New Zealand Groundwater Atlas: Depth to Hydrogeological Basement

RS Westerhoff
C Tschritter
ZJ Rawlinson

GNS Science Consultancy Report 2019/140
October 2019

DISCLAIMER

This report has been prepared by the Institute of Geological and Nuclear Sciences Limited (GNS Science) exclusively for and under contract to Ministry for the Environment. Unless otherwise agreed in writing by GNS Science, GNS Science accepts no responsibility for any use of or reliance on any contents of this report by any person other than Ministry for the Environment and shall not be liable to any person other than Ministry for the Environment, on any ground, for any loss, damage or expense arising from such use or reliance.

BIBLIOGRAPHIC REFERENCE

Westerhoff RS, Tschritter C, Rawlinson ZJ. 2019. New Zealand groundwater atlas: depth to hydrogeological basement. Lower Hutt (NZ): GNS Science. 19 p. Consultancy Report 2019/140.

CONTENTS

TABLES

FIGURES

GLOSSARY

Anisotropic: an object having a physical property with the different values in different directions

Aquifer: an underground geologic layer that contains significant quantities of water and has sufficient internal flow of water to be productive

Aquitard: a geologic layer that slows but does not stop flow between adjacent units

Bias: the difference between the probability-weighted average of all possible values for a modelled parameter and the true value of the parameter being estimated (ie a systematic [built-in] error that makes all values wrong by a certain amount)

Calibration: the process of adjusting model inputs and parameters to match model outputs to desired values, for example, historic observations

Depth to hydrogeological basement: loosely defined as ‘the base of aquifers’; more strictly defined as ‘the depth to where primary porosity and permeability of geological material is low enough such that fluid volumes and flow rates can be considered negligible’

Hinterland: the area behind, or upstream of, a coast or the shoreline of a river

Hydraulic conductivity: a parameter that describes the rate of flow of water in a geologic layer (the ease with which a water can move through pore spaces or fractures). Units are Length/Time, for example, m/day

Isotropic: an object having a physical property with the same value in different directions

Miocene: geological period from 23 million to 5.3 million years ago

Parameter: a numerical input that defines characteristics of the model and can be adjusted by the user or calibration software

Permeability: a number (units L^2) that describes how easily a fluid can pass through a geological unit (eg a sandstone). In many numerical models, permeability is incorporated into hydraulic conductivity

Pliocene: geological period from 5.3 million to 2.6 million years ago

Porosity: a measure of the volume of void space within the total volume of a geological mass

Quaternary: geological period from 2.6 million years ago to present

QMAP: the digital geological map of New Zealand, provided at the scale of 1:250,000

Tertiary: geological period from 66 million to 2.6 million, including the Miocene and the Pliocene

Uncertainty: a measurement of the possible variation of model inputs and/or outputs based on available information. The ‘true’ value is not known but is assumed to be within this range of values

Viscosity: a quantity expressing the magnitude of internal friction in a fluid, as measured by the force per unit area resisting uniform flow.

EXECUTIVE SUMMARY

This report describes an update of New Zealand's depth to hydrogeological basement map, including the methodology used to undertake this work and the resultant digital data sets. Depth to hydrogeological basement can be loosely defined as 'the base of aquifers', or more strictly as 'the depth to where primary porosity and permeability of geological material is low enough such that fluid volumes and flow rates can be considered negligible'. A multi-model (Monte-Carlo) approach was used to assess uncertainty, and a comparison with coal bores was used to assess similarity of our modelled depth to hydrogeological basement to the base of Quaternary deposits found within the coal bores.

Modelled depth to hydrogeological basement varies significantly; from near-zero where basement rock is exposed at the surface to several hundreds of metres in alluvial plains, for example, Canterbury Plains and Hauraki Plains. The updated version includes model uncertainty and statistics of depth to hydrogeological basement: mean, standard deviation of mean, minimum and maximum. Standard deviation also varies and increases with higher depth to hydrogeological basement. The mean depth to hydrogeological basement is classified into seven depth classes to encompass the uncertainty of the data set.

Although depth to hydrogeological basement is often similar to depth to base of Quaternary deposits, they are different concepts. Comparison with data from coal bores show that aquifers also still hold water in deposits that are older than Quaternary (eg Pliocene/Miocene Tertiary sediments). Hence other geological processes, for example, height and slope of hinterland, continental rift, faulting, also play a role in whether depth to base of the Quaternary is similar to the depth to hydrogeological basement. Future comparison should include use of groundwater bore logs throughout the country and the incorporation of geological structural processes in combination with hydrogeological system.

1.0 INTRODUCTION

This report describes an update of New Zealand's depth to hydrogeological basement map, including the methodology used to undertake this work and the resultant digital data sets. The work was completed by GNS Science (GNS), under commission to the Ministry for the Environment (the Ministry) as part of the Ministry's New Zealand Groundwater Atlas programme.

The Ministry requires national-scale groundwater data sets to inform groundwater work streams related to the Environmental Reporting Act (2015) and the National Policy Statement for Freshwater Management (2014, 2017), as well as to increase public awareness about groundwater. The scope of the work is to use pre-existing data only, using information already held by the authors in most cases. It is not in scope to compile and quality-check large amounts of data held by regional authorities (for example, borehole geological information and monitoring data) or to undertake detailed regional assessments. Due to the coverage of existing national data sets, the geographic scope of the work encompasses the contiguous land masses of the North and South islands of New Zealand. All data sets are developed in a nationally-consistent manner between regions and are provided in a digital format that facilitates future improvements and online access. Guidance around uncertainty of the data is also provided, as well as recommendations about how these data sets could be improved in the future.

Hydrogeological basement refers to geological material with primary porosity and permeability that is low enough such that fluid volumes and flow rates can be considered negligible. More loosely, depth to hydrogeological basement can be described as depth to 'the base of the aquifer system'. New Zealand's depth to hydrogeological basement map was first developed in 2017 and previous research is described by Westerhoff (2017); Tschritter et al (2017); and Westerhoff et al (2017).

The update presented in this report includes refinement of previous research. After the model review (Section 2), we describe how we incorporate uncertainty and provide depth ranges rather than absolute values (Sections 3 and 4). Due to the model assumptions, it is expected that the depth to hydrogeological basement will often correspond to the base of Quaternary sediments: this expectation is tested and described in the discussion (Section 5).

2.0 HYDROGEOLOGICAL BASEMENT MODEL REVIEW

2.1 General

The depth to hydrogeological basement model provides an indication of the potential depth to the hydrogeological basement across New Zealand (not including the outlying islands). The first version of this model was developed by Westerhoff (2017) based on work by Fan and Miguez-Macho (2010), Beven and Kirkby (1979), Ahnert (1970), and others.

Updated versions were developed as part of the GNS Groundwater Resource Programme (Tschritter et al 2017) and in the New Zealand Water Model project (Westerhoff et al 2017), a collaborative research project lead by the National Institute of Water and Atmospheric Research (NIWA). The following sections describes the input data and methodology used in the updated version. Unless indicated otherwise, the information in these sections is sourced from Westerhoff et al (2017).

2.2 Input Data

2.2.1 Geological Map

The national 1:250,000 geological map used in this work is the result of the seamless aggregation of the digital data sets from 21 QMAP sheets in a GIS vector format (Heron 2014). QMAP provides a polygon data set of geological units covering the entire New Zealand mainland without gaps. Furthermore, the attribute table of QMAP provides geological units/formations, and lithological and stratigraphic information for each mapped polygon feature, including the following parameters that were utilised in the model:

- 'MAIN_ROCK' – one descriptor for the main rock type
- 'SUB_ROCK' – one or multiple descriptors for secondary rock type(s)
- 'ABS_MIN' – minimum age of deposits (Ma)
- 'ABS_MAX' – maximum age of deposit (Ma).

