Development of hydrogeological information to evaluate national-scale hydrological parameters

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ABSTRACT

The National Institute for Water and Atmospheric Research established, and is leading, the 'National Hydrology Program' (NHP) research project. NHP, is a five-year project that aims to develop hydrological understanding across the New Zealand landscape, through combining surface water, soil, and geological information. GNS Science has been sub-contracted to provide subsurface and groundwater information, with the long-term aim to enable a better coupling of surface water to groundwater in the National Hydrological Model (TopNet).

A major initial task of the NHP project was to set up and test the geospatial framework, including combination and compilation of different datasets in a framework suitable for input to TopNet. In this report, the work carried out by GNS Science in the geospatial framework task in Year 1 of the NHP project is presented. This includes the development of the first version of national-scale datasets of three geologically derived hydrological parameters as spatial data layers (e.g., hydraulic conductivity (K); effective porosity (φ_e); and depth to hydrogeological basement). Furthermore, methods for estimation of K and φ_e over depth are presented.

At the national scale, the resulting datasets of K and φ_e follow the expected patterns, e.g., high values in the alluvial plains, medium values in the central volcanic region and low values in basement and Tertiary rocks. Also, the calculated depth to hydrogeological basement provides a general idea of the potential basement depth. These parameters are accurate in areas where basement is at the ground surface and seems adequate in some coastal plains such as the Hauraki and Canterbury Plains. However, in other areas, e.g., coastal plains and the central volcanic region, the calculated basement depth appears too shallow.

The results were evaluated in the Southland region using a 3D geological model previously developed by GNS Science, and field data provided by Environment Southland. This evaluation showed that the estimates of K and depth to hydrogeological basement of this study followed the same spatial pattern as the 3D geological model, but showing more spatial detail. However, field-observed K values were magnitudes higher than the NHP K values estimated in this study, and depths to hydrogeological basement in this study were shallower than earlier estimates of a 3D groundwater flow model.

The nationwide and regional findings lead to the conclusion that the methods used for this nationwide approach are warranted, but that input parameters should be adjusted. Specifically, future research is recommended to include testing of increased values of near-surface K for gravels and sand. These increased K estimates will also lead to improved estimates of depth to hydrogeological basement. These estimates can be further improved using additional information on geological system knowledge and possibly with calibration to field-observed values in a national groundwater model.

KEYWORDS

Hydrogeology, hydraulic properties, hydraulic conductivity, porosity, nationwide, depth to hydrogeological basement.

1.0 INTRODUCTION

The National Institute for Water and Atmospheric Research (NIWA) established, and is leading, the ‘National Hydrology Program’ (NHP) research project. NHP aims to develop hydrological understanding across the New Zealand landscape with a combination of data on surface water, soil, subsurface (geology), and groundwater. The expected project duration of NHP is five years. GNS Science has been sub-contracted to provide subsurface and groundwater information to NIWA, with the long-term aim to enable a better coupling of surface water to groundwater in the National Hydrological Model (TopNet). In addition, Landcare Research has been sub-contracted to provide national-scale information of soil and the vadose zone.

GNS Science will provide data according to the required geospatial framework and at the national scale where possible. Evaluation and testing of the data will take place in case studies.

The proposed work for GNS Science in the 2016/2017 financial year includes the following three major tasks:

- Task 1) set-up and testing of the geospatial framework, including delivery of nationwide data on hydraulic properties of the subsurface, and development of an understanding on how to best deliver those data to NIWA (i.e., with what resolution, in what format, and with what statistics). An evaluation of how those data compare to existing (field or modelled) data was also undertaken.
- Task 2) implementation of a groundwater model at the national scale; and
- Task 3) design and conceptualisation of a national isotopic data layer, including data-acquisition of isotope field samples.

This report describes the activities of Task 1. It provides the first version of national-scale datasets of three geologically derived hydrological parameters as spatial data layers: hydraulic conductivity; effective porosity; and depth to hydrogeological basement. Furthermore, methods to estimate how hydraulic conductivity and effective porosity decrease over depth are presented.

The results are presented at the national scale, including associated documentation and metadata. Initial evaluation of the data is performed in the Southland region.

2.0 REVIEW OF EXISTING WORK

The work presented in this section was largely developed in two national research programmes: the GNS Science-led SMART Aquifer Characterisation (SAC) Programme, funded by the Ministry of Business, Innovation and Employment (MBIE) (2011 to 2017); and the GNS Science Groundwater Resources of New Zealand (GWR) Programme, funded by MBIE CORE funding (now termed SIFF funding) (2011 – 2021). Collectively, the research programmes aimed to improve identification, characterisation, and management of New Zealand's aquifer systems.

2.1 NATIONAL SCALE HYDROGEOLOGICAL MAPPING

Tschritter et al. (2017) reviewed widely-accepted methods that mapped hydrogeological properties of aquifers. Based on that review, a method to map hydrogeological properties for New Zealand using the national geological map series QMAP was developed (Heron 2014). This method was partly based on a study from Gleeson et al. (2011), who compiled 230 hydrogeological units into seven hydro-lithological classes, first for North America and then at the global scale, including estimated values of mean and standard deviation for intrinsic permeability (kappa or κ) for these seven classes (Table 2.1). For the typical New Zealand situation, Tschritter et al. (2017) adjusted some of the values with accordance to national hydrogeological characteristics. For example: κ values for carbonate were lowered, assuming a more conservative 'non-karstic' estimate; κ values for coarse-grained unconsolidated deposits were increased, assuming higher conductivity in gravels and sand; an additional volcanic class was inserted to account for highly permeable volcanics, e.g., ignimbrites. This resulted in ten hydrogeological classes for New Zealand (Table 2.2), with each class having a median and standard deviation estimate for κ.

Table 2.1 Hydro-lithology classes, incorporating mean logarithmic intrinsic permeability κ and its uncertainty σ_κ. (Gleeson et al. 2011).

Hydro-lithology unit	Log κ (m^2)	Log σ_κ (m^2)
Fine-grained siliciclastic sedimentary	-16.5	1.7
Crystalline	-14.1	1.5
Fine-grained unconsolidated sedimentary	-14.0	1.8
Volcanic	-12.5	1.8
Coarse-grained siliciclastic sedimentary	-12.5	0.9
Carbonate	-11.8	1.5
Coarse-grained unconsolidated sedimentary	-10.9	1.2

Table 2.2 Compilation of hydro-lithology units in New Zealand, ranked by median intrinsic permeability (κ) from (Gleeson et al. 2011), after Tschritter et al. (2017).

Hydro-lithology unit	Median κ (log m^2)	Example lithologies
Fine-grained sedimentary	-16.5	Mudstone, claystone
Crystalline and meta-sediments	-15.0	Granite, greywacke
Fine-grained unconsolidated sedimentary	-14.0	Clay, silt
Carbonate	-14.0	Limestone, shell beds
Volcanic	-12.5	Andesite, basalt
Poorly-sorted sedimentary	-12.5	Turbidite, breccia
Poorly-sorted unconsolidated sedimentary	-12.5	Peat, till
Coarse-grained sedimentary	-12.5	Sandstone, greenstone
Volcanic with higher permeability	-11.6	Ignimbrite; scoria
Coarse-grained unconsolidated sedimentary	-10.5	Gravel; sand

2.2 PERMEABILITY AND HYDRAULIC CONDUCTIVITY DEFINITIONS

Permeability is the intrinsic capacity of a porous material to allow fluids to pass through. It is defined in units of area, which relates to the area of open pore space in a cross section that is perpendicular to the direction of flowing fluids in the material (Nolen-Hoeksema 2014). Common units for permeability is m^2 (the SI unit) or darcy (1 darcy is approximately 10^{-12} m^2).

Hydraulic conductivity is related to permeability. It "is a fundamental parameter that governs the flow of liquids such as groundwater through aquifers and other porous media. Specifically, hydraulic conductivity is a quantitative measure of the capacity of a geologic formation or other porous media to transmit a specific fluid. It is determined by the characteristics of both the porous medium and the fluid of interest." (Dielman 2005). In a simplified expression, hydraulic conductivity K of a saturated porous material, in the common unit of m/day, can be expressed as (Freeze and Cherry 1979):

$$K = 86400\frac{\kappa\rho g}{\mu} \qquad \text{(Eq. 2.1)}$$

Where:

- κ is the intrinsic permeability (m^2);
- μ is the dynamic viscosity of freshwater at 13 °C (= 1.2155 × 10^3 kg / m s);
- ρ is the density of fresh water (= 1000 kg/m^3);
- g is the gravitational constant (= 9.80 m/s^2).

