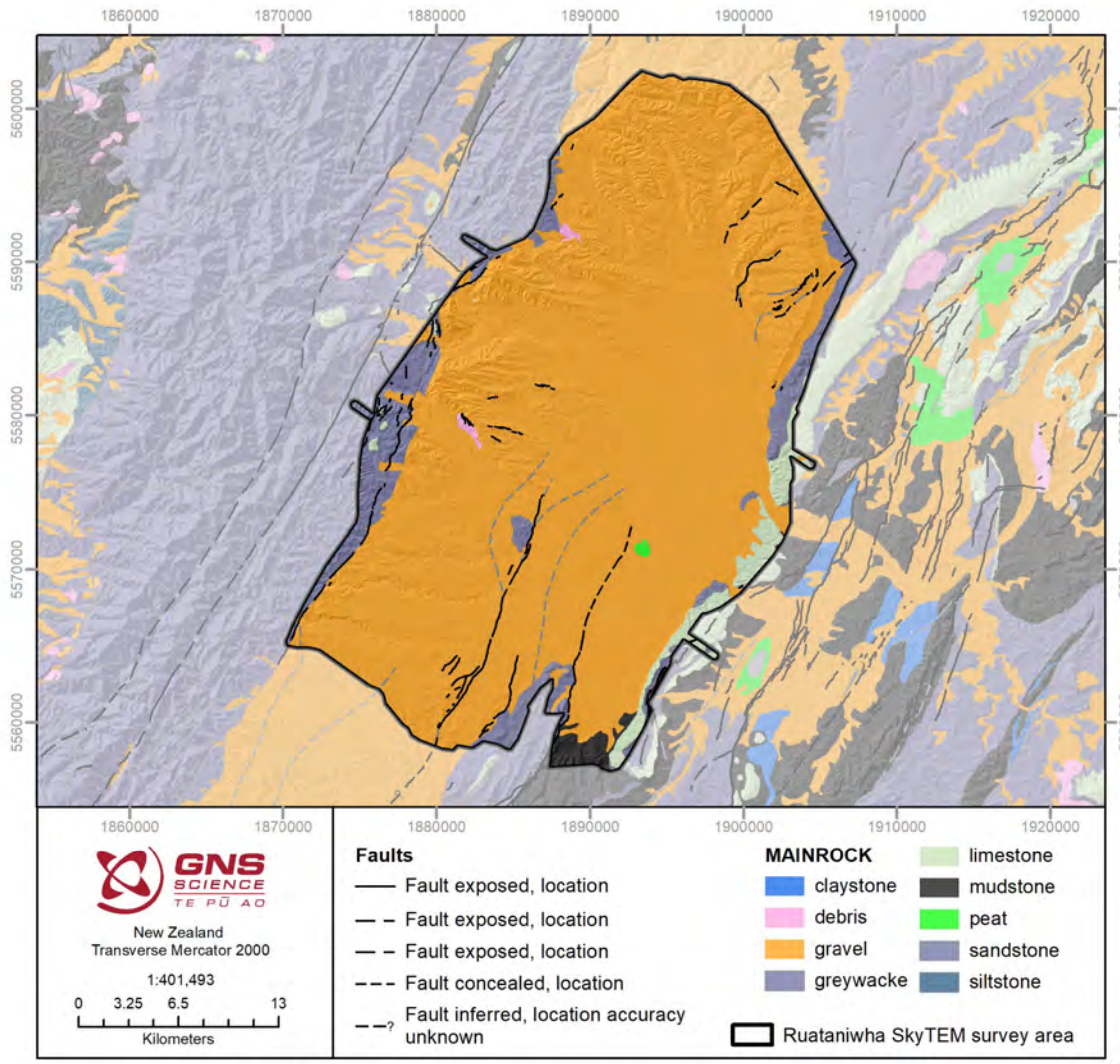

Figure 3.3 Main rock type for the wider survey area as recorded in the 1:250,000-scale geological map of New Zealand (Heron 2020).This map provides a clear overview of the prevalence of alluvial gravels and the locations of different types of pre-Quaternary deposits at or close to the ground surface.

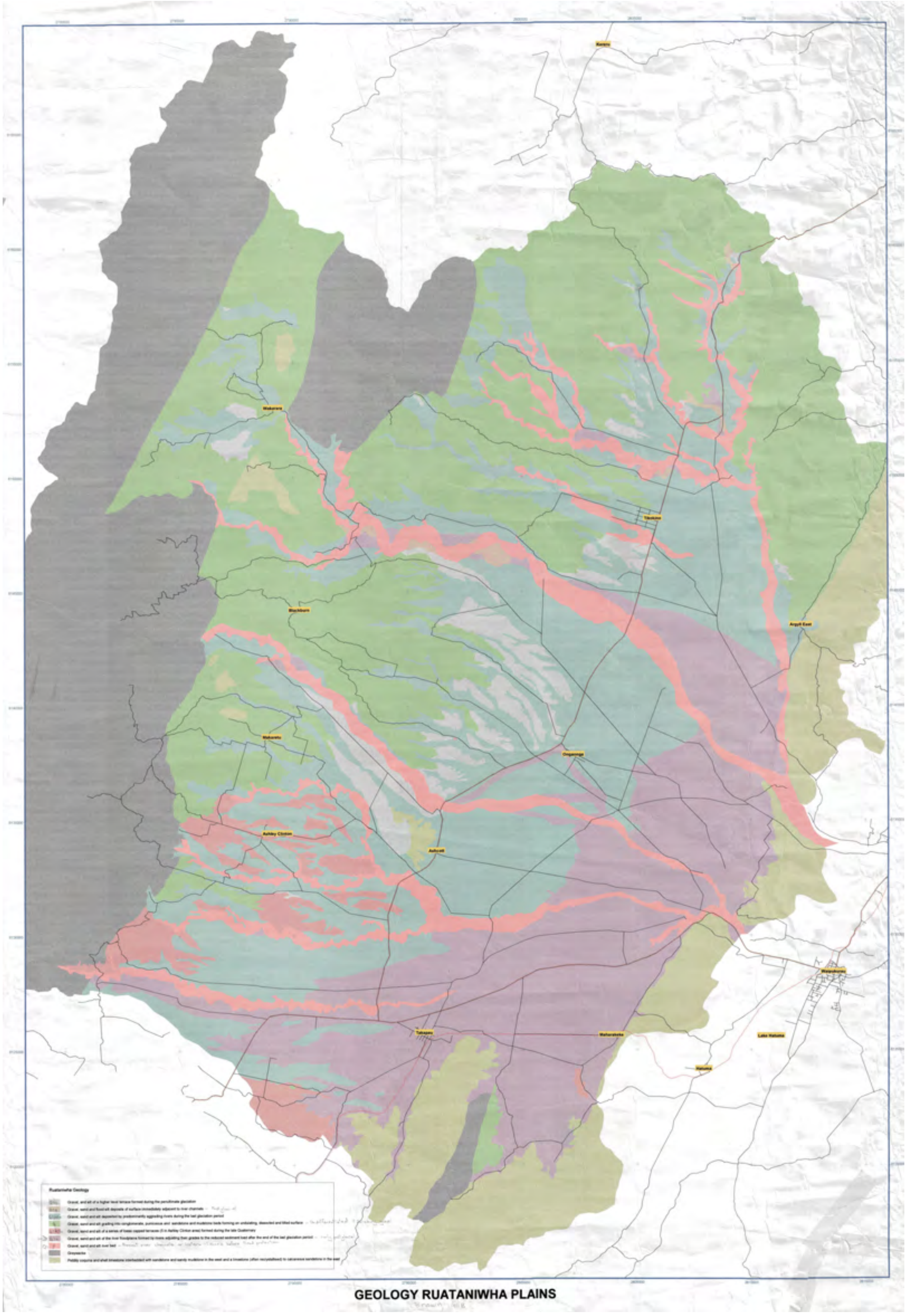

Figure 3.4 Scan of the 1:50,000 scale geological map of the Ruataniwha Plains by Brown (1998). **Map legend from top to bottom**: **light grey**: Gravel and silt of a higher level terrace formed during the penultimate glaciation; **light brown**: Gravel, sand and flood silt deposits of surface immediately adjacent to river channels (postglacial); **blue**: Gravel, sand and silt deposited by predominantly aggrading rivers during the last glaciation period; **green**: Gravel, sand and silt grading into conglomerate, pumiceous and sandstone and mudstone beds forming an undulating dissected and tilted surface (Undifferentiated Salisbury Gravel); **darker red**: Gravel, sand and silt of a series of loess capped terraces formed during the late Quaternary; **purple**: Gravel, sand and silt of the river floodplains formed by rivers adjusting their grades to the reduced sediment load after the end of the last glaciation period (early postglacial); **light red**: Gravel, sand and silt river bed (Present river channels or historic channels before flood protection); **dark grey**: Greywacke; and **olive**: Pebbly coquina and shell limestone interbedded with sandstone and sandy mudstone in the west and a limestone (often recrystalised) to calcareous sandstone in the east.

3.2.2 Geological Model Data

Modelled geological unit boundaries have been exported from the latest Leapfrog geological model (see Section 2.4) as 2D grid files (asci format; Harper 2022). In order from youngest to oldest, these consist of:

- 1_Refined_Hybrid_model_Hybrid_Top_Young_gravels.asc (Figure 3.5).
- 1_Refined_Hybrid model_Base_Hybrid_Young_gravels.asc (Figure 3.6).
- 2_Refined_Hybrid_model_Hybrid_ Top_Kidnappers_Group.asc (Figure 3.7).
- 2_Refined_Hybrid_model_Hybrid_Base_Kidnappers_Group.asc (Figure 3.8).
- 3_Refined_Hybrid_model_Coeval rocks_ Top_Mangaheia Group_Pl.asc (Figure 3.9).
- 3_Refined Hybrid_model_Coeval_rocks_Base_Mangaheia Group_PL.asc (Figure 3.10).
- 4_Refined_Hybrid_model_Coeval rocks_ Top_TolagaGroup_M.asc (Figure 3.11).
- 5_Refined_Hybrid_model_Coeval rocks_ Top_Mangatu_Group_EO.asc (Figure 3.12).
- 6_Refined_Hybrid_model_Coeval rocks_ Top_Tinui Group_Kia_Kiw.asc (Figure 3.13).
- 7_Refined_Hybrid_model_Coeval rocks_ Top_Mangapurupuru_Group_Kng_Kns.asc (Figure 3.14).
- 8_Refined_Hybrid_model_ Hybrid_ Top_TorlesseTerrane.asc (Figure 3.15).

In general, the tops of the formations were exported from the Leapfrog model. However, for the uppermost formations expected, the bases of the model layers were also exported. The names of the grids correspond to their names in the 3D model (Harper 2018), and the number corresponds to the model layer stratigraphic order in the model. The model grids are cut off at -2000 m as that was the base of the 3D model.

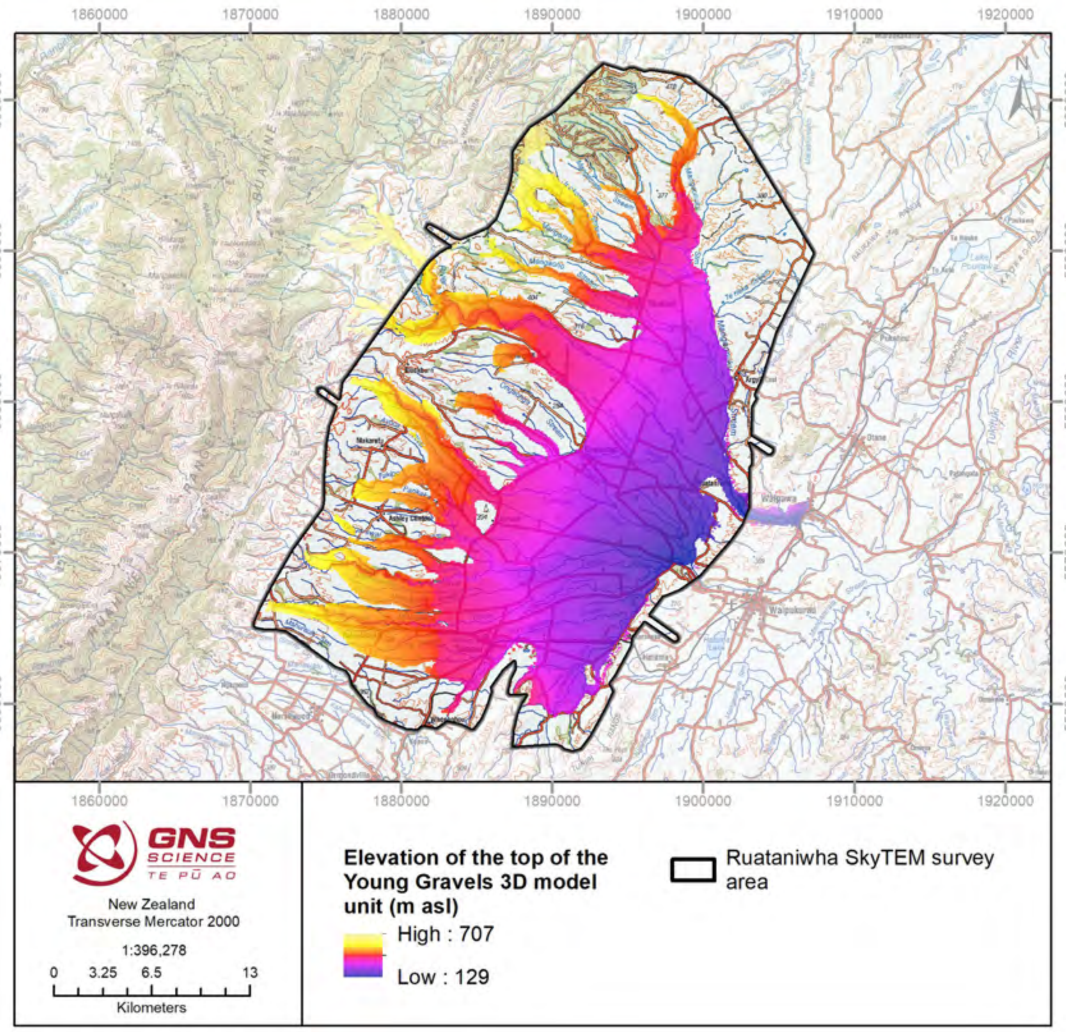

Figure 3.5 Elevation of the top of the Young Gravels model layer grid in the latest 3D geological model (Harper 2018).

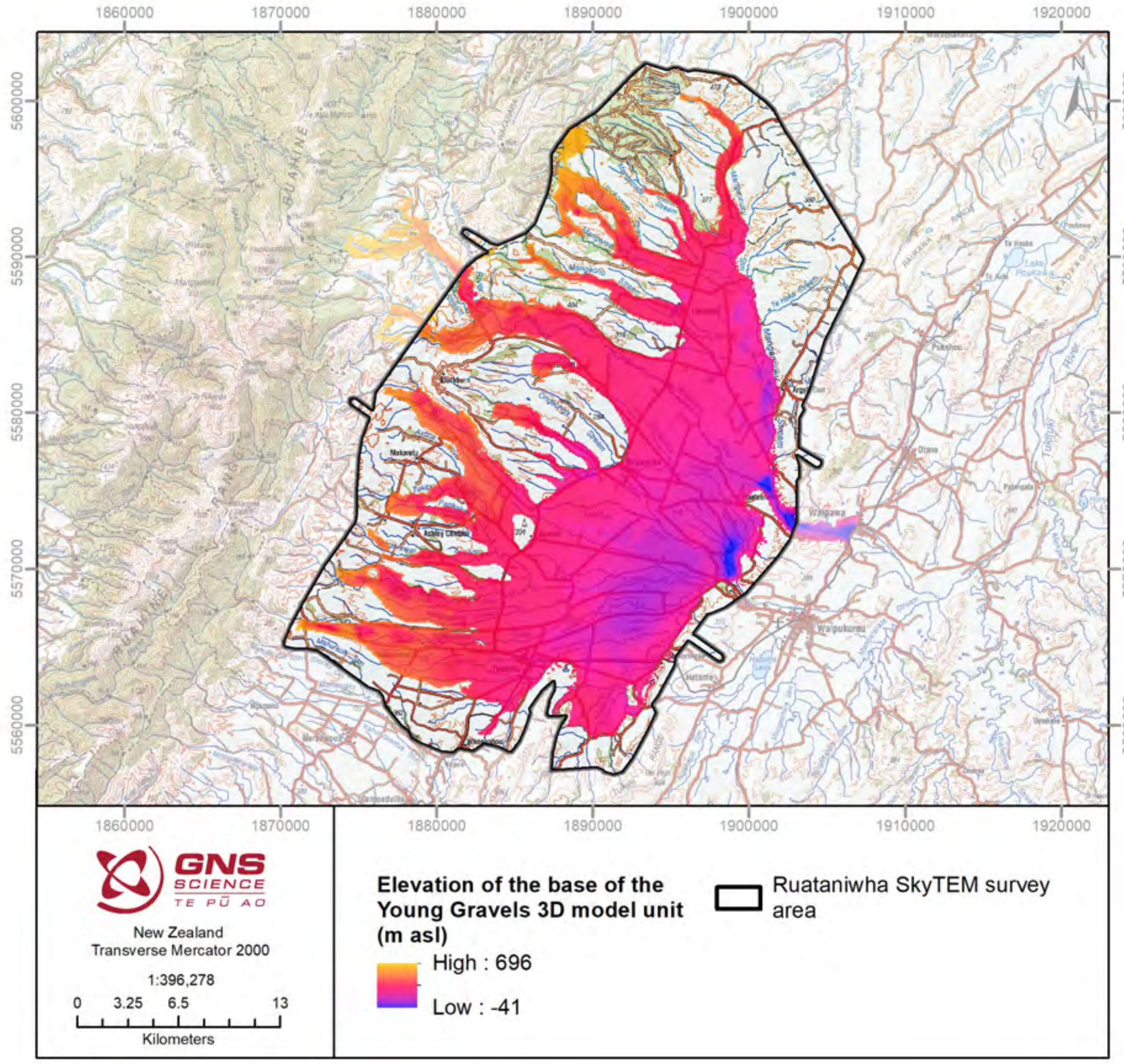

Figure 3.6 Elevation of the base of the Young Gravels model layer grid in the latest 3D geological model (Harper 2018).

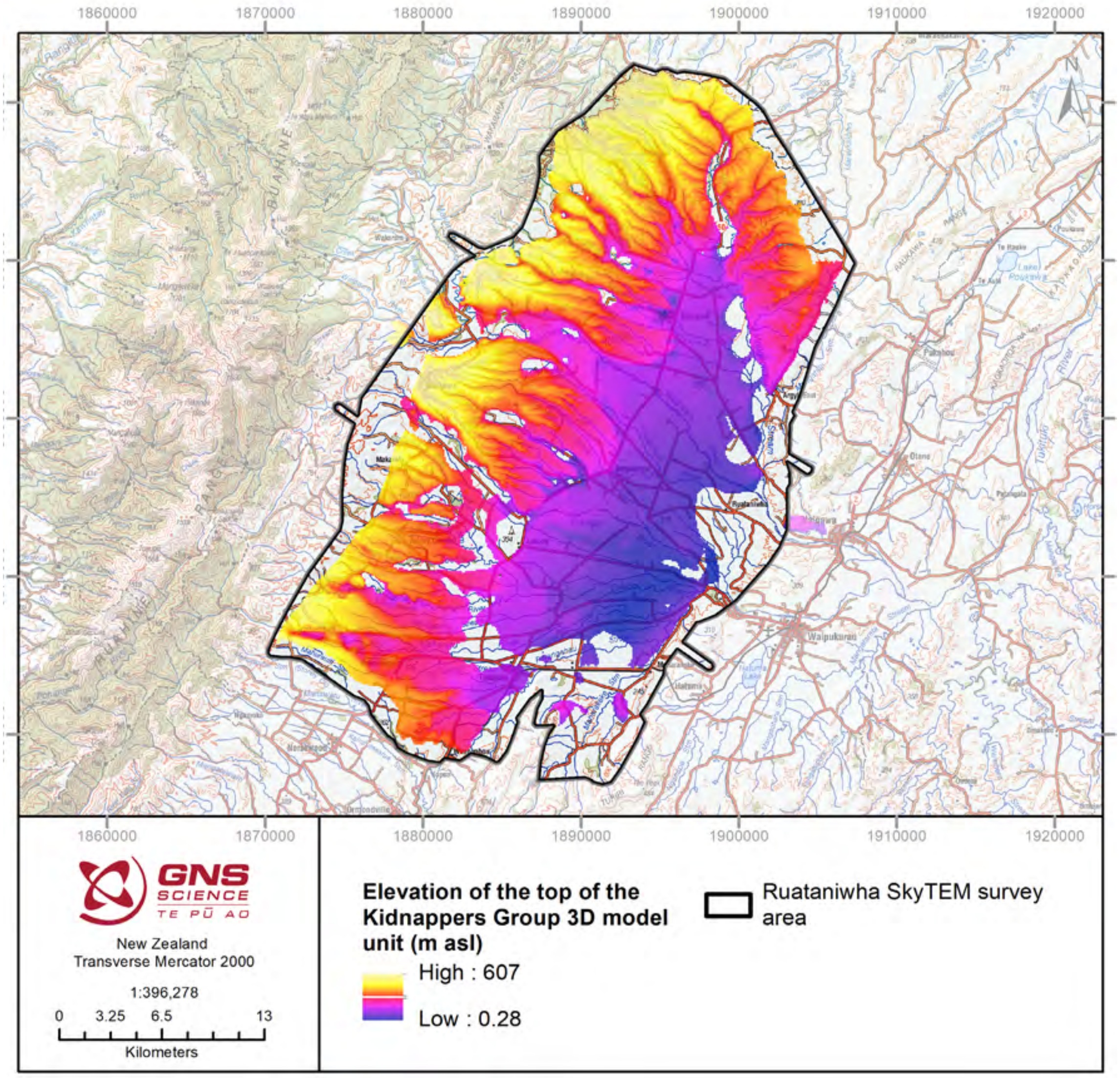

Figure 3.7 Elevation of the top of the Kidnappers Group grid in the 3D geological model (Harper 2018).

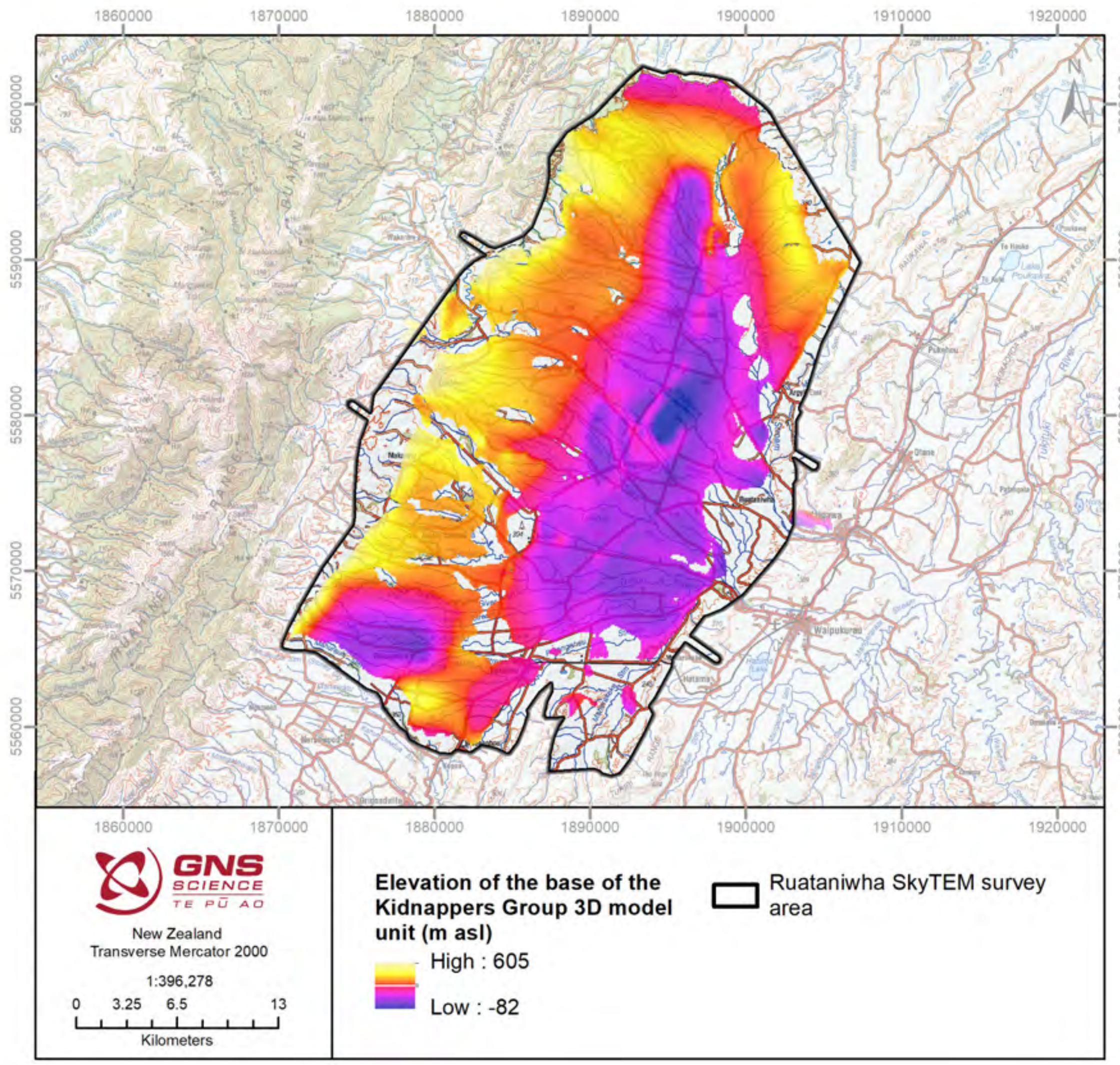

Figure 3.8 Elevation of the base of the Kidnappers Group grid in the 3D geological model (Harper 2018).

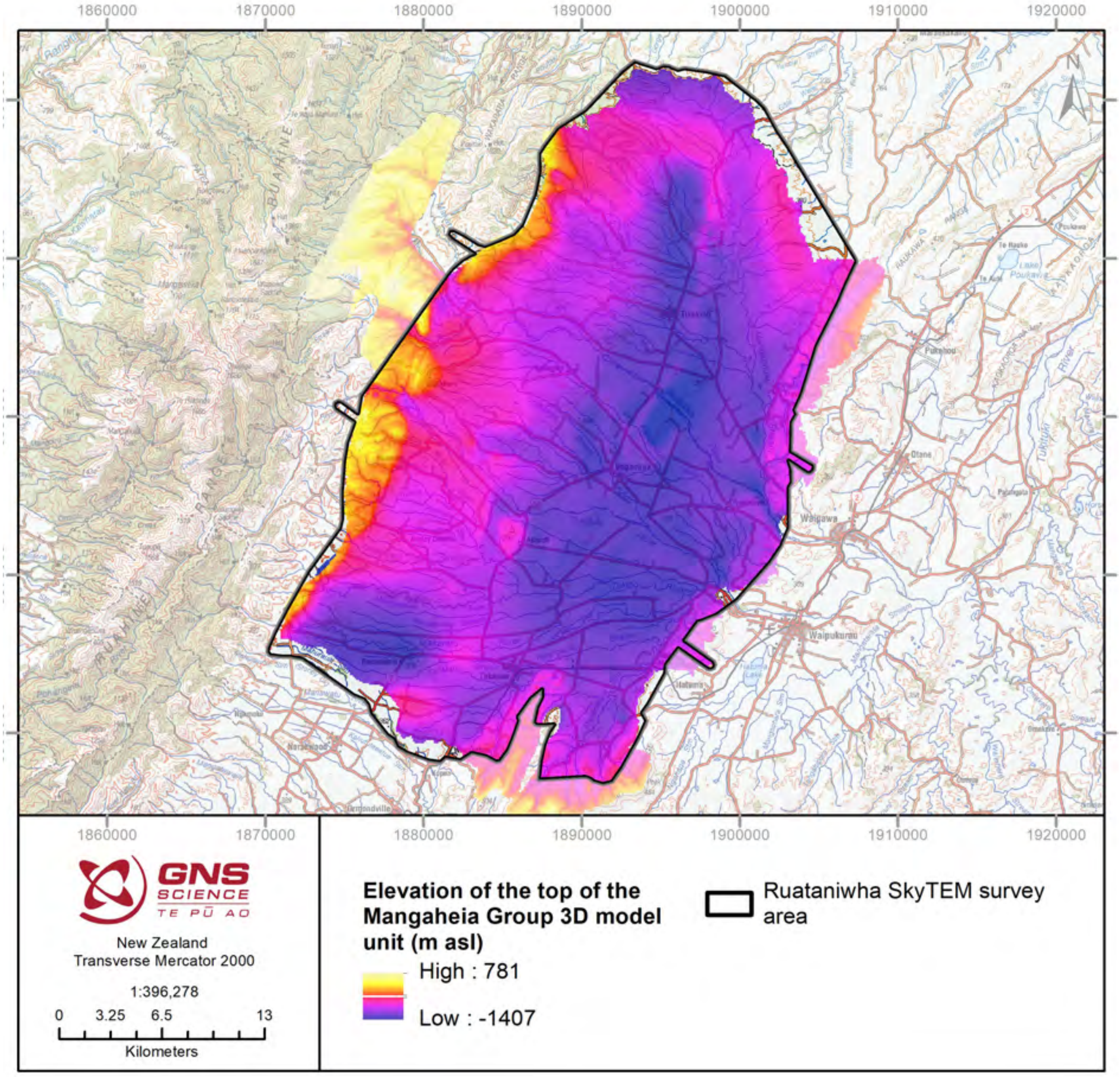

Figure 3.9 Elevation of the top of the Mangaheia Group grid in the 3D geological model (Harper 2018).