2.2.2 Digital Terrain Model

The national Digital Terrain Model (DTM) used by Westerhoff et al (2017) was the NZDEM_SoS_v1.0 (Columbus et al 2011), which is split into the North Island and the South Island. This DTM has a spatial resolution of 15 m that was downscaled to 250 m (taking the mean value of the 15 m cells) to accommodate for the national scale work in this project.

2.3 Methodology

Tschritter et al (2017) and Westerhoff et al (2017) describe the method to infer depth to hydrogeological basement map as a three-step approach. In the first step, near-surface hydraulic conductivity was calculated. In the second step, near-surface hydraulic conductivity was used to estimate hydraulic conductivity at depth. The third step then used the depth profile of hydraulic conductivity to derive the depth to hydrogeological basement. These three steps are explained in detail in this section.

2.3.1 Estimation of Near-Surface Hydraulic Conductivity

Tschritter et al (2017) assigned permeability values to each QMAP polygon via a 'Look-up table'. This Look-up table lists permeability values for each rock type based on international data from Gleeson et al (2011) and national data. Using this table, a permeability value was assigned to each rock type recorded in the QMAP 'MAIN_ROCK' and 'SUB_ROCK' attribute fields. When combining the values for the 'MAIN_ROCK' and 'SUB_ROCK' fields, 'MAIN_ROCK' was weighted twice as high as the mean of the permeability values for all rock types listed in the 'SUB_ROCK' attribute field, to accommodate for the difference in importance between the 'MAIN_ROCK' and 'SUB_ROCK' descriptors.

Hydraulic conductivity values for all QMAP polygons were then calculated from these permeability values via the following equation (Freeze and Cherry 1979):

$$K = 86400\frac{\kappa\rho g}{\mu} \qquad \text{Equation 2.1}$$

Where:

- κ is the intrinsic permeability (m^2)
- μ is the dynamic viscosity of fresh water at 13 °C (= 1.2155 × 103 kg / m s)
- ρ is the density of fresh water (= 1000 kg/m^3)
- g is the gravitational constant (= 9.80 m/s^2)
- 86400 is used to convert m/s to m/day.

In this study, κ and K are assumed to be isotropic (ie the same in all directions) unless stated otherwise.

Tschritter et al (2017) also scaled the hydraulic conductivity values with age using the following function (f_t), which is based on an exponential decrease of permeability with age as found by Ehrenberg et al (2009):

$$f_t = e^{-\frac{t}{\alpha}} \qquad \text{Equation 2.2}$$

where t is the mean age in millions of year (Ma) and α is a constant that controls the exponential decrease. The mean age was calculated as the mean of the minimum and maximum age for each polygon as provided in the QMAP attribute table (ABS_MIN and ABS_MAX). The age scale factor α was updated to 600 in accordance with Westerhoff et al (2017).

2.3.2 Calculation of the Decrease of Hydraulic Conductivity Over Depth

For the first 10 m below the ground surface, Tschritter et al (2017) assumed a constant hydraulic conductivity value that was equal to the near-surface hydraulic conductivity K_0 at that location. This assumption is based on QMAP mapping specifications that state that 'a geological unit must have a significant thickness (typically greater than 5–10 m)' and that any 'units thinner than this should normally be omitted, unless particular emphasis on the unit is wanted by the compiler' (Rattenbury and Heron 1997).

Below 10-m-below ground level, following the approach of Westerhoff et al (2017), near-surface hydraulic conductivity, K_0, was used to calculate hydraulic conductivity over depth via the following two equations:

$$K = K_0 e^{-z/f}$$ Equation 2.2

This equation largely represents compaction due to lithostatic pressure (overburden), that is, the weight of the overlying rock. In this equation, K_0 is the hydraulic conductivity at or near the surface, z is the depth, and f is a function of terrain slope, climate, geology derived from mechanical and chemical denudation, and tectonic uplift rates of large sedimentary basins (Ahnert 1970; Summerfield and Hulton 1994). For a 200 m resolution gridded model, Fan and Miguez-Macho (2010) used the following equation:

$$f = \frac{a}{1+bs};\ f \geq f_{\min}$$ Equation 2.3

where s is the terrain slope and a, b and f_{min} are constants that Fan and Miguez-Macho (2010) found to be 75, 150 and 4, respectively. In this project, terrain slope and depth were calculated using a down-scaled version of the national DTM NZDEM_SoS_v1.0 (Columbus et al 2011) (Section 2.2.2).

2.3.3 Determination of the Depth to Hydrogeological Basement

The depth to hydrogeological basement is calculated as the depth below which hydraulic conductivity values decrease below a threshold value. Based on expert knowledge, Tschritter et al (2017) and Westerhoff (2017) suggested a value of 0.1 m/day for this threshold, although Westerhoff et al (2017) noted that a lower value of 0.01 m/day may also be appropriate and that further investigation of this threshold value is advised.

3.0 METHODS

3.1 Exploration of Uncertainty

Uncertainty in the calculated depth to hydrogeological basement was investigated using a Monte-Carlo approach, where a total of 125 realisations of the model were run with the following parameter values randomly distributed:

- Hydraulic conductivity between 0.1 and 10 times its original value
- The threshold (Section 2.3.3) value between 1 cm and 1 m per day
- The calibration constants of the exponential decay (Equation 2.4) between 75 and 120 for *a* and between 4 and 5 for f_{min}.

The mean and standard deviation were estimated for all model runs combined. The minimum and maximum were taken as the 5th and 95th percentile, to avoid extremes.

Assuming that the Monte-Carlo simulations represent a wide enough spectrum of possible combinations of input components in the depth to basement model calculation, model uncertainty was captured by assessing these values of depth to hydrogeological basement:

- Mean
- Standard deviation of the mean
- Minimum, represented by the 5th percentile
- Maximum, represented by the 95th percentile.

3.2 Simplification to Depth Classes

Depth classes were defined to present the data set in a manner that captures the inherent uncertainty of the data set. Depth ranges were first classified into seven classes of depth ranges; and then further simplified into three classes: ‘Surficial’; ‘Moderately deep’ and ‘Very deep’. Details are shown in Table 3.1.

Table 3.1 Depth classes for depth to hydrogeological basement as defined in this study.

Depth Class	Depth Range (mBGL)	Simplified Classes
1	0–1	Surficial
2	1–10	
3	10–20	Moderately deep
4	20–50	
5	50–100	
6	100–200	Very deep
7	> 200	

4.0 RESULTS

4.1 Depths to Hydrogeological Basement

The overall New Zealand average modelled depth to hydrogeological basement is 35 m but varies significantly over the country (Figure 4.1), where values range from zero to several hundreds of metres. Deeper aquifers (up to hundreds of metres depth to their basement) occur in alluvial plains such as the Canterbury Plains, Hauraki Plains, Poverty Bay Flats, Horowhenua Plains and Southland Plains; medium depth aquifers occur in volcanic geology such as the Taupo Volcanic Zone and Taranaki; and alluvial sediments deposited in areas with a moderate (but not steep) terrain slope (eg foothills). Standard deviation of the overall New Zealand average is 20 m, but also varies significantly over the country, increasing with increasing depth to hydrogeological basement (Figure 4.2). Minimum and maximum modelled depths are shown in Figure 4.3 and Figure 4.4, respectively. Depth classes (as defined in Section 3.2) are shown in Figure 4.5.

