Technical review of the 2020 groundwater quality indicator to support methodological improvements

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Reviewers

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EXECUTIVE SUMMARY

Under the 2015 Environmental Reporting Act, the Ministry for the Environment and Statistics New Zealand (Stats NZ) have a responsibility to report on the state of different aspects of our environment every six months. These reports rely on technical information analysed by Stats NZ and presented in the form of indicators. In 2020, groundwater quality data was sourced for the first time via data feeds from regional and unitary councils' databases to produce the Groundwater quality (GWQ) indicator. The data feeds were being developed at the time as part of the Land, Air, Water Aotearoa (LAWA) collaboration. Also, for the first time these data were processed by Stats NZ using scripts adapted from scripts used to process data for the surface water quality indicators. The Ministry for the Environment commissioned GNS Science (GNS) to review the selection of sites and variables used in the GWQ indicator, review the processing methods used, and provide recommendations for future reporting.

In this current work, the site and variables used in the 2020 GWQ indicator were compared with previous groundwater quality state and trend assessments at the national scale, which used State of the Environment (SoE) data from national and regional networks. The data was collated via a targeted, nationwide data request to groundwater experts at councils and research organisations (the Institute of Environmental Science and Research [ESR], GNS). This process ensured that the sites used were the best estimate of SoE representativeness at the time. Data processing methods were tested by checking the data input, reviewing the data processing scripts and testing these scripts for reproducibility. In addition, a short, targeted literature review was undertaken to provide context to the recommendations for future indicator updates.

The list of sites used in the 2020 GWQ indicator was limited when compared with that of historical reports at the national scale. This site selection included only 60% of the sites currently monitored as part of national-scale monitoring programmes (quarterly sampling led by GNS; four-yearly sampling led by ESR). There were also discrepancies in the number of regionally monitored SoE sites between the 2020 GWQ indicator and previous reports. Site selection occurred as part of the data retrieval process prior to Stats NZ receiving the data. Possible causes for the partial representation of SoE networks included: use of pioneering data harvesting methods developed for LAWA purpose, possible lack of testing, inconsistencies in either the development or implementation of the data feeds, use of unrecorded manual or automatic data harvesting and the use of unsuitable site selection criteria during data retrieval.

Six variables were reported in the 2020 GWQ indicator. These variables are a subset of the total data set collected by councils, GNS and ESR as part of SoE monitoring. For example, current national monitoring programmes include over 17 inorganic chemistry variables that are measured quarterly throughout New Zealand and the list is growing to include a large range of anthropogenic compounds (at least 66 compounds were measured in 2018). While data processing methods used in the GWQ indicator are appropriate for groundwater data, adjustment of their technical implementation is required for some groundwater quality data, such as time series that include a large number of non-detects and/or a large number of variables.

Recommendations for future GWQ indicator updates are to:

- **Use national-scale, research-driven monitoring programmes to inform site and variable selection**. National groundwater monitoring programmes (major, minor ions, nutrients and pesticides surveys) involve systematic and comprehensive review and maintenance of groundwater monitoring networks and associated data. In the short term, we recommend that Stats NZ and Ministry for the Environment specify their data needs for sites in collaboration with councils, and move towards an objective and more

universal criteria for inclusion in national reporting. Inclusion of regional networks offers consistency with previous reporting and allows historical comparison. In the long term, national networks should be reviewed regularly to ensure they are representative of regional networks and fit-for-purpose for Stats NZ and Ministry for the Environment requirements. To achieve this will require national and regional monitoring programmes to be connected and appropriately resourced.

- **Revise state and trend assessments so they are fit-for-purpose for groundwater quality data**. To improve data analysis and assessment, we suggest that duplicate results are removed; processed data are rounded to a maximum of three significant figures; non-detects are processed appropriately; variability metrics are provided; minimum data requirements for state and trend assessment are revised; and a data dictionary is developed. We also recommend that processing scripts are released so that consistent data processing can be done by others at regional/district scale. This recommendation could be achieved in the short-term.
- **Report groundwater data by hydrogeological system.** It is more appropriate to use hydrogeological systems for analysis of groundwater quality data than regional boundaries or surface water catchments. Efforts are underway to produce a New Zealand hydrogeological-unit map, which aims to represent, in 3D, our aquifers and their properties. Once this information is available, it should be used for all national groundwater quality and quantity assessments. Ultimately all groundwater monitoring sites should be associated with their hydrogeological unit.
- **Use reference values in the GWQ indicator to provide context**. Reference values provide meaningful context to the derived statistics and should be included in the GWQ indicator accompanied by a clear description of limitations of the reference values. Reference values should be limited to published and peer-reviewed environmental baselines, informed by local conditions where possible. The continued use of the Drinking Water Standards for New Zealand and use of environmental baselines is recommended. The development of baselines at the sub-regional scale (i.e. aquifer or aquifer system level) to replace nationally derived values where appropriate is recommended.
- **Develop a framework to add groundwater indicators as they become available or relevant**. The framework should allow indicators that complement existing ones to be added to future assessments, e.g. groundwater use, level and mean residence time. It should also include and link cultural monitoring to SoE programmes, e.g. a cultural variable at an SoE site.
- **Coordinate development of automated data harvesting.** The following short-term steps may help ensure that a single consistent and reliable analytical system is used to harvest data. Stats NZ and Ministry for the Environment specify the site and variable selection criteria to councils prior to the next indicator update; assess the feasibility of developing in-house data harvesting scripts to evaluate relevant databases (councils, NGMP, pesticide surveys) and undertake testing; update existing data vocabularies (sites and variables) and develop a framework to maintain these; and review current initiatives on environmental data access and reporting undertaken by the Ministry for the Environment and Stats NZ.

GLOSSARY

Aquiclude: a hydrogeological unit type defined as a saturated but relatively impermeable material that does not yield appreciable quantities of water to wells; clay is an example.

Aquifer: a hydrogeological unit type defined as a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs; unconsolidated sands and gravels are a typical example.

Aquitard: a hydrogeological unit type defined as a saturated but poorly permeable stratum that impedes groundwater movement and does not yield water freely to wells that may transmit appreciable quantities of water to or from adjacent aquifers and, where sufficiently thick, may constitute an important groundwater storage zone; sandy clay is an example.

Controlled vocabulary: an organised set of phrases or words used to index content in a database so that it can be efficiently retrieved.

Data dictionary: a collection of names, definitions and attributes that describe the element and values contained in a dataset

Data curator: person or organisation responsible for data collection and edition, data quality and management.

EMaR: the Environmental Monitoring and Reporting initiative is a partnership between Te Uru Kahika (16 regional and unitary councils and unitary authorities of New Zealand), the Ministry for the Environment, Stats NZ, Department of Conservation and Cawthron Institute to achieve more consistent and integrated regional and national environmental data collection and reporting.

EOCs: emerging organic contaminants (EOCs) comprise an increasingly wide range of manufactured compounds mostly unregulated and with unknown toxicity risks. EOCs include: pharmaceuticals, personal care and veterinary products, industrial compounds, pesticides, food additives and nano-materials, as well as metabolites and transformation products of these. EOCs are classed as 'emerging' owing to their recent detection due to related advances in analytical techniques and better monitoring.

ESR: Institute of Environmental Science Research.

GIS: Geographic Information System.

GNS: GNS Science.

GWQ indicator: groundwater quality indicator report compiled by Stats NZ to support environmental reporting. Current groundwater-relevant indicators reported on by Stats NZ are: groundwater quality, groundwater physical stocks and consented freshwater takes.

Hydrogeological systems: geographical areas with broadly consistent hydrogeological properties, and similar resource pressures and management issues. The delineation and classification of these systems were developed consistently at the national scale, and the 2-D GIS dataset is publicly available.

Hydrogeological-unit map: map of hydrogeological units (i.e. aquifers, aquitards, aquicludes and basement) developed in a nationally consistent manner and illustrating geological layering. Geological and depositional facies are a key component of this mapping, as they enable connection of their spatial distribution with hydraulic properties. Surface facies are propagated in the sub-surface using the hydrogeological units. The 2.5-D GIS dataset (overlapping, stacked polygons) is publicly available.

LAWA: Land, Air, Water Aotearoa (LAWA) collaboration, representing all 16 regional councils and unitary authorities; aims to connect New Zealanders with the environment by sharing environmental data and information. The LAWA website was launched in 2014. LAWA has grown into a partnership between the Te Uru Kahika – Regional and Unitary Councils Aotearoa, the Cawthron Institute, the Department of Conservation, the Ministry for the Environment and Stats NZ, and has been supported by the Tindall Foundation and Massey University. LAWA is part of the EMaR initiative along with the National Environmental Monitoring Standards.

MAD: median absolute deviation (MAD) gives an indication of the data spread around the median; it is more robust than the standard deviation, particularly to long distribution tails.

Water quality variables: variables measured in water samples that inform on chemical, physical and microbiological state. The inorganic chemistry suite monitored for State of the Environment (SoE) purposes includes major cations and anions, nitrate and ammoniacal nitrogen, dissolved iron and manganese, pH, temperature and electrical conductivity. Water quality variables can be categorised by their relative concentrations into major (>1 mg/L), minor (between 0.001 and 1 mg/L) and trace (<0.001 mg/L) constituents. Organic chemistry variables include man-made compounds such as pesticides. Inorganic and organic chemistry variables may be measured in dissolved or total concentrations and can be measured in the field or the laboratory. Microbial variables include *E. coli*, total coliform and enterococci counts.

National Survey of Pesticides and EOCs in groundwater: Four-yearly surveys since 1990 to assess the quality of groundwater resources focussing on pesticides, co-ordinated by ESR and involving district and regional councils. In 2018, the analytical suite was extended to glyphosate and selected other EOCs.

NGMP: the National Groundwater Monitoring Programme is a long-term collaboration between GNS and New Zealand's regional authorities that began as a groundwater sampling programme in 1990. The current network currently consists of over 100 sites sampled quarterly by regional council staff and analysed by the New Zealand Analytical Laboratory facility since 1993 for a consistent suite of over 17 water quality variables and has national coverage.