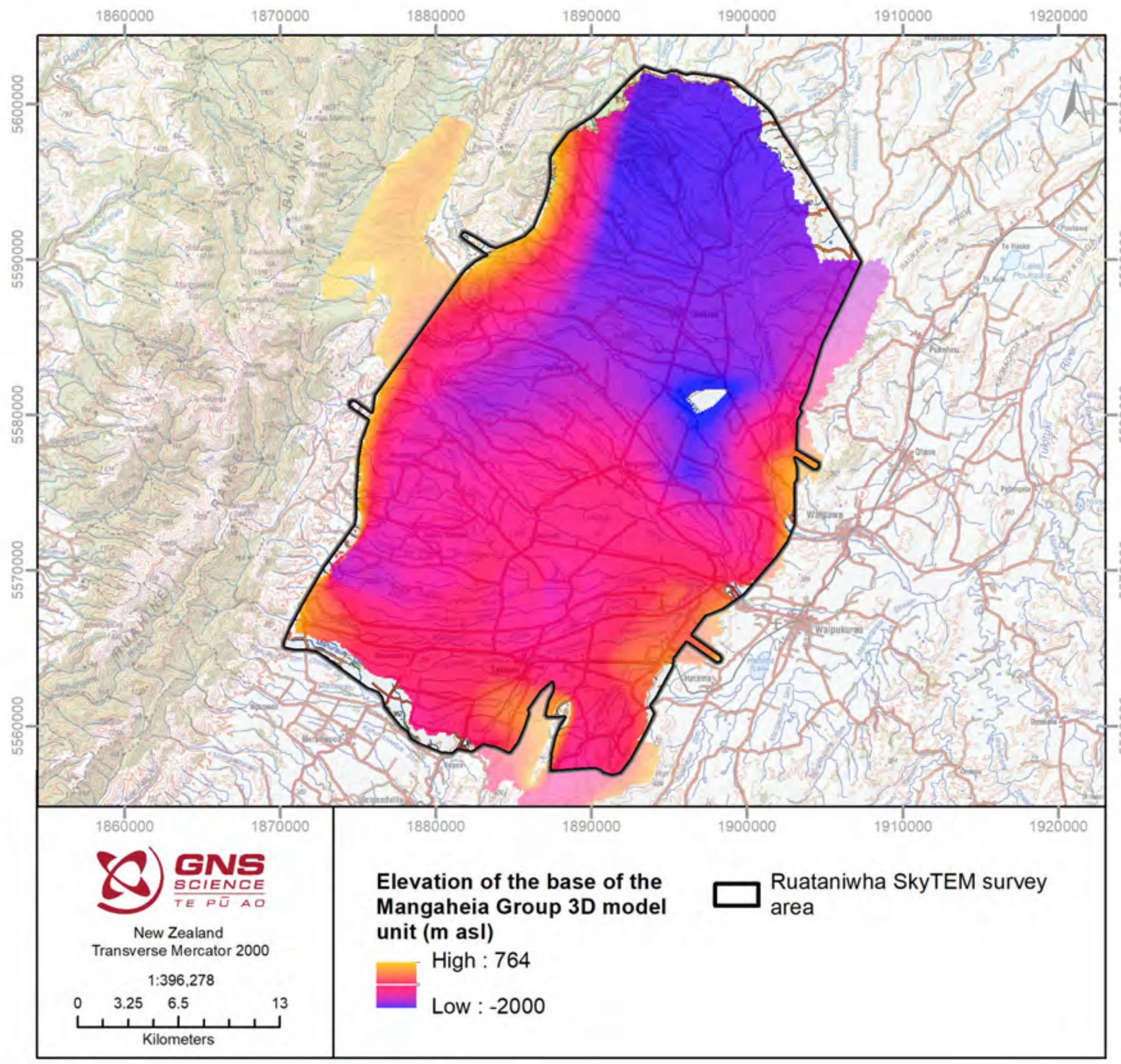

Figure 3.10 Elevation of the base of the Mangaheia Group grid in the 3D geological model (Harper 2018).

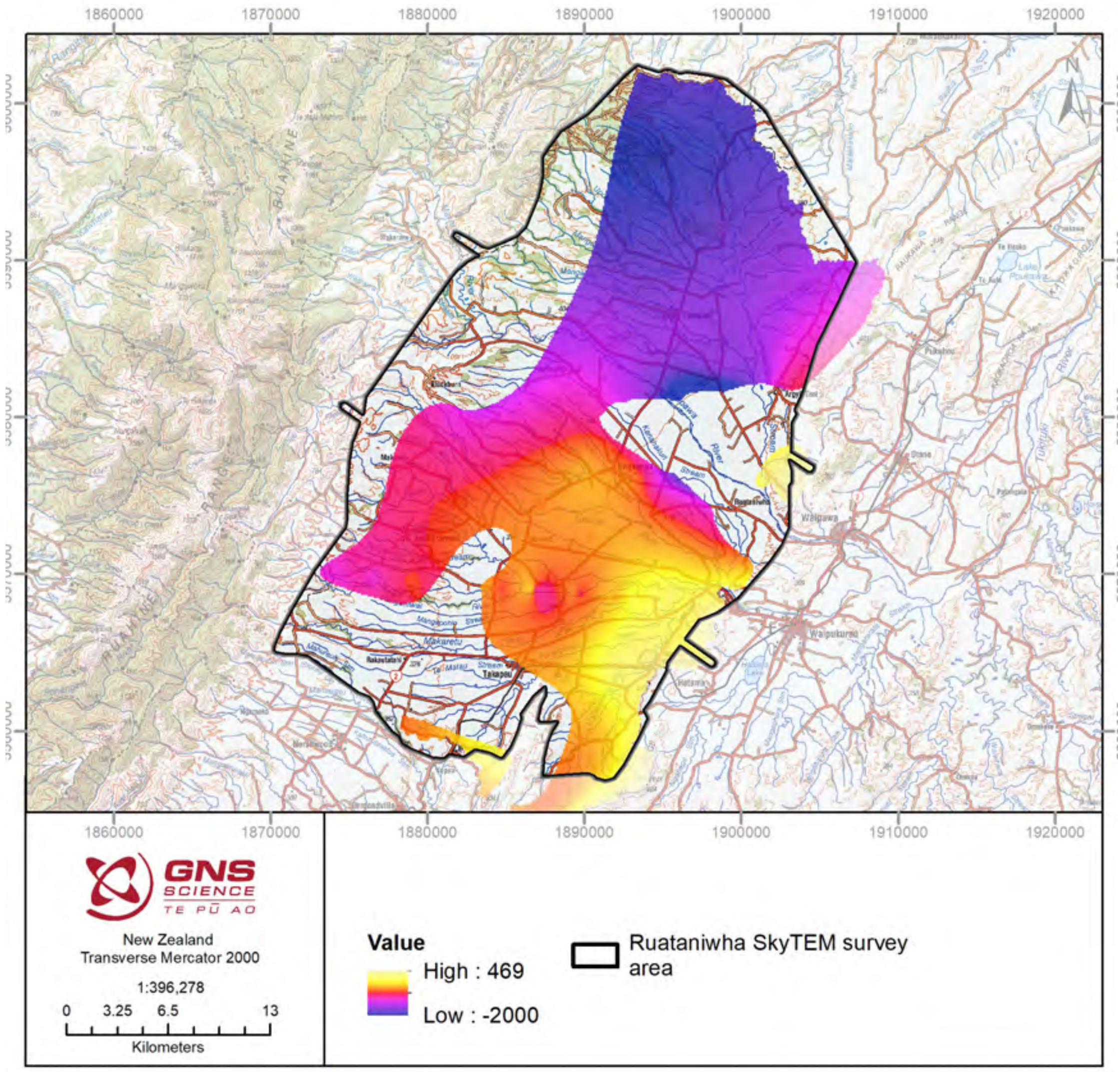

Figure 3.11 Elevation of the top of the Tolaga Group grid in the 3D geological model (Harper 2018).

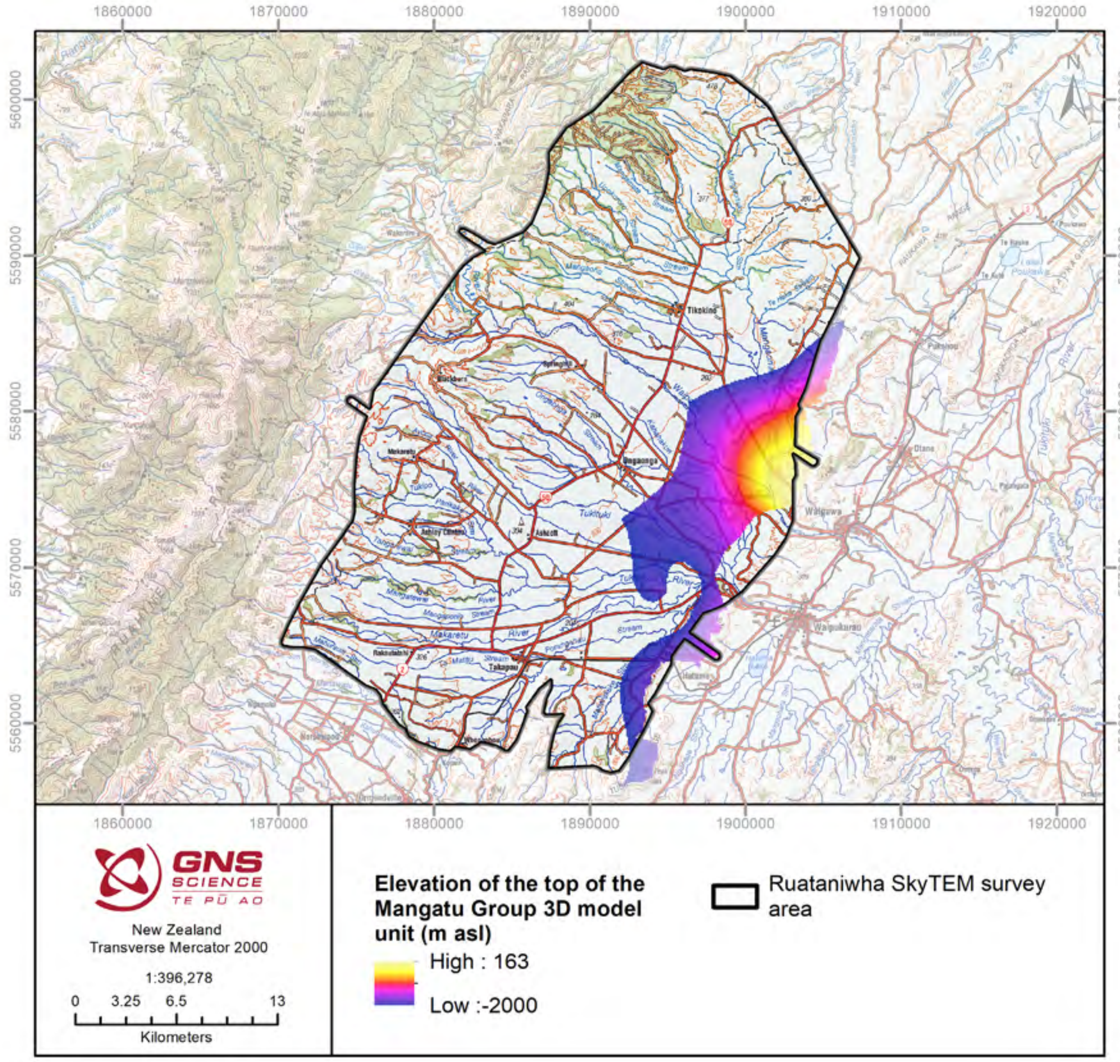

Figure 3.12 Elevation of the top of the Mangatu Group grid in the 3D geological model (Harper 2018).

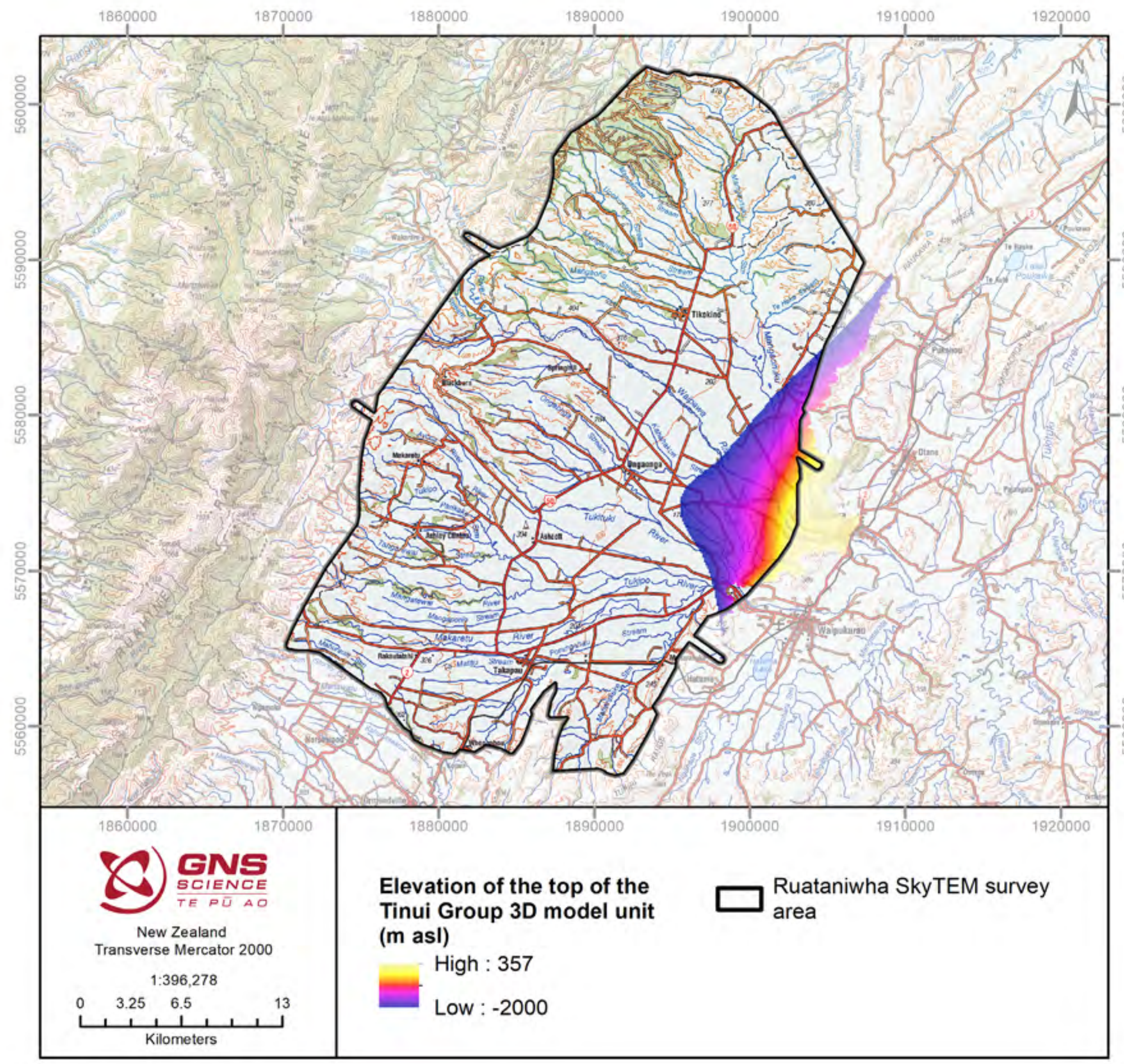

Figure 3.13 Elevation of the top of the Tinui Group grid in the 3D geological model (Harper 2018).

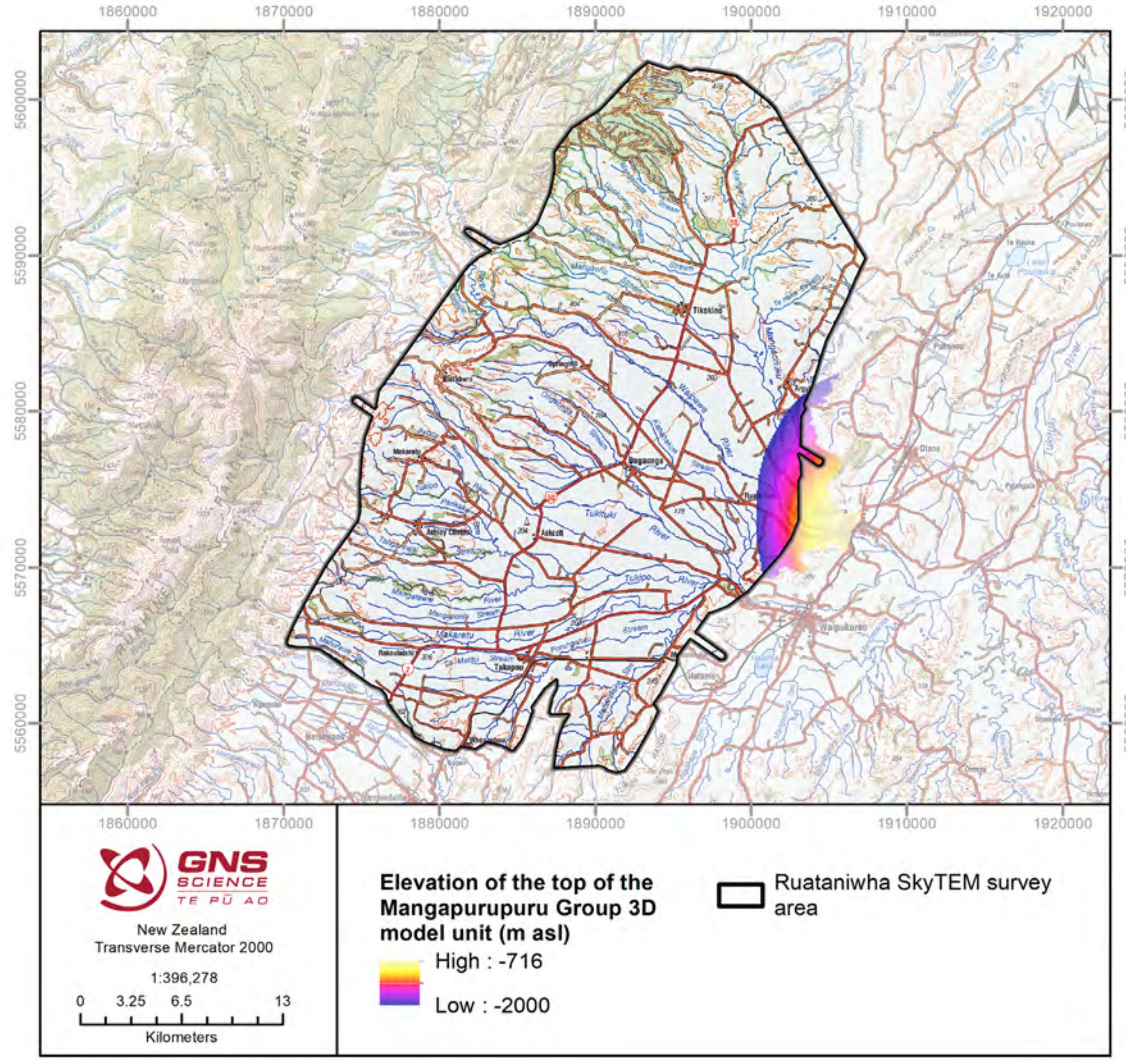

Figure 3.14 Elevation of the top of the Mangapurupuru Group grid in the 3D geological model (Harper 2018).

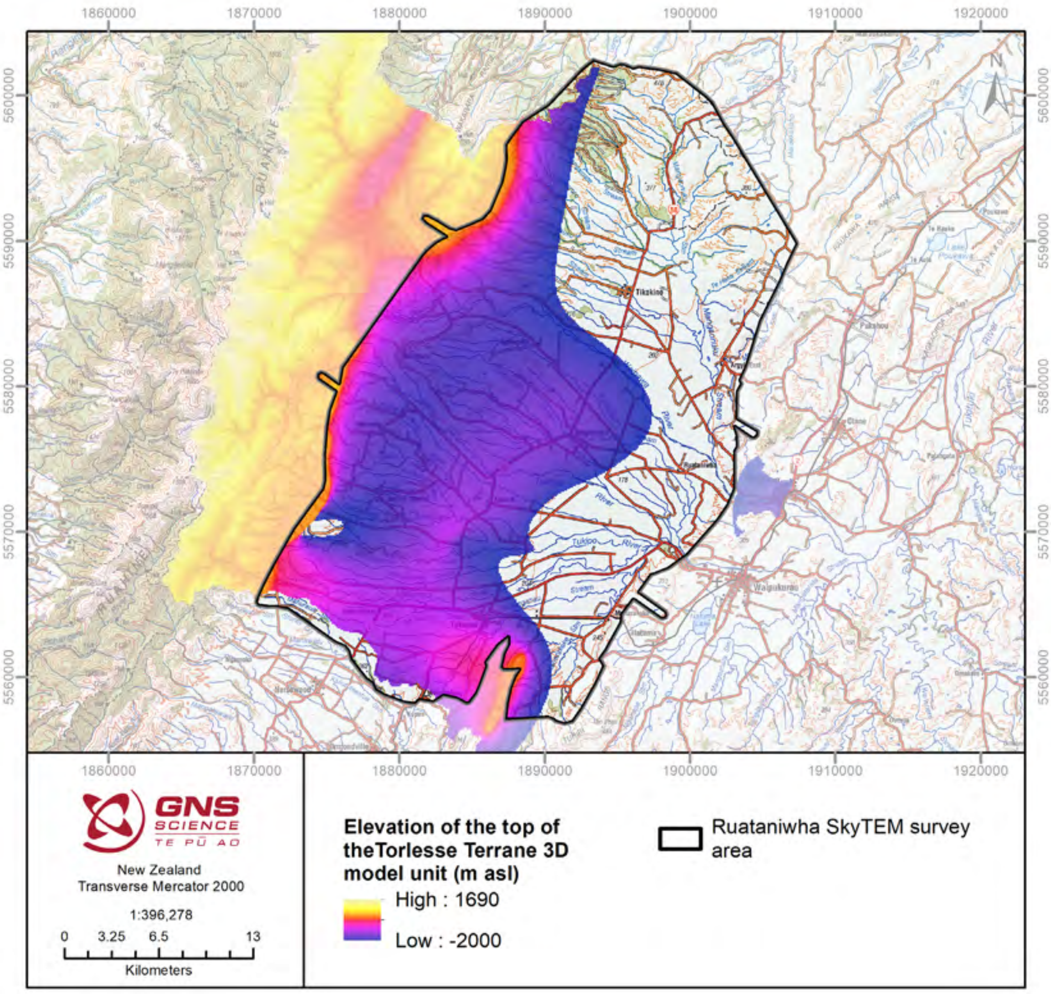

Figure 3.15 Elevation of the top of the Torlesse Terrane grid in the 3D geological model (Harper 2018).

3.2.3 Borehole Data Inventory

3.2.3.1 Petroleum Boreholes

Three petroleum exploration wells have been drilled within the area covered by the Ruataniwha Plains SkyTEM survey. Two petroleum wells lie to the north of the survey area and provide valuable information on the deeper stratigraphic intervals. All the petroleum wells are abandoned. The locations of the wells are shown in Figure 3.16 and details of the wells are given in Table 3.1.

The records of these five petroleum exploration wells provide a lot of detailed geological, stratigraphic and petrophysical data for deeper intervals in the SkyTEM survey area (Table 3.1 and Appendix 1). The top 100 m of the petroleum exploration wells were usually drilled using a water well drilling rig, and little data were recovered from the surface hole. Surface casing was typically set to 300 m, so shallow geological data and geophysical logs are absent.

Typical data available for the upper 400–500 m depth (mbgl) includes estimates of the rate of penetration (ROP) from the drilling data, and Gamma Ray log (GR) data collected through the steel casing. These logs can be used to qualitatively identify finer-grained clay-rich units from coarse-grained gravel-dominated intervals. All available data from the upper 500 m of these wells has been digitised and made available for importing into various geophysical interpretation software (see Appendices 1 and 2).

The deeper well log and stratigraphic data have been used to help tie the geological section to the seismic reflection data (see Section 3.3.1) to allow the interpretation of deeper geological horizons across the SkyTEM survey area. The complete set of information from the wells is available from New Zealand Petroleum & Minerals (NZP&M) in the well completion reports PR271 (Leslie 1971a), PR272 (Leslie 1971b), PR2537 (Johnston and Langdale 2000), PR2283 (Johnston and Francis 1996) and PR273 (Leslie 1971c).

Takapau-1 and Ongaonga-1 contain valuable information on the Quaternary geology, or they have nearby shallow monitoring wells that provide detailed lithological variations in the top 100 m. Speedy-1 was drilled on the southeastern edge of the Ruataniwha Plains and penetrated 69 m of Quaternary gravel and clay before entering the Pukeora Oyster Bed Formation (Johnston and Langdale, 2000). Mason Ridge-1 and Kereru-1 contain detailed geological descriptions of the Pliocene limestones and sandstone formations at the edges of the basin that are potential aquifers in deeper parts of the Ruataniwha Basin.

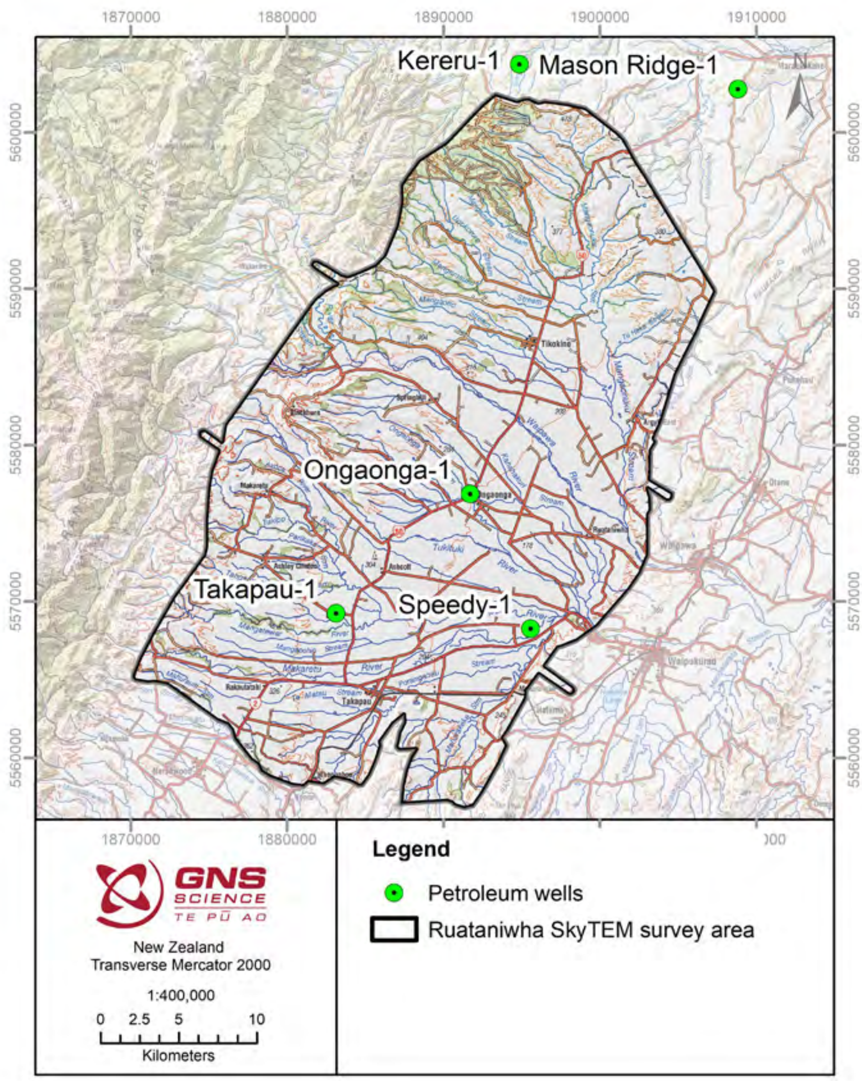

Figure 3.16 Location of petroleum wells in the Ruataniwha Plains.

Table 3.1 Petroleum exploration wells within the SkyTEM survey area. 'M asl' refers to metres above sea level. Mst = mudstone; Lst = limestone; Zst = Siltstone; Sst = Sandstone.

	Takapau–1	**Speedy–1**	**Ongaonga–1**	**Mason Ridge–1**	**Kereru–1**
NZP&M Report Number	PR273	PR2537	PR271	PR272	PR2283
Location (NZTM NZGD2000)	1,883,144 E 5,569,235 N	1,895,579 E 5,568,257 N	1,891,705 E 5,576,880 N	1,908,830 E 5,602,803 N	1,894,856 E 5,604,386 N
Surface Elevation (m asl)	262.7	160.0	202.9	236.2	357.1
Elevation Kelly Bushing[1] (m asl)	267.6	165.0	206.7	239.8	361.9
Total Depth (m)	1058.8	876.6	1573	1880	1938
Bottom Hole Elevation (m asl)	-791.2	-711.6	-1366.3	-1640.2	-1576.1
Drilling Dates	May 1971	June 2000	Apr 1971 – May 1971	May 1971 – June 1971	November 1996
Depth to Limestone, Mudstone, Lithology (formation)	51.8 m (M Pleistocene Mst / Lst, Kumeroa Fm)	74 m (Pukeora Oyster Bed) 86 m (Makateru Mst)	122.6 m (Maharakeke Clay, Pukerora Oyster Bed)	0 m (Mason Ridge Fm, Lst)	0 m, (Kidnappers Gp, Sst)
Formation at Bottom of the Borehole, NZ Stage, Age	Pahau Terrane Greywacke (Jurassic)	L Miocene Mst (Tongaporutuan)	Pahau Terrane Greywacke (Jurassic)	U Miocene Zst / Mst (Sw – Sl)	U Pliocene Mst (Waipipian)
Lithological Sampling	Cutting samples every 3.3 m	Irregular samples to 70 m, 10 m sample intervals 70–453 m	Lithology descriptions at 0.5 m intervals	Cutting samples every 3.3 m	Cutting samples every 5 m from 0 to 300 m, 3 m from 300 m to TD
Geophysical Data	Gamma ray from 7.5 mKB; resistivity and density logs from 80 mKB.	No logs collected	Gamma ray from 7.5 mKB depth. Resistivity and density logs from 145 mKB	Gamma ray from surface, density, self-potential, resistivity, sonic logs from 213 mKB	Gamma ray, density, self-potential, resistivity, from 480 mKB.
Rate of Penetration	Digitised from composite log	Digital data from 80 m	Digitised from composite log	Digitised from composite log	Digital data in log files

1 'Kelly Bushing' refers to the drilling floor that is above ground level and is often used as a measurement point for petroleum wells.

3.2.3.2 Research Boreholes

Eight groundwater exploration boreholes were drilled in the Ruataniwha Plains in 2001 as part of a research project to investigate the hydrogeology of the gravel aquifers in the plains (Brown 2002; Section 2.1). The details of each well are listed in Table 3.2. The boreholes were designed to provide information on the lithostratigraphy of the basin, including age of the deposits, paleoenvironment and depositional history, and to identify aquifers, aquicludes and aquitards. The locations of these boreholes are shown in Figure 3.17. The wells have been documented in an unpublished report (Brown 2002), and the data from the appendices have been captured for use in the project. They range in depth from 6.2 m to 150 m. Four of the boreholes (4697, 4700, 4701, and 4702) are greater than 100 m deep and provide valuable information on the geology of the Ruataniwha Plains. Boreholes 4693 and 4694 were drilled as paired wells in close proximity and completed as shallow and deep piezometers at the same locations. Boreholes 4695 and 4696 are nested piezometers at the same location.

As part of 3DAMP, in 2021 research Well 17136 (3DAMP Well-1; Lawrence et al. 2022a) was drilled on Ongaonga Waipukurau Road, northwest of Waipukurau, and research Well 17164 (3DAMP Well-3; Lawrence et al. 2022b) was drilled on Burnside Road, north of Takapau. The wells were designed to provide key geological and hydrogeological information in areas that are poorly mapped at depth. Figure 3.17 shows the location of these wells and details are listed in Table 3.3. More detailed information on the wells is included in the well completion reports (Lawrence et al. 2022a; Lawrence et al. 2022b). The new wells provide a better understanding of the continuity of geological units between the petroleum bores (Section 3.2.3.1).

Table 3.2 Wells drilled by Brown (2002).

HBRC Bore Number	4693	4694	4695	4696	4697	4700	4701	4702
Location (NZTM NZGD2000)	1,901,329 E 5,574,784 N	1,901,329 E 5,574,786 N	1,898,169 E 5,569,335 N	1,898,169 E 5,569,335 N	1,890,296 E 5,571,107 N	1,894,523 E 5,581,470 N	1,897,911 E 5,576,587 N	1,892,928 E 5,563,969 N
Surface Elevation (m asl)	153.6	153.8	145.2	145.2	201.1	217.9	174.3	179.2
Total Depth (m)	5.3	44.1	7.5	25.3	122.1	148.5	111.0	105.8
Bottom Hole Elevation (m asl)	148.3	109.7	137.7	119.9	78.9	69.4	63.3	73.4
Drilling Dates	26 Nov 2001	27 Nov 2001	28 Sept 2001	26 Sept 2001	24 Dec 2001	11 Dec 2001	2 Oct 2001	24 Sept 2001
Lithological Sampling	Descriptions of main units	Descriptions of main units	Descriptions of main units	Descriptions of main units	Samples 1–2 m	Samples 1–2 m	Samples 1–2 m	Samples 1–2 m
Depth to Base of Young Gravel	Shallow well	29 m (contact between grey and brown gravels)	Shallow well	8.2 m (contact with clay)	88.4 m (top ignimbrite)	110 m (top ignimbrite)	7 m (Change in gravel composition)	11 m (contact with clay)
Depth of Limestone or Mudstone	Shallow well	Gravel at base of well	Shallow well	22.3 m (Limestone)	Clay at base of well	Gravel at base of well	108 m (Pumice/ Ignimbrite)	60 m (Kidnappers Gp Clay) 100 m (Pukeora Oyster Bed)
Geophysical Data	GroundTEM	GroundTEM	None	None	GroundTEM	GroundTEM	GroundTEM	GroundTEM
Hydrogeological Sampling	Water chemistry, isotopic and water dating analysis	Water chemistry, isotopic and water dating analysis	Water chemistry, isotopic and water dating analysis	Water chemistry, isotopic and water dating analysis	Water chemistry, isotopic and water dating analysis	Water chemistry, isotopic and water dating analysis	Water chemistry, isotopic and water dating analysis	Water chemistry, isotopic and water dating analysis
Completion Details	Screen 4.1–5.1	Screen 42.9–43.9	Screen 5.0–6.2	Screen 22.8–24.0	Screen 84.5–86.5	Open at bottom of hole	Screen 108–111	Screen 103.3–105.5

Table 3.3 Wells drilled as part of 3DAMP.

