Aquifer classification and mapping at the national scale - Phase 1: Identification of hydrogeological units

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CONTENTS

FIGURES

TABLES

APPENDICES

APPENDIX FIGURES

APPENDIX TABLES

ABSTRACT

Mapping and classification of aquifers in a consistent manner across New Zealand has been identified by GNS Science as an essential initiative to improve the sustainable management of the nation's groundwater resources. Achieving this initiative is a recent objective of GNS Science's SSIF (Strategic Science Investment Fund) funded "Groundwater Resources of New Zealand" (GWR) Programme.

The objective of this study was to use the quarter-million scale geological map (QMAP) to identify a nationally consistent method to map hydrogeological units and potential aquifers. The resultant maps are the first phase of the aquifer delineation and characterisation that is planned within the GWR programme. The maps are intended to be used to define representative aquifer systems in New Zealand and to identify, characterise and assess groundwater resources with regard to their quality, quantity and flow pathways. The maps will enhance national monitoring and reporting of groundwater resources; and be a simple, relatable and informative dataset to enhance awareness and understanding of groundwater and associated environmental issues.

The first national aquifer map for New Zealand was published in 2001. A partially-updated national aquifer map was re-issued in 2015. However, with increasing demand on groundwater in New Zealand, more consistent aquifer characterisation and mapping techniques are needed to improve understanding and appreciation of the resource.

The QMAP, which is available as a seamless nationwide GIS dataset, includes comprehensive information about each surficially mapped geological unit as data attributes. As such, it provides a consistent, nationwide base map for aquifer mapping purposes. Two approaches (descriptive and numerical) were investigated using the QMAP attributes 'MAIN_ROCK', 'SUB_ROCKS' and age. The numerical solution provided a more suitable approach as it allowed the combination of different attributes, including a weighting component based on rock type predominance.

Three maps were developed in this study. The first map showed hydro-lithological units that were based solely on the QMAP 'MAIN_ROCK' attribute and were grouped and ranked by assumed intrinsic permeabilities. However, the restriction to just the 'MAIN_ROCK' attribute yielded misleading results, e.g., areas with higher permeability classes were associated with basement rocks. Therefore, the second map, representing hydrogeological units, was based on the QMAP 'MAIN_ROCK', 'SUB_ROCKS' and age attributes. The hydrogeological units were ranked by assumed permeabilities of the rock types in each unit. This map showed that areas with known higher or lower permeabilities (e.g., Quaternary sediments and basement rocks, respectively) show expected higher or lower ranked hydrogeological units. The third map estimates aquifer potential as a result of the aggregation of the hydrogeological units of the second map. The resulting maps are currently available upon request, and it is intended to make them available through a web application in the future. The next phase of work will enhance the maps by incorporation of additional data sets, such as measured hydraulic properties and rainfall recharge maps.

KEYWORDS

Aquifer, hydrogeology, QMAP, hydro-lithology, national mapping, GWR, groundwater

DISCLAIMER

These maps comprise preliminary datasets that have been prepared by GNS Science. In compiling the datasets, inferences and assumptions have been made about hydrogeological behaviour at a regional scale (1:250,000). At the time of publishing, no validations using actual observations have been made (e.g., yield, aquifer properties, etc.), and the maps do not include any information regarding the sustainability of a potential aquifer, e.g., recharge/discharge areas, water balance, etc. Experience and an appreciation of the limitations of the information is needed by persons using the dataset as an element in their decision making over access to and use of groundwater resources. In addition, the datasets should not be used for detailed studies at map scales of less than the one they were prepared for.

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1.0 INTRODUCTION

Groundwater is an important for water source for New Zealand's domestic, industrial and agricultural sectors, and maintaining its quality and quantity is hugely significant for the environment and ecology, including associated industries such as tourism (White, 2001). Groundwater demand has grown significantly in recent years, with weekly allocations (based on information from 14 councils) increasing by 94% from 1999 to 2010 (Rajanayaka *et al.*, 2010). The assessments of land use on water quality, including groundwater, have become more important as communities aim to protect, or restore, water bodies including lakes and streams (e.g., Lake Taupo; Environment Court, 2011). As the use of groundwater increases, it is necessary to improve the understanding and sustainable management of New Zealand's groundwater resources. GNS Science is the lead Crown Research Institute in several research areas, including groundwater processes and quality. As such, one of the outcomes of GNS Science's research work, as defined in its Statement of Core Purpose, is to "Improve the sustainable management of and increase economic returns from groundwater resources". Therefore, it is pertinent that GNS Science undertake research and development to provide a nationally-consistent approach to mapping and classification of aquifers.

Groundwater occurs in aquifers, which consist of saturated, porous or fractured, permeable stratum or group of strata. Within New Zealand, groundwater resources are managed at regional and local scales by regional councils and unitary authorities by zones. These zones are defined by regional authorities and may correspond to aquifer boundaries, groundwater management areas or freshwater management units that reflect hydrological and management parameters like roads and property or catchment boundaries (Lovett and Cameron, 2015). A side-effect of this regionally-variable approach to management zones is that hydrogeological data sets associated with aquifers are characterised by differing formats, data availability and data quality specific to individual organisations. As a result, research endeavours and nation-wide overviews of the groundwater state and trends, e.g., the Water Physical Stock Account (Statistics New Zealand, 2010), are hindered. A consistent approach to delineate or classify aquifers is needed to better understand and monitor New Zealand's groundwater resource on a national basis. The release of the New Zealand 1:250,000 Geological Map (QMAP) as a seamless GIS database in 2014 (Heron, 2014) provides a dataset suitable to use as the basis for a nationwide consistent classification and mapping of aquifer potential at or near the surface.

This report describes the derivation of surface hydro-lithological and hydrogeological units for the whole of New Zealand, from the digital QMAP data, and production of a national aquifer potential map. The datasets produced by this project will subsequently be used as the basis for developing a methodology for aquifer mapping at the national scales. This work was undertaken under GNS Science's Groundwater Resources of New Zealand (GWR) Strategic Science Investment Fund (SSIF) research programme.

1.1 GROUNDWATER RESOURCES OF NEW ZEALAND RESEARCH PROGRAMME (GWR)

This report is part of the Groundwater Resources of New Zealand (GWR) research programme (2011 – 2021), which aims to identify and characterise New Zealand's aquifer systems and improve the sustainable management of groundwater resources. To address these objectives, GWR investigates the quality, quantity and flow dynamics of groundwater resources at the national scale and is organised into the following six components: hydrogeology, water flux, National Groundwater Quality Monitoring Programme (NGMP), biogeochemical tracers, resource pressures, and stakeholder engagement (Figure 1.1).

The hydrogeology component, which began in the 2015 – 2016 financial year, has been divided into three main tasks: data connection, national classification and mapping, and geospatial analysis. Each of these tasks is split into phases. This report describes the first phase of the national classification and mapping task (Figure 1.1).

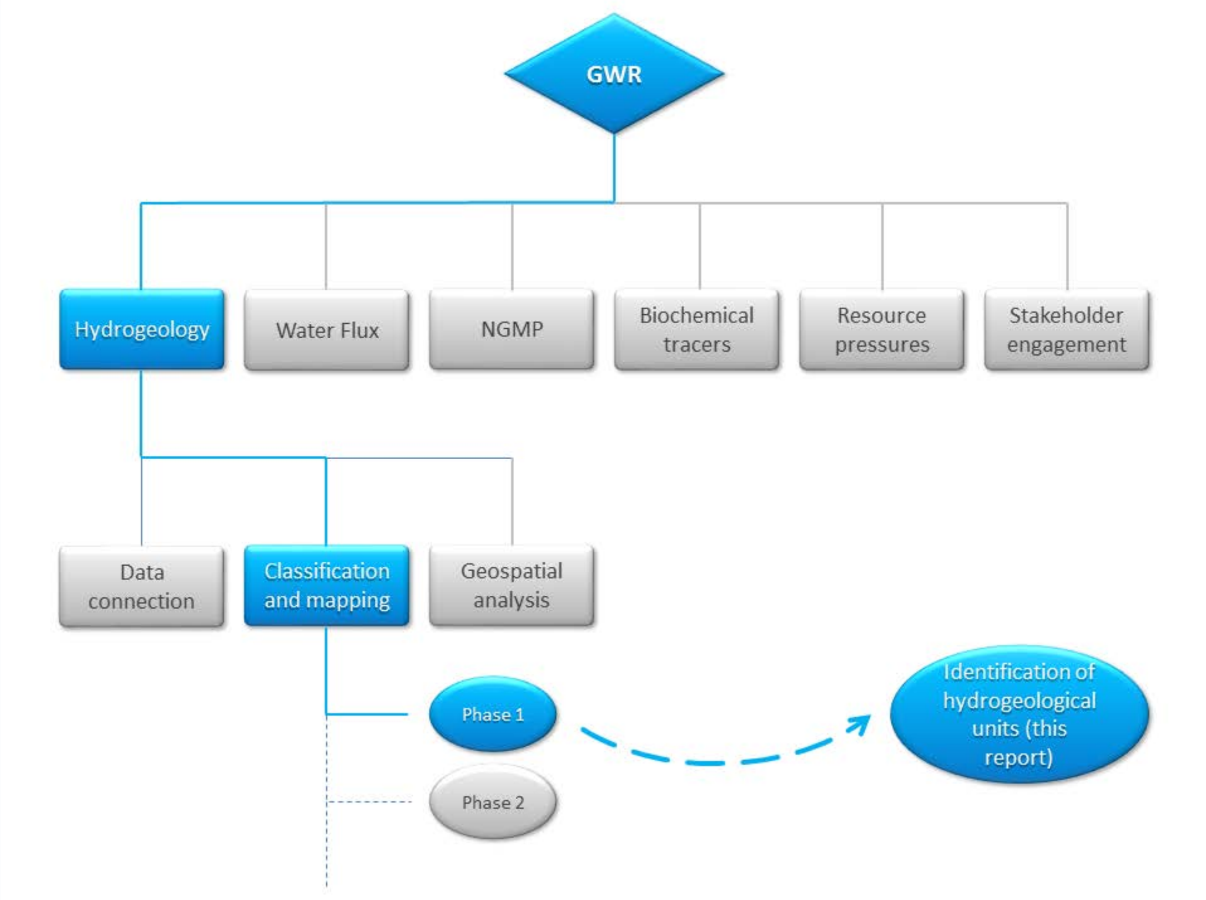

Figure 1.1 The structure of the GWR research programme and the setting of the work presented in this report.

1.2 GWR: CLASSIFICATION AND MAPPING

The GWR Classification and Mapping task aims to develop, over the next ten years, a national spatial database of New Zealand's aquifers, in which each aquifer will be characterised by a set of attributes that are derived from nation-wide aquifer definitions, assessments and classifications. These attributes will include, for example, hydraulic properties that have been measured or inferred for the aquifer. Other relevant information will also be developed or linked, such as depth to water table maps to enable temporal volume estimations, and water quality sites monitored as part of the NGMP, respectively. Another part of this task will focus on the development of indices for ascertaining risk and value, such as surface water connectivity, and state of information/uncertainty. In later stages of this project, links will be developed with known 3D geological models, flow models, and other databases, to improve interpretability, centralisation and management of hydrogeological-relevant information.

It is intended that this work will provide the basis for further resource assessment and will be utilised for a number of purposes that will support the sustainable management of New Zealand's groundwater resources. These purposes include: the capability to monitor national groundwater volumes at a robust enough level to detect major trends; and to enable knowledge from well-studied catchments to support under-studied catchments.

1.3 PHASE 1 AND THE AIM OF THIS PROJECT

The first phase of the Classification and Mapping task (this report) is to define two-dimensional hydro-lithological (based on lithological composition) and hydrogeological units (based on lithological composition and age) in New Zealand, using the digital version of the QMAP, and to derive a nation-wide map of aquifer potential from these units.

The next phase will use the hydrogeological unit and aquifer potential data sets as the basis for developing an updated aquifer map for New Zealand that uses a nation-wide consistent mapping methodology. Both pieces of work will then be used to describe and assign a suite of representative New Zealand aquifer systems, and rank these systems in order of importance (for prioritising system characterisation activities).

2.0 LITERATURE REVIEW

2.1 AQUIFER MAPPING WORK IN NEW ZEALAND

2.1.1 Aquifer boundaries defined in 2001 and their depositional environments

White (2001) developed a map of aquifer surficial boundaries at an approximately 1:5 million scale and a high-level classification of New Zealand's aquifers. The aquifer boundaries were derived from regional authorities, if this information was available, and geographical and geological boundaries.

The aquifer maps developed by White (2001) have provided useful aquifer boundary information for New Zealand over more than a decade. However, since their publication, some regional authorities have updated and refined several aquifer boundaries. In addition, the 1:250,000 geological map for New Zealand (QMAP) was completed and published as a seamless digital map in 2014 (Heron, 2014), providing an updated, higher-resolution, national geological map for the identification of potential aquifer boundaries from surface geology. Recent work on compiling national and regional aquifer boundaries (Moreau and Bekele, 2015; Section 2.1.3) resulted in updated boundaries based on the maps by White (2001), Figure 2.1.

2.1.2 Groundwater-related boundaries compiled in 2015

As part of the GWR research programme, Lovett and Cameron (2015) developed a map of groundwater-related boundaries (i.e., management zones, catchment zones and aquifer boundaries) for New Zealand (Figure 2.1). To do this, the authors contacted each of the 15 regional authorities in New Zealand and requested the most current aquifer boundaries available. If no aquifer boundaries were available, alternative boundaries (e.g., groundwater management zones) were requested. In response to this request, six regional authorities provided aquifer boundaries, and a further six regions provided groundwater management zones or similar boundaries. Three councils supplied no boundaries.

The compilation of Lovett and Cameron (2015) provided an up-to-date assessment of the state of knowledge of aquifer boundaries at the regional authority level. This compilation highlights a significant lack of consistency. Although some of the aquifer boundaries were, to some extent, based on QMAP, the methodologies of how each boundary (aquifer or groundwater management zone or other) was derived varied significantly region by region, as there is no standard methodology or process currently in use within New Zealand (Lovett and Cameron, 2015).

2.1.3 Aquifer boundaries updated in 2015

Prior to 2015, the Water Physical Stock Account (WPSA) was an overview of New Zealand's freshwater resources that was published every five years (Statistics New Zealand, 2010). Groundwater volume was one of the components of the WPSA, and previous groundwater stock accounts were calculated by White and Reeves (2002), White (2005), and Moreau-Fournier and Cameron (2011), based on the aquifer boundaries defined by White (2001). In 2015, while compiling the most recent national groundwater stock account, Moreau and Bekele (2015) refined some of the aquifer boundaries from White (2001) using datasets assembled by Lovett and Cameron (2015) (Section 2.1.2) and additional aquifer boundaries provided by Hawke's Bay Regional Council. The resulting boundaries comprise the most up-to-date map of aquifer boundaries for New Zealand (Figure 2.2). However, no systematic approach was used to delineate these boundaries. Under the recent Environmental Reporting Act (Parliament of New Zealand, 2015), the Ministry for the Environment (MfE) is now required to publish a synthesis report on the state of environment every three years, which includes freshwater quantity. Individual domains included in that report (air, atmosphere and climate, land, fresh and marine waters) are to be reported at six-monthly interval within that time period.

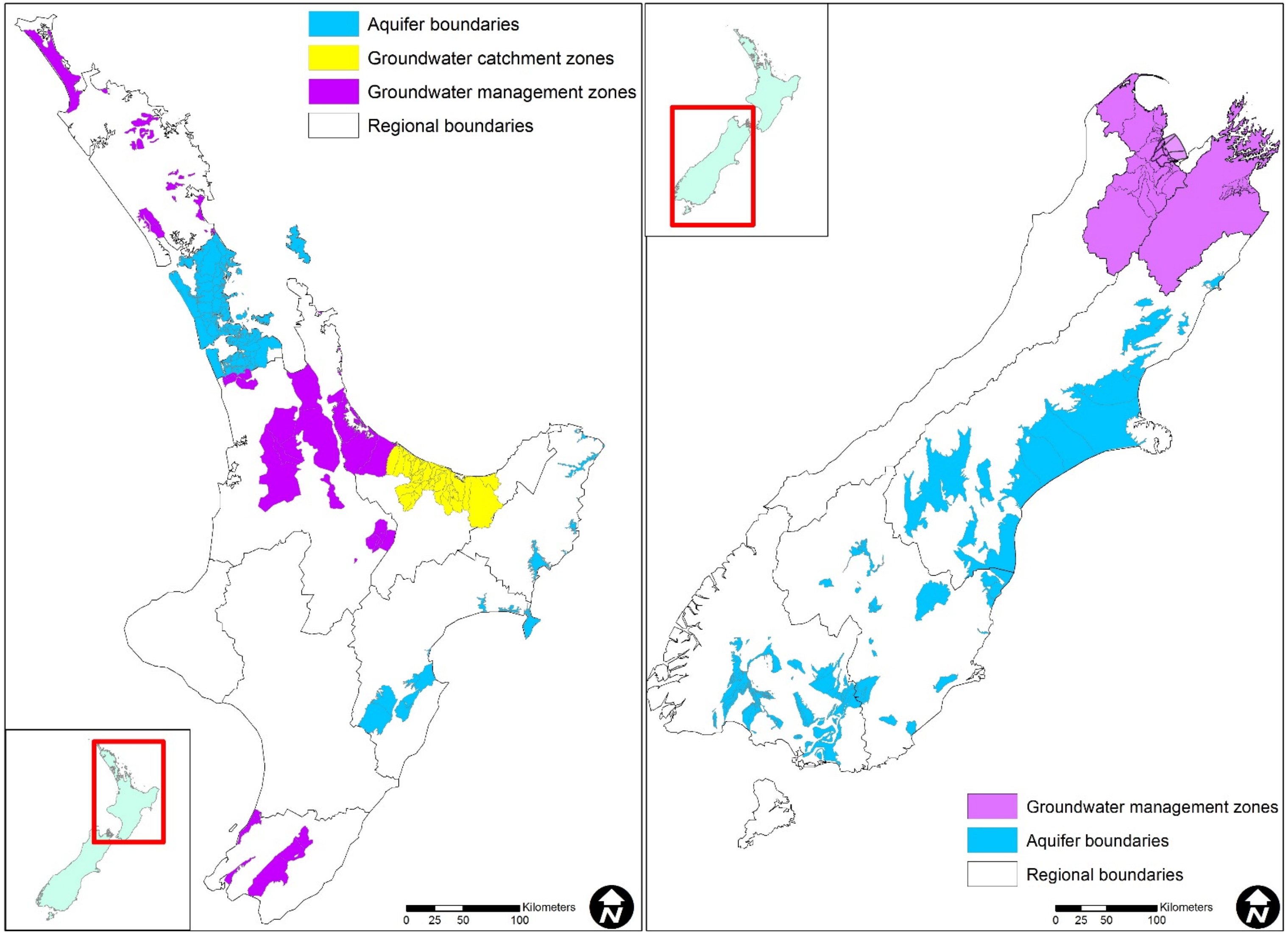

Figure 2.1 Maps of the North Island and South Island showing groundwater management zones, catchment zones, and aquifer boundaries provided by the respective regional authority (Lovett and Cameron, 2015).

