Classification of New Zealand hydrogeological systems

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GNS Science Report 2018/35
June 2019

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BIBLIOGRAPHIC REFERENCE

Moreau M[1], White PA[1], Mourot F[1], Rawlinson Z[1], Tschritter C[1], Cameron SG[1], Westerhoff R[1]. 2019. Classification of New Zealand hydrogeological systems. Lower Hutt (NZ): GNS Science. 28 p. (GNS Science report; 2018/35). doi:10.21420/42QW-MC74.

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ISSN 2350-3424 (online)
ISBN 978-1-98-856905-5 (online)
http://dx.doi.org/10.21420/42QW-MC74

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ABSTRACT

Digital datasets of New Zealand hydrogeological systems and their boundaries have been developed using a nationally-consistent and transparent methodology. Here, we define hydrogeological systems as geographical areas with broadly-consistent hydrogeological properties, and similar resource pressures and management issues.

These systems are represented in two Geographical Information System (GIS) datasets at the 1:250,000 scale, i.e., hydrogeological system polygons and system boundary polylines. The hydrogeological system polygons (1896 in total) include attributes corresponding to mapping levels, i.e.: unique names; unique identification numbers; system class; coastal information; aquifer overview; geology and age group; and description. The system boundary polylines have attributes identifying the data source and the type of each boundary line, providing transparency and traceability.

These datasets were developed through an iterative process that used GNS Science's QMAP (a national GIS database of surface geology) as the primary input dataset, supplemented by other national datasets (e.g., topographic contours, regional surface drainage and aquifer potential). A method to 'translate' QMAP data into the national map of hydrogeological systems was developed in a pilot region (Southland); validated in a second geologically-contrasting region (Waikato); and then applied nationally to the remaining on-shore New Zealand.

Eight classes of hydrogeological systems were defined as geographical areas with broadly-similar hydrogeological properties, i.e.:

- **Coastal Basin, Inland Basin, Coastal Volcanic and Inland Volcanic** consist of geological units younger than Cretaceous that may include regional and local aquifers that are generally bounded by hydrogeological basement. The prefix 'Coastal' indicates at least one coastal boundary, whereas the prefix 'Inland' indicates no coastal boundary. The suffix 'Basin' is used to identify areas where more than 50% of the surface geological units are of sedimentary origin, elsewhere the suffix 'Volcanic' is used;
- **Inland River Valley** systems include geological units younger than Cretaceous with aquifers that are located in river-valley landforms;
- **Coastal Independent and Basement Infill** systems include units younger than Cretaceous and features (e.g., lakes and ice) completely bounded by Basement Hard Rock. These systems are relatively small (less than 20 km^2);
- **Basement Hard Rock** system comprises Cretaceous and older units, which are considered aquicludes.

The hydrogeological system polygon and system boundary polyline GIS datasets provide a nationally-consistent basis for future hydrogeological mapping. They will be one foundation for future improvements to the understanding of New Zealand's hydrogeology, including: refinement of hydrogeological attributes; identification of new system attributes (e.g., water budget, groundwater chemistry and groundwater age); 3D geological and hydrogeological modelling at a variety of scales (local, regional and national); and linkages to other national datasets.

KEYWORDS

New Zealand, hydrogeology, hydrogeological systems, map, dataset

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1.0 INTRODUCTION

Stewardship of groundwater resources is highly significant for New Zealand's environment, ecology and economy, as well as social and cultural health (White 2001; Ministry for the Environment 2017). The demand for groundwater has grown substantially in recent years, with weekly allocations (based on information from 14 regional and district councils) increasing by 94% from 1999 to 2010 (Rajanayaka et al. 2010). This important resource is mainly used for irrigation use (74% of total groundwater allocation; White 2001). Other uses include industrial and drinking (domestic as well as municipal supplies) by 26% of the population (White 2001). The contribution of groundwater irrigation to the New Zealand economy is sizeable (estimated at $2 billion per annum; Corong et al. 2014). Other New Zealand groundwater uses include processing and bottled water production. Assessments of the effects of land use on water quality, including pathways via groundwater, have become more important as communities aim to protect, or restore, freshwater bodies such as lakes and streams (e.g., Lake Taupo; Environment Court 2011).

New Zealand's aquifers are numerous (more than two hundred), diverse (geological material, flow-process, hydraulic properties, extent, hydrochemistry) and unevenly distributed between regions (White 2001). Groundwater management zones are used by regional councils and unitary authorities to meet their obligations for sustainable management of natural resources under the Resource Management Act (1991). These zones are defined by regional authorities and may correspond to aquifer boundaries, surface water catchments, groundwater management zones, freshwater management units or physiographic zones (e.g., Kroon 2016; Lovett and Cameron 2015; and Rissmann et al. 2016). However, the approach to define groundwater management zones is variable across New Zealand, and the methodology is not typically recorded for each groundwater management zone approach. As a result, research endeavours are hindered and nation-wide overviews of the groundwater state and trends, e.g., the Water Physical Stock Account (Statistics New Zealand 2011), are inconsistent across regions.

A consistent approach to delineate and classify aquifers is needed to better understand, monitor and preserve New Zealand's groundwater resources on a national basis. As multiple aquifers may reside within a single hydrogeological system, the delineation and classification of hydrogeological systems is considered necessary in order to undertake a subsequent step of delineating and classifying aquifers. Here, we define hydrogeological systems as geographical areas with broadly-consistent hydrogeological properties and similar resource pressures and management issues. The release of the New Zealand 1:250,000 Geological Map (QMAP) as a seamless Geographical Information System (GIS) database in 2014 (Heron 2014) provided a dataset suitable to use as the basis for a consistent nationwide classification of hydrogeological systems and delineation of their boundaries at the ground surface. This report describes the methodology used to undertake this work and the resultant digital datasets of New Zealand's hydrogeological systems and their boundaries.

This work is funded by the Ministry of Business, Innovation and Employment under the Strategic Science Investment Fund (SSIF) as part of GNS Science's Groundwater Resources of New Zealand (GWR) research programme.

2.0 METHOD

2.1 Scope

The geographic scope for this project was defined as the New Zealand extent of QMAP polygons, which are available as GIS datasets identifying geological units (Heron 2014). The systems datasets (polygons and polylines) and associated metadata (attributes) were delineated seamlessly using the ArcGIS software, version 10.5.1, with consistency checks and minimal manual delineation.

2.2 Input Datasets

Hydrogeological systems were classified using the following datasets: QMAP GIS data (e.g., polygons and faults; Heron 2014), a digital elevation model to investigate the use of varying interval's on topographic contours (NZSoSDEM v1.0, Columbus et al. 2011), 20 m-interval digital topographic contours and regional surface drainage information (Topo50 maps; LINZ 2018; regional council surface water catchment boundaries), relevant publications (e.g., Quaternary shorelines; Turnbull and Allibone 2003), a digital aquifer potential map (Tschritter et al. 2017) and a map of New Zealand's marine weather zones (MetService 2015).

2.3 Uncertainty of Input Datasets

Each dataset used to create the hydrogeological system classification was associated with some uncertainty pertaining to its scale, resolution and capture. The four key datasets used were: the QMAP dataset, the NZSoSDEM, the topographic contours of the Topo50 dataset, and surface water catchment polygons for 10 regional councils (Auckland, Bay of Plenty, Canterbury, Gisborne, Wellington, Hawkes' Bay, Northland, Tasman, Taranaki and Waikato regions).

Uncertainty is associated with the boundaries of the QMAP polygons. At a scale of 1:250,000, the absolute error in the location of polygon boundaries is estimated as typically +/- 100 m (Begg 2011). However, the uncertainty is variable because individual QMAP polygons were commonly developed at different scales. For example, the absolute uncertainty of polygon boundaries that were developed at a 1:250,000-scale is larger than the uncertainty of polygon boundaries that were developed first at a 1:15,000-scale and propagated to a 1:250,000 scale. Additionally, QMAP represents surface geological units that are at least 10 m thick, or are 'very important', which can result in QMAP unit boundaries that are quite different to actual boundaries (Begg 2011).

The NZSoSDEM covers the whole of New Zealand at a spatial resolution of 15 m. In this model, the contour bias was calculated as 27%, which corresponds to an expectation that 27% of the point height should lie within ±2 m of a contour (Columbus et al. 2011).

Contours at a 20 m contour interval held in the Topo50 data have an accuracy of half the contour interval. The coastline is shown as the mean high-water mark. Contours and spot elevations in forest and snow areas may be less accurate (Land Information New Zealand 2019).

2.4 Mapping Process

A four-step process was adopted to define hydrogeological systems and develop associated mapping rules, as follows:

- Initial definitions and rules developed for the Southland region.
- Initial definitions and rules tested and refined for the Waikato region.
- Hydrogeological systems mapped in all other New Zealand regions, and definitions and rules were modified as appropriate.
- National definitions and rules were finalised and applied to the Southland and Waikato regions for consistency.

