Tairāwhiti Gisborne groundwater dynamics and hydrochemical evolution as inferred from regional water age and chemistry data

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ABSTRACT

This study aims to holistically describe the flow sources, pathways and lag times of water through the rivers and aquifers of the Tairāwhiti Gisborne catchments. It brings together geochemical data from shallow and deep groundwater sources, providing an update from the 2001 regional synthesis. This information is required to ground truth and improve groundwater flow models and management tools. This study was funded through the Ministry of Business, Innovation and Employment (MBIE) Endeavour Fund programme Te Whakaheke o Te Wai.

Groundwater chemistry and age tracer data were assembled from a range of sources, namely: (1) GNS Science's national and regional datasets (National Groundwater Monitoring Programme, North Island Hikurangi margin forearc fluids composition), (2) regional datasets (State of the Environment monitoring and specific site investigations), (3) existing data from the Water Dating Laboratory and (4) water samples collected in March 2020 and November 2022 as part of this study. The aggregated dataset consists of 238 sites and spans the period from 1963 to 2023. The environmental tracer data (age, isotopes, temperature, gas concentration and chemistry) were combined and interpreted using graphical analysis (e.g. Piper diagram) spatial analysis and multivariate statistics. These analyses inform the characterisation of groundwater flow and hydrochemical processes in the Tairāwhiti Gisborne district's aquifers.

Tairāwhiti Gisborne groundwaters consist of relatively fresh groundwater held within gravels of the flats, separated from deep brines upwelling from the Hikurangi Subduction Zone (HSZ). The fresh groundwaters have significantly higher solute concentrations in relation to average concentrations of New Zealand groundwaters. At the ground surface, the brines are expressed as springs (both cold or warm) or mud volcanoes at various locations in the district. In the Poverty Bay flats, the aquifer system comprises successive gravel aquifers, with varying thickness and lateral continuity. The hydrochemical signature of this system is generally of calcium-carbonate type without strong distinctive features between aquifers, likely reflecting the same source rocks. Moderate to long residence times (six to over 100 years) are typical even at shallow depths, and reducing conditions are prevalent in older waters. The smaller East Coast alluvial aquifers also generally exhibit moderately old freshwater (10 to 35 years). The deeper brines have a distinct sodium chloride signature and significantly more positive stable isotope (δ^2H and δ^{18}O) signatures than the fresh groundwaters. These brines are mostly disconnected hydraulically from the overlying freshwater systems.

Rivers and streams are hydraulically connected to shallow Holocene gravels within the flats (both Poverty Bay and East Coast), however, estimated recharge rates are typically low (25 mm/yr for rainfall recharge, 200 mm/yr for river recharge). Long-term declining water levels occurring in the deepest Poverty Bay aquifers indicate continuing storage depletion.

In the Poverty Bay flats, two opposite, long-term trends are observed at multiple locations and depths: freshening and salinisation. Freshening trends likely reflect localised river recharge, leakage from overlying aquifers or possible irrigation at unconfined shallow locations. Salinisation trends indicate limited recharge and suggest that deeper, more saline water is captured. In the Poverty Bay Te Hapara Sand aquifer (shallow and coastal), chemistry changes are rapid and significant, indicating a locally responsive aquifer. Recommendations in the light of long-term trends in groundwater quality are provided to review and consolidate the existing quality and quantity networks.

KEYWORDS

Groundwater, Tairāwhiti Gisborne, age tracers, radon, isotopes, hydrochemistry, brines, hydrogeology, Poverty Bay, East Coast Aquifers.

1.0 INTRODUCTION

In this section, an overview of the geology, climate and hydrology is provided as context for the analysis and interpretation of environmental tracers.

1.1 Regional Context

Tairāwhiti Gisborne's groundwater resources are hosted in the district's flats. For resource management purposes, these flats are split between the Poverty Bay flats and the East Coast Aquifers (ECAs) (Tschritter et al. 2016; White et al. 2012). The Poverty Bay flats cover a large area (185 km^2) of sedimentary basin formed within the Quaternary floodplain of the Waipaoa River (White et al. 2012). The ECAs are individual Holocene-filled coastal valleys along the east coast of the district (Tschritter et al. 2016). Until recently, groundwater development in the district has been focussed on the Poverty Bay aquifer system. The Poverty Bay aquifer system is multi-layered and complex, consisting of the following aquifers (in order of increasing depth): the shallow Te Hapara Sands (THS) along the coast; the Shallow Fluvial Gravels (SFG) (associated with the Waipaoa River); the Waipaoa Gravels (WPG) (strongly connected hydraulically with the Waipaoa River); the extensive Makauri Gravels (MKG); and the deep Matokitoki Gravels (MTK), which directly overlie the greywacke basement and are recharged by the Waipaoa River. The connection to the sea for both the MKG and MTK is uncertain (Taylor 1994; Moreau and White 2020). Aquifers in the ECAs are generally uncharacterised, although Gisborne District Council (GDC) is in the process of establishing a monitoring network in these areas (Moreau and White 2020 [and references therein]) and, at the time of writing this report, some of the ECAs are being investigated as part of a geophysical data acquisition programme (Aqua Intel Aotearoa 2024). The ECAs include, from north to south, the Wharekahika; Karakatuwhero; Orutua; Tunanui; Waiapu; Mangahauini; Waipare; Ūawa; Pakarae, Waiomoko, Wainui and Muriwai areas (Figure 1.1).

Drinking water is an important water use in Tairāwhiti Gisborne. Approximately 0.28 million m3/week is allocated for drinking water, which is approximately 46% of total water allocation (Rajanayaka et al. 2010). In 2010, consented water takes for irrigation in Tairāwhiti Gisborne were reported to cover 3925 ha, equivalent to 0.4% of the land area (Rajanayaka et al. 2010). Irrigation was reported to be used exclusively for arable land. Water takes for irrigation consist of 70% surface water take and 30% groundwater take, with no irrigation storage (Rajanayaka et al. 2010). A recent increase in water allocation for irrigation (51% since 2016), predominantly in the Poverty Bay flats, reflects the recent expansion and intensification of horticultural activities, particularly kiwifruit and apples (Gisborne District Council 2020). As a result, a water restriction system is in place in the Poverty Bay flats to prioritise the Gisborne municipal water supply over commercial and industrial use, with minimum flows measured in the Waipaoa River used as triggers (Gisborne District Council 2021a).

A long-term decline in groundwater elevations has been previously reported in the MKG and MTK aquifers (White et al. 2012; Moreau et al. 2017; Moreau and White 2020). In 2012, these observations triggered the development of Groundwater Available for Allocation volumes for Poverty Bay aquifer systems to support sustainable freshwater management (White et al. 2012). Seawater intrusion due to increased groundwater abstraction or reduced groundwater recharge has previously been identified as a potential risk (Tschritter et al. 2016; Moreau and White 2020). Increasing salinity has been recently measured in the Makauri Aquifer (Eade Road Bore [Gisborne District Council 2020]). Occurrences of *E. coli* in shallow groundwater have been reported in the Poverty Bay flats, as well as occurrences of selected, mostly legacy, pesticides (e.g. atrazine) in groundwater at selected wells (Gisborne District Council 2020).