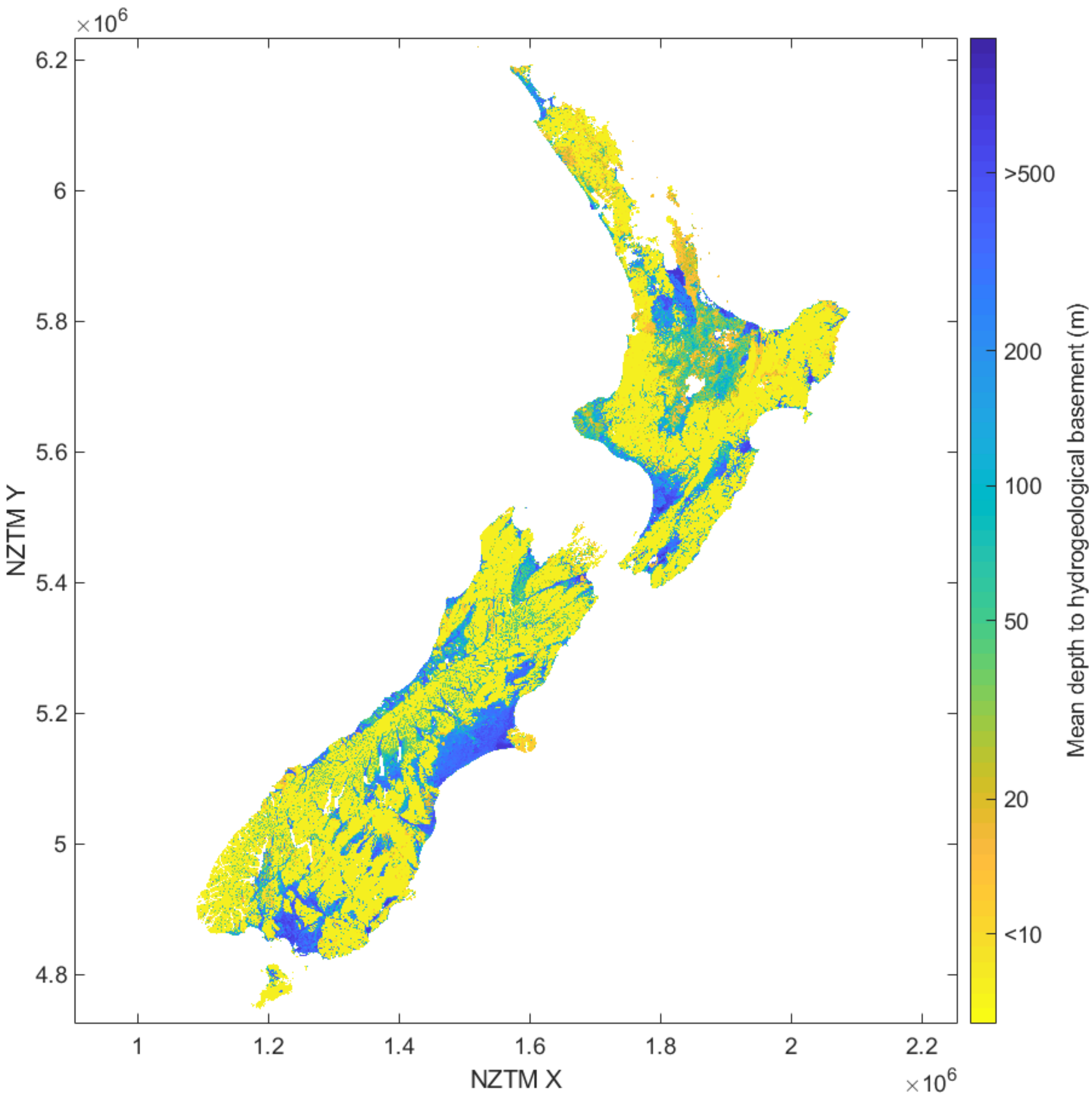

Figure 4.1 Mean modelled depth to hydrogeological basement.

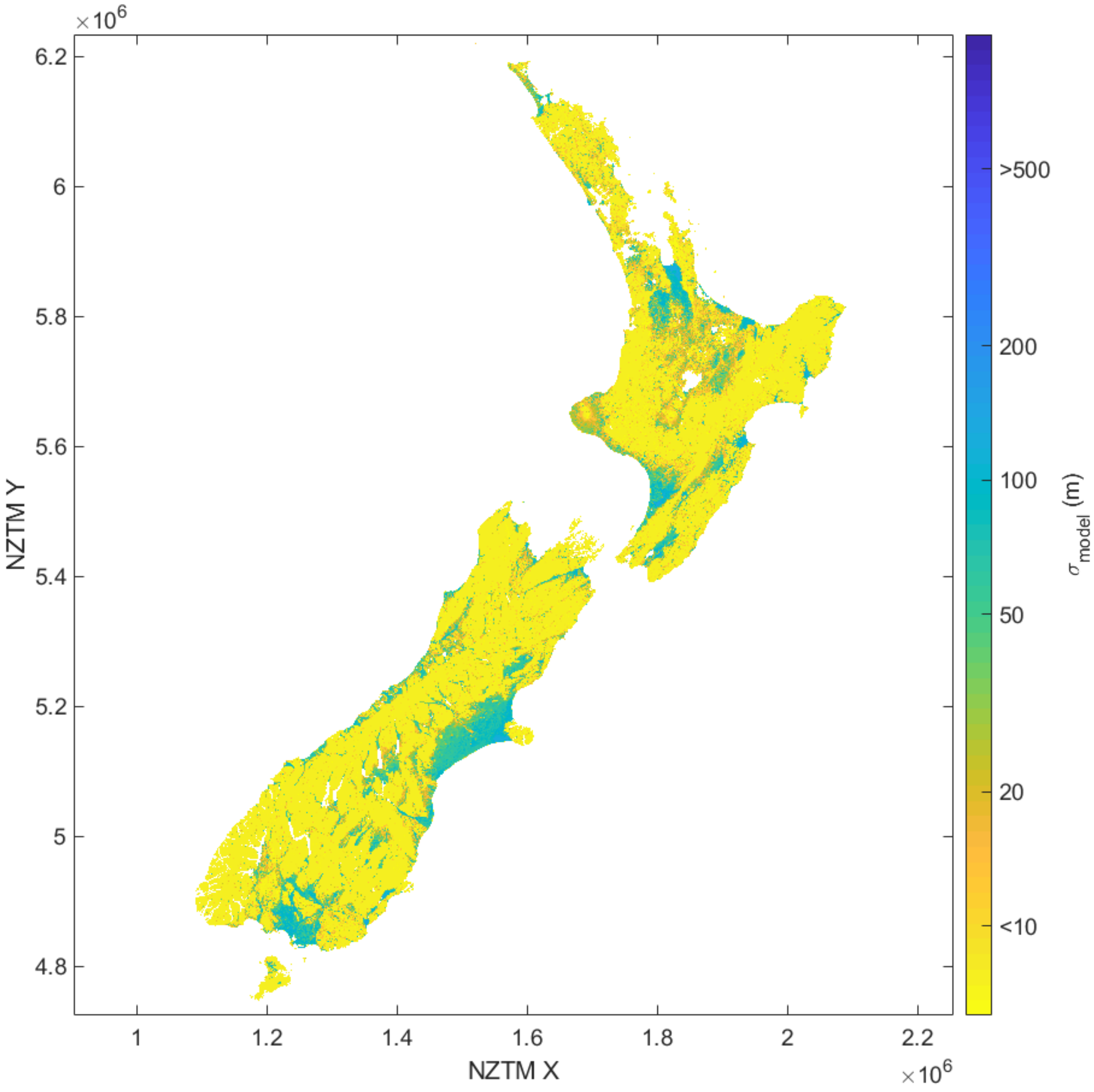

Figure 4.2 Standard deviation $\boldsymbol{\sigma_{model}}$ of mean modelled depth to hydrogeological basement.