Nutrient: substance used by an organism to survive, grow and reproduce.

Pathogens: bacterium, virus or other microorganism that can cause illness for anyone who ingests them and should not be present in drinking water.

SoE monitoring: State of the Environment (SoE) monitoring is undertaken in many countries and aims to provide measurements to inform state and trend reporting. In New Zealand, SoE monitoring is undertaken at the national scale via CRI-coordinated programmes (NGMP, National Survey of Pesticides and EOCs in groundwater) and at the regional scale through councils' dedicated programmes.

Stats NZ: Statistics New Zealand.

1.0 INTRODUCTION

Under the Environmental Reporting Act (2015), the Ministry for the Environment and Statistics New Zealand (Stats NZ) have a responsibility to report on five environmental domains every six months and synthesise these reports every three years. Domain reports are supported by indicators published by Stats NZ. At the time of writing this report, the Ministry for the Environment was preparing the 2023 freshwater report (Our freshwater 2023, published in April 2023), which covers groundwater and surface water. The latter report relies primarily on the groundwater quality indicator published in 2020 for statistics relating to groundwater quality.

The Groundwater quality (GWQ) indicator relies on data collected as part of State of the Environment (SoE) monitoring programmes, which collect data specifically to inform state and trend reporting (Daughney and Wall 2007; Moreau et al. 2016). In New Zealand, SoE monitoring is undertaken at the national scale through two programmes: the National Groundwater Monitoring Programme (NGMP), co-ordinated by GNS Science (GNS), and the National Survey of Pesticides and EOCs in groundwater, co-ordinated by the Institute of Environmental Science Research (ESR). Both programmes are long-standing collaborations with regional and district councils (initiated in 1990). At the regional scale, regional and district councils run dedicated SoE monitoring programmes. Collected data is publicly accessible and is included in most council's databases.

The 2020 GWQ indicator was for the first time compiled using data harvesting techniques developed as part of and for the Land, Air, Water Aotearoa (LAWA) collaboration, which represents all 16 regional and district councils. In this process, data was sourced from regional and unitary councils' databases. Data harvesting was performed by a third-party, IT Effect, generating two datasets: one which was used as the input data for the indicator and another which was used by LAWA for its own data dissemination purpose. At the time, the data feeds were being developed and, to meet Ministry for the Environment and LAWA reporting timelines, some councils provided spreadsheets instead (Loughnan 2023). Since 2020, data feeds have been fully developed by and for all relevant councils, and a subset of these continues to be harvested annually by LAWA to update its website. The LAWA data schema was not designed to identify sites monitored as part of national programmes (NGMP, National Survey of Pesticides and EOCs in groundwater).

The reporting of Stats NZ and LAWA include state and trend assessments for groundwater quality variables performed on SoE data. Stats NZ's scope for the statistical analysis is national reporting, with an emphasis on data consistency and, where possible, re-use of sites and variables enabling temporal comparison between indicator release. In contrast, LAWA aims to present the current regional SoE network. To date, there are no nationally consistent criteria for site inclusion on the LAWA platform; instead, site selection is reviewed annually at council level. Sites exposed to LAWA harvesting are a subset of the current SoE monitoring wells with possible addition of sites monitored for other purposes. Exclusion rules include, but are not limited to, minimum data abundance requirements and inactive or decommissioned sites (Hanson 2023; Loughnan 2023).

In the context of planning for the next update of the GWQ indicator, the Ministry for the Environment commissioned GNS to review the methods used in 2020, specifically:

- Whether the site selection was suitable to inform on groundwater quality state and trends in the context of national environmental reporting, with a focus on representativeness of New Zealand groundwater diversity. It is important to note that it is beyond the scope of this report to assess the representativeness of individual monitoring networks.

- Whether the water quality variable selection satisfies the Ministry for the Environment's intent for the indicator to be meaningful and useful. In this context, meaningful and useful indicators enable enduring environmental stewardship by communicating the best scientific understanding of: (1) the health of the groundwater environment and how it is changing over time; (2) how human and environmental pressures are affecting the groundwater environment; and (3) how observed changes in groundwater and the groundwater environment impact people and the wider environment.
- The technical implementation of data processing methods used to derive state and trend metrics, and the suitability of these methods developed and used for the lake water quality indicator and the river water quality suite of indicators (i.e. clarity and turbidity, *Escherichia coli*, macroinvertebrate community index, nitrogen and phosphorus).
- The potential to use reference values to inform environmental reporting and whether their use is deemed meaningful and useful as defined above.
- Spatial reporting units with consideration of recent advances in New Zealand's hydrogeological research.
- If applicable, provide recommendations for future GWQ indicator updates on site and variable selection.

This report summarises the data sources and methods used for the review, outlines findings and provides recommendations for future updates to the GWQ indicator.

2.0 METHODS

To review the site selection and data harvesting used in the GWQ indicator, the following files were used:

- Technical information on the data selection and extraction, provided by LAWA representatives.
- The data input file used by Stats NZ (*GWExport-25-11-2019.xlsx*), compiled by IT Effect, to calculate state and trend metrics published in the GWQ indicator. This file was supplied to GNS by LAWA.
- The 2020 LAWA state and trend report file (*Groundwater quality monitoring data state and trend 2005–2019.xlsx*), which includes data inputs and outputs for the 2005–2019 time period. This file was provided to GNS by LAWA.
- The 2020 GWQ indicator data bundle (*data.zip*), which contains two files: *state_clean.csv* and *trend_clean.csv*, retrieved from the indicator webpage.
- Data processing R programming language scripts (*gwq_scripts.zip*) used for the GWQ indicator update, provided by Stats NZ. The bundle contains three scripts: 'pre-processing' (*1.2-lawa-preprocessing.R*), 'state' (*2-state_analysis.R*) and 'trend' (*3-trend-calculation.R*).
- A review by Ton Snelder from LWP Ltd of the trend analysis implementation by Stats NZ. This review was contracted by the Ministry for the Environment as part of the indicator update in 2020. LWP Ltd published an R library to compute the Mann-Kendall trend test and Kruskal-Wallis seasonality tests, and Sen's slopes for trend magnitudes – these statistical tests all have a long history of use in water quality studies (*LWPTrends_v1804.R*; Snelder and Fraser 2018). It also incorporates a recent change in state and trend assessment methods, by which the trend diagnostic (i.e. whether a decrease or an increase is detected) no longer relies on the sole comparison of the probability value to an arbitrarily defined confidence level, but introduces a symmetric confidence interval around the trend magnitude. This method was applied to recent national-scale river quality state and trend assessments (Larned et al. 2016; McBride 2019).
- Pre-2020 technical reports on groundwater quality state and trends at the national scale since 2009, and accompanying datasets, available from the Stats NZ's website.

The site selection criteria used by regional councils could not be retrieved within the timeframe of this project. In the absence of this rationale, the sites selected for the GWQ indicator were compared with previous national reporting, which involved a nationwide data request, co-ordinated by GNS and circulated to groundwater monitoring experts within councils and ESR, using the peer network from NGMP and the Groundwater Forum Special Interest Group (Daughney and Wall 2007; Daughney and Randall 2009; Moreau and Daughney 2015; Moreau et al. 2016). The data request specifically provided: the scope of the reporting, a list of required ancillary data to analyse and interpret groundwater quality data (e.g. well depth), and the time period for which data was required. This process ensured that the site selection used in each report represented the best estimate of representativeness of New Zealand groundwater diversity at the time. The GWQ indicator site selection was also compared with recent site numbers reported for SoE programmes (Parliamentary Commissioner for the Environment 2019; Moreau and Cameron 2020).

To assess the suitability of the water quality variable selection, two approaches were used: a comparison with variables included in previous national reports (Daughney and Wall 2007; Daughney and Randall 2009; Moreau and Daughney 2015; Moreau et al. 2016) and a stocktake of variables monitored as part of SoE programmes at the national and regional scale. The latter comparison is based on the technical work undertaken to inform the 2009 groundwater quality state and trend report (Moreau-Fournier et al. 2010).

Technical implementation of data processing methods was tested by: checking the data input file for non-sensical values or replicates; stepping through the provided scripts to ensure data processing matched requirements outlined in the GWQ indicator; testing script reproducibility by running the data input files; and comparing processing to current best-practice for statistical analysis on water resources (Helsel et al. 2020).

A short, targeted literature review was undertaken to provide context for the tasks outlined above. It also aimed to reflect current international research relevant to groundwater and wider environmental reporting to develop recommendations for future reporting. The reviewed material was selected in consultation with the Ministry for the Environment and consisted of the following sources grouped by topic:

- Recent international SoE reports or supporting data on groundwater quality aligned with the United Nations Sustainable Development Goals (Subcommittee on Groundwater of the Advisory Committee of Water Information 2013; European Environment Agency 2018; Green and Moggridge 2021; UK Government 2022).
- Recent work on reference conditions for New Zealand groundwaters (Morgenstern and Daughney 2012; Moreau and Daughney 2021; Daughney et al. 2023).
- Guidance on the representativeness of surface water and groundwater quality and quantity monitoring programmes (European Environment Agency 2008).
- Recent guidance on groundwater quality data collection analysis and data storage, and statistical analysis for censored data (Milne 2019; Helsel et al. 2020).
- Recent datasets relevant to groundwater resources to inform future reporting (Moreau et al. 2019; White et al. 2019; LAWA 2023; GNS Science 2023).

Together with the findings from the GWQ indicator review, this literature review informed recommendations for future updates to the GWQ indicator presented in Section 4.

3.0 REVIEW OF THE 2020 GROUNDWATER QUALITY INDICATOR

3.1 Site Selection

Site filtering applied to data harvesting prior to applying trend analysis requirements is related to both the site suitability for inclusion and the representativeness which pertains to the monitoring network design. This section focusses on this type of filtering. Note that site filtering may also occur through variable selection or data processing (see Sections 3.2 and 3.3).