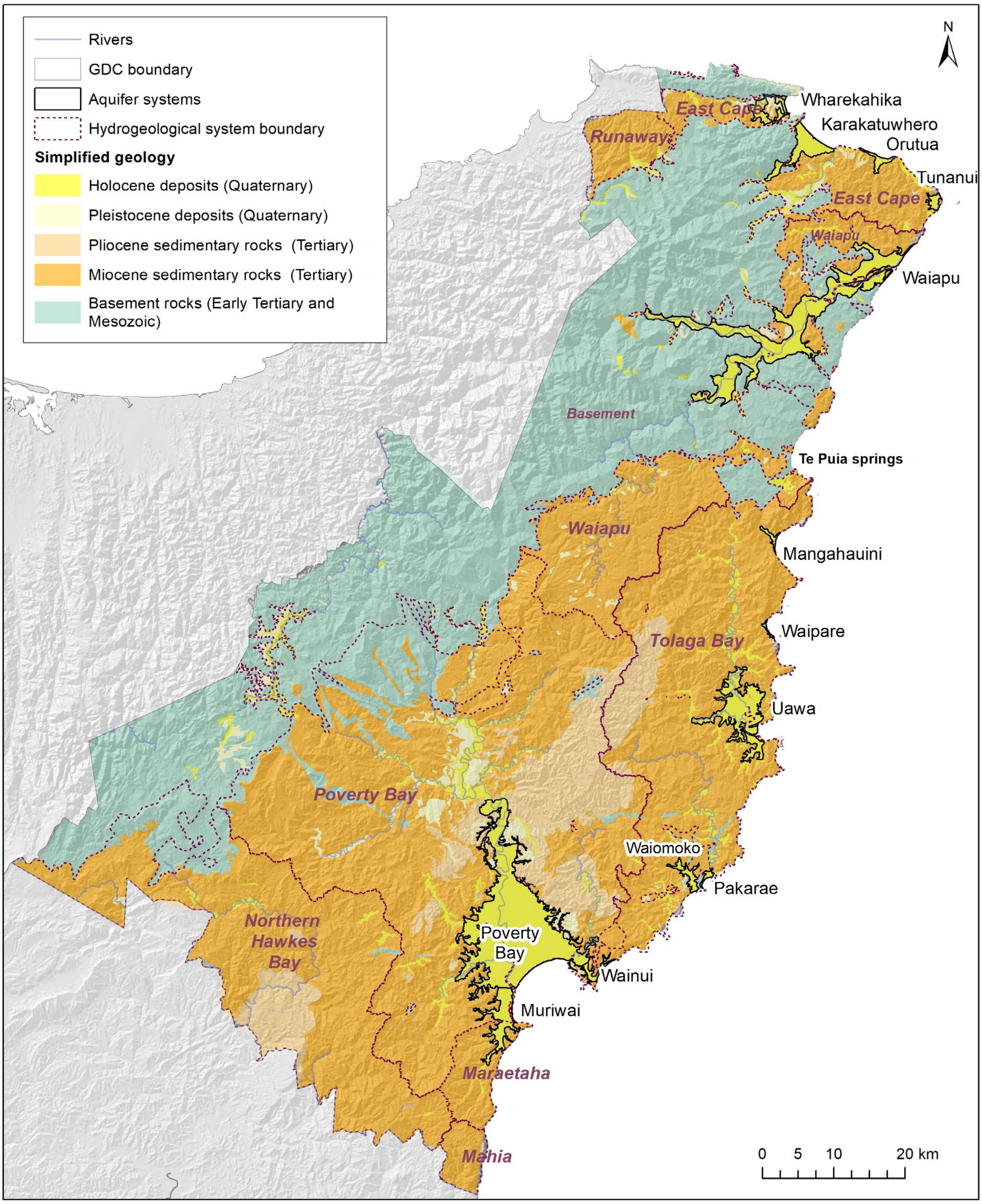

Figure 1.1 Simplified geology and hydrogeology of the Gisborne district (White et al. 2019; LINZ 2019).

The Tairāwhiti Resource Management Plan (TRMP) outlines key challenges and aspirations for the future wellbeing of the district for the next 30 years, sets strategic direction and identifies where critical infrastructure will be required (Gisborne District Council 2021a). Key challenges relevant to freshwater resources include: contaminants that degrade water quality and reduce biodiversity, overallocation of groundwater and increasing freshwater demands. In particular, the plan includes reduction targets for total annual allocation in each aquifer by 2025 (Gisborne District Council 2021a). The TRMP incorporates the district plan, regional policy statement, regional coastal plan, regional plans and freshwater plan (in part). The regional policy statement identifies ecosystem health, water quality and quantity, social and cultural importance of water bodies, recognition of cultural values and a need for integrated management. Catchment planning for the region will determine flows and limits by catchment area. These metrics will need to respond to the National Policy Statement for Freshwater Management and will be informed by monitoring data identified in the State of the Environment (SoE) reporting for 2020 (Ministry for the Environment 2024).

In parallel to the TRMP, the following water resources initiatives are underway:

- Hydrogeological mapping using airborne transient electromagnetic data (SkyTEM), including targeted drilling to support water-budget development and data interpretation; as well as an exploration into high-flow harvesting (Aqua Intel Aotearoa 2024). SkyTEM data collection were completed in February 2024. At the time of writing this report, electromagnetic data were being processed and targeted drilling was undertaken to support interpretation.
- Address stormwater and wastewater issues affecting water quality via the long-term (2018–2028) Wastewater Management and DrainWise project (Gisborne District Council 2021b).
- Downhole camera surveys are underway at GDC's monitoring wells to review well status and suitability. Targeted drilling will support the replacement of aging infrastructure. At the time of writing of this report, bores that underwent these checks were in good condition.
- A groundwater monitoring review is underway to review monitoring infrastructure against current resourcing and align with the Surveillance and Evaluative national groundwater quality monitoring framework (Hadfield 2023). The national framework is currently being developed through the Groundwater Forum Working Group and will address the inconsistencies in environmental reporting identified by the Parliamentary Commissioner for the Environment (Parliamentary Commissioner for the Environment 2019).

1.2 Context of the Study

This study was completed as part of the Ministry of Business, Innovation and Employment (MBIE) Endeavour Fund programme Te Whakaheke o Te Wai (TWOTW) (Pathways and Flows of the Waters), the National Groundwater Monitoring Programme, and the Strategic Science Investment Fund (SSIF) Groundwater Programme.

One of the cornerstones of TWOTW is the application of age tracers to inform flow velocities (of water and contaminants) up-gradient from the measurement point. These measurements are interpreted in association with hydrogeological, chemical and isotope data to improve the understanding of the origin of recharge, flow pathways, effects of geology, seasonality and stream order. New modelling approaches integrate age tracers and other data across scales for applications that include setting national policies, managing catchment-scale contaminant inflows to groundwater-fed rivers and protecting local potable water supplies.

This report is part of a series of regional synthesis reports on environmental tracers planned within TWOTW and aims to holistically describe the flow sources, pathways and time lags of water moving through catchments at the regional scale (Morgenstern et al. 2017; Morgenstern et al. 2019; Moreau et al. 2021). In addition to previous modelling approaches of water mass balance and hydrochemistry, and the evaluation of age tracer, isotope and hydrochemistry data, TWOTW aims to provide a consistent interpretation of all available data. The resulting improved characterisation of water ages will enhance the understanding of observed hydrochemistry trends and flow rates. It will also inform the assessment of hydraulic parameters and support addressing region-specific water issues. This information is required to ground truth and improve groundwater flow models and management tools. Such improvements will help to prevent degradation of rivers and aquifers from land-use discharges, which impact on cultural, recreational and economical values, as well as on drinking water supplies and quality. At the time of writing this report, similar work is being undertaken in the Otago, Taranaki and Tasman regions.

1.3 Aim of this Project

This collaborative project between GDC and GNS Science aims to improve the understanding of groundwater dynamics in the district to enable robust policy development. Environmental tracers (age, isotopes, temperature, gas concentrations and chemistry) are used to characterise: (1) the dynamics of the groundwater from recharge to discharge, (2) groundwater interaction with surface water, (3) source(s) of groundwater recharge and (4) the processes that control the hydrochemical properties (quality) of the groundwater (including sources of contaminants).

Specifically, this study aims to address the following questions:

1. Groundwater recharge, flow and discharge questions

- How are groundwaters and surface waters connected within the flats across the district?
- Where does river-recharged groundwater flow within the aquifers?
- Where is groundwater recharged from local rain?
- What are the timescales of water flow through the aquifers?

2. Groundwater chemistry questions

- How do brines relate to fresher groundwaters in the district?
- What are the drivers of long-term chemistry trends in the Poverty Bay flats?

3. Groundwater management questions

- Are SoE monitoring wells influenced by local conditions?

Finally, recommendations are provided to support a review of GDC’s monitoring network.

2.0 SETTINGS

2.1 Geology

The district covers 8374 km^2 of heavily faulted area on the east coast of the North Island. Its western border is defined by the prominent Raukumara Range, which consists of basement rocks (early Cretaceous and older). Towards the east, the basement is covered by younger deposits (Figure 2.1). The basement rocks comprise early Cretaceous and older, structurally complex, eroded, indurated sandstone and mudstone. These are unconformably overlain by a early Cretaceous to Oligocene autochthonous (in-place) sequence deposited during and following marine transgression. Miocene to Pliocene (Tertiary) sediments, up to 5 km thick, outcrop over most of the district and were deposited in a major forearc basin. These sediments consist of muddy sandstones, bathyal mudstones and alternating mudstone and sandstone turbidites, all typical of marine environments (Mazengarb and Speden 2000; Heron 2020).

Pliocene to Holocene (Quaternary) shallow marine and lacustrine sediments outcrop in river valleys. The most extensive valleys are the Poverty Bay flats (Gisborne), Tolaga Bay, Ruatoria and Tikitiki, Hicks Bay and Te Araroa. These sediments comprise extensive alluvial terraces and floodplain deposits inland and, closer to the coast, dune complexes, swamps and uplifted marine terraces resulting from rapid uplift, erosion and changes in sea level during the Quaternary (Mazengarb and Speden 2000; Heron 2020).