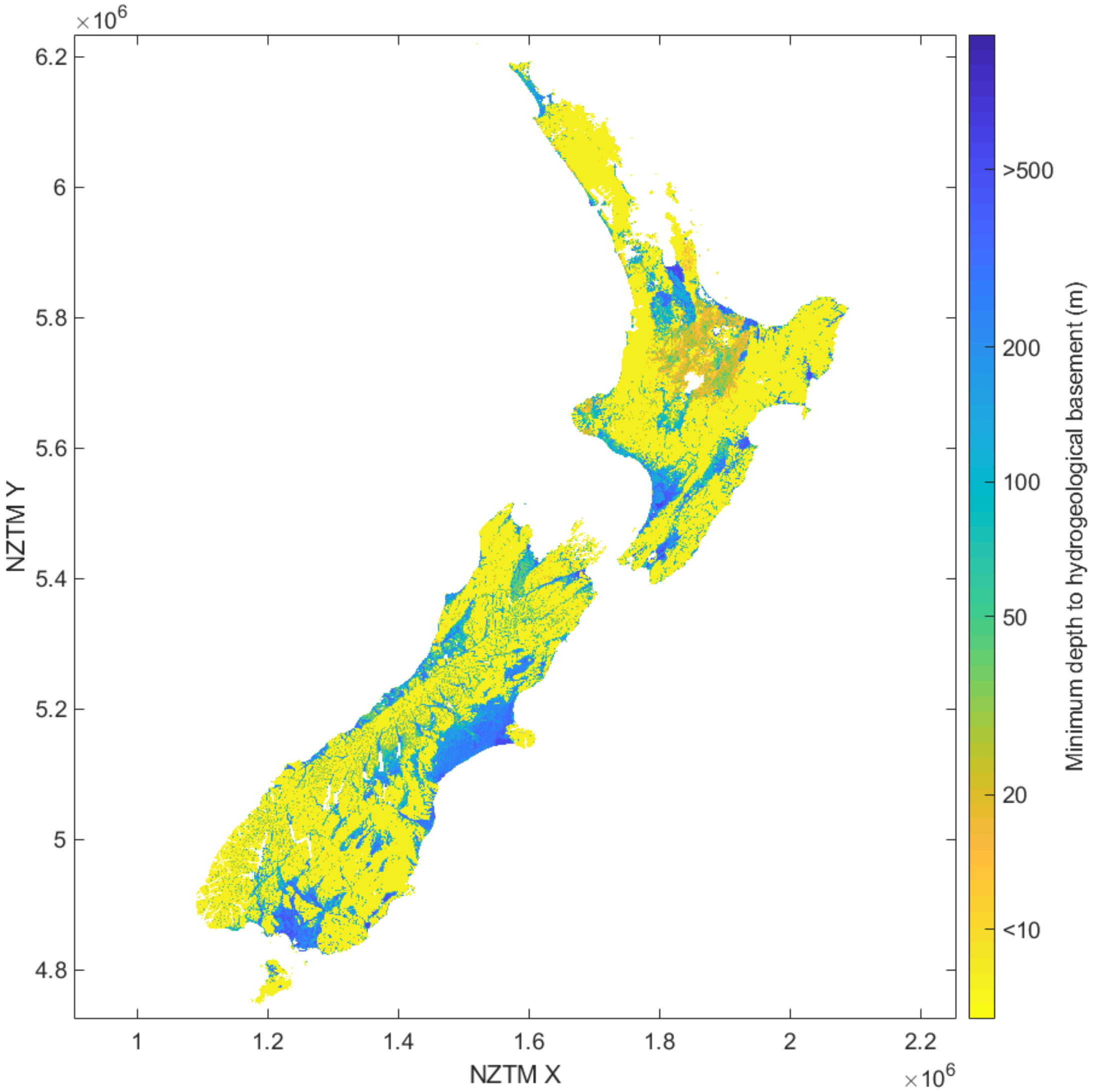

Figure 4.3 Minimum (5th percentile) modelled depth to hydrogeological basement.

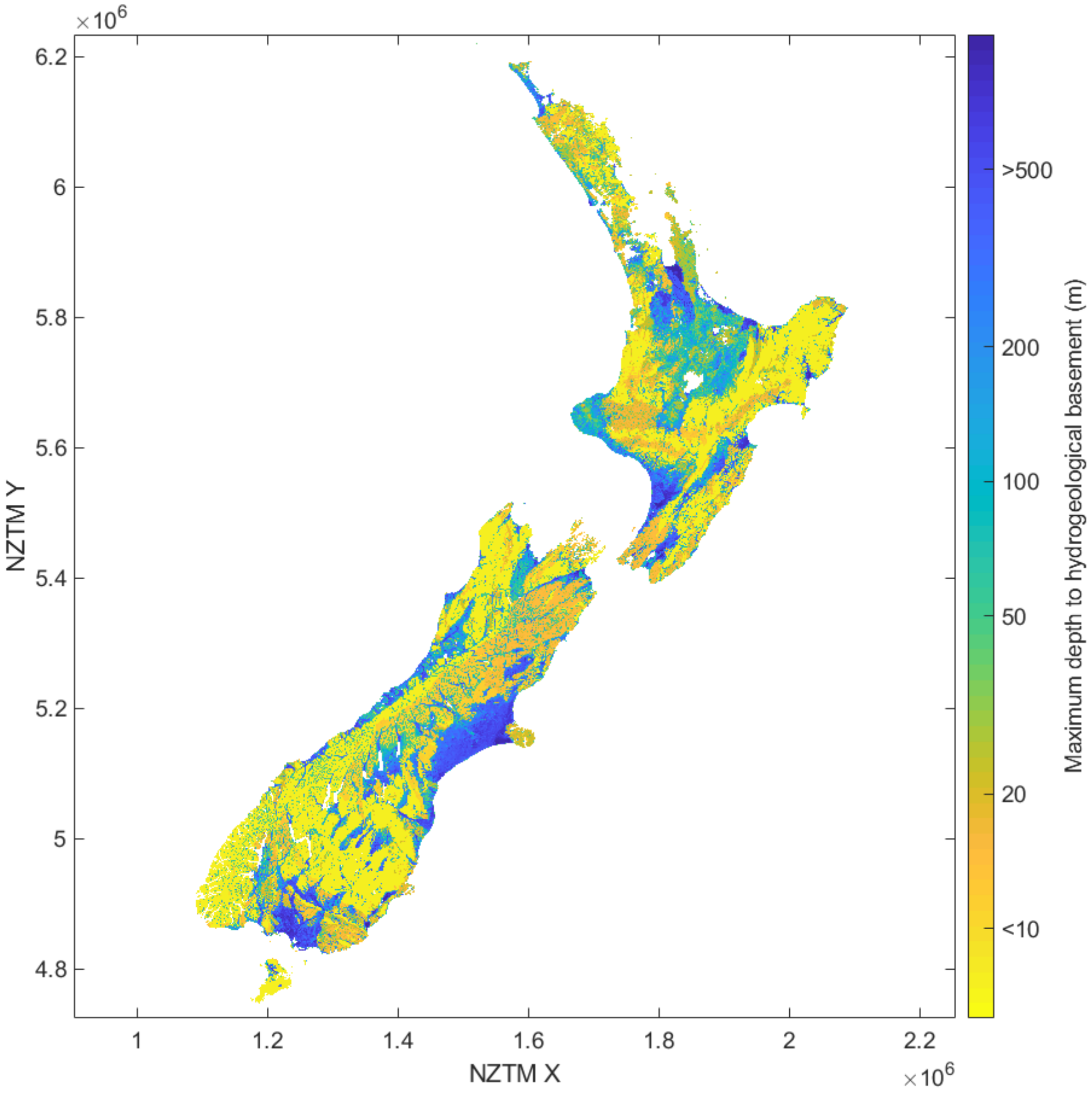

Figure 4.4 Maximum (95th percentile) modelled depth to hydrogeological basement.