SoE monitoring involves active data collection, which means that networks may undergo modifications with time. For example, in 2021, the NGMP network included 202 sites: 111 sites regularly monitored (15 of which have been replaced since 1990 – the latest replacement occurring in 2020), 34 sites used only occasionally for pilot surveys, 56 decommissioned sites (includes the sites that were replaced) and one abandoned site (permanently damaged following the 2016 Kaikoura Earthquake). It is also common that, within a given monitoring year, the number of monitored sites varies due to unforeseen circumstances (e.g. the pump is not working on the day of the visit). Therefore, collating data for state and trend analysis requires tracking network changes during the time period of interest.

The GWQ indicator processing script uses LAWA IDs as unique identifiers and outputs a combination of LAWA IDs and regional council IDs denoted ‘RC_ID’, which may correspond to various councils’ database identifiers (e.g. well name, bore number, bore ID or site ID). However, LAWA IDs were created as part of the data feeds set up and led, in multiple regions, to the renaming of sites. Therefore, to compare the sites used in 2020 and those previously reported on, LAWA IDs and current site names must be matched to historical site names or aliases.

GNS maintains a reference list of groundwater monitoring site names and IDs (including LAWA IDs) within its Geothermal and Groundwater database, where NGMP data is stored. This controlled vocabulary was first assembled in 2010 as part of national reporting (Moreau-Fournier et al. 2010) and is currently updated for NGMP sites as part of the programme data management. About 36% of the NGMP sites are currently unmatched to LAWA IDs, which was reported to LAWA managers. The LAWA data schema was not set up to identify NGMP sites and, while an update of the schema is possible, a decision is first required to determine which agency is responsible to supply authoritative data (Loughnan 2023).

The outcome of the GWQ indicator sites mapping to previous national reporting is provided in Table 3.1. The indicator list includes just over half of the NGMP networks (60%) with some regions missed entirely (Auckland, Manawatu-Wanganui). NGMP data is made available to councils and stored in their databases. It is possible that either a limited awareness of the dataset or the absence of clear tags within data feeds caused this under-representation of the national network. The limited representation of NGMP sites is consistent with the current LAWA data schema, and illustrative of differences between LAWA and national reporting purposes. Only 62% of the 826 sites used in the indicator had ID information able to be mapped to sites in previous reports, which included both SoE and NGMP networks. The success of the mapping differed drastically between regions. In five regions, there were more unidentified sites than identified ones (Bay of Plenty, Hawke’s Bay, Otago, Southland and West Coast). In Canterbury, the mapping was very successful (16% unidentified), yet the number of sites differs significantly between the indicator (125 sites) and historical reporting (over 300 reported sites in 2009 and 2016).

Possible causes for these discrepancies include: data required for site filtering is not or only partially mapped and therefore cannot be used for site selection during harvesting (e.g. there was no SoE tag in the data feed); inconsistencies in the implementation of data feeds (e.g. the SoE tag exists but is only partially filled); instances of externally sourced manual data extraction; and use of unsuitable site selection criteria (e.g. inclusion of sites monitored for other purposes than SoE). When comparing the GWQ data input files with the same-year LAWA data input files, both created using data feeds, only a partial site overlap (682 sites) was found using ‘LAWA_ID’ and ‘RC_ID’. There were 144 sites reported in the indicator that were absent from the LAWA dataset, and 262 LAWA sites were unmatched in the indicator. Possible causes for the discrepancies between the indicator and the LAWA data input files include: staging of data extract with considerations for the pioneering data harvesting methods and the differing timeframes between IT Effect and LAWA; instances of externally sourced manual data extraction or unrecorded data harvesting scripts; and use of differing site selection criteria, particularly considering that LAWA site selection is reviewed annually at council level; and the current lack of consistent site criteria for inclusion on the LAWA platform.

Interestingly, when comparing the GWQ indicator site numbers per region with Table A2 of the 2019 Parliamentary Commissioner for the Environment report on New Zealand environmental monitoring reporting systems depicting the regional council network density, significant (>20%) discrepancies occur, with a mixture of under-representation (Canterbury) and over-representation (Manawatu-Wanganui, Marlborough, Northland, Southland, Tasman). Although it is not possible to elucidate the cause of the discrepancies, this further highlights the difficulties in consistently aggregating groundwater quality monitoring data from regional to national scale.

Table 3.1 Number of sites used in state and trend reporting between 2009 and 2020 compared with the number of active sites for the National Groundwater Monitoring Programme and State of the Environment (SoE) programmes. Number in brackets indicates the number of sites that were SoE monitored regionally and nationally at the time of the report publication; 'unidentified' refers to sites included in the 2020 report that could not be identified in the 2009 site list using the Land, Air, Water Aotearoa (LAWA) IDs and site name aliases.

Region	**National Reporting**				**LAWA 2020**		**Current SoE Networks**	
	2009[1]	**2016[2]**	**2020[3]**				**Regional[4] (2019)**	**National[5] (2020)**
			Identified	**Unidentified**	**Identified**	**Unidentified**		
Auckland	24 (6)	26 (6)	8 (0)	1	8 (0)	1	9	6
Bay of Plenty	62 (6)	27 (4)	12 (4)	31	11 (3)	30	47	4
Canterbury	279 (6)	330 (7)	108 (1)	17	309 (4)	45	329	6
Gisborne	80 (6)	56 (7)	43 (7)	24	47 (7)	25	57	6
Hawke's Bay	50 (8)	43 (8)	37 (6)	50	29 (5)	38	74	6
Manawatū-Whanganui	32 (4)	37 (4)	22 (0)	9	22 (0)	17	14	3
Marlborough	24 (13)	26 (8)	21 (8)	2	21 (8)	2	14	8
Northland	36 (7)	42 (9)	36 (7)	5	33 (5)	3	32	7
Otago	101 (7)	47 (7)	19 (1)	40	16 (1)	31	51	7
Southland	65 (8)	37 (7)	28 (1)	86	34 (7)	34	34	6
Taranaki	71 (6)	79 (5)	17 (5)	10	17 (5)	16	24	8
Tasman	16 (10)	18 (11)	17 (10)	3	17 (10)	3	11	10
Waikato	111 (9)	120 (9)	76 (9)	4	76 (3)	4	90	10
Wellington	71 (15)	71 (15)	57 (4)	14	24 (4)	2	66	12
West Coast	8 (8)	10 (10)	8 (8)	21	8 (8)	21	28	8
Total	**1030 (119)**	**969 (117)**	**509 (71)**	**317**	**672 (70)**	**272**	**880**	**107**

[1] Daughney and Randall 2009; [2] Moreau et al. 2016; [3] Stats NZ 2020 and the site mapping undertaken as part of this project, [4] Parliamentary Commissioner for the Environment 2019; [5] Moreau and Cameron 2020.

Monitoring objectives are fundamental to select network site locations, water quality variables and sampling frequency. The representativeness of a monitoring network is a relative concept tied to the monitoring objective; for instance, it may refer to how well represented a water resource is or how well a particular issue has been quantified (European Environment Agency 2008). Using these two examples of representativeness, focussing on establishing water quality baselines relates to how well water resources are represented, whereas ensuring that seawater intrusion is monitored aims to represent an issue. Through time, New Zealand SoE programmes grew in size and scope; for instance, establishing reference conditions was an objective added to NGMP in 2002 (Daughney et al. 2012). In practice, however, monitoring programmes represent a compromise between scientific value and available resources to achieve such objectives. For example, the static size of the NGMP network, despite growing regional networks and understanding of groundwater systems, is a reflection of the funding model, which is mostly unchanged since 2011.

At the national scale, the NGMP network was designed to capture data from a range of hydrogeological settings representative of New Zealand groundwater resources, and therefore generally includes a single well per aquifer uniformly nationwide (Rosen 1999). NGMP data was subsequently assessed against the (denser) aggregation of regional networks using multi-variate statistics, and findings were consistent with that of the aggregated dataset (Daughney et al. 2012). Note that, at the time of NGMP inception, groundwater environments were uncharacterised and therefore could not be used as design criteria. Microbial communities were first mapped at NGMP sites in 2014 and are currently being monitored as part of research activities since groundwater ecosystem indices or variables are yet to be developed (Sirisena et al. 2014).

At the regional scale, councils are required under the Resource Management Act 1991 to ensure that desired environmental results are being achieved via SoE monitoring. Data is collected to inform both council and national environmental reporting needs by enabling the detection of changes in environmental conditions and their significance, and the impact on the environment of regional policies (LAWA 2023). Regional networks are reviewed by councils as part of their internal processes independently of the national programme and each other. For example, in 2007, the West Coast Regional Council network increased by the inclusion of 16 bores (Moreau 2019). More recently, Gisborne District Council identified the need to develop a new monitoring network in the recently mapped, and back then unmonitored, East Coast Aquifers (Tschritter et al. 2016). The disconnect of network reviews of SoE networks implies that objectives and ways to achieve representativeness may vary between regions.

The conjunctive use of both the national and regional networks for national reporting from 2007 onwards induced a network coverage/spatial bias between regions (e.g. 337 sites in Canterbury compared with 32 sites in Auckland used in the 2016 report), but enabled the use of maximum information recorded on groundwater quality.

Stats NZ indicators aim to use a consistent set of sites through time in order to report on changes at the sites. According to Table 3.1, the number of nationally monitored sites has remained mostly unchanged (119, 112 and 107 sites in 2009, 2016 and 2020, respectively). In contrast, the number of regionally monitored sites appears to have decreased from 1030 in 2009 to 880 in 2019 and to 826 in 2020.

Site stability is also key to enable long-term monitoring. The GWQ indicator scope included testing for 10- and 20-year trends (year ending 2018). To qualitatively assess whether long-term monitoring sites were captured, the number of sites featuring in all reports since 2009 was mapped (Table 3.2). Time records considered for previous national reporting were: 1995–2008 (2009) and 2005–2014 (2016), and the regional site distribution was consistent between the two reports. Of the 765 sites reported in 2016, only 423 were successfully mapped to the indicator, suggesting that there are sites with long-term SoE data that were not harvested (this includes NGMP sites). This further indicates that the site selection was not optimal to report on long-term trends in groundwater quality.