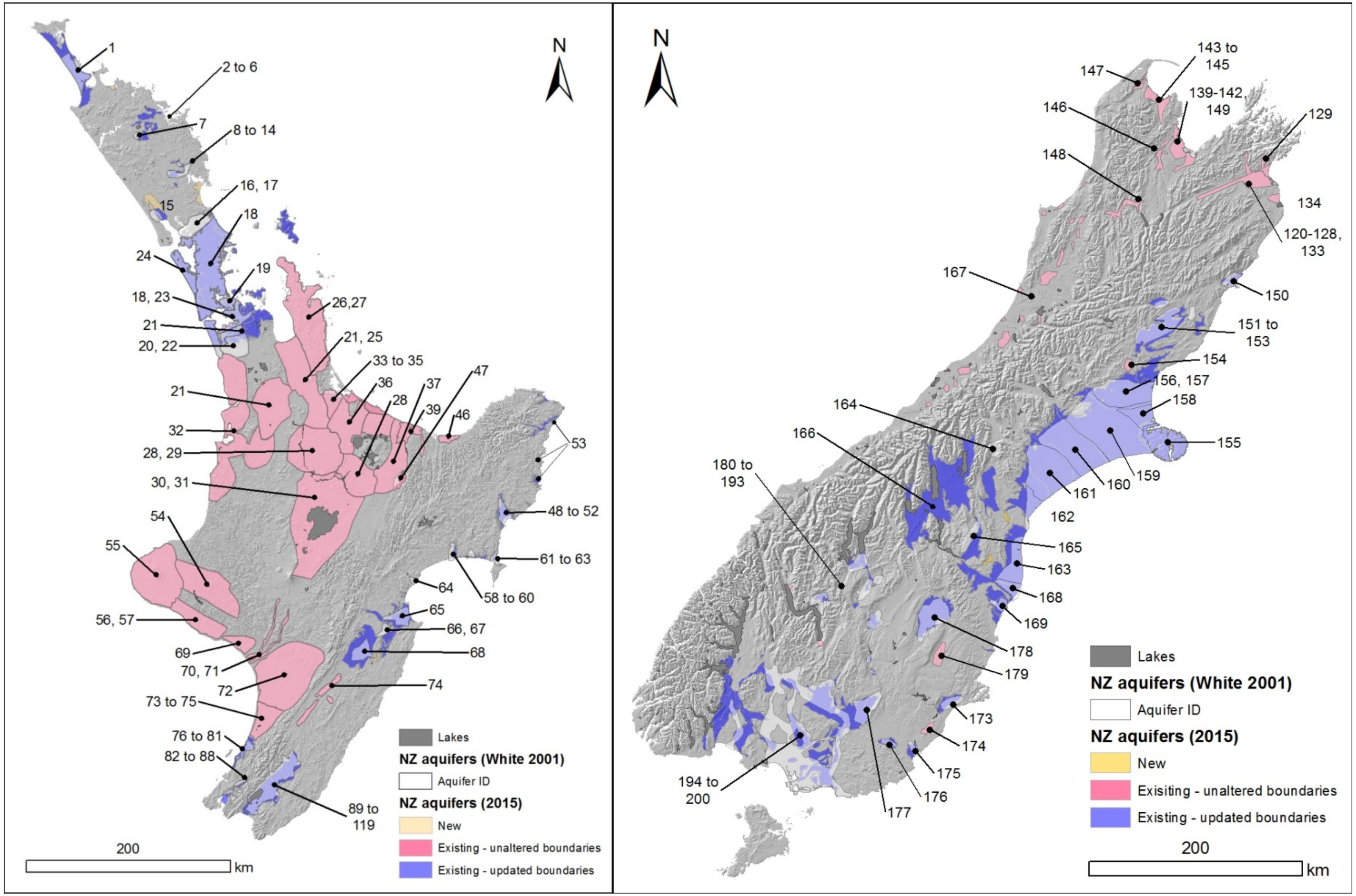

Figure 2.2 Location of North Island and South Island aquifers, Moreau and Bekele (2015), modified from White (2001), with aquifer IDs listed in White (2001). Note that some of the polygons present more than one aquifer listed by White (2001), e.g., “73 to 75” and “143 to 145”.

2.2 INTERNATIONAL AQUIFER MAPPING AND HYDROGEOLOGICAL UNIT CLASSIFICATION METHODS

This section describes a selection of approaches to aquifer mapping and classification, relevant to this project.

2.2.1 Hydrogeological map guidelines by Struckmeier and Margat (1995)

Struckmeier and Margat (1995) published guidelines for the development of hydrogeological maps and the associated map legends. The development of these guidelines was supported by the International Association of Hydrogeologists, and they have been used internationally in hydrogeological classification and mapping projects, including the 2013 Southern African Development Community (SADC) Hydrogeological Map and Atlas (HGM) (Section 2.2.2).

Struckmeier and Margat (1995) define a hydrogeological map as the visual representation of a "huge variety of earth and water-related parameters". As such, hydrogeological maps describe a three-dimensional, complex system that is time-dependent and should include a vertical component as well as a reference date. Hydrogeological mapping is defined as "all programmes and techniques that are suitable to collect, document, retrieve, plot, interpret and represent hydrogeological information in graphical form". Hydrogeological maps are generally designed for two different objectives: as visual result of a hydrogeological mapping project or as "thematic synthesis of existing data, maps and reports". Therefore, visual representations and formats of hydrogeological maps may differ hugely depending on the purpose of the maps. Aside of the main map, hydrogeological maps may include thematic inset maps and cross-sections as well as a standard legend and additional explanations. Hydrogeological maps are based on, and may include information from, topographical, geological and hydrological maps. Topographical maps provide, for example, surface contours and locations of springs, bogs and rivers. Geological maps allow "the conversion of litho-stratigraphical units into hydro-lithological units" and identify potential structural controls on groundwater flow. Hydrological maps provide for example rainfall and evapotranspiration patterns or spring flow rates. Other parameters that may be represented in hydrogeological maps are for example, depth to groundwater, and yield of aquifer productivity.

Struckmeier and Margat's (1995) methodology describing the conversion of litho-stratigraphical units into hydro-lithological units is of particular interest for this GWR project and will be summarised in the following text. This conversion is often used when only limited actual hydrogeological field data is available. To convert lithological (or litho-stratigraphic) facies on a geological map into hydro-lithological classes, facies are first grouped into permeable and impermeable, then permeable facies are grouped into unconsolidated and consolidated and on the expected connectivity and flow mechanism of the rocks as follow:

- permeable
  - consolidated
    - continuous
      - porous
      - fissured
      - karstified
  - unconsolidated
    - discontinuous

        - porous
        - fissured
        - karstified

- impermeable
    - unconsolidated
    - consolidated

Examples of hydro-lithological classes include:

- permeable - gravel, sand and volcanic scoria (porous);
- permeable - sandstone, marlstone, basalt (frequently fissured); or
- permeable - limestone, dolomite, gypsum (frequently karstified).

Hydraulic conductivity (K) values, which are linked to lithological rock type, may be used to further refine this classification. It is noted that K-values in the same rock type can vary over short distances. Ranges of published mean K values for a selection of common rock types were provided in their description (Figure 2.3). It is possible to use transmissivity values calculated from K values as an alternative to K values, however, this requires knowledge of the saturated thickness and as a result the uncertainty involved with the hydrogeological mapping may increase.

Using the K values, the guidelines classify and rank hydrogeological units into the following groups:

- permeable formations ($K > 10^{-6}$ m/s) forming important aquifers of comparatively high permeability and productivity;
- semi-permeable formations (K between 10^{-6} and 10^{-9} m/s) forming less productive aquifers, which are subdivided into:
    - Relatively thick aquitards
    - Resistant layers in multi-aquifer systems
- impermeable formations (aquicludes) ($K < 10^{-9}$ m/s)

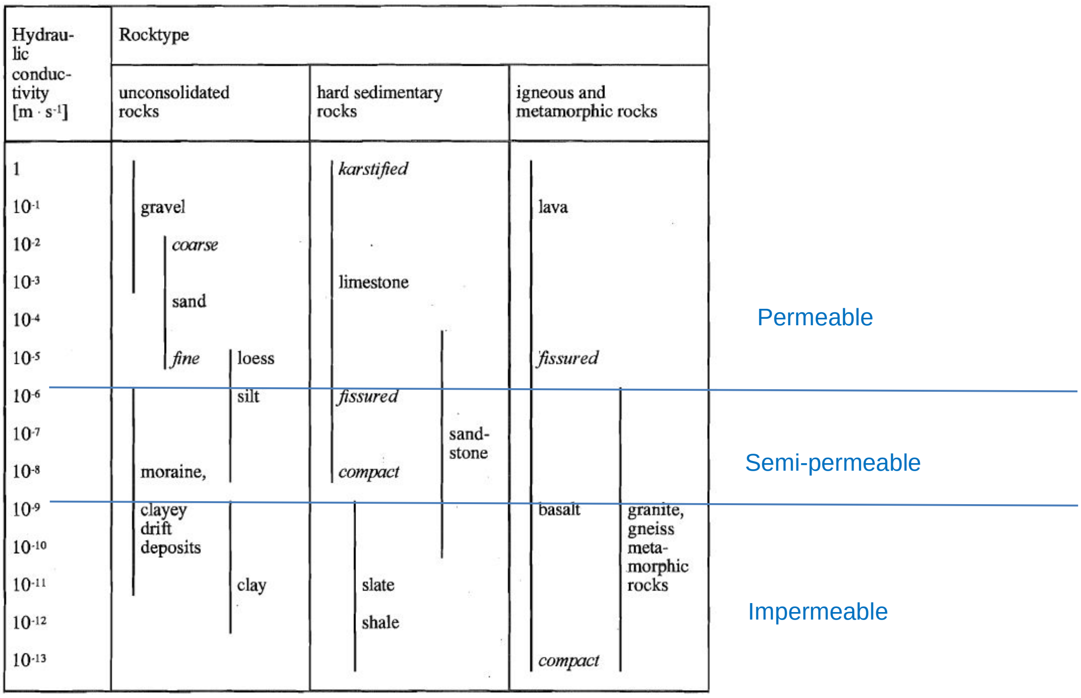

Figure 2.3 Ranges of permeability values of different lithological rock types (Struckmeier and Margat, 1995).

2.2.2 South African Development Community

Hydro-lithological mapping at a scale of 1:2.5 million has been conducted as part of the Southern African Development Community (SADC) Hydrogeological Map and Atlas (HGM) project (Ramoeli *et al.*, 2010, Pietersen *et al.*, 2013). The hydro-lithological map was converted from the SADC geological map using the Struckmeier and Margat classification method (1995) as a guideline (Section 2.2.1). Approximately 730 lithological units from the SADC geological map were grouped into 29 lithological classes based on their hydrogeological characteristics and age. Older, metamorphosed units were separated from younger, less deformed and metamorphosed units. These 29 lithological classes were then grouped into 12 classes to form a hydro-lithological base map (Figure 2.4) following consultation with the SADC countries:

- unconsolidated sands and gravel;
- clay, clayey loam, mud, silt and marl;
- unconsolidated to consolidated sand, gravel, arenites, locally calcrete, bioclastites;
- sandstone;
- shale, mudstone and siltstone;
- interlayered shales and sandstone;
- tillite and diamictite;
- dolomite and limestone;
- volcanic rocks, extrusive;
- intrusive dykes and sills;
- paragneiss, quartzite, schist, phyllite, amphibolite; and
- granite, syenite, grabbro, gneiss and migmatites.

Any explicit geochronological split was removed during this classification. However, there is still a clear chronological distinction, which is implied by the occurrence of certain lithologies at specific stratigraphic ages. For example, unconsolidated sediments are of Quaternary age, and granites, paragneiss and quartzites are of Precambrian age.

The lithologies were then grouped into high permeability and low-permeability deposits, based on expert judgement. The high permeability deposits were further categorised into the following aquifer types:

- Unconsolidated intergranular aquifers (gravel, sand etc);
- Fissured aquifers (sandstone, basalt, etc.);
- Karst aquifers (limestone, dolomite, etc.); and
- Layered aquifer.

The layered aquifer type incorporates an additional three-dimensional component. The term 'layered aquifer' is used here to describe aquifer systems that consist of a number of unconfined aquifers and underlying confined aquifers.

Low-permeability deposits generally correspond to basement rocks, which in Southern Africa, cover 55% of the land surface (Ramoeli *et al.,* 2010). These are characterised by poor fracture connectivity and low storage capacity that can vary considerably over local scales. The aquifer types are then classified into eight aquifer productivity classes (Table 2.1), Figure 2.5. This classification was based on aquifer properties and sustainability (local recharge), Figure 2.6, Table 2.2.

Table 2.1 Aquifer productivity classes and aquifer type classification for the SADC-HGM (Ramoeli *et al.,* 2010).

Productivity Class / **Aquifer Type**	1. High productivity	2. Moderate productivity	3. General low productivity but locally moderate productivity	4. Generally low productivity
A. Unconsolidated Intergranular aquifers	A1	A2	X	X
A. Fissured aquifers	B1	B2	X	X
B. Karst aquifers	C1	C2	X	X
C. Low permeability formations	X	X	D1	D2
	(striped pattern)	Denotes an extensive aquifer overlain by cover		

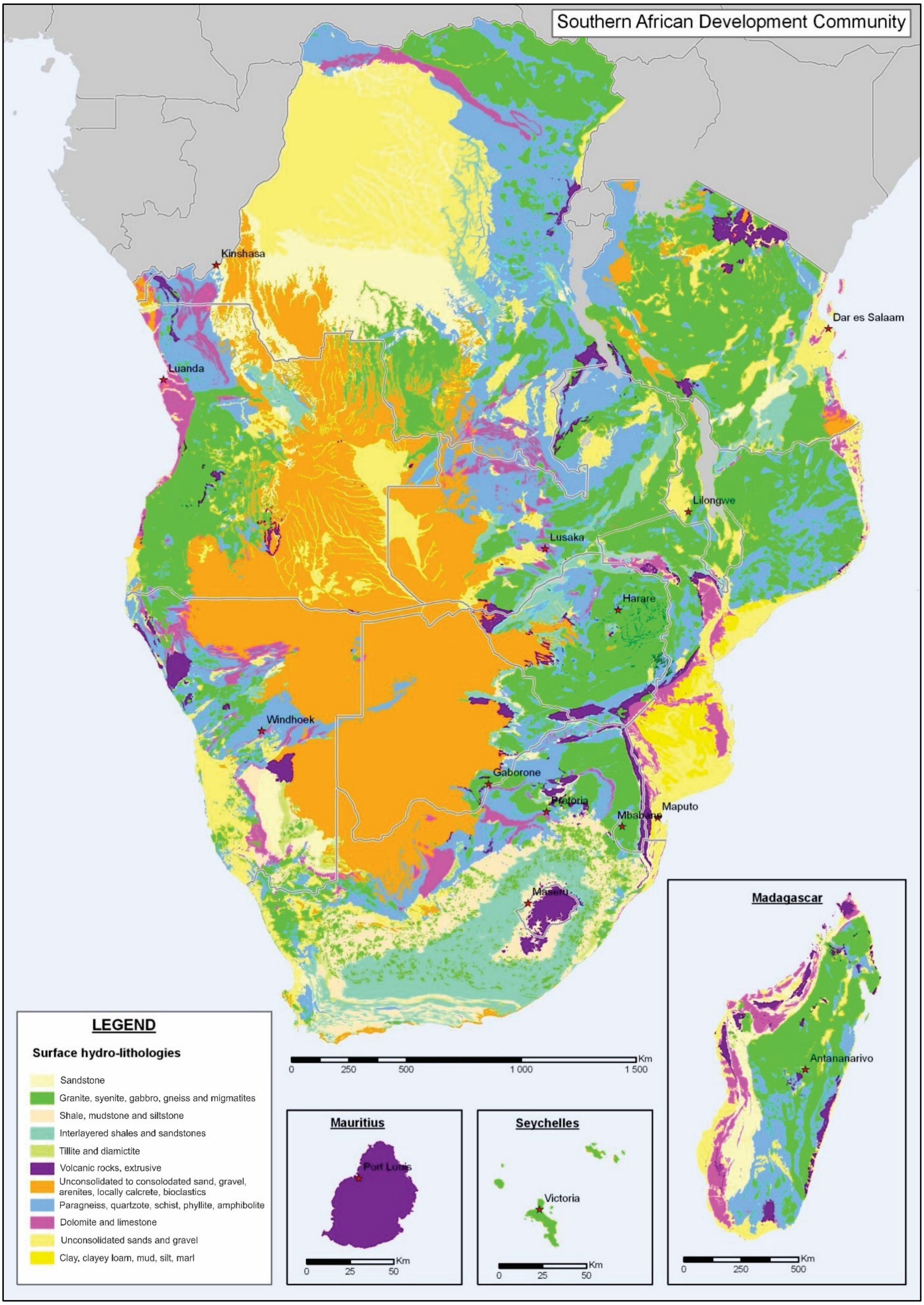

Figure 2.4 SADC hydro-lithology map (Ramoeli *et al.,* 2010).

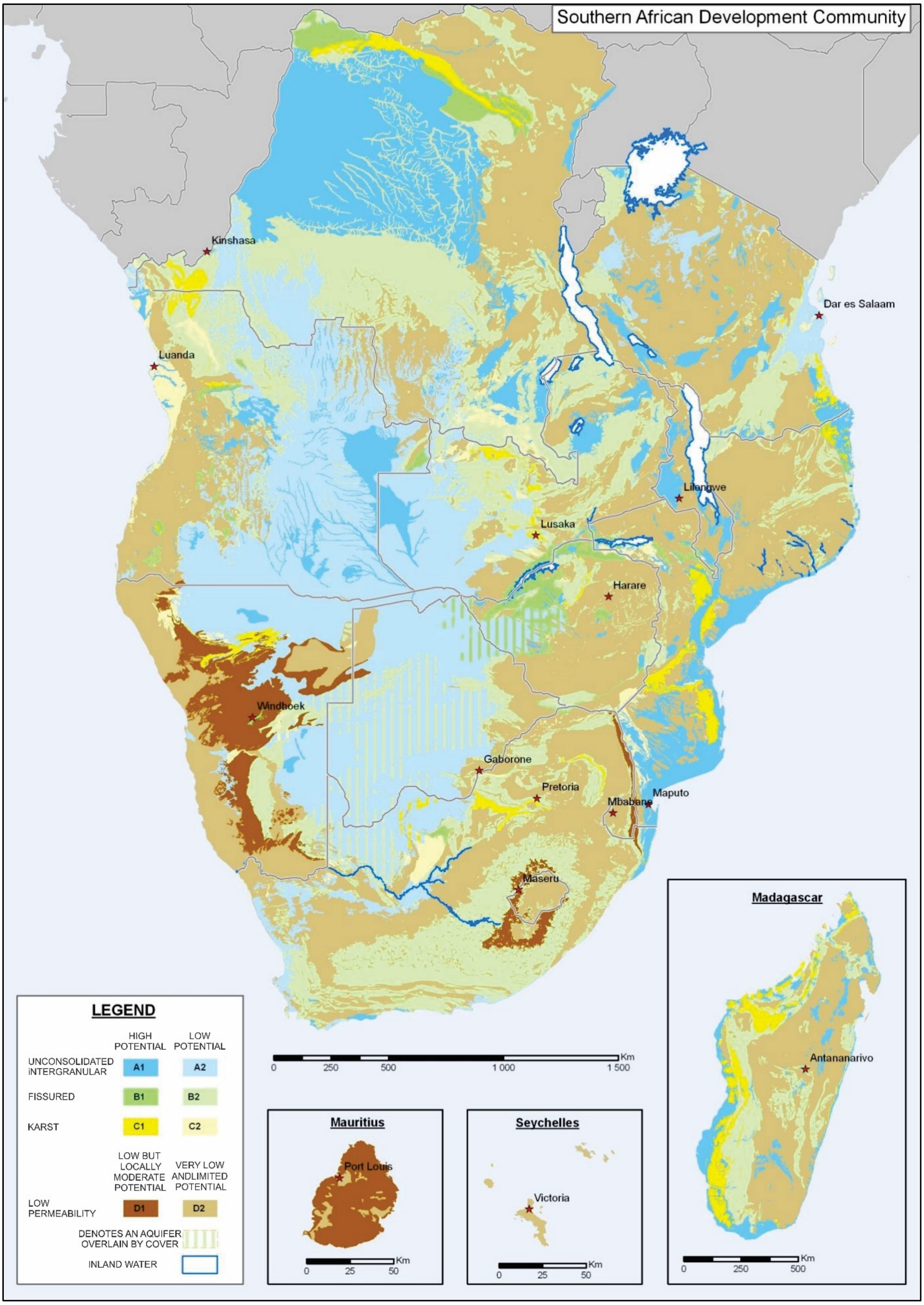

Figure 2.5 SADC hydrogeology map (Ramoeli *et al.,* 2010).