Tectonically, the district is part of the Subaerial Hikurangi Forearc of the subduction zone where the Pacific Plate is being subducted under the Australian Plate, which occurs off-shore of the East Coast. The forearc exhibits a decrease in seismic coupling and slip rate from south to north (Reyes et al. 2022). It is potentially the largest source of earthquakes and tsunami in the country. A number of fluid manifestations (hot and cold springs, mud volcanoes and mounds) linked to the subduction zone occur along the East Coast of the North Island (Reyes et al. 2022). In the district, numerous mud volcanoes have been mapped, which can be accompanied by oil and gas seeps and brine springs (Figure 2.1). In the late 1880s, shallow, hand-dug wells allowed local extraction of oil until a fire incident led to the closure of these operations. Exploration remained limited due to difficulties in understanding the deep geological structure, although multiple formations with reservoir potential remain mostly untapped (Mazengarb and Speden 2000).

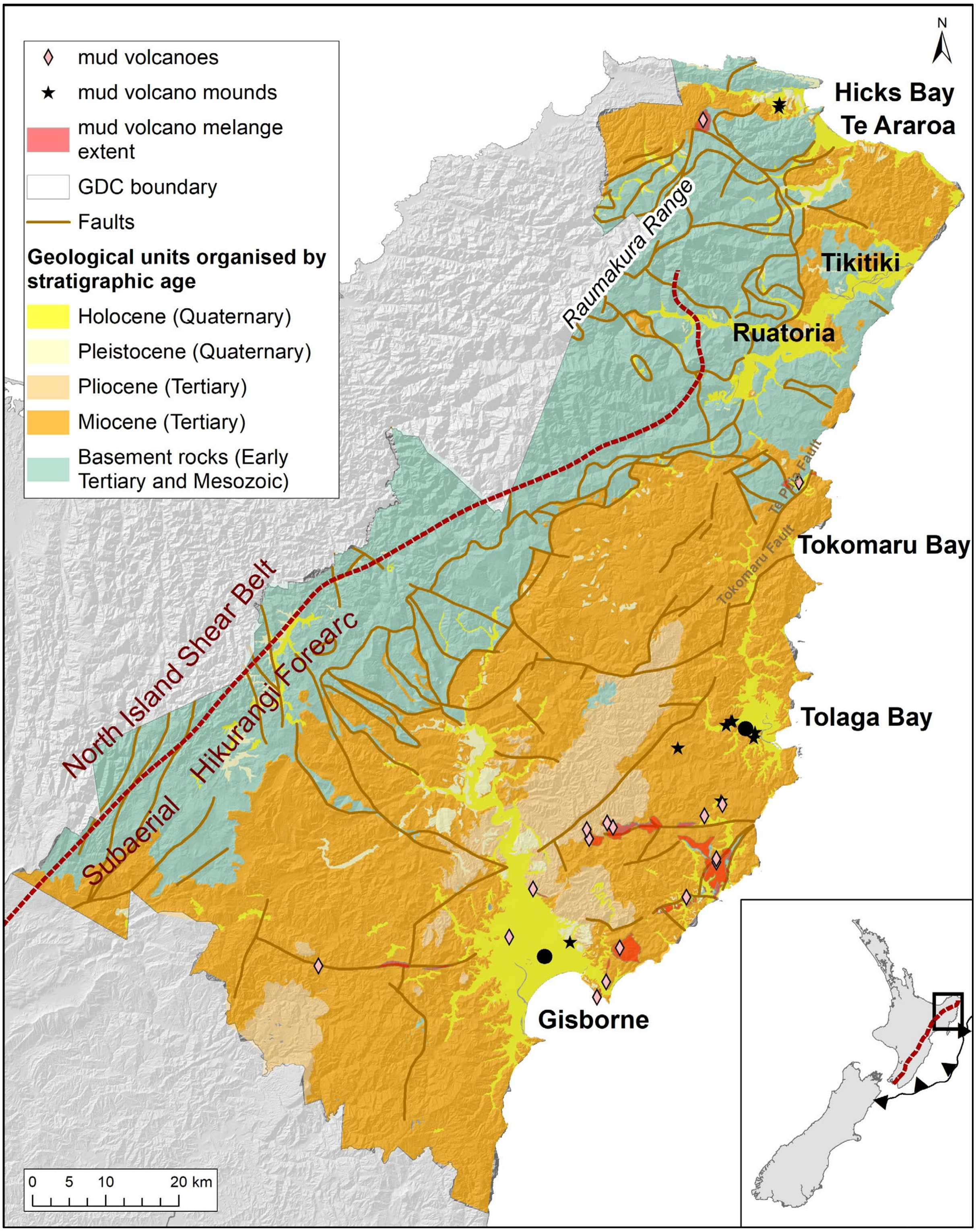

Figure 2.1 Simplified geology of the Tairāwhiti Gisborne district and major faults (modified from Heron 2020, Griffin et al. 2022; Reyes et al. 2022). The inset highlights the North Island Shear Belt (red dashed line) and the Hikurangi subduction margin (black line).

2.2 Climate and Hydrology

2.2.1 Climate

Due to its easternmost location, the district is warmer than most parts of New Zealand, with high sunshine hours, low temperatures over winter and moderate levels of rain occurring relatively evenly throughout the year (Figure 2.2). The weather is strongly influenced by the topography. Under westerlies, the Raukumara Range shelters the district from rain, allowing for high temperatures. Under easterlies, the uplift caused by the mountains serves to enhance the rainfall, and high intensities are recorded at all altitudes (Chappell 2016). Summers are warm and breezy, and winters are mild with infrequent frosts in flat areas. Mean annual temperatures (1981–2010) in the district range from 9°C in the ranges to 16.5°C in low-lying coastal areas (Chappell 2016). Mean annual rainfall (1981–2010) is similarly influenced by the topography, varying from 1300 mm to 1800 mm/yr in coastal areas, to more than 2200 mm/yr in the highest part of the Raukumara Range (Figure 2.2). Seasonal patterns show that 30% of the total annual rainfall occurs in winter and 20% of the total annual rainfall occurs in summer, with heavy rainfall occasionally accompanied by thunderstorms (Chappell 2016).

Gisborne regularly experiences extreme weather events associated with significant damage and disruption (recording began in 1900) (NIWA 2021). Recently (1982–2023), at least six extreme weather events associated with significant damage and disruption were recorded, three of which were declared Civil Defence Emergencies (8–10 April 1982; 26–27 July 1985; 6–12 March 1988; 20–22 October 2005; 20 September 2015; 13–14 February 2023).

Future climate change projections are relevant to water resources in Tairāwhiti Gisborne because projected temperatures and rainfall may impact groundwater recharge and water demand. Temperature and rainfall changes in the long term have been calculated using four Representative Concentration Pathways (Ministry for the Environment 2018a). These projections include mean annual temperature increases of 0.7°C to 3.8°C and annual rainfall decreases in the district of 1% to 4% for the period 1986–2005 and 2081–2120, respectively (Ministry for the Environment 2018a). This is consistent with recent climate change projections for the Tairāwhiti Gisborne district estimating a 2.1°C increase in annual average temperature and a 5% reduction in annual average rainfall by 2090 (Gisborne District Council 2020). The seasonal variability of future Tairāwhiti Gisborne district’s climate under climate change is predicted to see an increase in mean summer rainfall, with Tairāwhiti Gisborne likely to receive increases in precipitation in the summer by 2090. It is important to note that there are uncertainties in climate change predictions, and the predictions reflect a likely range of possible futures.