Table 3.2 Total number of State of the Environment sites reported in 2009, and the number of the same sites that were also reported in 2016 and 2020 (Daughney and Randall 2009; Moreau et al. 2016; Stats NZ 2020).

Region	Reporting Year			NGMP Sites for which 20 Years of Data are Available
	2009	2009 and 2016	2009, 2016 and 2020	
Auckland	24	23	5	6
Bay of Plenty	62	25	10	6
Canterbury	279	200	62	6
Gisborne	80	54	42	6
Hawke’s Bay	50	39	33	7
Manawatū-Whanganui	32	27	14	4
Marlborough	24	19	17	10
Northland	36	34	30	6
Otago	101	45	19	7
Southland	65	32	26	5
Taranaki	71	70	15	5
Tasman	16	16	15	11
Waikato	111	105	73	10
Wellington	71	68	56	15
West Coast	8	8	6	8
Total	**1030**	**765**	**423**	**112**

3.2 Water Quality Variables

The GWQ indicator reported on six water quality variables: nitrate (nitrate-nitrogen form), ammonia (ammoniacal nitrogen form), phosphate (dissolved reactive phosphorus form), chloride, conductivity and *Escherichia coli* (*E. coli*). The selection of water quality variables induces site filtering, which reflects data availability and part of the monitoring design (variable and sampling frequency selection). For example, nitrate-nitrogen concentrations were collected at 770 sites, whereas *E. coli* was collected at 742 sites.

Since 2007, only these six variables have been consistently reported, with large variations between reporting years (Table 3.3). The first national report included 33 water quality variables, monitored as part of SoE to enable unequivocal attribution of groundwater-specific chemical processes (Daughney and Wall 2007). This work expanded on hydrochemical characterisation of New Zealand groundwaters undertaken on NGMP data by combining regional and national datasets (Daughney and Reeves 2005; Daughney and Reeves 2006). In 2009, statistics were compiled for a very similar list of variables (total of 32), but detailed interpretation was only provided for six variables selected, because they highlighted health or environmental issues or changes in recharge mechanisms (Daughney and Randall 2009). In 2016, at the Ministry for the Environment’s request, 74 variables were reported, 66 of which were man-made compounds (pesticides). The inclusion of these variables is directly relevant to inform on how human and environmental pressures are affecting our environment, and a rise in awareness in pesticides use and fate in groundwater.

Table 3.3 Reported variables grouped into categories, over the time period 2007–2020 (Daughney and Wall 2007; Daughney and Randall 2009; Moreau et al. 2016; Stats NZ 2020). Note that in this table, some variables are used for multiple purposes and the reported chemical form (e.g. nitrate-nitrogen) was omitted to enable comparison of indicators at an overview level.

<table>
<tr><th colspan="2">Variable Category</th><th>2007</th><th>2009</th><th>2016</th><th>2020</th></tr>
<tr><td colspan="2">Field-measured</td><td colspan="2">Conductivity, pH, temperature</td><td>Conductivity, salinity</td><td>Conductivity</td></tr>
<tr><td rowspan="3">Inorganic chemistry / Hydro-geochemical processes</td><td>Major constituents</td><td colspan="2">Calcium, chloride, bicarbonate, potassium, magnesium, nitrate, sodium, silica, total dissolved solids</td><td>Nitrate</td><td>Chloride, nitrate</td></tr>
<tr><td>Minor constituents</td><td colspan="2">Boron, bromide, fluoride, iron, manganese, ammonia, phosphorus</td><td>Iron, manganese, ammonia, phosphorus</td><td>Ammonia, phosphorus</td></tr>
<tr><td>Trace constituents</td><td colspan="2">Lithium, aluminium, arsenic, cadmium, chromium, copper, nickel, nitrite, lead, tin, zinc</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Organic chemistry / Man-made compounds</td><td colspan="2">-</td><td>Pesticides*</td><td>-</td></tr>
<tr><td colspan="2">Microbial</td><td>Maximum biological indicator**</td><td>E. coli</td><td>E. coli</td><td>E. coli</td></tr>
</table>

* The pesticide suite included 66 variables.

** This variable represents the maximum analytical result for *E. coli*, enterococci, faecal coliforms or total coliforms, of which only *E. coli* is considered in the Drinking Water Standards.

Currently, monitored groundwater quality variables as part of SoE programmes include field-measured, inorganic and organic chemistry, and microbial variables. Field-measured variables inform on in-situ aquifer conditions and on the quality of the sample being taken. Inorganic chemistry variables consist of major (>1 mg/L), minor (between 0.001 and 1 mg/L) and trace (<0.001 mg/L) constituents. These variables are monitored to understand a range of hydrogeological processes occurring inside the aquifer along the flow path. Examples of such processes are mineral dissolution, mineral precipitation, mixing, ion exchange and leaching of land surface established contaminants, such as nutrients, to the groundwater (Daughney and Wall 2007). At the national scale, there are 17 quarterly monitored water quality variables, which have been consistently monitored since 1990 and consistently analysed since 1993. At the regional scale, the list of monitored variables and the frequency of collection are selected individually by councils to suit the region's needs. Trace constituents testing may be less frequent due to the increased cost of analysis. For instance, at the national scale, trace metals have been measured prior to 1998 (six variables) and 2022 (13 variables). There is variability in the frequency and variable selection at the regional scale, some of which reflect specific hydrogeological conditions (e.g. arsenic in groundwater is monitored in the Waikato region, with considerations to geothermal sources [Piper and Kim 2006]). Organic chemistry variables consist of man-made compounds (e.g. pesticides, pharmaceuticals, surfactants). These variables may be monitored as part of regional programmes and/or via the four-yearly national surveys of pesticides and Emerging Organic Contaminants (EOCs) in groundwater. The ability to monitor pesticides (analytical detection and cost) in groundwater has increased since 1990, which has resulted in an increasing number of wells and tested compounds (Close and Humphries 2019, and references therein).

A common difficulty in aggregating inorganic chemistry water quality variables between data sources is the need to cater for multiple reporting units (e.g. nitrate reported as nitrogen), forms (e.g. dissolved reactive), analytical methods or database capture change over time (e.g. alkalinity vs bicarbonate concentrations), and determining when it is suitable to aggregate dissolved and total forms from a chemistry perspective. In 2009, the New Zealand protocol for SoE monitoring recommended the monitoring of dissolved species, preferably from field-filtered samples (Daughney et al. 2006). Following this recommendation, regional databases increasingly captured variables' form descriptions, a process further facilitated by the release of the Discrete Groundwater Quality National Environmental Standard, which remains a guideline (Milne 2019). However, the dissolved form might refer to either field or laboratory filtration, for instance if a sample is field-filtered and analysed to measure "total iron" concentration, since field-filtering was performed, this is equivalent to a "dissolved" iron concentration. Therefore, when piecing together historical datasets, sampling protocol or information should be included in the data request or harvesting process. Up to 2016, such information was generally only provided for some regions, and its format ranged from reported references to notes included in the data files (Moreau et al. 2016, and references therein). To date, the only mandatory list of monitored variables is that of NGMP, and differences in monitored variables, and the way these are captured in regional databases, persist. The only published variable vocabulary was assembled as part of national reporting and highlighted large variations in data capture (Figure 3.1; Moreau-Fournier et al. 2010). It is possible that variables were excluded from national reporting post-2009, with consideration for the work involved in data collection and processing. It will require some resourcing to develop access to this data. However, in the long run, including this information will provide better context for groundwater characterisation and more robust application of data science techniques.

The variables reported in the GWQ indicator were aggregated as part of LAWA pre-processing. The variable mapping was undertaken by regional councils using their databases' variable names. In total, between six and 12 different variable names were mapped for each of the six reported variables, highlighting significant database differences.

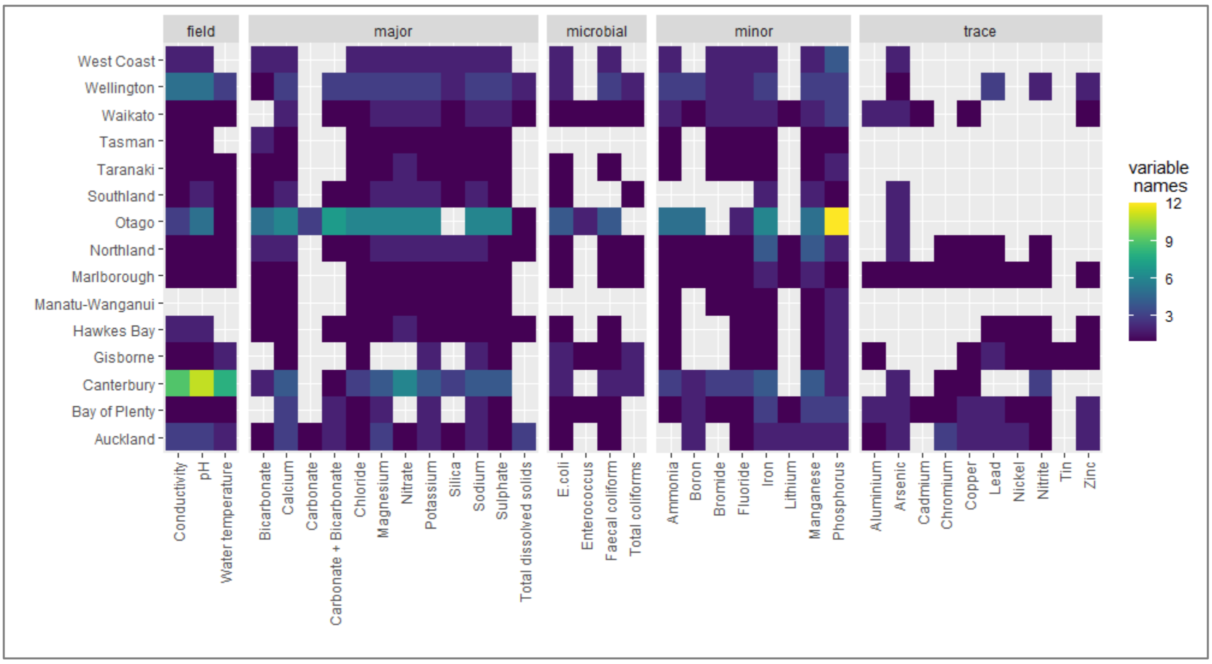

Figure 3.1 Variable names recorded in the 2010 vocabulary per region, per class (Moreau-Fournier et al. 2010). Note that this is a compilation of historical data and, over time, changes in methods and laboratories may have incurred a change of the form monitored for a particular variable.