In addition, a set of mapping levels of these hydrogeological systems was devised as the intended outputs were GIS maps where hydrogeological attributes (e.g., geology and age descriptors) could be displayed. Note that geology and age descriptors are commonly used in developing hydrogeological or aquifer productivity maps as they influence the way groundwater flows (Tschritter et al. 2017 and references therein). The following paragraphs summarise the evolution of the hydrogeological systems definitions and mapping rules. To ensure transparency regarding the source of boundary lines defining hydrogeological system, the resulting hydrogeological system dataset was split into a polygon and a boundary polyline dataset. The system boundary dataset only applied to the mapping levels corresponding to the system type. Final definitions are listed in Section 3.1 and mapping rules in Table 2.1.

2.4.1 Step 1 – Development of Initial Definitions and Rules (Southland Region)

Initial definitions and rules were developed for the Southland region because of the relative geological homogeneity of the Quaternary deposits and the natural enclosure of these deposits by Basement rocks compared to other regions. The mapping process for this step can be summarised as:

- **Spatial extent**: Southland region (on- and off-shore).
- **Hydrogeological system definition** (six): Coastal Basin, Coastal Sediments, Inland Basin, Inland River Valley, Volcanic, and Basement. Hydrogeological systems were generally defined as geographical areas with broadly-consistent hydrogeological properties and similar resource pressures, and management issues, using QMAP geology as base units.
- **Mapping level definition** (five): unique name, unique identification number, hydrogeological system type, geology, and age group, and geology and age descriptor. Each system was attributed a name, except for the Inland River Valley, and the Basement system, because of the large number of disaggregated polygons in these systems.
- **Mapping rules**: “Coastal Sediments” systems were defined as deposits outside coastal basins occurring between the coastline and the 20 m elevation contour. The 20 m elevation contour was selected because it best matched mapped Q5 and Q7 paleo-shorelines (Turnbull and Allibone 2003). Sedimentary deposits were broadly classed into recent (Holocene (Q1) and Q2) and older sediments. Volcanic deposits were classed into: “Quaternary”; “Tertiary”, and “Pre-Tertiary” (volcanic exposure in the area is limited to Solander Islands).

2.4.2 Step 2 – Testing of Initial Definitions and Rules (Waikato Region)

Rules developed in Southland were tested in the Waikato region. The Waikato region was selected because of its diverse geology, including large volcanic systems (both recent and older) that are absent in Southland. Changes to the mapping process from the previous Southland process are summarised below:

- **Spatial extent**: Waikato region, excluding units outside systems enclosed within the regional boundary. These units were left as "unclassed" to be refined in the next step (region-by-region mapping).
- Hydrogeological system definition (six): as listed above.
- Mapping level definition (five): as listed above.
- **Mapping rules:** as listed above. In addition, volcanic deposits were classed to differentiate intrusive (e.g., granite, diorite) and extrusive (e.g., basalt; ignimbrite); as well as enclosed river valley deposits (e.g., Holocene and Q2 sediments) and water bodies (e.g., lakes). In this region, a 10 m elevation contour was used to delineate "Coastal Sediments", as this contour line provided a better match to mapped paleo-shorelines in the Coromandel, Hauraki Plains and at the Waikato river mouth.

2.4.3 Step 3 – Mapping of Hydrogeological Systems (New Zealand Excluding Southland and Waikato Regions)

Rules tested in Waikato and Southland were applied to the rest of the country, using a region-by-region approach from South to North. National mapping rules were created (Table 2.1). Changes to the mapping process from the previous steps are summarised below:

- **Spatial extent**: on-shore New Zealand. Due to both technical complexities associated with disconnected polygons and scientific complexities associated with hydrogeological system definitions, it was decided to reduce the mapping scope to on-shore polygons only to keep the task within the available resources. The 'on-shore' polygons included only the contiguous land masses of the North and South Islands inside a QMAP shoreline polygon, and the remaining QMAP polygons were classed as 'off-shore'. During the individual system delineation process, references to the depositional basin were used (e.g., South Wanganui Basin). Off-shore polygons were kept in the dataset.
- **Hydrogeological system definition** (eight): Coastal Basin, Inland Basin, Coastal Volcanic, Inland Volcanic, Inland River Valley, Coastal Independent, Basement Infill and Basement Hard Rock.
- **Mapping level definition** (seven): unique name, unique identification number, hydrogeological system type, coastal information, aquifer overview, geology and age group, and geology and age descriptor. The two new mapping levels (coastal information and aquifer overview[1]) were added to enable the identification of low-lying (below 20 m elevation) coastal areas and separate hydrogeological basement from aquifer systems, respectively. Inland River Valley and Coastal Independent systems were attributed "general" names based on regions and marine zones, respectively. Off-shore polygons were attributed the 'Island' value for coastal information and 'Unclassed' values for all remaining levels.

[1] The aquifer overview is a binary flag to separate Basement Hard Rock from the other systems.

- **Mapping rules:** a systematic definition based on outcrop percentage was used to differentiate between Coastal Basin and Coastal Volcanic, as well as Inland Basin and Inland Volcanic systems. This 50% threshold was set arbitrarily to highlight, in some regions, the occurrence of significant volcanic deposits, whose aquifer properties may differ markedly from sedimentary deposits (Fetter 2001; White 2001; Tschritter et al. 2017). A combined area threshold of 20 km^2 was introduced to accommodate areas of extensive sedimentary outcrops bounded by narrow valleys within Basement. This threshold was uniformly applied to differentiate Inland Basin from Inland River Valley systems. After reviewing both the 10 m and the 20 m elevation contour nationwide to represent paleo shorelines, the 20 m contour was selected. In areas where large-scale consistent geological structures were identified (e.g., Hawke's Bay), surface water catchments were used to split the systems either manually or using an existing dataset. Where headwaters ran on geological formations that were separated from the downgradient structure by a large Basement outcrop, the headwater geological formations were cut from the system delineated by the catchment boundaries and attributed to the adjoining hydrogeological system.

  The Coastal Independent system replaced the Inland River Valley and Coastal Sediments systems, where these are of limited extent and end at the coast (Figure 2.1). The term "Independent" here referred to this system being directly connected to the sea as opposed to located upgradient from either a Coastal Basin or Coastal Volcanic system.

  Systems boundaries were also refined using a systematic approach combining age and lithological descriptors. Melange deposits that were not encountered in Southland or Waikato were integrated into Basement Hard Rock.

2.4.4 Step 4 – Application of the Final National Definitions and Rules to Pilot Regions (Southland and Waikato)

For both regions, the hydrogeological system classification was updated. Individual system boundaries were reviewed to ensure consistency with other regions, which led to boundary adjustments and delineation of smaller coastal basins and numerous coastal independent systems. Name attribution was extended to the Coastal Independent, Inland River Valley and Basement systems (Figure 2.2).

2.5 Application of the Rules and Mapping Order

The national mapping rules presented on Table 2.1 summarise, in no specific order, all the rule combinations to define system polygons and boundaries. During each step of the mapping process, Basement Hard Rock and Basement Infill systems were always mapped first and Inland River Valley last. In between, individual system mapping was performed region by region after a global understanding of the regional geological structure was developed.

Table 2.1 Hydrogeological systems and mapping rules for boundary lines and polygons.

Hydrogeological system	Mapping rules: system boundary lines	Mapping rules: system polygons	Mapping rule exceptions and comments
Coastal Basin and Inland Basin	• Geological contacts with Basement Hard Rock polygons. • Topographic divides that are consistent with surface catchment boundaries or groundwater divides. • Geomorphological features that constrain outflow (i.e., surface and groundwater), for example, a gorge. • Arbitrary boundary lines across Quaternary river valley sediments proximal to the system. • Delineated geological structural features such a faults or anticline axes. • Inferred faults below lakes where applicable. • Topographic features that identify gravel fans (manually drawn). • Adjacent hydrogeological system boundaries. • The coastline.	• Geological unit polygons younger than Cretaceous. • More than 50% of the outcropping units are of sedimentary origin. • Lake polygons completely contained within the system. • Lake polygons when lakes are located on the boundary of the system. • Non-contiguous polygons may be assigned to adjacent basins where the geology is similar. • Connected polygons enclosed by Basement Hard Rock polygons, with a combined area greater than 20 km^2, except where these correspond to large braided-river valleys, or long, thin valleys.	• A basement-bounded group of polygons, with total area greater than 20 km^2, was excluded as it includes top of Mt Garibaldi (Tasman). • Systems may consist of connected and/or disconnected polygons. • Surface water catchment boundaries are relevant to the definition of the basin boundaries. • A polygon was added to cover the Lake McKerrow area located on the western side of the Alpine Fault (Big Bay Coastal Basin) missing from QMAP.
Coastal Volcanic and Inland Volcanic	• Geological contacts with Basement Hard Rock polygons. • Topographic divides that are consistent with surface catchment boundaries or groundwater divides. • Geomorphological features that constrain outflow (i.e., surface and groundwater), for example, a gorge. • Arbitrary boundaries across proximal Quaternary river valley sediments or adjacent coastal systems. • Delineated geological structural features such faults or anticline axes. • Inferred faults below lakes (QMAP). • Hydrogeological system boundaries. • The coastline.	• Geological unit polygons younger than Cretaceous. • More than 50% of the outcropping units are of volcanic origin. • Lake polygons completely contained within the system. • Lake polygons when lakes are located on the boundary of the system. • Non-contiguous polygons may be assigned to adjacent basins where the geology is similar. • Completely contained polygons consisting of Cretaceous and older units.	• Systems may consist of connected and/or disconnected polygons. • Surface water catchment boundaries are relevant to the definition of the basin boundaries.