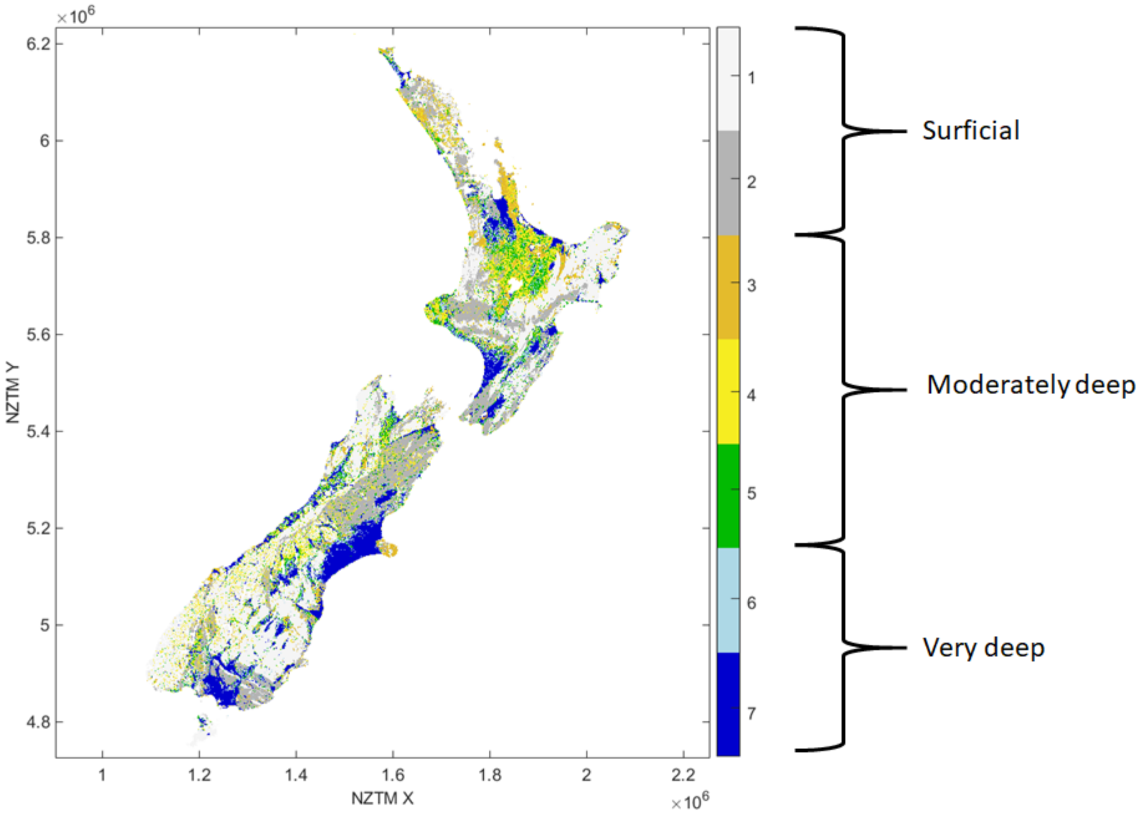

Figure 4.5 Depth classes for depth to hydrogeological basement.

4.2 Output Data Set

The data set provided to the Ministry along with this report is in GeoTIFF format and contains the depth classes for depth (Figure 4.5) to hydrogeological basement, named:

'NZDepthToHydrogeologicalBasement_Classes.tif'

4.3 Disclaimer on Use and Limitations

This report has been prepared by the Institute of Geological and Nuclear Sciences Limited for the Ministry for the Environment. While all care and diligence has been used in processing, analysing, and extracting data and information in this publication, if used by other parties, no warranty is given in relation to the report or data used in the report – including its accuracy, reliability and suitability – and no liability is accepted whatsoever in relation to any loss, damage or other costs relating to the use of any part of the report (including any data) or any compilations, derivative works or modifications of the report (including any data). These data have been developed for the purpose of national-scale assessments.

5.0 DISCUSSION AND RECOMMENDATIONS

5.1 Uncertainty and Limitations

The method applied in this study is based on geological assumptions for large-scale sedimentary basins and is a function of terrain slope, climate, geology derived from mechanical and chemical denudation, and tectonic uplift rates of large sedimentary basins (Ahnert 1970; Summerfield and Hulton 1994). Uncertainty is embedded in most of these assumptions. The Monte-Carlo simulations have covered realistic ranges of hydraulic conductivity, threshold values and calibration constants to encompass for this model bias. However, other assumptions can also generate bias, of which a few relevant ones are listed here:

- The method was developed for large-scale basins, but there was no consideration for how small a basin can be for the rules to still apply, nor the extent to which active tectonic movements may change the relationship
- The method was developed for fluvial sedimentary basins. We therefore expect uncertainty to be smaller in inland river basins than for other hydrogeological systems. Due to significantly different depositional processes, the model is not expected to represent volcanic aquifers well
- The method does not take into account confining layers – it assumes relative homogeneity of a fluvial sedimentary sequence with depth and does not consider marine transgression sequences that are common in New Zealand coastal areas. This is essentially not a limitation: despite that hydraulic conductivity profile with depth is known to be inaccurate in these areas, porosity and permeability are still similarly reduced with over-burden pressures causing compaction, and so the depth to hydrogeological basement is still considered to provide a valid indication of potential depth to hydrogeological basement in these areas
- The method does not consider anisotropy within units. As with the simplification of aquifer confinement, anisotropy effects should not compromise the use of the model as a useful indicator of hydrogeologic depth, but this approach may be an oversimplification in select cases where unusual vertical flow effects are present
- Given different depositional sources such as marine transgression sequences and volcanic depositions as described above, not all water above depth to hydrogeological basement is expected to necessarily be ‘extractable’. Combination of depth to basement data of this model with the location of aquitard layers would give more insight into what water would be extractable, and where.

These assumptions all require more attention and are therefore listed as recommendations for future research.

5.2 Towards Application of National-Scale Data to Smaller-Scale Research

The data sets presented in this report are primarily considered suitable for national-scale assessments. However, if no finer-scale information exists, they are considered suitable for non-national-scale assessments provided that the uncertainty information is considered within such assessments.

Although national guidelines in freshwater management exist (ie the National Policy Statement for Freshwater Management), regional councils are ultimately responsible for policy on water allocation. Therefore, most approaches associated with water allocation follow the regional guidelines, data, models and formats and are thus prone to inconsistency regions. To date, New Zealand does not have many data sets describing consistent nationwide characterisation of key groundwater parameters. The lack of these data hinders further scientific advances in national-scale overviews of water resource management. For example, the New Zealand national surface water model could benefit from better information of groundwater fluxes, for example, subsurface information described in this report or recharge to groundwater, described in Westerhoff et al (2019).

The key challenge to incorporate nationwide approaches is a framework for national-to-regional scale collaboration, with both the Ministry for the Environment and regional councils. Currently, nationwide approaches suffer from a lack of validation at the regional scale, because regional data are inconsistent and requires an excessive amount of pre-processing, which usually cannot be covered by limited project budgets. The flipside of that is that regional councils are less likely to use nationwide data, because they are not validated well enough at the regional scale.