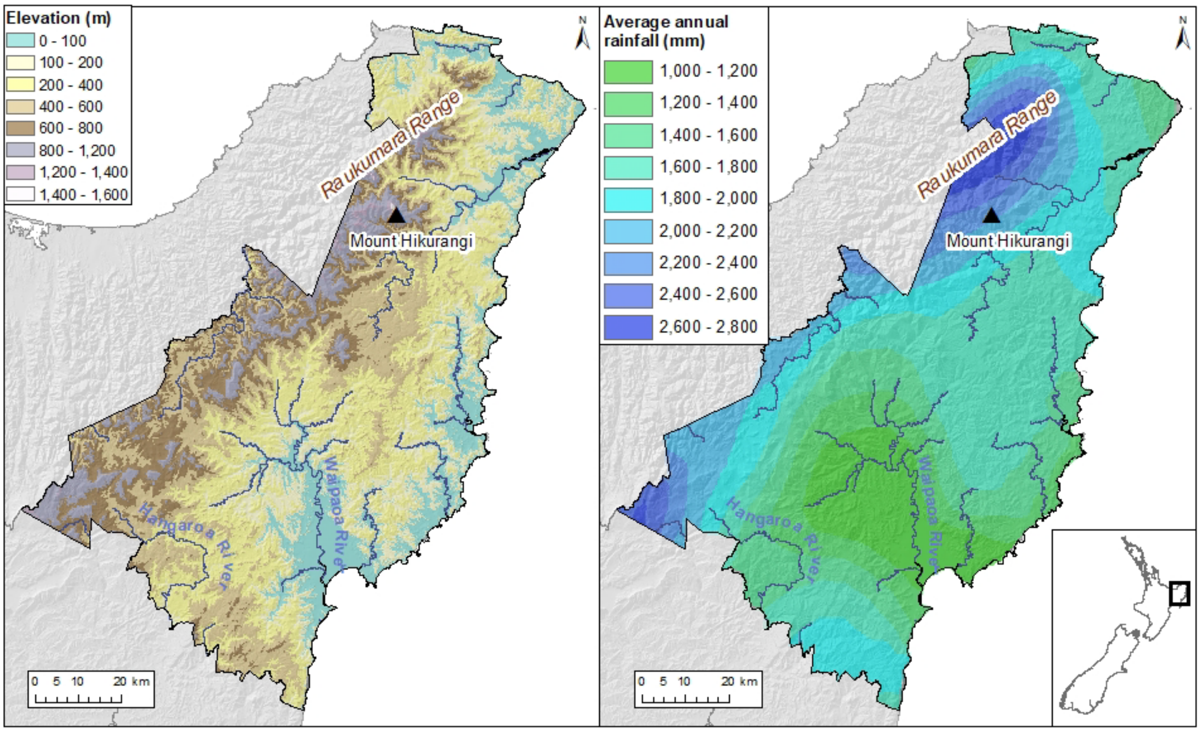

Figure 2.2 Elevation (left) and mean annual rainfall (right) for Tairāwhiti Gisborne district. Rainfall data from the Ministry for the Environment (2021).

2.2.2 Hydrology

The district is bounded in the north and east by the coast, in the west by the Raukumara Range, for which the highest point is Mount Hikurangi (1753 m), and in the south by parts of the Hangaroa River and Waipaoa River catchments (Figure 2.3). The district consists mostly of hill country subject to significant land erosion, where river flats provide areas of productive flat land of varying sizes, the largest being the Poverty Bay flats, which cover an area of 185 km^2 (Gisborne District Council 2021a).

Six major rivers run through the district: the Waipaoa, Waikohu, Maraetaha, Te Arai, Taruheru and Waiapu rivers. Smaller north-flowing rivers are clear, fast-flowing and highly regarded for their recreational value for fishing, canoeing and white-water rafting (Gisborne District Council 2021c). The Waipaoa River and its major tributaries, the Waikohu and Te Arai rivers, drain the Poverty Bay flats, along with the Taruheru River. The Maraetaha River drains the catchment located immediately south of the Poverty Bay flats. The Waiapu River has one of the highest sediment yields in the world, with an annual suspended sediment yield of 36 Mt, which is more than twice that of the adjacent Waipaoa River (the next highest yielding New Zealand river) and nearly 10 times that of the Manawatu River (Walling and Webb 1996; Ministry of Primary Industry 2012). This phenomenon was aggravated in the early 2000s by extensive gully erosion caused by afforestation, which accounted for 49% of annual sediment load in 2012.

The district also contains the headwaters of four major rivers flowing into other regions, including: the Hangaroa River flowing into Hawke's Bay, and the Motu, Waioeka and Waikura rivers flowing into the Bay of Plenty. The Motu River has been under a Water Conservation Order since 1984 (Ministry for the Environment 2018b), which recognises and protects the outstanding values of the river under the Resource Management Act (1991). Lake sediments and water samples from five lakes (Lake Kaikereru, Lake Kaikiore, Lake Karangata, Lake Rotokaha, Lake Waihau [Figure 2.3]) have been studied to determine the current and historic health of each lake as part of the Lakes380 Endeavour project (2017–2022). The Lakes380 datasets are a public resource for New Zealand and global scientific advancement (Lakes380 2022).

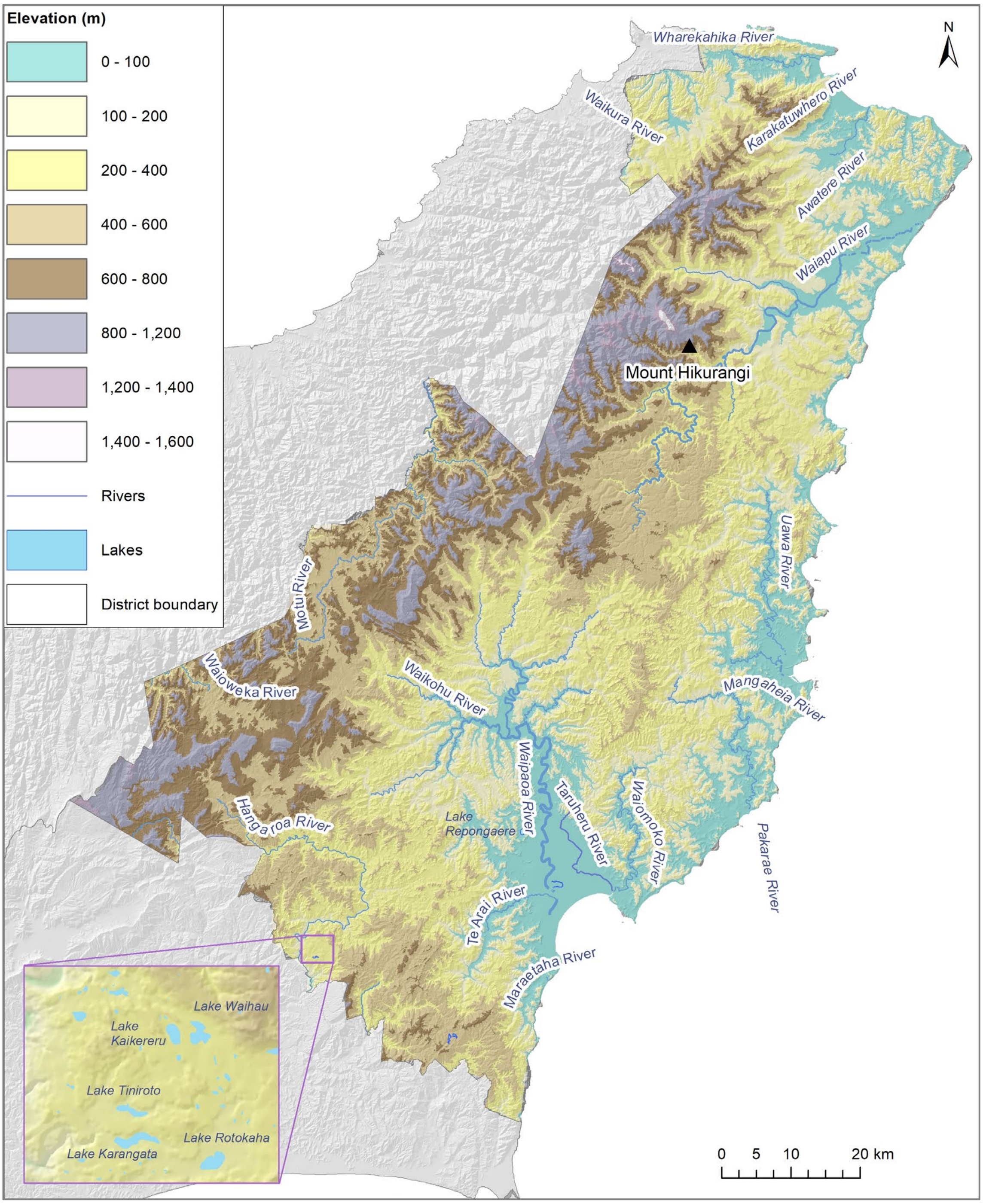

Figure 2.3 Tairāwhiti Gisborne hydrological features. The inset shows the location of the five lakes included in the Lakes380 research programme.

2.3 Hydrogeology

2.3.1 Overview

Fresh groundwater resources occur in the Pleistocene and Holocene deposits that make up the district's flats (Figure 2.4). The Poverty Bay flats provide the largest and most understood groundwater resources (monitoring was initiated in the 1980s). Flats located outside the

Poverty Bay flats (ECAs) have only recently been mapped (Tschritter et al. 2016) and fitted with a recent monitoring network (Moreau and White 2020). Saline groundwater (sourced by subducted seawater interacting with sedimentary strata and mixing with meteoric waters) also features in the district, with multiple occurrences of cold springs and one hot spring cluster (Figure 2.4).