3.3 Technical Implementation of State and Trend Assessments

The GWQ indicator indicates that dataset ‘adjustments’ were made to ensure national consistency, providing, as an example, the removal of results obtained by non-comparable analytical methods. Indeed, the provided data input file includes field names recording data edition (e.g. ‘Result-raw’, ‘Result-edited’), which allude to: the separation of the ‘greater than’ or ‘less than’ symbols and the result value (required for state and trend analysis); the replacement of ‘*’ results into blank results, and, in one record, rounding of the reported result (3.511017799 rounded to 3.5110178).

The GWQ indicator data input file includes duplicated analyses, i.e. at a given site on a given day multiple concentrations of the same variable are recorded. For instance, at site LAWA-101776 on 27/11/2018, multiple results exist for the following ‘aggregated_variable’ (number of results shown in brackets): nitrite-nitrogen (1), conductivity (2), chloride (2), total ammonia (2), dissolved reactive phosphorus (2), nitrate-nitrogen (3) and nitrate-other (7). This means that on the same day, nitrate-nitrogen concentration is averaged over three readings while nitrite-nitrogen concentration corresponds to a single measurement. These duplicated results create an unwanted statistical sampling bias and are not addressed in the R scripts. Same-season (defined as quarterly) replicates are expected in the dataset, as some sites are reported as monitored monthly. The data input file also included instances of ‘zero’ result (e.g. Site G40/0120, 14/03/2012, dissolved reactive phosphorus), which indicates a data capture error and should be removed from the dataset. Recommendations on how to handle same-day and same-season replicate samples are provided in Section 4.2.

The R scripts were adequately documented for the analysis and required only minor modifications to run. At line 61 of *2-state_analysis.R*, the ‘rename’ function was replaced by the ‘mutate’ function and lines 55–68 of *3-trend-calculation.R* were replaced by a copy of lines 38–51, adjusted for the correct time period and filename. The modified scripts were run using the input file and the *LWPTrends_v1901.R* package for trend analysis (R studio version 2022.02.3 build 492, R version 4.2.1). Random checks yielded similar state and trend outputs between the files from the GWQ indicator and the manually run files. Running the pre-processing script required the use of the *LWPTrends* package and correctly removed blank records, corrected conductivity values based on the reported units, and filtered out the variables aggregated under the ‘Nitrogen – others’ label.

Within the *2-state_analysis.R* script, state percentiles were calculated using the *Base-R* package. Percentiles were attributed if the number of uncensored data was >3 data points, then values were provided regardless of the proportion of values reported below or above the detection limit (i.e. censoring level) (detection limit of 0.002 mg/L). For instance, site LAWA-102098 had a censoring level greater than 80% and was reported as a median of 0.00213 mg/L, where it would be better reported as <0.002 mg/L (Helsel et al. 2020). Guidance to adequately handle censored data is provided in Section 4.2. Exceedances were obtained by comparing medians with threshold values using logical statements in the script, which is the correct implementation.

Within the *3-trend-calculation.R* script, trend metrics were calculated using the (recently developed at the time) *LWPTrends* package, and its implementation was satisfactorily checked by the developer (Snelder 2019). The occurrence of trend was assessed using a Mann-Kendall test and quantified using a Sen’s slope calculation. Seasonal adjustment was applied when the Kruskal-Wallis test was validated within a 95% confidence. The trend test assessment was made using acceptable ‘certainty’ thresholds consistent with Intergovernmental Panel on Climate Change (IPCC) guidance and Environmental Reporting (rivers, lakes and groundwater) as follows (IPCC 2013; Ministry for the Environment and Stats NZ 2022):

- 0–0.1: very likely increasing trend
- 0.11–0.33: likely increasing trend
- 0.33–0.67: uncertain trend
- 0.67–0.89: likely decreasing trend
- 0.9–1: very likely decreasing trend

Probability thresholds are set arbitrarily (Helsel et al. 2020), and it is a consistent approach to use the same thresholds for groundwater, river and lake quality reporting. However, it is not yet possible to propagate a similar calculation to seasonality testing. Therefore, the 95% confidence interval threshold for seasonality testing used in the GWQ indicator is deemed reasonable.

Trend assessments were subsequently expressed as trend_directions using the *LWPTrends* package. The function embedded in the script assigns an “improvement” direction to decreases and “worsening” direction for increases. The script outlines explicit exceptions (clarity and the macroinvertebrate community index), where direction is defined by the opposite trend asssessment, i.e. an improvement corresponds to an increases. The assignment of trend direction is variable-specific; however, for the six variables reported in the GWQ indicator, this assignment was deemed adequate.

The GWQ indicator output file provides four trend descriptors: “trend_category”, “trend_direction”, “direction_confidence” and “direction_confidence_lawa”. Inconsistencies in the selection of significance thresholds were noted in the scripts producing the reported trend descriptors in (Table 3.4). For instance, in Example 1 listed in Table 3.4, the chloride concentration time series at site LAWA-100767 is described as having insufficient data to have a trend_category, yet it is also reported as “very likely worsening” under the direction_confidence_lawa, but the direction_confidence is “very unlikely”. To resolve these inconsistencies requires either the development of metadata or removal of unused categories for clarity (only direction_confidence_lawa is used in the indicator).

Table 3.4 Criteria used for trend descriptors and selected examples. Note that the definition of an improvement is a decreasing trend for all reported groundwater quality variables.

Trend Output Descriptor	Example 1	Example 2	Example 3	Criteria
Site	LAWA-100767	LAWA-100767	LAWA-100767	Not applicable
Period	2009–2018	2009–2018	2009–2018	Not applicable
Measure	Chloride	Nitrate-nitrogen	Electrical conductivity / salinity	Not applicable
trend_category	Insufficient data	Increasing	Increasing	Sen’s slope and probability (95% confidence threshold)
trend_direction	Not applicable	Worsening	Worsening	
direction_confidence_lawa	Very likely worsening	Very likely worsening	Very likely worsening	IPCC confidence thresholds
direction_confidence	Very unlikely	Exceptionally unlikely	Exceptionally unlikely	

State and trend assessment was also constrained by the following minimum data requirements:

- Filtering for the desired date range, data is available for four out of five years and data is available for each season within the full time period for state.
- Filtering for the desired date range, data is available for each of the years within the data period, there is data for at least three quarters of all the seasons contained within the full time period for trend.

There are large differences in sampling frequency between groundwater, river and lake monitoring dictated by the dynamics of the respective domains. Groundwater is a typically slow-responding system offering a buffered response compared with rivers and lakes, which are impacted by storm events. International guidance on groundwater quality monitoring is to use, by default, a quarterly sampling frequency (Barcelona et al. 2002) compared with monthly and higher for river water (Harmeson and Barcelona 1981). A pan-European review of groundwater quality monitoring highlighted a range of sampling frequencies from once every two years to 12 times per year, the differences being attributed to varying monitoring purposes (European Environment Agency 2008). At the national scale, a sampling frequency review was undertaken in 2012, using an adaptive non-parametric method tested on the NGMP network. The outcome of this review was that the current quarterly sampling frequency could not be lowered without incurring a loss of information (Moreau-Fournier and Daughney 2012). Sampling frequency reviews have also been conducted at the regional scale (e.g. Moreau and Hodson 2015), however, there is currently no national overview of how often these reviews take place and what methods were/are used. In addition, it is common to review groundwater quality long-term monitoring frequency at a lower value, e.g. annually (Moreau 2019; Hadfield 2022). Therefore, the stringent minimum data requirements used in the GWQ indicator are not regarded as suitable for groundwater quality data. This is demonstrated by the impact on the spatial distribution for the trend assessment, which resulted in the exclusion of six regions for the longer time period (Table 3.5). Minimum data requirements suited to groundwater quality are provided in Section 4.3.

Table 3.5 Impact of minimum data requirements on the number of sites per region for the data input, state and trend outputs.

Region	Data Input	State Output	Trend Output (10 year)	Trend Output (20 year)
Auckland	9	9	3	3
Bay of Plenty	43	5	-	-
Canterbury	125	109	41	18
Gisborne	67	28	4	5
Hawke’s Bay	87	61	36	29
Manawatū-Whanganui	31	27	5	-
Marlborough	23	23	20	2
Northland	41	36	33	4
Otago	59	41	17	-
Southland	114	30	26	-
Taranaki	27	21	-	-
Tasman	20	20	15	10

Region	Data Input	State Output	Trend Output (10 year)	Trend Output (20 year)
Waikato	80	31	29	27
Wellington	71	66	61	38
West Coast	29	10	8	-
Total	**826**	**517**	**298**	**136**

4.0 RECOMMENDATIONS FOR FUTURE UPDATES TO THE GROUNDWATER QUALITY INDICATOR

The recommendations presented in this section are consistent with international SoE reporting and the design of the United States National Ground-Water Monitoring Network, active in the United States framework (Subcommittee on Groundwater of the Advisory Committee of Water Information 2013; European Environment Agency 2018; Green and Moggridge 2021; UK Government 2022).