	3DAMP_Well 1	3DAMP_Well 3
HBRC Bore Number	17136	17164
Location (NZTM NZGD2000)	1,896,508 E 5,572,997 N	1,887,256 E 5,567,708 N
Surface Elevation (m asl)	161	209.6
Total Depth (m)	168	79
Bottom Hole Elevation (m asl)	-7	132.7
Drilling Dates	16 March – 30 July 2021	28 July – 14 October 2021
Lithological Sampling	Lithology descriptions at 0.5 m intervals	Lithology descriptions at 0.5 m intervals
Geophysical Data	Gamma ray, Density, Caliper	Gamma ray, Density, Caliper
Hydrogeological Sampling	11 aquifer tests (1 pump test and 10 slug tests), water chemistry, isotopic and water dating analysis	4 Slug tests
Completion Details	Screen 166.8–168 m	Screen 75.15–76.35 m

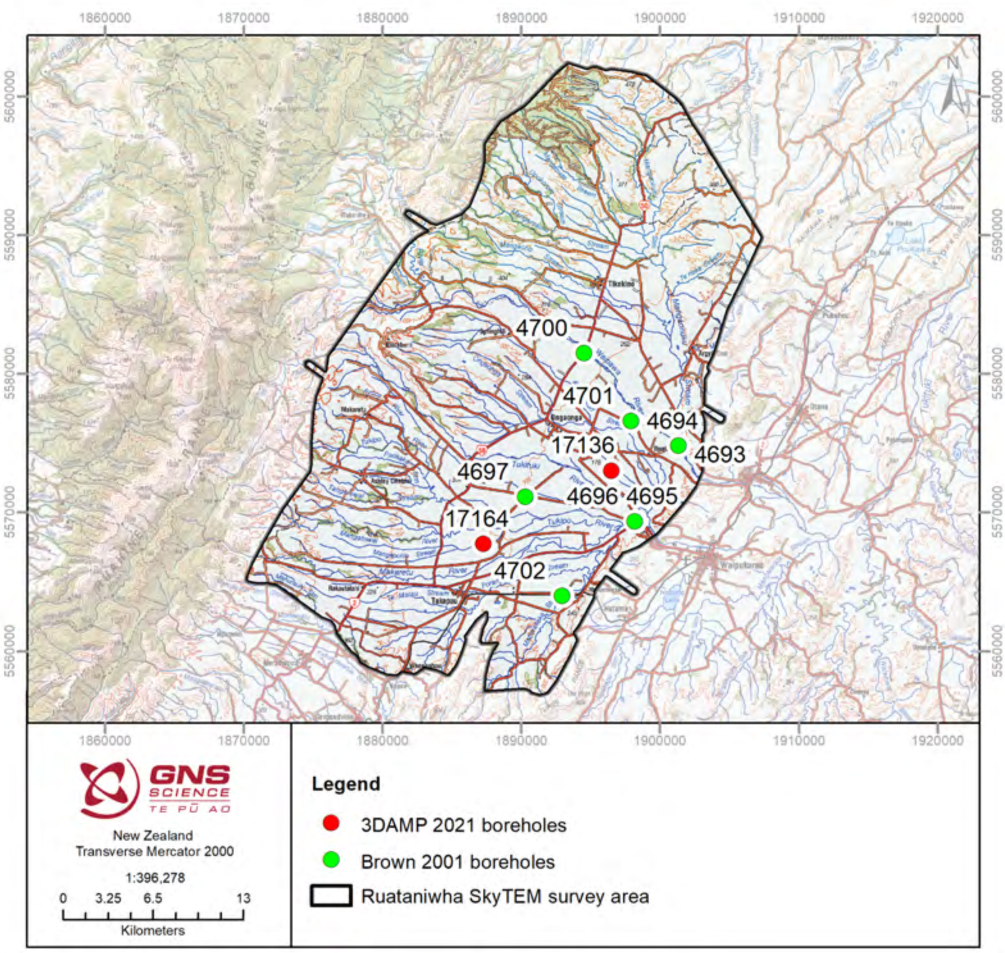

Figure 3.17 Location of groundwater research boreholes in the Ruataniwha Plains.

3.2.3.3 New SOE Bores

HBRC drilled four additional State of the Environment (SOE) bores in the Ruataniwha in 2021 and 2022 (Table 3.4, Figure 3.18). As part of the drilling, grain size analyses and resistivity measurements were performed on a selection of samples from the bores using the methodology described within Lawrence et al. (2022a). This information is provided in Appendix 1 and will be interpreted within future 3DAMP reports. Additionally, PDF copies of the lithological logs and construction details were quality checked against the HBRC well database details and corrections provided to HBRC where errors were found.

Table 3.4 State of the Environment (SOE) bores drilled by HBRC in 2021 and 2022.

HBRC Bore Number	Bore Name	Location (NZTM NZGD2000)	Total Depth (m)	Number of Samples	Sample Depth Range (m)
17184	Butler Road	1,897,402 E 5,587,575 N	75.0	8	9.0–75.0
17183	Brow Road	1,900,355 E 5,579,273 N	76.6	4	7.5–70.0
17180	Makaroro Road	1,898,320 E 5,582,275 N	85.94	10	5.0–81.0
17185	Burnside Road	1,892,461 E 5,572,836 N	73.40	9	6.0–73.0

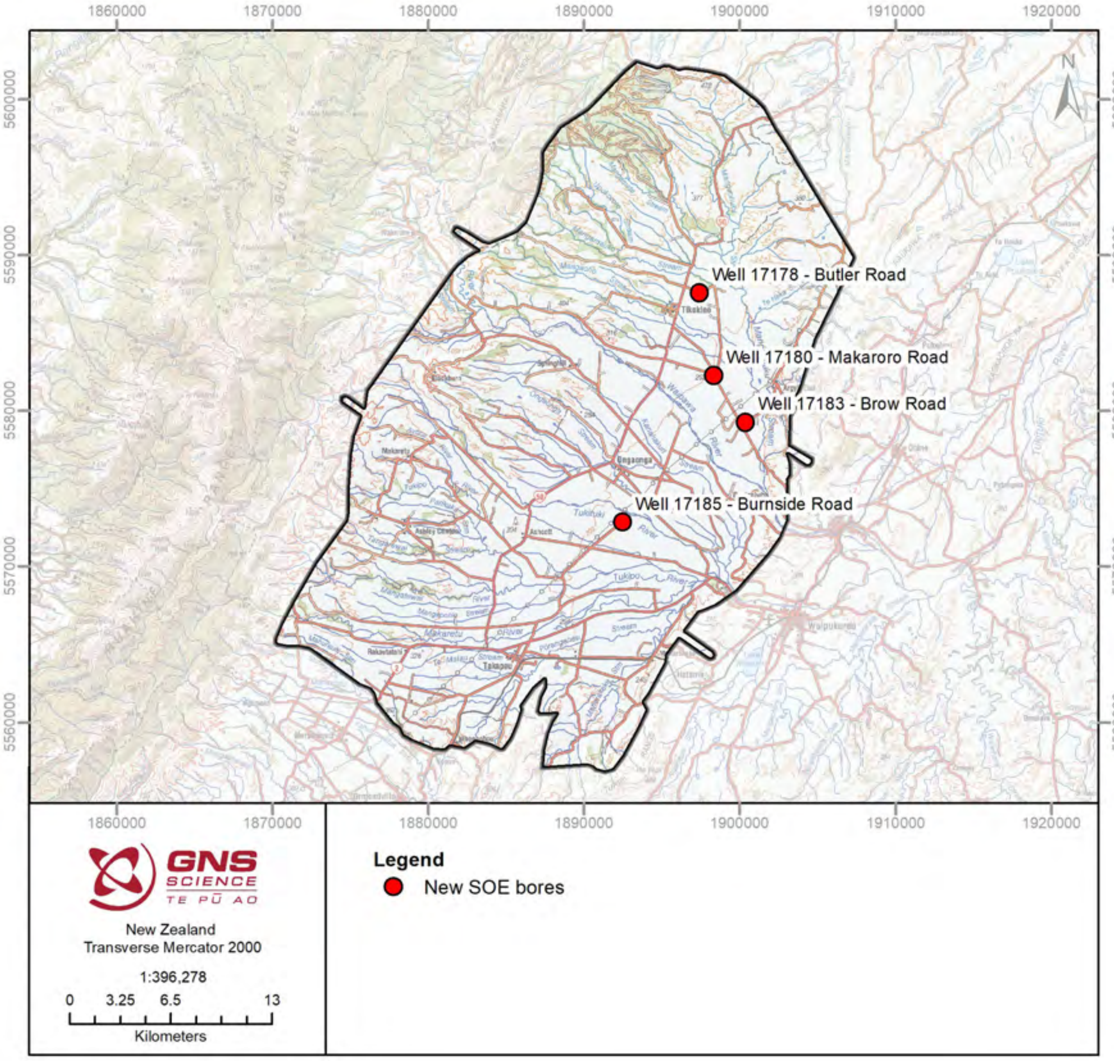

Figure 3.18 State of the Environment (SOE) bores drilled by HBRC in 2021 and 2022.

3.2.3.4 Baylis Bros Hard Copy Lithological Logs

During early discussions on 3DAMP, the drilling company Baylis Bros Ltd offered to provide some of their highest-quality paper logs from their records, many of which had been logged by a geologist involved in the 1990s groundwater studies in the area (Len Brown of Dravid and Brown [1997]). The approximately 100 logs considered of their highest quality were selected by Baylis Bros Ltd. and provided to GNS as PDF scans. GNS assessed the information in these original paper logs versus the HBRC well database via spot checks and found sufficient differences to consider digitisation of the logs to be of value. Of these lithological logs, 12 are within the Ruataniwha SkyTEM survey area and were digitised (Figure 3.19; see Appendix 1).

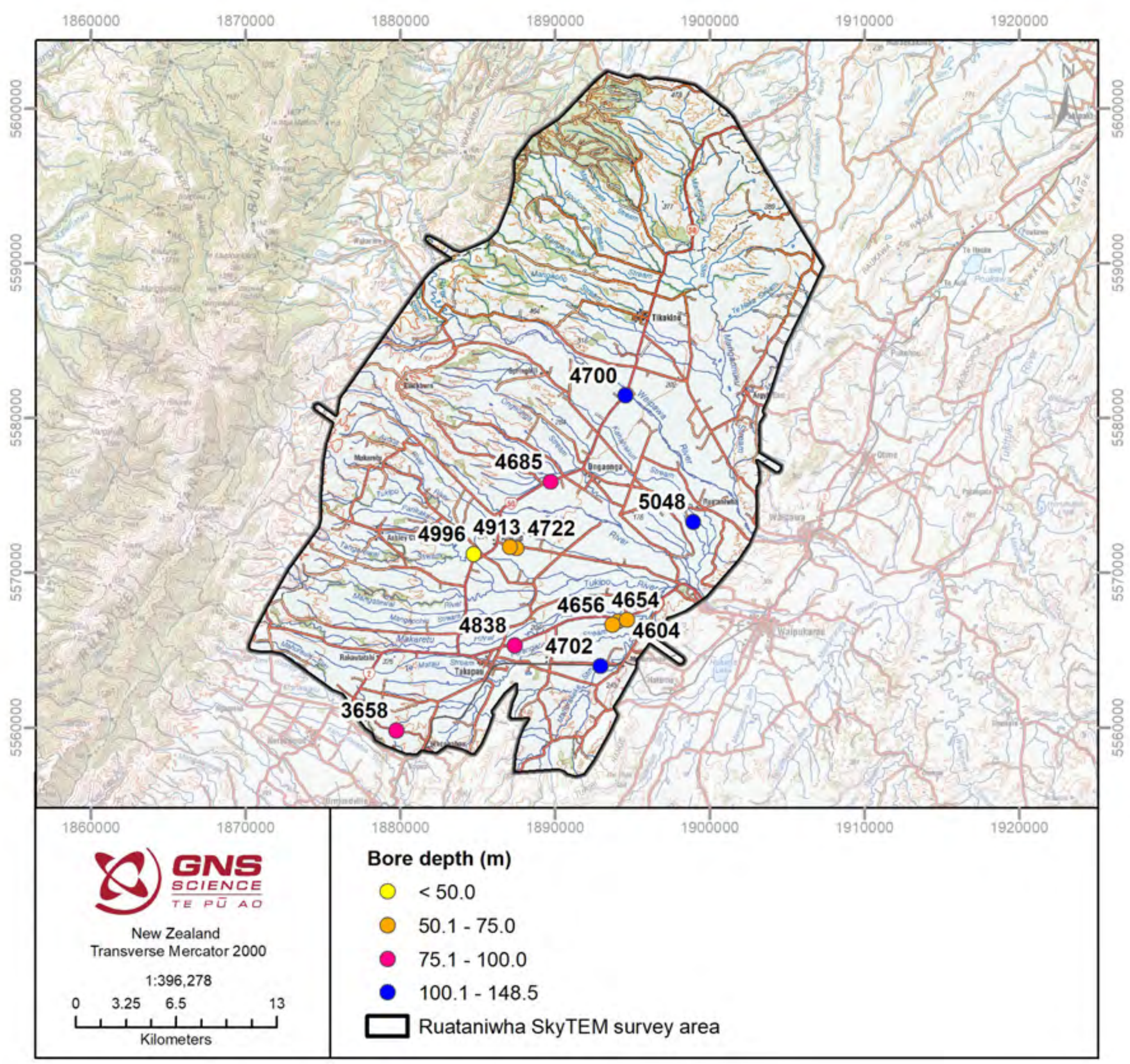

Figure 3.19 Locations and depths of high-quality lithological logs provided by Baylis Bros Ltd and digitised as part of this report.

3.2.3.5 Hawke's Bay Regional Council Well Database Lithological Logs

The Hawke's Bay Regional Council well database (WellStor) contains 748 boreholes within the limits of the survey area (Figure 3.20; Harper 2022). This database includes both bore construction and lithological information. However, only 654 of those bores have lithological information. The lithological dataset includes a primary lithology field, a full lithology description field and notes related to those (Appendix 1).

The attribute table of the bore construction dataset includes two columns that are related to the bore depth: 'Depth' and 'BoreDepth'. As communicated by HBRC (Harper 2019), the column 'Depth' represents the finished 'well depth', whereas the column BoreDepth "is the maximum depth the borehole was drilled". Some bores have information for both fields, but many only have information in one of these fields. For the purpose of this project, and the figures shown in this section, both columns were reconciled by making a 'FullDepth' column that used the maximum value between 'Depth' and 'BoreDepth'. The mean depth of these bores is 34.2 m, the median is 38 m and the mode is 6 m (Figure 3.21). Of all 748 HBRC bores in the survey area, 44 bores do not have 'Depth' or 'BoreDepth' information.

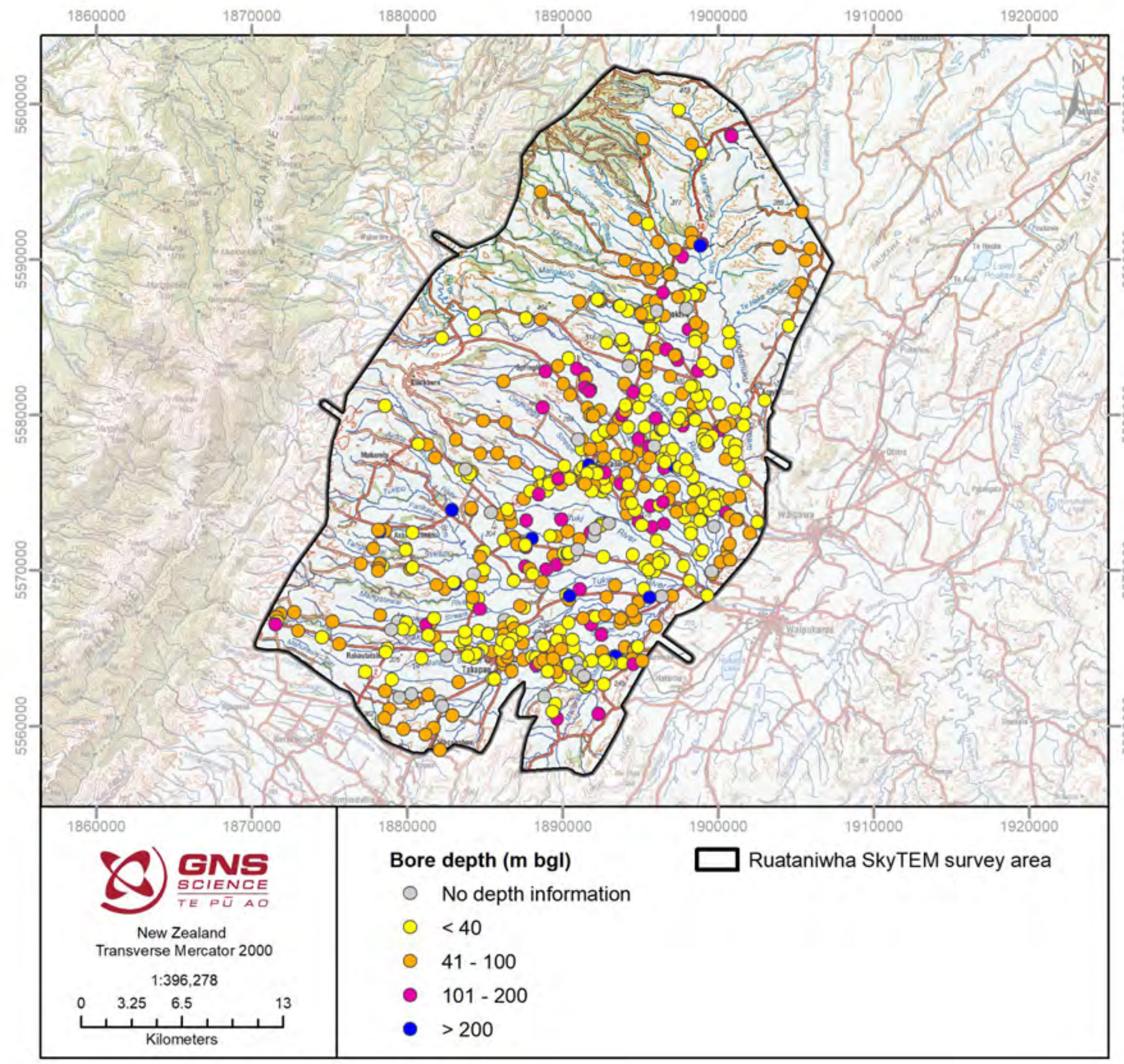

Figure 3.20 Location of Hawke's Bay Regional Council boreholes within the SkyTEM survey area, colour-coded by depth.

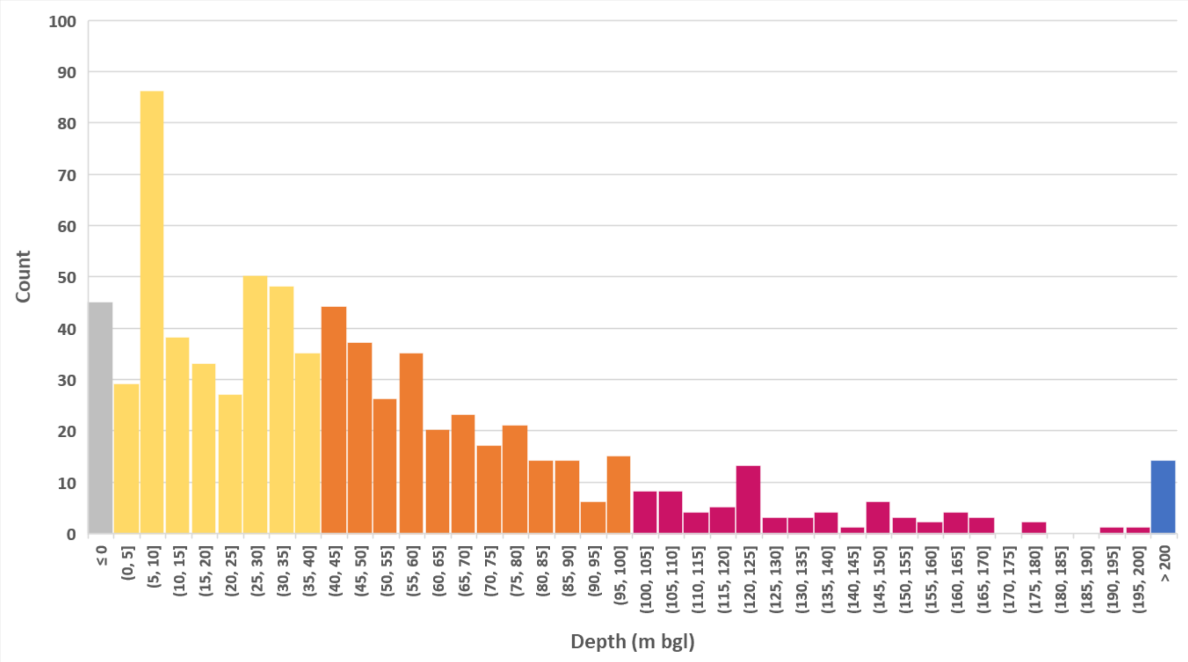

Figure 3.21 Depth of Ruataniwha Plains bores in the Hawke's Bay Regional Council well database. For clarity, the x-axis of the plot has been limited to 200 m. Bores without depth information are represented as having a depth of 0. These bores are not included in the calculations of the mean and median bore depth, which are 34.2 m and 38 m, respectively.

3.2.3.6 Lithological Log Quality Coding

Quality coding from 1 to 5 was undertaken for the boreholes, where 1 is the highest quality and 5 the lowest (Figure 3.22; see Appendix 1). Information utilised for the quality assessment included:

- Type of lithological log (petroleum, research, SOE, Baylis Bros Ltd or HBRC well database log).
- Availability of GPS locations within the well construction file.
- An automated assessment of the average interval length, as finer interval logging is considered to correspond to a greater attention to detail and less bulk simplifications being undertaken during the logging.

The resulting quality index was defined as:

1 = Petroleum and research wells (wells from Brown (2002) and the two wells drilled in 2021 by GNS/HBRC (3DAMP wells 1 and 3)).

2 = Baylis Bros Ltd wells, SOE bores and HBRC well database logs that were GPS located and had an average logged interval of less than 4 m.

3 = HBRC well database logs that were GPS located and had an average logged interval of greater than 4 m.

4 = HBRC well database logs that were not GPS located and had an average logged interval of less than 4 m. Two bores manually identified as having location errors in their comments (see Appendix A1.3).

5 = HBRC well database logs that were not GPS located and had an average logged interval of greater than 4 m.

Uncertainties are present with the dataset that were not able to be fully considered within this assessment. For example, Lee et al. (2014) noted two potential sources of uncertainty inherent in the borelog descriptions in the Heretaunga Plains area that are relevant for the Ruataniwha Plains data:

- The encountered lithologies are usually described by commercial drillers during the drilling and not experienced geologists, resulting in non-standardised, potentially inaccurate descriptions that commonly do not include a geological unit or formation.
- Data-entry errors resulting from the manual transfer of borelogs from often non-digital sources into the borelog database.

Additionally, bore location errors may arise from incorrect surveying of the locations, conversion of historically used spatial reference systems with low location accuracy (e.g. map reference coordinates), data-entry errors etc. Different databases also have different naming conventions and attribute limitations, and different drilling methods (e.g. rotary drilling vs. cable-tool drilling) provide different quality information.

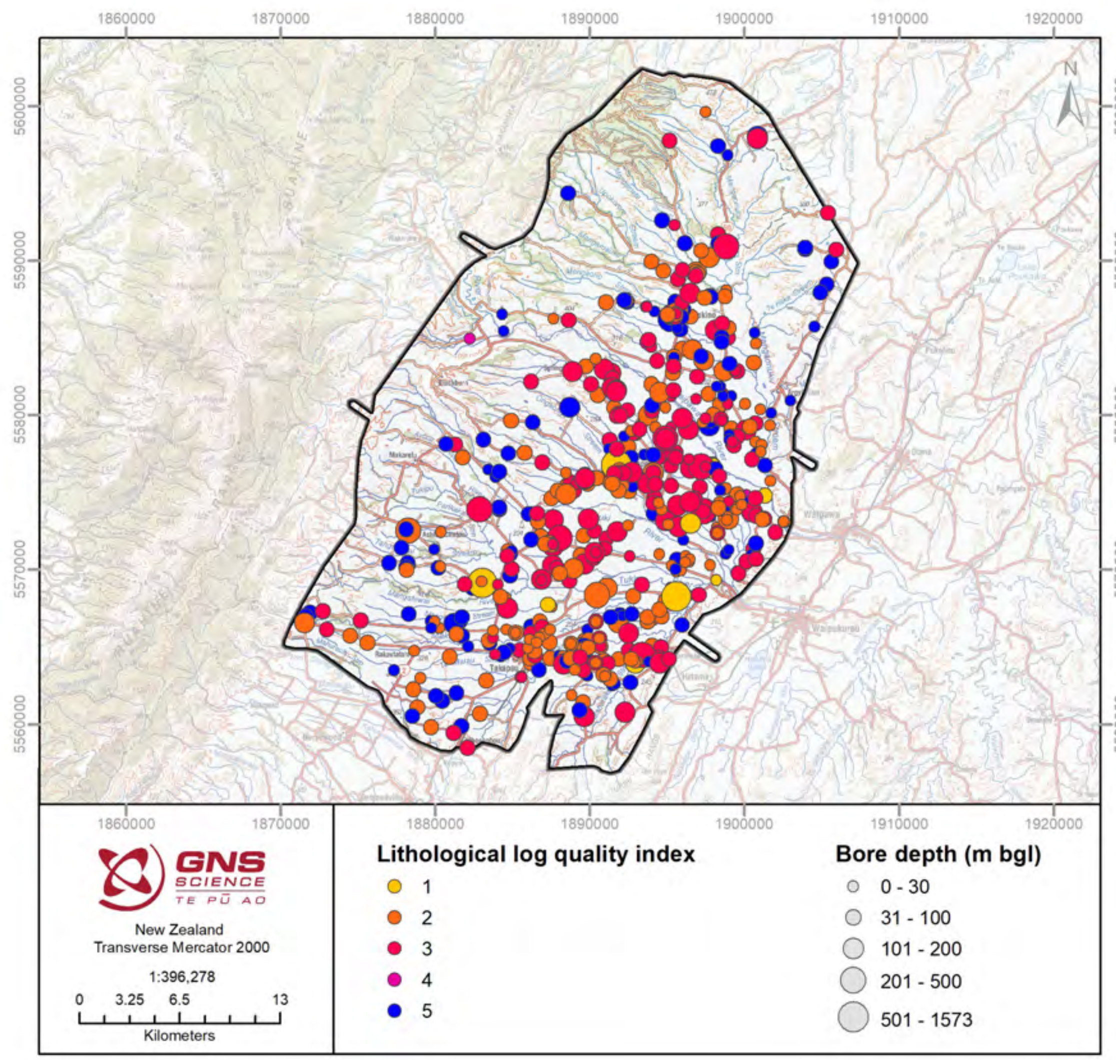

Figure 3.22 Results of quality coding of lithological logs in the SkyTEM survey area.

3.3 Geophysical Data Inventory

3.3.1 Seismic Reflection Data

Seismic reflection surveys have been undertaken by the petroleum exploration industry onshore in Southern Hawke's Bay since the mid-1960s. Surveys made more recently than 1980 are available in digital format. Figure 3.23 shows the location of the onshore seismic lines across the SkyTEM survey area. The details of each seismic programme are given in Table 3.5.

The petroleum exploration data were designed to image the complex structure in the 1–3 km depth range. The sources were a mixture of dynamite and vibroseis trucks. The extensive Beaver Exploration data set collected in 1971 around Tikokino (Hollingsworth 1971) is only available as paper sections and these have been scanned and included in the digital version of the seismic lines. The data were collected using a 24-channel recording system with sparse geophone and sparse shot spacing, producing a low-resolution image of the subsurface with limited processing. The shot holes were between 30 and 60 m deep (Figure 3.24) so the drillers logs provide some additional information for the shallow part of the section.

For most of the modern seismic surveys, the recording systems used had between 120 and 500 channels recording offsets up to 1500 m, yielding high-quality data at depths of 2000 m. Despite the small geophone spacing (5–10 m) the low frequency vibroseis data were not able to image much detail in the top 200 m.

In addition to the petroleum industry data, the Department of Scientific and Industrial Research (DSIR) Geophysics Division undertook a high-resolution seismic reflection survey for groundwater and structural geological studies in the vicinity of Takapau (Melhuish 1993). The DSIR data were collected with a higher-frequency source to maximise the resolution of the reflection images. However, the shorter cable length and weaker sources prevented any data from being usable below 1 second (two-way travel time) or approximately 1 km.

All of the seismic data that is available in digital format has been compiled and interpreted alongside the boreholes, wells and additional geophysical data. The network of seismic lines has been tied at the intersection points to allow the picking of prominent reflectors across the Ruataniwha Plains SkyTEM survey area. Several lines pass through the locations of the petroleum exploration wells, and these wells have been used to identify the age and lithologies of the units picked in the seismic. There are few estimates of the compressional wave (P-wave) velocity in the top 500 m of the seismic lines or exploration wells (Table 3.1), so making the conversion from seismic travel-time to depth is challenging. A regional velocity of 2000 m/s has been used to make most of the conversions. This velocity was derived from the Takapau-1 well, where a velocity survey produced an average velocity between 1800 and 2000 m/s over the depth of interest for the grids.

The key seismic markers are:

- Base of Young Gravel (Base Holocene).
- Base of Salisbury Gravel (Early Pleistocene).
- Top of Upper Pliocene Limestone (Wn, Kumeroa Fm, Mason Ridge Fm).
- Top of the Mid Pliocene Limestone (Wm, Te Onepu Fm).

These units have been picked across the survey area, the horizons have been gridded to extend across the study area and then clipped to the extents of the utilised seismic lines. The grids of the horizons have been converted into depth/elevation (see Appendix 2).

Figure 3.24 shows seismic line IP328-97-11 with the interpreted horizons. The petroleum well Ongaonga-1 is located on the seismic line. The top 700 m of the lithological log from the petroleum report (Leslie 1971a) has been plotted on top of the seismic data. The top of the Nukumaruan and Mangapanian stages are also shown on the well log. The more detailed geology determined from the drill cuttings has been digitised for the top 500 m.