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

2.3 THE RELATION BETWEEN PERMEABILITY AND POROSITY

Porosity, with regard to geology, is defined as: "a measure of its capacity to contain or store fluids. Porosity is calculated as the pore volume of the rock divided by its bulk volume" (e.g., Ezekwe 2011);

Pore spaces may be isolated by geological processes (e.g., diagenesis). These isolated pores will not participate in fluid flow through the interconnected pores, leading to two distinct categories of porosity: absolute (φ_{abs}) and effective porosity (φ_e). According to Tiab and Donaldson (2004): "Absolute porosity is the ratio of the total void space in the sample to the bulk volume of that sample, regardless of whether or not those void spaces are interconnected. A rock may have considerable absolute porosity and yet have no fluid conductivity for lack of pore interconnections. Examples of this are lava, pumice stone, and other rocks with vesicular porosity". For these example rocks φ_{abs} might be considerably higher than φ_e. For hydrogeological purposes, φ_e is deemed more important for groundwater flow calculations. In this section, values found for aquifers (and petroleum) reservoirs are reviewed.

Physics-based relations between permeability κ and φ_{abs} exist, e.g., the. Kozeny-Carman or KC model (Kozeny 1927; Carman 1937). However, these relations are often not straightforward for practical use, because they are based on many unknown and inter-related parameters. Simplifications of those models exist, e.g., Costa (2006) described the use of fractal functions resulting in a simplified KC κ-φ relation for volcanic eruptive material and silicic pumices (Figure 2.1). However, KC κ-φ relations do not take into account the effect of faults and fractures, nor the difference between φ_{abs} and φ_e. Therefore, Figure 2.1 does not represent realistic values for φ_e, compared to data from field studies, like for example by Moore et al. (2010), who found a more realistic φ_e = 0.3 for pumice sand.

Ehrenberg and Nadeau (2005) found a relationship between permeability and effective porosity by compiling global data of approximately 30,000 siliclastic and 10,000 carbonate petroleum reservoirs. For the data in shallow reservoirs (< 250 m below ground level (BGL)), they determined the 10-percentile (P10), median (P50), and 90-percentile (P90) porosities for both siliclastic and carbonate reservoirs (Table 2.3), and they defined a relation between permeability and φ_e for petroleum reservoirs (Table 2.4). Substantial work of Tiab and Donaldson (2004) showed compilations of permeability and φ_e for several siliclastic reservoirs (Figure 2.2), and highlighted the importance of grain size on that relation.

The uncertainties associated with permeability and porosity estimates are high. This is mainly due to the heterogeneity of the subsurface. For example, standard deviations of permeability estimates of Gleeson et al. (2011) are of the same (or higher) order of magnitude as the permeability values themselves. Similar for porosity, Ehrenberg and Nadeau (2005) and Ehrenberg et al. (2009) calculated median porosity values and showed the significant range of the distribution of those values.

Moore et al. (2010) derived a range of typical New Zealand aquifer types based on the main lithologies of the host deposits or rocks (Table 2.5). This work included the derivation of average hydraulic properties (i.e., effective porosity and hydraulic conductivity) that are representative for these aquifer types through data collection (literature and regional council datasets) and modelling analyses. For gravel, they found extremely high hydraulic conductivity values (up to more than 5000 m/day), which could only be explained by secondary flow through ‘macro-channels’. The (very low) estimates of φ_e only represented the effects of those macro-channels on bulk porosity; realistically, gravel should be defined with a primary φ_e (e.g., 0.3) and a secondary φ_e, representing the macro-channel flow.

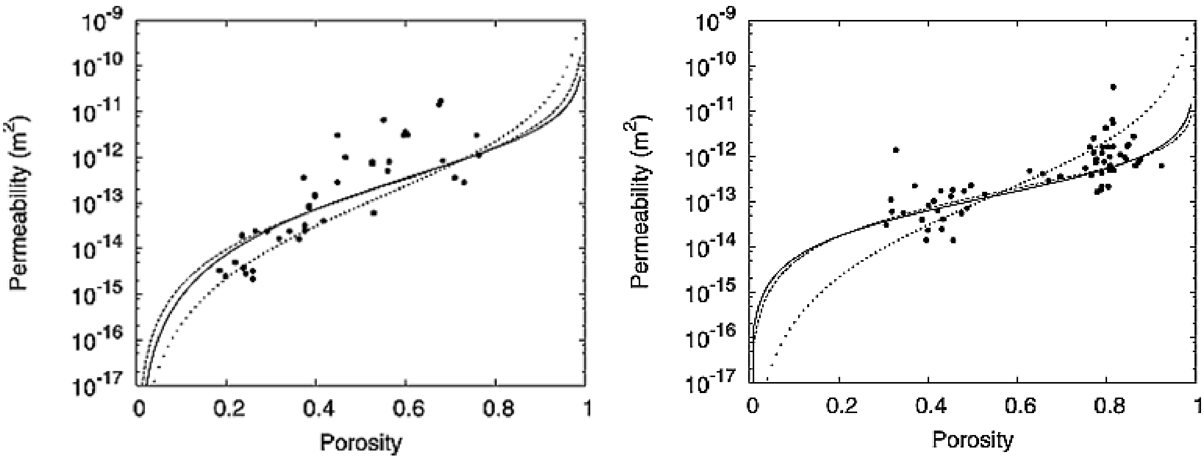

Figure 2.1 Permeability-porosity relation for natural eruptive material (left) and silicic pumices (right). Adapted from Costa (2006).

Table 2.3 Average effective porosity (%) for shallow (< 250 m BGL) siliclastic and carbonate (petroleum) reservoirs according to Ehrenberg and Nadeau (2005).

Percentile	Siliclastic	Carbonate
P10	31	28
P50	24	18
P90	13	6

Table 2.4 Average permeability (as log10 of m^2) vs. average effective porosity according to Ehrenberg and Nadeau (2005). P10, P50 and P90 are the 10^{th}, 50^{th}, and 0^{th} percentile, respectively.

	P10		P50		P90	
Porosity (%)	Siliclastic	Carbonate	Siliclastic	Carbonate	Siliclastic	Carbonate
2.5 – 7.5	-13.0	-13.0	-14.0	-13.8	-15.5	-15.0
7.5 – 12.5	-12.7	-12.8	-13.5	-13.4	-14.7	-14.3
12.5 – 17.5	-12.7	-12.6	-13.4	-13.3	-14.3	-14.2
17.5 – 22.5	-12.3	-12.3	-13.0	-13.2	-13.8	-14.2
22.5 – 27.5	-12.0	-12.2	-12.6	-13.0	-13.3	-14.0
27.5 – 32.5	-11.8	-11.7	-12.2	-12.6	-13.1	-13.7