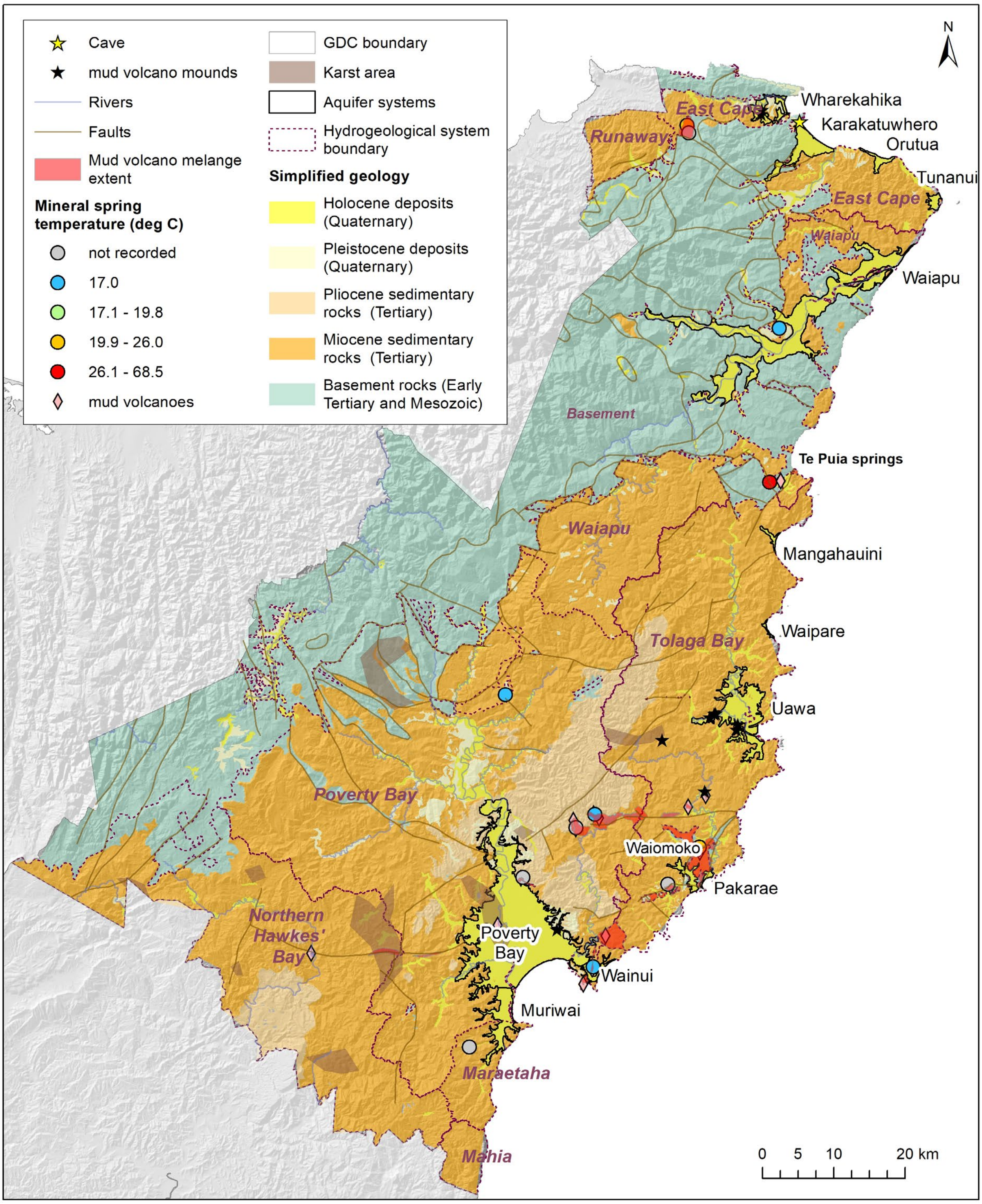

Figure 2.4 Simplified hydrogeology of the Tairāwhiti Gisborne district, caves and spring locations (White et al. 2019; LINZ 2019; Reyes et al. 2022).

2.3.2 Fresh Groundwater Resources

The Poverty Bay aquifer system is a multi-layered river aquifer system (Figure 2.5), comprising alternating silt and gravel layers where five distinct aquifers have been identified (Figure 2.6), listed below in order of increasing depth (White et al. 2012):

- The Te Hapara Sands (THS) consists of beach sands and dunes deposited at the coast and extending for about 5 km inland. These deposits (up to 20 m thick) have accumulated over the last 4000 years, forming a shallow, mainly unconfined aquifer. This aquifer has been identified by GDC as vulnerable to a range of risks to groundwater quantity and quality, including contamination from stormwater, wastewater and landfill leachate, as well as seawater intrusion (Moreau et al. 2017).
- The Shallow Fluvial Gravels (SFG) deposits are centred on the present-day Waipaoa River but cover a larger area. They can be up to 10 m thick and form a shallow, unconfined aquifer. Historical stable isotope measurements (δ^2H and $\delta^{18}O$) have shown slightly different signatures between the eastern and the western margins of the flats (Taylor 1994). In particular, replicate samples collected from Brewery Spring and the deep artesian well GPF056 (also referred to as Gray's Bush) showed more negative oxygen isotope values, which were not consistent with recharge from the river; consequently additional slow recharge through the flats was hypothesised at that time.
- The Waipaoa Gravels (WPG) are also centred around the present course of the Waipaoa River and result from gravel deposition during the phase of coastal advance (7000–4000 years BP). These gravels are strongly hydraulically connected with the river and generally 10–30 m thick. The thickness of sediment between SFG/WPG and underlying MKG decreases with distance from the coast.
- The extensive Makauri Gravels (MKG) aquifer is relatively shallow in the northern part of the Poverty Bay flats (elevation approximately -45 m near Ormond) and deeper (elevation approximately -60 m) below the middle of the flats. The gravel thickness in the middle of the flats is approximately 20 m, and it appears to thin considerably towards the coast, with MKG being absent underneath Tairāwhiti Gisborne, and evidence of a basement rise (Taylor 1994). The MKG gravels have higher transmissivities (ranging from about 750 m^2/day in the southeast to about 2500 m^2/day in the centre of the flats near Waerengaahika) than the other aquifers (range 50–500 m^2/day). At Kaitaratahi, the aquifer is already under artesian pressure and, 5 km further downstream, the aquifer underlies the WPG aquifer. Between 2017 and 2019, a Managed Aquifer Recharge (MAR) trial involving the injection of river water into the MKG aquifer was undertaken to assess potential to manage the effects of increasing irrigation demand (Margarey 2021).
- The deep Matokitoki Gravels (MTK) lie directly over the geological basement and are believed to be remnants of earlier gravels that survived the postglacial processes. These gravels are separated from the shallower MKG by a confining silt layer, which was deposited during the immediate postglacial period 14,000–10,000 years BP. This aquifer is generally confined, with frequent artesian wells and overlies the hydraulic basement.

Groundwater underlying the flats is recharged by the Waipaoa River in the shallower aquifers (Taylor 1994; Gordon 2001; White et al. 2012). Strong connection to surface water has also been evidenced through radon measurements along a 20 km reach of the Te Arai River, which identified multiple groundwater discharge locations (Martindale and van der Raaij 2018; Martindale et al. 2018). However, the deeper, confined aquifers are almost tritium-free, indicating long residence times. The lack of tritium at depth suggests limited natural throughflow, if any. Groundwater ages have been estimated using tritium and carbon 14 (^{14}C), and measured groundwater ages range from 100 to 200 years in the MKG and 3500 to 5300 years in the MTK aquifer (Taylor 1994). Consequently, the connection to the sea for the deeper aquifers is uncertain (Moreau and White 2020).