Hydrogeological system	Mapping rules: system boundary lines	Mapping rules: system polygons	Mapping rule exceptions and comments
Coastal Independent	• Geological contacts with Basement Hard Rock polygons. • The coastline.	• Geological unit polygons younger than Cretaceous.	• In specific cases[2] , these systems are bounded by systems other than Basement Hard Rock. • These systems consist of disconnected polygons.
Inland River Valley	• Hydrogeological system boundaries.	• Geological unit polygons younger than Cretaceous. • Water and lake polygons completely contained within the system.	• A polygon was added to cover the Lake McKerrow area located on the eastern side of the Alpine Fault (Southland Inland River valley). • These systems consist of disconnected polygons.
Basement Infill	• Geological contacts with Basement Hard Rock polygons.	• Geological unit polygons younger than Cretaceous units. • Water, ice and lake polygons completely contained within the system, with a combined area of less than 20 km^2.	• Geological units younger than Cretaceous located in the area of Mt Garibaldi (Tasman) are included in this system, as they are unlikely to act as aquifers due to their location. • Local groundwater resources may be found within the basement infill.
Basement Hard Rock	• Hydrogeological systems. • The coastline.	• Geological unit polygons Cretaceous and older-unit. • Limited transitional sequences (late Cretaceous to early Tertiary).	• Limited transitional sequences (late Cretaceous to early Tertiary).

[2] * Auckland: Waitakere Group Coastal Basin (Karekare, Piha, Waitakere River outlet); Clevedon Coastal Basin (Umupuia Beach). Bay of Plenty: Runaway Coastal Basin (Waihau Bay). Canterbury: Canterbury Inland River Valley (Waiau and Oaro rivers outlets). Greater Wellington: Riverdale Coastal Basin (west of Flat Point); White Rock and Wairarapa coastal basins (coastline between basins); Whakataki Coastal Basin (Mataikona River outlet). Manawatu-Wanganui: Pongaroa Inland Basin (Akitio River outlet). Marlborough: Kaituna Valley (north of Okaramio). Northland: the Whangarei Coastal Basin; the Glenbervie Coastal Volcanic (Sherwood Rise and Onerahi); Northland Inland River Valley (Kawakawa); Kopuokai Coastal Basin (Taipa); Tara Coastal Volcanic (Pukekaroro). Southland: Waiau and Southland Plains coastal basins (area from Orepuki to Colac Bay; Otara area). Tasman region: Farewell Spit area. Waikato: south of the Limestone Downs Coastal Basin; west of the Aotea Harbour and Kawhia Harbour coastal basins; the Coromandel Peninsula Coastal Volcanic; northern edges of Hauraki Coastal Basin (Waitakaruru on the west and Thames on east); northwest of the Lower Waikato Coastal Basin (towards Miranda). West Coast: Karamea and Westport coastal basins (c. Hector).

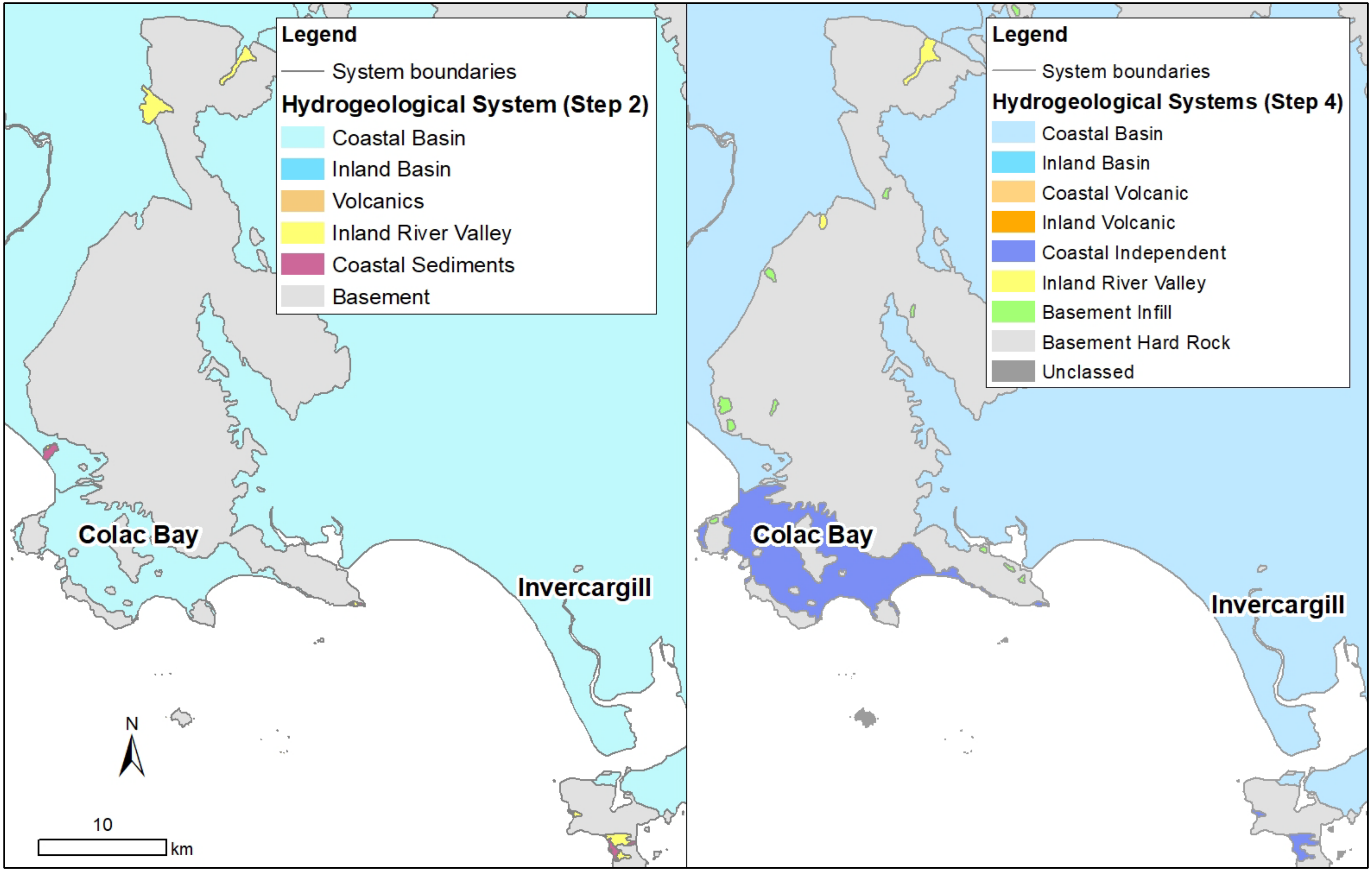

Figure 2.1 Comparison between the Coastal Sediments and the Coastal Independent systems through two mapping stages (Step 2 and Step 4).