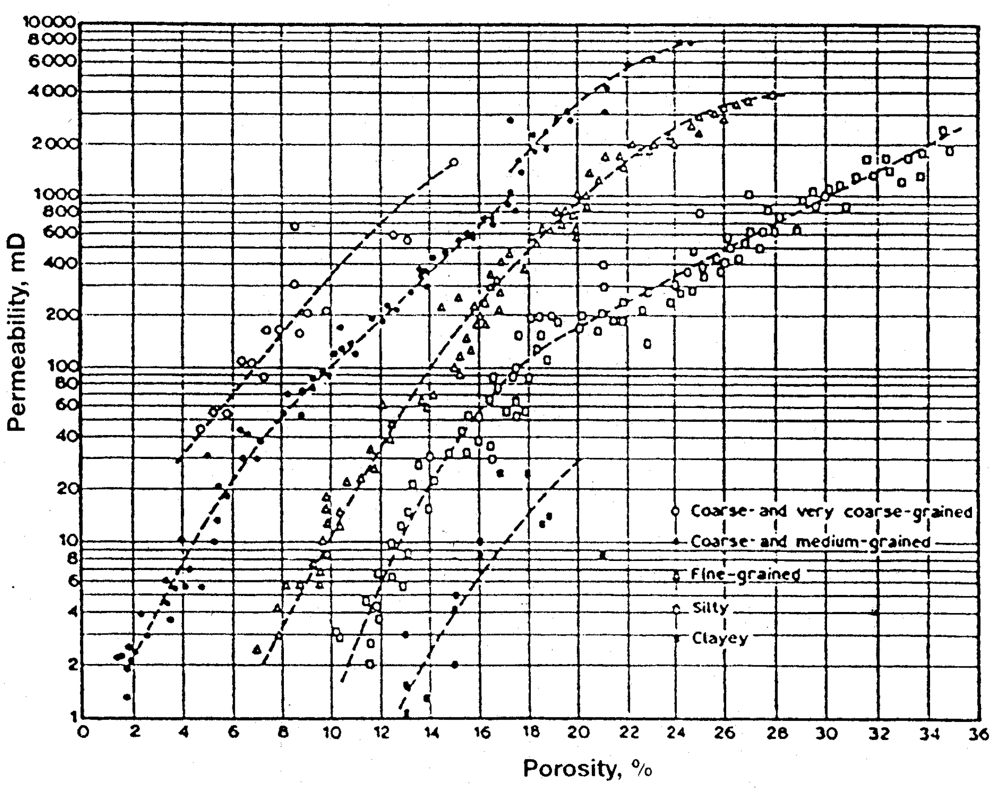

Figure 2.2 Influence of grain size on the relationship between (effective) porosity and permeability (Tiab and Donaldson 2004). 1 milliDarcy (mD) = 9.869233E-16 m^2.

Table 2.5 Average effective porosity and hydraulic conductivity values for common New Zealand aquifer types (Moore et al. 2010).

Aquifer type	Effective porosity, n (unitless)	Hydraulic conductivity, K (m/day)
Alluvial gravel	0.0032	1,300
Alluvial (coarse) sand	0.2	80
Pumice sand	0.3	80
Coastal sand	0.2	10
Sandstone and non-karstic limestone	0.1	0.01
Karstic and fractured rock (e.g., basalt and schist)	0.1 and 1 for matrix and fractures respectively	1000

2.4 DECREASE OF PERMEABILITY AND POROSITY OVER DEPTH

For hydraulic conductivity, an exponential decrease function over depth was applied by Fan et al. (2013), who used it to estimate hydraulic conductivity over depth for the application of basin-wide groundwater models. Fan et al. (2013) defined *K* as:

$$K = K_0 e^{-z/f} \qquad \text{(Eq. 2.2)}$$

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:

$$f = \frac{a}{1+bs}; f \geq f_{\min} \qquad \text{(Eq. 2.3)}$$

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.

The relation of Fan et al. (2013) is partly based on assumed exponential decay of porosity due to diagenesis in older and deeper sediments that are expected to be less conductive and porous than younger formations (Hart and Hammon 2002; Parker and Sellwood 1983), and on a study of Beven and Kirkby (1979), who simplified the basin-wide effects of long-term sedimentation, denudation, and flow in their model and assumed that subsurface flow and porosity decreased exponentially with depth. Similar exponential decrease functions are often used in petrology, amongst which are porosity reduction functions with depth by King Hubbert and Rubey (1959) and Ramm (1992), which were defined as:

$$\phi = \phi_0 e^{-cZ} \qquad \text{(Eq. 2.4)}$$

Where ϕ_0 is the critical (maximum possible) porosity of the deposit, Z is depth (m) and c a constant assumed to be 0.27/km. This equation (shown in blue in Figure 2.3) assumes that mechanical compaction dominates diagenetic reduction of porosity, up to approximately

2.5 km depth and no infill of clay. Ramm and Bjørlykke (1994) included a clay dependence in the following equation (shown in red in Figure 2.3):

$$\phi = \phi_0 e^{-(\alpha + \beta \cdot Cl)Z} \quad \text{(Eq. 2.5)}$$

With α = 0.23, β = 0.27, and *Cl* a clay index that was set to 0.1 for relatively 'clean' sandstone.

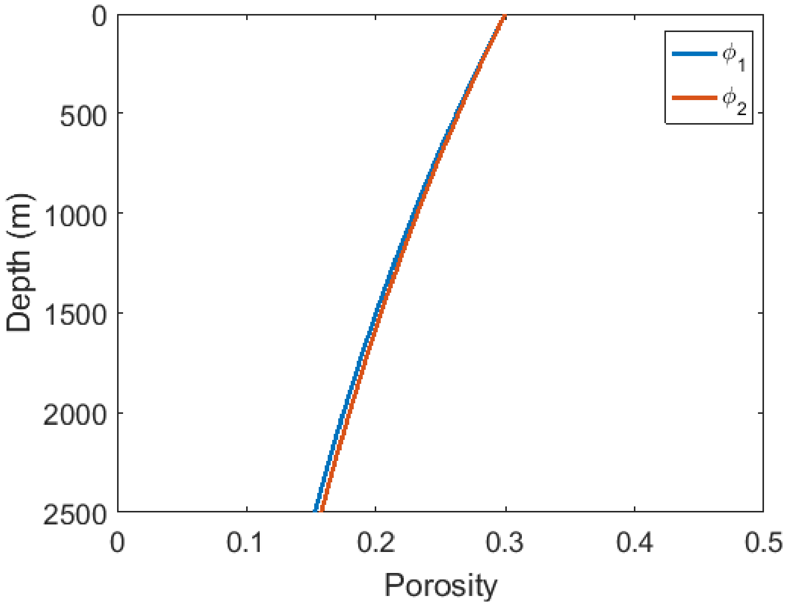

Figure 2.3 Porosity over depth relation for sandstones ϕ_1 (Ramm 1992; Eq. 2.3) and ϕ_2 (Ramm and Bjørlykke 1994; Eq. 2.4).

2.5 DECREASE OF PERMEABILITY AND POROSITY OVER AGE

Tschritter et al. (2017) derived hydrogeological classes based on their median permeability values. They showed that the inclusion of age through a correction factor results in a more realistic distribution of aquifers throughout New Zealand. Their age scale (f_t) was based on an exponential decrease of permeability with age:

$$f_t = e^{-t/\alpha} \quad \text{(Eq. 2.6)}$$

where t is the geological age in millions of year (Ma) and α is a constant that controls the exponential decrease. The value of α was set to 40 (Figure 2.4), so that f_t was close to 1 for Quaternary (i.e., younger than 1.8 Ma) rock types. This relation was arbitrary and not based on actual ground data or existing permeability-age relations.

Ehrenberg et al. (2009) used available data from 36,783 producing petroleum reservoirs for which average porosity, top depth, age, and lithology were available. They found a relation between porosity and age for depth intervals, of which the 0 – 1 km relation is shown in Figure 2.5.

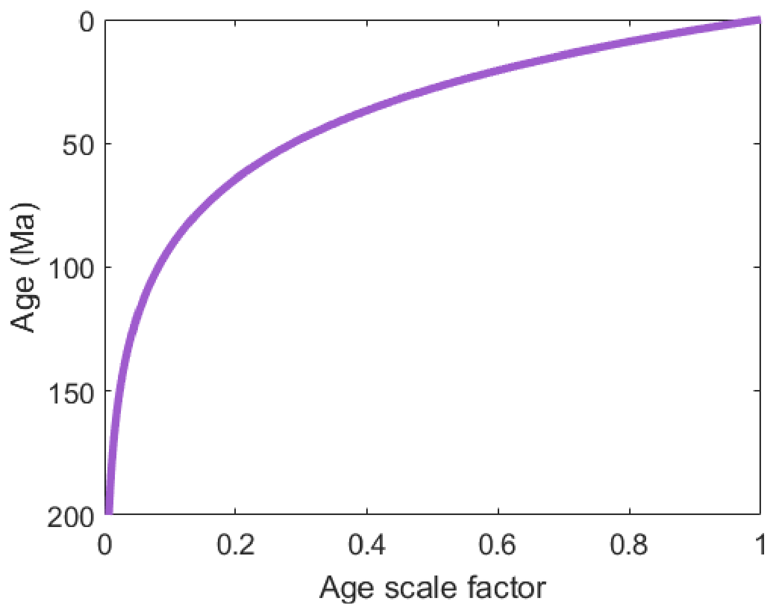

Figure 2.4 Age scale factor for permeability-based hydrogeological classes as used by Tschritter et al. (2017).