Hence, recommendation for further research is not only in the further development of nationwide consistent methods, but also in the set-up of a validation data-source that is consistent across regions.

The data sets presented in this report are primarily considered suitable for national-scale assessments. However, if no finer-scale information exists, they are considered suitable for non-national-scale assessments provided that the uncertainty information is considered within such assessments.

5.3 The Relation between Depth to Hydrogeological Basement and Depth of Quaternary Deposits

New Zealand aquifers are commonly found in geological material that was deposited in the Quaternary geological era (1.8 million years ago to present). As such, we tested the hypothesis that depth to hydrogeological basement as modelled in this study equals the depth to the base of Quaternary deposits.

The derived depth to hydrogeological basement values were compared with the depth to the base of Quaternary from 3021 coal bores (Scadden 2015) distributed throughout New Zealand. Using the digital elevation model used in this research (NZDEM_SoS_v1.0, Section 2.2.2), the elevations from the bore data were converted to depth to be directly comparable with the depth to hydrogeological basement data. The depth to hydrogeological basement model pixel overlapping the coal bore coordinate was sampled and the difference between the depth to hydrogeological basement data and the depth of the base of Quaternary observed in coal bores was calculated. This comparison was performed taking into account the different hydrogeological systems of New Zealand (Moreau et al 2019).

This comparison shows that: 45% of all modelled depth to hydrogeological basement falls within 25 m of coal bore depths and that the median depth difference between coal bore and modelled depth is 5 m (Table 5.1).

Modelled depth to hydrogeological basement compares best to coal bore Quaternary depths in these hydrogeological systems: Basement Infill, Basement Hard Rock, Inland volcanic (100%, 89% and 84% under 25 m, respectively); largest differences are found in Inland basin and Coastal Basin (12% and 25% under 25 m, respectively).

The histogram for the depth differences of the entire bore data set (Figure 5.1) has a unimodal distribution with a peak at approximately zero and skewed to the right (ie the depth to the base of Quaternary in coal bores is generally shallower than the depth to hydrogeological basement). The depth-difference distribution in the histograms for Coastal Basins (Figure 5.2) generally mirrors the distribution for all data, reflecting the large component of bores located in these systems. The histogram for Inland Volcanics (Figure 5.2) shows a very narrow depth-difference distribution (largely less then +/- 40 m) with a distinct peak close to 0.

Table 5.1 Summary of differences (Δ) between modelled depth to hydrogeological basement and depth to Quaternary from coal bores. For median Δ values: if the coal bore is deeper than the modelled depth, the value is negative. Median model σ refers to the median model standard deviation (as depicted in Figure 4.2) per system.

Hydrogeological System	Median Δ	Median Model σ	Δ < 10 m	Δ < 25 m	Number of Samples
All	5 m	14 m	32%	45%	3021
Coastal Basin	42 m	20 m	25%	38%	2397
Inland Basin	133 m	29 m	12%	12%	86
Coastal Volcanic	-3.5 m	6 m	71%	79%	15
Inland Volcanic	-2 m	0 m	71%	84%	329
Coastal Independent	-	-	-	-	0
Inland River Valley	18 m	12 m	25%	50%	4
Basement Infill	-3 m	0 m	95%	100%	21
Basement Hard rock	-3 m	6 m	66%	89%	161
Unclassed	-	-	-	-	0

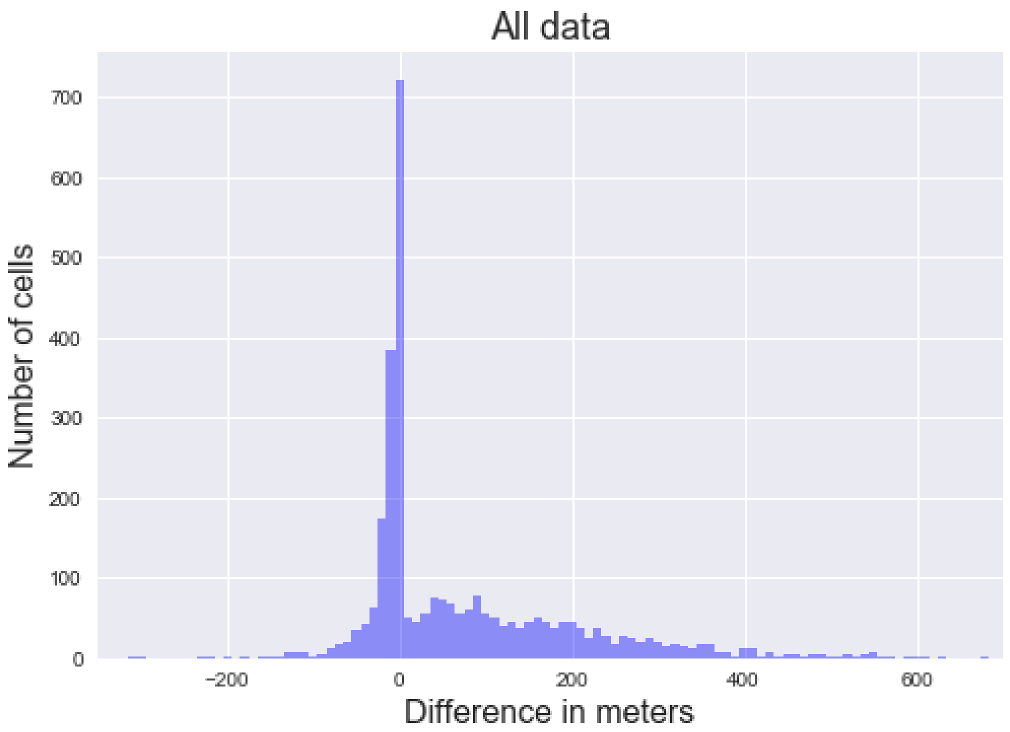

Figure 5.1 Histogram showing the frequency distribution of depth differences between the depth to the base of Quaternary from coal bores and the depth to hydrogeological basement data at the same location.