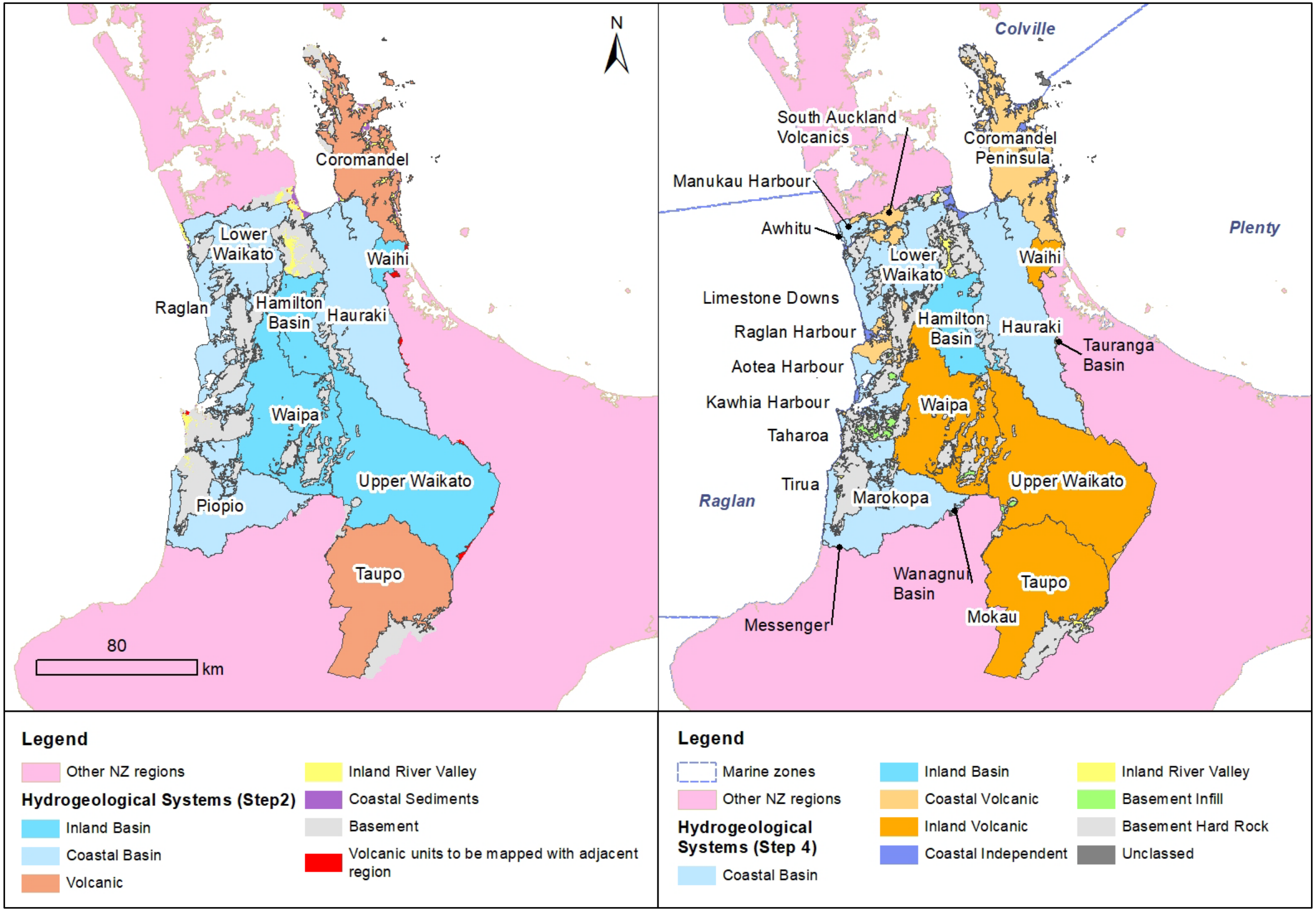

Figure 2.2 Evolution of the hydrogeological system mapping in the Waikato region between Step 2 and Step 4.

3.0 RESULTS

3.1 New Zealand's Hydrogeological Systems

Eight hydrogeological systems were mapped (Table 3.1, Figure 3.1):

- **Coastal Basin, Inland Basin, Coastal Volcanic and Inland Volcanic** consist of geological units younger than Cretaceous that may include regional and local aquifers that are generally bounded laterally by basement. The prefix 'Coastal' indicates at least one coastal boundary, whereas the prefix 'Inland' applies elsewhere. The suffix 'Basin' is used to identify relatively large areas (over 20 km^2), where more than 50% of the outcropping geological units are of sedimentary origin. The suffix 'Volcanic' identifies relatively large areas (over 20 km^2), where more than 50% of the outcropping units are of volcanic origin. Together, these four systems cover about 50% of the mapped area.
- **Inland River Valley** systems include geological units younger than Cretaceous with aquifers that are located in river-valley landforms. It is assumed that Quaternary river valley sediments host most groundwater flow. These systems cover 2% of the mapped area.
- **Coastal Independent and Basement Infill** systems include units younger than Cretaceous and features (e.g., lakes and ice) completely bounded by Basement Hard Rock systems. These systems are relatively small (less than 20 km^2), either intersecting the coast (Coastal Independent) or bounded by basement (Basement Infill). It is assumed that the geological units and features overlying basement of the Basement Infill are shallow (i.e., groundwater flow is dominated by basement). Coastal Independent and Basement Infill systems cover 1% and 3% of the mapped area, respectively.
- **Basement Hard Rock** systems comprise of Cretaceous and older units and limited transitional sequences, e.g., late Cretaceous to early Tertiary age sequences. These systems typically form extensive aquicludes, but local groundwater resources may be found in hard rock, e.g., in association with fracturing and weathering. They cover 44% of the mapped area.

In total, 1896 individual systems were named. The names of larger systems were based on geographical location (e.g., Southland Plains Coastal Basin and Ettrick Inland Basin), resulting in unique identification of approximately 220 systems in New Zealand. However, it was impractical to individually name the numerous disaggregated systems. Therefore, inland systems were grouped and assigned the region's name (e.g., Waikato Inland River Valley system). At the coast, disaggregated systems were named by marine weather zones to reflect their connection to the coast (e.g., Brett Coastal Independent systems).

Table 3.1 Hydrogeological systems with examples of system names and equivalent published aquifer names (White 2001).

Hydrogeological system (New Zealand land cover)	System overview	System example (location)	Example of aquifer name
Coastal Basin (30%)	Groundwater is a key water supply for municipal, industrial and agricultural uses	Southland Plains	Southland colluvial, Southland alluvial
Inland Basin (11%)	Groundwater is a very important supply for agricultural uses	Ettrick	Ettrick Basin
Coastal Volcanic (4%)	Locally-important supplies	Pongakawa	Pongakawa Breccia
Inland Volcanic (4%)	Locally-important supplies	Taupo	Taupo ignimbrites, Taupo sand
Inland River Valley (2%)	Local supplies to independent users (e.g., rural drinking-water)	Marlborough (Upper Wairau Valley)	Upper Wairau Valley
Coastal Independent (1%)	Largely unexplored	Colville (Pauanui Peninsula)	Coromandel sand
Basement Infill (3%)	Largely unexplored	Southland (Fiordland)	Not applicable
Basement Hard Rock (44%)	Water supplies from Basement fractures are rarely used	Basement (Hokonui Hills)	Caples and Murihiku Terrain

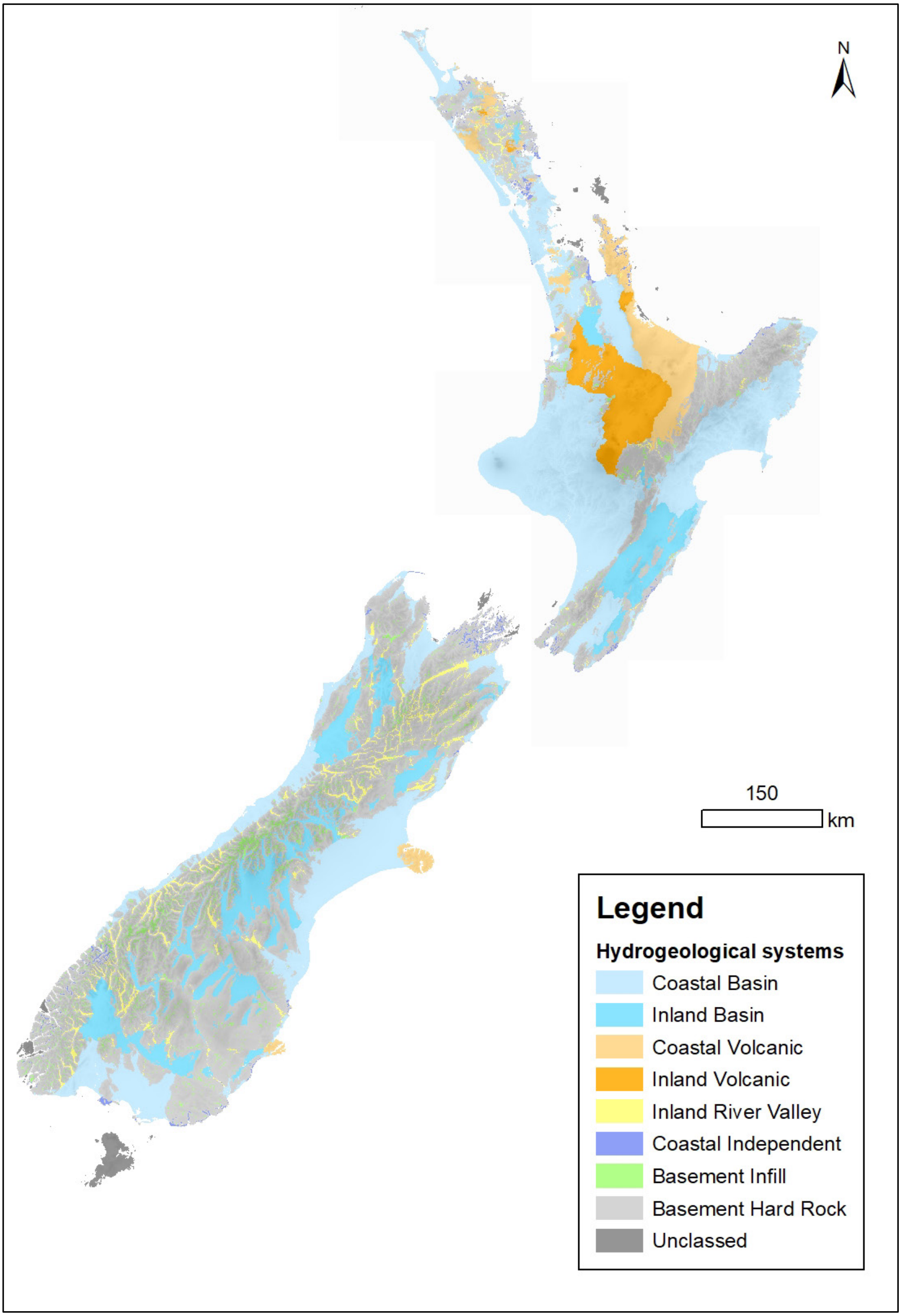

Figure 3.1 New Zealand hydrogeological systems.