The Holocene gravel deposits are dominated by incoherent reflectivity consistent with unconsolidated gravels. The shallow marker defines the top of the first set of continuous strata. The base of the Salisbury gravel unit is another change in reflection character. The Upper Pliocene Limestone is a strong reflector at wells Takapau-1 and Ongaonga-1. The Pliocene is characterised by well bedded units that produce strong reflectivity in the better of the seismic data sets. A prominent reflector has been picked that correlates to a Limestone near the base of the Nukumaruan. At Takapau-1 this unit has been identified as the Te Onepu Fm. At Speedy-1 this unit is immediately below the Quaternary gravel units.

The details of the seismic surveys are provided in reports listed below, with additional information in Table 3.5:

- PR270: Hollingsworth (1971)
- PR1759: Inglis (1991)
- Melhuish (1993)
- PR2299: Small (1997)
- PR2392: Schlumberger Geco Prakla (1998)
- PR2393: Schlumberger Geco Prakla (1999)
- PR2478: Schlumberger Geco Prakla (2000)
- PR3898: Excel Seismic Services Ltd (2008)

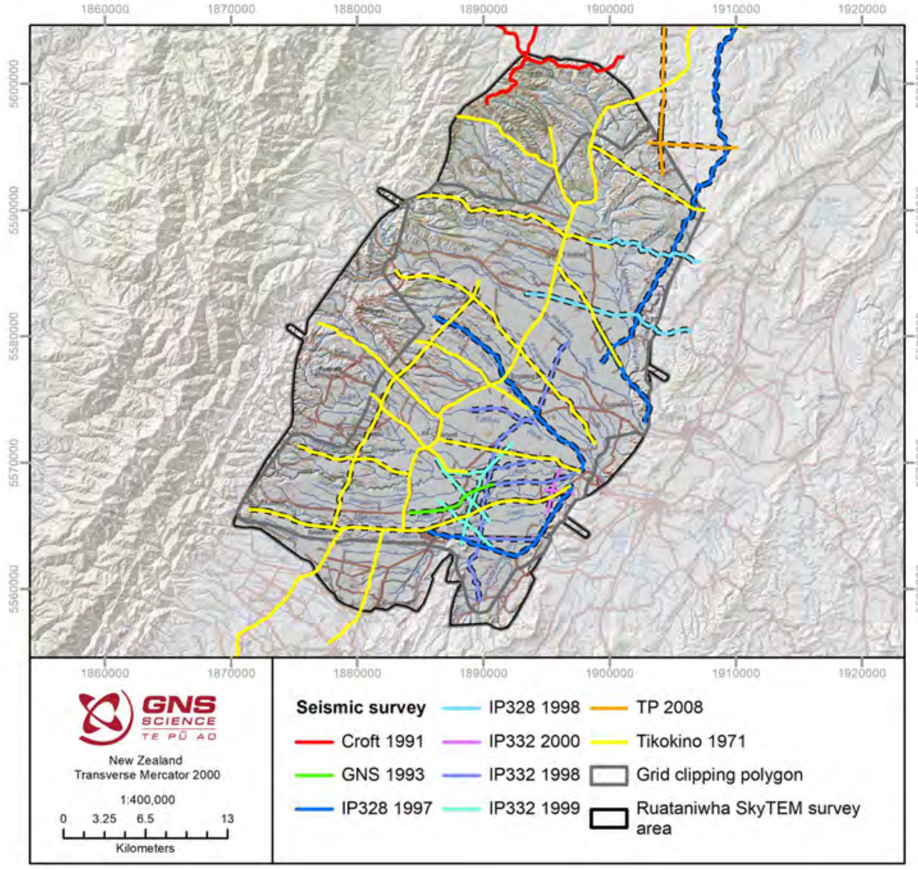

Figure 3.23 Location of seismic lines in the wider area of the Ruataniwha Plains. Lines framed by a black dashed line are the seismic lines that were actually used in the interpretation.

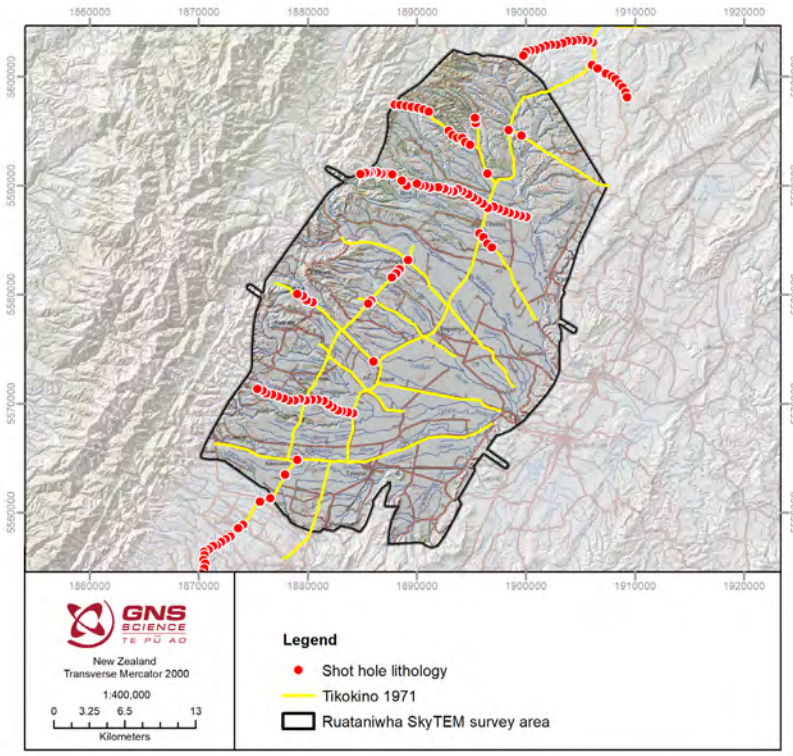

Figure 3.24 Location of seismic shot hole with velocity and lithology data for the top 30–60 m across the Ruataniwha Plains.

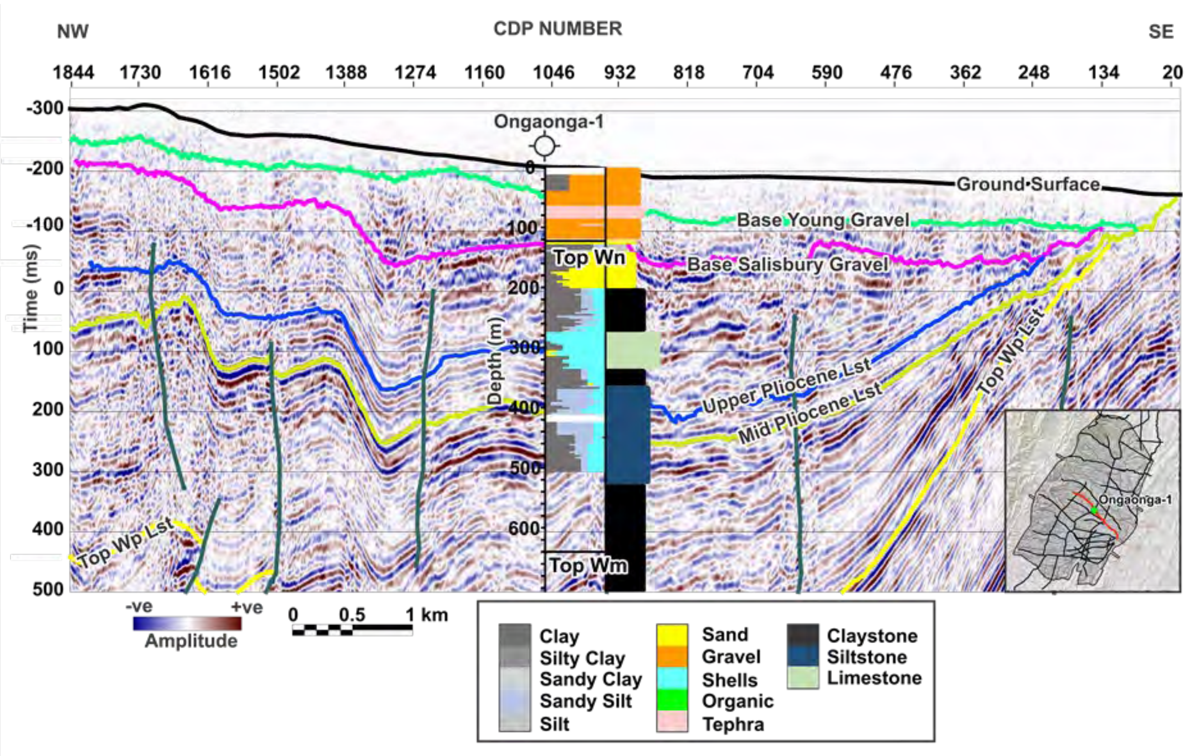

Figure 3.25 Interpreted seismic Line IP328-97-11. The location of the line is shown in the inset map along with the location of well Ongaonga-1. The seismic data are shown in two-way-travel time (ms). The lithology logs from Ongaonga-1 are shown in depth (m). The seismic has been stretched based on the velocity model derived at Takapau-1. Faults are shown as dark green lines.

Table 3.5 Seismic surveys (GP = geophone group; SP = shot point).

	Survey Date	NZP&M Report Number	Line Names	Seismic Source	Source and Receiver Spacing	Data Available
Tikokino-1971	1971	PR270	TB, TB(Ext), TDC, TE, TF, TG, TH, TI, TJ, TK, TL, TP, TV, TW, TY, TZ	Dynamite + geoflex	GP 45 m SP 540 m	Scanned, Up-holes, Shothole lithology
Croft-91	1991	PR1759	Line 1, Line 5	Dynamite + Vibroseis	GP 25 m SP 50 m	Original
DSIR	1993	Melhuish (1993)	L17	Dynamite	GP 10 m SP 40 m	Scanned
IP328-97	1997	PR2299	L05, L09, L10, L11	Vibroseis	GP 5 m SP 10	Original
IP332-98	1998	PR2392	L201, L202, L203, L204, L205	Vibroseis	GP 10 m SP 30 m	Original
IP328-98	1998	PR2393	L109, L109	Vibroseis	GP 10 m SP 10 m	Original
IP332-99	1999	PR2392	L301, L301A, L401, L402	Vibroseis	GP 10 m SP 10 m	Original
IP332-00	2000	PR2478	L501, L502	Vibroseis + Dynamite	GP 10 m SP 10 m	Original
TP08	2008	PR3898	L1004, L1010	Dynamite	GP 12.5 m SP 25 m	Original

3.3.2 GroundTEM

Ground-based TEM (groundTEM) soundings have been made within the Ruataniwha Plains in three campaigns. In 2009, detailed investigation of the Waipawa River was undertaken using a combination of GroundTEM and shallow drilling (Meilhac et al. 2009). A total of 22 locations were surveyed. Ten sites were occupied with a combination of TEM and NanoTEM and twelve sites were collected with the shallow mapping NanoTEM system. The sites were chosen to lie on a densely sampled profile along the Waipawa River and also to be close to research wells 4700, 4701, 4693, 4694, and 4697.

In 2019, a single sounding was undertaken adjacent to Well 4702 with good lithological data to provide information on the sensitivity of the TEM method to changes in the subsurface. The sounding was collected prior to the collection of the SkyTEM data, and the results of the analysis helped define the configuration of the SkyTEM system for the main hydrogeophysical survey. The details of the survey are presented in Reeves et al. (2019). Following the completion of the SkyTEM survey, GroundTEM soundings were made at the proposed locations of Well 17136 (Lawrence et al. 2022a) and Well 17164 (Lawrence et al. 2022b). Figure 3.26 shows the locations of the soundings. Details of all sites are in Table 3.6 and Table 3.7.

In all cases, measurements were undertaken using a Zonge GDP 32^{II} instrument. At most sites, the survey comprised a NanoTEM sounding with a small loop (20 x 20 m) that provides a similar response to the low-moment SkyTEM measurement and a TEM sounding with a larger loop (100 x 100 m) that is analogous to the high-moment SkyTEM measurement. The raw data from the 2009 campaign are available in digital format. The data from the 2019 and 2021 surveys were downloaded from the Zonge receiver and saved in the standard USF format. As part of this project, all of the data were edited, stacked and processed in the Aarhus SPIA software. The sounding curves for the NanoTEM and TEM data at each site were processed separately using SPIA’s smooth and layered 1D inversion routine (Auken et al. 2005). The smooth 1D models for the NanoTEM and TEM soundings were exported in a standard ascii format for importing into 3D interpretation software (see Appendix 2).

Prior to the acquisition of the SkyTEM data, the GroundTEM soundings provided a valuable dataset to help determine the optimal configuration of the SkyTEM system. The resistivity model for each sounding was used to develop an initial relationship between electrical resistivity and lithology (Reeves et al. 2019). Following more processing and the collection of the additional sites, the GroundTEM data are considered to be of value for improving the interpretation of the SkyTEM data. The 2009 survey is a detailed profile along the Waipawa River and was designed to look at the thick sequence of gravels in the river valley. The GroundTEM produce resistivity profiles that are similar in resolution to the SkyTEM inversions, so provide a valuable link between the geology derived from the well and the resistivity derived from the SkyTEM survey.

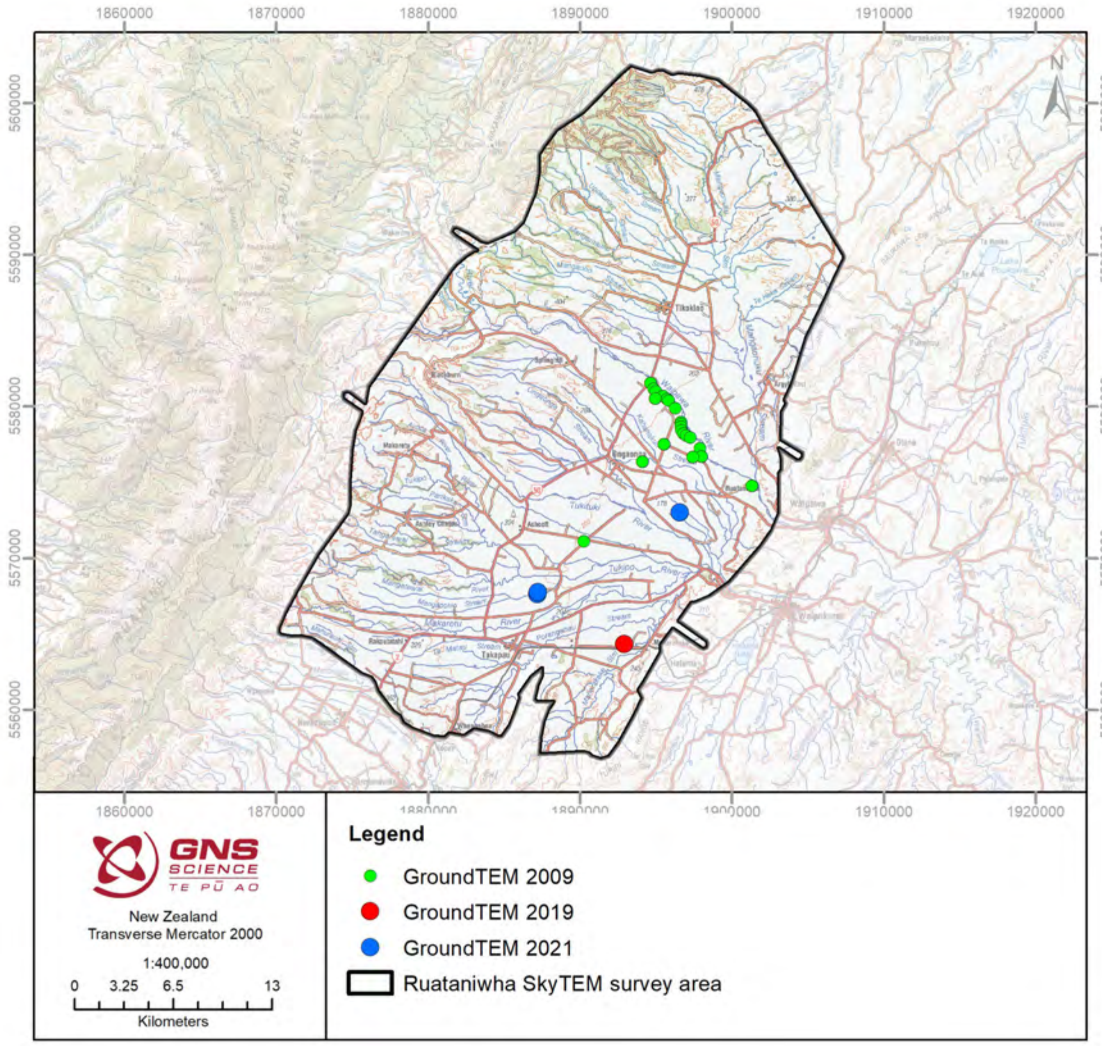

Figure 3.26 Location of GroundTEM soundings made on the Ruataniwha Plains from 2009 to 2021.

Table 3.6 GroundTEM soundings 2019 and 2021.

Bore No.	Site Name	Location	Elevation (m asl)	Date
4702	TEM4702	1892913 E 5564330 N	178.2	2019
17164	TEM 3A	1887198 E 5567620 N	216.0	2021
17136	TEM 1	1896578 E 5572993 N	161.0	2021
17164	TEM 3B	1887218 E 5567757 N	209.0	2021

Table 3.7 GroundTEM soundings 2009.

Bore No.	Site Name	Location	Elevation (m asl)	TEM/NTEM
4700/15021	1	1894639 E 5581531 N	215.4	TEM/NTEM
	4	1894839 E 5581156 N	213.3	NTEM
	6	1894979 E 5581000 N	211.5	NTEM
	11	1895460 E 5580695 N	207.0	NTEM
	13	1895713 E 5580463 N	204.4	TEM/NTEM
	14	1895836 E 5580364 N	203.2	NTEM
	17	1896278 E 5579862 N	198.8	NTEM
4744	21	1894950 E 5580502 N	209.7	TEM/NTEM
	22	1896623 E 5578953 N	190.7	NTEM
	23	1896634 E 5578818 N	189.9	NTEM
	24	1896633 E 5578648 N	189.7	NTEM
	25	1896674 E 5578393 N	188.8	NTEM
	26	1896813 E 5578222 N	187.0	TEM/NTEM
	27	1896982 E 5578071 N	185.9	NTEM
	28	1897236 E 5577941 N	184.9	NTEM
2744	29	1897882 E 5577208 N	178.8	NTEM
4701	30	1897998 E 5576694 N	175.3	TEM/NTEM
1452/1881/15015/4781	31	1895522 E 5577489 N	190.9	TEM/NTEM
4830/5671	32	1894101 E 5576346 N	187.4	TEM/NTEM
4693/4694	33	1901315 E 5574735 N	154.1	TEM/NTEM
4697/15020/5445/10953	34	1890240 E 5571083 N	201.4	TEM/NTEM*
11006/10922/4736	35	1897413 E 5576642 N	175.5	TEM/NTEM

*NTEM data was not modelled due to noise.

3.3.3 SkyTEM Magnetic Data

The SkyTEM system includes a total field magnetometer that measures the intensity of Earth's magnetic field. The data are collected continuously on all flight lines and can be processed to produce a map of the variations in total magnetic intensity (TMI) across the survey area (Figure 3.27).

The magnetic field is sensitive to lateral and vertical changes in the concentration of magnetic minerals in the rocks. The changes in the shallow subsurface produce high-intensity short spatial wavelength anomalies, and the changes in the deeper part of the section produce a broader anomaly. Magnetic minerals such as magnetite, ilmenite, and titanomagnetite are common in igneous and metamorphic rocks producing very strong anomalies. The variation in the magnetic properties of sedimentary rocks is subtle and usually results from changing provenance of the sediment. Gravel and sand deposits that include clasts eroded from volcanic, plutonic, or metamorphic basement often retain the magnetic minerals and can be mapped in the subsurface by their magnetic anomaly.

Man-made sources of magnetic anomalies can often dominate a magnetic anomaly map and they are difficult to filter out. Powerlines, houses, buildings, vehicles, and railway tracks produce anomalies that are much stronger than the geological signal. The map shown in Figure 3.27 shows some evidence for the main power line crossing diagonally from the southwest to the east through the Ruataniwha Plains but is, otherwise, relatively free of man-made noise. The primary purpose of a SkyTEM survey is to collect Transient Electromagnetic (TEM) data so the magnetic data acquisition is secondary. There are still some line levelling anomalies in the magnetic data in the southern part of the survey area. Collecting additional tie lines to improve the levelling between flights would not have been cost-effective. Additional processing such as the reduction to pole, calculation of vertical and horizontal gradients, and inversion can be used to further investigate the source of the magnetic anomalies.

The magnetic anomaly map is dominated by a 55 nT positive anomaly in the centre of the Ruataniwha plains. This anomaly is strong and quite localised for a sedimentary basin. The anomaly needs more analysis including modelling before its source can be identified. Potential causes of the anomaly are:

- Anomalously magnetic sandstone units in the Neogene.
- Basement structure.
- The distribution of tephra and ignimbrites in the Pleistocene.

More subtle linear anomalies are seen running from west to east across the Ruataniwha Plains and these are interpreted to be gravel and sand deposits in the Quaternary. The pattern may be influenced by the topography as SkyTEM system is flown on a smoother drape over the ground than a typical helicopter airborne magnetic survey.

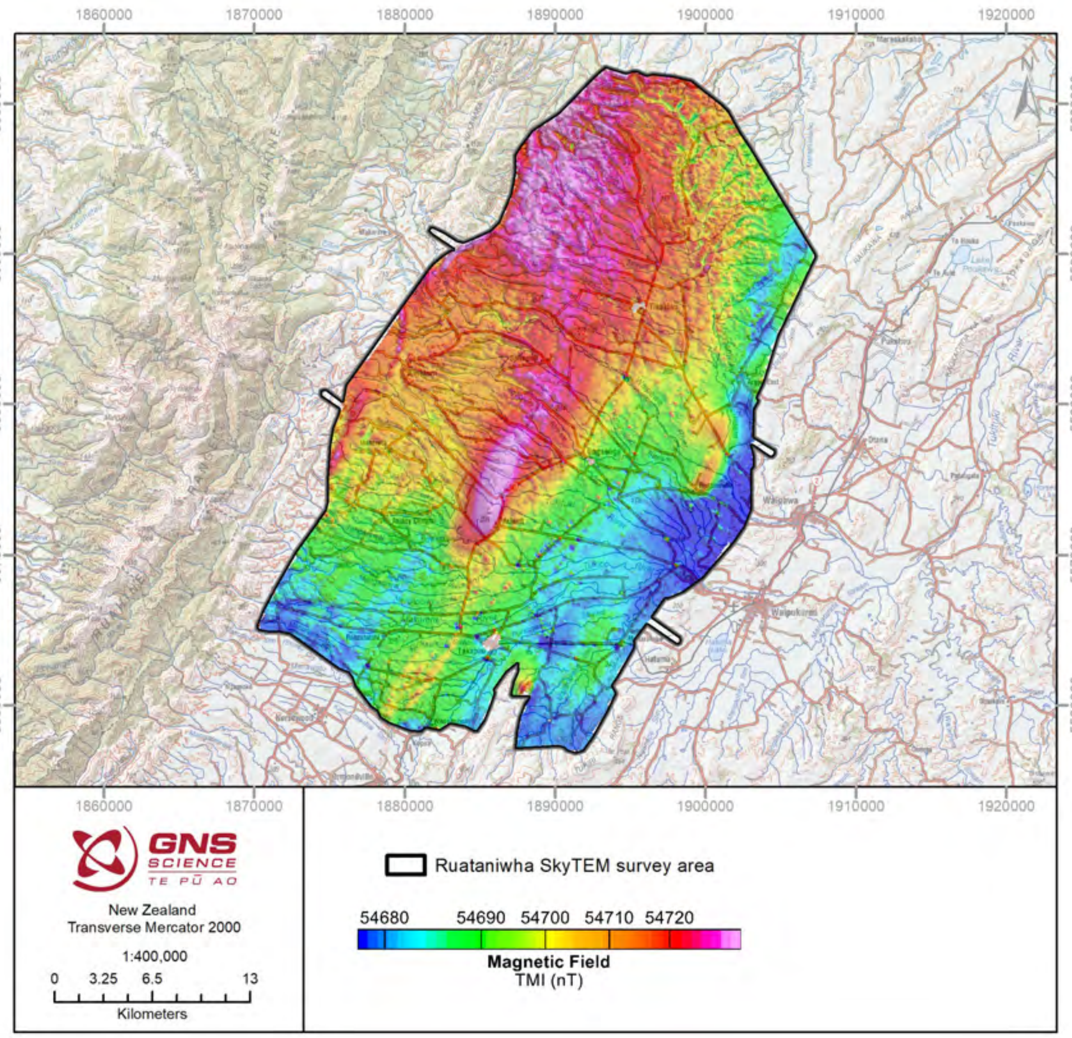

Figure 3.27 Airborne magnetic data (Total Magnetic Intensity in nanoTesla) collected during the SkyTEM survey.

3.4 Hydrogeological Data Inventory

3.4.1 Water Levels

HBRC undertook a water-level survey during January/February 2020 to coincide with the approximate time of the SkyTEM data collection in the area. Water levels were collected at 54 sites in the Ruataniwha survey area, and contours were developed based on these water levels. (Figure 3.28). Artesian flow[3] was observed at one bore (HBRC Bore ID 16490), which is a 79 m deep bore located near the confluence of the Ongaonga stream with the Tukituki River. In survey data from February 1997, two other deep bores in the vicinity of 16490 showed artesian conditions: 1869, a 98 m deep bore 500 m away, and 2043, a 83.5 m deep bore 3 km away from 16490. The only other bores with artesian flow recorded during the 1997 survey are two bores approximately 10 km north of 16490: 3870, a 77 m deep bore, and 1518, a 65.83 m deep bore 600 m east from 3870. The non-artesian bores in the vicinity of the artesian bores generally have shallower depths.

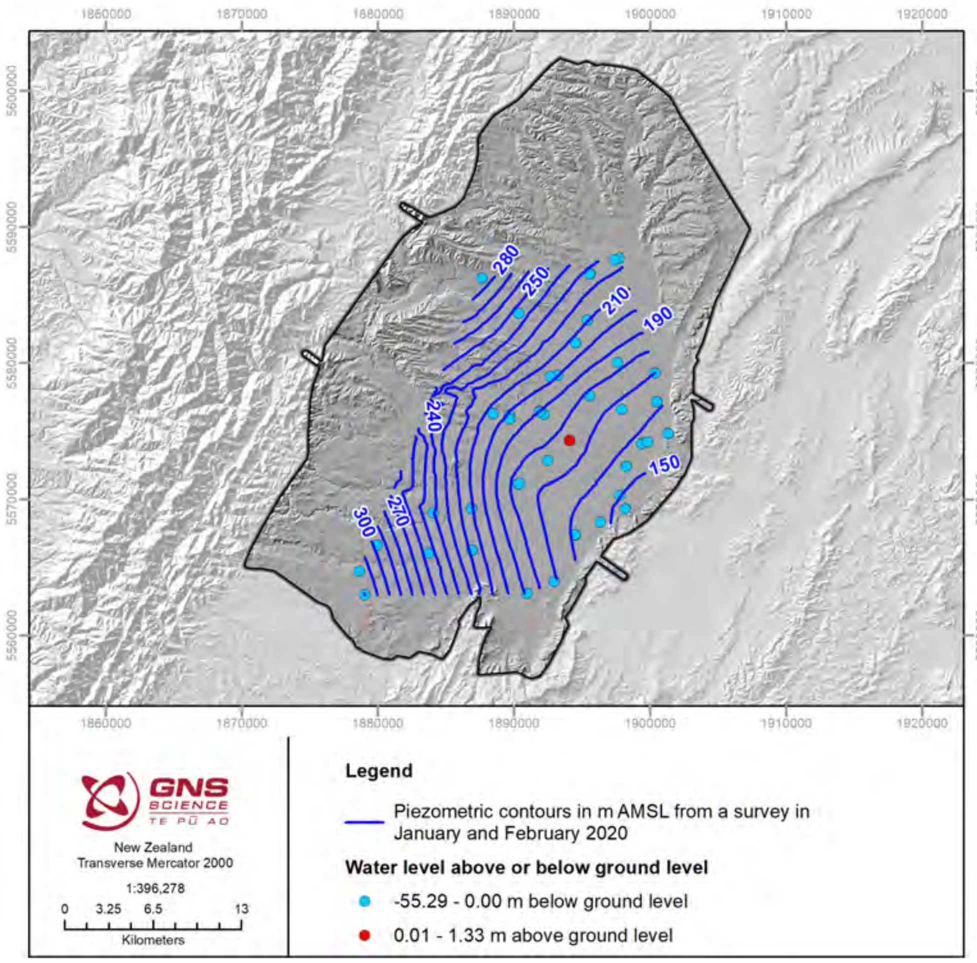

Figure 3.28 Piezometric contours and the water-level measurements that were used to derive the contours from a survey in January and February 2020. While the contours are in metres above sea level, the water-level measurements are shown as above or below the ground surface.

[3] In this report, artesian flow refers to groundwater levels measured above their measuring point, which is typically the top of the well casing.

3.4.2 Measured Electrical Conductivity of Groundwater Samples

Electrical Conductivity (EC) data measured from water samples are available from State of the Environment (SOE) monitoring, the National Groundwater Monitoring Programme (NGMP) and measurements from a 2021 sampling campaign (Morgenstern 2021).

Resistivity is the reciprocal of EC, and such data from water samples can be used to assist with the interpretation of the SkyTEM-derived resistivity models, as the SkyTEM-derived resistivity values are a function of the resistivity of the water. To best inform this assessment, the measurements would ideally be available from the time that the SkyTEM data were collected (January/February 2020). Following the approach in Tschritter et al. (2022), where feasible, the December – March time period was selected as the time period closest to the SkyTEM survey time (January/February 2020), and hydrogeological conditions are expected to be comparable.

In total, 35 sites in the Ruataniwha Plains had EC information for this timeframe available. All EC data for this time period were converted to resistivity (ohm.m) (Figure 3.29). If more than one measurement per site was available, the average was calculated. These data include:

- SOE data for 29 sites provided by HBRC (Mitchell 2021); the February 2020 data was selected for this study.
- NGMP data for three sites was extracted from the online Geothermal and Groundwater database; however, two of these sites were already included in the SOE dataset and were not used. Site 1558 had two measurements from February 2017 (“Total solids (electrical conductivity) uS/cm at 25 degrees”), and the average of both measurements was calculated. 2017 was the last year measurements were available.
- Two samples undertaken at a bore during drilling in late February and mid/late March 2021 as part of 3DAMP, which were averaged: well 17136 (Lawrence et al. in press).
- Measurements undertaken as part of an HBRC sampling campaign in February 2021 (Morgenstern et al. 2021). Of the 22 samples collected as part of this campaign, four were additional to the February 2020 SOE data and were included in the EC dataset.