4.1 Site and Variable Selection with the Future in Mind

It is recommended that the future selection of sites and variables to include in the indicator report is informed by continued close collaboration between councils, GNS and ESR through existing collaborative national programmes. The list of sites and variables may grow with time, or change to represent the current concerns for groundwater quality to be meaningful and useful. This recommendation is consistent with the opportunity to review/modify our monitoring as a collective identified by the Parliamentary Commissioner for the Environment (Parliament Commissioner for the Environment 2019). It is also consistent with wider monitoring needs identified by the Groundwater Forum Special Interest Group (Morris et al. 2021).

Characteristics of monitoring programmes that are highly effective in providing crucial information for environmental policy are (Lovett et al. 2007):

- Clear and compelling scientific questions.
- An integrated research programme.
- Variables should be selected with the future in mind.
- Adaptive design supported by regular reviews, long-term data accessibility and sample archiving.
- Continuous use of the data.
- Maintaining data quality and consistency.

The following sections develop practical steps to undertake this in the short- and long-term.

4.1.1 Site Selection

In the short-term, it is recommended to include historical and current sites monitored as part of national groundwater quality programmes (GNS's, NGMP's and ESR's pesticides) and regional SoE sites. The inclusion of regionally monitored sites addresses spatial data gaps and provides a more up-to-date representation of New Zealand groundwater resources than the national programmes. However, including data from regional networks also introduces possible bias in the site selection due to variable monitoring objectives and density of coverage, and data inconsistencies (e.g. varying variable forms and analytical methods between regions) which complicate dataset aggregation. Their inclusion also maintains consistency with previous reporting and therefore provides some ability for comparison with previous indicator reports.

In the long-term, a research-driven and groundwater focussed national programme could provide the list of sites from which Stats NZ makes its selection. The scope and resourcing of this programme need to be identified and secured for the long term. Achieving this will require the following tasks to be completed:

- **Development of a monitoring brief for national environmental reporting.** For instance, should saltwater intrusion monitoring be included in the context of a changing climate.
- **Development of a national overview of monitoring programmes relevant to national reporting.** This overview should include programmes such as community supply monitoring, synoptic surveys and nitrate monitoring projects, but not consent compliance monitoring. For example, Waikato Regional Council operates a long-term 'community' network (Hadfield 2022); Horizons has been operating a nitrate monitoring programme in the Horowhenua District (Pattle Delamore Partners 2013); Northland operates groundwater investigations in addition to SoE monitoring (Northland Regional Council 2013); and Tasman rotates synoptic surveys to complement long-term regional-scale monitoring (Westley 2022). This overview should include monitoring objectives, site and variable selection criteria, and monitoring frequency. This overview will increase transparency on monitoring activity at the national scale, enabling Stats NZ to identify potential gaps in the collected data and support the review of the national programmes.
- **Assessment of the feasibility of merging NGMP and the pesticide surveys into an integrated research-led monitoring programme**. Both programmes are relevant and complementary but are currently managed through different funding models. With considerations for the effectiveness of monitoring programmes outlined above, this feasibility assessment should address: research objectives, data consistency, management, access and use, and long-term resourcing options. It should also be guided by the monitoring brief for environmental reporting at the national scale.

It is important to note that the current national programmes already include regular reviews as part of their activities. For instance, the network for the ESR pesticide surveys has grown over time. However, currently these reviews are undertaken separately and constrained by the current funding models, which lead to a compromise between scientific value, available resources and the ability to prioritise work across the 15 councils involved. Therefore, the reviewed network that would be obtained from a separate review of the NGMP and ESR networks is likely to lead to a different outcome than the review of the network of an integrated programme.

4.1.2 Variable Selection

In the short term, recommended variables to include for future reporting consist of major, minor and trace constituents (calcium, chloride, bicarbonate, potassium, magnesium, nitrate, sodium, silica, boron, bromide, fluoride, iron, manganese, ammonia, phosphorus, lithium, aluminium, arsenic, cadmium, chromium, copper, nickel, nitrite, lead, tin, zinc) and man-made compounds monitored as part of ESR's four-yearly surveys. These variables are monitored to understand processes specific to groundwater, and it is common practice overseas to report on them at the national scale (European Environment Agency 2018; Green and Moggridge 2021; United Kingdom Government 2022). Note that some of these variables are monitored at a much lower frequency than major and minor constituents, mostly due to the recent ability to analyse and associated costs. Repeating the sampling at a low frequency will inform on long-term changes, which may be triggered by changing flow paths. Where data is collected at low sampling frequency intervals, the indicator should include the most recent data, as is undertaken overseas (for instance, pharmaceuticals data from 2012 was shown in the 2022

United Kingdom reports). Inclusion of new variables should be accompanied by appropriate wording to emphasise the sources, pathways and fate of these variables, which can be developed in consultation with groundwater quality experts.

It is possible that these variables were excluded from national reporting post-2007, with consideration for the work involved in data collection and processing. It will require some resourcing to develop access to this data. However, in the long run, including this information will provide better context for groundwater characterisation and more robust application of data science techniques. This inclusion may also be relevant to report in the context of climate change impact on groundwater quality.

In the long-term, variable selection should be performed by Stats NZ using information supplied by a research-driven and groundwater-focussed national programme. To achieve this will require the development of a stocktake of current and historical monitored variables within SoE scope at the regional and national scale. This will enable the sizing of data inconsistencies and inform decisions on adding more variables and a nationally consistent framework for data aggregation. It will also inform activities undertaken at the national scale, for instance, when to resample for heavy metals.

It should be noted that as more variables are included in future GWQ indicator updates, their assignment to trend categories should be mapped accordingly (e.g. for each variable whether an increase is regarded as an “improvement” or a “worsening”).

4.2 Revised Technical Implementation of State and Trend Assessments

4.2.1 Removal of Duplicated Results

Removal of duplicates should be undertaken prior to statistical analysis. Two types of duplicated analytical results occur in groundwater quality datasets:

- True duplicates, which are associated with errors in data capture and can be easily removed from datasets by grouping results.
- Duplicated analyses, which arise when multiple samples are collected in the field and sent to different laboratories. The latter are frequent in groundwater quality datasets because duplicate sampling is part of routine monitoring quality assurance procedures, which are standard practice (Milne 2019). One sample bottle may be analysed for more than one variable (this depends on the analytical method). Therefore, when removing duplicated results, it is important to use the analysis identification number so the batch of duplicated results is removed consistently. This removal may require arbitrary rules applied consistently, for instance, a data source is preferred over another or the analysis that holds the most variables is kept.

4.2.2 Rounding to Significant Digits

Rounding should be undertaken after the statistical analysis but prior to data release. Best-practice state calculation and reporting include the use of an appropriate number of significant digits, such as two or three significant figures as dictated by the detection limit threshold, i.e. for a detection limit of 0.001 mg/L, a calculated value of 0.00213 mg/L should be reported as 0.002 mg/L and a value of 4.5126 mg/L reported as 4.51 mg/L (Milne 2019).

4.2.3 Inclusion of a Variability Metric

Current state should inform for each variable on what a typical value is and how it varies throughout the variable record. It is therefore recommended to include a measure of variability to complement state and trend metrics in future editions of the indicator, and, if deemed applicable, to other indicators. There are multiple statistics used to describe variability – in previous reports on groundwater quality, the Median Absolute Deviation (MAD) was used because it does not infer a normal distribution for the dataset, which is better suited for water resource data (Helsel et al. 2020).

Note that MADs can also be used to qualify trends as 'perceptible' or 'imperceptible' by adopting a method similar to that of signal-to-noise ratio. This concept was first introduced in 2021 by comparing the magnitude of the change within the time period to the variability of the observed variable and tested on NGMP data (Moreau and Daughney 2021). It is recommended that the concept of 'perceptible' trends, to provide a quantitative certainty over statistically calculated trends, is explored by Stats NZ and, if deemed acceptable, used in future reporting for the GWQ indicator and potentially other indicators.

4.2.4 Censored Data Handling

The following approach is recommended to adequately handle censored data for environmental reporting purposes (Helsel et al. 2020):

- Where there is no censoring, median, MAD and percentiles can be estimated using statistical formulas.
- Below 25% censoring, median and MAD are estimated using Regression on Order Statistics models, and percentiles are calculated using statistical formula.
- Above 25% and below 80% censoring, no percentiles are calculated, and median and MAD are computed using Regression on Order Statistics models.
- Above 80% censoring, there is no estimate of percentiles, and values are shown as below the highest detection limit. Trend analysis is not performed.
- Where trend testing is performed, censored values and all non-censored values are replaced with the numeric value of the highest detection limit. For example, if a detection limit was 0.05, analytical results of <0.05, 0.04, <0.01 and 0.06 would be replaced with 0.05, 0.05, 0.05 and 0.06 for the purpose of trend testing. This approach converts highly censored datasets into a large number of tied values, with the effect that the calculated trend magnitude is likely to be near or equal to zero, and the trend significance is likely to be low. Alternatively, Maximum Likelihood Estimation may be used to address multiple censoring levels.

Regression on Order Statistics and Maximum Likelihood Estimation methods can be implemented using the Non-Detects and Data Analysis R package (Lee 2022).

4.2.5 Minimum Data Point Requirements for State and Trend Assessment

The following minimum data requirements are suitable for quarterly collected data. For variables collected at the lower frequencies (e.g. four-yearly pesticide surveys), these criteria should be adjusted accordingly, for instance by removing the need for seasonal adjustment of the Mann-Kendall test and lower minimum data point requirements.

To enable seasonality-adjusted state and trend assessments, all seasons must have at least one observation, and individual seasons will require at least two data points. The specific time window used in reporting is largely arbitrary; however, a 10-year duration containing at least eight data points is considered the minimum needed for assessing trends in groundwater quality (European Commission 2007; Moreau and Daughney 2015). The same threshold may be used to assess state and a measure of variability around the median. When using quarterly data, a 10-data-points requirement translates to at least three years of data. The selected 10-year period may be split into three-year (at a minimum) intervals and checked for such a minimum number of data points for each period. This will ensure that the data has no temporal bias while allowing for multiple sampling frequencies. An additional requirement may be to restrict trend analysis to time series with at least eight non-outlier results over the time period of interest. Outliers in trend analysis are commonly defined as values greater than four MADs from the median over the same time period (Moreau et al. 2016). Finally, the minimum data requirements may also be adjusted to ensure national coverage is maintained.