3.2 The GIS Datasets

New Zealand's hydrogeological systems are represented by two complementary GIS datasets:

- 'NZ_hydrogeologicalsystem_polygon.shp' (Figure 3.2); and
- 'NZ_hydrogeologicalsystem_boundary.shp' (Figure 3.3).

The 'NZ_hydrogeologicalsystem_polygon.shp' attributes provide, for each system, seven hydrogeological attributes as follows (attribute name as it appears in the dataset shown in brackets):

- unique name (HS_name);
- unique identification (HS_id);
- system type (HS_type), Table 3.1;
- coastal information (HS_coast), Figure 3.4;
- aquifer overview (HS_overview), Figure 3.5;
- geology and age group (HS_geo_gr), Figure 3.6;
- geology and age descriptor (HS_geo_age), Figure 3.7.

There can be multiple polygons associated with a named hydrogeological system. Attribute names, descriptions and values are detailed in Appendix 1.

The 'NZ_hydrogeologicalsystem_boundary.shp' attributes identify, for each linework, the source and methods of boundary delineation. These attributes provide an additional layer of transparency on the delineation process to allow for future reviews and revisions of boundaries. Boundary attributes are: "type" and "source". Attribute names, descriptions and values are detailed in Appendix 2.

The disclaimer and licence for these datasets are detailed in Appendix 3.