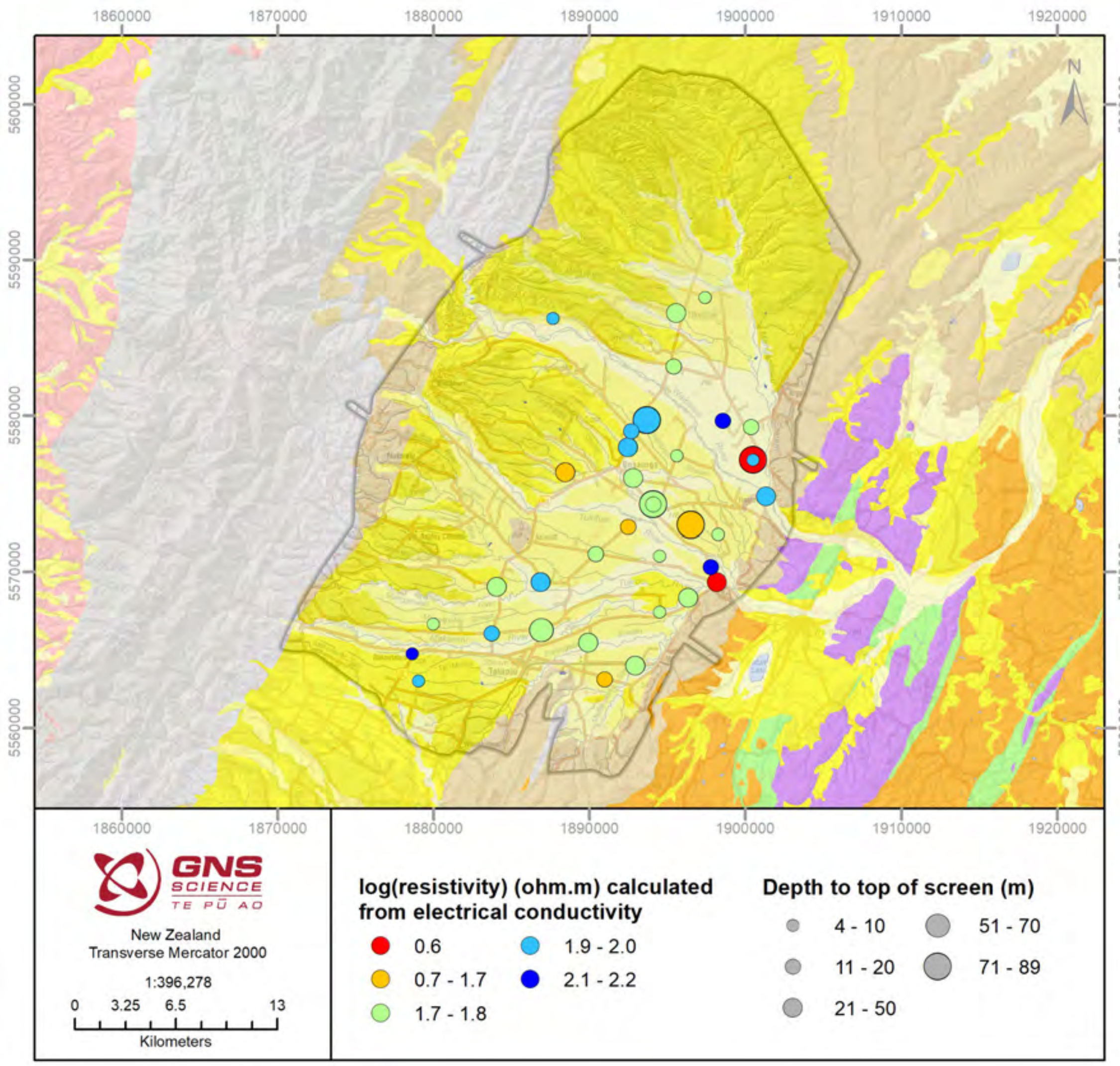

Figure 3.29 Resistivity calculated from electrical conductivity measured at State of the Environment, National Groundwater Monitoring Programme and HBRC 2021 sampling campaign sites, and well 17136.

The resistivity data calculated from EC measurements throughout the Ruataniwha Plains shows that most data points are available in the eastern part of the plains (Figure 3.29), which is reflective of the higher number of bores in this area, in general. The lowest resistivities occur at the eastern edge of the plains, at sites in close proximity to the pre-Quaternary deposits. However, patterns are difficult to establish, and resistivities vary laterally and vertically throughout the survey area.

3.4.3 Consented Takes

Data on consented groundwater takes was provided by HBRC (Harper 2019); Figure 3.30. The maximum groundwater take rate is of interest for the SkyTEM interpretation, as it provides an indication of aquifer yield and permeability.

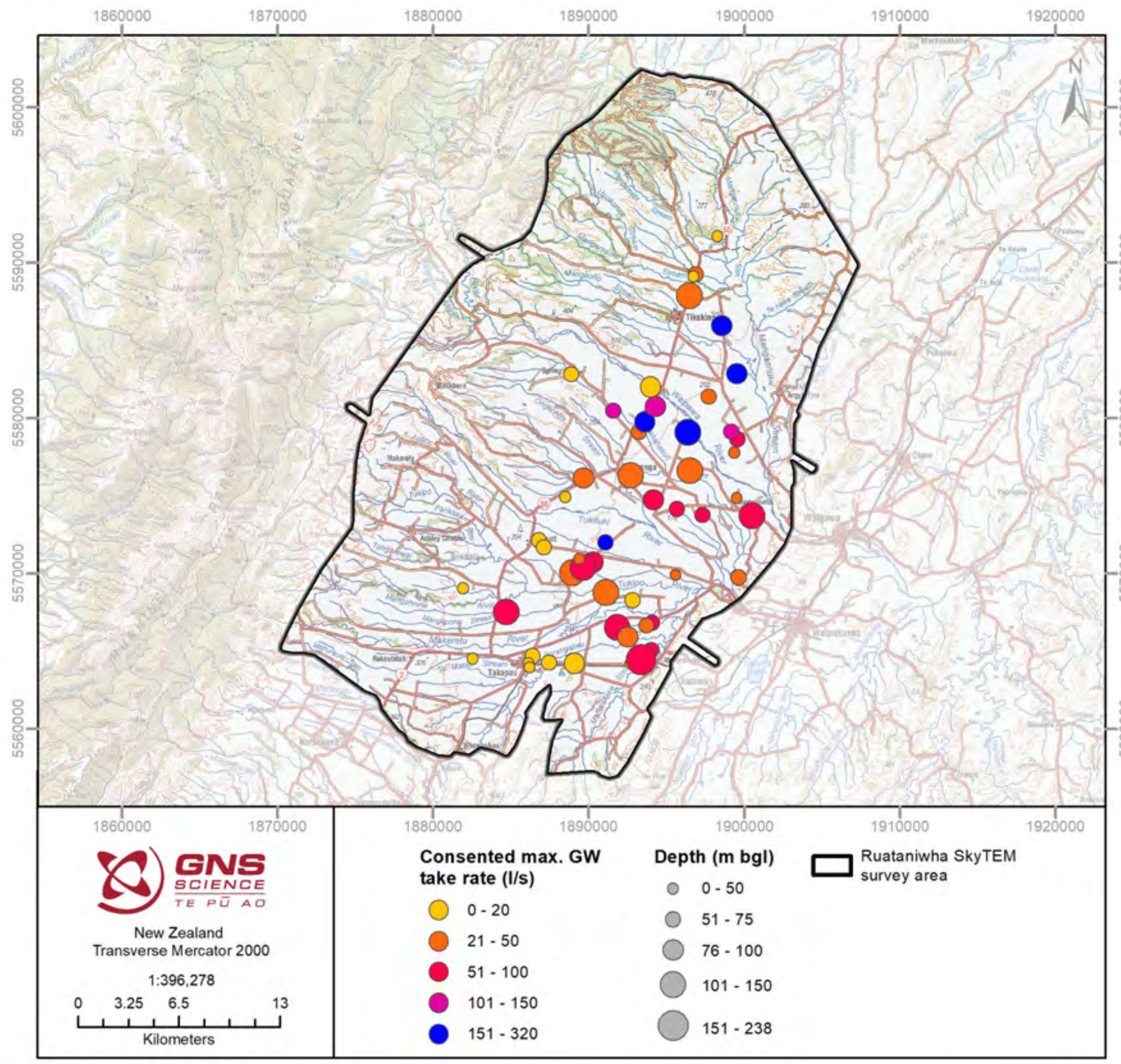

Figure 3.30 Hawke's Bay Regional Council consented maximum groundwater take rates in the survey area, shown by bore depth. The graduated colours represent the consented rate in L/s, whereas the symbol size indicates the depth of the bore. For simplification, the take rates are shown as one bore per consent. If a consent includes more than one bore with the assigned same rate, only one of the bores is displayed.

3.4.4 Previous Borehole Interpretations

Based on borehole information, PDP (1999) identified two hydrogeological units within the 'Recent Terrace Aquifer' (Young Gravels) in the eastern part of the Ruataniwha Plains: the 'Central Plains Unconfined Aquifer' and the 'Tukipo Aquitard' (also named Shallow Tukipo Aquitard and Tukipo Aquiclude in the PDP 1999 report). The Central Plains Unconfined Aquifer was described as clean gravels and sand with minor silt or silt-bound layers, whereas the Tukipo Aquitard was defined as predominantly comprising clay-bound gravels (PDP 1999).

These hydrogeological units could provide useful markers for the hydrostratigraphic interpretations of the SkyTEM data, therefore the locations, top elevations (Figure 3.31), bottom elevations, and thicknesses (Figure 3.32) of the two units were digitised from the PDP (1999) report (see Appendix 3).

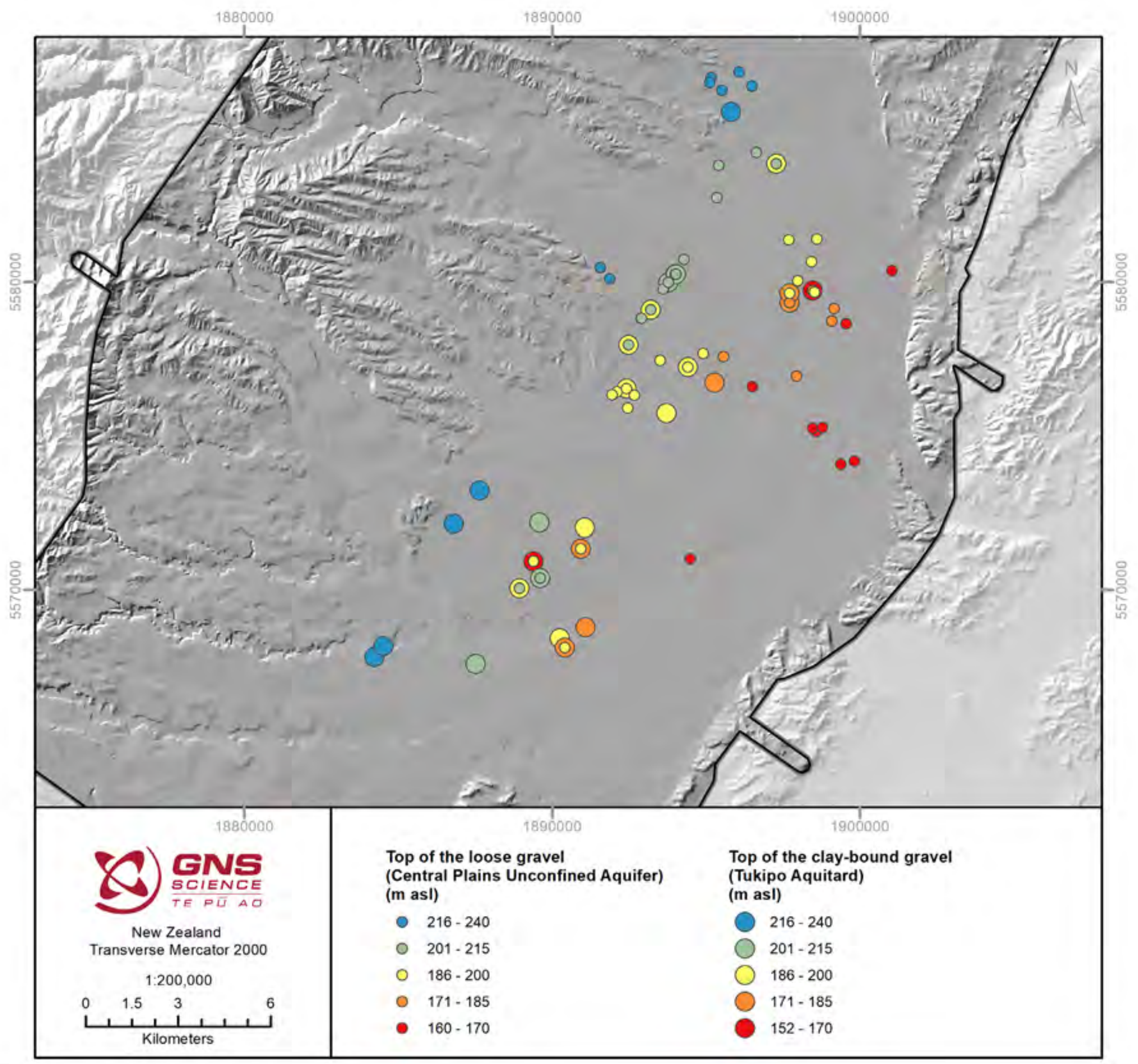

Figure 3.31 Top elevation of the Central Plains Unconfined Aquifer and the Tukipo Aquitard as identified by PDP (1999).

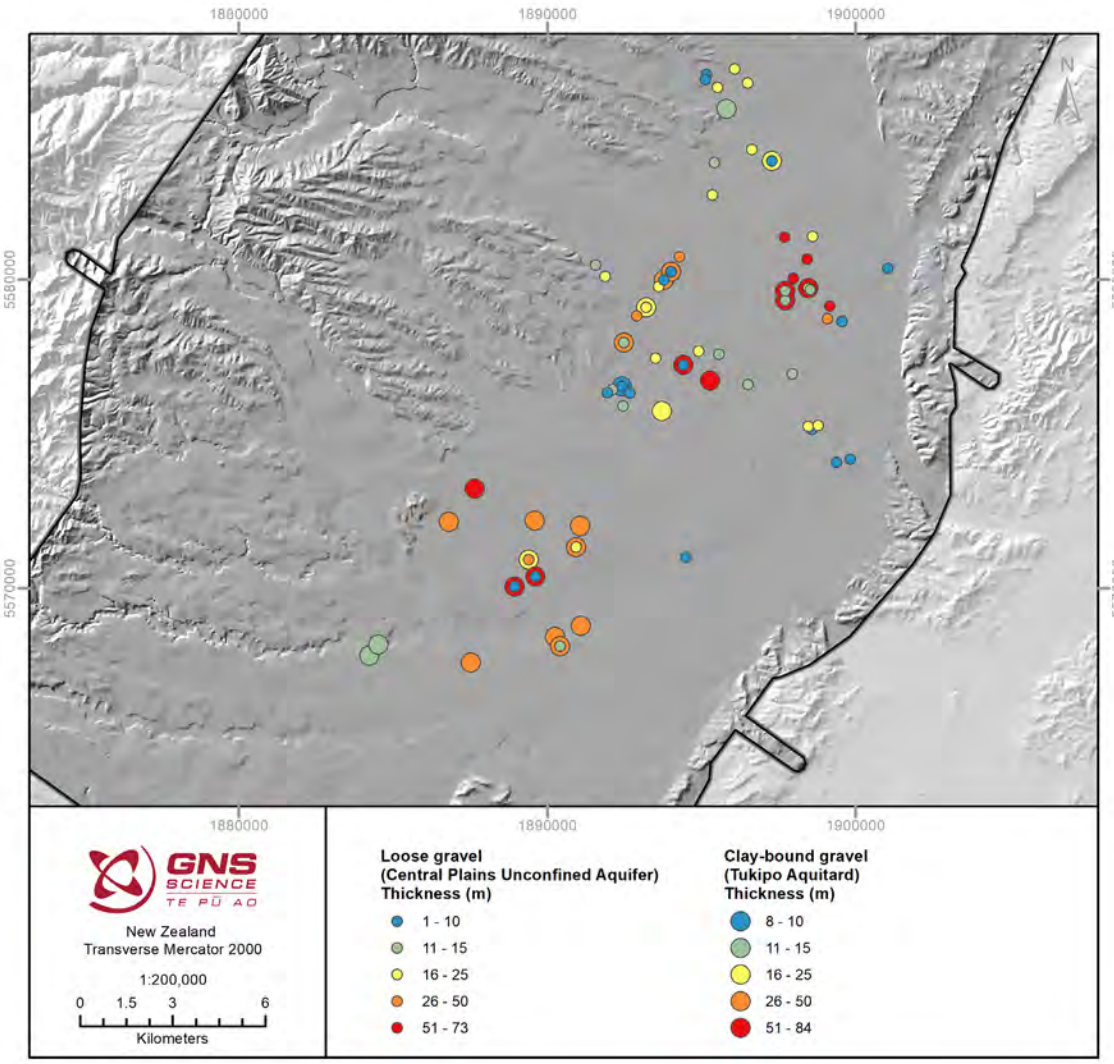

Figure 3.32 Thickness of the Central Plains Unconfined Aquifer and the Tukipo Aquitard as identified by PDP (1999).

3.4.5 Water Supply Intervals and Lithologies

For the resistivity model interpretation, it is useful to understand what lithologies are being utilised for water supplies and at what depths. To assist in such an assessment, the construction information of boreholes used for water supplies with lithological data (see Sections 3.2.3.2–3.2.3.5) were assessed.

Many of the Ruataniwha Plains bores do not have screen or open-hole details, or there are inconsistencies with details. Therefore, a combination of automated and manual assessments was utilised, with associated assumptions (see Appendix 3), to convert bore construction information (screen and open-hole details, depth of the bore) into quality-checked depth intervals being utilised for water supplies (‘water supply intervals’). From this assessment, 599 bores have a single water supply interval, and 27 bores have multiple water supply intervals.

The water supply intervals were utilised alongside the borehole lithological logs (see Sections 3.2.3.2–3.2.3.5) to obtain the location of different lithologies supplying water. A lithology was defined as the ‘water supply lithology’ if it was the largest fraction of aquifer-type material within the water supply interval. Aquifer-type materials were defined as gravel, sand, sandstone and limestone. If no such aquifer-type material was present, then the dominant lithology within the interval was chosen as the water supply lithology. A match could not be identified for 12 bores due to inconsistencies between logged lithology and bore construction details (insufficient logged lithology data available within the database). A total of 671 water supply intervals were able to be matched with lithology (Table 3.8).

The locations of the four aquifer-type lithological units utilised for water supplies are depicted in Figure 3.33 to Figure 3.36. The distribution of the sandstone identified intervals shown in Figure 3.36 suggest that sandstone may be mis-identified within some lithological logs (e.g. at shallow depths in the centre of the plains).

Table 3.8 Lithology within defined water supply intervals.

Water Supply Lithology	Count	Percentage
Gravel	548	81.67
Clay	37	5.51
Limestone	33	4.92
Sand	23	3.43
Sandstone	19	2.83
Siltstone	7	1.04
Silt	2	0.30
Ash/Pumice	1	0.15
Mudstone	1	0.15
Total	***671***	***100***

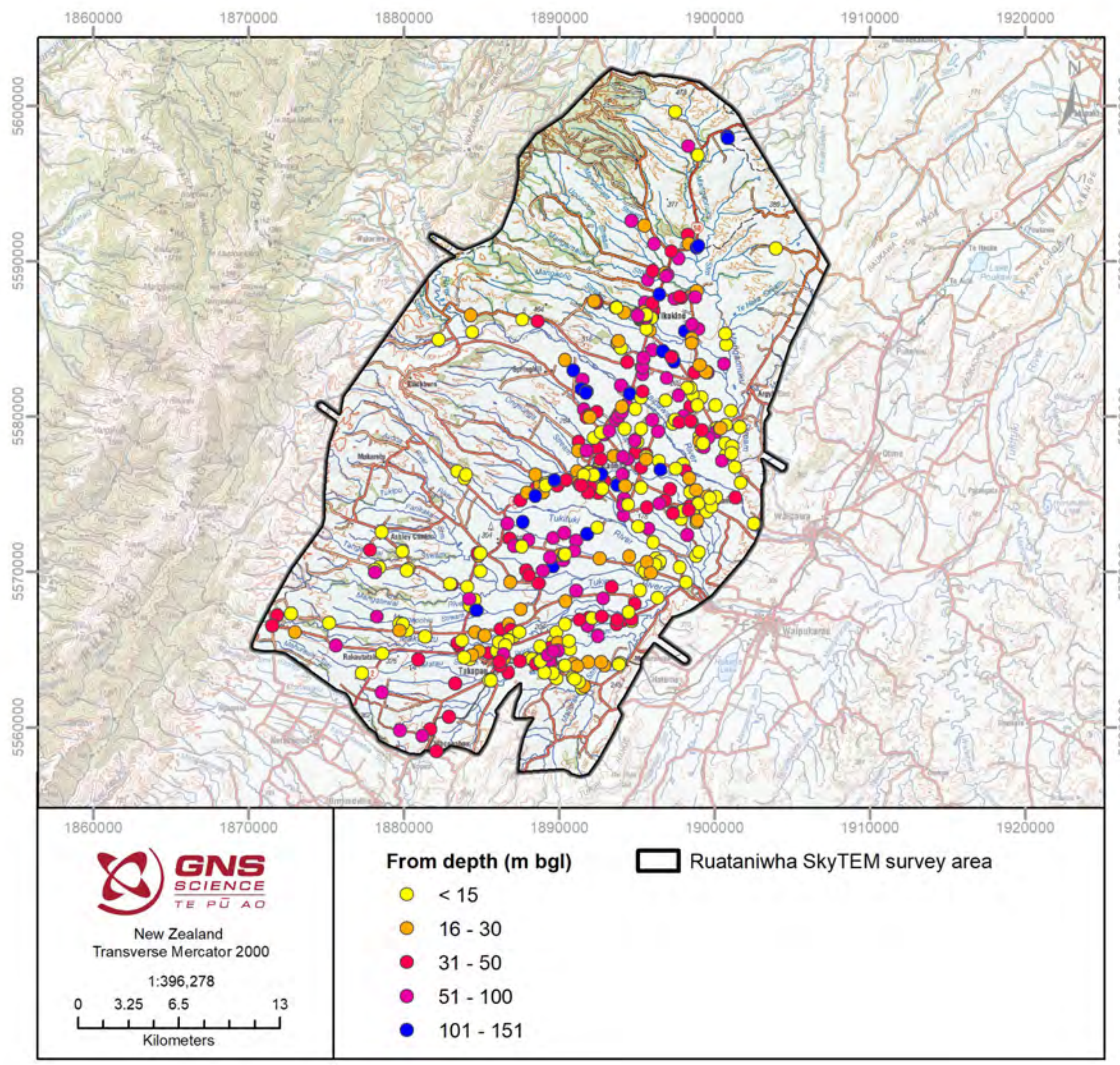

Figure 3.33 Bores supplying water from gravel, coloured by the depth of the top of the water supply interval.

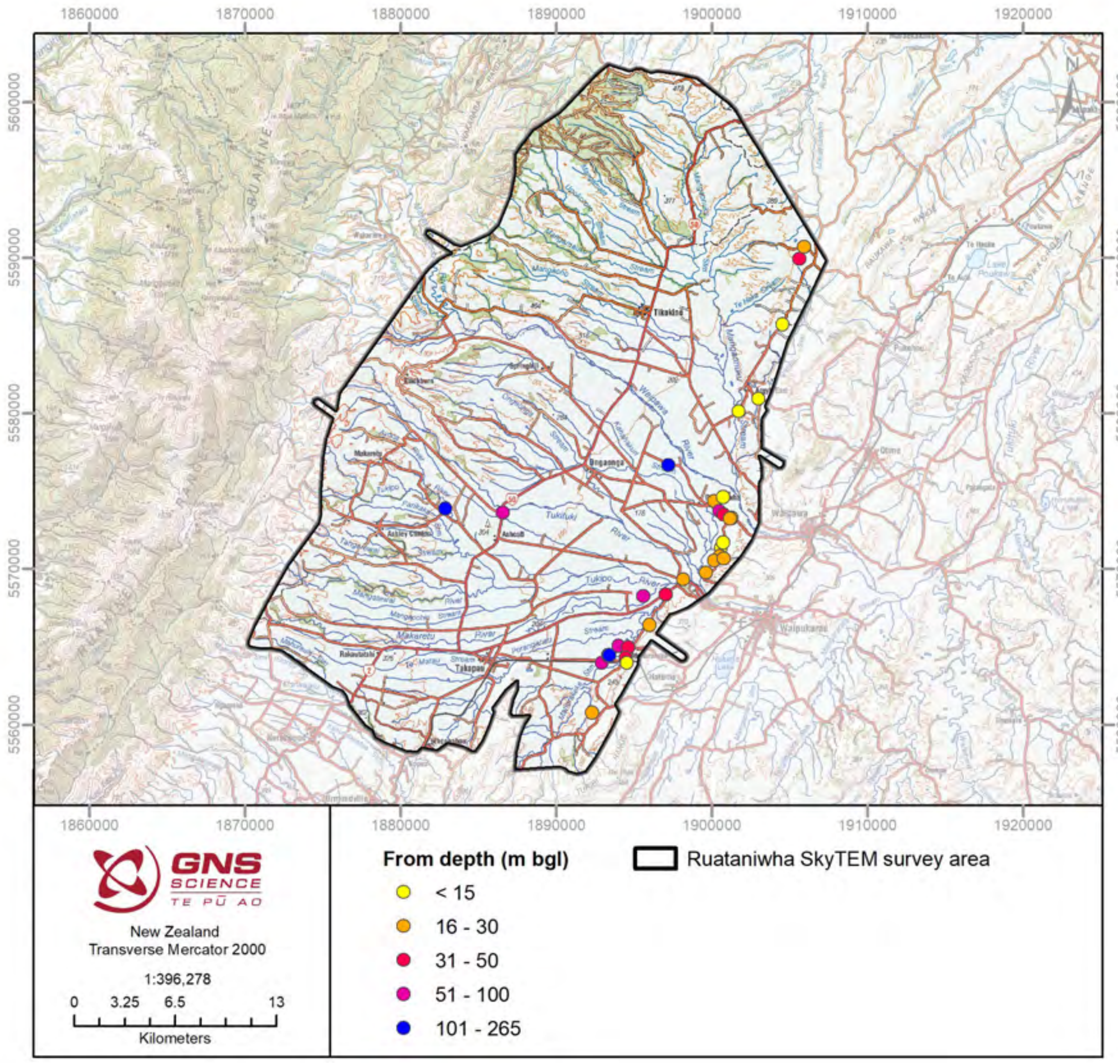

Figure 3.34 Bores supplying water from limestone, coloured by the depth of the top of the water supply interval.

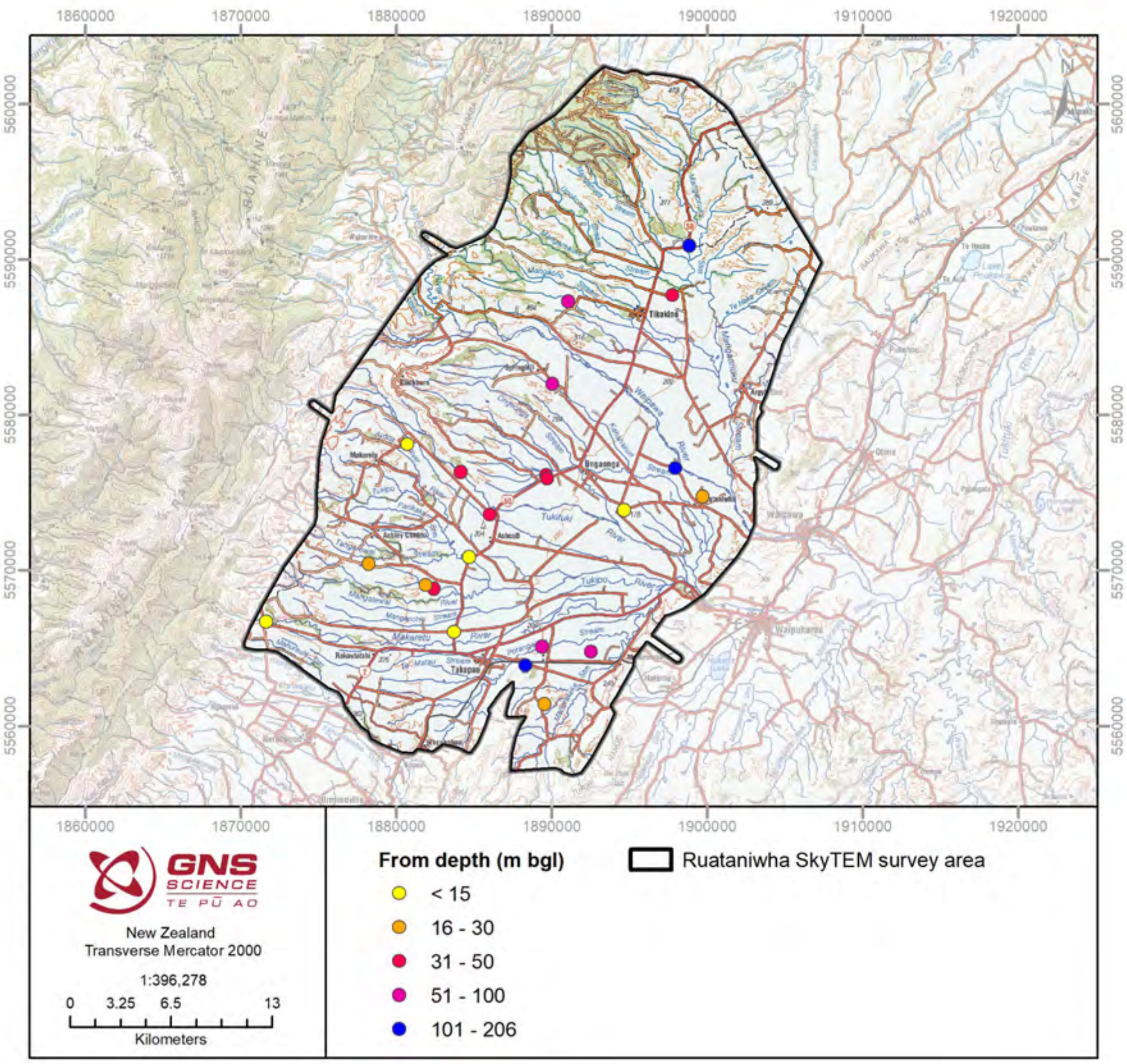

Figure 3.35 Bores supplying water from sand, coloured by the depth of the top of the water supply interval.

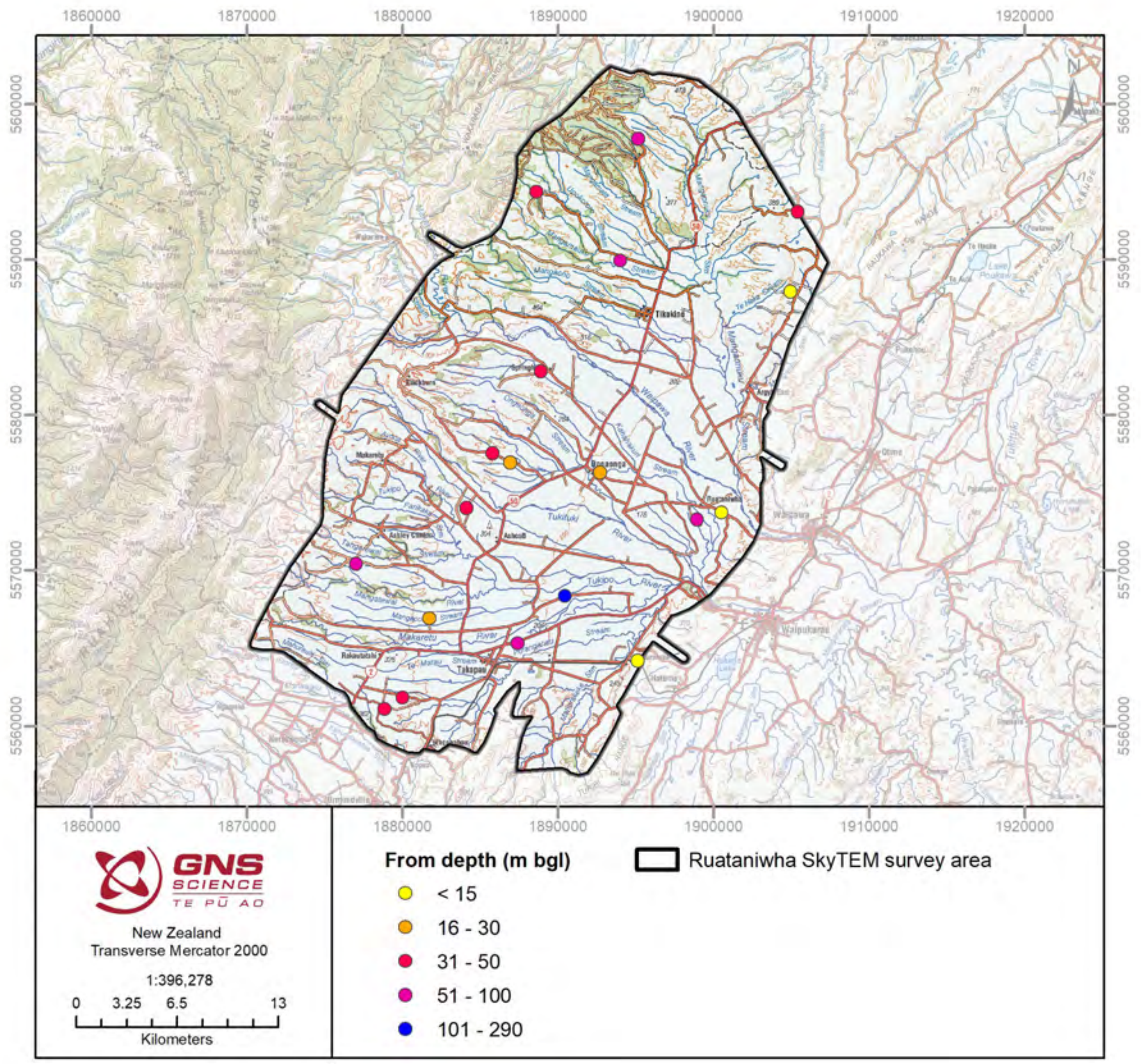

Figure 3.36 Bores supplying water from sandstone, coloured by the depth of the top of the water supply interval.