4.2.6 Provision of a Data Dictionary

A list of reported metrics, metrics descriptors (e.g. number, text) and associated units and descriptions would be useful to add transparency and could be added to the data bundle accompanying the GWQ indicator. For instance, in the *trend_clean.csv*, the ‘probability’ metric is a number, which represents the Mann-Kendall probability of a decreasing trend. An example of a data dictionary can be accessed in the New Zealand hydrogeological-unit map data bundle (White et al. 2019).

4.2.7 Release of Processing Script to Enable Re-Use

State and trend assessments are regularly undertaken by central and regional organisations, as well as research providers. These assessments feed the development of policies and plans. Recently there has been increased need and use of open-source code; however, implementation is *ad-hoc,* and consistent sharing platforms are missing for New Zealand government and research organisations. It is recommended that when addressing the above shortcomings in data processing recommendations, a peer review step is built in to enable customisation of these scripts to suit re-use by regional monitoring programme managers. The benefits will be increased transparency in data processing, re-use of developed scripts and, therefore, consistency in analysis between reporting agencies across scales. This could provide a blueprint for future good practice relevant to other environmental domains.

4.3 Change in Spatial Reporting Units

The GWQ indicator outputs are currently represented in multiple forms, one of which is a map infographic where the following layers can be turned on or off: regions, territorial authorities and catchment boundaries, individual variable, state, trend assessment and threshold exceedances. Overseas, recent national environmental reports use either aquifer grouped by dominant flow and productivity types (Green and Moggridge 2021) or water bodies and dominant flow types to report on the resource (European Environment Agency. 2018).

Over 200 aquifers were first mapped in New Zealand in 2001 (White 2001), most of which may be regarded as hydrogeologically distinct (some aquifers were mapped as ‘systems’). Since then, three digital datasets directly relevant to national reporting were developed:

- GIS datasets have been created by councils to manage groundwater resources in the form of aquifer boundaries, groundwater management zones or alternative management boundaries (Lovett and Cameron 2014). The extent of each individual dataset is also limited to administrative boundaries. There is no standard approach for defining a groundwater management zone or an aquifer boundary, and therefore the method for development of these shapefiles differs between regions (Figure 4.1).
- The New Zealand Hydrogeological Systems map (Figure 4.1, Figure 4.2) is a 2-D GIS dataset representing geographical areas with broadly consistent hydrogeological properties, and similar resource pressures and management (Figure 4.2; Moreau et al. 2019). The systems' delineation and classification were developed consistently at the national scale. This dataset is readily available and is increasingly being used by New Zealand researchers to support a range of groundwater-related topics, such as ecosystem classification and mapping, resource prospection, policy applications and modelling (e.g. Mourot and White 2020; Fenwick et al. 2021; Morgan and Mountjoy 2022; Fernandes 2021; Mourot et al. 2022).
- The New Zealand Hydrogeological Unit Map (Figure 4.2) is a 2.5-D GIS dataset (overlapping, stacked polygons) that represents hydrogeological units (i.e. aquifers, aquitards, aquicludes and basement) developed in a nationally consistent manner and illustrates geological layering (Figure 4.2; White et al. 2019). Geological and depositional facies are a key component of this mapping, as they enable connection of their spatial distribution with hydraulic properties. Surface facies are propagated in the sub-surface using the hydrogeological-unit map (HUM) units. This dataset was initially developed in 2019 and is currently being refined by GNS as part of its Groundwater Strategic Science Investment Fund programme. The latest version is dated 2022 and features increased consistency with the 1:125,000 New Zealand geological map (Heron 2014), the hydrogeological systems map, and the current status of facies mapping. Although this dataset represents a significant opportunity regarding reporting on both quantity and quality, the data framework is not yet configured to connect to monitoring. Therefore, while it was not considered in this report for national reporting, it is regarded as a promising future resource. Note that the hydrogeological-unit map is developed in conjunction with the hydrogeological systems dataset to enable transition from one to the other.

The hydrogeological systems provide a nationally consistent, useful context to the spatial distribution of GWQ indicator sites and enable the visualisation of systems that may not be hydraulically connected. Therefore, the hydrogeological systems dataset could be further used to group data per system type for the purpose of reporting. This would provide a sub-national level that would contribute to represent the diversity of New Zealand's groundwater. This use of the system classification is an approach comparable to using the River Environment Classification (NIWA 2023). The current indicators for groundwater quantity are: the consented freshwater takes and the groundwater physical stocks. Both quantity indicators could be reported using the system classification, the consented takes using the existing source information and the geolocation; the stock account using the systems to divide its current base reporting unit which are aquifers.

Therefore, it is recommended that Stats NZ and the Ministry for the Environment use conjunctively surface water catchment and hydrological system boundaries. These reporting units are suitable for current and future groundwater indicators (e.g. water levels). Note that to meaningfully connect quality and quantity indicators will require connecting monitoring site and management information with mapped systems and aquifers.

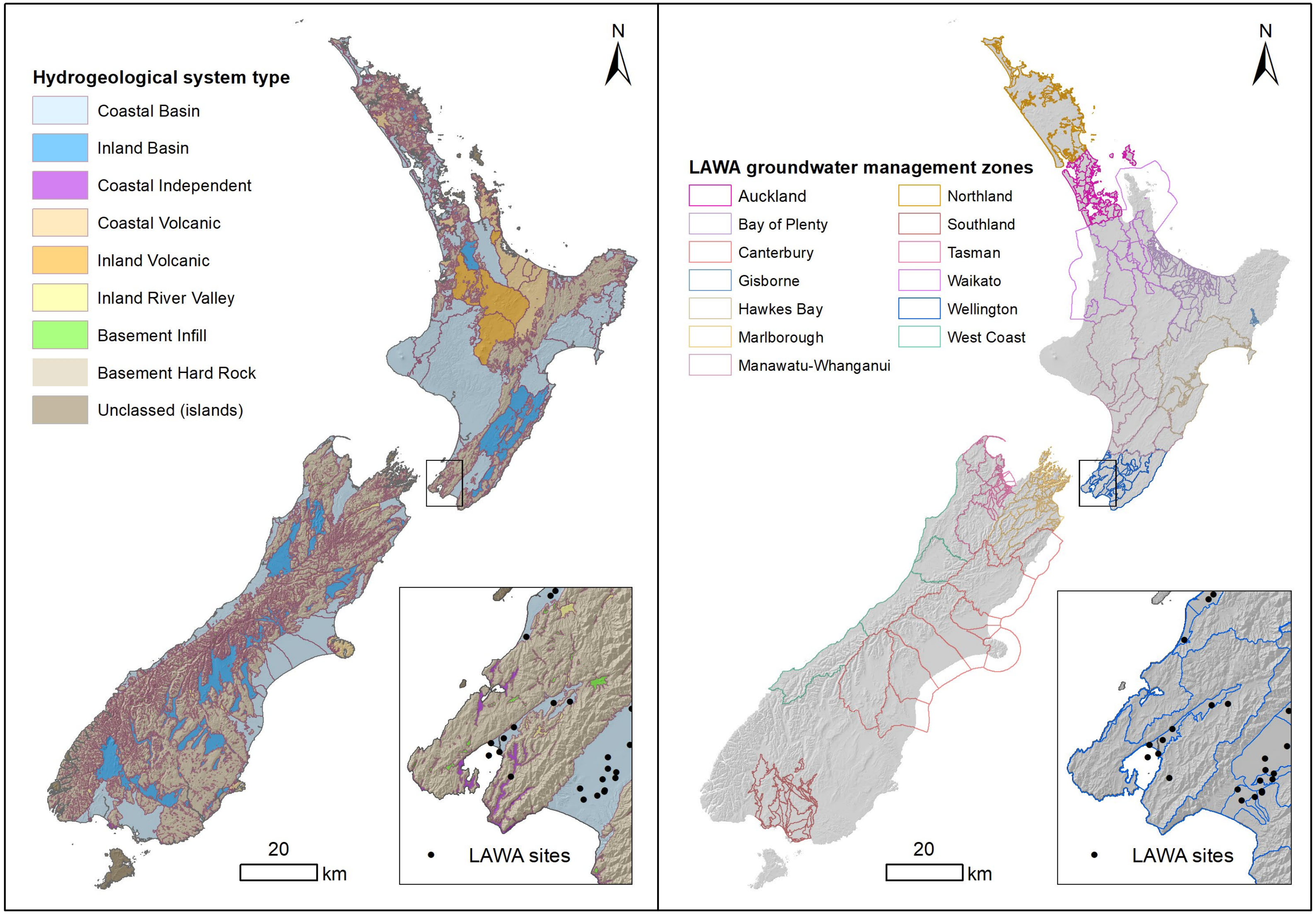

Figure 4.1 Comparison between the spatial distribution of New Zealand hydrogeological systems (adapted from Moreau et al. 2019) (left) and Land, Air, Water Aotearoa (LAWA) groundwater zone boundaries (right). Note that the provided LAWA dataset did not include zones for Otago, and that data retrieval failed from the Taranaki URL.