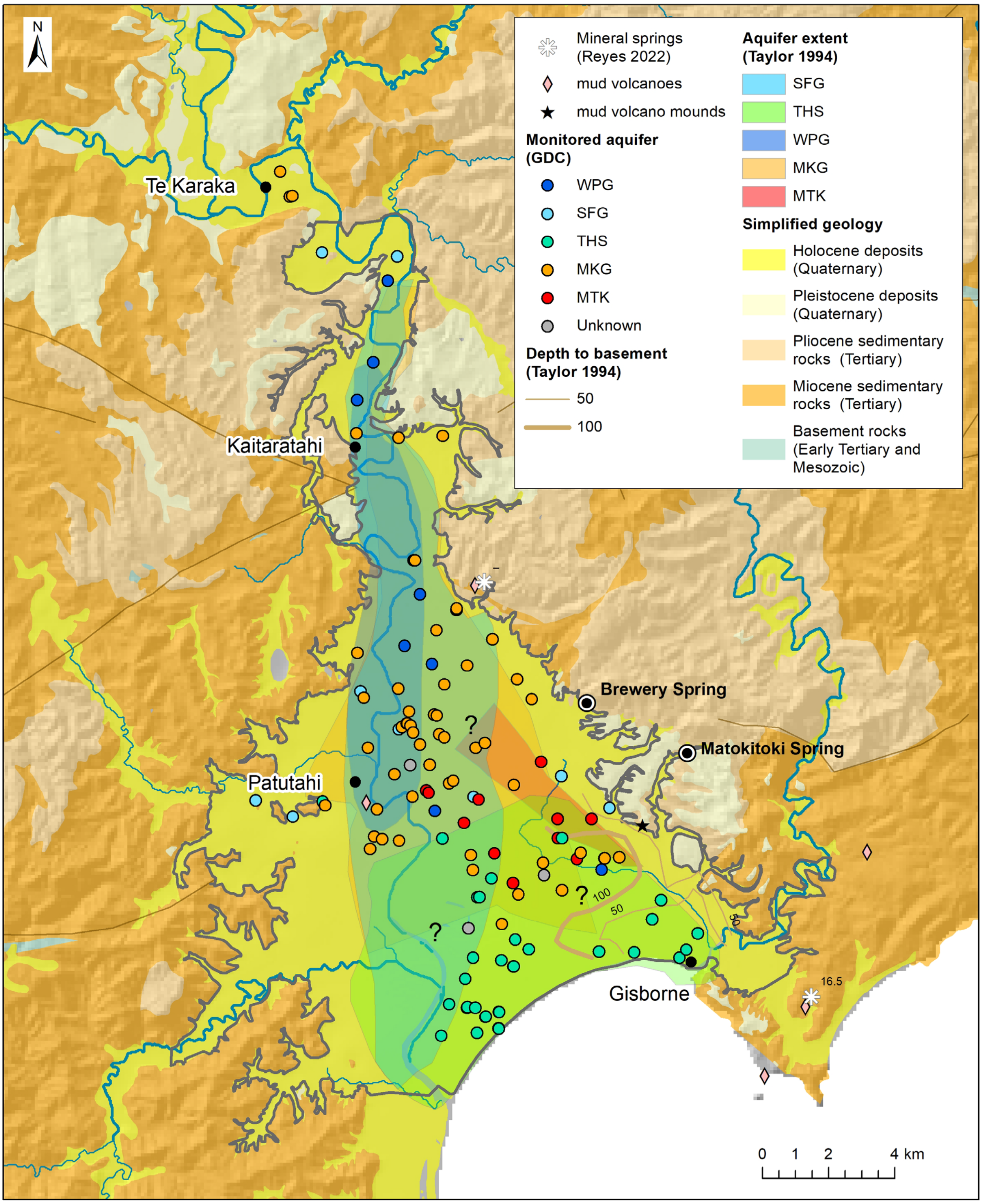

Figure 2.5 Simplified hydrogeology of the Poverty Bay flats, caves and spring locations (White et al. 2019; LINZ 2019).

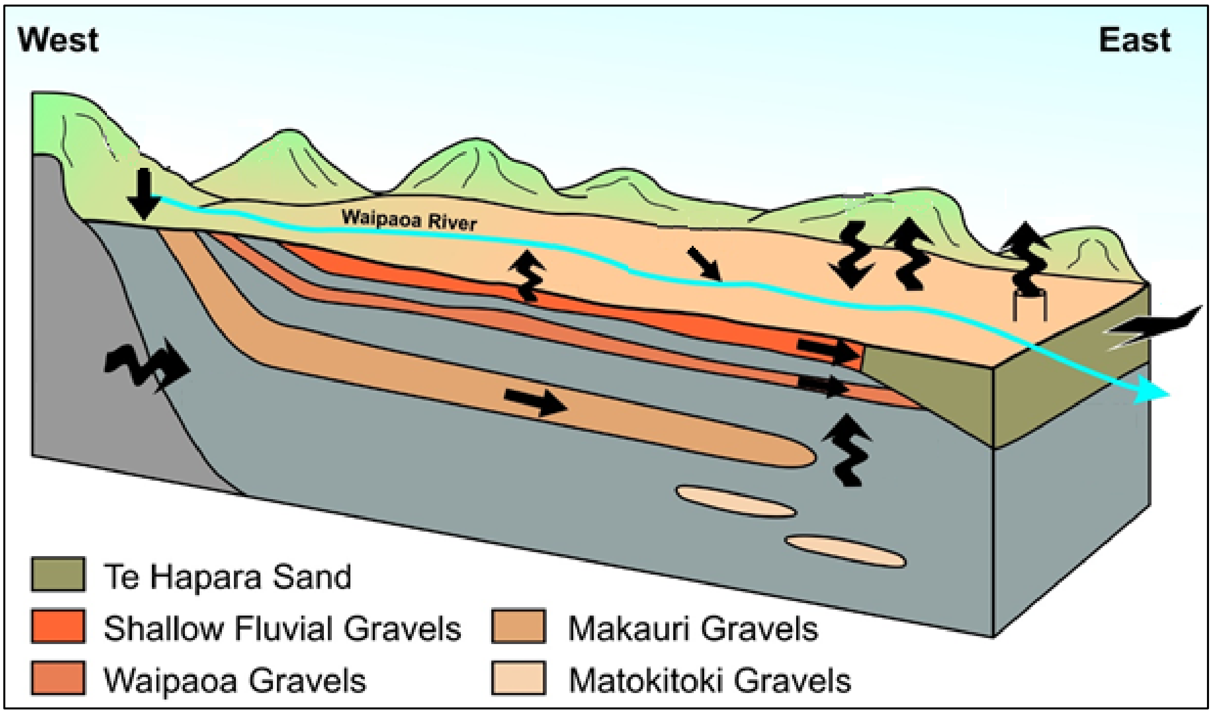

Figure 2.6 Conceptual model of groundwater flow in the Poverty Bay aquifer systems, the arrows indicate water budget components (modified from White et al. 2012).

The ECAs consist of Holocene sediments in alluvial plains and river flats along the Tairāwhiti Gisborne district coastline. These aquifers are shallow and coastal, and vulnerable to threats that may affect groundwater quantity and quality (e.g. anthropogenic activities or environmental hazards). Limited data is available for the ECAs, as the establishment of a monitoring network was only initiated in 2016 (Tschritter et al. 2016; Moreau and White 2020). Aquifer boundaries defined by Murphy and Tschritter (2012) were primarily based on the distribution of Holocene sediments in alluvial plains and river flats along the Tairāwhiti Gisborne district coastline. The ECAs include the following, from north to south, Figure 2.4 (Tschritter et al. 2016):

- The Wharekahika and Karakatuwhero ECAs are located within the East Cape. Groundwater is likely to be hydraulically connected with the corresponding rivers and associated wetlands.
- The Orutua and Tunanui ECAs are small coastal areas near the East Cape.
- The Waiapu ECAs consists of land areas upstream of Ruatoria, including both the Mata and Tapuaeroa river terraces. The Waiapu River is the largest river catchment on the East Coast and is underlain by a thick gravel bed. It is possible that the river recharges a deeper Pleistocene aquifer through that gravel bed. The lagoon located at the river mouth may be hydraulically connected to groundwater. Springs are a common occurrence in the catchment and many people rely on them as freshwater sources (Gisborne District Council 2014).
- The Mangahauini and Waipare ECAs are generally coastal strips that follow the coastline and are bounded inland by steep hill country.

- The Ūawa ECAs comprise river silts and sands, and likely discharges through the Ūawa River. Eleven wells were drilled there in 2021 (Figure 2.7). These showed that the flats consist of Holocene estuarine and fluvial sediments up to 80 m thick (Johansen 2022). The shallow, unconfined dune sand aquifer provides a local groundwater source with modest aquifer properties. The deeper marine gravels overlying the geological basement yield saline water (total dissolved solids content of several 1000s mg/L), often accompanied with elevated hydrocarbon levels and, therefore, are not regarded as a freshwater resource.
- The Pakarae and Waiomoko ECAs comprise river terrace deposits and sands. It is likely that the corresponding rivers are hydraulically connected to groundwater. Note that alluvial Holocene sediments pinch out around Mahana and Mangaone (Pakarae).
- The Wainui ECAs is a relatively thin coastal strip that follows the coastline. Consequently, Wainui is probably comprised primarily of sand deposits. However, the Sponge Bay area was historically an estuary and likely has estuarine silt sediments. Groundwater is expected to flow to the Wainui or Hamantua streams and across the coastal boundary.
- The Muriwai ECAs include the Wherowhero Lagoon, which may be hydraulically connected to groundwater.