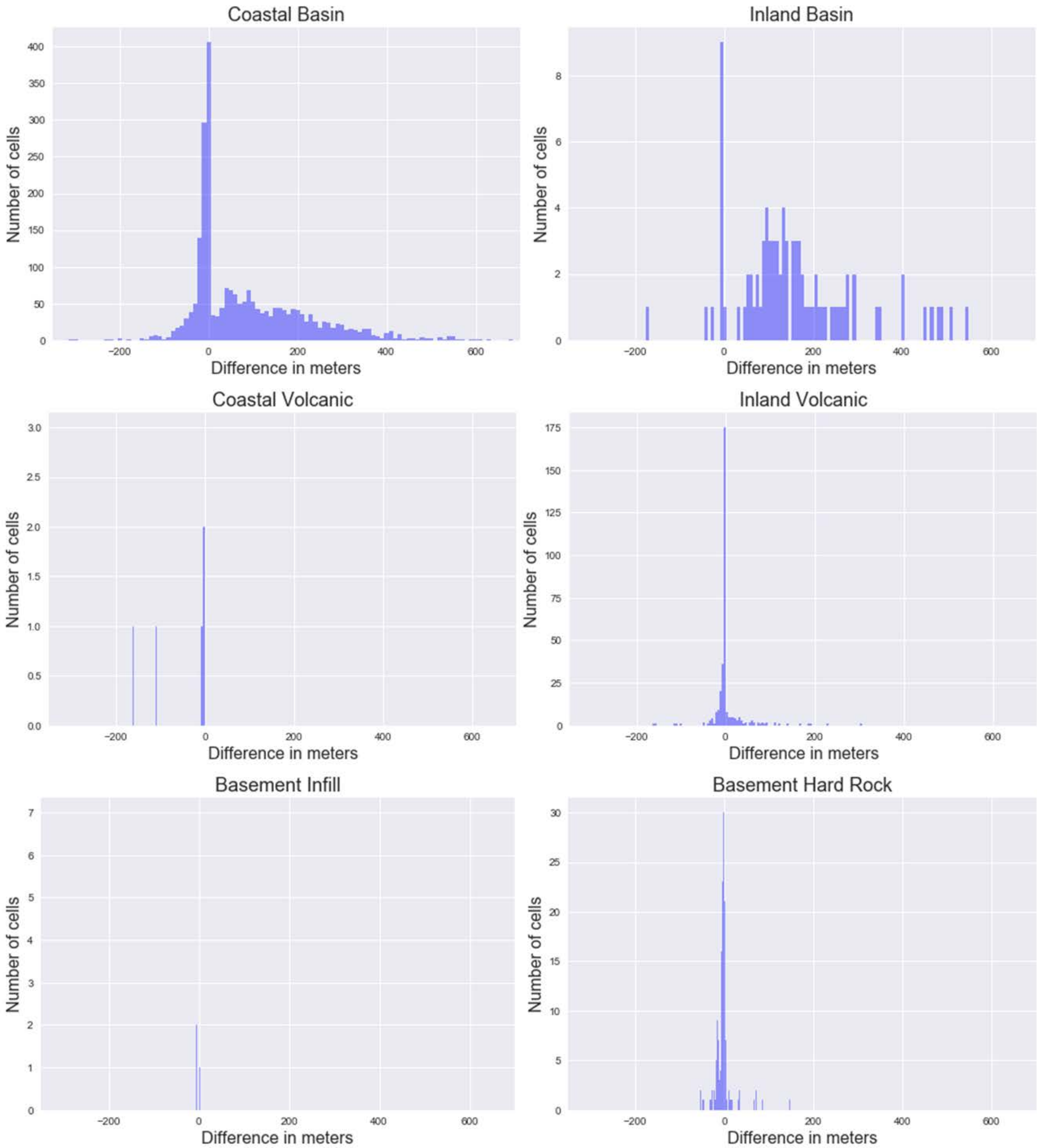

Figure 5.2 Histograms showing the frequency distribution of depth differences between the depth to the base of Quaternary from coal bores and modelled depth to hydrogeological basement, clustered per hydrogeological system. The system 'Inland River Valley' is not shown, since it only contains four samples.

Spatial behaviour of the depth differences shows that depth differences are noticeably larger (>+100 m) for most bores in the Southland Plains area (Figure 5.3), that is, most bores have a shallower depth to the base of Quaternary than the depth to hydrogeological basement. This is because the Southland Plains have Pliocene and Miocene deposits (from 1.8Ma to 15Ma or older) that could, in terms of water quantities, have a significant aquifer potential up to depths of 1 km or more (Tschritter et al 2016). This also explains why the comparison for Coastal Basin and Inland Basin system is skewed, that is many coal bore samples are from the Southland Plains.

The comparison with coal bore data is a useful indicator of how the depth to hydrogeological basement compares to observed data on Quaternary depths. However, the distribution of the coal bores throughout New Zealand is limited to areas of interest to the coal mining industry. Therefore, there is a high density of data points for this comparison in some areas, but large parts of New Zealand are without any such data. For a more in-depth comparison, logs from groundwater bores throughout the country could be included in the future, carefully chosen for their depth (reaching at least the base of the Quaternary) and the quality of their lithological log descriptions.

Although depth to base of the Quaternary can, in some cases, be similar to depth to hydrogeological basement, they are different concepts. Also, depth to the base of Quaternary does not only depend on the hydrogeological system, but also on the structural control of the geology. For example, the Southland Plains and the Canterbury Plains are both Coastal Basins but with different tectonic settings. The Canterbury Plains extend from the margin of the uplifting Southern Alps into a subsiding sedimentary basin. Long-term subsidence near the coast at Christchurch is between 0.3 and 0.5 mm/yr (Begg et al 2015) and has resulted in several hundred metres of alluvial and interfingering coastal sediments having accumulated through the Quaternary (Jongens 2011; Jongens et al 2012). Total Quaternary sediment thicknesses range from ~250 m to ~700 m, with ongoing creation of accommodation space for sediment due to the subsidence. The Southland Plains occupy a tectonically stable, eroded terrain of mountains, basins and valleys, with relatively thin deposits of Quaternary alluvial sediments beneath terraces and floodplains in the valley and basin floors. Sediment thicknesses are typically no more than a few tens of metres (Tschritter et al 2016). Interactions between river systems and eustatic sea level variations through glacial cycles have been the main control on Southland Plains deposition. It is recommended that structural controls are also taken into account when further comparing in-situ information with modelled depths. Other structural factors can also play an important role. For example, the geological process of continental rift in the Hauraki Plains has resulted in many hundreds of metres of unconsolidated sedimentary deposits that contain both Quaternary and older (Pliocene and Miocene) sediments (eg White et al 2018). It is recommended that properties of geological structural processes (eg tectonic uplift, faulting, continental rift, height and slope of hinterland, speed of process) are also considered when further comparing in-situ information with modelled depths.