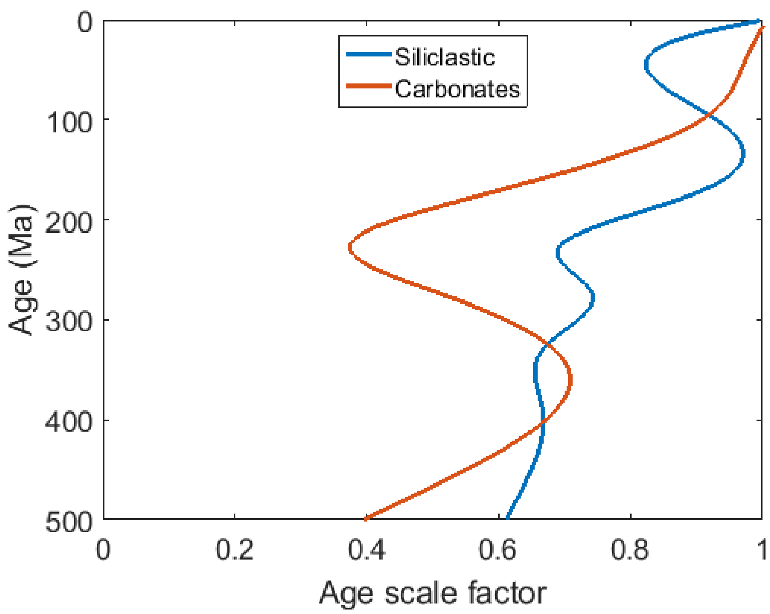

Figure 2.5 Age scale factor for porosity as found by Ehrenberg et al. (2009) for siliclastic and carbonate reservoirs at 1 km depth and deeper.

3.0 METHODOLOGY

3.1 INPUT DATA

3.1.1 Geological Map

The Geology Map of New Zealand 1:250,000 (GMNZ250K) consists of a seamless aggregation of the digital datasets from 21 QMAP sheets in a GIS vector format (Heron 2014). In the QMAP series, polygons of geological units at or just beneath the ground surface that are at least 5 – 10 m thick, or particularly geologically significant, were compiled (Rattenbury and Heron 1997). The positional accuracy of the boundaries between QMAP polygons is assumed to be no better than +/- 250 m (Rattenbury and Heron 1997). Therefore, the GMNZ250K comprises the most accurate and up-to-date geological maps at a regional scale in New Zealand.

The GMNZ250K vector data is accompanied by an attribute table, which contains information about each geological unit polygon, including the name of the mapped unit, its lithological composition, and measured or inferred ages.

The following GMNZ250K attributes were used in this approach:

- 'MAIN_ROCK': one keyword for the main rock type;
- 'ABS_MIN': minimum age of deposit (Ma);
- 'ABS_MAX': maximum age of deposit (Ma); and
- 'SUB_ROCKS': multiple keywords for secondary rock type(s).

3.1.2 Digital Network Polygons

The Digital Network (DN) of NIWA defines rivers and streams based on a digital elevation model (DEM) and subsequent hierarchy of river tributaries using the Strahler (1957) stream order. The finest spatial definition, taking into account all tributaries, is called the Strahler1 polygon definition.

GMNZ250K polygons are much larger than DN Strahler1 polygons of catchment areas. For example, the region of Southland has 36 times less GMNZ250K polygons than DN Strahler1 catchment area polygons (Table 3.1). For the same region, the mean polygon areas are 4.6×10^6 m^2 and 1.27×10^5 m^2 for GMNZ250K and DN Strahler1 polygons, respectively. That is approximately equal to 73 versus 2 pixels of 250 m x 250 m, respectively.

Table 3.1 General statistics of QMAP and DN Strahler1 polygons.

	GMNZ250K Southland	DN Strahler1 catchment
Number of polygons	6,791	247,026
Mean area	4,620,034 m^2	127,457 m^2
Median area	715,698 m^2	78,080 m^2
Min area	5.6 m^2	64 m^2
Max area	519,173,036 m^2	19,211,904 m^2

3.1.3 National Digital Terrain Model

A national digital terrain model (DTM) of 15 m was provided by NIWA. This DTM is based on the free 15 m DTM, 'NZSoSDEM', v1.0 (Columbus et al. 2011). Regional subsets were downloaded separately and used to create a mosaic by NIWA (Shankar 2017).

3.2 ESTIMATION OF NEAR-SURFACE HYDRAULIC CONDUCTIVITY

Permeability values for all GMNZ250K polygons were derived through a similar approach as developed by Tschritter et al. (2017) (Section 2.5). Firstly, each 'MAIN_ROCK' and 'SUB-ROCKS' (Table 2.2) attribute of each GMNZ250K polygon were matched to a permeability value. This was completed using a look-up table approach, i.e., by linking attribute keywords of each GMNZ250K polygon to a 'dictionary' of permeability values for each rock type (Tschritter et al. 2017). The combination of the main and secondary rock type was taken as a weighted mean, where 'MAIN_ROCK' was weighted twice as high as the mean of the 'SUB_ROCKS'. This resulted in estimates of median permeability for each polygon.

Saturated hydraulic conductivity K (m/day) was estimated from the median permeability following Eq. 2.1.

3.3 SCALING OF NEAR-SURFACE POROSITY AND HYDRAULIC CONDUCTIVITY WITH AGE

Near-surface porosity was scaled with an age scale factor after Ehrenberg et al. (2009), (Section 2.5). The empirical values of Figure 2.5 were fitted using a smoothing spline function. That function was used on the GMNZ250K information of geological age. Separate values were taken for carbonates and siliclastic rock types. Crystalline rock types and meta-sediments were not scaled.

Following the approach by Tschritter et al. (2017) (Section 2.5), hydraulic conductivity was scaled with age using Eq. 2.6, where the age was estimated as the mean of minimum and maximum age (GMNZ250K ABS_MIN and ABS_MAX, respectively) of the deposit. However, the age scaling factor α of 40 of Tschritter et al. (2017) was arbitrary and non-proven. In this project, the factor α was changed to 600 since that allowed scaling of similar magnitude for both permeability and porosity to be undertaken (Figure 3.1).

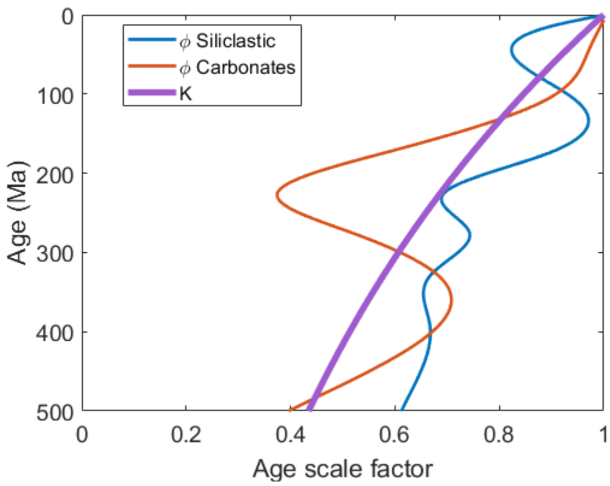

Figure 3.1 Age scaling for porosity (φ) and hydraulic conductivity (K) used in this research. An age scaling factor α (Eq. 2.6) of 600 was used.

3.4 ESTIMATION OF THE DECREASE OF HYDRAULIC CONDUCTIVITY AND POROSITY OVER DEPTH

The estimation of hydraulic conductivity over depth was calculated using Eqs. 2.2 and 2.3, using the NZSoSDEM v1 DTM, resampled to 250 m. It was assumed that the first 10 m subsurface had a constant value, equal to the near-surface hydraulic conductivity K_0. Depth to hydrogeological basement was set at the depth where hydraulic conductivity was lower than 1 cm / day. It is recommended that the estimation of porosity over depth to be performed using Eq. 2.5.

4.0 RESULTS

4.1 HYDRAULIC CONDUCTIVITY

Hydraulic conductivity K, in m/day, for New Zealand is shown in Figure 4.1. The distribution of K-values at the ground surface is as expected. For example, high K-values are found in coastal plains such as Canterbury Plains, Canterbury, and Waimea Plains, Nelson. Medium K-values dominate in the central volcanic region of the North Island. In comparison, low K-values are observed in areas dominated by basement rock and Tertiary deposits including Fiordland and the Raukumara Peninsula.