3.4.6 Aquifer Properties

Transmissivity, horizontal and vertical hydraulic conductivity (K_h and K_v, respectively) and storativity data were compiled and calculated by Pattle Delamore Partners (PDP 2018) and combined with slug test data from Meilhac (2009), HBRC hydraulic property data (Harper 2019) and slug and pump test data from Lawrence (2022a and 2022b). A range (minimum, maximum and average) was calculated for each bore across all datasets. Only average values are displayed in Figure 3.37 to Figure 3.44.

This resulted in a dataset of 75 K_h values (Figure 3.37 and Figure 3.38), 25 K_v values (Figure 3.39 and Figure 3.40), 81 transmissivity values (Figure 3.41 and Figure 3.42) and 43 storativity values (Figure 3.43 and Figure 3.44).

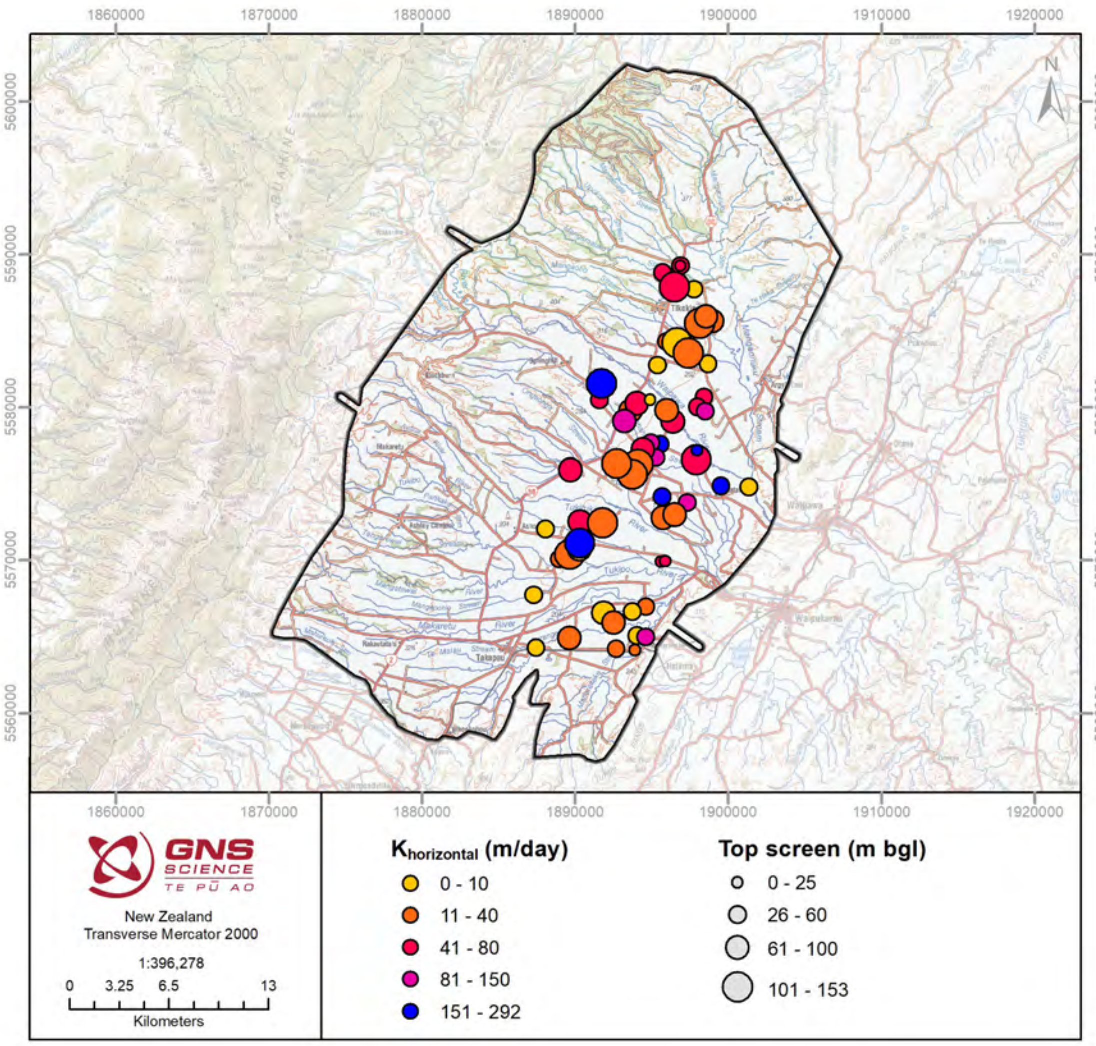

Figure 3.37 Horizontal hydraulic conductivity (K_h) data in the survey area combined from Meilhac (2009), PDP (2018), Harper (2019) and Lawrence (2022a and 2022b) datasets, shown by top of the screen depth. The graduated colours represent the hydraulic conductivity ranges, whereas the symbol size indicates the depth of the bore.

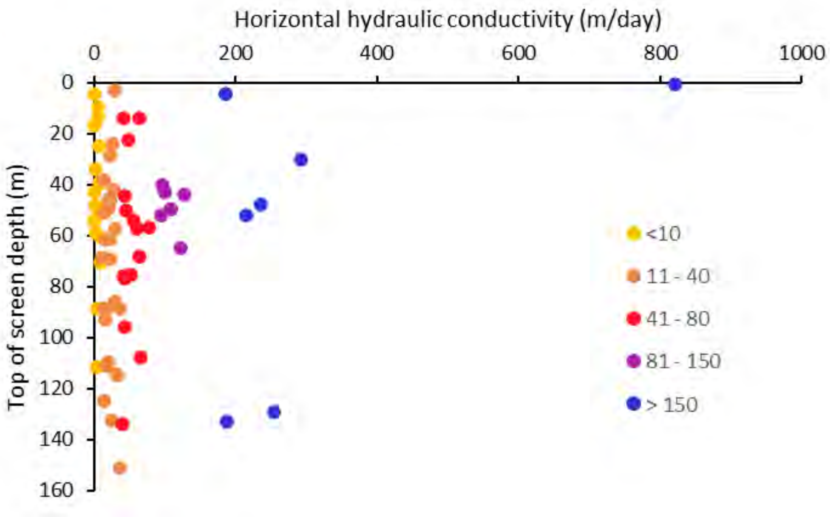

Figure 3.38 Horizontal hydraulic conductivity (K_h) data in the survey area combined from Meilhac (2009), PDP (2018), Harper (2019) and Lawrence (2022a and 2022b) datasets, shown by top of the screen depth. The colour of the dots is indicative of the hydraulic conductivity value.

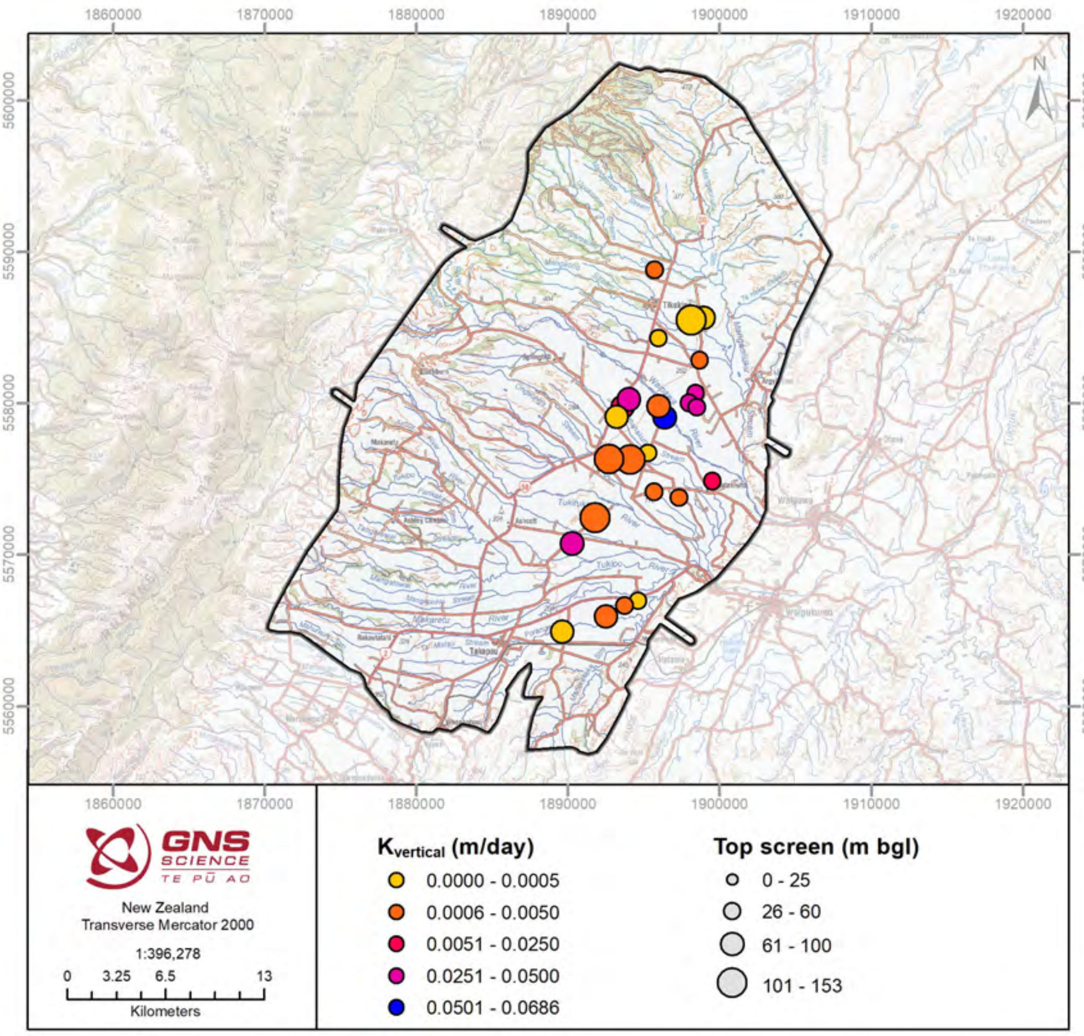

Figure 3.39 Vertical hydraulic conductivity (K_v) data in the survey area from PDP (2018) and Harper (2019) datasets, shown by top of the screen depth. The graduated colours represent the hydraulic conductivity ranges; the symbol size indicates the depth of the bore.

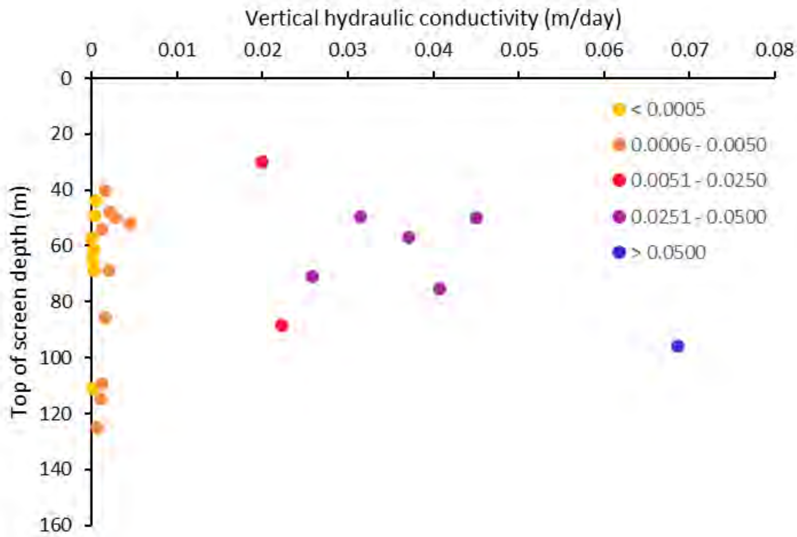

Figure 3.40 Vertical hydraulic conductivity (K_v) data in the survey area from PDP (2018) and Harper (2019) datasets, shown by top of the screen depth. The colour of the dots is indicative of the hydraulic conductivity value.

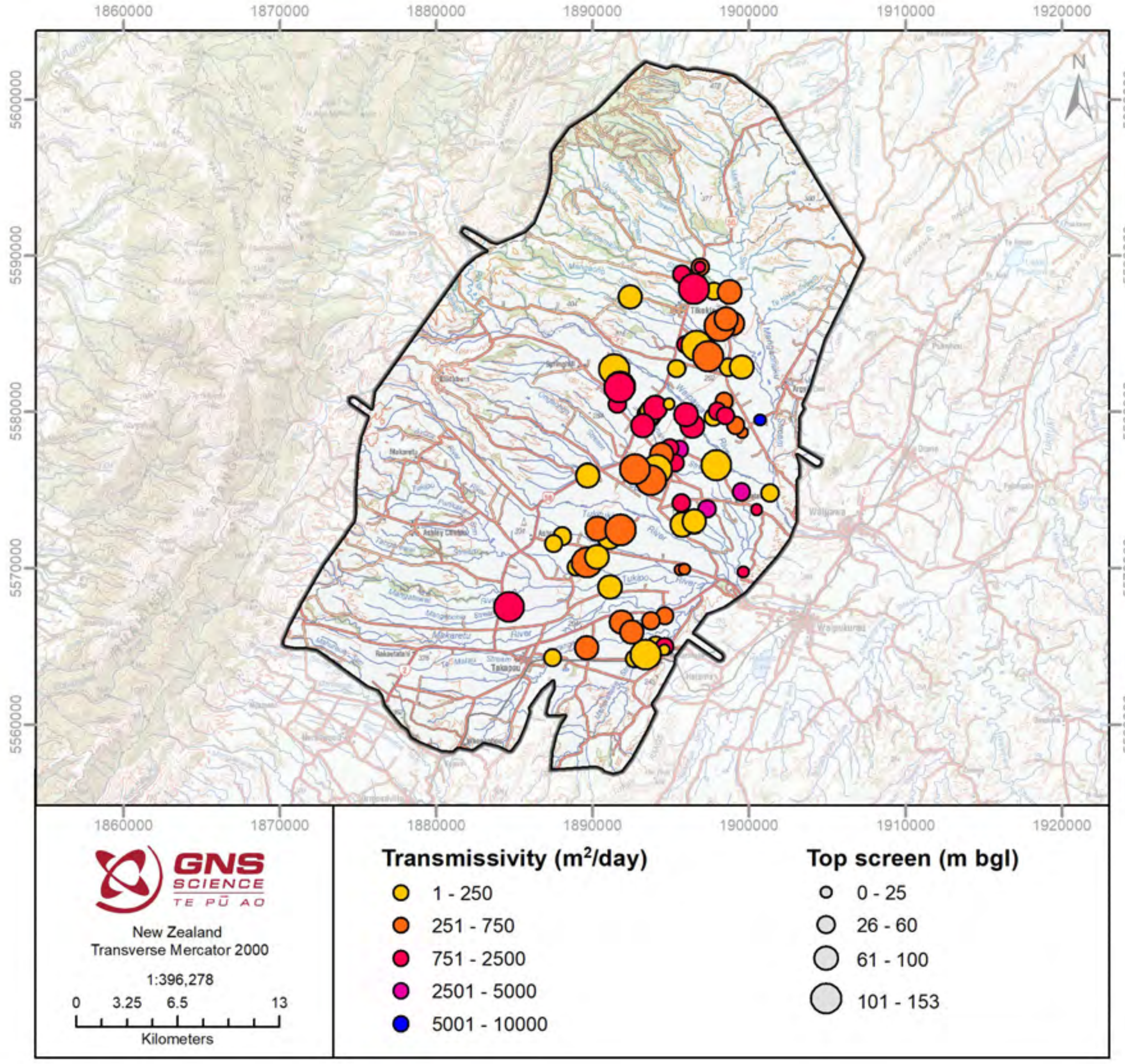

Figure 3.41 Transmissivity data in the survey area combined from Meilhac (2009), PDP (2018), Harper (2019) and Lawrence (2022a and 2022b) datasets, shown by top of the screen depth. The graduated colours represent the transmissivity ranges; the symbol size indicates the depth of the bore.

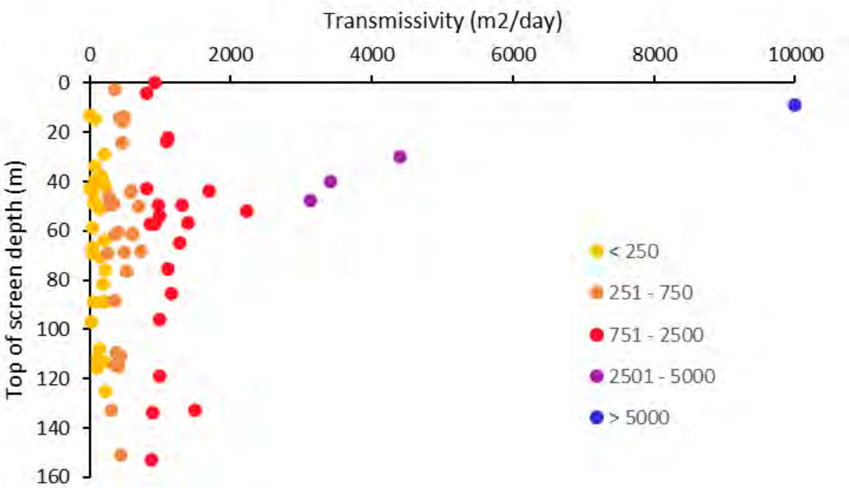

Figure 3.42 Transmissivity data in the survey area combined from Meilhac (2009), PDP (2018), Harper (2019) and Lawrence (2022a and 2022b) datasets, shown by top of the screen depth. The colour of the dots is indicative of the transmissivity value.

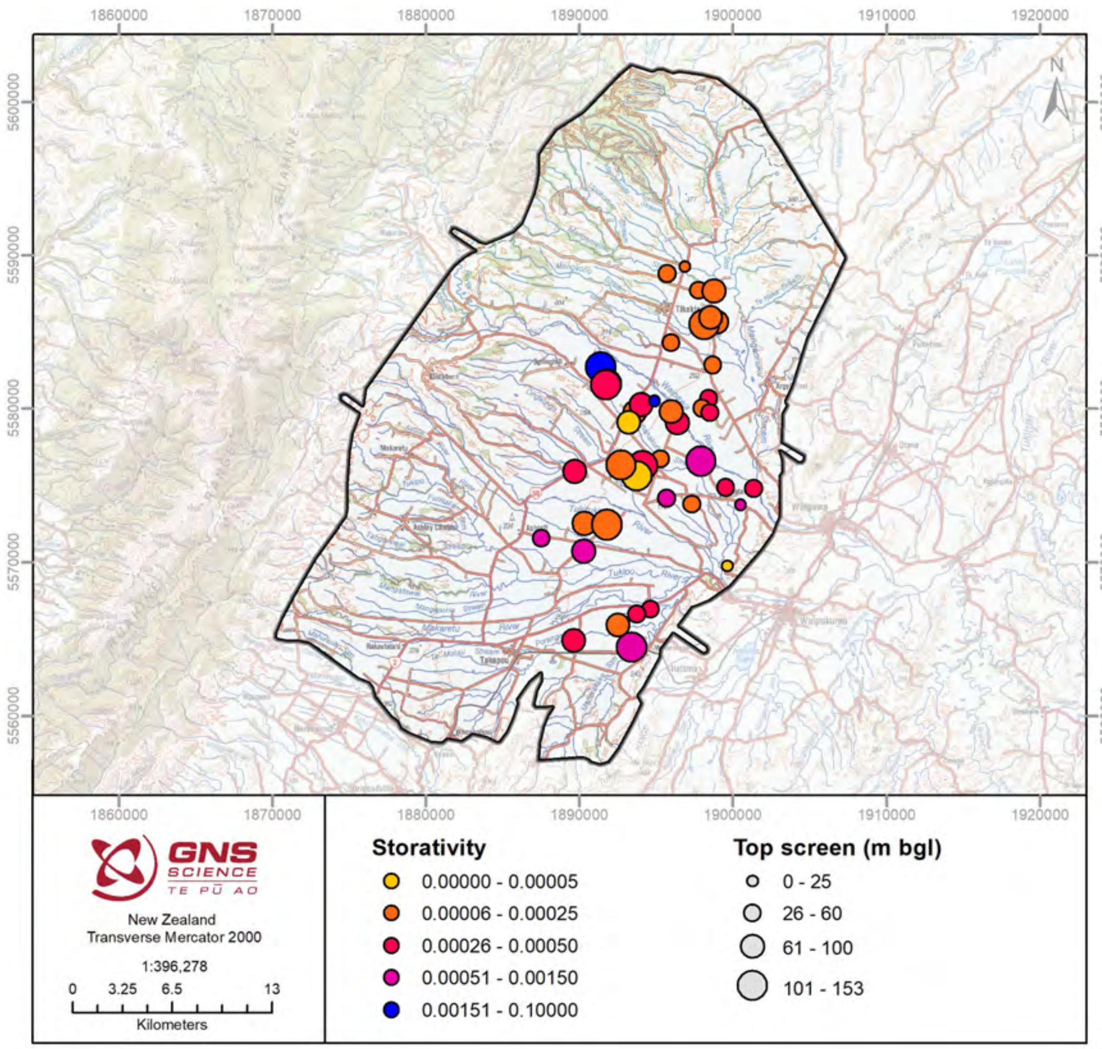

Figure 3.43 Storativity data available in the survey area combined from Meilhac (2009), PDP (2018) and Harper (2019) datasets, shown by top of the screen depth. The graduated colours represent the storativity ranges; the symbol size indicates the depth of the bore.

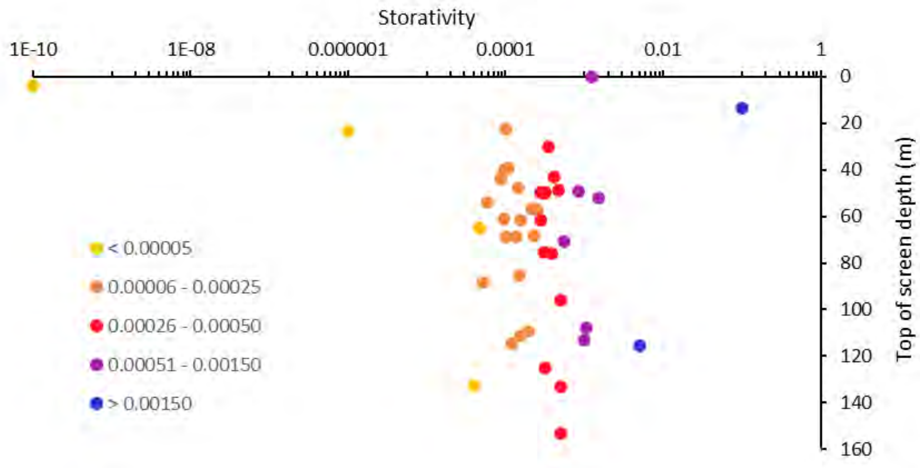

Figure 3.44 Storativity data available in the survey area combined from Meilhac (2009), PDP (2018) and Harper (2019) datasets, shown by top of the screen depth. The colour of the dots is indicative of the storativity value.

3.4.7 Groundwater Age

As part of their investigations of the Ruataniwha Plains groundwater dynamics, Morgenstern et al. (2012) (Section 2.3) collected and analysed hydrochemistry, dissolved gases, and age tracer samples from groundwater bores. In 2021, Morgenstern et al. (2021) (Section 2.7) analysed hydrochemistry, groundwater age and stable isotope data from State of the Environment wells in the Ruataniwha Basin and put them into the context of the 2012 results. As part of 3DAMP, two water samples were collected, analysed and interpreted during the drilling of research borehole Well 17136 (3DAMP Well-1) in 2021 (Lawrence 2022a). The data from those three datasets have been combined and are displayed in Figure 3.45.

Morgenstern et al. (2012) found that geological units with a low permeability in the SE of the basin were linked to old groundwater (>100 years) in the area indicating "slow movement of groundwater and slow recharge, consistent with the geology of the area." While groundwater ages throughout the plains vary, older groundwaters are predominant in the Pleistocene gravels and, in particular, in the south of the plains (Morgenstern 2021).

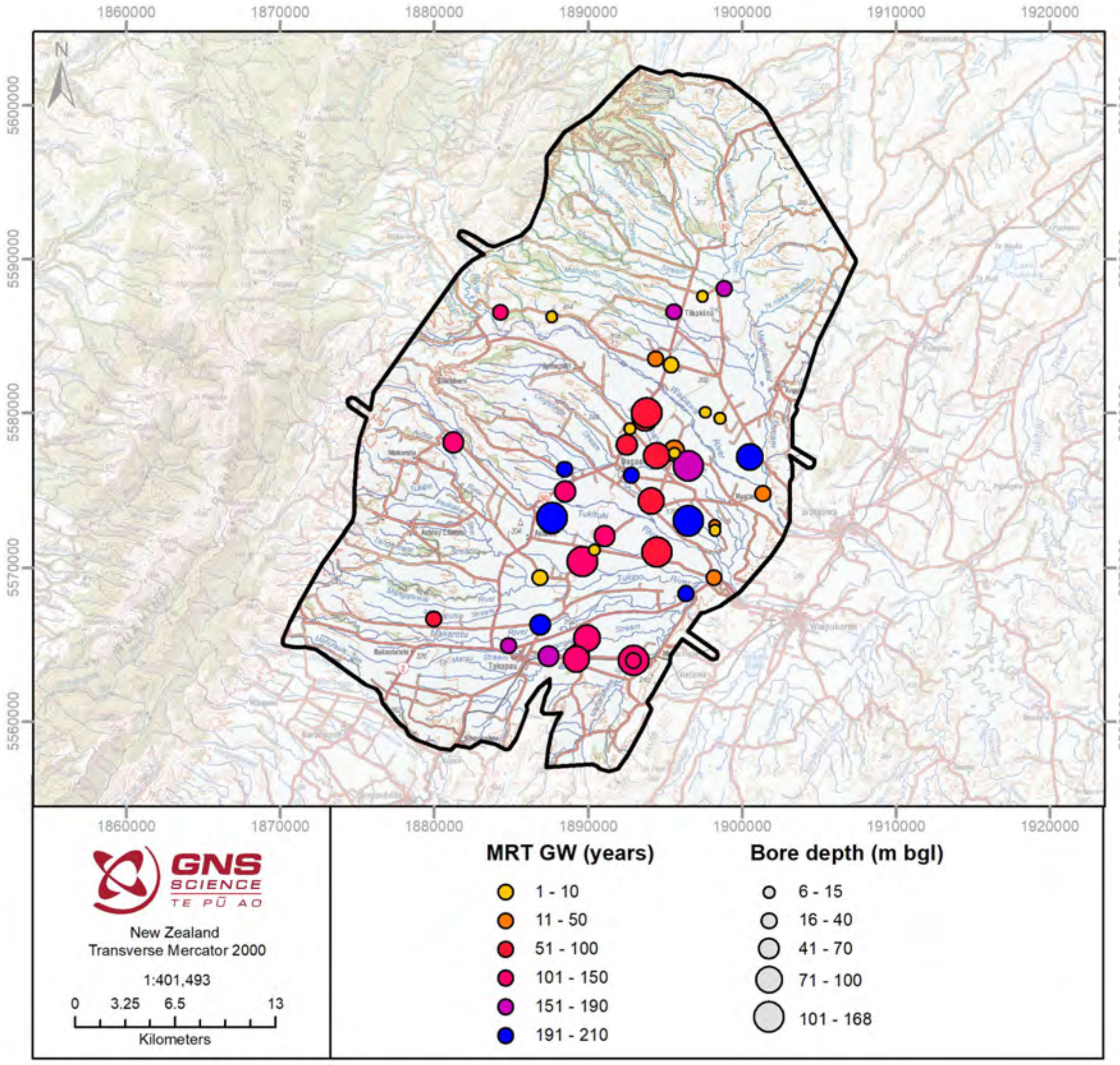

Figure 3.45 Groundwater age (MRT) data available in the survey area from Morgenstern (2012 and 2021) and Lawrence (2022a) datasets, shown by bore depth. The colours are representative of the MRT; the size of the dot indicates the depth of the bore.

4.0 KEY FINDINGS OF RELEVANCE FOR THE SKYTEM SURVEY

4.1 Geological and Hydrogeological Nomenclature of Current and Historical Maps, Bore Logs and Models

PDP (1999) used the geological map created by Grant-Taylor (1978), and the nomenclature of geological units in that map, to derive a map of hydrogeological units in the Ruataniwha Plains (Figure 4.1, left). Since then, the geological map nomenclature for the Ruataniwha Plains area has changed, however, the hydrogeological nomenclature is still widely in use.

In 2011, the QMAP sheet for the Hawke's Bay was published (Lee et al. 2011). The QMAP project aimed to map all of New Zealand, divided into map sheets at the 1:250 000 scale, and to combine all of these map sheets to a consistent and seamless national geological map. This work also included making the naming of geological units consistent across adjacent map sheets. The first seamless digital version of the national map was published in 2014 (Heron 2014). The latest update has been published in 2020 (Heron 2020) (Figure 4.1, right).

The geological unit names in the updated geological map for the Ruataniwha Plains from Heron (2020) (Figure 4.1, right) vary distinctly from the hydrogeological unit names in the older map (Figure 4.1, left), and the extents of the recently mapped geological units differ in places from those hydrogeological units, they are most likely equivalent to. This could be due to lack of data in the past, differences in scales and mapping focus, the heterogeneity of deposits of the same age and origin, and/or difficulties with distinguishing younger from older gravels in the plains (Section 4.2.4). Nevertheless, this hydrogeological unit nomenclature is still in use in more recent geological and hydrogeological reports and models (Baalousha 2012; Morgenstern et al. 2012; Wallbridge Gilbert Aztec 2019), and it is also used in this report to refer to hydrogeological units as it provides a convenient system to describe the hydrogeological conditions in the survey area. Therefore, in the following sections, geological nomenclature is used to the describe the geology, whereas the traditional hydrogeological nomenclature is used to describe the hydrogeology of the basin.

Table 2.1 provides an overview linking recent geological map units to the traditional hydrogeological units they are (approximately) equivalent to, so that older and newer geological and hydrogeological descriptions, maps and models can be easier correlated with each other.