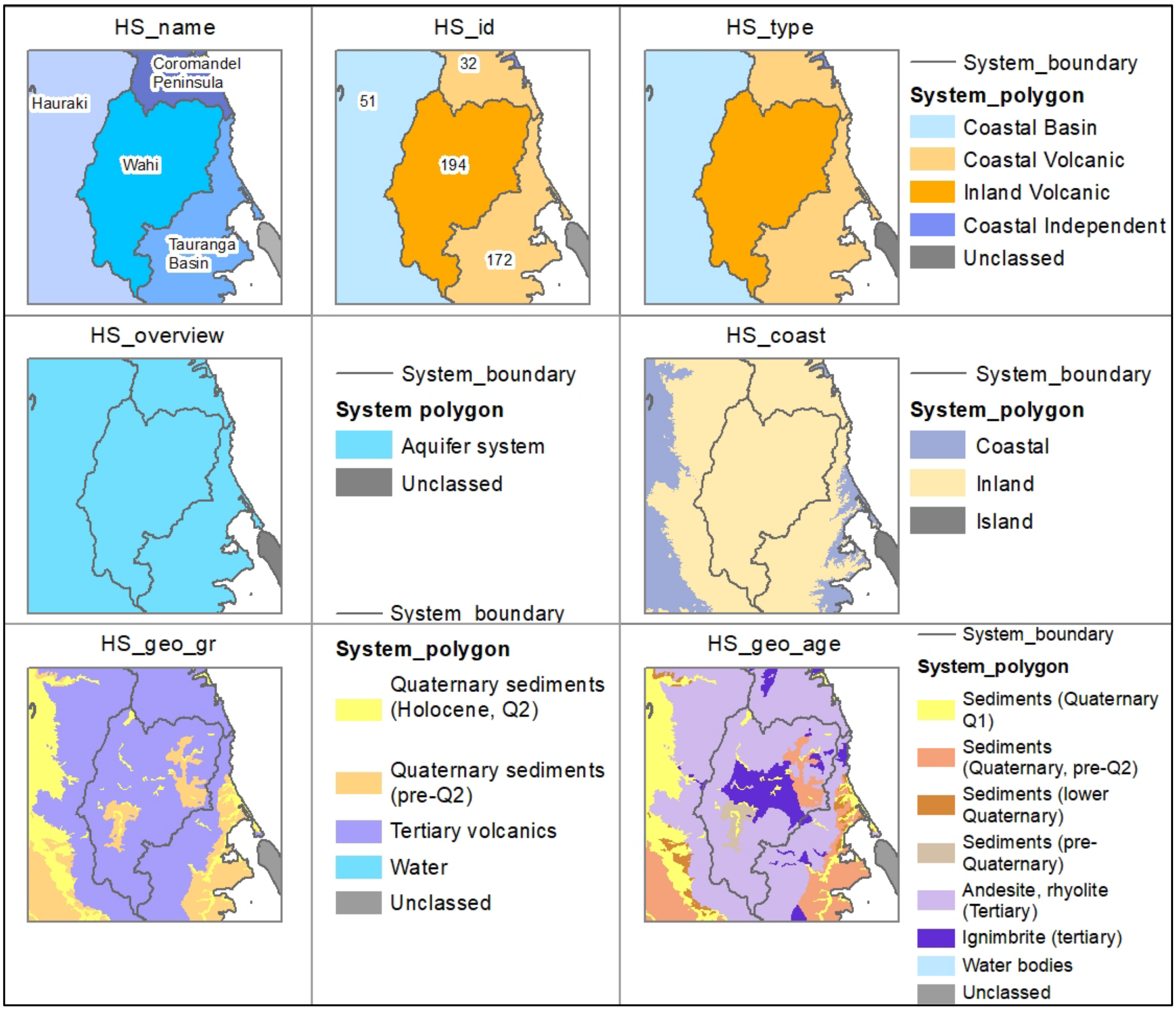

Figure 3.2 'NZ_hydrogeologicalsystem_polygon.shp' dataset attributes

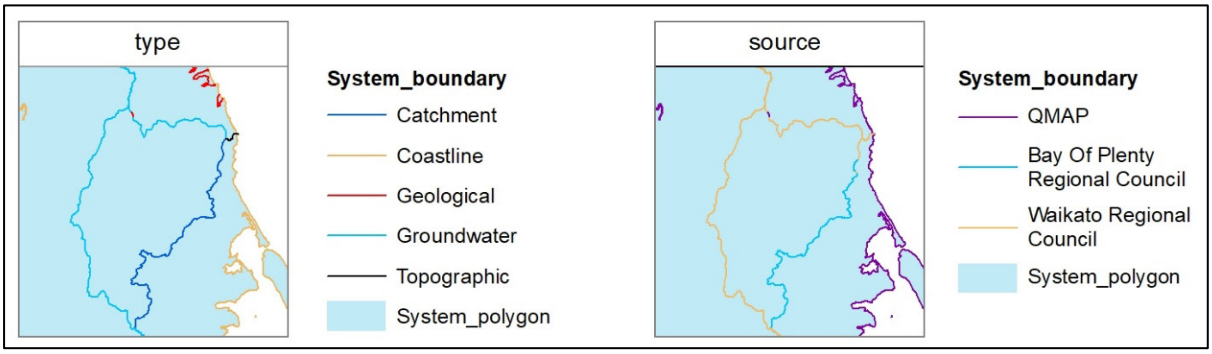

Figure 3.3 'NZ_hydrogeologicalsystem_boundary.shp' dataset attributes

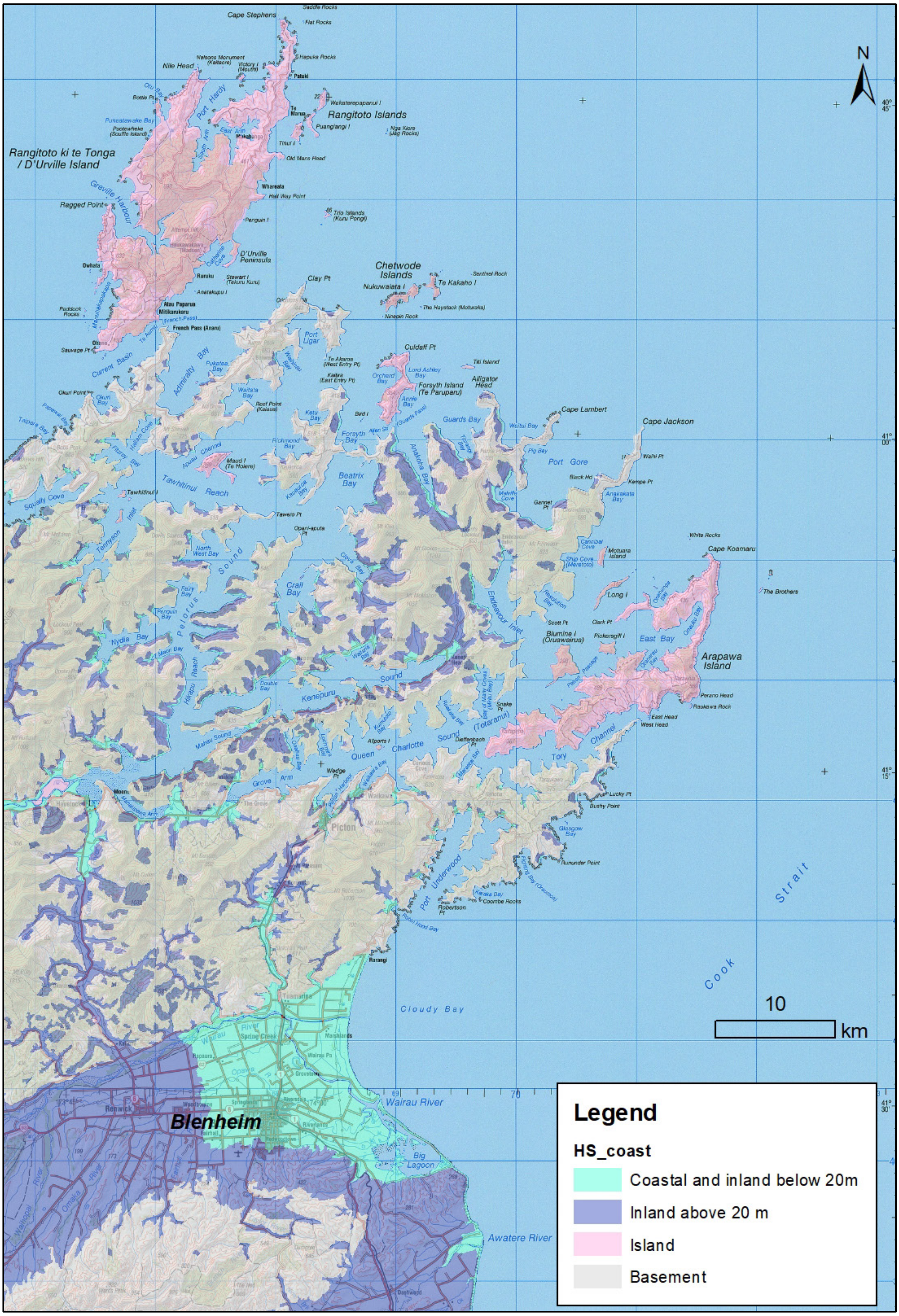

Figure 3.4 New Zealand's hydrogeological systems coastal information attributes (HS_coast), Marlborough region.

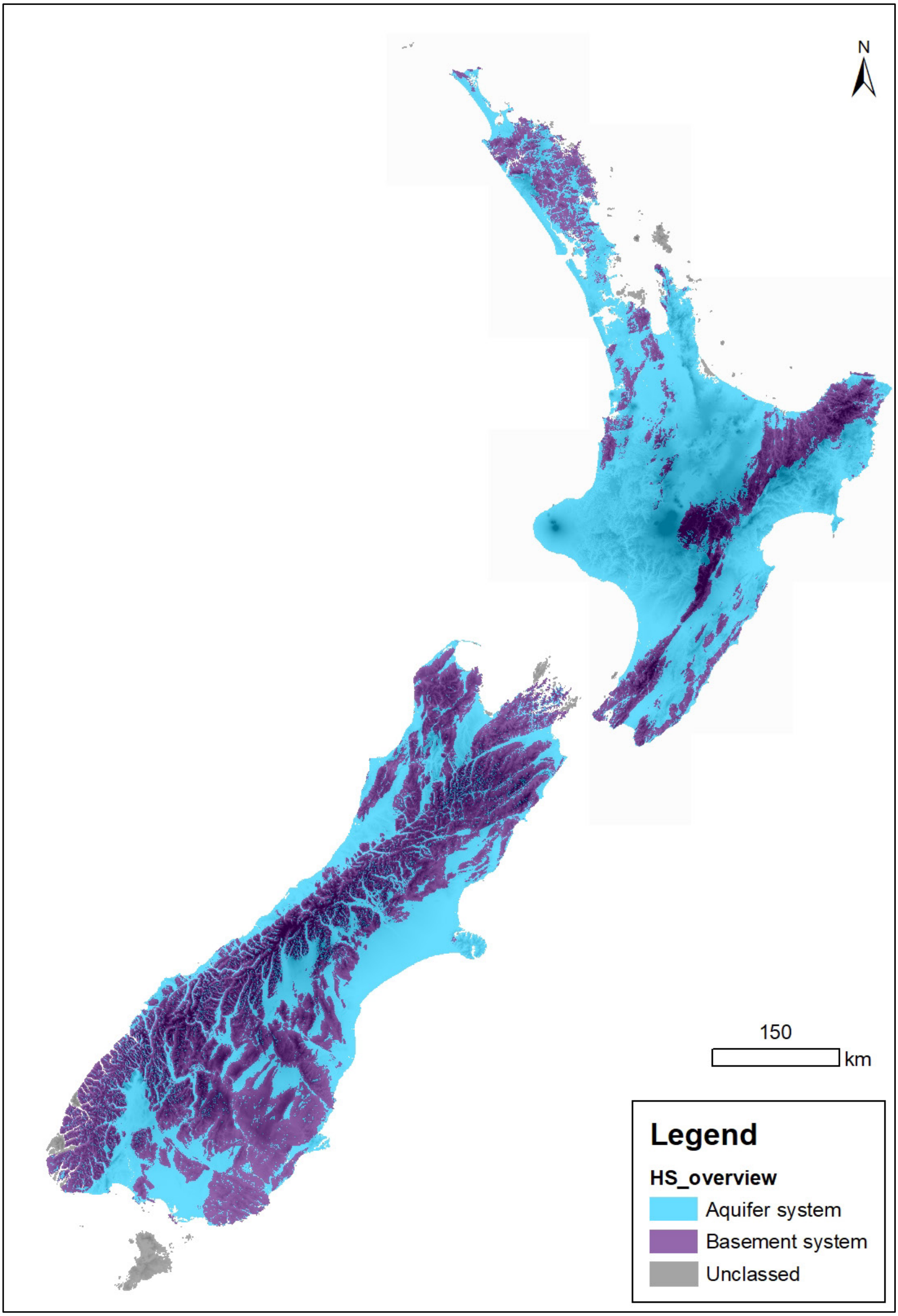

Figure 3.5 New Zealand's hydrogeological systems, aquifer overview attributes (HS_overview).

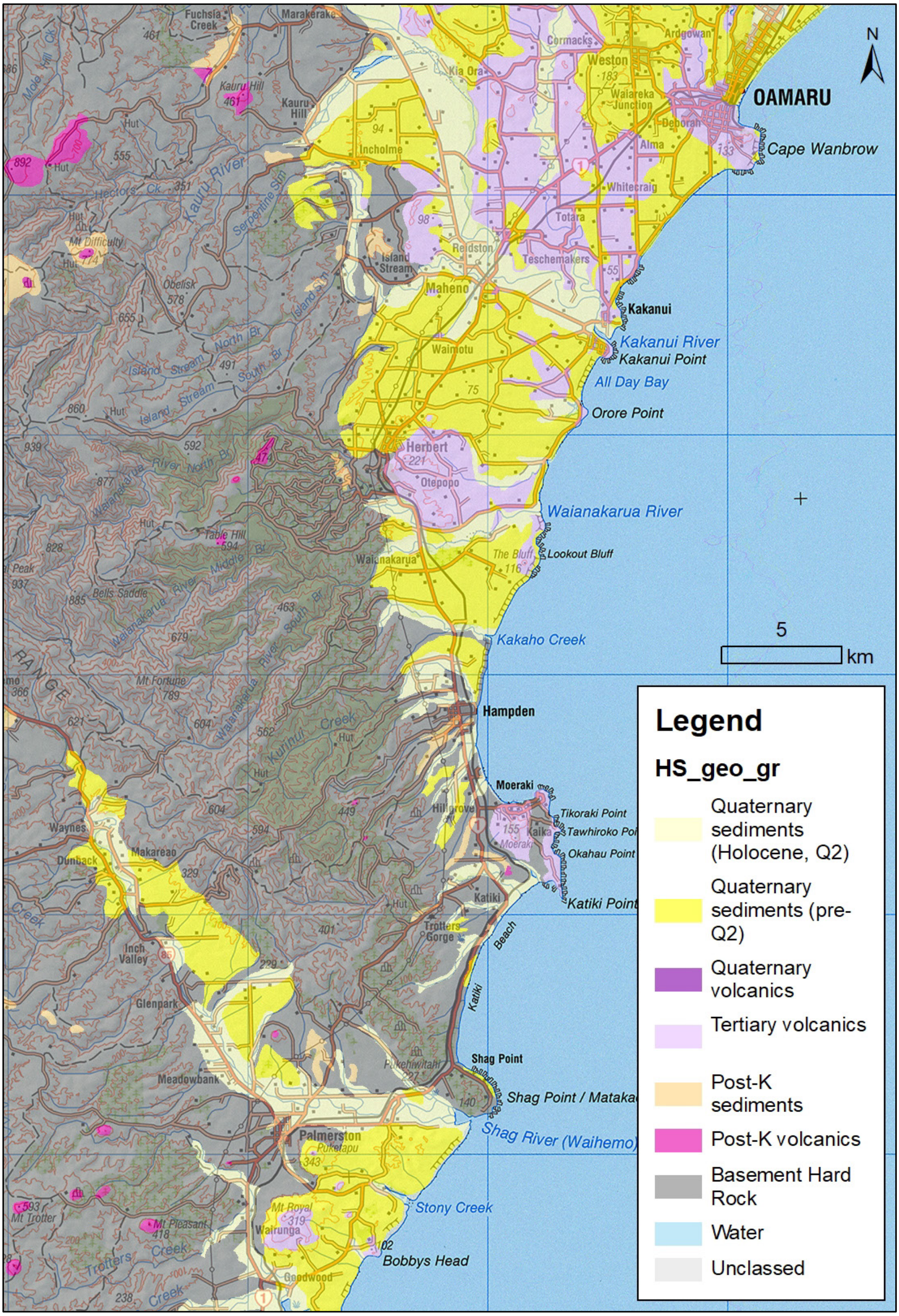

Figure 3.6 New Zealand's hydrogeological systems geology and age group attributes (HS_geo_gr), Oamaru area.