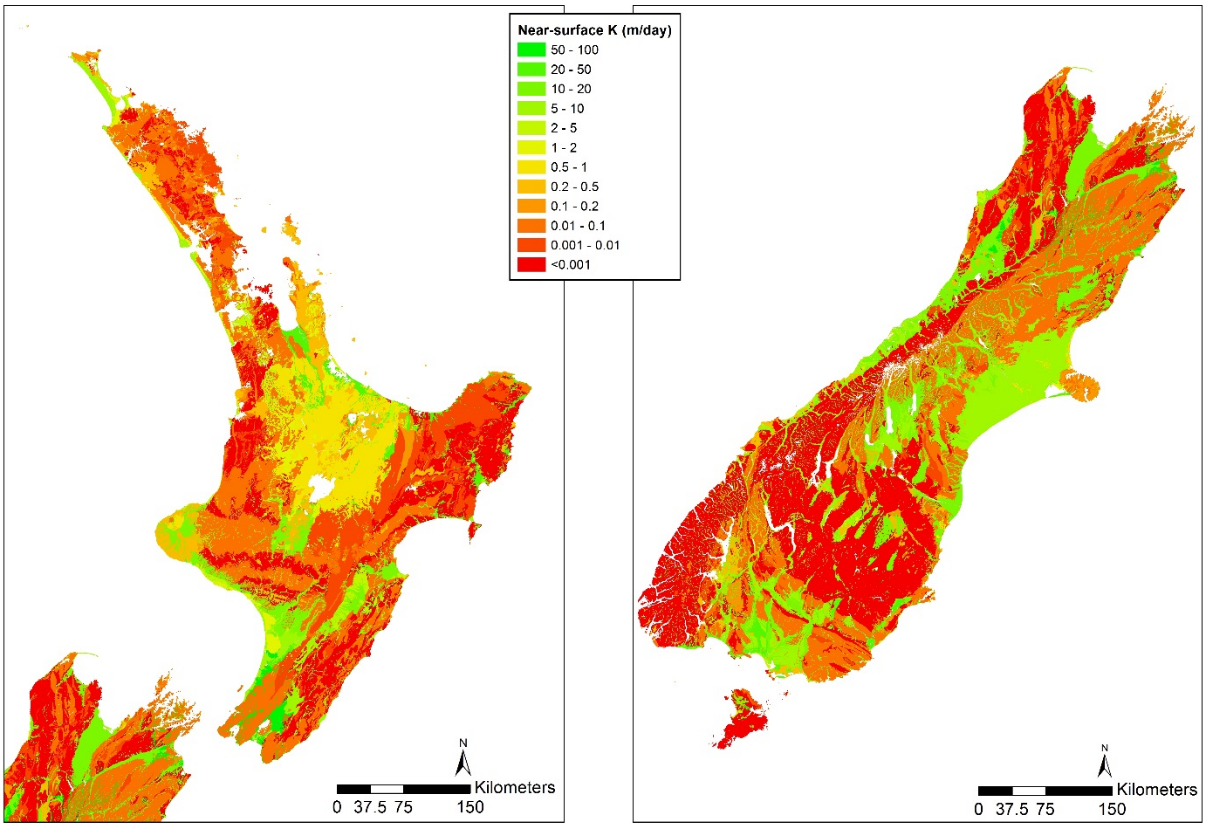

Figure 4.1 Near-surface hydraulic conductivity estimates for New Zealand that were developed in this study.

4.2 EFFECTIVE POROSITY

Effective porosity, represented as a fraction, is shown for New Zealand in Figure 4.2. Effective porosity is high in areas dominated by Quaternary sediments (e.g., Canterbury Plains) and volcanics (e.g., central volcanic region of the North Island). These values are in agreement with expected values for these deposits. Both Tertiary deposits and basement rock show a range of medium to low effective porosities.

4.3 DEPTH TO HYDROGEOLOGICAL BASEMENT

Depth to hydrogeological basement (in m BGL), are shown for New Zealand in Figure 4.3. The calculated depth to hydrogeological basement provides a general idea of the potential basement depth. It is accurate in areas where basement is at the ground surface, and seems adequate in some coastal plains like the Hauraki and Canterbury Plains. However, in other coastal plains areas, like the Waimea Plains near Nelson, the calculated basement depth appears too shallow. In addition, the basement depth is depicted as very shallow in the central volcanic region of the North Island where basement rocks are located at depths of several kilometres (Leonard et al. 2010; Milicich 2013; Downs et al. 2014).

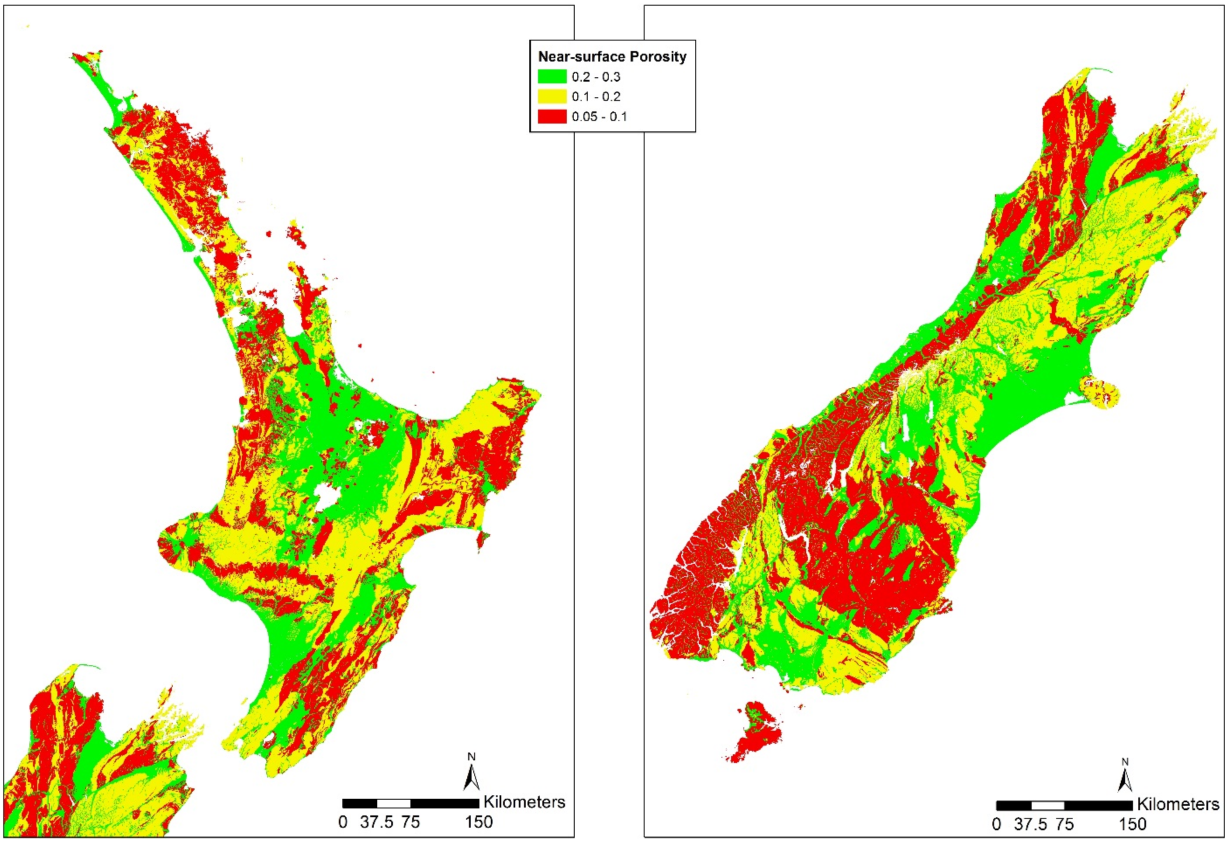

Figure 4.2 Estimates of effective porosity for New Zealand, that were developed in this study.