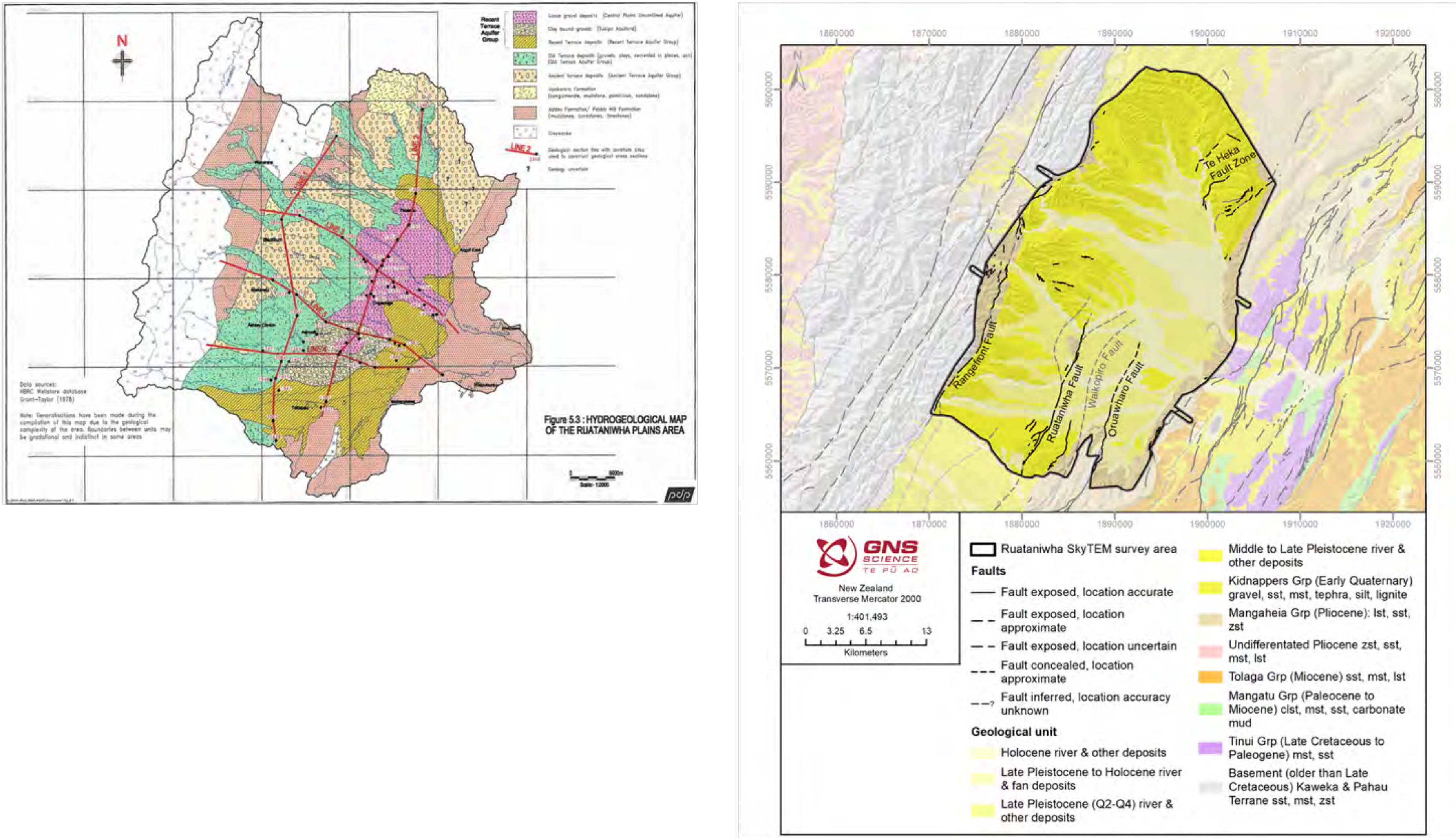

Figure 4.1 Left: 1999 Hydrogeological map of the Ruataniwha Plains by PDP (1999); right: 2020 geological map by Heron (2020).

4.2 Geology

A detailed summary of the geological formations and tectonic structure encountered in the Ruataniwha Plains is provided by Harper (2018). This section will summarise the key findings of relevance to the interpretation of the SkyTEM data from that report and other sources as indicated.

The Ruataniwha Plains are located in a relatively young basin structure, the Ruataniwha Basin, that was formed less than 2 million years ago due to uplift of the Ruahine Ranges and Otane Anticline, which form the western and eastern boundary of the basin, respectively (Brown 2002). Marine sediments filling large areas of the basin were deposited in a marine seaway that extended from the Wairarapa to Hawke Bay, connecting the Ruataniwha Plains with the Heretaunga Plains (Dravid and Brown 1997). Erosion of the uplifted areas, and subsequent sediment deposition in the basin, resulted in the infilling of the basin with thick sequences of terrestrial sediments. The continued infilling of sediments due to the uplift displaced the seaway approximately 500k years ago, and the marine deposits were subsequently also covered by 200—300 m of terrestrial sediments from rivers originating in the Ruahine Ranges, including the predecessors of today's Waipawa and Tukituki rivers and a southeast-flowing Ngaruroro River (Brown 2002, Harper 2018). Ignimbrite and ash layers from recurrent volcanic activity in the Taupo Volcanic Zone were deposited within these sediments (Brown 2002). Due to the continued tectonic uplift, the oldest terraces (Early Quaternary) are folded by reverse faults (Lee et al. 2011). A lithostratigraphic overview summarising the geological formations in the wider Ruataniwha Plains area is provided in Figure 4.2.

There are two surface geological maps available that cover the entire survey area. The geological units at the ground surface in and around the Ruataniwha Plains have been mapped at the 1:250,000 scale (Heron 2020). Also, a surface geological map at the 1:50,000 scale that was created by Brown (1998), may be of interest to the SkyTEM data interpretation, as it covers the entire Ruataniwha SkyTEM survey area at a higher level of detail.

4.2.1 Pre-Quaternary Deposits

Pre-Quaternary deposits in the survey area are comprised of:

- "Hard, indurated metasedimentary rocks" (Francis 2001), i.e. siltstone, mudstone, and sandstone (greywacke) from the Kaweka and Pahau terranes, which pre-date the Late Cretaceous period, and
- "moderately hard to moderately soft" (Francis 2001) limestone, siltstone, sandstone, mudstone and claystone deposited during the Late Cretaceous to Pliocene (Heron 2020).

These older deposits are outcropping at the surface primarily in the ranges west and east of the Ruataniwha survey area and are expected to underlie the plains at depth. However, data on the pre-Quaternary units underneath the plains is sparse, as most bores are less than 60 m deep (median depth is 38 m) and terminate in Quaternary deposits (Section 3.2.3.5). Logs from three petroleum exploration bores within the plains show limestone and sandstone deposits starting at depths between 42.7 and 122 m. Brown (2002) logged pre-Quaternary deposits in some of the research bores starting at depths between 15 m (4696) and 31 m (4702), but some of the deeper bores (e.g. 4697, 4700) did not reach pre-Quaternary even at total depth of up to 149 m.

Of the five petroleum exploration bores that have been drilled within, and in the vicinity of, the Ruataniwha survey area, only the Takapau-1 and Ongaonga-1 bores reached greywacke basement at depths of 1003 m and 1468 m, respectively (Section 3.2.3.1).

Pre-Quaternary deposits that have been mapped at the ground surface or found at depth in the survey area, so far, are, from oldest to youngest, (Lee et al. 2011; Harper 2018; Heron 2020):

- **Basement rocks of the Kaweka and Pahau terranes**: primarily siltstone, mudstone, and sandstone (greywacke).
- **Mangatu Group**: Paleocene to Miocene claystone, mudstone, sandstone and carbonate mud of the Wansted and Weber formations. Wansted Formation overlies Tinui Group Whangai Formation conformably outside of the plains. Smectitic, soft to moderately hard claystone, greensand, sandstone and marl; and Smectitic greenish-grey or reddish mudstone, calcareous mudstone, sandy mudstone (Wanstead Formation, 75–300 m thick); Calcareous mudstone, limestone and alternating sandstone and mudstone (Weber Formation).
- **Tolaga Group**: Miocene sandstone, mudstone and limestone that overlie Mangatu Group, Tinui Group or basement unconformably; occurs at the ground surface east of the Ruataniwha Basin, and deposits logged in the Speedy-1 bore may be part of this group.
- **Mangaheia Group**: Pliocene limestone, sandstone and siltstone, including shell beds and shelly conglomerates, deposited in a marine environment. Limestones in this group, like the Te Onepu Limestone and younger limestones have the potential to be aquifers (Francis 2001). The Te Onepu and Whetukura limestone horizons have been uplifted to form the ranges east of the Ruataniwha Plains and dip towards the west. Whetukura limestone is generally less than 50 m thick, whereas Te Onepu limestone can be up to 140 m thick. A thickness of 99 m of the latter was found in the Takapau-1 bore from a depth of 839 m onwards and was described as “very porous silty coquina limestone, medium to dark grey, poorly consolidate and very friable”. Other Pliocene deposits have also been encountered in the Ongaonga-1 and Speedy-1 bores (Francis 2001). In Speedy-1, Te Onepu limestone is overlying Tukituki Sandstone (Francis 2001), which has been described by Thomson (1926) and others in outcrops as Tukituki Sands, which are fossil bearing grey and brown sands with bands of brown and greenish soft sandstone.
- Late Pliocene Okauawa Formation consists of blue-grey to green, 20–2000 mm-thick interbeds of fine sandstone and mudstone, massive mudstone, shell conglomerates, and granule to pebble conglomerates (Kelsey et al. 1993). Okauawa Formation was potentially encountered by two groundwater exploration bores (4696, 4702) described by Brown (2002), located along the eastern boundary of the Ruataniwha Plains.

Other pre-Quaternary deposits that may occur at depth in the survey area, but have not been drilled, so far, are (Lee et al. 2011; Harper 2018; Heron 2020):

- **Mangapurupuru Group**: Early Cretaceous poorly sorted basal breccia; conglomerate; and pebbly siltstone to muddy sandstone, grading to alternating sandstone-siltstone, matrix-supported sedimentary conglomerate (Gentle Annie Formation, <400 m thick); or massive, fossiliferous mudstone or massive concretionary mudstone, alternating sandstone and mudstone and minor conglomerate with sparse limestone beds and tuffs (Springhill Formation, <750 m thick); outcropping in the ranges southeast of the survey area and has been estimated at depth within the Ruataniwha Plains (Francis 2001).
- **Tinui Group**: Late Cretaceous to Paleogene mudstone and sandstone; unconformably overly Mangapurupuru Group and other deposits in the ranges east and southeast of the Ruataniwha survey area where they crop out; Whangai Formation <400 m thick, Waipawa Formation <35 m; So far, they have not been drilled in exploratory bores within the plains, either because they were not present (Takapau-1, Ongaonga-1) or because the bores terminated above the stratigraphic level of this group (Speedy-1, Mason Ridge-1, Kerereu-1). Whangai Formation has aquifer potential due to extensive fractures (Francis, 2001).

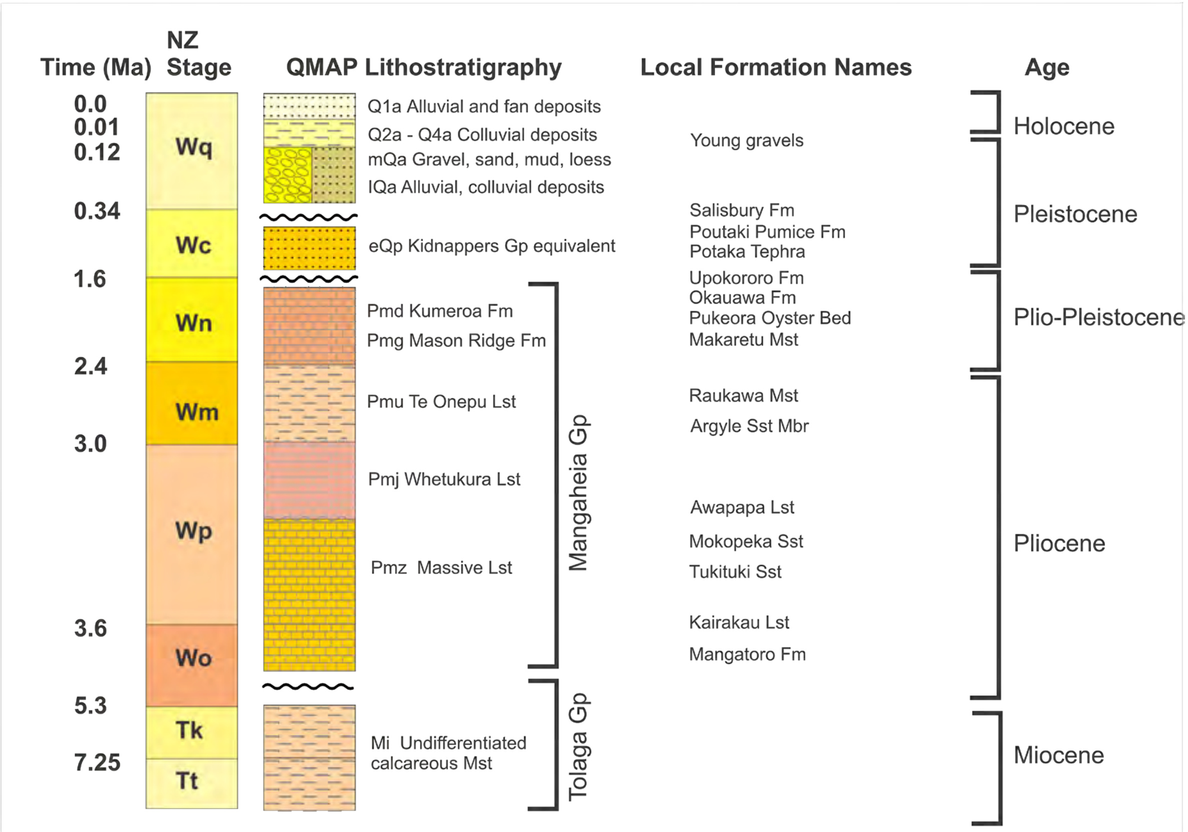

Figure 4.2 Stratigraphic column derived from the QMAP geology of the Ruataniwha Plains north of Dannevirke and the Poukawa around Waipukurau. The following abbreviations are used: Formation (Fm), Group (Gp) and Lst (Limestone) for local divisions. The New Zealand stages are Haweran (Wq), Castlecliffian (Wc), Nukumaruan (Wn), Mangapanian (Wm), Waipipian (Wp) and Opoitian (Wo).

4.2.2 Pleistocene

The pre-Quaternary deposits are unconformably overlain by terrestrial to marginal marine deposits of the Pleistocene Kidnappers Group throughout the major parts of the survey area. These deposits primarily consist of thick-bedded conglomerate, sandstone and pumiceous sandstone with minor lignite, ignimbrite beds and paleosols. Kidnappers Group deposits have been mapped at the ground surface in the northern and western parts of the Ruataniwha survey area (Heron 2020) and underlie the plains at depth (Francis 2001; Brown 2002; Harper 2018). Across the wider area of, and beyond, the Ruataniwha Basin, Kidnappers Group comprises various formations that were previously mapped individually, including Mangaratata Formation, Ashley Formation[4], Upukororo Formation, Blackburn Formation, Poutaki Formation and Salisbury Gravel (Lee et al. 2011). This older nomenclature has been used in numerous past and recent reports on the geology and hydrogeology of the basin. Francis (2001) also noted that, in some of the older reports, the name “Upukororo Formation” has been used for the Mangatarata and Salisbury Gravel formations. Most reports discuss the Salisbury Gravel and its interaction with other pre-Quaternary formations (Kidnappers A ignimbrite, Okauawa Formation, Poutaki Formation, Pukeora Oyster Shellbed).

Salisbury Gravel was, for example, encountered during drilling of the Ongaonga-1 well at 40–120 m depth (Francis 2001).

A basal ignimbrite unit (Kidnappers A ignimbrite, Wilson et al. 1995) marks the base of the Salisbury Gravel Formation, which overlies, underlies and/or is interbedded with the Poutaki Formation in the survey area. Kelsey et al. (1993) describes Poutaki Formation as sand, silt and clay beds with ignimbrite, tuff and pumice layers. Peat layers, wood fragments and other carbonaceous matter may also be present.

The base of the Salisbury Gravel was mapped at the first distinct ignimbrite bed. However, where the basal ignimbrite is absent, Salisbury Gravel is difficult to distinguish from the underlying Poutaki Formation, due to both formations containing massive mudstone beds interbedded with pumiceous sandstone and conglomerate beds (Kelsey et al. 1993). Francis (2001) noted that the lower part of the Salisbury Gravel in the east of the plains shows a more marine influence, whereas it’s mostly terrestrial in other parts of the plains. However, towards the south, the facies changes to a more lacustrine depositional environment indicated by less gravel or conglomerate beds and the existence of clays and peat beds (Francis 2001). Due to this facies change, Francis (2001) uses the name Mangatarata Formation for the less gravel-rich deposits in the south.

Poutaki Formation overlies Late Pliocene Okauawa Formation (Mangaheia Group) unconformably in areas where both formations exist (Kelsey et al. 1993). Four of the drilled groundwater research bores reported by Brown (2002) (4697, 4700, 4701, 4702) encountered Poutaki Formation starting at depths between 31 m and 108 m, with the shallowest occurrence closest to the eastern boundary of the Ruataniwha Plains (bore 4702). Two of these bores also reached Salisbury Gravel, which was underlying Poutaki Formation at those locations, starting at depths of 108 and 138 m. Also, two of the Brown (2002) bores located closest to the eastern margin of the plains (4696, 4702) encountered a unit that Brown (2002) tentatively identified as Okauawa Formation (1.5M years old) starting at depths of 15 and

[4] Ashley Formation is included in Kidnappers Group in a table in QMAP, however, there is no further information on this formation available in QMAP. According to Grant-Taylor (1978), however, it appears to be equivalent to Mangaheia Group rather than Kidnappers Group. Lee (2022) confirmed that Ashley Formation should be part of Mangaheia Group.

60 m, and Pukeora Oyster Shellbed (2M years old) starting at depths of 22 and 100 m, respectively. At well 4702, Okauawa Formation likely underlies Poutaki Formation (Brown 2002).

Flights of raised mid to late Pleistocene river terrace deposits are located throughout the Ruataniwha Plains (Grant-Taylor 1978). Younger terraces are generally better preserved than older terraces, which have been dissected by erosion over time. Remnants of older terraces are often capped by a loess layer of less than 1 m thickness. The terrace gravels are generally unsorted. Grant-Taylor (1978) noted that the terraces were often difficult to distinguish from each other as they don't have any distinct characteristics. Therefore, they used the height of the terraces for age correlation. Gradients measured at better preserved terrace surfaces showed that older terraces consistently had steeper gradients than then younger terraces (Grant-Taylor 1978). For example, the 400k years old Blackburn Terrace surface had a gradient of 28.5 m/km, whereas the surface of the <15k old post-glacial Fairfield Terrace had a gradient of 6.2 m/km.

4.2.3 Holocene

Unconsolidated Holocene river sediments overlie the Kidnappers Group and other older deposits in the eastern part of the Ruataniwha Basin. These have been described as part of the Young Gravels unit by Francis (2001), who observed that these deposits are thicker in the east than in the west of the plains. A thickness of 57 m of these deposits has been logged as Holocene alluvial gravels in the Speedy-1 petroleum exploration bore. Brown (2002) identified the youngest deposits in the eight groundwater exploration bores as Fairfield Formation (<15k years old; informal name from Grant-Taylor 1978, not defined in QMAP). The thickness of these deposits varies across those bores between 4.5 m at well 4702, the southernmost of the Brown (2002) wells, and 28 m at well 4694, which is located further north and more central in the plains.

4.2.4 Differentiation between Younger and Older Gravel Units

As mentioned in Section 4.2.2, Grant-Taylor (1978) mapped the river terraces in the Ruataniwha Plains using the relative heights of the terraces, as they did not find any distinct characteristics that would have allowed them to differentiate older from younger terrace deposits. They did find that one of the things that differentiated the younger terraces from the older ones was the gradient of the terrace surfaces: Older terrace surfaces exhibited a steeper gradient than younger terraces (Grant-Taylor 1978).

Of the seven terraces (Table 2.1, from oldest to youngest: Ongaonga, Ngaruru, Glen Appin, Hugenden and Blackburn, Tikokino and Fairfield), the two youngest terraces, Tikokino and Fairfield, are the most widespread terraces in the Ruataniwha Plains (PDP 1999). PDP 1999 observed that the older terraces seemed to be “similarly compacted and cemented”, whereas the Tikokino and Fairfield terraces were not cemented but the older one of the two, Tikokino, showed some compaction. In addition, Kingma (1971) noted that older terraces, including Salisbury, were more eroded, more weathered, and had a higher proportion of pumice than younger terraces.

Francis (2001), who included the five oldest terraces into the Salisbury Gravels, also found that it was often difficult to distinguish between Salisbury Gravel and Young Gravels (Fairfield and Tikokino formations) just from driller's logs. Markers for Salisbury Gravel, noted by Francis (2001), were the thick ignimbrite unit as well as common lignite and thick lacustrine clay beds. In addition, they observed that Salisbury Gravel typically were blue-grey, while younger gravels usually were red. As described in Section 4.2.2, where the thick ignimbrite bed is absent, Poutaki (Pumiceous) Formation, which has been found overlying, underlying and interbedded with Salisbury Gravel, is difficult to distinguish from Salisbury Gravel. Brown (2002) included both formations into the same aquifer system due to their similarities.

With regard to the identification of “hydrofacies”, Harper (2018) found that due to the gravel prevalence in both the aquifers as well as the confining layers, and the lack of clear patterns, the distinction between aquifers and confining layers within the geological formations is not possible from information within the Council’s wells database.

4.2.5 Geological Structure

As mentioned above, the geological conditions in the Ruataniwha Plains are the result of its ongoing tectonic deformation. The NNE-SSW trending basin is constrained by major faults in the west. In the east, it is bounded by WNW dipping Miocene to Pliocene deposits (Francis 2001).

The structure in the basin is characterised by asymmetric synclines and anticlines that are bounded in the east by reverse faults that dip towards the west. As noticeable on Figure 3.2, faults in the southern part of the basin can be mapped as fault traces at the surface, but in the northern part, they are concealed under younger deposits. This is due to the faults in the south being more complex and active than the faults in the north (Francis 2001), Figure 4.3.

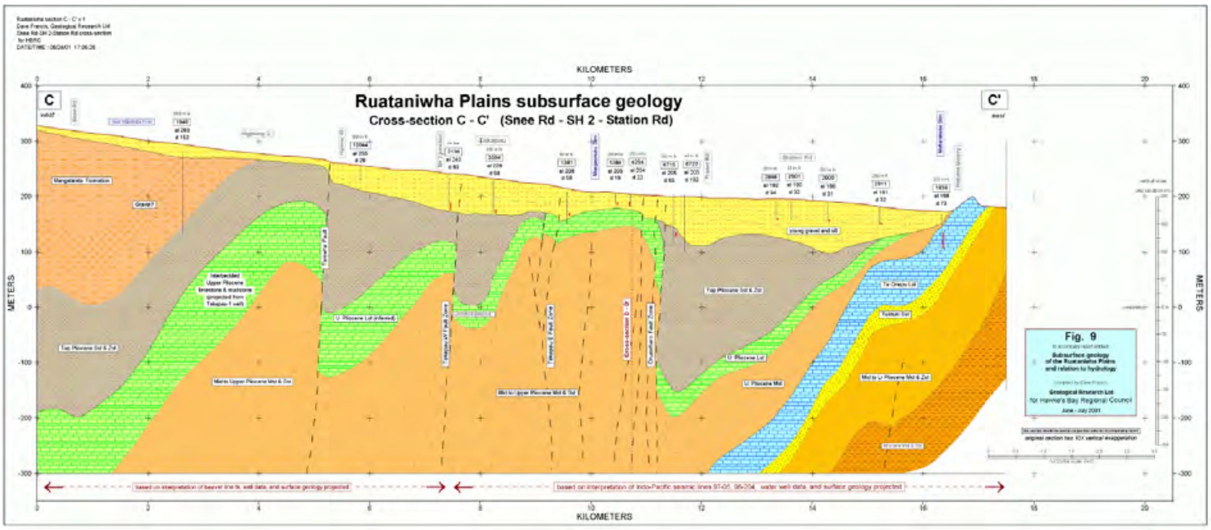

Figure 4.3 Cross-section from Francis (2001) illustrating the complex structure of the southern part of the survey area. The section is orientated along a near horizontal line from west to east just north of Takapau. Geological units from youngest to oldest as labelled by Francis (2001) are: light yellow: Young Gravels; reddish-brown: Mangatarata Formation; grey: top of Pliocene sandstone and siltstone; green: Interbedded Upper Pliocene limestone and mudstone; brown: Mid to Upper Pliocene mudstone and sandstone; blue: Te Onepu limestone; yellow: Tukituki sandstone; orange: Mid to Lower Pliocene mudstone and siltstone; and dark orange: Miocene mudstone and sandstone. The name Mangatarata Formation is used here by Francis (2001) instead of Salisbury Gravel as the latter becomes less gravel-rich towards the south of the plains.

Fault movement and folding in this area has occurred from the mid-Pliocene onwards. Francis (2001) noted that Lower and Upper Pliocene, as well as lower Salisbury Gravel formation are moderately to strongly folded, which will have an impact on groundwater flow through these units.

The following descriptions of major faults in the area have been derived from the digital 1:250,000 Geological Map of New Zealand dataset (Figure 3.2; Heron 2020) and were generally interpreted from geological and seismic data. More details are shown in Beanland et al. (1998).

Rangefront Fault: active, high angle (70° dip) reverse fault; total slip in the range of 1–10 km; dips towards the northwest, throw down is to the southeast.

Ruataniwha Fault: active, high angle (60° dip) reverse fault; total slip in the range of 0.1–1 km; dips towards the west, throw down is to the east.

Waikopiro Fault: inactive, high angle (60° dip) reverse fault; total slip in the range of 0.1–1 km; dips towards the west, throw down is to the east.

Oruawharo Fault: active, high angle (75° dip) reverse fault; total slip in the range of 1–10 km; dips towards the northwest, throw down is to the east.

Not much information is available from the NZ geological map (Heron 2020) on the Te Heka Fault Zone in the north of the survey area, except that these are normal faults. The total slip, where known, is less than 0.1 km, with throw down to the east.

No information is available on the synclines and anticlines from the NZ geological map (Heron 2020). However, a map developed by PDP (1999) based on seismic data and data from Grant-Taylor (1978) shows the complexity of the Ruataniwha SkyTEM survey area (Figure 4.4). More details on the synclines and anticlines are also shown in Beanland et al. (1998).

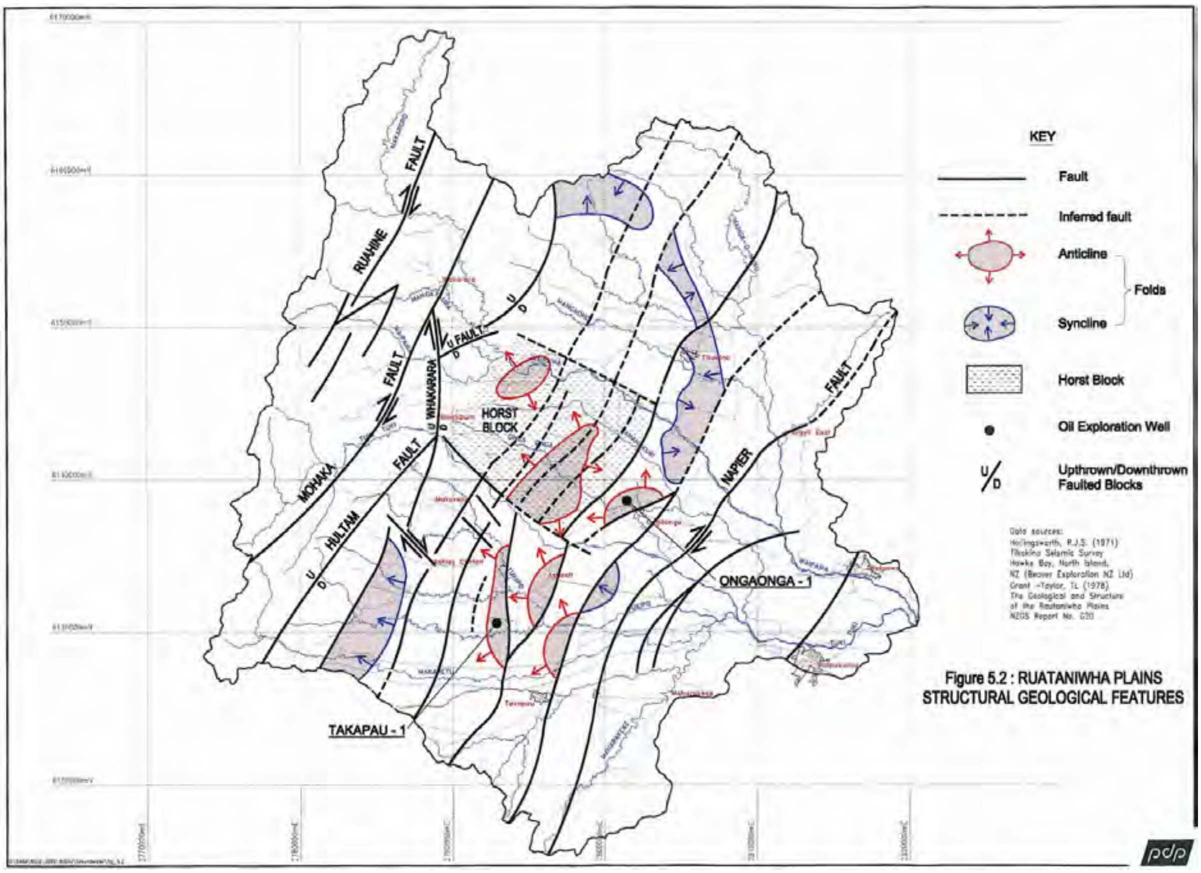

Figure 4.4 Structural features of the Ruataniwha Plains. Figure from PDP (1999).

4.3 Hydrogeology

4.3.1 The Ruataniwha Plains Aquifer System

The Ruataniwha Plains aquifer system is a structurally and geologically complex multi-layer aquifer system, whose heterogeneous nature can be observed in well log and seismic data as well as in aquifer properties, and age tracer and hydrochemistry data (PDP 1999; Francis 2001; Brown 2002; Morgenstern et al. 2012; Harper 2018; PDP 2018; Morgenstern 2021). This heterogeneity is due to the occurrence of gravel layers and gravel lenses; loose, clean gravel and clay-bound gravels; clay and silt layers; pumice and ignimbrite beds; mudstone, siltstone, sandstone and limestone; as well as faulting and folding of the aforementioned deposits. Table 4.1 shows an overview of geological formations that influence groundwater flow in the Ruataniwha Plains (Francis 2001). While PDP (2018) conclude that the aquifer system in the plains more comprises a series of discontinuous alluvial deposits, than discrete aquifers, the broad aquifer grouping used by Francis (2001), Brown (2002), Morgenstern et al. 2012, Wallbridge Gilbert Aztec (2019) and others is usually employed in this area and provides a convenient framework to describe the hydrogeology of the basin.

The two main aquifer systems in the Ruataniwha Plains are the Young(er) Gravel aquifer system and the Salisbury Gravel aquifer system, named after the older names of the geological formations they are hosted in (Section 4.1). Due to similarities in the nature of the deposits, these formations are often difficult to distinguish from each other in bore logs and in the field (Section 4.2.4).