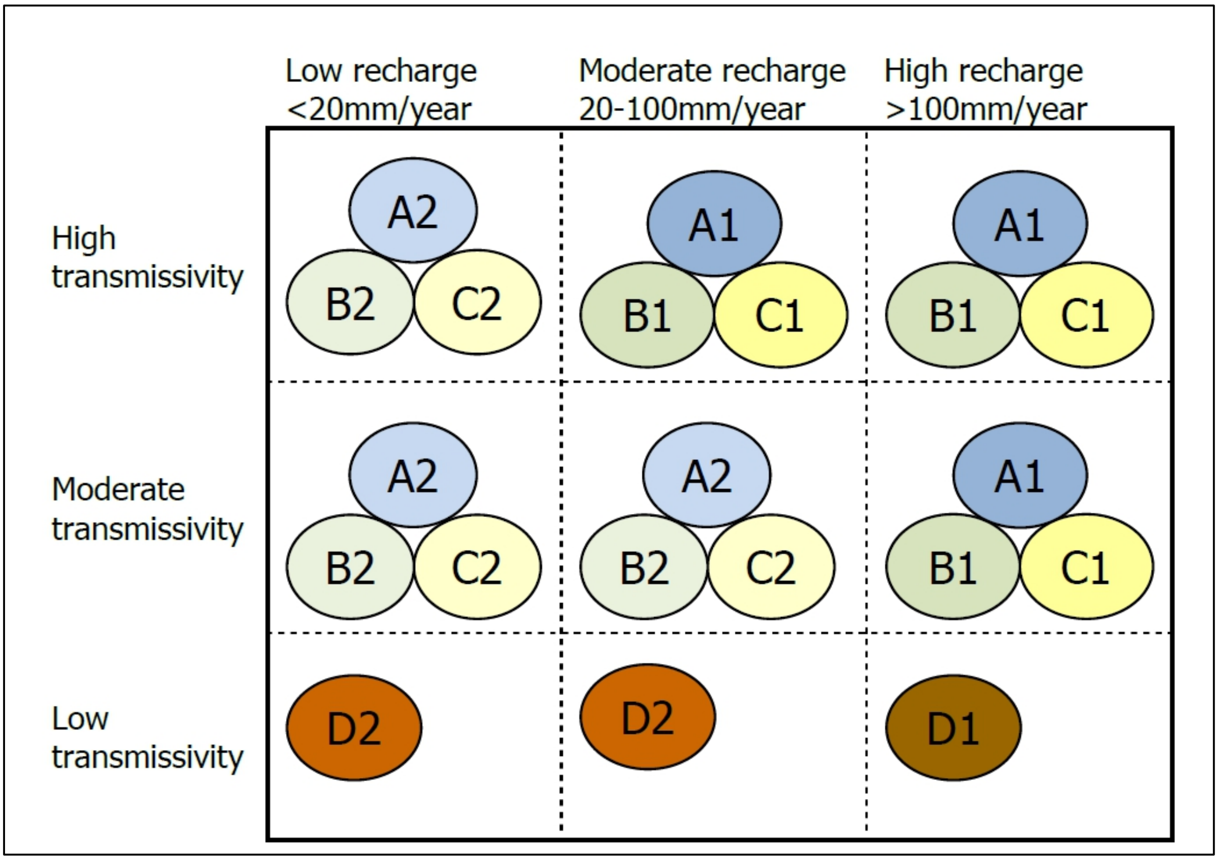

Figure 2.6 Scheme for the aquifer productivity classification on the SADC-HGM (Ramoeli *et al.*, 2010).

Table 2.2 Aquifer productivity from measured hydraulic properties as classified by Struckmeier and Margat (1995) (Ramoeli *et al.*, 2010).

Aquifer Category	Specific Capacity (L/s/m)	Transmissivity (m2/d)	Permeability (m/d)	Very aprox. Expected yield (L/s)	Groundwater Productivity
A, B, C	>1	>75	>3	>10	High: Withdrawals of regional importance (supply to towns, irrigation)
A, B,C	0.1 – 1	5 – 75	0.2 – 3	1 – 10	Moderate: Withdrawals for local water supply (smaller communities small scale irrigation etc.)
D1	0.001 – 0.1	0.05 – 5	0.002 – 0.2	0.01 – 1	Generally low productivity but locally moderate productivity: Smaller withdrawals for local water supply (supply through hand pump, private consumption)
D2	<0.001	<0.05	<0.002	<0.01	Generally low productivity: Sources for local water supply are difficult to ensure

2.2.3 Hydrogeological mapping in the United Kingdom

2.2.3.1 The 1:625,000 national hydrogeological map

Between 1967 and 1994, the British Geological Survey (BGS) published numerous hydrogeological map sheets for the United Kingdom at scales varying between 1:25,000 and 1:625,000 (BGS, 2016a). Recently, these maps were revised, updated and merged to a scale of 1:625,000, which is consistent with the geological map for the United Kingdom (BGS DiGMapGB 1:625,000; BGS, 2016b). This new map is available online via a mapping application (Figure 2.7) as the 1:625,000 digital hydrogeological map of the United Kingdom (BGS, 2016c). The hydrogeological map shows aquifers and aquitards classified into the following groups:

- extensive and highly productive aquifers;
- locally important aquifers;
- concealed aquifers;
- aquifers of limited potential; and
- rocks without significant groundwater.

Aquifers are divided according to the dominant flow mechanism (intergranular and fractured flow). Additionally, it includes the geological formation or group that hosts the aquifer/non-aquifer and summarises other useful hydrogeological information that is available for the aquifer (BGS, 2016c).

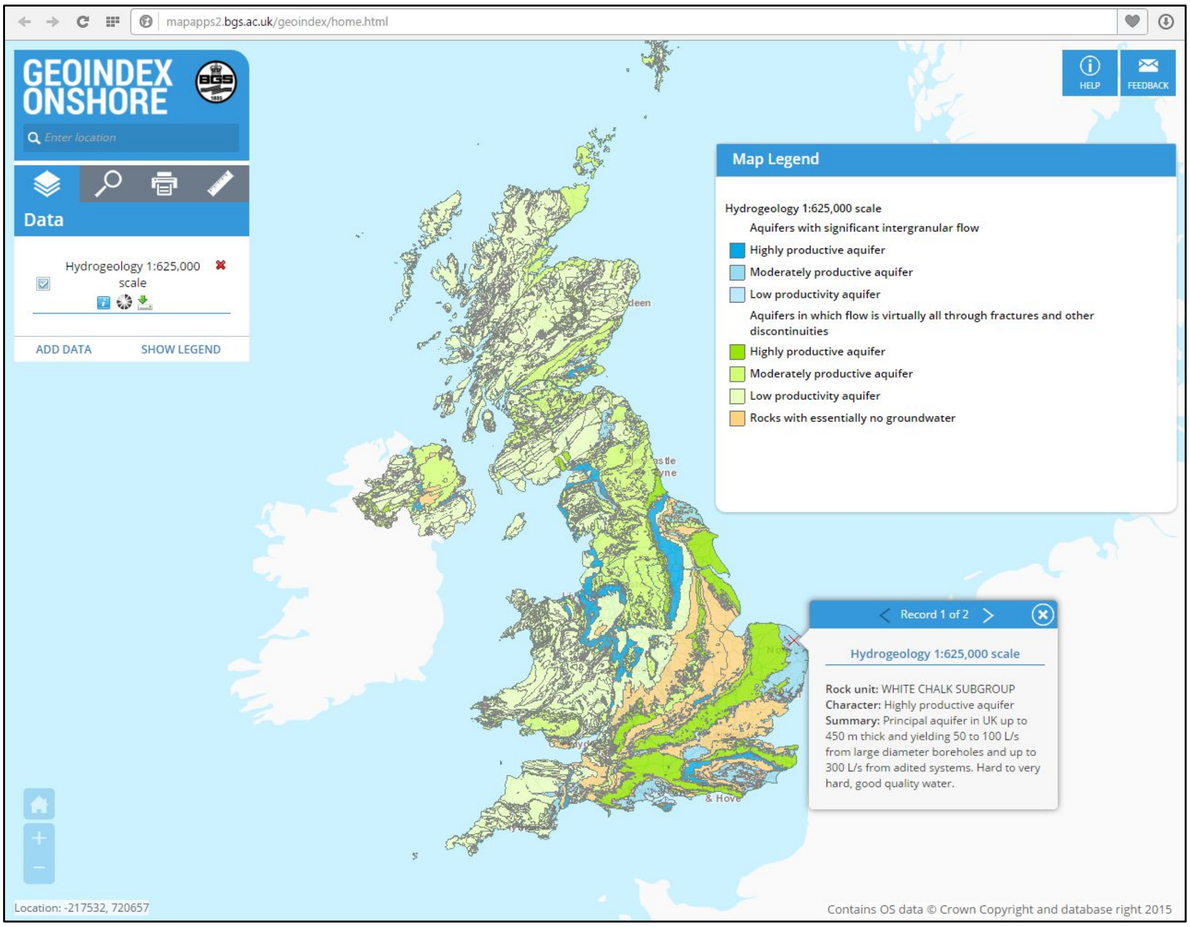

Figure 2.7 Hydrogeological map for the United Kingdom at a 1:625,000 scale, demonstrated with the BGS web mapping application (BGS, 2016c).

Due to the large scale, BGS (2016d) recommend the use of this map for hydrogeological applications at the national and regional scale only. Higher resolution hydrogeological maps are available, for example, for England and Wales (Abesser and Lewis, 2015), Section 2.2.3.2, and for Scotland (MacDonald *et al.*, 2004).

2.2.3.2 Themed national hydrogeological maps: aquifer productivity and depth-to-source maps for England and Wales

The bedrock aquifer productivity map

Whereas the 1:625,000 hydrogeological map was developed using a descriptive mapping approach, the aquifer productivity map from Abesser and Lewis (2015), Figure 2.8, was assembled using a numerical classification. BGS defines all geological formations of Pliocene age or older as ‘bedrock’. Bedrock aquifers were classified by groundwater yield into the following three groups: ‘no/small yield’ (< 1 L/s), ‘moderate yields’ (1 – 6 L/s) and ‘large yields’ (> 6 L/s). Additionally, the aquifers were divided into ‘outcrop’ aquifers that are at, or close to, the surface, and concealed aquifers, which are at depth, and likely confined and less permeable than ‘outcrop aquifers’. This distinction is due to the differences in interaction with surface water features, response of groundwater level to pumping and assumed confinement status (Abesser and Lewis, 2015).

The bedrock aquifer productivity map (Figure 2.8) was constructed using aquifer productivity data and the geological map at a 1:250,000 scale. Aquifer productivity was derived from transmissivity, specific capacity and borehole yield data (2,862 values retrieved from the BGS Aquifer Property database and the Environmental Agency’s National Abstraction License Database). Supported by expert opinion, these datasets were linked to 127 of the 593 lithostratigraphic unit codes in the geological map, covering 70% of the surface area of England and Wales. Expert opinion was then utilised to assign each lithostratigraphic code or polygon in the geological map with a productivity class. In some cases, available aquifer yields varied considerably across a mapped geological unit, which was solved by adding a geographical condition to the attribution process.

The depth-to-source map

In addition to the aquifer productivity map, Abesser and Lewis (2015) also produced a depth-to-source map (Figure 2.9), which shows the depth of the shallowest aquifer. To do this, the authors assumed that the depth to the aquifer was the water table depth, or the thickness of superficial deposits above concealed aquifers. Therefore, the data that were used to construct these maps were BGS’s River Head Space Model (RHSM) and Superficial Deposits Thickness Model (SDTM), as well as digital data of the top surfaces of major geological units in Great Britain (Atlas GIS data). The RHSM is a digital map showing the approximate depth to the (shallow) water table in Great Britain under natural flow conditions (i.e., without abstractions). The water table was derived from river locations and river base level data, digital terrain model data and water levels from bores. The SDTM was constructed by interpolating data from approximately 600,000 bore logs and it comprises the following three datasets (BGS, 2016e):

- a model of the thickness of Quaternary deposits derived from bore logs (basic version),
- a model of the thickness of Quaternary deposits derived from bore logs in combination with the extent of the deposits from geological maps (advanced version); and
- a distance buffer dataset which allows the specification of uncertainties by calculating the distance to any data point in the model.

In areas for which no bore data was available, the SDTM was manually corrected.

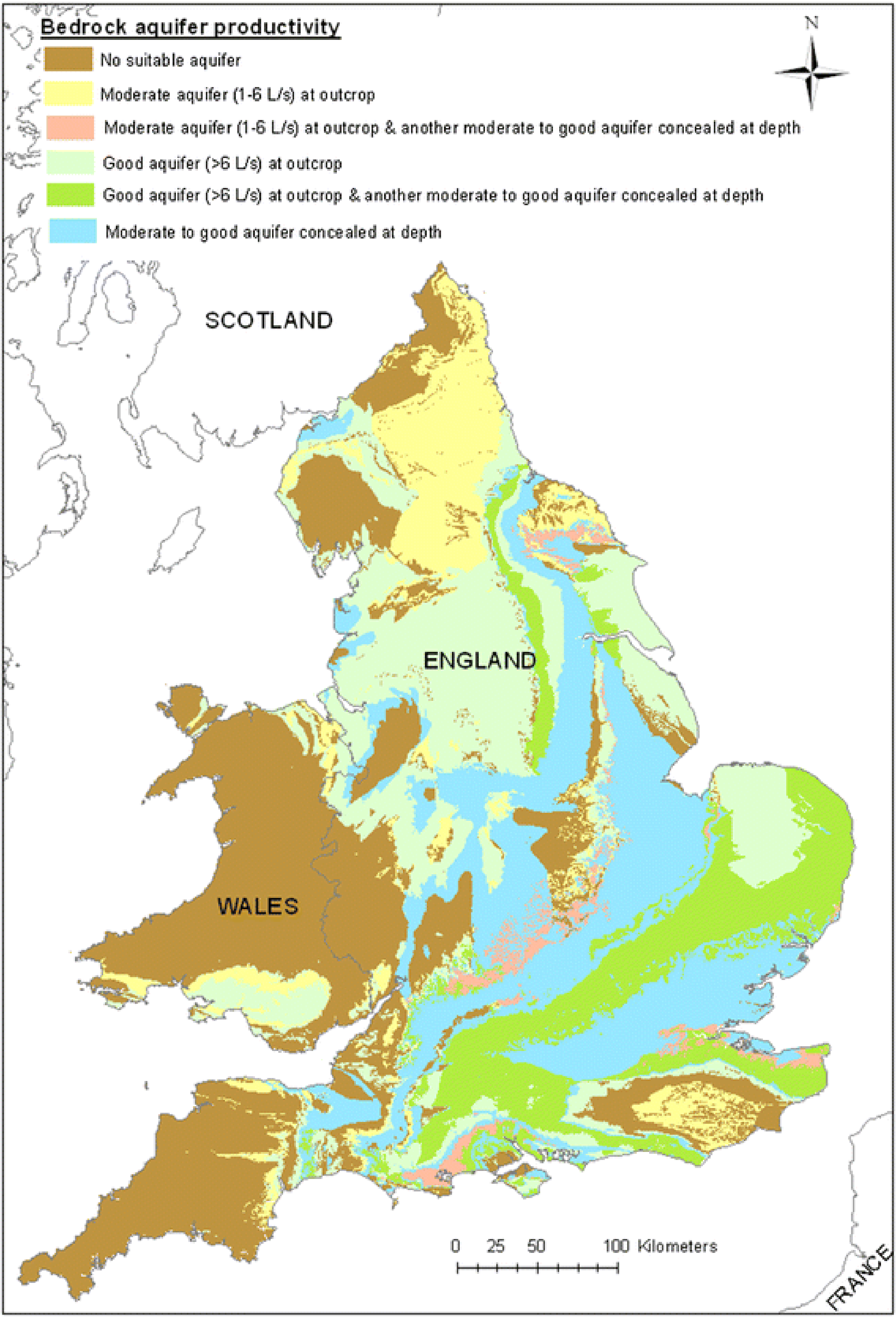

Figure 2.8 Bedrock aquifer productivity map for England and Wales (Abesser and Lewis, 2015).

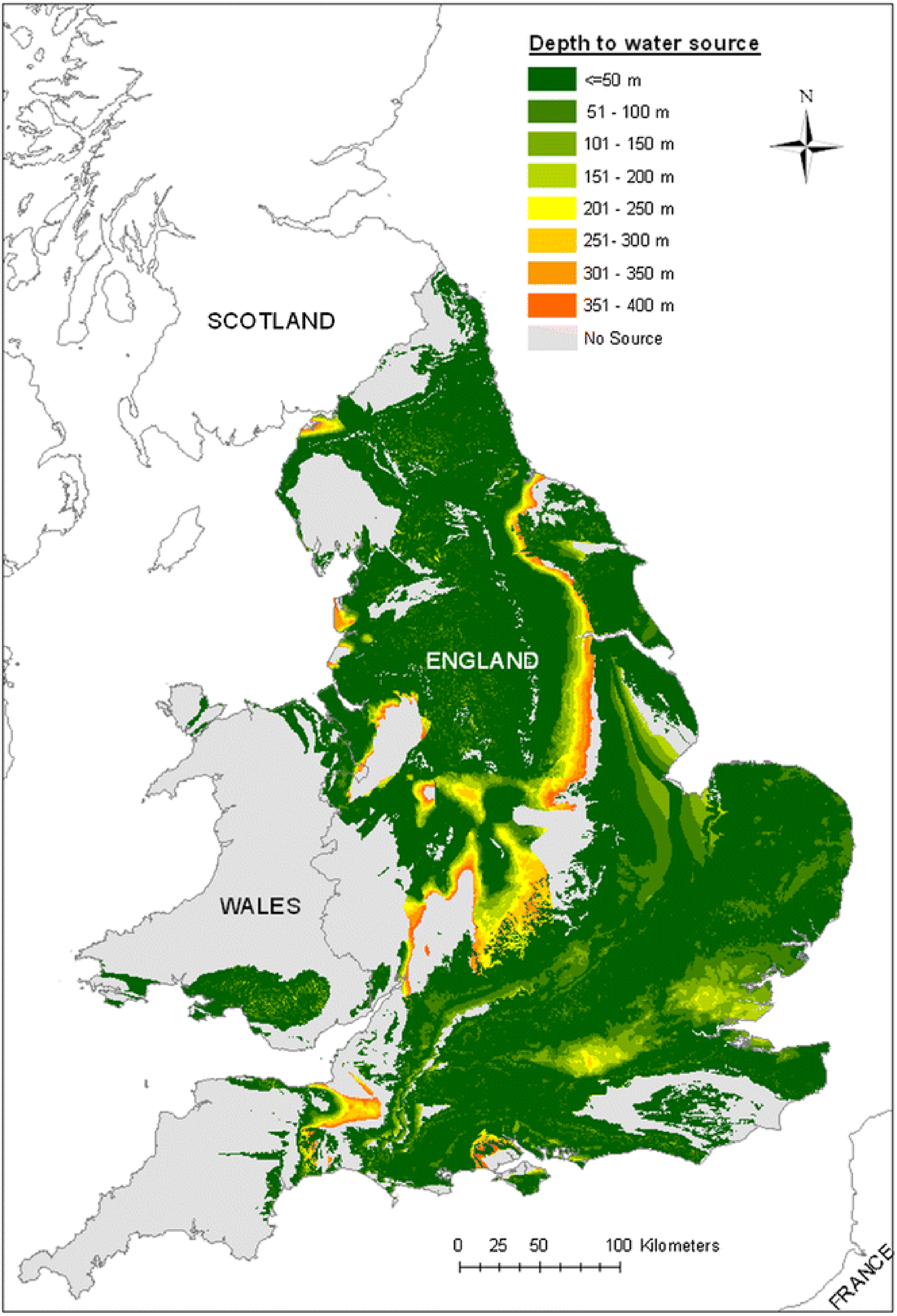

Figure 2.9 Depth-to-source map for England and Wales (Abesser and Lewis, 2015).