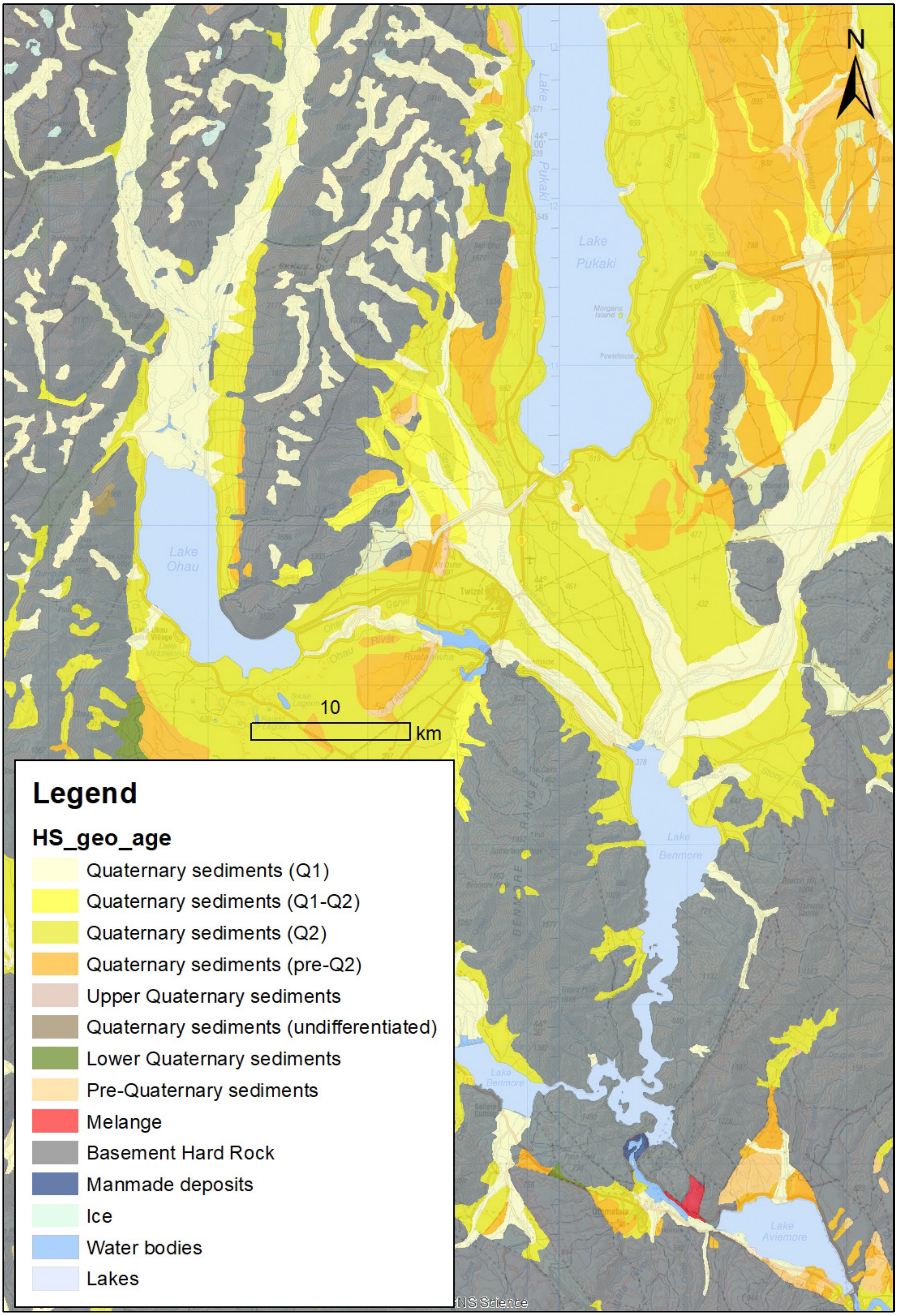

Figure 3.7 New Zealand's hydrogeological systems geology and age descriptor attributes (HS_geo_age), Upper Waitaki River catchment.

4.0 APPLICATION AND RECOMMENDATIONS

The consistent hydrogeological classification described in this report is a suitable base to undertake a range of studies at variable scales.

At the national scale, this classification will be useful for environmental reporting purposes (e.g., state and trends for quality and quantity), including calculations of groundwater volumes (e.g., Moreau and Bekele 2015). The classification may also be used to inform the development of freshwater management strategies (e.g., system type may be used to select drinking-water supply protection strategies) including long-term planning (e.g., development of water quantity protection zones (e.g., Carey et al. 2009)). The classification will also be useful for outreach purposes, as system attributes allow easy access to system information.

At the regional or local scale, systems may be used to complement State of the Environment reporting purposes (state and trends for quality and quantity focused on individual hydrogeological systems); intra-regional comparisons; consistent regional aquifer characterisation between hydrogeological systems (boundaries and hydraulic properties); and assist groundwater flow model development (e.g., provide insights into boundary conditions, hydrogeological unit delineation). The classification may also inform resource management (e.g., delineation or refinement of freshwater management units); policy and strategic plan development (e.g., surface water and groundwater interactions); resource consent applications and assessment; and district and city council water supply management (where no other source of hydrogeological data are available).

This classification was developed and designed to allow future updates, such as the integration of regional and local expert knowledge, or to include islands. Therefore, when using and referencing the hydrogeological system maps it is recommended to include the release date.

This classification was developed to allow consistent delineation of New Zealand's aquifers. It is expected that multiple aquifers may reside within a single hydrogeological system.

Concisely, the following incremental improvements of the datasets are recommended:

- extend mapping to cover off-shore New Zealand;
- identify areas of QMAP improvements that assist groundwater resource assessment;
- integration with 3D data including field data (e.g., well logs) and geological models;
- addition of new hydrogeological attributes (e.g., geological profiles). Note that the development of attributes may result in slight modifications to the mapping rules;
- linkage to existing national datasets (e.g., National Groundwater Monitoring Programme dataset, Moreau 2017). This may require identification of aquifers within systems and development of a consistent aquifer naming framework between datasets (e.g., as applied by the Australian Bureau of Meteorology 2013);
- collection, collation and reporting of aquifer properties aiming to characterise systems and collate system knowledge (Allen et al. 1997). These synthesis reports may cover a range of geographical scales (e.g., national, regional or system);
- development of outreach tools for users to utilise/access the dataset.

5.0 SUMMARY

This report describes the methodology developed to consistently define and map New Zealand's on-shore hydrogeological systems as part of GNS Science's SSIF funded GWR research programme. This programme aims to identify and characterise New Zealand's aquifer systems and improve the sustainable management of groundwater resources.

To define and map these hydrogeological systems, a step-wise process was undertaken: 1) a pilot region (Southland) was selected to develop an initial methodology; 2) the methodology was tested in another region with a different geological context (Waikato); 3) the methodology was applied to the remaining on-shore New Zealand regions; and 4) the two pilot regions (Southland and Waikato) were remapped to ensure national consistency. The methodology was iteratively modified after Steps 1, 2 and 3 and involved setting: a mapping extent; hydrogeological system definitions; mapping rules (e.g., classification of volcanic deposits into intrusive and extrusive units); and mapping levels (e.g., unique identification). Mapping was performed using digital GIS data (QMAP, a digital elevation model, topographic contours, regional surface drainage information and aquifer potential) and New Zealand's marine weather zones (Columbus et al. 2011; Heron 2014; MetService 2015; Tschritter et al. 2017 and LINZ 2018).

In total, eight types of hydrogeological systems were defined as geographical areas with broadly-consistent hydrogeological properties and similar resource pressures and management issues. Coastal Basin, Inland Basin, Coastal Volcanic and Inland Volcanic systems consist of geological units younger-than-Cretaceous generally bounded by Basement Hard Rock, or the coast, covering large areas (over 20 km^2). Inland River Valley, Coastal Independent and Basement Infill are disaggregated systems covering smaller areas (less than 20 km^2) comprising younger-than-Cretaceous deposits bounded by Basement Hard Rock or by the coast. The Basement Hard Rock system comprises Cretaceous and older geological units which typically act as aquicludes. Seven mapping levels were assigned: unique name; unique identification; system type; coastal information; aquifer overview; geology and age group; and a geology and age descriptor.

Two GIS maps were produced at the 1:250,000 scale: 1) a map of hydrogeological system polygons with hydrogeological attributes (e.g., system type, aquifer overview, etc.); and 2) a map of hydrogeological system boundaries identifying the source and type of each boundary line. These maps are publicly available (refer to Appendix 3 for disclaimer and license).

The hydrogeological system classification provides a nationally-consistent basis for enhanced hydrogeological mapping (e.g., aquifer mapping). It is a rapid and simple way to communicate hydrogeological information and complements existing hydrogeological maps at the national scale (e.g., aquifer potential, Tschritter et al. 2017).