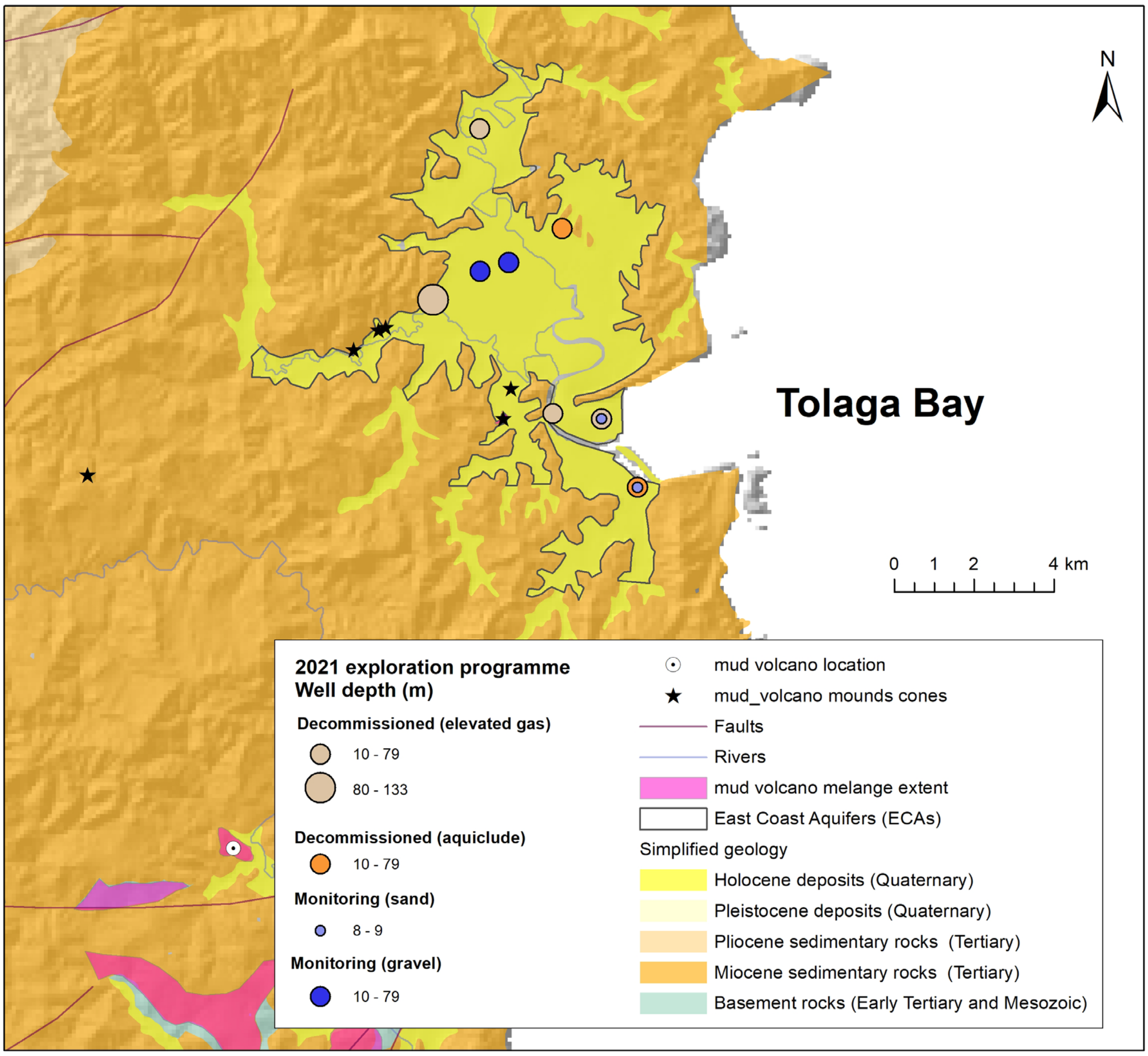

Figure 2.7 Locations and status of the wells drilled as part of the 2021 Tolaga Bay Gisborne District Council exploration programme (data source: Johansen 2022).

2.3.3 Saline Groundwaters

The geochemical signature of these saline springs is relatively unique as the Hikurangi Forearc is one of the few subduction zones in the world where both an actively growing accretionary prism and basin are partly exposed onshore (enabling the sampling of subduction-related fluids). A recent geochemical survey, which compiled historical and new geochemical datasets, demonstrated that the decrease in seismic coupling and slip rate (from south to north) is likely to be a consequence of increasing fluid-saturated sediments in the north (Reyes et al. 2022 [and references therein]). Most brines and fluid manifestations issue from Plio-Pleistocene to Cretaceous sedimentary rocks and, in the district, are generally not associated with active faults (Reyes et al. 2022). Te Puia Springs (54–69°C) occur on an active landslide (Late Cretaceous sedimentary blocks sliding at 55 mm/yr towards the coast, Figure 2.4). A 600-m-long by 20-m-wide calcareous sinter (travertine) deposit occurs around the active hot springs and pools, and forms a prominent east-west ridge up to 30 m above the present hot springs (Pohatu et al. 2010 [and references therein]). The springs are highly mineralised with sodium and chloride concentrations of 7500 mg/L and 4500 mg/L, respectively. Cl/Br ratios of the springs' waters suggest a seawater origin. The elevated lithium concentration (13–14 mg/L) are similar to springs in the Taupō Volcanic Zone (TVZ) and suggest that the waters are heated to 200–330°C. Estimated residence times of aqueous fluids from the subduction zone are of the order of 20,000 years. Hydraulic connectivity between the saline groundwater and shallow Quaternary aquifers is highly unlikely, with reported significantly different water levels in wells that intercept brines suggesting the occurrence of a caprock, e.g. Tolaga Bay (Johansen 2022).

2.3.4 Groundwater Wells

In 2017, a comprehensive review on bore integrity was undertaken, with a large desktop component complemented by fieldwork to identify groundwater-use volumes and inspect wellheads at selected locations. Although this assessment focussed on GDC-owned bores and privately owned bores that GDC uses for monitoring purposes, it is expected that the findings will also apply to privately owned bores. The review findings are summarised below (Cave 2018):

- There are around 1800 water wells in the district, of which 414 belong to GDC. Most of the wells (80%) are located in the Poverty Bay flats.
- Most well records are of poor quality: 315 of the GDC wells are sourced from unidentified aquifers (115 within the Poverty Bay flats).
- Most bores were drilled between the 1970s and 80s (Table 2.1), and issues, including poor capping under artesian pressure, associated flammable gas, obstructions and damaged headworks, have been identified at 24 out of the 83 wells monitored for static water levels. The downhole condition of the remaining wells is unknown. Artesian pressures and the occurrence of gas are common within the Poverty Bay flats, particularly associated with the deeper aquifers.

Table 2.1 Age of the wells reviewed by Gisborne District Council (Cave 2018).

Age (years)	Number of Wells
0–10	26
10–20	48
20–24	132
25–29	147
30–39	283
40–49	27
50–59	23
60–99	19
unknown	237
Total	**942**

2.3.5 Groundwater Monitoring

Groundwater is currently monitored in the region via three programmes (Figure 2.8):

1. **GDC State of the Environment (SoE) groundwater monitoring programme:** the GDC SoE groundwater quality monitoring dataset is a combination of site-specific studies and ongoing monitoring managed by GDC to inform environmental reporting and groundwater resource management. The current network comprises 63 wells for groundwater quality and 88 for groundwater quantity (Jeune 2022). Groundwater monitoring started in 1982, making it one of the longest monitoring records in New Zealand. Sampling frequency varies between sites and time periods, for instance, samples were collected monthly between 2012 and 2017 in the Poverty Bay flats, then reduced to bi-monthly at most wells since 2017 (Moreau and White 2020).
2. **National Groundwater Monitoring Programme (NGMP):** the NGMP is a long-term (late 1990s to current) collaborative programme operated between GNS Science and all regional authorities. It aims to identify spatial patterns and temporal trends in groundwater quality at the national scale and relate them to specific causes. In this programme, groundwater samples are collected quarterly at *c.* 110 sites nationwide and analysed for over 17 chemical parameters. Water dating at all sites was undertaken in 2009, with irregular ongoing re-sampling. In the district, the NGMP dataset consists of six active and two retired wells (shared with the SoE network). Monitoring started in 1998, and all sites are shared with the SoE network. This programme is funded by MBIE's SSIF infrastructure.
3. **GNS Science's National Tracer Survey (NTS):** this programme aims to collect age-tracer data in data-sparse regions of New Zealand, which complements age-tracer information collected under the NGMP. This programme was initiated in 2011. Targeted sites are shallow wells where the water is expected to be young enough for the well to have already responded to anthropogenic changes. In the district, the NTS network consists of eight wells. This programme is co-funded between MBIE's SSIF and TWOTW.