2.2.3.3 Permeability indices for the United Kingdom

The British Geological Survey (BGS) (Lewis *et al.*, 2006) developed permeability indices for the United Kingdom at a 1:50,000 scale. The indices were based on the DiGMapGB-50, the digital geological map for Great Britain. The permeability indices were assigned from expert judgement and attributes of geological formation and lithology recorded in the geological map. Each index included three components: predominant flow mechanism, maximum permeability and minimum permeability (Figure 2.10).

Predominant flow mechanism	Maximum permeability	Minimum permeability
	Very high	Very high
Intergranular	High	High
Fracture	Moderate	Moderate
Mixed (intergranular and fracture)	Low	Low
	Very low	Very low

Examples:

Gravel	Intergranular	Very high	Very high
Peat	Mixed	Low	Very low
Mudstones younger than Jurassic	Fractured	Low	Very low
Mudstones older than Jurassic	Fractured	Low	Low*

*Older mudstones are assumed to have more fractures and therefore a slightly increased permeability

Figure 2.10 Permeability indices and examples (Lewis *et al.*, 2006).

In some cases, more than one lithology was listed in an attribute field. To resolve this, Lewis *et al.* (2006) assumed that the order of listed lithologies equated to the order of maximum occurrence, (e.g., the dominant rock type was listed at the beginning of the field). Maximum and minimum permeability were based on the most, and least, permeable lithology in an attribute field. The permeability indices are directly linked to the attributes of the geological map. As a result, they are generated dynamically and will be updated automatically when the geological map is updated.

Lewis *et al.* (2006) do not include other factors that may influence permeability, i.e.:

- structural features (i.e., faults and folds) - These were assumed to generally only affect a limited part of a geological unit and the permeability indices aim to represent the unit as a whole;
- soil – a preliminary study found little difference in permeabilities between soils and the underlying deposits from which they are derived.
- weathering – the permeability indices were developed assuming little-weathered deposits because, aside of granites, the weathered material was generally more permeable.

- variability with depth – this was not included as at the time the indices were developed there was not enough information available for all of Great Britain.
- topography – in some deposits (e.g., chalks) transmissivities may vary with topography. Topography was not included in the process of deriving the permeability indices, but could potentially be added at a later stage as an additional dataset.

The authors state that the permeability indices have been developed for use at the catchment scale and should not be used at the local scale. Additionally, the indices were set as broad indicators of permeability encompassing a wide range of possible permeabilities. As such, they are not equivalent to hydraulic conductivity or intrinsic permeability and should not be translated to these in any way

2.2.4 Hydro-lithologies in continental and large-scale basin studies

Gleeson *et al.* (2011) compiled values of mean and standard deviation for intrinsic permeability κ (Table 2.3), based on values in Freeze and Cherry (1979; their Table 2.2) and a multitude of global regional-scale calibrated hydrogeological models (Figure 2.11). Subsequently, they categorised geological units from geological maps or hydrogeological models into hydro-lithologies, based on intrinsic permeability. These are defined by Gleeson et al. (2011) as “broad lithologic categories with similar hydrogeologic characteristics such as permeability”, and are based on the commonly employed concept of hydro-stratigraphy in groundwater modelling of sedimentary basins (Person *et al.*, 1996). Gleeson *et al.* (2011) compiled 230 hydrogeological units into seven hydro-lithological classes, first for North America and then at the global scale.

Table 2.3 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	-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	-10.9	1.2

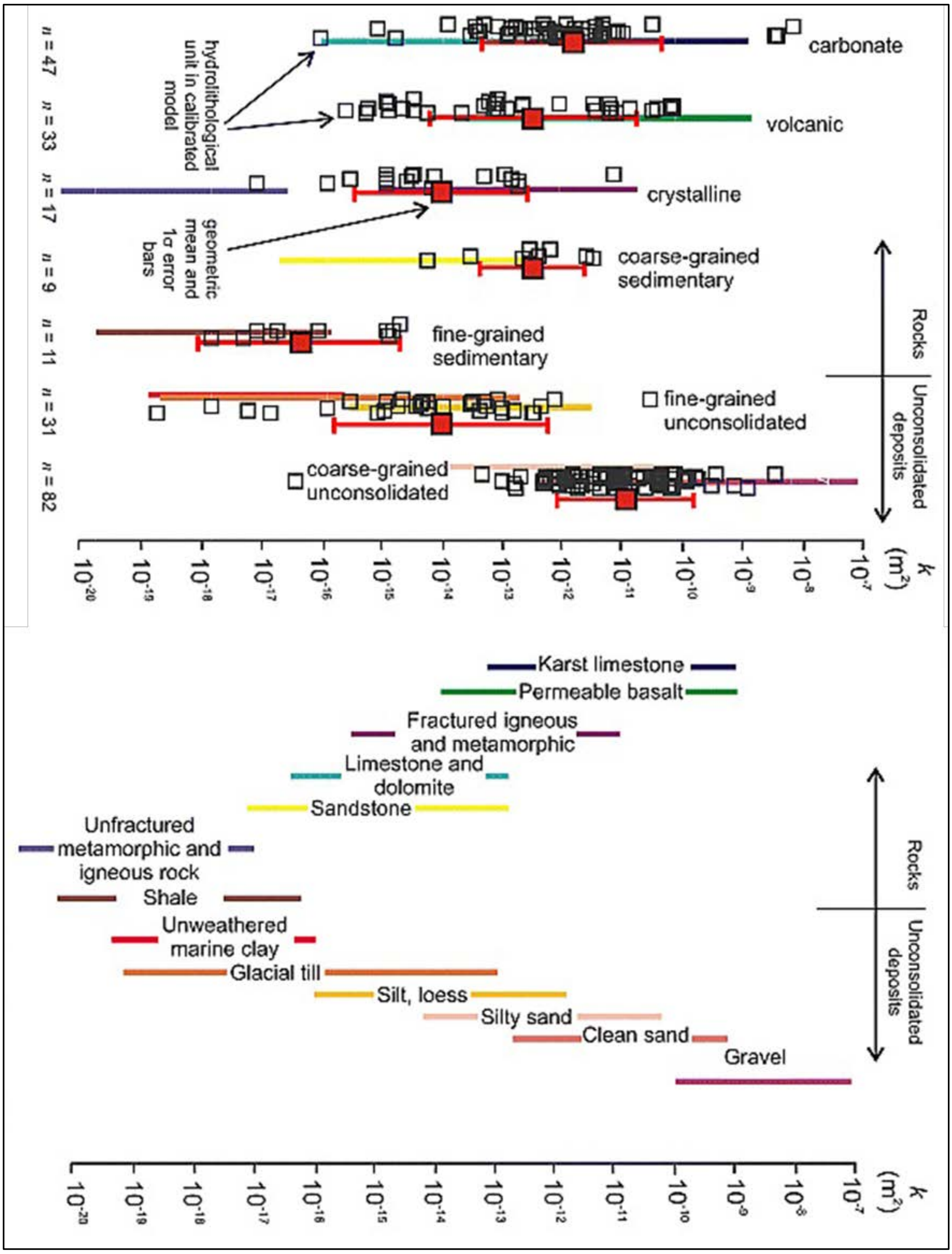

Figure 2.11 Comparison between intrinsic permeability ranges from calibrated regional-scale hydrogeological models, top, and from Freeze and Cherry (1979), bottom. Figures from Gleeson et al. (2011).

2.3 AQUIFER SYSTEM CLASSIFICATION AND RANKING

The identification and characterisation of a representative suite of New Zealand's aquifer systems is intended to improve the understanding, management, and protection of all of New Zealand's aquifers: specifically, to enable knowledge from well-studied catchments to support under-studied catchments. This section aims to provide an overview of aquifer classification and ranking work that has been done in New Zealand and overseas.

2.3.1 Aquifer classification in New Zealand

White (2001) broadly classified New Zealand's aquifers based on the origin of the host rocks or deposits into the following groups:

- Sedimentary:
  - o Terrestrial – this includes alluvial, fluvial, glacial and aeolian deposits. For example, Wakatipu Basin, Otago, which comprises fluvial, alluvial and glacial deposits that host unconfined aquifers with a thickness between 5 – 30 m. Other examples are the Galatea Basin and the North Canterbury Plains.
  - o Shallow marine – this includes Deltaic carbonates, evaporites and siliciclastic deposits. For example, Whenuakura Group, Taranaki, which is 400 m thick, hosts 6 aquifers with thicknesses between 5 to 10 m and comprises siliciclastic deposits (sands, sandstone, shell beds, silt, and siltstone). Karstic limestones are also important aquifers in this class, e.g., Te Kuiti Group, Waikato, which includes Otorohanga Limestone that is approximately 75 m thick at the Waitomo Caves. Other examples are Kaawa Formation, Waikato, and Chatton Formation, Southland.
  - o Terrestrial and shallow marine – this includes coastal systems that result from transgressive-regressive depositional sequences due to sea level change. The aquifers are generally layers of unconfined/semi-confined (terrestrial sand, silt and gravel) and confined deposits (marine clay and mud). For example, Christchurch – West Melton (Figure 2.12), Canterbury, which includes up to 305 m thick gravel deposits. Other examples are the Heretaunga Plains, Hawke's Bay, and the Rangitaiki Plains, Bay of Plenty
  - o Deep sea marine – This includes turbidite fan deposits comprising mudstone-sandstone units. For example, Waitemata Group, Auckland, a Neogene mudstone-sandstone deposit with a thickness up to 1000 to 2000 m.
- Volcanic
  - o Basalt aquifers – These consist of weathered lava, scoria and ash deposits, like for example, the South Auckland Volcanics, which have thicknesses of up to 100 m. Lava with cooling fractures, lava tubes and scoria layers generally are high-permeability layers, whereas tephra and weathered basalts usually have poor permeability. The flow direction depends on the internal structure of the basalt aquifer. For example, cooling fractures are generally perpendicular to the flow plane, whereas lava tubes are generally linear features parallel to the lava flow direction.
  - o Ignimbrite aquifers – These are widespread deposits (up to 200 km away from source caldera) with thicknesses of up to more than 200 m. This includes, for example, the Whakamaru Group, Waikato. Ignimbrite units generally have poor permeabilities at the base of the deposit, whereas the fractured central part is moderately permeable and may host aquifers.
- Metamorphic – For example, the Arthur Marble, which is found in the Takaka Valley in the Tasman region, has a thickness of more than 1000 m. It contains caves and other karstic features, and hosts the Waikoropupu Springs, the largest springs in New Zealand.

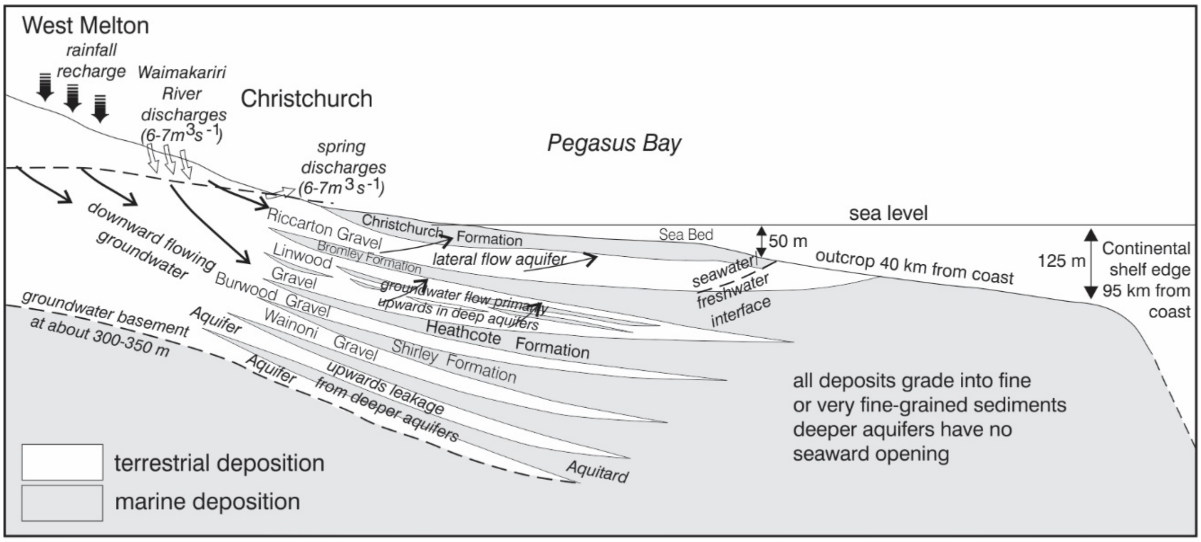

Figure 2.12 Example for an aquifer system deposited in terrestrial and marine environments: Christchurch - West Melton (White, 2001). Grey marine layers inter-fingering with terrestrial deposits act as confining layers.

In another example of aquifer system classification work in New Zealand, 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 2.4). The purpose of this classification was to provide hydrogeological settings for groundwater flow and virus transport modelling, and their work included the derivation of average hydraulic properties (i.e., effective porosity and hydraulic conductivity) that were representative for these aquifer types. To determine the hydraulic property values, Moore *et al.* (2010) collected and analysed information from the literature and data provided by regional councils.

Table 2.4 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/d)**
Alluvial gravel	0.0032	1300
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

2.3.2 National ranking of aquifers by economic value of water in New Zealand

White *et al.* (2004) calculated the economic values of water in New Zealand's surface water catchments and groundwater aquifers in \$/year based on allocation in m^3/year, estimates of actual use (rate of allocation) and estimates of the economic value of water in \$/m^3

V = AL*U*E,

With: V the economic value of water; AL the allocation; U the actual water use, a ratio of allocation; and E the economic value. The economic value was estimated for catchments and aquifer regions in different categories, i.e., domestic, livestock, fields (e.g., parks, golf courses), and industry. The authors also included projections for 2021, based on projections of population. The scope of the work by White *et al.* (2004) did not include irrigation for agriculture, which is the largest user of groundwater: on a global level it is 70% of all water demand (Wada *et al.*, 2014); in New Zealand it is approximately 77%, corresponding to approximately 500,000 ha of irrigated land, of which 41% is from groundwater (White *et al.*, 2004). Christchurch – West Melton and Heretaunga Plains are the aquifers with the highest estimated economic values of groundwater for domestic use (economic value \$60 Million/year and \$20 Million/year, respectively) and industrial use (economic value \$2328.1 Million/year and \$1078.7 Million/year, respectively) (White *et al.*, 2004).

2.3.3 Aquifer classification and ranking in British Columbia

The Ministry for the Environment in British Columbia, Canada, devised an aquifer classification system for groundwater management purposes based on a combination of descriptive and numerical attributes, to indicate the relative importance of an aquifer (Kreye *et al.*, 1994). The descriptive attribute qualifies the use of an aquifer (heavy, moderate, light) and its vulnerability to contamination (high, moderate, low). The ranking attribute is the sum of individual rankings, from 1 to 3, qualifying the aquifer productivity, vulnerability, size and demand, type of use of the aquifer and concerns regarding its groundwater quality and quantity. The system is applicable at the 1:50,000 scale for aquifers for which sufficient well information is available (e.g., geological logs, yield, etc.). By 2009, more than 900 aquifers were classified in British Columbia using this method (Liggett and Talwar, 2009).

2.3.4 Aquifer ranking by groundwater yield in New Jersey

The New Jersey Geological Survey developed an aquifer ranking system for New Jersey (Herman *et al.*, 1998) based on the ability of aquifers to yield groundwater to wells. This classification consists of five ranks (A to E) from more than 500 gallons per minute to less than 25 gallons per minute. The aquifers were mapped based on statistics of approximately 8000 high-capacity wells, and surface extents of geological formations. This classification only shows aquifers at or near the surface without any depth information (Herman *et al.*, 1998).

3.0 METHODS

3.1 CLASSIFICATION OF QMAP ATTRIBUTES

The aim of this project was to identify surface hydrogeological units from the QMAP geological map, and this is described in the following sections. QMAP has been published as a digital dataset (ESRI shapefile; Heron, 2014) and represents the extent of geological units that are at the ground surface or shallow subsurface as map polygons. Each map polygon is attributed with metadata including:

- descriptions of stratigraphy (e.g., 'STRAT_UNIT', 'Formation'),
- lithological composition ('MAIN_ROCK' – the main lithology encountered in the geological unit, 'SUB_ROCKS' – other lithologies encountered in the geological unit, in order of importance),
- geochronology/age (e.g., 'STRAT_AGE', 'ABS_MIN' – the minimum age of a unit; 'ABS_MAX' – the maximum age of a unit), and
- depositional environment (e.g., 'Description').

Due to the nationwide extent of the QMAP, as well as the comprehensive metadata attributes associated with it, this geological map can be used to systematically identify and categorise hydro-lithological classes, which could in turn be used as a basis for aquifer mapping at the national and regional scale. The methodology used for this identification and classification is largely based on the work of Gleeson *et al.*, 2011 (Section 2.2.4) but has also been influenced by other work, e.g., Struckmeier and Margat (1995) (Section 2.2.1).

The classification of hydrogeological units from QMAP attributes followed a tiered workflow (Figure 3.1). The tiers were set based on QMAP attributes describing the lithological composition and age of the geological units. These attributes were assumed to have the largest impact on the hydraulic properties of the geological units in QMAP. Each tier resulted in a classification that was based on one of the QMAP polygon attributes, or a combination of attributes. First, a descriptive approach was applied, which used the main rock type and age of the geological units (Tier 1a and Tier 2a, respectively). However, this approach did not allow for other lithologies that may be interbedded (e.g., mudstone-sandstone units) or mixed (e.g., sandy gravel) with the main lithology, and may also be of importance for groundwater flow, to be considered. These other lithologies are listed in the secondary rock type attribute field of the QMAP. As the secondary rock type is assumed to be less dominant than the main lithology, a classification approach was necessary that allowed the use of a weighted function. Additionally, the inclusion of age as a classification parameter resulted in too many hydrogeology classes to be manageable within a map display of Tier 2a. The descriptive approach was therefore not split further than Tier 2; and a numerical approach was applied, which enabled to generate classes down to Tier 4, accounting for secondary rock type, age and aquifer potential to be included (Tier 1b, Tier 2b, Tier 3 and Tier 4).

From these two approaches, the following four classes were defined:

Hydro-lithology Class (Tier 1a/Tier 1b) – The 'MAIN_ROCK' QMAP attribute was grouped into 10 classes, based on the expected hydraulic properties of the lithologies. The resulting descriptive (Tier 1a) and numerical (Tier 1b) classes were identical to each other.