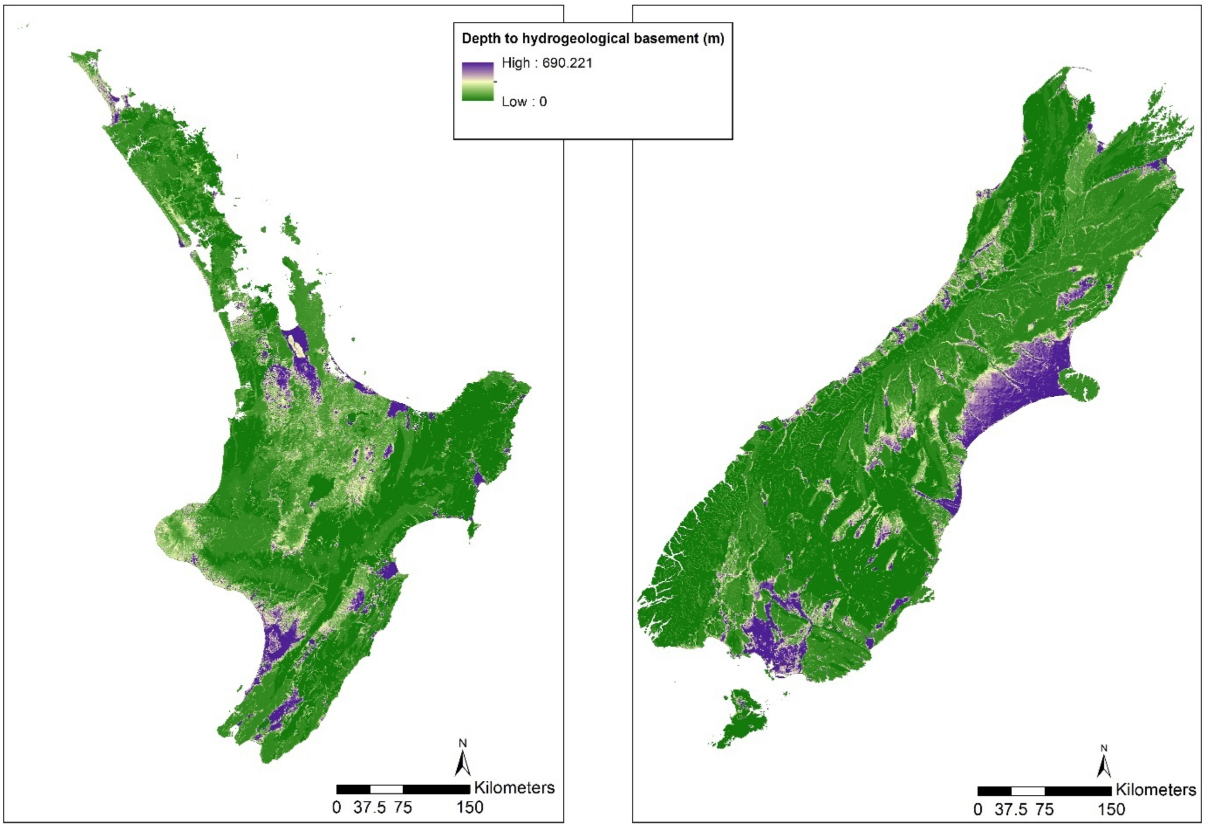

Figure 4.3 Estimated depth to hydrogeological basement (m BGL) as developed in this study.

4.4 DATA FORMATS

Data of K_0 and ϕ_0 are in three formats and are all at the national scale, including:

1. a shapefile file containing K_0 and ϕ_0 for each GMNZ250K polygon;
2. a GeoTIFF file of gridded K_0 and ϕ_0 (250 m x 250 m resolution raster).

Data of depth to hydrogeological basement was delivered in two formats, including:

3. a GeoTIFF of gridded data (250 m x 250 m resolution raster);
4. a NetCDF of gridded data (250 m x 250 m resolution raster).

All data was also delivered in an ASCII format, including:

5. an ASCII-XYZ file with grid cell information of K_0, ϕ_0, depth to hydrogeological basement, terrain slope, and elevation, based on the 250 x 250 m raster.

Data is accompanied by text files, which contain information of Eqs. 2.2 and 2.3 for the decrease of K over depth, and Eq. 2.5 for the decrease of ϕ over depth.

5.0 EVALUATION SOUTHLAND CASE STUDY

Initial evaluation of the national data of hydraulic conductivity and depth to hydrogeological basement was performed in the Southland region.

A geological model was developed by GNS Science (Tschritter et al. 2016) for Environment Southland (ES). The ES geological model covers a large part of the Southland region (i.e., four freshwater management units: Aparima, Mataura, Oreti, and Waiau; Figure 5.1). The ES geological model was subsequently used as the basis for developing a regional groundwater flow model. Due to the availability of seismic reflection data, differentiation between older geological units was achieved in the ES geological model. This level of detail was not required for the regional flow model. Therefore, the ES geological model units were grouped into regional flow model units (Rawlinson et al. 2017). The hydrogeological basement flow model unit of Rawlinson et al. (2017) was compared to the depth of the hydrogeological basement derived within this study. Rawlinson et al. (2017) also compiled field observations of K derived from borehole aquifer tests (locations shown in Figure 5.1); these are called 'field-observed K' onwards. Field observed K values were used to evaluate the K estimates of this study (from here on referred to as NHP K values).

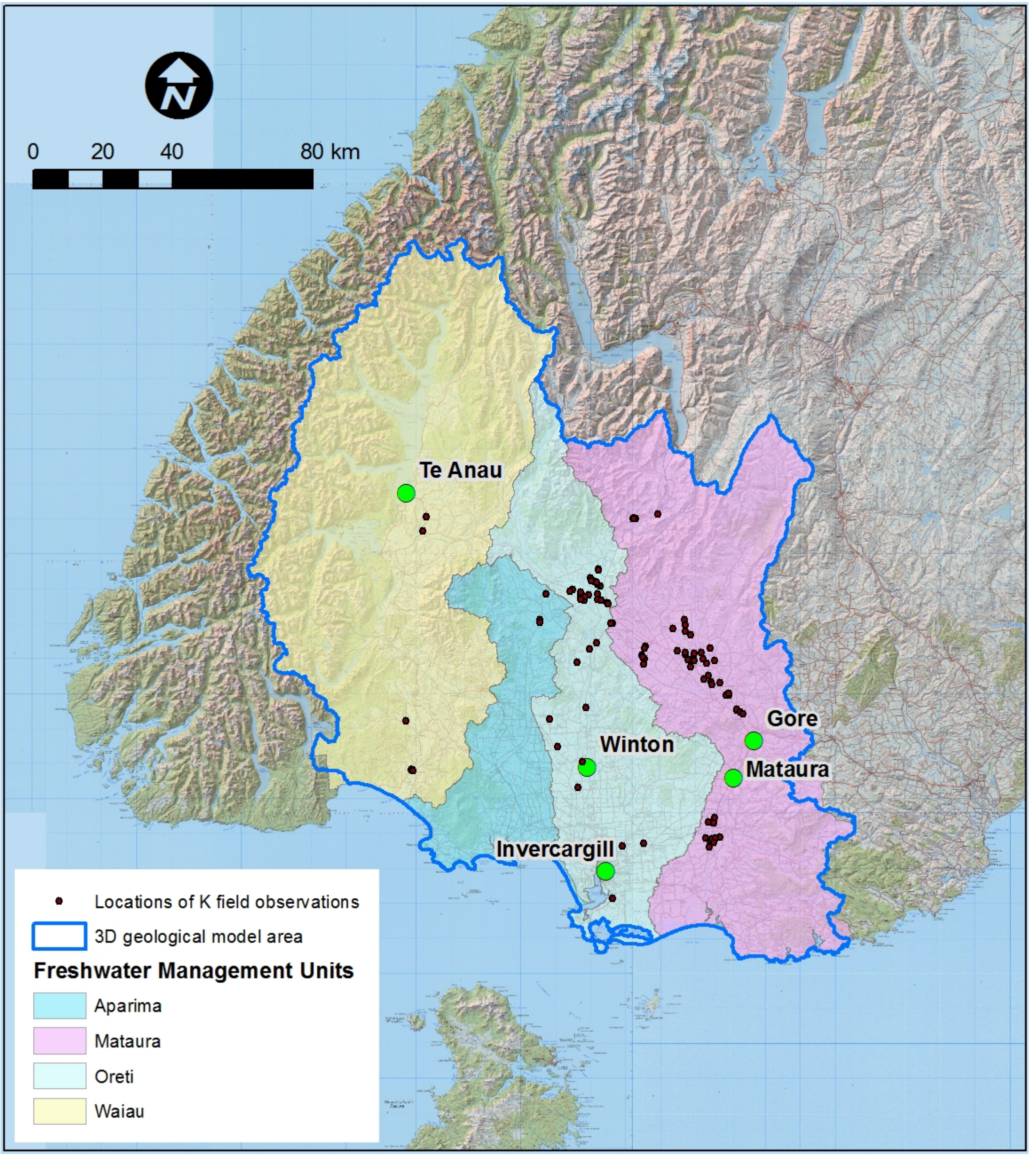

Figure 5.1 Southland geological model boundary, including four main freshwater management units and locations of field observations from aquifer testing.