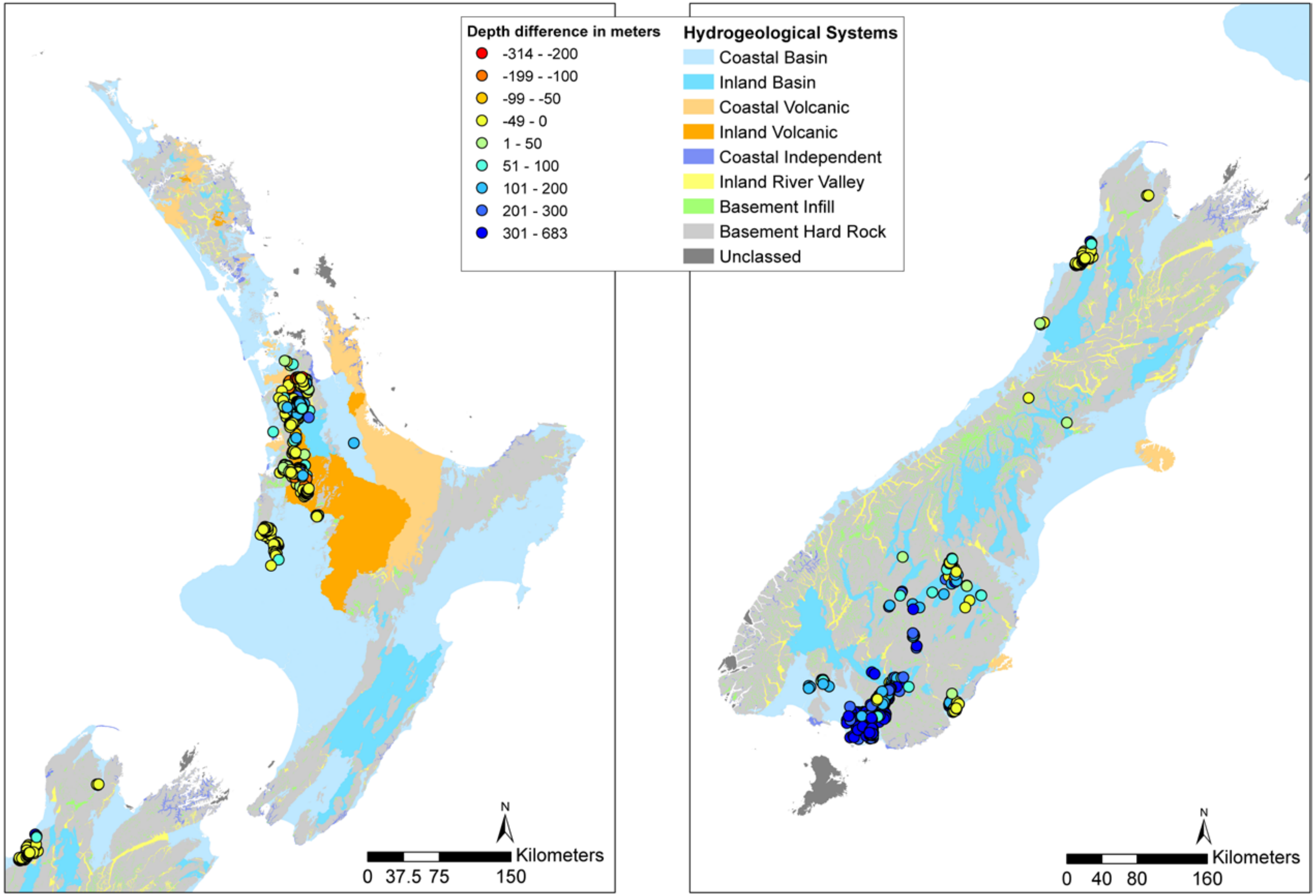

Figure 5.3 Depth difference in meters between the depth to hydrogeological basement and the depth to the base of Quaternary at coal bores. The hydrogeological systems are shown in the background.

6.0 CONCLUSION

Modelled depth to hydrogeological basement varies significantly over the country and values range from zero to several hundreds of metres. Aquifer bases are deeper in alluvial plains, for example, the Canterbury Plains, Hauraki Plains; medium depth aquifer bases occur in volcanic geology, for example, Taupo Volcanic Zone; and alluvial sediments in foothills. Statistics from 125 model runs with pseudo-randomised input values resulted in depth ranges that better captured model uncertainty and statistics of depth to hydrogeological basement (ie mean, standard deviation of mean, minimum and maximum) than previous attempts to model depth to hydrogeological basement in New Zealand. Standard deviation also varies across the nation and increases with increasing depth to hydrogeological basement.

Although depth to hydrogeological basement is often similar to depth to base of the Quaternary, they are different concepts. Comparison with data from coal bores show that aquifers still hold water in deposits that are older than Quaternary (eg Pliocene/Miocene Tertiary sediments). Other geological processes, for example, height and slope of hinterland, continental rift, faulting, also play a role in whether depth to base of the Quaternary is similar to the depth to hydrogeological basement. Future development of this work should include use of groundwater bore logs and the incorporation of geological structural processes within hydrogeological systems.

7.0 REFERENCES

Ahnert F. 1970. Functional relationships between denudation, relief, and uplift in large, mid-latitude drainage basins. *American Journal of Science.* 268(3):243–263. doi:10.2475/ajs.268.3.243.

Begg JG, Jones KE, Barrell DJA, (compilers). 2015. Geology and geomorphology of urban Christchurch and eastern Canterbury: digital vector data 2015. Lower Hutt (NZ): GNS Science. 101 p. (Geological map; 3).

Beven KJ, Kirkby MJ. 1979. A physically based, variable contributing area model of basin hydrology / Un modèle à base physique de zone d'appel variable de l'hydrologie du bassin versant. *Hydrological Sciences Bulletin.* 24(1):43–69. doi:10.1080/02626667909491834.

Columbus J, Sirguey P, Tenzer R. 2011. A free, fully assessed 15-m DEM for New Zealand. *Survey Quarterly.* 66:16–19.

Ehrenberg SN, Nadeau PH, Steen Ø. 2009. Petroleum reservoir porosity versus depth: influence of geological age. *AAPG Bulletin.* 93(10):1281–1296. doi:10.1306/06120908163.

Fan Y, Miguez-Macho G. 2010. Potential groundwater contribution to Amazon evapotranspiration. *Hydrology and Earth System Sciences.* 14(10):2039–2056. doi:10.5194/hess-14-2039-2010.

Freeze RA, Cherry JA. 1979. Groundwater. Englewood Cliffs (NJ): Prentice-Hall. 604 p.

Gleeson T, Smith L, Moosdorf N, Hartmann J, Dürr HH, Manning AH, van Beek LPH, Jellinek AM. 2011. Mapping permeability over the surface of the Earth. *Geophysical Research Letters.* 38(2):L02401. doi:10.1029/2010GL045565.

Heron DW. 2014. Geological map of New Zealand 1:250 000: digital vector data 2014. 2nd ed. Lower Hutt (NZ): GNS Science. 1 DVD-ROM. (GNS Science geological map; 1).

Jongens R. 2011. Contours for the base of Quaternary sediments under the Canterbury Plains between the Ashley and Rakaia rivers. Lower Hutt (NZ): GNS Science. 17 p. + 1 CD. Consultancy Report 2011/132. Prepared for Environment Canterbury.

Jongens R, Barrell DJA, Campbell JK, Pettinga JR. 2012. Faulting and folding beneath the Canterbury Plains identified prior to the 2010 emergence of the Greendale Fault. *New Zealand Journal of Geology and Geophysics.* 55(3):169–176. doi:10.1080/00288306.2012.674050.

Moreau M, White PA, Mourot F, Rawlinson ZJ, Tschritter C, Cameron SG, Westerhoff RS. 2019. Classification of New Zealand hydrogeological systems. Lower Hutt (NZ): GNS Science. 28 p. (GNS Science report; 2018/35). doi:10.21420/42QW-MC74.

Rattenbury MS, Heron DW. 1997. Revised procedures and specifications for the QMAP GIS. Lower Hutt (NZ): Institute of Geological & Nuclear Sciences. 52 p. (Institute of Geological & Nuclear Sciences science report; 97/03).

Tschritter C, Rawlinson ZJ, Barrell DJA, Alcaraz S. 2016. Three-dimensional geological model of Environment Southland's area of interest for freshwater management. Wairakei (NZ): GNS Science. 67 p. Consultancy Report 2015/123. Prepared for Environment Southland.

Scadden P. 25 Sep 2015. Personal communication. Custodian of the Mineral and Coal bore database at GNS Science.

Summerfield MA, Hulton NJ. 1994. Natural controls of fluvial denudation rates in major world drainage basins. *Journal of Geophysical Research: Solid Earth.* 99(B7):13871–13883. doi:10.1029/94JB00715.

Tschritter C, Westerhoff RS, Rawlinson ZJ, White PA. 2017. Aquifer classification and mapping at the national scale – phase 1: identification of hydrogeological units. Lower Hutt (NZ): GNS Science. 52 p. (GNS Science report; 2016/51).

Westerhoff RS. 2017. Satellite remote sensing for improvement of groundwater characterisation [PhD thesis]. Hamilton (NZ): University of Waikato. 363 p.

Westerhoff RS, Tschritter C, White PA. 2017. Development of hydrogeological information to evaluate national-scale hydrological parameters. Lower Hutt (NZ): GNS Science. 21 p. (GNS Science report; 2017/23).

Westerhoff RS, Dark A, Zammit C, Tschritter C, Rawlinson ZJ. 2019. New Zealand Groundwater Atlas: Groundwater Fluxes. Wairakei (NZ): GNS Science. 60 p. Consultancy Report 2019/126. Prepared for the Ministry for the Environment.

White PA, Raiber M, Tschritter C. 2018. Geological model and water budget of the Hauraki Plains, Waikato region. Wairakei (NZ): GNS Science. 63 p. Consultancy Report 2015/232. Prepared for Waikato Regional Council.

www.gns.cri.nz

Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657