This report identifies possible uses for this national classification at multiple scales, for instance to complement environmental reporting (national and regional scales) and to assist with the development of groundwater flow models or delineation of freshwater management units more locally when existing data is sparse and/or lack consistency. The report also provides recommendations for incremental improvements of the datasets such as the addition of hydrogeological attributes to the system classification and the integration of 3D geological field data and models into these datasets.

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APPENDICES

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APPENDIX 1 'NZ_HYDROGEOLOGICALSYSTEM_POLYGON.SHP' FILE ATTRIBUTES, VALUES AND DESCRIPTIONS

NZ_hydrogeologicalsystem_polygon.shp attributes			**Value description including QMAP units**
Name	**Description**	**Value**	
HS_name	Name of the hydrogeological system	Text value for mapped systems, "Unnamed" for unclassed systems	Names of larger systems were based on geographical location. Coastal Independent systems were named by New Zealand marine weather zones. Inland River Valley systems were grouped and assigned the region's name.
HS_id	Unique identifier per hydrogeological system	Number from 1 to 1896, unclassed systems are assigned a zero.	Numeric value
HS_type	Hydrogeological system	Basement Infill	Units younger than Cretaceous and features completely bounded by Basement Hard Rock
		Basement Hard rock	Cretaceous and older geological units and limited transitional sequences (Late Cretaceous to early Tertiary).
		Coastal Basin	Geological units younger than Cretaceous generally bounded by basement
		Coastal Independent	Units younger than Cretaceous and features generally bounded by Basement Hard Rock
		Coastal Volcanic	Geological units younger than Cretaceous generally bounded by basement
		Inland Basin	Geological units younger than Cretaceous generally bounded by basement
		Inland Volcanic	Geological units younger than Cretaceous generally bounded by basement
		Inland River Valley	Geological units younger than Cretaceous with aquifers that are located in river-valley landforms
HS_overview	Hydrological overview of each system	Aquifer	Coastal Basin, Coastal Volcanic, Inland Basin, Inland Volcanic, Coastal Independent, Inland River Valley and Basement Infill hydrogeological systems
		Basement	Basement Hard Rock hydrogeological system
		Unclassed	Unclassed
HS_coast	Coastal information	Basement	There is no coastal information for this system
		Coastal	On-shore land between the coast and the 20 m elevation contour that is connected to the coastline
		Inland	On-shore land disconnected from the coastline
		Island	Offshore islands unclassed as hydrogeological systems
HS_geo_gr	Grouped geology and age descriptors to differentiate major geological types	H-Q2 sediments	Holocene-to-Q2 geological units
		Hard rock	Geological units older than Cretaceous
		Melange	Transitional sequences (Late Cretaceous to early Tertiary)
		pre-Q2 sediments	Holocene-to-Q2 geological units
		post-K sediments	Sedimentary units younger than Cretaceous
		post-K volcanics	Volcanic units younger than Cretaceous
		Q volcanics	Quaternary volcanic units
		T volcanics	Tertiary age volcanic units
		Unclassed	Unclassed
		Water	Water units

NZ_hydrogeologicalsystem_polygon.shp attributes			Value description including QMAP units
Name	**Description**	**Value**	
HS_geo_age	Geology and age descriptor to differentiate major geological types by age group	Andesites, rhyolites, basalts etc.	Quaternary or Tertiary volcanic units, where main_rock is described as andesites, rhyolites, basalt etc. ignimbrite
		Granodiorites, diorites	Quaternary or Tertiary volcanic units, where main_rock is described as granite, granodiorites, granitoids
		Hard rock	Geological units older than Cretaceous
		Ice	Ice units
		Ignimbrites	Quaternary or Tertiary volcanic units, where main_rock is described as ignimbrite
		Lakes	Water units (combined area above 10 km^2)
		lQ sediments	Lower Quaternary sedimentary units
		Manmade deposits	Manmade deposits
		Melange	Transitional sequences (Late Cretaceous to early Tertiary)
		pre-Q sediments	pre-Quaternary sedimentary units
		pre-Q2 sediments	pre-Q2 sedimentary units
		Q1 sediments	Q1 sedimentary units
		Q1-Q2 sediments	Q1 and Q2 sedimentary units
		Q2 sediments	Q2 sedimentary units
		Qundiff sediments	Undifferentiated Quaternary sedimentary units
		Sediments younger than Cretaceous	Sedimentary units younger than Cretaceous completely enclosed by Basement Hard Rock
		Unclassed	Unclassed
		uQ sediments	Upper Quaternary sedimentary units
		Volcanics younger than Cretaceous	Volcanic units younger than Cretaceous completely enclosed by Basement Hard Rock
		Water bodies	Water units (combined area under 10 km^2)

APPENDIX 2 'NZ_HYDROGEOLOGICALSYSTEM_BOUNDARY.SHP' FILE ATTRIBUTES, VALUES AND DESCRIPTIONS

System_boundary.shp attributes			Value description	Reference
Name	Description	Value		
Type	Type of boundary	Arbitrary	Manually drawn straight line used to delineate Inland River Valley or Inland Basin boundaries. In most cases these arbitrary lines were drawn where the Basement outcrop narrowed, i.e., a valley entrance.	N/A
		Basement	Basement boundary	
		Catchment	Regional council-defined surface water catchment, groundwater catchment, or regional boundary. Where available groundwater catchment boundaries were used first, then regional council-defined surface water catchment or regional boundary. Where regional-council boundaries did not reflect the topographic catchment, the line segments were removed.	
		Coastline	Coastline	
		Geological	Geological boundary	
		Geomorphological	Geomorphological boundary	
		Groundwater	Groundwater catchment boundary	
		Structural	Bounding or inferred fault, structural feature	
		Topographic	Manually defined topographic divide using topo50 contours	
Source	Source for the digital boundary	AC	Auckland Council-ConsolidatedReceivingEnvironment.shp	Reid (2018)
		BOP	Bay of Plenty Regional Council – BOP_GreatCat_diss.shp	Allard (2017)
		ECAN	Environment Canterbury-ECAN_great_Cat_diss.shp	Data.govt.nz. (2017a)
		GDC	Gisborne Regional Council - GDC_Great_Cat_diss.shp	Data.govt.nz. (2017b)
		GDC and HBRC	Gisborne and Hawke's Bay regional councils – GDC_Great_Cat_diss.shp and HBRC_Great_Cat_diss.shp	Data.govt.nz. (2017b) Data.govt.nz. (2017c)
		GWRC	Greater Wellington Regional Council – Catchments.shp	Greater Wellington – Regional Environmental Data (2017)
		HBRC	Hawke's Bay Regional Council – HBRC_Great_Cat_diss.shp	Data.govt.nz. (2017c)
		HZ	Horizons Regional Council – OnePlan_WaterManagementZones	Chakraborty (2017)
		NRC	Northland Regional Council – NRCRiverCatchments.shp	Osbaldiston (2017)
		WRC	Waikato Regional Council – WRC_catchments.shp	White et al. (2015)
		GNS Science QMAP	1:250 000 Geological Map of New Zealand (QMAP)	Heron (2014)
		GNS Science SR2018-35	Boundary defined as part of the Classification of New Zealand Hydrogeological Systems project	GNS SR2018-35 (this report)

APPENDIX 3 DISCLAIMER AND LICENCE IN RESPECT OF DATASETS CREATED BY THE INSTITUTE OF GEOLOGICAL AND NUCLEAR SCIENCES LIMITED (GNS SCIENCE)

‘Datasets’ means the:

- ‘NZ_hydrogeologicalsystem_polygon.shp’ and
- ‘NZ_hydrogeologicalsystem_boundary.shp’

files or any part of them (shape format .shp, shape index .shx, attribute .df, spatial index format .sbn, projection .prj, character encoding .cpg and geospatial metadata .shp.xml).

A3.1 Disclaimer

In compiling the datasets, inferences and assumptions have been made about hydrogeological systems at a regional scale (i.e., 1:250,000). At the time of publishing, no validations using actual observations have been made (e.g., yield, aquifer properties, etc.), and the datasets do not include any information regarding the sustainability of a hydrogeological system (e.g., recharge/discharge areas, water balance, etc.). Experience and an appreciation of the limitations of the datasets is needed by persons using the datasets as an element in their decision making over access to and use of groundwater resources. In addition, the datasets should be treated with caution for detailed studies at map scales of less than 1:250,000.

The data user acknowledges that neither GNS Science nor any of its representatives has made or makes any representation or warranty, expressed or implied, as to the accuracy or completeness of the datasets or the accompanying report. GNS Science accepts no responsibility for any use or reliance on the datasets and shall not be liable to any person, on any ground, for any loss, damage or expense arising from such use or reliance.

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Any party using or relying on the datasets will be regarded as having accepted the terms of this disclaimer.

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Use of the datasets is licensed under a Creative Commons Attribution 4.0 International (CC BY 4.0) Licence. You are free to share and adapt the datasets for any purpose provided you give appropriate credit, a link to the license, and note the changes that were made. For more details visit http://creativecommons.org/licenses/by/4.0/. Where the datasets are used in a figure, GNS Science requests attribution in the following manner: © GNS Science 2019. Where reference to the datasets is to be included in a reference list please cite the reference contained in the enclosed Readme file.

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