5.1 EVALUATION OF NHP-K ESTIMATES AGAINST FIELD-OBSERVED DATA

Field-observed K values are generally much higher than the values for NHP K values used in this study (Figure 5.2). Field-observed values have a K that is generally between 10 and 2,000 m/day, whereas the look-up table values in this study are in between 8 and 22 m/day. This large discrepancy requires investigation and is included as a recommendation for further work in this report (Section 6).

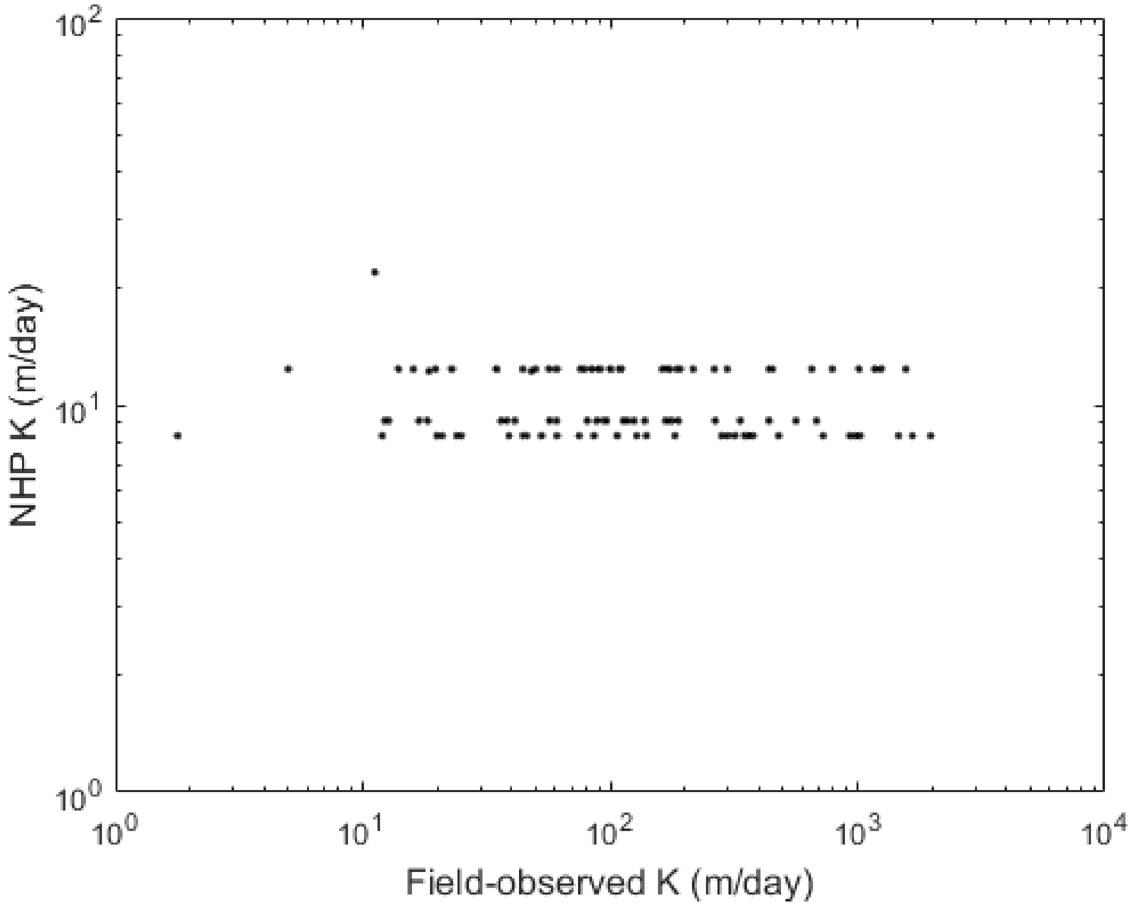

Figure 5.2 Hydraulic conductivity from field observed data (x-axis) plotted against K values used in this study (NHP K, y-axis).

5.2 EVALUATION OF DEPTHS TO HYDROGEOLOGICAL BASEMENT ESTIMATES AGAINST 3D MODEL

The depth to hydrogeological basement of this study (Figure 5.3, left) shows the same spatial pattern to the hydrogeological basement flow model unit of Rawlinson et al. (2017) (Figure 5.3, right) and identifies deep aquifers in the same areas. However, maximum depths to hydrogeological basement from this study have a maximum of approximately 600 m (Figure 5.4, left), whereas the 3D model of Rawlinson et al. (2017) interprets deeper hydrogeological basement, up to 2,500 m (Figure 5.4, right).

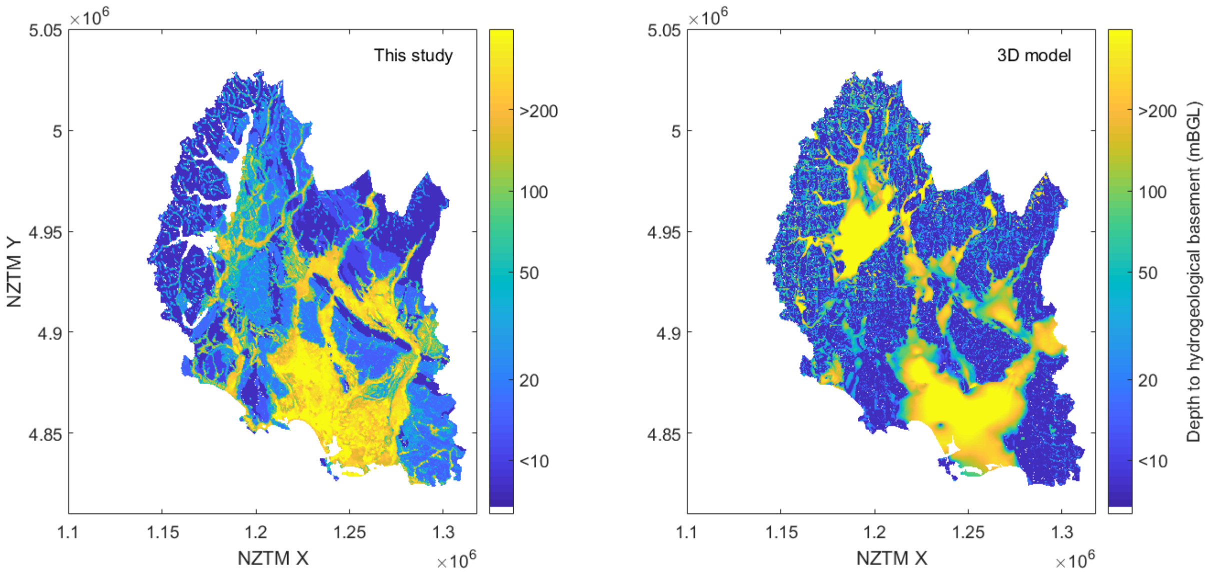

Figure 5.3 Comparison between depths to hydrogeological basement from this study (left) and from the recently developed 3D groundwater flow model input components by Rawlinson et al. (2017) (right).