Hydrogeology Class (Tier 2a/Tier 2b) – The 'MAIN_ROCK' and age QMAP attributes were grouped into 40 (Tier 2a) or 10 classes (Tier 2b), respectively, based on the expected hydraulic properties of the lithologies and the expected hydraulic behaviour based on the geological age of the unit. Age is an important factor as the permeabilities of rocks and deposits decreases over time due to weathering, compaction and diagenesis processes. Tier 2a uses the 'STRAT_AGE' QMAP attribute, which is a descriptive classification, whereas Tier 2b used the 'ABS_MIN' and 'ABS_MAX' QMAP attributes, and is a numerical classification.

Hydrogeology Class (Tier 3) – 'MAIN_ROCK', 'SUB_ROCKS', and age QMAP attributes ('ABS_MIN' and 'ABS_MAX') were combined and subsequently grouped into 10 classes, based on the expected hydraulic properties of the main and minor lithologies and hydraulic behaviour based on the age of the geological unit. Tier 3 is a numeric approach that extends on Tier 2b by integrating items listed in the 'SUB_ROCKS' field with a lower weighting than the main rock type.

Aquifer Potential Class (Tier 4) – the Tier 3 hydrogeology classes were simplified into four aquifer potential categories for this classification, using preliminary threshold definitions. For this definition of an aquifer, the categories indicate the potential of the map unit to transport and store groundwater: economic abstraction is not considered within the definition as this is considered a temporal property not solely linked to geology.

The following sections describe the approaches used in more detail.

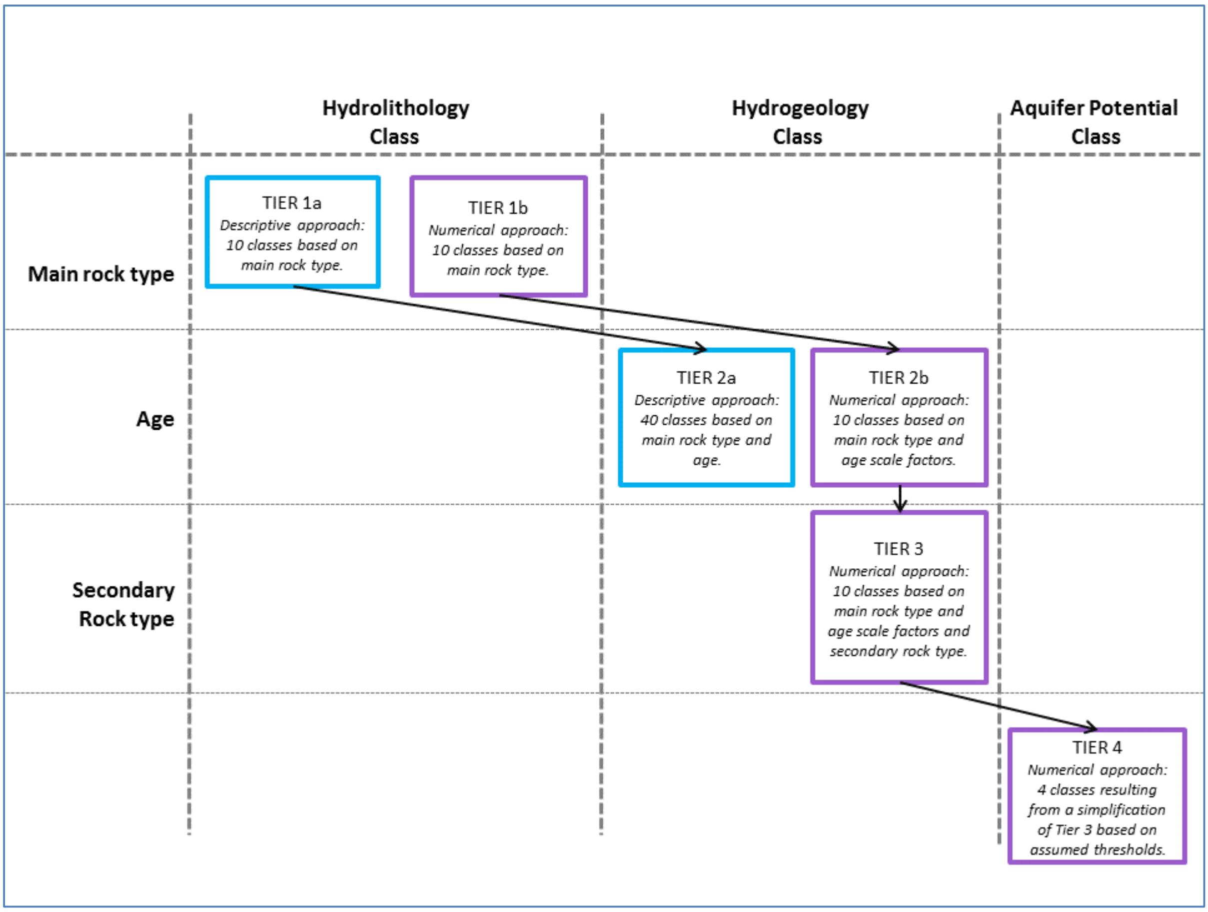

Figure 3.1 Workflow of the methodology used in this project. Blue boxes represent the descriptive approach and purple boxes the numerical approach.

3.1.1 Descriptive approach

Microsoft Excel and ESRI ArcGIS were used for the classification in Tier 1a and Tier 2a. The descriptive approach primarily relied on the following QMAP attributes:

- 'MAIN_ROCK': one keyword for the main rock type (Tier 1a).
- 'STRAT_AGE': time period of deposit (Tier 2a);

3.1.1.1 Tier 1a

Tier 1a units were initially based on the hydro-lithological units defined by Gleeson *et al.* (2011), Section 2.2.4 Table 2.3, and then adjusted to better reflect New Zealand's geological setting. For example, ignimbrite, a volcanic deposit that is widely distributed throughout the central North Island, is generally more permeable than the typical 'volcanic' hydro-lithological unit as per Gleeson *et al.* (2011) (e.g., Tschritter *et al.*, 2014). Therefore, an extra unit, 'Volcanic with higher permeability', was added to the classification, which included rock types such as scoria and ignimbrite. Also, crystalline and meta-sedimentary rocks were combined into one group, because these deposits represent predominantly basement rocks in New Zealand that generally act as impermeable strata. Ten descriptive hydro-lithological units were used to categorise all of the main rock types within QMAP. All hydro-lithology units and the associated QMAP main rock types are listed in Appendix 1:

3.1.1.2 Tier 2a

Tier 2a classes were derived from the geological time period of QMAP units. The classification by age was predominantly based on the 'STRAT_AGE' attribute field of the QMAP. Additional attribute fields, 'TEXT_CODE' 'SIMPLE_NAME', 'ABS_MIN' and 'ABS_MAX', were also relevant where the 'STRAT_AGE' field yielded ambiguous results (e.g., Cretaceous to Paleogene).

Four age-related categories were defined based on the expected hydraulic properties of the deposits (Begg, 2016): Quaternary, Neogene, Late Cretaceous to Paleogene and basement (including Early Cretaceous).

The ten descriptive classes from Tier 1a were further split using these four age categories, resulting in a maximum number of possible categories of 40 to categorise all of the main rock types and their age within QMAP.

3.1.2 Numerical approach

The numerical approach was scripted in MATLAB, which allowed the inclusion of functions to determine the relationships between main rock type and sub rock type, as well as age of the deposits and their permeability. The following QMAP 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).
- 'SUB_ROCKS': multiple keywords for secondary rock type(s);

3.1.2.1 Tier 1b

Tier 1a hydro-lithology classes were ordered based on their permeability values (Gleeson *et al.*, 2011; Tschritter *et al.*, 2014) and ranked between 1 and 10 (Table 4.1), 10 being the most permeable. Using MATLAB, the 'MAIN_ROCK' attribute of each QMAP polygon was matched to a hydro-lithology unit using a look-up table approach, i.e., by matching attribute keywords of each QMAP polygon to the dictionary class values. This resulted in maps with 10 hydro-lithology classes which correspond to the numerical equivalent of hydro-lithology defined in the Tier 1a workflow

3.1.2.2 Tier 2b

For the numerical equivalent of Tier 2a, the 'MAIN_ROCK' attribute was classed into age categories. As a result of the higher flexibility of the numerical approach, it was possible to use a different methodology for Tier 2b than what was used in Tier 2a. First, a mean age was calculated for each unit from the average values of the 'ABS_MIN' and 'ABS_MAX' attributes. This age was then converted to a scaling factor using an assumed exponential decrease (Figure 3.2), based on the assumed decrease of porosity due to diagenesis in older sediments that are expected to be less conductive and porous than younger formations (Hart and Hammon, 2002; Parker and Sellwood, 2012). Beven and Kirkby (1979) simplified the basin-wide effects of long-term sedimentation, denudation and flow in their model and assumed that porosity and subsurface flow decreased exponentially with depth. This assumption was applied by Fan *et al.* (2013), who used it to estimate hydraulic conductivity over depth for application of basin-wide groundwater models. Fan *et al.* (2013) define K as:

$$K = K_0 e^{-z/f} \qquad \text{(Eq. 3.1)}$$

In this equation, K_0 is the hydraulic conductivity at or near the surface, z is 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).

Equation 3.1 was adapted within this work to:

$$\mathrm{f_T} = \mathrm{e}^{-\mathrm{T}/\alpha}, \qquad \text{(Eq. 3.2)}$$

with T being the geological age [Ma] and α, a constant that controls the decrease rate. The value of α was set to 40, so that Quaternary rock types (i.e., younger than 2.58 Ma) have a factor $\mathrm{f_T}$ that is close to 1 (i.e., the permeability is hardly affected by $\mathrm{f_T}$). Tier 1b hydrogeological classes (i.e., integers from 1 to 10) were multiplied by $\mathrm{f_T}$, resulting in a new (Tier 2b) hydrogeology classes, with floating values in between 1 and 10.

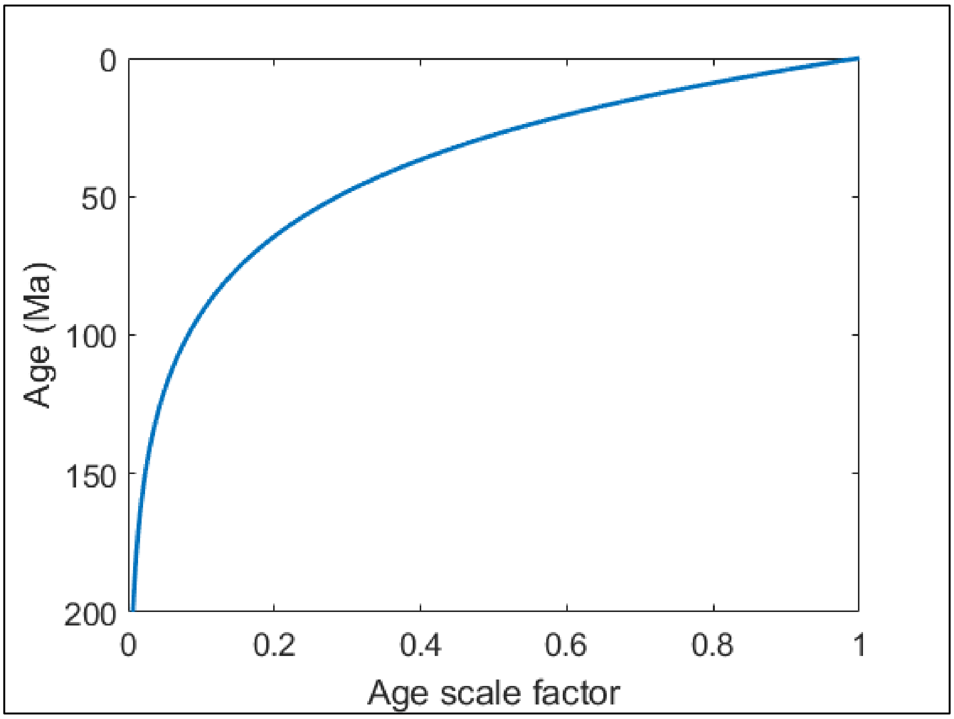

Figure 3.2 Age scale factor as a function of geological age (Ma).

3.1.2.3 Tier 3

The numerical approach allows for the inclusion of the 'SUB_ROCKS' QMAP attribute. Each of the (multiple) keywords in the attribute field were classified into the equivalent dictionary class values (similar to Tier 1b). This procedure was applied at each QMAP polygon and resulted in a 'dictionary' of 172 rock type descriptions, listed in Appendix 2. The mean 'SUB_ROCKS' hydrogeology class value was then calculated (floating number) based on all secondary rock types listed in the attribute field for each polygon. The 'MAIN_ROCK' (Tier 1b) and 'SUB_ROCKS' class values were then averaged in a weighted average, where 'MAIN_ROCK' was weighted twice as high as the mean of the 'SUB_ROCKS'. This resulted in the Tier 3 hydrogeology class values with floating numbers between 1 and 10 that were binned into 10 classes. For example, all decimal values between 0 and 1 were aggregated in class 1, and all values between 7 and 8 were aggregated in class 8

3.1.2.4 Tier 4

Tier 4 represents a simplification of the results from Tier 3. The hydrogeology classes from Tier 3 were rounded to integer values and classified into the following four aquifer potential classes: 'Poor', 'Low', 'Medium', and 'High'. The aquifer potential class was defined as 'Poor' for hydrogeological class values between 0 and 2, 'Low' for classes 3 and 4, 'Medium' for classes 5 to 7, and 'High' for classes 8 to 10. At this stage, these thresholds have been set based on assumed hydrogeological behaviour in a New Zealand context, and have not been validated against actual yields.

3.2 Comparison with Aquifer Systems

This comparison was based on the aquifer potential classes (Section 3.1.2.4). All polygons with the classes 'medium' and 'high' were compared with representative aquifer categories in New Zealand, reported by White (2001). The results of this comparison will be used in the next phase to further investigate representative aquifer systems in New Zealand, in particular with regard to their extents, depositional environment and three-dimensional structure.

4.0 RESULTS

4.1 CLASSIFICATION OF QMAP ATTRIBUTES

Following the methodology described in Section 3.1, a map for each tier has been developed for New Zealand at a 1:250,000 scale (Figure 4.1). Figure 4.2 and Figure 4.3 show these maps for two regions, Bay of Plenty and Southland, in more detail.

The hydro-lithology classes for Tier 1a and Tier 1b and example lithologies are shown in Table 4.1. The resulting Tier 1a and Tier 1b hydro-lithology maps are identical except for their legend descriptions (text description for Tier 1a; class number for Tier 1b). However, both maps have been included in the results to follow the structure established in the methodology. The Tier 1 maps show that some known aquifers, for example the Rangitaiki Plains, are already recognisable as having a higher hydro-lithology class, and therefore comparatively higher permeabilities, than surrounding areas. However, the Tier 1 hydro-lithology maps can also be partly misleading. For example, the Bay of Plenty maps (Figure 4.2) show predominantly hydro-lithological classes that are inferred to have higher permeabilities, including an area where basement rocks are the dominant outcropping geology. However, basement rocks are generally inferred to be hydraulic basement in New Zealand. This occurs due to basement rocks that have a main rock type classified as being permeable, e.g., sandstone. Similarly, the Southland hydro-lithology maps (Figure 4.3) display some of the basement areas as low permeability classes as expected, e.g., Fiordland. However, other basement areas including the Hokonui Hills and other areas that are part of the Murihiku terrane, are shown as permeable classes, owing to their main rock type. This result was expected and therefore, age was incorporated to create hydrogeological classifications. The hydro-lithology classes for these two maps and example lithologies are shown in Table 4.1.

Table 4.1 Hydro-lithology units (Tier 1a) and hydro-lithology classes (Tier 1b), ranked by median permeability (K). The median ages were calculated from Tier 2b.

Hydro-lithology unit	Hydro-lithology class	Median age	Median κ (log m^2)	Example lithologies
Fine-grained sedimentary	1	Neogene	-16.5	mudstone, claystone
Crystalline and meta-sediments	2	Triassic	-15	granite, greywacke
Fine-grained unconsolidated sedimentary	3	Quaternary	-14	clay, silt
Carbonate	4	Paleogene	-14	limestone, shell beds
Volcanic	5	Neogene	-12.5	andesite, basalt
Poorly-sorted sedimentary	6	Neogene	-12.5	turbidite, breccia
Poorly-sorted unconsolidated	7	Quaternary	-12.5	peat, till
Coarse-grained sedimentary	8	Paleogene	-12.5	sandstone, greenstone
Volcanic with higher permeability	9	Quaternary	-11.6	ignimbrite; scoria
Coarse-grained unconsolidated sedimentary	10	Quaternary	-10.5	gravel; sand

The hydrogeological maps for Tier 2a and Tier 2b were derived using main rock type and age of the deposits. The Tier 2a map highlights the limitations of the descriptive classification approach: based on the ten classes derived in Tier 1a, incorporating a minimum of four age classes into this classification resulted in a map with 40 classes, which makes the map more difficult to interpret than the numerical approach of Tier 2b. Additionally, using this method it would not have been possible to include additional information, e.g., secondary rock type. However, this map can still be useful to communicate high-level information about the geological composition of potential aquifers. Compared with the hydro-lithology maps, the hydrogeology class maps from Tier 2b shows a noticeable change, in particular with regard to the basement rocks. For example, the eastern part of the Bay of Plenty is depicted as less permeable than in the Tier 1 maps (Figure 4.1, Figure 4.2 and Figure 4.3). As a result, the Bay of Plenty map shows a strong east-west contrast, with the much younger volcanic and sedimentary rock-types in the western part of the region. Likewise, in Southland the basement ranges composed of, for example, sandstone of Cretaceous age and older, are now more accurately described by lower permeability classes (Figure 4.1, Figure 4.2 and Figure 4.3).

Tier 3 includes main rock type, age and secondary rock type of the deposits. More than 30% of the entire area shows a decrease of the hydrogeology classes from Tier 2b to Tier 3, Table 4.2 compared to about 11% of the area which shows an increase, because of the inclusion of the secondary rock type information (Figure 4.1, Figure 4.2 and Figure 4.3). This includes most of the western side of the Bay of Plenty, as well as the Southland Plains. Other areas, like for example the eastern part of the Gisborne region and the Te Anau Basin, show a higher hydrogeology class than in Tier 2b. However, between Tier 2b and Tier 3, overall, there are more areas with lower hydrogeology classes than areas with higher classes.

The potential aquifer classes derived in Tier 4 show which areas have a high, medium, low or poor potential to be an aquifer (Figure 4.1, Figure 4.2 and Figure 4.3). Known aquifers are easily recognisable in the Tier 4 maps. for example, the Galatea Plains and Rangitaiki Plains in the Bay of Plenty, as well as the Southland Plains and Waimea Plains in Southland. Areas with basement rocks can also be identified from the Tier 4 map, like for example, Fiordland and the Southern Alps on the South Island.

Figure 4.4 shows the comparison of the aquifer potential map with the QMAP geological map that it is based on. For the QMAP legend the reader is referred to the QMAP itself. The 1112 different geological units in the national QMAP are difficult to distinguish at the small scale of the map provided and the complex map legend has been omitted.

Table 4.2 Comparison of the areas that show a decrease, increase or no change of class numbers between Tier 2b and Tier 3, reflecting the influence of the QMAP secondary rock type. For example, an increase of the class number between Tier 2b and Tier 3 is due to the secondary rock type being more permeable than the main rock type.