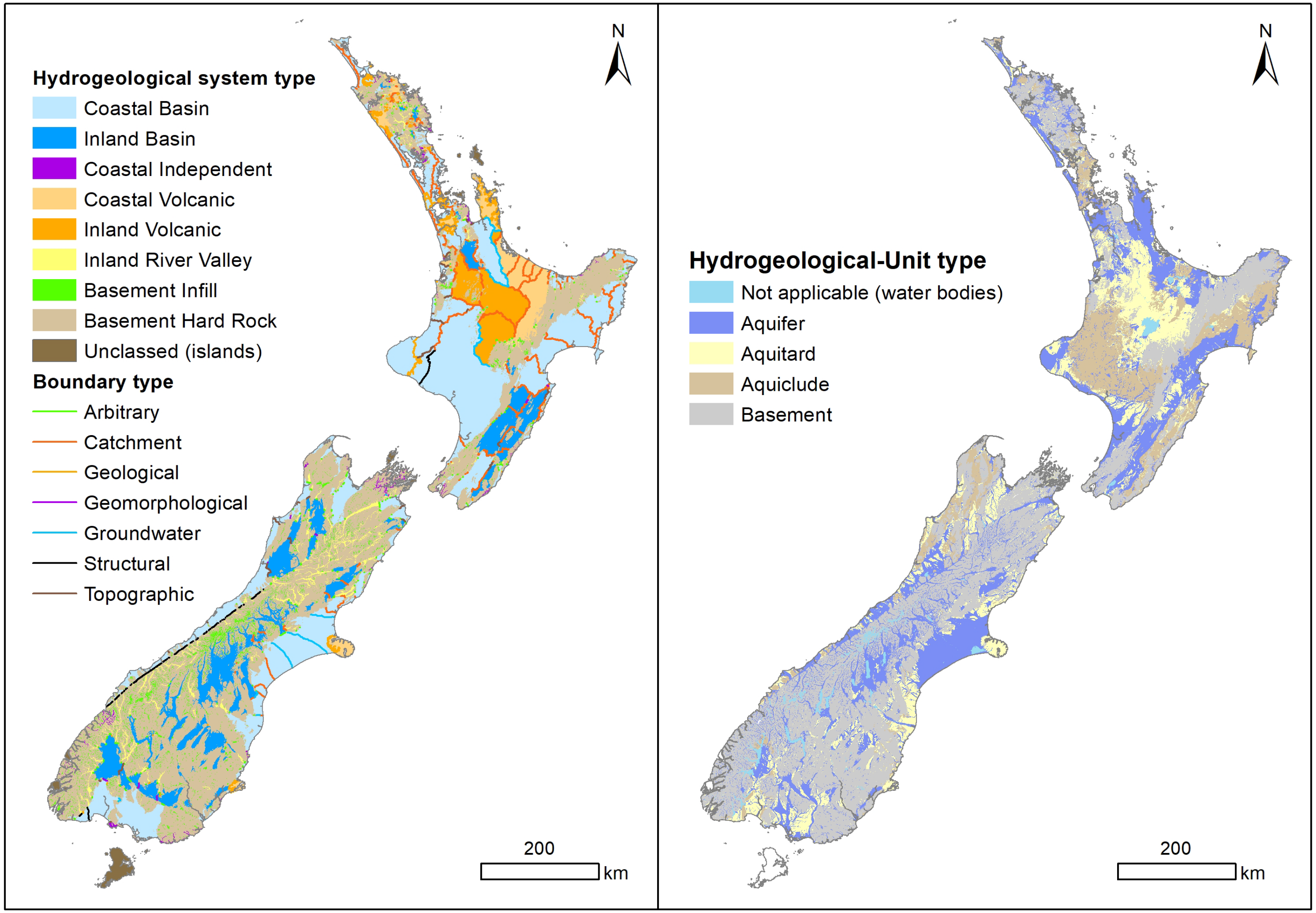

Figure 4.2 Definition and spatial extent of the New Zealand hydrogeological systems (left) and hydrogeological units (right) (adapted from Moreau et al. 2019; White et al. 2019).

4.4 Use of Reference Values

It is recommended to continue using reference values in the GWQ indicator to provide meaningful context to the derived state and to extend their use to trend statistics reporting. The use of references values complements the proposed variability metric for state (Section 4.2.3) to bring the state and trend metrics in perspective with respect to how small/large, fast/slow and stable.

Reference values should be limited to published and peer-reviewed baselines, informed by local conditions where possible. This is particularly important when defining the sensitivity of ecosystems, for instance, in the most recent Guidelines for Fresh and Marine Water Quality (Australian and New Zealand Government 2020), groundwater ecosystems are viewed as an exception to which the guidelines do not apply (due to poor characterisation of groundwater ecosystems and therefore preference for locally derived values). It is therefore recommended not to apply these freshwater and marine water quality guidelines to groundwater, until thresholds derived using local conditions are developed. Reference values derived using a consistent approach between domains should be preferred to equivalent reference values derived using other methods (Daughney et al. 2023).

Only peer-reviewed reference values should be used in reporting. For instance, in recent years, an association between nitrate levels in drinking water supplies and bowel cancer risk in adults has been identified in some overseas studies at concentrations lower than those outlined in the current Drinking Water Standards (currently set with consideration for infant methemoglobinemia conditions or Blue Baby syndrome). However, the evidence base is not conclusive with respect to whether the relationship is causal or coincidental and, at the time of writing this report, the guidance from the Office of the Prime Minister's Chief Science Advisor is to monitor and assess compliance with the current Maximum Admissible Value (Prime Minister's Chief Science Advisor 2022 [revised 2023] and references therein). In this example, it is therefore recommended to continue using the Drinking Water Standards and check for updates.

Reference values should be accompanied by a clear description of limitations of the reference values. For instance, if the Drinking Water Standards are used, it should be clearly stated that drinking water wells' spatial distribution and depths may vary from that of SoE monitoring sites. Where a particular reference includes multiple values (e.g. toxicology and aesthetic reference values), it is recommended to use them together to illustrate the potential significant differences between them and where our environment state may lie.

The following specific reference values are deemed suitable for inclusion in future GWQ indicator updates:

- The Drinking Water Standards for New Zealand (New Zealand Government 2022), which include thresholds based on toxicology, aesthetic criteria or specific water-use quality requirements, such as hardness thresholds, for cooling purposes. The Drinking Water Standards is regularly reviewed and updated.
- Environmental baselines or 'natural' reference values that describe the chemical, physical and/or biological conditions that can be expected in natural waters with minimal or no anthropogenic influence (Edmunds et al. 2003; Morgenstern and Daughney 2012). It is not possible to identify human impacts and assist with gauging the effectiveness of groundwater management policies without these baselines (Edmunds and Shand 2008; Müller et al. 2008; Moreau and Daughney 2021; Daughney et al. 2023). State baselines are usually defined as a range, with thresholds that specify the upper and lower levels expected for each monitored parameter under natural conditions. For instance,

in the Taupo Volcanic Zone, arsenic concentrations may exceed the Drinking Water Standards due to localised input from natural geothermal sources (Hadfield 2022). At the time of writing of this report, state baselines have been derived as a range in the New Zealand context derived for major, minor ions and nutrients at the national scale (Daughney et al. 2012). In the case of nitrate-nitrogen a more recent baseline derived using methods consistent with river quality should be preferred (Daughney et al. 2023). Baseline sets could be used as a range or maximum thresholds, with considerations to impacts.

- Trend baselines are defined as the range of rates of change for major, minor ions and nutrients through naturally driven processes (Moreau and Daughney 2021). These could be used as a range when reporting trend magnitudes.
- When the data allows, it is recommended to develop baselines derived at the sub-regional scale (i.e. aquifer or aquifer system level) to replace nationally derived values where appropriate to inform environmental reporting.

4.5 Develop a Framework to Introduce Additional Groundwater Indicators

It is recommended that the Ministry for the Environment and Stats NZ develop a framework to include the following additional indicators:

- Groundwater use/abstraction (Pressure).
- Groundwater level/quantity (State).
- Groundwater mean residence time, indicative of the time lag of the environmental response, for instance to a change in recharge (State).

These recommendations are consistent with technical recommendations from the environmental performance indicators for groundwater (Bright et al. 1998) and the omission of the ‘Response’ in environmental reporting recommended by the Parliamentary Commissioner for the Environment in the Drivers, Pressures, State, Impact, Response (DPSIR) framework (Parliament Commissioner for the Environment 2019; Gupta et al. 2020).

The framework should include a methodology to link cultural monitoring to SoE monitoring programmes, for instance, a criteria to bring springs of cultural significance into an SoE monitoring network and/or monitoring of cultural variables at SoE sites.

4.6 Consolidate the Development of Automated Data Harvesting

To support the sourcing of data using a single data harvesting system in the long term, the following short-term practical steps are recommended:

- The feasibility of developing in-house data harvesting scripts from relevant databases (councils, NGMP, ESR) using existing data feed infrastructure should be assessed by Stats NZ. This feasibility should include a testing phase.
- Existing data vocabularies (sites and variables) should be updated and publicly released by Stats NZ. These datasets are required to identify and harvest data currently missing from the GWQ indicator.
- A pilot framework should be developed to enable data curators (councils, ESR, GNS) to maintain these vocabularies. The data flow, and tapping the relevant technical expertise, should be central to this framework. It will identify technical requirements needed for implementing automated processes.

- A review of current initiatives around environmental data should be undertaken by Stats NZ and the Ministry for the Environment to assess the feasibility of incorporating in-house harvesting scripts, vocabularies and data workflow into current nationwide data initiatives. This assessment should include: scope, traceability of the source-of-truth for data, consistency in implementation and design, and implementation relevant to the development of controlled vocabularies. Current initiatives include: the Environmental Data Management System, the Environmental Outcome Platform, the data analysis system, the regionally driven Wells database, regional and CRI databases, and LAWA.

5.0 CONCLUSION

The GWQ indicator was compiled using open-source data channels to access SoE groundwater quality data. Such channels potentially broaden our ability to present a more representative view of what is currently monitored and, through this, convey a better representation of our groundwaters. However, this review highlighted shortcomings in the current data harvesting, and identified technical work and modifications to data processing required to enable this potential to be reached. Central findings from this review included: unexplained site filtering during the data harvesting process, partial representation of current national scale monitoring networks and shortcoming in data processing. It also provided insights on the stability of our long-term monitoring sites, which may become essential in the context of a changing climate. Recommendations provided in this report aim to enhance future indicator reporting, to open SoE data to data science, to seize the opportunity to review/modify our monitoring as a collective identified by the Parliamentary Commissioner for the Environment (Parliament Commissioner for the Environment 2019), and to address wider monitoring needs identified by the Groundwater Forum Special Interest Group (Morris et al. 2021).

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