In the north and east of the plains, the gravel deposits are thicker and more extensive, whereas in the south and west, they are thin or absent (Brown 2002). The majority of the bores in the survey area, as listed in the HBRC database, are 60 m or less deep (Section 3.2.3.5), and 66% of the bores are screened in the upper 50 metres (Harper 2018). This is in agreement with (PDP 2018), who recently analysed all transmissivity data available for the Ruataniwha Plains and found that the highest transmittivities can be observed at depths between 40–60 m. Morgenstern (2021) found that the higher transmissivity of Holocene versus Pleistocene gravels was illustrated by the occurrence of young groundwater with high nitrate levels in shallow bores (7–26 m deep) in Pleistocene deposits, and in shallow and deeper (<79 m) bores in Holocene deposits.

The Young Gravel aquifer system is a generally unconfined aquifer that is at the ground surface across large parts of the eastern Ruataniwha Plains (Brown 2002; Undereiner et al. 2009; Morgenstern et al. 2012). However, it can be confined or semi-confined in places (Brown 2002), see below. The Young Gravel aquifer system thickens towards the east and can be up to 80 m thick. It comprises unconsolidated mid-Pleistocene to Holocene river deposits, i.e. clean and clay-bound gravel, clay, silt, volcanic ash (Francis 2001; Harper 2018; Wallbridge Gilbert Aztec 2019; Heron 2020), that have been previously described as the Old Terrace Aquifer Group and the Recent Terrace Aquifer Group by PDP (1999). This aquifer is represented by the Late Quaternary deposits model layer in the most up-to-date geological 3D model by Harper (2018) (Table 4.1).

Near Takapau, Francis (2001) noted some paleo-channel features in the Young Gravels in subsurface contours that were developed based on well and seismic data. Other paleo-channel features were identified north of Ongaonga by Francis (2001). These appear to be partly overlapping with the areas of higher transmissivities mapped by (PDP 2018), which the author also considered to be paleochannel structures.

The Salisbury Gravel aquifer system (Francis 2001; Harper 2018; Wallbridge Gilbert Aztec 2019) is hosted in Kidnappers Group deposits that are at the ground surface in the west of the plains and dip beneath the plains towards the east, where they are overlain by the Young Gravel deposits (Heron 2020). Brown (2002) also included Poutaki (Pumiceous) Formation pumice aquifers and interbedded underlying gravel aquifers into this aquifer system.

The Salisbury Gravel aquifer system is represented by the Early to Middle Quaternary deposits model layer in the most up-to-date geological 3D model by Harper (2018) (Table 4.1). As described in Section 4.2.2, it comprises porous gravel with ignimbrite beds, lignite and impermeable clay layers (Francis 2001). Where the Salisbury Gravels are at or near the surface, the aquifer system is generally unconfined, however it can be confined in deeper parts (Brown 2002).

A shallow aquitard comprising dominantly clay-bound gravel, the “Shallow Tukipo Aquitard/Aquiclude”, was identified by PDP (1999) up to a depth of 80 m within Recent Terrace Aquifer Group deposits between the Tukituki and Makaretu rivers (see Section 3.4.4). Brown (2002) concluded that this ‘aquitard’ probably consists of “poorly sorted last glaciation and older late Quaternary gravel deposits and is not a valid unit to be retained for aquifer grouping”. However, the deposits are assumed to act as an aquitard in this area, and the increased clay content of these deposits may be noticeable in the resistivity data. Noteworthy is that the boundary of the aquitard, as delineated by PDP (1999), includes an area of gravels of “substantial thickness” north of Waipawa River (near well 3076), which was of interest to the managed aquifer recharge pre-assessment investigation by Wallbridge Gilbert Aztec (2019). In this area, the aquitard was not identified in bore logs by PDP (1999).

Due to the majority of the groundwater bores targeting the gravel aquifers, there is less information available on the deeper aquifers. Francis (2001) noted that the younger limestone deposits have “high porosity and permeabilities” and may potentially be aquifers. This included for example the Te Onepu Limestone and the younger Pliocene to Early Pleistocene limestones. Brown (2002) observed that the limestone aquifers were confined and that the groundwater yield of these aquifers was lower than the yield of the gravel aquifers (e.g.1 l/s in well 4702). Groundwater that has been in contact with limestone may exhibit higher bicarbonate, calcium and sodium concentrations due to dissolution processes (PDP 1999). This may affect resistivity readings beyond the areas where the limestone deposits exist.

In the eastern parts of the plains, the limestone layers are covered by claystone and siltstone, whereas on the western side of the plain, mudstone layers were found to overly the highest limestone layers in both the Takapau-1 and Ongaonga-1 bore at depth. Therefore, Francis (2001) suggested that the limestone aquifers are likely closed aquifer systems. Francis (2001) also found no evidence of a potential fault along the eastern margin of the basin that had been proposed by PDP (1999) to explain the geological conditions in that area. Instead, Francis (2001) suggested that the Pliocene formations, including the limestone beds, dipped underneath the plains, potentially providing an additional groundwater resource at economically viable depths in that area.

The Late Cretaceous to Paleocene Whangai Formation is generally highly fractured and may comprise an aquifer (Francis 2001). Francis (2001) pointed out that the drilling report of the Ongaonga-1 bore noted that all encountered reservoirs contained "relatively fresh water, indicating that they had been opened to circulating fresh water after deposition". In case of the Ongaonga-1 bore, water-bearing deposits were reported to be encountered up to a depth of 1403 m (Leslie 1971). However, in other bores across the plains, groundwater was not encountered below the base of the gravel aquifers which varied for those bores between 67 and 134 m (Brown 2002).

Table 4.1 Table from Francis (2001) showing the geological formations in the plains that are potentially relevant to groundwater flow.

Formation Name(s)	**Age**	**Distribution**	**Comments**
Torlesse	Triassic–Lower Cretaceous (300–115 Ma)	Ruahine & Kaweka Ranges, Oruawharo	Provides well rounded gravel to younger aquifers
Whangai, Waipawa	Upper Cretaceous–Paleocene (80–58 Ma)	Otane, Waipawa, Waipukurau	Possible fractured reservoir (Whangai)
Wanstead	Upper Paleocene–Eocene (58–43 Ma)	Tukituki & Waipawa rivers near Waipawa & Waipukurau	Provides downstream barrier to Ruataniwha system
Mid Miocene–Pliocene mudstones	15–2 Ma	widespread in surrounding hills	Provide seal to porous Pliocene limestones
Te Onepu Limestone	Mid Pliocene (3.2–2.6 Ma)	hills east of plains & subsurface (see map)	Highly porous & permeable, deeper target to east
Younger limestones	Upper Pliocene to lower Pleistocene (2.6–1.6 Ma)	hills east, south & west of plains & subsurface (see map)	Generally porous & permeable, likely targets
Salisbury Gravel	early to mid Pleistocene (1.6–0.4 Ma)	hills N & NE, & subsurface (see map)	beds porous gravel, ignimbrite, lignite & impermeable clays
Younger gravels	late Pleistocene (<0.4 Ma)	widespread over plains; shallow	clean & claybound gravels, silt, clay

4.3.2 Groundwater Flow Dynamics

Due to the geological structure of the basin, the Ruataniwha Plains comprise a closed groundwater system with the only outflow being the seepage to the rivers exiting the plains in the east (Morgenstern et al. 2012).

Groundwater flow dynamics within the plains are influenced strongly by the complex geology and structure, which results in a heterogenous aquifer system. Leakage from the different shallow to deeper aquifers is likely, as well as movement of older groundwater upwards into shallower aquifers due to the geological setting of the plains (Morgenstern et al. 2012; PDP 2018). Brown (2002) noted that groundwater was flowing upwards in the east of the plains, recharging the shallow water table aquifer and feeding into springs and wetlands, resulting in drains having to be dug to lower the water table for farming and agriculture. Undereiner (2009) found that spring and seeps occurred in the east of their study area where the shallow water table was close to the surface. For example, losses from the Waipawa River.

Groundwater recharge (rainfall and river recharge) occurs across the entire plains, starting from the western margin at the contact with the pre-Quaternary deposits. The confined aquifers are recharged on the western side of the plains where the older Quaternary deposits are at the ground surface (Brown 2002).

River recharge signatures were only found in groundwater from bores near the lower reaches of larger rivers, like the Waipawa and Tukituki rivers, downstream of losing reaches (Figure 2.9). River and mixed river and rain recharge signatures in wells and springs in the vicinity of a gaining Waipawa River reach close to the eastern boundary of the plains indicated upwelling of groundwater in this area, including river water that was lost from the river further upstream. This is likely due to the closed nature of the Ruataniwha Plains groundwater system (Morgenstern et al. 2012). Undereiner (2009) observed that in the vicinity of the Waipawa River in the eastern part of the plains, the deeper, confined aquifer had a hydraulic head above the shallow Young Gravel aquifer, which could result in flow from the deeper aquifer to the shallow aquifer. Brown (2002) observed that on the eastern margin of the plains, the Waipawa River had a wider gravel bed and was underlain by thicker gravel deposits than the Tukituki River, which may result in more underflow for the Waipawa River. Losses from the Waipawa River were found to feed into Mangaonuku Stream, Kahahakakuri Stream and Cockrane’s Creek, and hydrochemistry indicated that Mangaonuku Stream also received water from the confined aquifer (Undereiner 2009).

Groundwater chemistry variation across the plains generally reflects the heterogenous nature of the area and the complexity of the aquifer system (Morgenstern et al. (2012). Morgenstern et al. (2012) observed seasonally changing hydrochemistry concentrations in some deep wells and suggested that these were due to “pockets of water with different hydrochemistry” that were existing in close proximity with each other, and which were affected by changes in recharge and groundwater abstraction over time. However, they also found that the relationship between groundwater chemistry and groundwater age generally appeared consistent throughout the plains, indicating that the larger scale groundwater flow dynamics were more homogeneous.

The groundwater ages for most wells sampled by Morgenstern et al. (2012) and Morgenstern et al. (2021) were old enough to suggest no recent connection to surface water (MRT >25 years), except for one bore (Figure 2.14). The latter was likely due to a paleo channel that enabled a faster flowing pathway to that bore. The older groundwaters, which occurred primarily in Pleistocene gravels, and in particular in the south of the plains, are considered indicative of the predominance of lower permeability deposits in that area and are unlikely to be strongly influenced by nearby surface water recharge sources (Morgenstern et al. 2012; Morgenstern 2021). The locations of older groundwaters (Morgenstern et al. 2012; Morgenstern 2021) appear to partly overlap with the extent of the Tukipo Aquitard mapped by PDP (1999), however, a detailed analysis of the lateral and vertical extent of the aquitard was beyond this data inventory.

As mentioned in Section 4.2.5, ongoing tectonic movement since the mid-Pliocene has resulted in moderately to strong faulting and folding in the older geological formations up to the lower Salisbury Gravels, which is expected to have an impact on groundwater flow (Francis 2001). For example, Francis (2001) suggested that “partly artesian” conditions could occur along or near the axis of the syncline in the north of the plains, and that in the south of the plains, the complex fault system may provide vertical flow pathways between shallow and deeper aquifers.

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APPENDICES

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APPENDIX 1 BOREHOLE DATA

A1.1 Petroleum Boreholes

Excel files provided in the format shown in Table A1.1:

- *\Appendix1\Kereru_1_Data.xlsx*
- *\Appendix1\Mason_Ridge_1_Data.xlsx*
- *\Appendix1\Ongaonga_1_Data.xlsx*
- *\Appendix1\Speedy_1_Data.xlsx*
- *\Appendix1\Takapau_1_Data.xlsx*

Table A1.1 Format of Petroleum bore files, e.g. *\Appendix1\Kereru_1_Data.xlsx*, digitised from the relevant petroleum reports (see Section 3.2.3.1).

Tab	Description
Well Data	Summary details and lithology code descriptions
Tops_0-500m	Summary lithology intervals with primary lithology and description
Markers	Age definitions
Primary_Lithology	Detailed lithology intervals and hardness, using lithology codes
%_lithology	Estimated percentages of lithologies from cuttings, using lithology codes
ROP	Rate of penetration information

A1.2 Combined Lithological Log Data

CSV file provided in the format shown in Table A1.2:

- *\Appendix1\CombinedLitho_Ruataniwha.csv*

Table A1.2 Format of file *\Appendix1\CombinedLitho_Ruataniwha.csv*.

Column	Description
BoreNo	HBRC Bore No.
FromDepth	Depth (m) to top of lithological interval.
ToDepth	Depth (m) to bottom of lithological interval.
PrimaryStrata	Dominant lithology.
FullStrata	Lithological descriptions.
StrataNote	Strata Note.
SedColour	Sediment Colour, where noted separately.
Comment	Comment.
DataOrigin	One of: Baylis PDFs (Section 3.2.3.4); Brown (Brown 2002, Section 3.2.3.2); GNS (3DAMP wells, Section 3.2.3.2); HBRC_2022 (Section 3.2.3.3 and 3.2.3.5); Petroleum bore (Section 3.2.3.1).
East_NZTM	Easting coordinate in New Zealand Transverse Mercator coordinate system, converted from New Zealand Map Grid location provided in the HBRC well database.
North_NZTM	Northing coordinate in New Zealand Transverse Mercator coordinate system, converted from New Zealand Map Grid location provided in the HBRC well database.
DEM	Elevation from DEM (mASL).

A1.3 Lithological Log Quality Index

CSV file provided with the quality index applied to each bore, in the format shown in Table A1.3:

- *\Appendix1\Ruataniwha_bores_QualityIndex.csv*

Table A1.3 Format of file *\Appendix1\Ruataniwha_bores_QualityIndex.csv*.

Column	Description
BoreNo	HBRC Bore No. or Petroleum well name.
EastNZTM	Easting coordinate in New Zealand Transverse Mercator coordinate system.
NorthNZTM	Northing coordinate in New Zealand Transverse Mercator coordinate system.
QualityIndex	Number from 1 to 5 defined as outlined in Section 3.2.3.6.

Two bores, 1394 and 2809, despite having mention of a handheld GPS location, had their location accuracy downgraded because of an inaccuracy mentioned in their comments – they were assigned a quality index of 4 instead of 2.

A1.4 Baylis Bros Lithological Logs

CSV file provided with digitised boreholes (see Section 3.2.3.4), in the format shown in Table A1.4:

- *\Appendix1\Ruataniwha_BaylisPDFbores.csv*

Table A1.4 Format of file *\Appendix1\Ruataniwha_BaylisPDFbores.csv*.

Column	Description
BoreNo	HBRC Bore No.
EastNZTM	Easting coordinate in New Zealand Transverse Mercator coordinate system.
NorthNZTM	Northing coordinate in New Zealand Transverse Mercator coordinate system.
FromDepth_m	Depth (m) to top of lithological interval.
ToDepth_m	Depth (m) to bottom of lithological interval.
PrimaryStrata	Dominant lithology.
FullStrata	Lithological descriptions.
StrataNote	Any strata note.
Waterbearing	Water bearing stated where this was noted.
OwnerOnLog	Information about the bore’s owner as written on the log.
LocationOnLog	Information about the bore’s location as written on the log.

Out of those 12 wells, most of them had a similar lithological description in the HRBC dataset. However, well 5048 did not have a lithological description in the dataset provided by HBRC and consequently was added from the PDFs provided by Baylis Bros Ltd.

A1.5 New 2022 SOE Bores

CSV file provided with results from sample resistivity and grain size analyses (see Section 3.2.3.4), in the format shown in Table A1.5:

- \Appendix1\Ruataniwha_SOEbores_2022_grainsize&resistivity.csv

Table A1.5 Format of file *\Appendix1\Ruataniwha_SOEbores_2022_grainsize&resistivity.csv.* See Lawrence et al. (2021) for further details.

Column	Description	Method
BoreNo	HBRC Bore No.	-
BoreName	Bore Name	-
EastNZTM	Easting coordinate in New Zealand Transverse Mercator coordinate system	-
NorthNZTM	Northing coordinate in New Zealand Transverse Mercator coordinate system	-
SampleNo	Sample number	-
SAMPLEDEPTH_from	Sample depth – start of interval (m)	-
SAMPLEDEPTH_to	Sample depth – end of interval (m)	-
SAMPLE_RESISTIVITY_ohmm_min	Sample resistivity (ohmm): minimum value if repeat measurement made. Repeat of SAMPLE_RESISTIVITY_ohmm_max if only one measurement made.	-
SAMPLE_RESISTIVITY_ohmm_max	Sample resistivity (ohmm): maximum value if repeat measurement made. Repeat of SAMPLE_RESISTIVITY_ohmm_min if only one measurement made.	-
SAMPLE_TYPE	Sample type	-
TEXTURAL_GROUP	Textural Group	-
SEDIMENT_NAME	Sediment Name	-
FWM_ µm_Mean	Mean	FOLK AND WARD METHOD (µm)
FWM_ µm_Sorting	Sorting	FOLK AND WARD METHOD (µm)
FWM_ µm_Skewness	Skewness	FOLK AND WARD METHOD (µm)
FWM_ µm_Kurtosis	Kurtosis	FOLK AND WARD METHOD (µm)
FWM_ description_Mean	Mean	FOLK AND WARD METHOD (Description)
FWM_ description_Sorting	Sorting	FOLK AND WARD METHOD (Description)

Column	Description	Method
FWM_ description_Skewness	Skewness	FOLK AND WARD METHOD (Description)
FWM_ description_Kurtosis	Kurtosis	FOLK AND WARD METHOD (Description)
MAJORCOMPONENTS_%_Gravel	Gravel	MAJOR COMPONENTS (%)
MAJORCOMPONENTS_%_Sand	Sand	MAJOR COMPONENTS (%)
MAJORCOMPONENTS_%_Mud	Mud	MAJOR COMPONENTS (%)
CLASSSIZES_%_VeryCoarseGravelorPebble	Very Coarse Gravel or Pebble	CLASS SIZES (%)
CLASSSIZES_%_CoarseGravelorPebble	Coarse Gravel or Pebble	CLASS SIZES (%)
CLASSSIZES_%_MediumGravelorPebble	Medium Gravel or Pebble	CLASS SIZES (%)
CLASSSIZES_%_FineGravelorPebble	Fine Gravel or Pebble	CLASS SIZES (%)
CLASSSIZES_%_VeryFineGravelorPebble	Very Fine Gravel or Pebble	CLASS SIZES (%)
CLASSSIZES_%_VeryCoarseSand	Very Coarse Sand	CLASS SIZES (%)
CLASSSIZES_%_CoarseSand	Coarse Sand	CLASS SIZES (%)
CLASSSIZES_%_MediumSand	Medium Sand	CLASS SIZES (%)
CLASSSIZES_%_FineSand	Fine Sand	CLASS SIZES (%)
CLASSSIZES_%_VeryFineSand	Very Fine Sand	CLASS SIZES (%)
CLASSSIZES_%_VeryCoarseSilt	Very Coarse Silt	CLASS SIZES (%)
CLASSSIZES_%_CoarseSilt	Coarse Silt	CLASS SIZES (%)
CLASSSIZES_%_MediumSilt	Medium Silt	CLASS SIZES (%)
CLASSSIZES_%_FineSilt	Fine Silt	CLASS SIZES (%)
CLASSSIZES_%_VeryFineSilt	Very Fine Silt	CLASS SIZES (%)
CLASSSIZES_%_Clay	Clay	CLASS SIZES (%)

A1.6 Shothole Lithology

Excel file provided with digitised lithology information from seismic shothole data (see Section 3.3.1), in the format shown in Table A1.6.

- *\Appendix1\Ruataniwha_Seismic_Shothole_Lithology.xlsx*

Table A1.6 Format of file \Appendix1\Ruataniwha_Seismic_Shothole_Lithology.xlsx.

Column	Description
Line	Line name
SP	Shot Point number
NZTM_East	Easting coordinate in New Zealand Transverse Mercator coordinate system
NZTM_North	Northing coordinate in New Zealand Transverse Mercator coordinate system
Ground_level(m)	Ground level calculated from DEM
Shot_Type	Type of shot: Geoflex*, Borehole or unknown
Base_Layer_1(m)	Depth to base of layer 1 (m)
Base_Layer_2(m)	Depth to base of layer 2 (m)
Base_Layer_3(m)	Depth to base of layer 3 (m)
Base_Layer_4(m)	Depth to base of layer 4 (m)
Litho_layer_1	Lithology of layer 1
Litho_layer_2	Lithology of layer 2
Litho_layer_3	Lithology of layer 3
Litho_layer_4	Lithology of layer 4
Charge_depth(m)	Depth of charge (m)
UpHole_Time(ms)	Travel time (ms)
Velocity(m/s)	Derived velocity from shot hole (m/s)
Comment	Comment

*Geoflex is a strip of explosive cord so no lithology information was recorded for these shot holes.

APPENDIX 2 GEOPHYSICAL DATA

In all cases, 'STD' refers to Standard Deviation and 'UTC' refers to Coordinated Universal Time.

A2.1 Seismic Reflection Data

2D elevation grids in surfer grid format:

- \Appendix2\Seismic\base_young_gravel_clipped.asc
- \Appendix2\Seismic\base_salisbury_gravel_clipped.asc
- \Appendix2\Seismic\wn_lst_clipped.asc
- \Appendix2\Seismic\u_pliocene_lst_clipped.asc
- \Appendix2\Seismic\top_greywacke_clipped.asc

Location of seismic lines used to derive elevation grids, in the format shown in Table A2.1:

- \Appendix2\Seismic\Rua_Seismic_Lines_Interpreted.shp

Table A2.1 Attributes of the shapefile *\Appendix2\Seismic\Rua_Seismic_Lines_Interpreted.shp*.

Attribute	Description
Line_Name	Name of each line as described in the Petroleum Reports
Survey	The name of the survey which typically includes the operator and the year of acquisition, e.g. DSIR_1989
Purpose	Petroleum or Groundwater
SurveyDate	Survey date
Report	Report number
SourceType	Source type
Source SP	Source spacing
GeophoneSP	Geophone spacing
Data	Data type
Shotholes	Shotholes

The seismic data are available from New Zealand Petroleum & Minerals (NZP&M) through the online database:

- https://data.nzpam.govt.nz/GOLD/system/mainframe.asp

The data are described in the associated Petroleum Report or DSIR/GNS report.

A2.2 GroundTEM Data

The groundTEM data collected by GNS in three field programmes are provided in Universal Sounding Format (USF). The GroundTEM files are saved here:

- \Appendix2\GroundTEM\Ruataniwha_TEMnanoTEM_2009_raw.usf
- \Appendix2\GroundTEM\Ruataniwha_TEMnanoTEM_20192021_raw.usf
- \Appendix2\GroundTEM\Ruataniwha_TEMnanoTEM_2009_stacked.usf
- \Appendix2\GroundTEM\Ruataniwha_TEMnanoTEM_20192021_stacked.usf

The details of the file format can be found here:

- http://ags-cloud.dk/Wiki/tiki-download_wiki_attachment.php?attId=17&page=S_ImportUSF&download=y

GroundTEM model files – format described in Table A2.2:

- \Appendix2\GroundTEM\Ruataniwha_TEMnanoTEM_2009_inv.xyz
- \Appendix2\GroundTEM\Ruataniwha_TEMnanoTEM_20192021_inv.xyz

Table A2.2 Format of the resistivity model xyz-ascii files, for example: *\Appendix2\GroundTEM\Ruataniwha_TEMnanoTEM_2009_inv.xyz*, as exported out of Aarhus Workbench software (i.e. the naming of the attributes is based on the Aarhus Workbench export format). Due to the different data types and subsequent modelling utilised, not all attributes are present within all datasets.

Attribute	Description
LINE_NO	Line number
MODEL_NAME	Model name
UTMX	Easting coordinate in New Zealand Transverse Mercator coordinate system
UTMY	Northing coordinate in New Zealand Transverse Mercator coordinate system
FID	Fiducial / Field ID
RECORD	Record
ELEVATION	Topography (m; GPS position taken during data collection)
ALT	Input altitude (metres above ground level)
INVALT	N/A (not utilised by ground-based inversion)
INVALTSTD	N/A (not utilised by ground-based inversion)
DELTAALT	N/A (not utilised by ground-based inversion)
TILT	N/A (not utilised by ground-based inversion)
INVTILT	N/A (not utilised by ground-based inversion)
INVTILTSTD	N/A (not utilised by ground-based inversion)
SHIFT	N/A (not utilised by ground-based inversion)
INVSHIFT	N/A (not utilised by ground-based inversion)
INVSHIFTSTD	N/A (not utilised by ground-based inversion)
NUMDATA	Number of gates inverted (number of data points)
SEGMENTS	Moment ID (low moment = 1, high moment = 2, both = 12 or 21)
RESDATA	Data mis-fit (Equation A2.1 for each 1D inversion)
RESTOTAL	Total mis-fit (Equation A2.2 for the entire inversion)

Attribute	Description
RHO_I_1	Resistivity (Ohm.m) for layer_1
RHO_I_2	Resistivity (Ohm.m) for layer_2
…	…
RHO_I_N	Resistivity (Ohm.m) for layer N
RHO_I_STD_1	STD on resistivity for layer_1
RHO_I_STD_2	STD on resistivity for layer_2
…	…
RHO_I_STD_N	STD on resistivity for layer_N
SIGMA_I_1	Conductivity (mS/m) for layer_1
SIGMA_I_2	Conductivity (mS/m) for layer_2
…	…
SIGMA_I_N	Conductivity (mS/m) for layer_N
DEP_TOP_1	Depth (m) to top of layer_1
DEP_TOP_2	Depth (m) to top of layer_2
…	…
DEP_TOP_N	Depth (m) to top of layer_N
DEP_BOT_1	Depth (m) to botttom of layer_1
DEP_BOT_2	Depth (m) to botttom of layer_2
…	…
DEP_BOT_N-1	Depth (m) to botttom of layer_N-1
THK_1	Thickness (m) of layer_1
THK_2	Thickness (m) of layer_2
…	…
THK_N-1	Thickness (m) of layer_N-1
THK_STD_1	STD on thickness of layer_1
THK_STD_2	STD on thickness of layer_2
…	…
THK_STD_N-1	STD on thickness of layer_N-1
DEP_BOT_STD_1	STD on depth bottom of layer_1
DEP_BOT_STD_2	STD on depth bottom of layer_2
…	…
DEP_BOT_STD_N-1	STD on depth bottom of layer_N-1
DOI_CONSERVATIVE	DOI Conservative for resistivity (m)
DOI_STANDARD	DOI Standard for resistivity (m)

$$\left(\frac{1}{N}\sum_{i=1}^{N}\frac{\left(d_{obs,i}-d_{forward,i}\right)^2}{C_{obs,i}}\right)^{\frac{1}{2}}$$

Equation A2.1 Calculation of the RESDATA attribute in Table A2.2. Observed data (d_{obs}), forward model calculation of data from inversion model ($d_{forward}$), standard deviation of the measured data (C_{obs}).

$$\underbrace{\left(\frac{1}{N}\sum_{i=1}^{N}\frac{\left(d_{obs,i}-d_{forward,i}\right)^2}{C_{obs,i}}\right)^{\frac{1}{2}}}_{\textbf{Data}}+\underbrace{\left(\frac{1}{M}\sum_{i=1}^{M}\frac{\left(m_{i}-m_{prior,i}\right)^2}{C_{P,i}}\right)^{\frac{1}{2}}}_{\textbf{A priori}}+\underbrace{\left(\frac{1}{N_{con}}\sum_{i=1}^{N_{con}}\frac{\left(m_{par1,i}-m_{par2,i}\right)^2}{C_{R,i}}\right)^{\frac{1}{2}}}_{\textbf{Constraints}}$$

Equation A2.2 Calculation of the RESTOTAL attribute in Table A2.2. Data related calculation: observed data (d_{obs}), forward model calculation of data from inversion model ($d_{forward}$), standard deviation of the measured data (C_{obs}). *A-priori*-related calculation: model parameter (m_i), *a priori* model parameter (m_{prior}), standard deviation of *a priori* model parameter (C_P). Inversion constraint (regularisation) -related calculation (laterally or vertically): model parameter (m_{par1}), model parameter (m_{par2}), standard deviation given to the regularisation constraints (C_R).

A2.3 Borehole Geophysical Data

The raw borehole geophysical logs from petroleum wells are available from NZP&M in digital format and as scanned images. Data not commonly provided by NZP&M include Gamma Ray data collected behind the surface steel casing and the rate of penetration (ROP) for the drilling. In some of the wells in the Ruataniwha Plains, the shallow sections of the geophysical logs have been digitised, merged and edited to provide more valuable data for groundwater investigations. The data are provided in Log Ascii Standard (LAS) format.

Borehole geophysics files:

- *\Appendix2\Geophysical_Logs\Mason_Ridge-1_Shallow.las*
- *\Appendix2\Geophysical_Logs\Ongaonga-1_Shallow.las*
- *\Appendix2\Geophysical_Logs\Takapau-1_Shallow.las*

The petroleum well data are available from NZP&M through the online database:

- https://data.nzpam.govt.nz/GOLD/system/mainframe.asp

The details of LAS format can be found here:

- https://www.cwls.org/wp-content/uploads/2014/09/LAS_3_File_Structure.pdf

APPENDIX 3 HYDROGEOLOGICAL DATA

A3.1 Water Supply Intervals and Lithologies

Excel or CSV tables with QC information:

- \Appendix3\Ruataniwha_screen_corrections_mergedintervals.csv
- \Appendix3\Ruataniwha_screen_corrections_removed.xlsx
- \Appendix3\Ruataniwha_screenedlithologies_mergedintervals.csv

As file formats generally correspond with HBRC well database formats, only additional relevant columns are mentioned in this section. Construction information has been assessed only for bores with lithology information (Sections 3.2.3.2–3.2.3.5). For files 1 and 2, construction information within the files is copied from the HBRC well database. Additionally, quality-checked water supply interval values (top and bottom) are in the columns ‘top_s’ and ‘bot_s’. An ‘assumptions’ column is included that describes how ‘top_s’ and ‘bot_s’ have been obtained.

Where only bore depth information is available and no screen or open-hole information, bores with full depth <= 2 m have been removed.

Some additional manual checks were undertaken. Bores that were manually removed are in the file *Ruataniwha_screen_corrections_removed.xlsx* with a comment as to why (e.g. ‘dry hole’ in notes.)

Assumptions:

- Screened and open-hole intervals are continuous.
- Only open-hole interval.
- No screen or open-hole information. Screen assumed at Full Depth -2 m to Full Depth.
- No screen, open-hole, or Depth information. Screen assumed at Full Depth -2 m to Full Depth (2 m is the median screen length in the Ruataniwha Plains).
- No top screen. Bottom screen assumed accurate and Top screen at Bottom screen -2 m.
- Top and bottom screens present and assumed accurate.

Within (3), lithology information from the HBRC well database is copied for the water supply intervals defined in (1).

A3.2 Previous Borehole Interpretations

CSV files with borehole interpretation information described in Section 3.4.4, with formats as described in Table A1.3:

- *\Appendix3\Digitised_Aquifer_PDP1999_GISFormat.csv*
- *\Appendix3\Digitised_TukipoAquitard_PDP1999_GISFormat.csv*

Table A3.1 Format of files, e.g. *\Appendix3\Digitised_Aquifer_PDP1999_GISFormat.csv*.

Column	Description
BoreNo	HBRC Bore No. or Petroleum well name
Top_RL	Top of interpreted interval in mASL
Bottom_RL	Bottom of interpreted interval in mASL
Thickness	Thickness of interpreted interval (m)
GravelType	Interpretation: Loose Gravel (Central Plains Unconfined Aquifer) or Clay bound Gravel (Tukipo Aquiclude)
EastNZTM	Easting coordinate in New Zealand Transverse Mercator coordinate system
NorthNZTM	Northing coordinate in New Zealand Transverse Mercator coordinate system

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