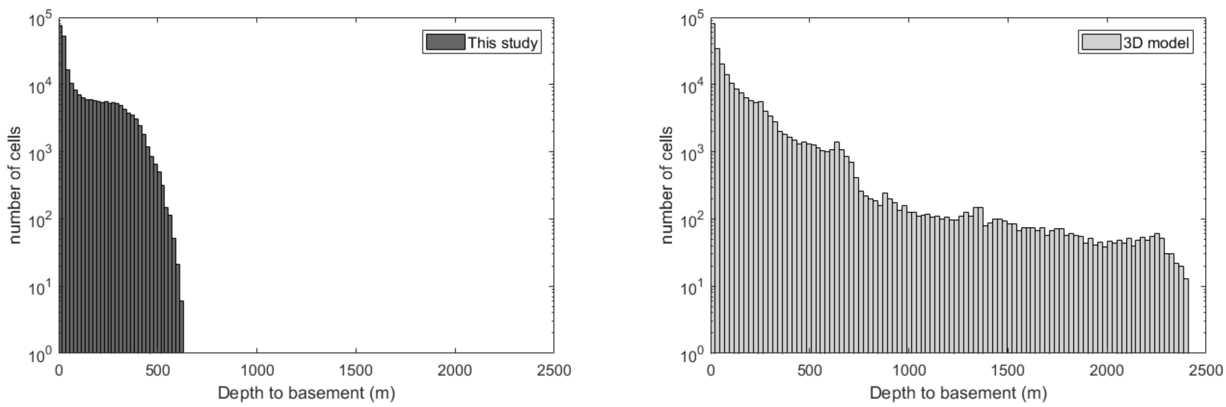

Figure 5.4 Histogram of depths to hydrogeological basement from this study (left) and from the recently developed 3D groundwater flow model by Rawlinson et al. (2017) (right).

6.0 DISCUSSION AND RECOMMENDATIONS

6.1 IMPROVEMENTS TO ESTIMATION OF K

The national map of K generally shows high values in areas that correspond to the locations of known aquifers. This result indicates that the approach undertaken in this study is a suitable basis for the further estimation of nationwide hydraulic conductivity. However, field-observed K-values from boreholes in Southland were several orders of magnitude higher than the current NHP K-values. High values of field-observed K generally occurred in clean gravels and sands, and are supported by other studies such as Moore et al. (2010), see Table 2.5.

NHP K-value estimation thus needs to be improved for gravel and sand, at least in in coastal and alluvial plains in Southland, and probably in other regions. Three options for improvement of K-values are: higher look-up table permeability values; inclusion of uncertainty in k-values; and calibration to a groundwater flow model. These options, including limitations, are discussed below.

The current NHP K-values were estimated from median permeability values for coarse unconsolidated sediments using a look-up table (Table 2.2). Higher look-up table permeability values for sand and gravel could lead to a better match of NHP K-values against field observations. Higher K-values would also lead to higher estimates of the depth to hydrogeological basement, which would better match the 3D groundwater model depths (Figure 5.4). However, testing higher NHP K-values would also need to be evaluated against data from other New Zealand regions, in order to preserve the generic national character of the NHP estimates.

The look-up table values of Gleeson et al. (2011) and Tschritter et al. (2017) represented the median value of permeability, including the uncertainty. It is well-known that permeability (and therefore K-values) can be heterogenic, and can vary by orders of magnitude over relatively short distances. Future research should define how the uncertainty of permeability can be included into nationwide estimation of K-values.

Westerhoff (2017) used the uncertainty estimate of permeability and calibrated the hydraulic conductivity with a national groundwater model, using ground observations of groundwater level. They showed that K-values in the Canterbury Plains are probably much higher than the median value used in this research (i.e., they can be > 700 m/day). Similar local calibrations have not been implemented in the estimations of this report, as no groundwater flow model was used to calibrate values. It is recommended that calibration of hydraulic conductivity be completed using the same method employed in groundwater flow models, for example, the national water table model of Westerhoff (2017), should be included in future developments.

6.2 DEPTH TO HYDROGEOLOGICAL BASEMENT

For this study, the estimates of depth to hydrogeological basement of Rawlinson et al. (2017) were used in the evaluation. Although these depths are estimated through geological interpretation and can contain considerable uncertainty, they are the only known large-scale and comprehensive dataset of its kind in Southland. They are therefore considered the benchmark.

The depths to hydrogeological basement identified in this project are coincident with deep aquifers identified by Rawlinson et al. (2017), and show the same spatial patterns. However, total depths to hydrogeological basement identified in this project were lower than those estimated by Rawlinson et al. (2017). In order to better fit the benchmark results, three options for improvements are discussed below, including: increase in near-surface K-values; adjustment of model equations of decrease over depth; and the change in the cut-off threshold for K-values of the basement.

It was previously identified in Section 6.1 that an increase in permeability of gravel and sand will likely improve estimates of near-surface K-values. This increased K-value will lead to a larger estimate of depth to basement. This is because the starting value (i.e., the near-surface K), will then be higher, and thus the threshold value of 1 cm day will be deeper.

The model equations for the decrease of K over depth were calculated using Eqs. 2.2 and 2.3. Constants *a* and *b* in Eq. 2.3 were chosen after a study of Fan and Miguez-Macho (2010), who used a terrain model of 200 m in the Amazon Basin. In the present study, a 15 m DTM of New Zealand was resampled to 250 m. The variation of depths occurring due to the different spatial resolution of the terrain model, including possible variation in constants *a* and *b*, should be further quantified.

The hydrogeological basement was defined to be at locations where K < 1 cm/day. That threshold was chosen as an arbitrary value and should also be assessed in future research.

6.3 EVALUATION AGAINST HYDROGEOLOGICAL SYSTEMS

All nationwide estimates in this report are currently based on a generic method that uses GMNZ250K attributes of rock type and age (Sections 3.2 – 3.4) and one (nationwide) method of the behaviour of hydraulic properties over depth. Inclusion of the origin of rock types by their geological system, could possibly improve this method. For example, volcanic deposits will likely have a different decrease of K-value over depth than alluvial deposits; and multiple sea-level changes in past geological climates have created different depositional environments, and therefore aquifers, in near-coastal areas compared to foothills. Geological system knowledge is well-known for most of New Zealand, and it is recommended that this knowledge be included for improved estimates of nationwide hydraulic properties.

6.4 INTER-RELATION OF POROSITY, PERMEABILITY, AGE AND DEPTH

The relationship between permeability and porosity has been identified in many studies. Logically, permeability and porosity relations with depth and age are inter-related. However, in this project, the decrease of permeability and porosity over depth and over age was treated separately. In order to estimate the decrease of K over depth, Eqs. 2.2 and 2.3 were used, as they are known to work well from groundwater flow related research. To estimate the decrease of porosity over depth, Eqs. 2.4 and 2.5 can be used, as forthcoming from literature research, mostly relating to petrology. Furthermore, age relations of permeability (Eq. 2.6) and porosity (Figure 2.5) are presented as unrelated, while realistically they are not.

Future research should take into account depth and age corrections that are consistent in the four-dimensional space of permeability, porosity, depth, and age. Advanced curve fitting or machine learning techniques could possibly assist in this 4D quantification.

7.0 CONCLUSION

In this report, the set-up and testing of the NHP geospatial framework by GNS Science has been presented. This included the development of the first version of national-scale datasets of three geologically derived hydrological parameters as spatial data layers, including: hydraulic conductivity K; effective porosity φ_e; and the behaviour of these parameters over depth.

At the national scale, the resulting datasets of K and φ_e follow the expected patterns (e.g., high values in the alluvial plains, medium values in the central volcanic region, and low values in basement and Tertiary rocks). Calculated depths to hydrogeological basement are accurate in areas where basement is at the ground surface and seem adequate in some coastal plains like the Hauraki and Canterbury Plains. However, in other areas, i.e., coastal plains and central volcanic region, the depths appear to be too shallow.

Evaluation of K-values and depth to hydrogeological basement in Southland showed similar patterns to earlier research results (i.e., groundwater flow model units based on a 3D geological model); they have the same spatial pattern and can even help improve the spatial detail. However, both K-values and depth to hydrogeological basement in this study were generally too low in Southland, and thus possibly elsewhere. In particular, field-observed K-values were magnitudes higher than the K-values as estimated in this study, and depths to hydrogeological basement in this study were shallower than earlier estimates of the groundwater flow model units by Rawlinson et al. (2017).

The nationwide and regional findings lead to the conclusion that the methods used for this nationwide approach are warranted, but adjustments to input parameters are recommended. More specifically, future research should include testing of increased K-values for gravels and sand, to test if final K-value estimates compare better to nationwide field-observed K, and other modelled depths to hydrogeological basement. These estimates can be further improved using additional information on geological system knowledge. Additional recommendations include: calibration to field-observed K-values in a national groundwater model; testing of the model equations of decrease over depth; and better inter-relation of permeability, porosity, age, and depth.

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