Area (km^2) where Tier 2 class higher than Tier 3 class	87250
Area (km^2) where Tier 2 class lower than Tier 3 class	30242
Area (km^2) with no change between Tier 2 and Tier 3	145097
Area in (km^2) of ice/water	4758
Total area (km^2)	**267347**

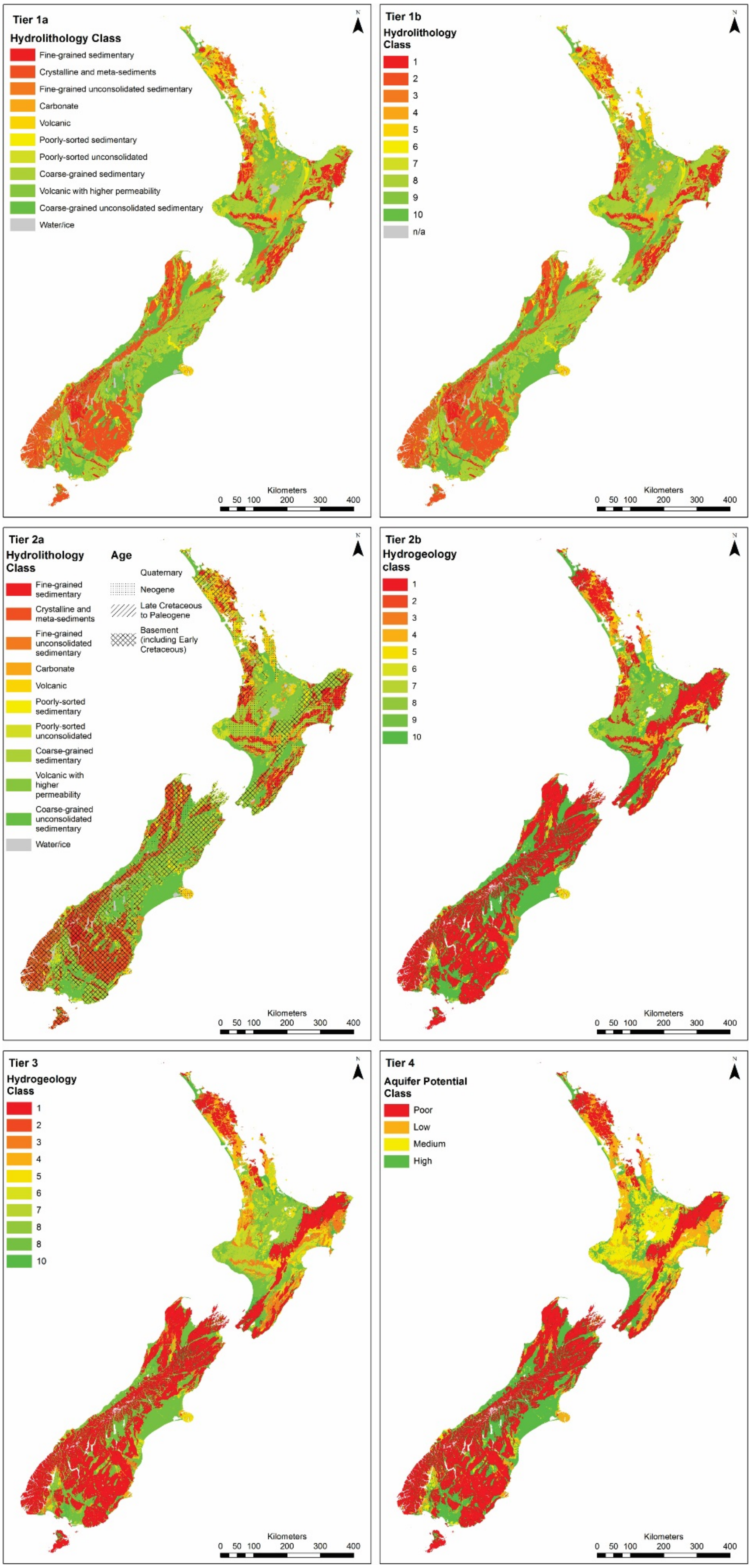

Figure 4.1 QMAP classification for hydro-lithology, hydrogeology and aquifer potential for New Zealand.

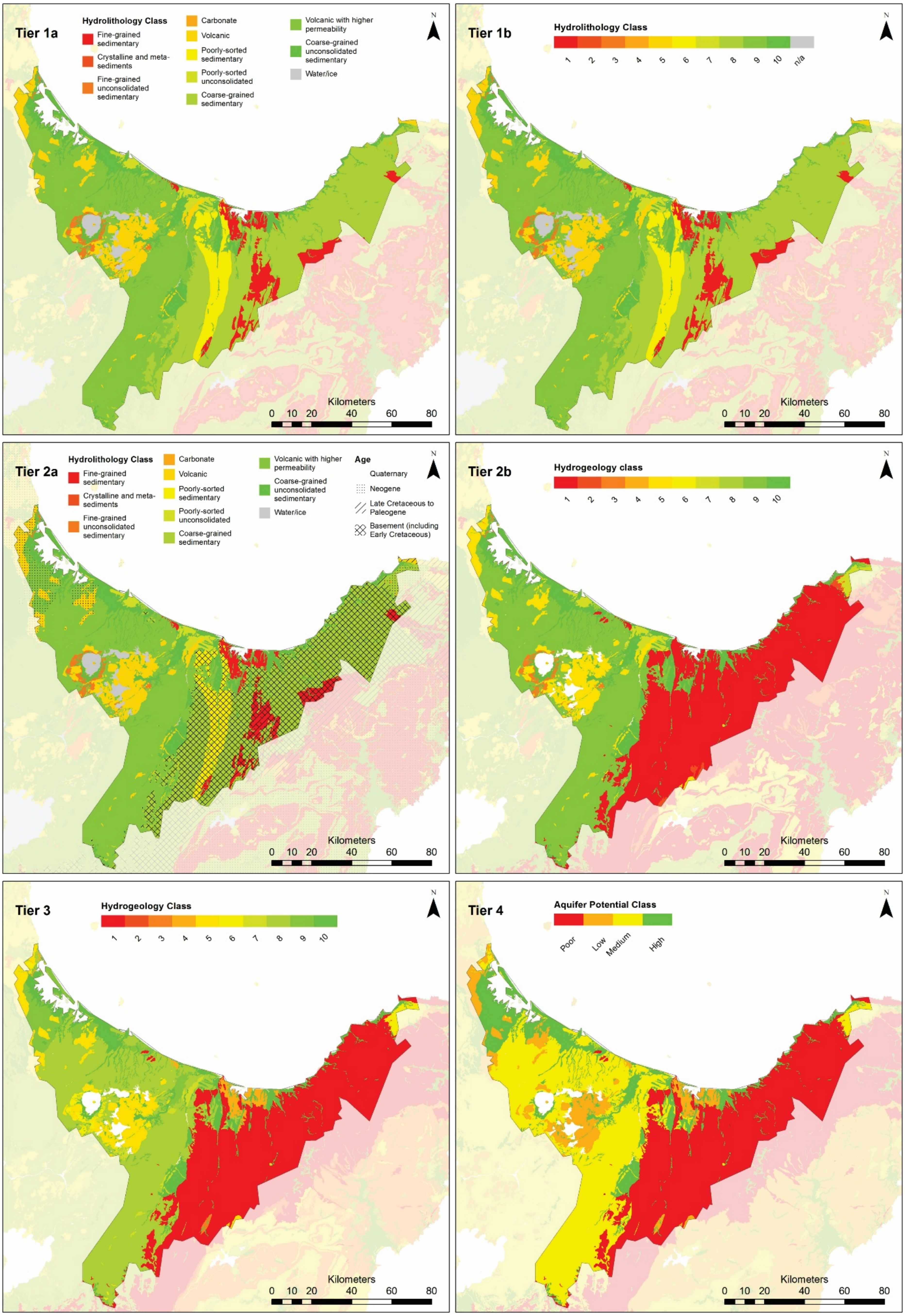

Figure 4.2 QMAP classification for hydro-lithology, hydrogeology and aquifer potential for the Bay of Plenty region.

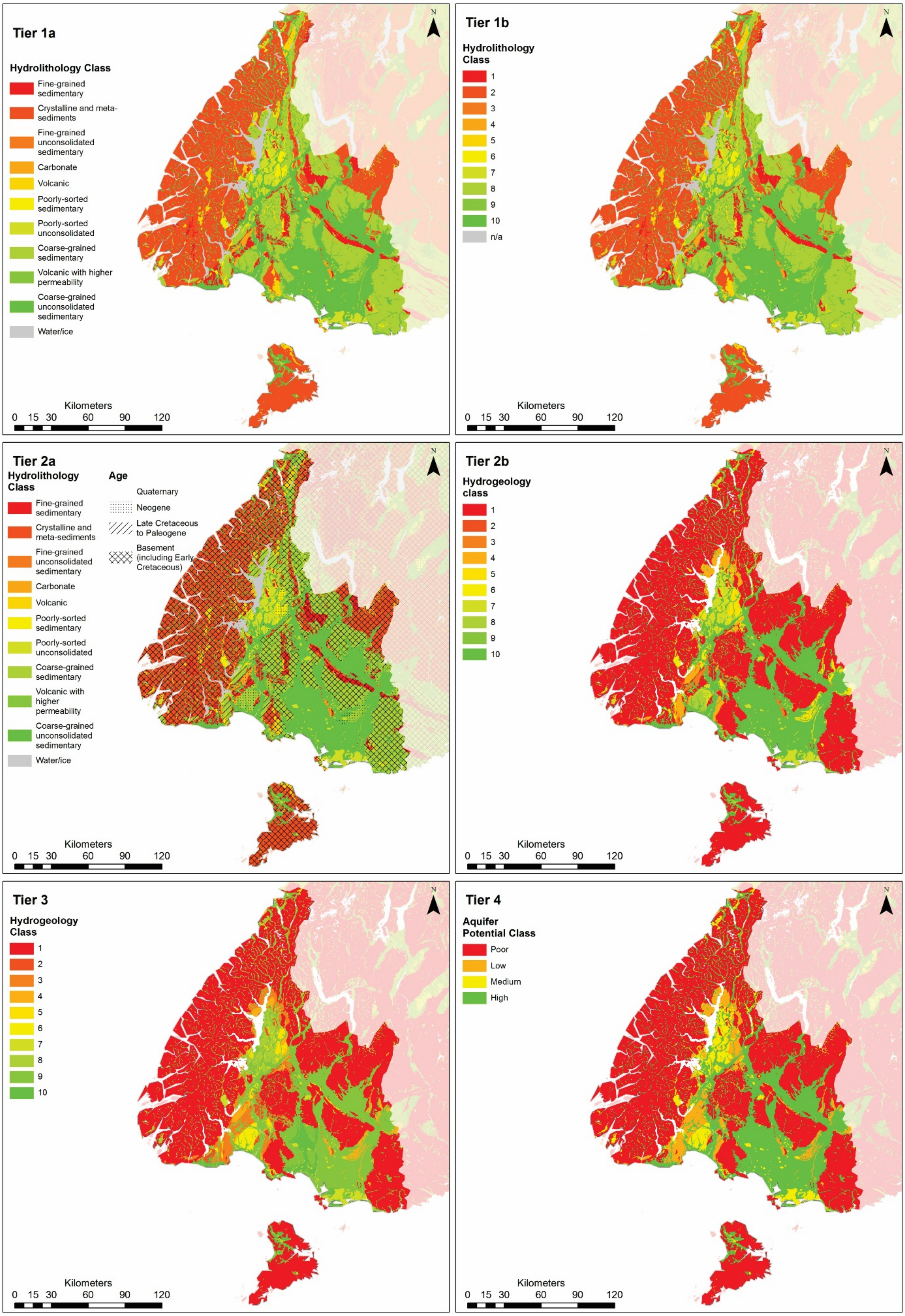

Figure 4.3 QMAP classification for hydro-lithology, hydrogeology and aquifer potential for the Southland region.

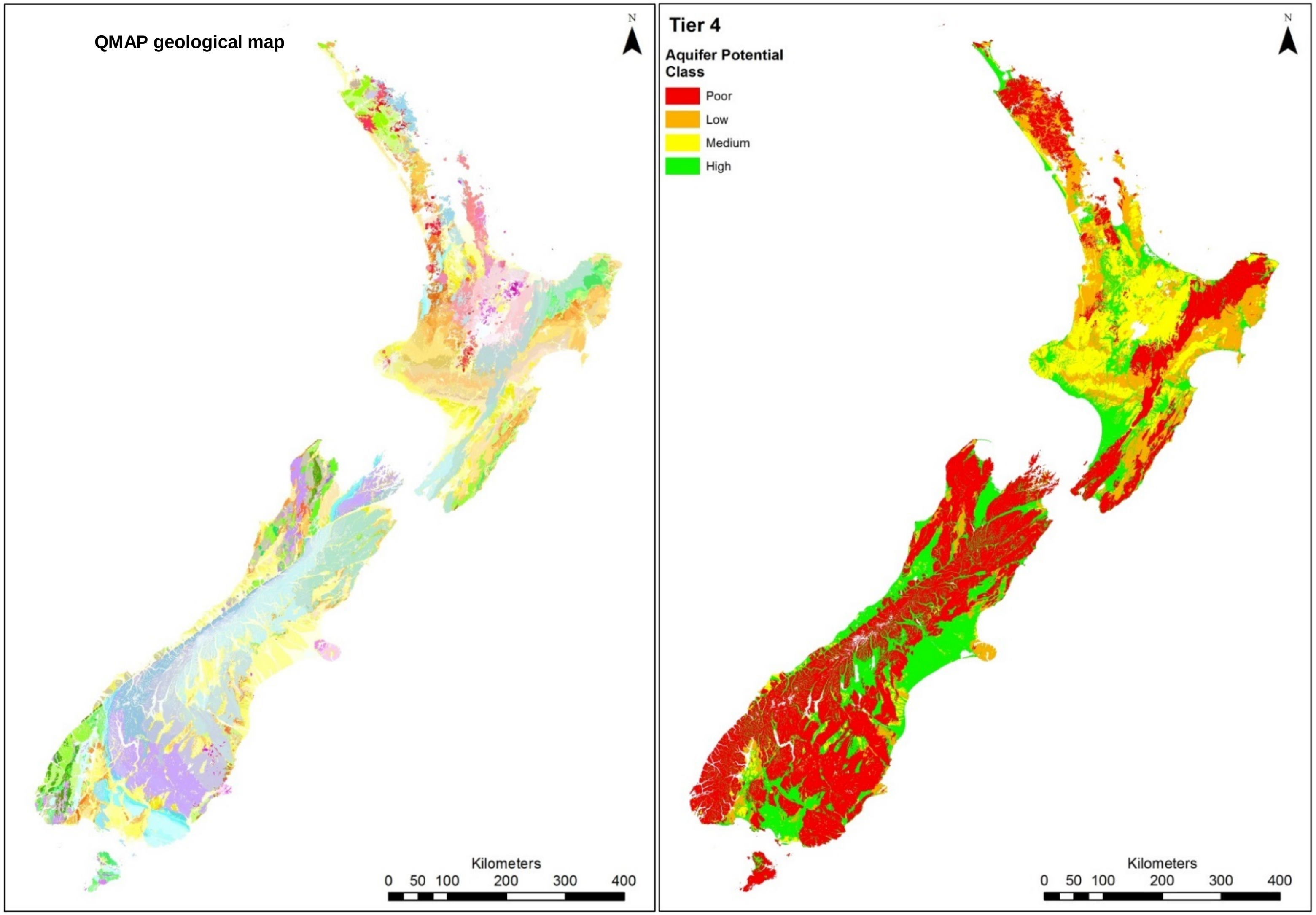

Figure 4.4 Comparison between the QMAP geological map (left) and the aquifer potential map (right) that was based on main rock type, age and sub rock type of the geological units in the QMAP. Purple, grey and blue tones in the QMAP represent basement rocks, green tones Cretaceous rocks, orange tones Neogene and Paleogene sedimentary deposits, darker rose tones Neogene volcanics, light rose tones Quaternary volcanics, and yellow tones Quaternary sediments. Due to the complexity of the QMAP, the reader is referred to Heron (2014) for the full QMAP legend. Other QMAP features, like for example faults, have been omitted in this figure.

4.2 REPRESENTATIVE AQUIFER SYSTEMS IN NEW ZEALAND

The representative aquifer systems are based on the classification of aquifers by White (2001), Section 2.1.1. The comparison of the 'high' and 'medium' classes of the aquifer potential map with the aquifer boundaries and depositional environments from White (2001) generally shows a good level of agreement (Figure 4.5). In particular, the boundaries are well matched for example, in Canterbury and central Otago. However, the aquifer potential map also identifies additional areas, outside of the mapped aquifer boundaries, that could be used to refine the aquifer boundaries and to identify potential unmapped aquifers that could fall into the aquifer categories. For example, a larger deviation between the boundaries is evident in particular in the northern part and on the west coast of the South Island, and, to a smaller degree, for example, in the central and lower North Island.

Terrestrial sedimentary aquifers as shown in White (2001) appear to have primarily high aquifer potential, for example, in the Southland and Greater Wellington regions. Shallow marine sedimentary aquifers show predominantly low aquifer potential in Waikato (Te Kuiti Group), but medium to high aquifer potential in Taranaki (Matemateteonga Formation and Whenakura Group). Terrestrial and shallow marine sedimentary aquifers primarily appear to have high aquifer potential, like for example in the Manawatu-Wanganui and Canterbury regions. There is only one deep sea marine sedimentary aquifer that was defined by White (2001), i.e., the Waitemata Group aquifer, which has been primarily classed as low aquifer potential. The aquifer potential of volcanic aquifers seems to be low to medium. For example, the volcanics in the central North Island show predominantly medium aquifer potential, whereas the older volcanics of the Banks Peninsula have a low aquifer potential. There is only one, comparatively small metamorphic aquifer that has been delineated by White (2001), the Takaka Valley aquifer. The aquifer potential for this aquifer varies between high and poor.

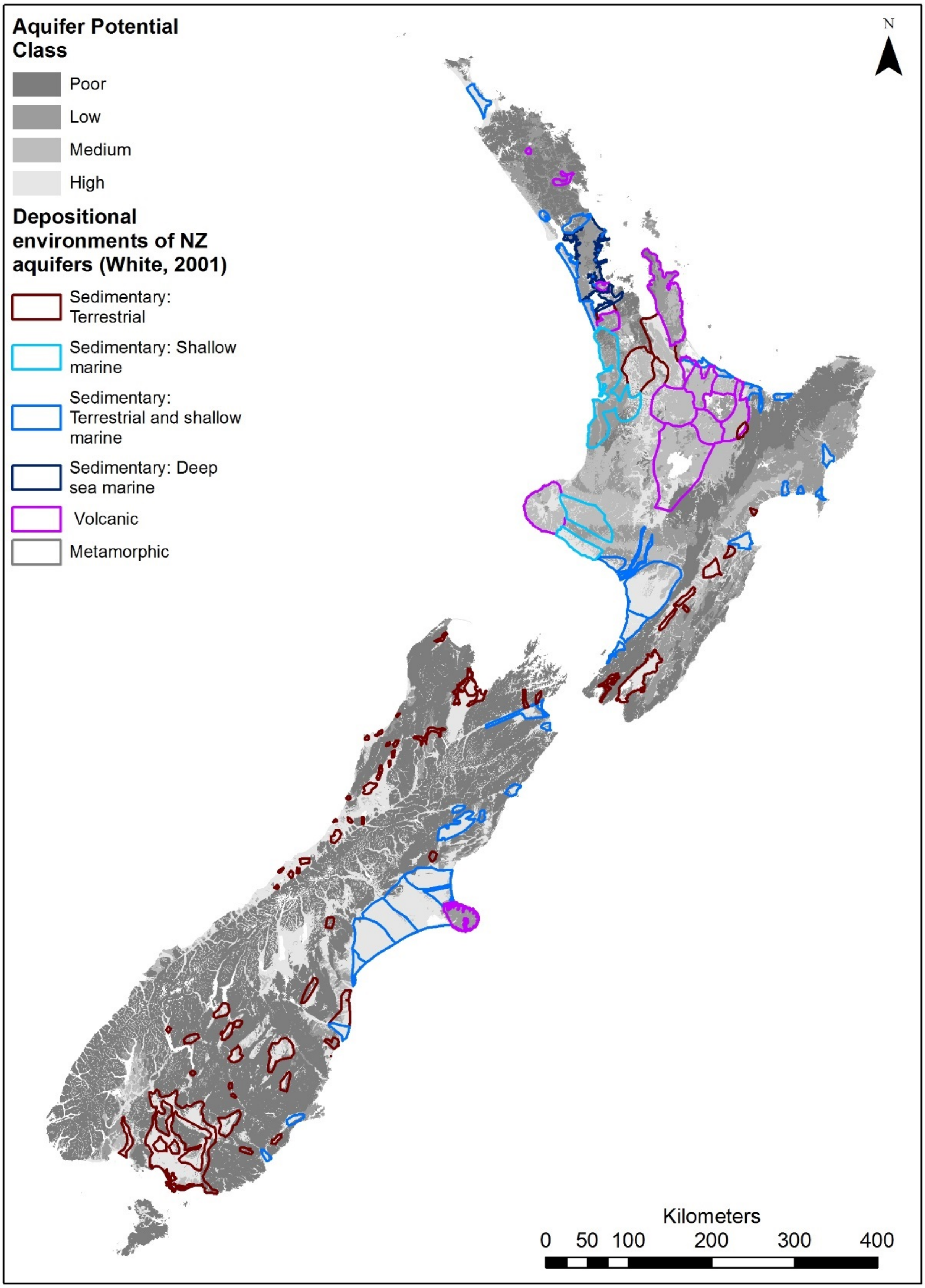

Figure 4.5 Map overlay of Tier 4 aquifer potential map with the aquifer boundaries and depositional environments from White (2001).

5.0 DISCUSSION AND RECOMMENDATIONS

The QMAP geological map, and GIS attribute information associated with the map, was used to derive hydro-lithological, hydrogeological and aquifer potential maps for New Zealand. The QMAP has been compiled at a scale of 1:250,000, which therefore, is also the scale of these interpretive maps. Map scales depend primarily on the size of the area mapped as well as the purpose of the map. For example, Struckmeier and Margat (1995) recommend using map scales of 1:1M for national scale groundwater assessments, 1:200,000 for regional scale and 1:50,000 for local investigations. The scale of the interpretative maps is only slightly larger than the recommended scale for regional groundwater investigations. Additionally, as the QMAP provides the highest resolution nationwide geological map, it serves well as the basis for the hydro-lithological, hydrogeological and aquifer potential maps. The QMAP geological map is subject to several limitations and uncertainties (GNS Science, n.d.) that are transferred to the hydrogeological maps. The accuracy of the boundaries between QMAP polygons is limited to +/- 250 m. Additionally, geological units that are less than 5 – 10 m thick are generally not displayed in the QMAP unless they are particularly geologically significant. As a result, the QMAP data is generalised, and some aquifers may not be distinguishable in the hydrogeological maps at this scale.

Other uncertainties are based on decisions and thresholds used in the methodology, such as the relation with age, the incorporation of secondary rock types, and the thresholds defined for the classes. These are described below.

The combined use of the main rock, sub rock and age attributes of the geological units in the QMAP has achieved good results for the nationwide hydrogeological classification and mapping. The comparison of the results of the Tier 1 hydro-lithology and Tier 2 hydrogeology maps (main rock and age) highlights the inadequacy of using just the main rock attribute. For example, geological units that are known as hydrogeological basement are represented by higher permeability hydro-lithological classes in the Tier 1 maps, but are appropriately depicted as lower permeability hydrogeological classes in the Tier 2b map, due to the addition of age information. However, the age curve function that was used to model the inverse correlation between permeability and age of the deposits (Section 3.3.2) was based on the relationship between porosity and depth of deposits (Section 2.2.6), but the exact decrease of that exponential decrease function was chosen arbitrarily at this stage. Such a relationship is considered valid within a sedimentary basin depositional environment, where age and depth are directly linked, and permeability is decreased via weathering, compaction and diagenesis processes. However, this relationship will vary depending on the depositional environment, and in some environments, secondary permeability will result in increased permeability with age (rather than decreased). Such complex relationships will be incorporated within future work that will include refinement of an age-permeability relationship for each aquifer system type, combined with compilations of measured hydraulic properties for ground-truthing and calibration.

Augmenting the Tier 2b maps with secondary rock type in Tier 3 resulted in higher hydrogeology classes over large areas. Lower hydrogeology classes occurred to a lesser degree. Decrease of hydrogeological classes implies lesser permeabilities and therefore, results in a more conservative hydrogeological map. The 'SUB_ROCKS' field (i.e., secondary rock type) in the QMAP generally lists several items that were assumed to occur in the same proportion and were weighted against the 'main rock type'. Lewis *et al.* (2006) based the weight of each secondary rock type on the order in the secondary rock type list, assuming that the order of listed lithologies equated to the order of maximum occurrence. However, in QMAP, these proportions, and the weighting against the 'main rock type', may however vary for each map polygon or even for each QMAP sheet, depending on the compiler. This limitation is inherent to the QMAP data, as the QMAP attributes do not describe at which proportions each secondary rock type occurs. Therefore, it is also not possible to improve the weighting ratios by looking at the attributes only. However, weighting and proportions could be adjusted for each aquifer system via ground-truthing and more detailed literature reviews of specific formations relevant to each aquifer system. For example, if it is known that the depositional environment of a sand deposit was marine, then components of silt and clay may be large. On the contrary, the components of silt and clay are likely to be smaller if the depositional environment was fluvial.

Tier 4 simplifies Tier 3 hydrogeological classes to derive aquifer potential classes. The thresholds for this simplified classification have been set arbitrarily and this should be assessed and refined in future work. Similarly, thresholds of Tier 2b and Tier 3b were also binned, e.g., all values in between 2 and 3 were assigned to class 3. This binning and classification needs to be reviewed and uncertainties in the classification, due to the above mentioned age curve or uncertainties arising from the QMAP resolution, should be quantified. Future work will assess and refine this classification.

The overlay of the aquifer potential map with the aquifer boundaries from Moreau and Bekele (2015), Figure 5.1, shows that some of the boundaries match areas with high and medium aquifer potential very well. Other aquifer boundaries, like for example in the West Coast region, vary considerably from areas with high and medium aquifer potential and the actual extents of potential aquifers should be investigated further.

The comparison between the aquifer potential map and representative aquifer system boundaries yielded expected results for New Zealand's aquifers in different depositional environments. For example, terrestrial and terrestrial and shallow marine aquifers, which comprise some of the most important aquifers in New Zealand, generally show the highest aquifer potential. The one metamorphic aquifer represented in the map shows, as expected, low aquifer potential. The agreement between the representative classes and expected aquifer potential confirms that the approach used in this project was appropriate for a nationwide hydrogeological classification.

The comparison between the QMAP geological map and the aquifer potential map highlighted some of the rationales behind this project. There are such a large number of mapped geological units within QMAP that it is not possible to display its map legend on a one-page national map in a readable and useable way. Additionally, due to the complexity of the QMAP unit codes and descriptions, geological and hydrogeological expertise is required to be able to apply QMAP map data to hydrogeology. The aquifer potential map is straightforward and easy to understand, providing a quick and simple way to communicate hydrogeological information.

The move from a descriptive approach to a numerical approach allows higher flexibility in incorporating age and sub rock type. The descriptive approach yielded adequate results when only one dataset (main rock type) was used. However, it was not sufficient for the combined application of several attributes (main rock type, age and sub rock type). Furthermore, it is expected that the inclusion of additional datasets in the future (e.g., rainfall recharge) is best achieved with the numerical approach.

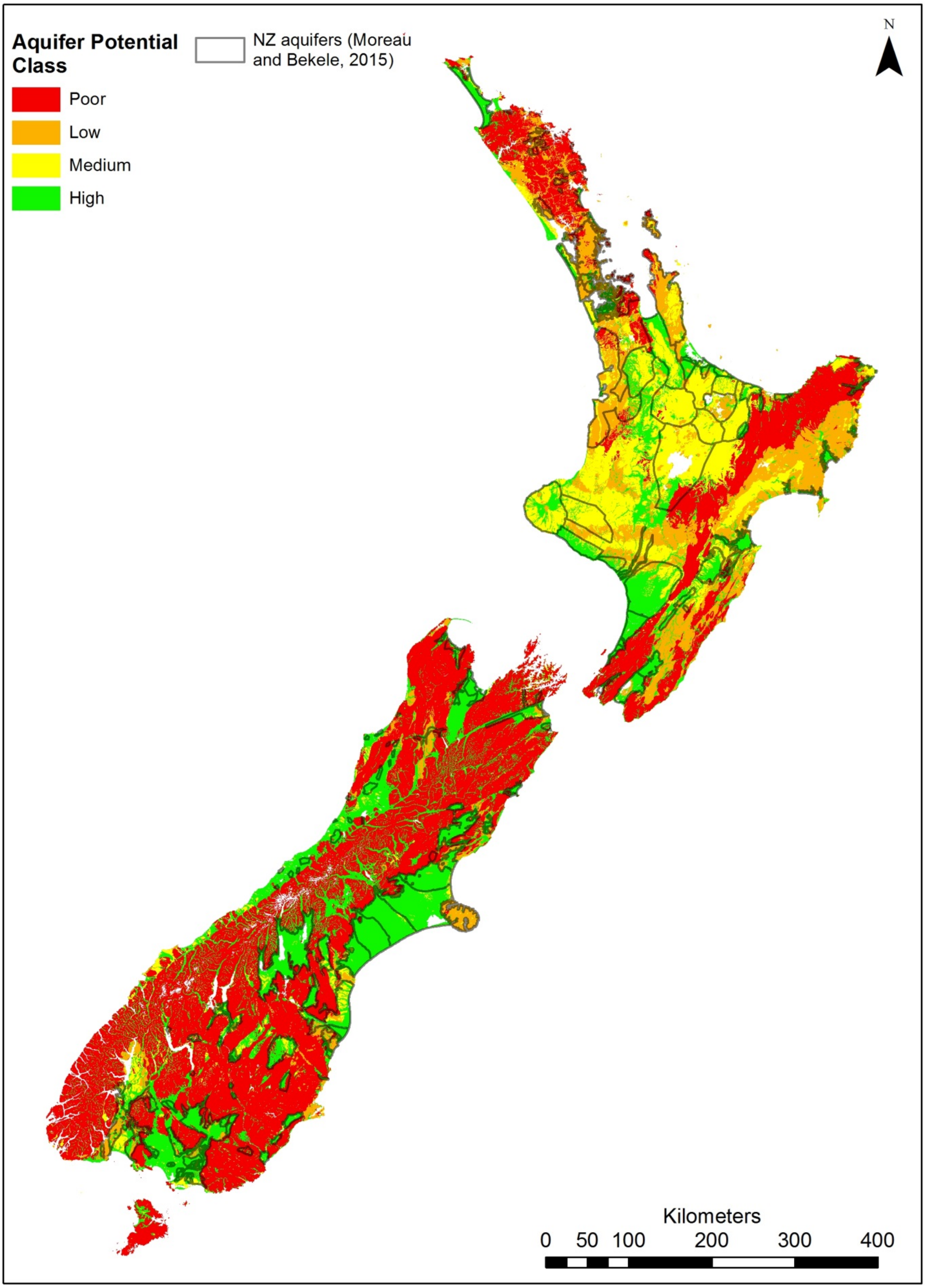

Figure 5.1 Map of New Zealand showing the aquifer potential classes inferred in this report and the aquifer boundaries from Moreau and Bekele (2015).

There is currently no national database for hydraulic properties, bore holes or other groundwater information, such as the BGS Aquifer Property database and the Environmental Agency's National Abstraction License Database, Section 2.2.3.2, and at present, there has been no validation using observations (e.g., measured hydraulic properties) of the developed maps. Therefore, hydraulic properties will need to be compiled in the next phase of the project and then linked to the hydrogeology class and aquifer potential maps.

Future work could also include the incorporation of socio-economic aspects, like aquifer productivity, as done for example by Abesser and Lewis (2015) and Ramoeli *et al.* (2010), based on assembled hydraulic properties, Section 2.2.3.2 and Section 2.2.2, respectively. Furthermore, the datasets from this phase of the project and future phases could be enhanced with additional information, including a national groundwater table or a thickness of Quaternary deposits map, similar to what has been done by BGS (2016e), Section 2.2.3.2. as well as the calculation of a distance buffer dataset, which could be used to determine the data uncertainty (BGS 2016e), Section 2.2.3.2. In addition, tectonic features like faults were not included in other works, for example the permeability indices developed for the United Kingdom by Lewis *et al.* (2006). However, those are a far more significant issue in the tectonic active New Zealand landscape, and future work should also look at the implications of tectonic processes on groundwater flow and could consider settings of and connections with geothermal systems.

6.0 CONCLUSIONS

This report describes Phase 1 of the GWR National Classification and Mapping project, which is the utilising QMAP surface geological data to build aquifer potential classes in New Zealand at the national scale. The first three hydrogeology-related digital maps have been developed for New Zealand at the 1:250,000 scale:

1. A New Zealand map (polygon shapefile) of hydro-lithological units (Tier 1).

2. A New Zealand map (polygon shapefile) of hydrogeological units (Tier 3).

3. A New Zealand map (polygon shapefile) of aquifer potential (Tier 4).

These maps are publically available (refer to Section 4.3 for the disclaimer) under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0) licence. The datasets match well with overlays of current maps of aquifer boundaries. The datasets also match well to the expected hydrogeological character of the regional case studies presented (Southland and Bay of Plenty regions), which have previously been studied in detail by the authors. Additionally, they provide a quick and simple way to communicate hydrogeological information, e.g., the aquifer potential of an area.

It is important to note that the maps derived as a result of the work presented in this report are preliminary results that will be ground-truthed and refined in the next phase of this project. It is also acknowledged that further work is required to ascertain depth information. Therefore, the maps should not be used for much more than an indication of potential hydraulic behaviour, and no decisions should be made on the basis of these maps.

The next phases of this project include:

- assessing the inclusion of additional nation-wide datasets such as rainfall recharge;
- including actual hydraulic properties measured throughout New Zealand to characterise aquifer systems and use as a classifier for aquifer potential;
- ground-truthing of the maps using yield, water levels and other indicator;
- deriving a new national aquifer boundary map using the datasets derived in this report, previous aquifer boundaries and additional data (e.g., well data); and
- classifying the derived aquifer boundary map into representative New Zealand aquifer systems to enable more advanced future work such as 3D assessments (e.g., layered aquifer types, syncline structures, etc.).

7.0 ACKNOWLEDGEMENTS

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8.0 REFERENCES

Abesser, C.; Lewis, M. 2015. A semi-quantitative technique for mapping potential aquifer productivity on the national scale: example of England and Wales (United Kingdom). Hydrogeol. J. 23, 1677-1694. doi:10.1007/s10040-015-1295-5

Ahnert, F. 1970. Functional relationships between denudation, relief, and uplift in large, mid-latitude drainage basins. Am. J. Sci. 268, 243-263.

Begg, J., 2016. Senior Scientist, Regional Geology, GNS Science, personal communication.

Beven, K.J. ; Kirkby, M.J. 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. Hydrol. Sci. J. 24, 43-69.

BGS, 2016a. Hydrogeological maps of the United Kingdom [WWW Document]. URL http://www.bgs.ac.uk/data/maps/maps.cfc?method=listResults&mapName=&series=HYDRO&scale=&pageSize=100& (accessed 4.5.16).

BGS, 2016b. Digital hydrogeological map of the United Kingdom and Isle of Man [WWW Document]. URL http://www.bgs.ac.uk/research/groundwater/datainfo/hydromaps/hydro_map_625.html (accessed 4.5.16).

BGS, 2016c. Web map: Digital hydrogeological map of the United Kingdom and Isle of Man at 1:625,000 scale [WWW Document]. URL http://mapapps2.bgs.ac.uk/geoindex/home.html?layer=BGSHydroMap (accessed 4.5.16).

BGS, 2016d. 1:625,000 scale digital hydrogeological data [WWW Document]. URL http://www.bgs.ac.uk/products/hydrogeology/maps.html (accessed 31.5.16).

BGS, 2016e. Superficial Deposits Thickness Model [WWW Document]. URL http://digimap.edina.ac.uk/webhelp/geology/data_information/bgs_products_available/superficial_thickness_model.htm (accessed 4.5.16).

Environment Court, 2011. Decision No. NZEnvC 163 on the Proposed Waikato Regional Plan Variation 5 - Lake Taupo catchment, 48p.

Fan, Y.; Li, H.; Miguez-Macho, G. 2013. Global patterns of groundwater table depth. Science 339, 940-943.

Freeze, R.A.; Cherry, J.A. 1979. Groundwater. Prentice Hall, 604p.

Gleeson, T.; Smith, L.; Moosdorf, N.; Hartmann, J.; Dürr, H.H.; Manning, A.H.; van Beek, L.P.H.; Jellinek, A.M. 2011. Mapping permeability over the surface of the Earth. Geophys. Res. Lett. 38, L02401. 6p. doi:10.1029/2010GL045565

Hart, D.J.; Hammon, W.S. 2002. Measurement of hydraulic conductivity and specific storage using the Shipboard Manheim Squeezer, in: Salisbury, M.H., Shinohara, M., Richter, C., others (Eds.), Proceedings of the Ocean Drilling Program, Initial Reports Volume 195. 15p.

Herman, G.C.; Canace, R.; Stanford, S.D.; Pristas, R.S.; Sugarman, P.J.; French, M.A.; Hoffman, J.; Serfes, M.S.; Mennel, W.J. 1998. Aquifers of New Jersey. Open-File Map OFM 24.

Heron, D.W. (Ed.), 2014. Geological Map of New Zealand 1:250 000, 1 DVD containing digital GIS vector data + all 21 QMAP texts as PDFs. GNS Science, Lower Hutt.

Kreye, R.; Ronneseth, K.; Wei, M. 1994. An Aquifer Classification System for Ground Water Management in British Columbia. Ministry of Environment - Water Stewardship Division - Aquifer Classification [WWW Document]. URL http://www.env.gov.bc.ca/wsd/plan_protect_sustain/groundwater/aquifers/Aq_Classification/Aq_Class.html (accessed 28.6.16).

Lewis, M.A.; Cheney, C.S.; O Dochartaigh, B.E. 2006. Guide to permeability indices. British Geological Survey Open Report, CR/06/160N. 29p.

Liggett, J.E.; Talwar, S. 2009. Groundwater vulnerability assessments and integrated water resource management. Watershed Manag Bull 13, 18-29.

Lovett, A.; Cameron, S.G. 2015. Development of a National Groundwater Atlas for New Zealand.pdf, GNS Science Report SR2014/030. 8p.

MacDonald, A.M.; Ball, D.F.; Ó Dochartaigh, B.E. 2004. A GIS of aquifer productivity in Scotland: explanatory notes. British Geological Survey Commissioned Report, CR/04/047N. 21p.

Moore, C., Nokes, C., Loe, B., Close, M.E., Pang, L., Smith, V., Osbaldiston, S., 2010. Guidelines for separation distances based on virus transport between on-site domestic wastewater systems and wells, ESR Client Report No. CSC1001. Environmental Science and Research, Porirua, N.Z., 269p.

Moreau, M.; Bekele, M. 2015. Groundwater component of the Water Physical Stock Account (WPSA), GNS Science Consultancy Report CR2014/290. 35p.

Moreau-Fournier, M.; Cameron, S.G. 2011. New Zealand groundwater volume stock account, Unpublished GNS Science Letter Report to Statistics New Zealand 2011/99LR. GNS Science, 21p.

Parker, A.; Sellwood, B.W. 2012. Sediment Diagenesis. Springer Science & Business Media, 431p.

Person, M.; Raffensperger, J.P.; Ge, S.; Garven, G. 1996. Basin-scale hydrogeologic modeling. Rev. Geophys. 34, 61-87.

Pietersen, K.; Kellgren, N.; Roos, M. 2013. Compiling the South African Development Community Hydrogeological Map and Atlas: Opportunities for the future, in: Cobbing, J., Adams, S., Dennis, I., Riemann, K. (Eds.), Assessing and Managing Groundwater in Different Environments, IAH - Selected Papers on Hydrogeology 19. p. 265-283.

Rajanayaka, C.; Donaggio, J.; McEwan, H. 2010. Update of water allocation data and estimate of actual water use of consented takes 2009-2010, Aqualinc Research Report H10002/3. New Zealand Ministry for the Environment, 118p.

Ramoeli, P.; Farrington, T.; Quist-Hoffmann, P.; Katai, O.; Lekgowe, O. 2010. SADC - Explanatory Brochure for the South African Development Community (SADC) Hydrogeological Map & Atlas.pdf, A report to the southern Aftrican Development Community (SADC) and cooperating partners: European Union and GTZ. 51p.

Statistics New Zealand, 2010. Environmental economic accounts [WWW Document]. URL http://www.stats.govt.nz/browse_for_stats/environment/environmental-economic-accounts.aspx (accessed 17.5.16).

Struckmeier, W.F.; Margat, J. 1995. Hydrogeological maps: a guide and a standard legend, International Contributions to Hydrogeology 17. Heise Hannover, 177p.

Summerfield, M.A.; Hulton, N.J. 1994. Natural controls of fluvial denudation rates in major world drainage basins. J. Geophys. Res.- Ser.- 99, 13-871.

Tschritter, C.; Cameron, S.G.; White, P.A. 2014. Incorporation of hydraulic properties in three-dimensional geological models, GNS Science Report SR2013/53, 30p.

Wada, Y.; Wisser, D.; Bierkens, M.F.P. 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dyn. 5, 15.

White, P.A. 2001. Groundwater resources in New Zealand., in: Rosen, M.R., White, P.A. (Eds.), Groundwaters of New Zealand. pp. 45-75.

White, P.A. 2005. New Zealand groundwater volumes - Update for June 2005, GNS Science Unpublished Letter Report to Statistics New Zealand. GNS Science, 2p.

White, P.A.; Reeves, R.R. 2002. The volume of groundwater in New Zealand 1994 to 2001, Institute of Geological and Nuclear Sciences CR2002/79. GNS Science, 37p.

White, P.A.; Sharp, B.M.H.; Reeves, R.R. 2004. New Zealand water bodies of national importance for domestic use and industrial use, Prepared for the Ministry of Economic Development by the Institute of Geological and Nuclear Sciences, Wellington. 96p.

APPENDICES

APPENDIX 1: LOCATION MAPS

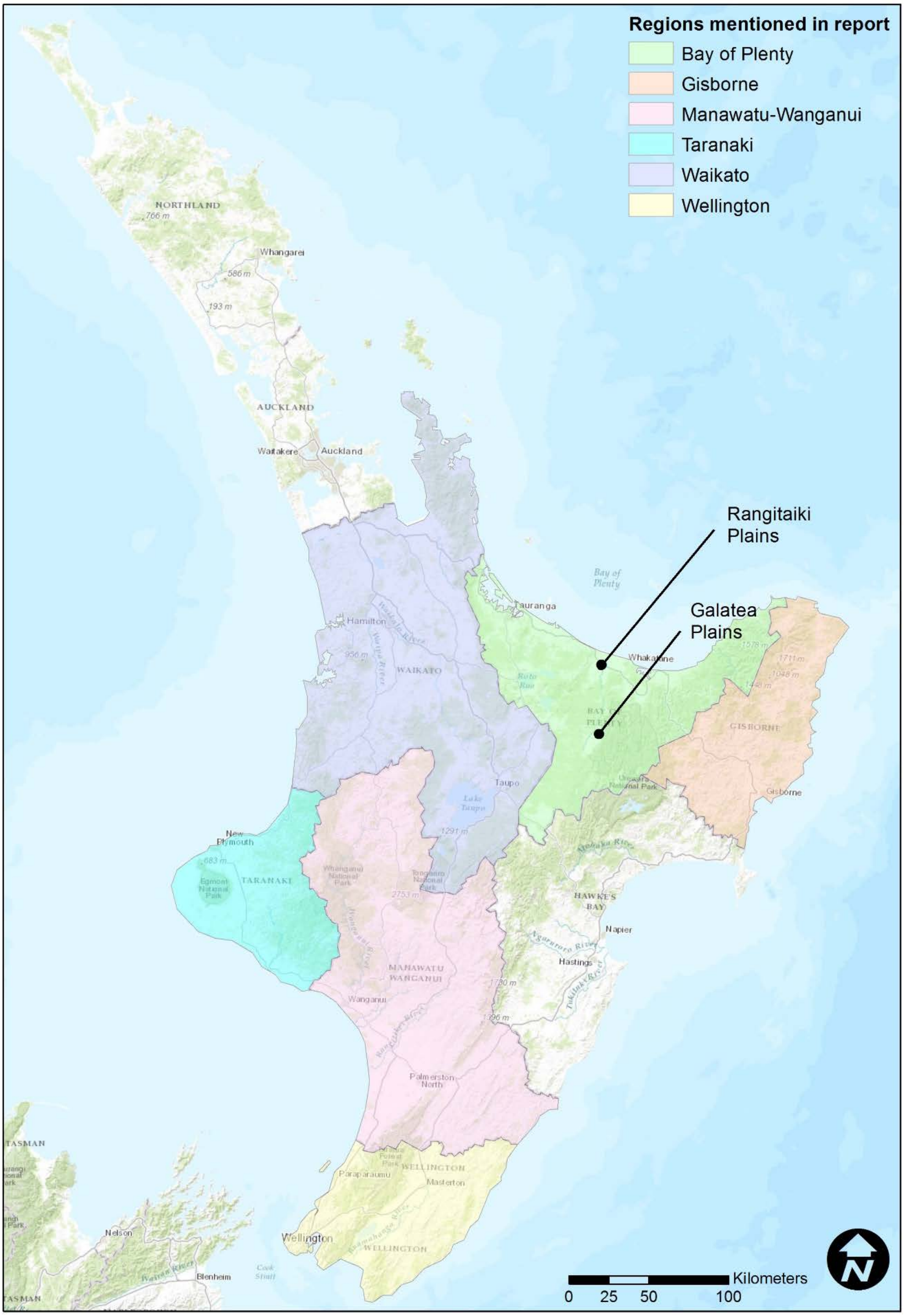

Figure A1.1 North Island regions and places mentioned in this report.

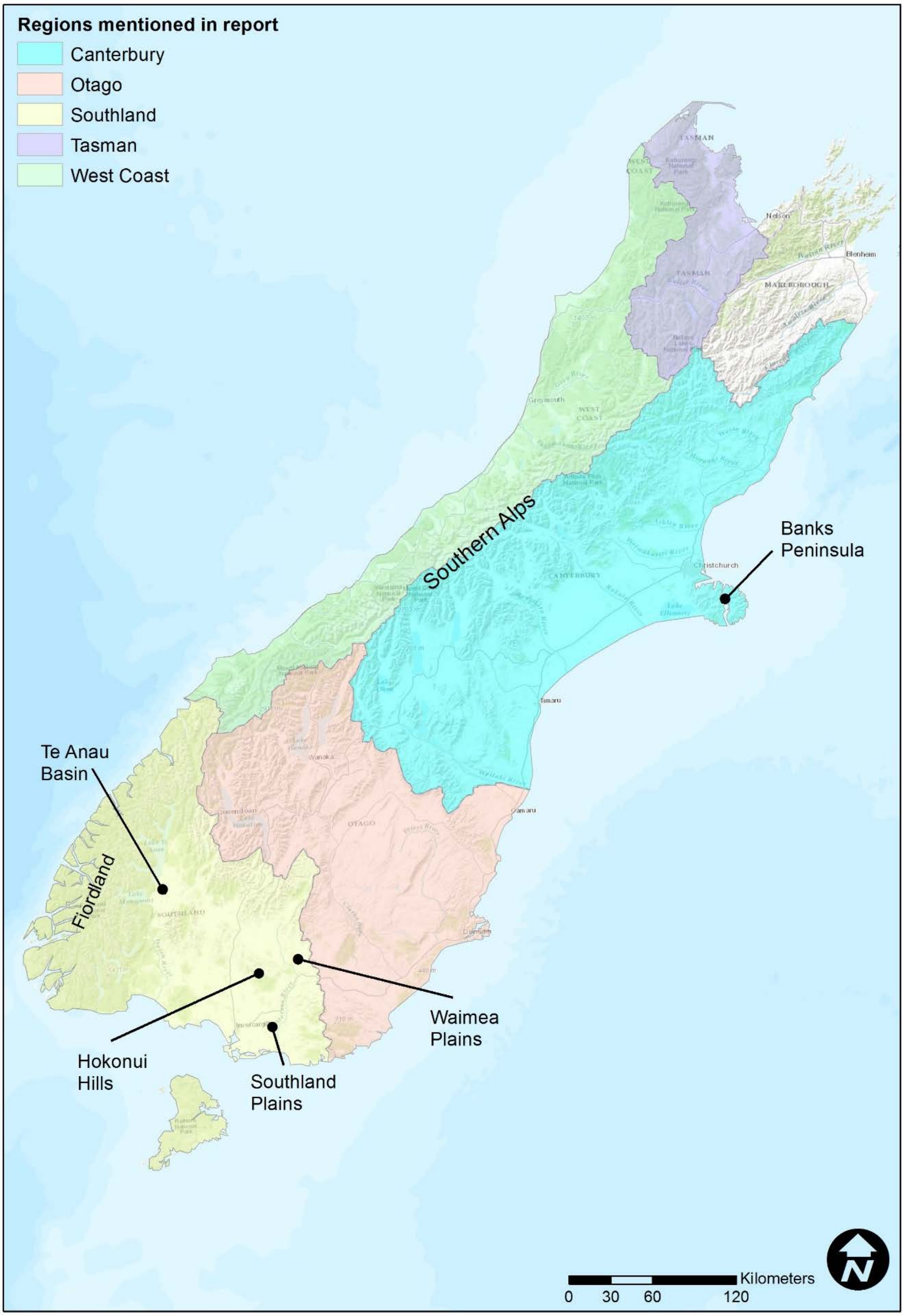

Figure A1.2 South Island regions and places mentioned in this report.

APPENDIX 2: CLASSIFICATION OF QMAP 'MAIN_ROCK' AND 'SUB_ROCKS' ATTRIBUTES INTO HYDRO-LITHOLOGY UNITS AND CLASSES

Table A2.1 Classification of QMAP 'MAIN_ROCK' and 'SUB_ROCKS' attributes into hydro-lithology units and classes.

Name in QMAP Attribute table	Hydro-lithology unit	Hydro-lithology class
agglomerate'	poorly sorted unconsolidated	7
agmatite'	crystalline and metasediments	2
algal limestone'	carbonate	4
alkali'	crystalline and metasediments	2
amphibolite'	crystalline and metasediments	2
'andesite'	volcanic	5
'andesite lava'	volcanic	5
anorthosite'	crystalline and metasediments	2
anothosite'	crystalline and metasediments	2
aplite'	crystalline and metasediments	2
'argillite'	crystalline and metasediments	2
ash'	volcanic	5
'basalt'	volcanic	5
'basaltic andesite'	volcanic	5
basanite'	crystalline and metasediments	2
benmoreite'	volcanic	5
'biosparite'	carbonate	4
boulder'	coarse-grained unconsolidated	10
'boulders'	coarse-grained unconsolidated	10
'breccia'	poorly sorted sedimentary	6
'broken formation'	poorly sorted sedimentary	6
'calcareous mudstone'	fine-grained sedimentary	1
'calc-silicate'	crystalline and metasediments	2
calc-silicates'	crystalline and metasediments	2
carbonaceous'	carbonate	4
'cataclasite'	crystalline and metasediments	2
'chert'	crystalline and metasediments	2
'clay'	fine-grained unconsolidated	3
'claystone'	fine-grained sedimentary	1
'clinopyroxenite'	crystalline and metasediments	2
'coal'	carbonate	4
cobble'	coarse-grained unconsolidated	10
'conglomerate'	poorly sorted sedimentary	6
'coquina'	carbonate	4
'dacite'	volcanic	5
'debris'	poorly sorted unconsolidated	7
'diatomite'	fine-grained sedimentary	1
dikes'	volcanic	5
'diorite'	crystalline and metasediments	2
'dioritic orthogneiss'	crystalline and metasediments	2
'dolerite'	crystalline and metasediments	2

Name in QMAP Attribute table	Hydro-lithology unit	Hydro-lithology class
domestic waste'	fine-grained unconsolidated	3
'dunite'	crystalline and metasediments	2
eclogite'	crystalline and metasediments	2
epidiorite'	crystalline and metasediments	2
feldspar'	crystalline and metasediments	2
'fill'	fine-grained unconsolidated	3
'gabbro'	volcanic	5
'gabbroic orthogneiss'	crystalline and metasediments	2
'gabbronorite'	crystalline and metasediments	2
'gneiss'	crystalline and metasediments	2
gold'	poorly sorted unconsolidated	7
'granite'	crystalline and metasediments	2
granitic'	crystalline and metasediments	2
'granitoid'	crystalline and metasediments	2
'granodiorite'	crystalline and metasediments	2
granophyre'	crystalline and metasediments	2
'granulite'	crystalline and metasediments	2
'gravel'	coarse-grained unconsolidated	10
'greensand'	coarse-grained sedimentary	8
'greenschist'	crystalline and metasediments	2
greyschist'	crystalline and metasediments	2
'greywacke'	crystalline and metasediments	2
grit'	poorly sorted unconsolidated	7
'harzburgite'	crystalline and metasediments	2
'hawaiite'	volcanic	5
hornblende'	crystalline and metasediments	2
'hornblendite'	crystalline and metasediments	2
'hornfels'	crystalline and metasediments	2
hyaloclastite'	crystalline and metasediments	2
'ignimbrite'	highly permeable volcanics	9
industrial waste'	fine-grained unconsolidated	3
'keratophyre'	crystalline and metasediments	2
'lamprophyre'	crystalline and metasediments	2
'lapilli tuff'	volcanic	5
lavas'	volcanic	5
leucodiorite'	crystalline and metasediments	2
leucogranite'	crystalline and metasediments	2
leucogranitic'	crystalline and metasediments	2
leuco-tonalite'	crystalline and metasediments	2
lherzolite'	crystalline and metasediments	2
'lignite'	carbonate	4
'limestone'	carbonate	4
'loess'	fine-grained unconsolidated	3
'marble'	crystalline and metasediments	2
marl'	carbonate	4

Name in QMAP Attribute table	Hydro-lithology unit	Hydro-lithology class
megacristic'	crystalline and metasediments	2
megacrystic'	crystalline and metasediments	2
meladiorite'	crystalline and metasediments	2
'melange'	poorly sorted sedimentary	6
metabasite'	crystalline and metasediments	2
'metachert'	crystalline and metasediments	2
'metaconglomerate'	crystalline and metasediments	2
'metamudstone'	crystalline and metasediments	2
'metapelite'	crystalline and metasediments	2
metapsammite'	crystalline and metasediments	2
'metasandstone'	crystalline and metasediments	2
metasediment'	crystalline and metasediments	2
metatuff'	crystalline and metasediments	2
metavolcanic'	crystalline and metasediments	2
metavolcanic'	volcanic	5
'metavolcanics'	crystalline and metasediments	2
'micrite'	crystalline and metasediments	2
'microdiorite'	crystalline and metasediments	2
'migmatite'	crystalline and metasediments	2
'monzodiorite'	crystalline and metasediments	2
'monzogranite'	crystalline and metasediments	2
monzonite'	crystalline and metasediments	2
'mud'	fine-grained unconsolidated	3
'mudstone'	fine-grained sedimentary	1
'mylonite'	crystalline and metasediments	2
'none'	fine-grained sedimentary	1
'norite'	crystalline and metasediments	2
obsidian'	volcanic	5
oil'	poorly sorted sedimentary	6
'olivine basalt'	volcanic	5
olivine nephelinite'	crystalline and metasediments	2
'orthogneiss'	crystalline and metasediments	2
'paragneiss'	crystalline and metasediments	2
'peat'	poorly sorted unconsolidated	7
pebble'	poorly sorted unconsolidated	7
pegmatite'	crystalline and metasediments	2
'pelite'	fine-grained sedimentary	1
'peridotite'	crystalline and metasediments	2
'phonolite'	crystalline and metasediments	2
phyllite'	crystalline and metasediments	2
'phyllonite'	crystalline and metasediments	2
plagiogranite'	crystalline and metasediments	2
'porphyry'	crystalline and metasediments	2
'psammite'	crystalline and metasediments	2
'pumice'	volcanic	5

Name in QMAP Attribute table	Hydro-lithology unit	Hydro-lithology class
pyroclastic'	volcanic	5
'pyroclastic breccia'	volcanic	5
'pyroclastics'	volcanic	5
'pyroxenite'	crystalline and metasediments	2
'quartz diorite'	crystalline and metasediments	2
quartz monozodiorite'	crystalline and metasediments	2
'quartz monzodiorite'	crystalline and metasediments	2
'quartz monzonite'	crystalline and metasediments	2
quartz syenite'	crystalline and metasediments	2
'quartzite'	crystalline and metasediments	2
'rhyodacite'	volcanic	5
'rhyolite'	volcanic	5
rodingite'	crystalline and metasediments	2
'sand'	coarse-grained unconsolidated	10
'sandstone'	coarse-grained sedimentary	8
'schist'	crystalline and metasediments	2
'scoria'	highly permeable volcanics	9
semi-pelite'	crystalline and metasediments	2
'semischist'	crystalline and metasediments	2
serpenitinite'	crystalline and metasediments	2
'serpentinite'	crystalline and metasediments	2
'shale'	fine-grained sedimentary	1
'shell beds'	carbonate	4
shellbeds'	carbonate	4
shingle'	fine-grained sedimentary	1
'silt'	fine-grained unconsolidated	3
'siltstone'	fine-grained sedimentary	1
'sinter'	poorly sorted sedimentary	6
slate'	crystalline and metasediments	2
'spilite'	crystalline and metasediments	2
'syenite'	crystalline and metasediments	2
'syenogranite'	crystalline and metasediments	2
'tephra'	volcanic	5
'till'	poorly sorted unconsolidated	7
'tonalite'	crystalline and metasediments	2
trachyandesite'	volcanic	5
trachybasalt'	volcanic	5
trachydacite'	crystalline and metasediments	2
'trachyte'	crystalline and metasediments	2
'travertine'	carbonate	4
troctolite'	crystalline and metasediments	2
'trondhjemite'	crystalline and metasediments	2
trondjemite'	crystalline and metasediments	2
'tuff'	highly permeable volcanics	9
'turbidite'	poorly sorted sedimentary	6

Name in QMAP Attribute table	Hydro-lithology unit	Hydro-lithology class
ultramafic'	crystalline and metasediments	2
'unknown'	poorly sorted unconsolidated	7
'vitric tuff'	volcanic	5
'volcanic breccia'	poorly sorted sedimentary	6
'volcanic conglomerate'	poorly sorted sedimentary	6
'volcanic sandstone'	coarse-grained sedimentary	8
wehrlite'	crystalline and metasediments	2

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