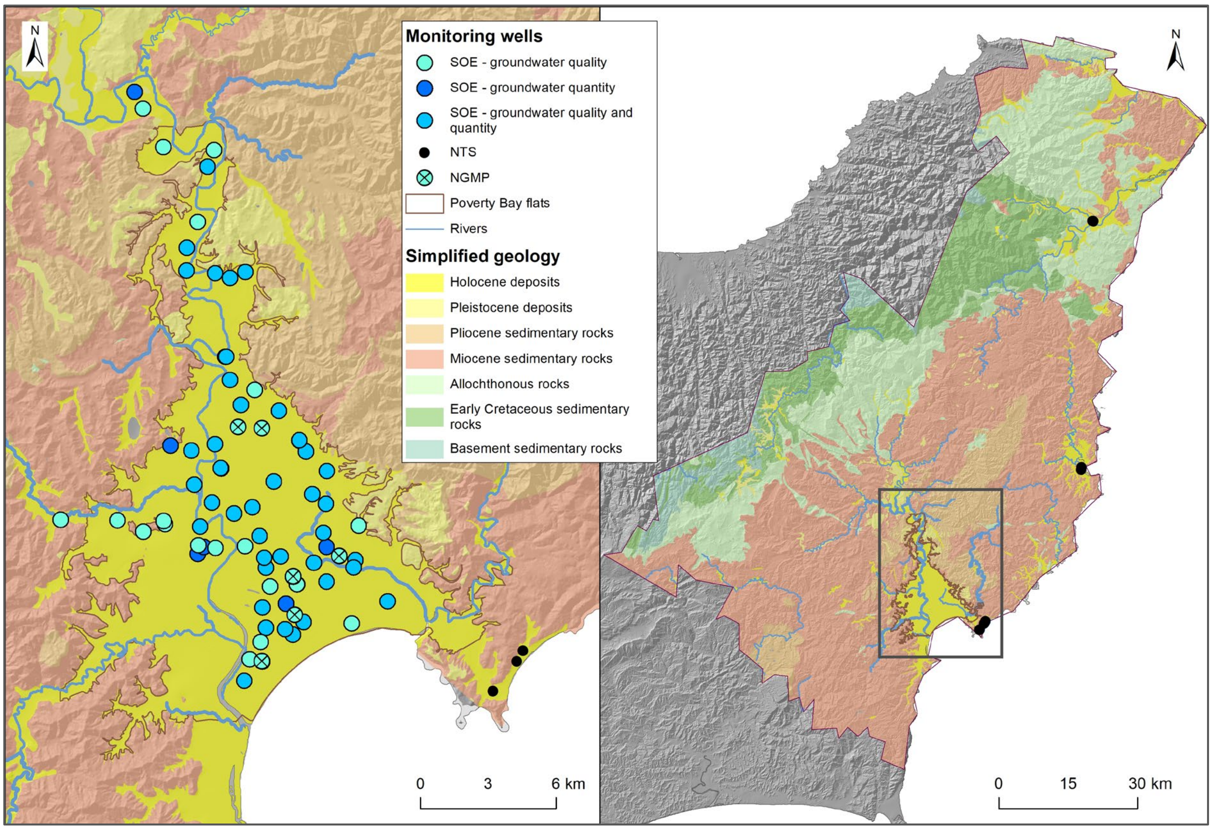

Figure 2.8 Location of groundwater monitoring sites.

3.0 METHODS

In this section, a general description of the method and interpretation techniques is presented for the following environmental tracers: water age tracers, radon, stable isotopes, hydrochemistry, temperature, argon and nitrogen gases.

3.1 Groundwater Dating

Methods for groundwater dating in the southern hemisphere are described in Morgenstern and Daughney (2012). Groundwater dating utilises convolution of a known time-dependent tracer input (via the rain into the groundwater) with a suitable system response function and matching to the tracer concentration measured in groundwater. A range of groundwater age tracers are available (Beyer et al. 2014); they should be applied in a complementary way, as application of a single tracer can result in ambiguous interpretations. Multi-tracer approaches can improve the robustness of the age interpretation and enhance the characterisation of groundwater recharge processes. The most robust and cost-effective age tracers in New Zealand were used in this study, i.e. tritium, sulphur hexafluoride (SF_6), chlorofluorocarbons (CFCs) and Halon-1301 (Figure 3.1). In this study, five types of tracer were used to establish residence times: age tracers with long-term, time-dependent input concentrations in the atmosphere or those exhibiting radioactive decay for groundwater dating in the age range of 1–100 years (tritium, SF_6, CFCs and Halon-1301), and radon (Radon-222) build-up in groundwater for dating periods of up to several weeks.

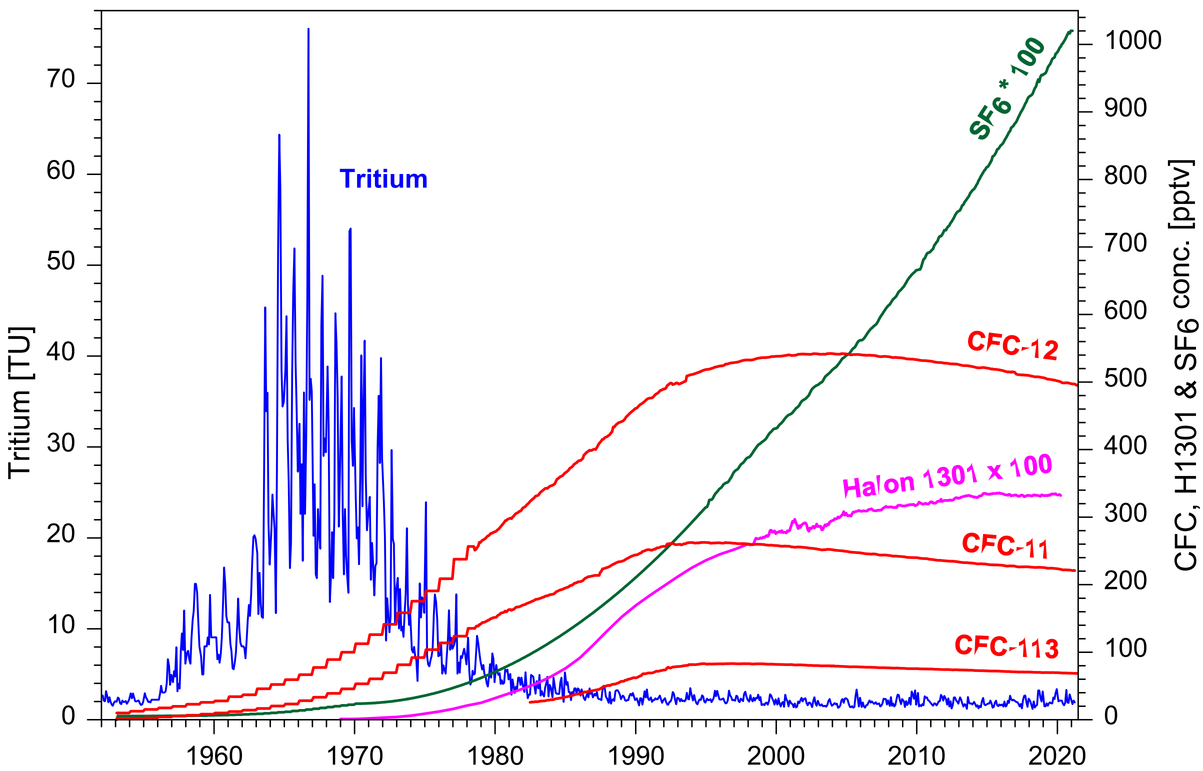

Figure 3.1 Tritium, CFCs, Halon-1301 and SF_6 input for New Zealand rain. Tritium concentrations have been measured in rain at Kaitoke, 40 km north of Wellington (monthly samples), and CFCs, Halon-1301 and SF_6 concentrations are for southern hemispheric air. TU=1 represents a 3H/1H ratio of 10–18, and 1 ppt is one part per trillion by volume of CFCs, Halon-1301 or SF_6 in air, or 10–12. Pre-1978 CFC data are reconstructed using methods of Plummer and Busenberg (2000) and scaled to the southern hemisphere by a factor of 0.83 (CFC-11) and of 0.9 (CFC-12). Post-1978 CFC data were collected in Tasmania. Pre-1970 SF_6 data are reconstructed, 1970–1995 data are from Maiss and Brenninkmeijer (1998) and post-1995 data were measured in Tasmania. Halon-1301 data are from Beyer et al. 2017.

The measured tracer output concentration in the groundwater (C_{out}) is compared with its historical input (C_{in}) using the convolution integral:

$$c_{out}(t) = \int_0^{\infty} c_{in}(t-\tau)\, e^{-\lambda\tau} g(\tau, f) d\tau \qquad \text{Equation 3.1}$$

where *t* is the time of observation; *τ* is the transit time (age); $e^{-\lambda\tau}$ is a decay term, with *λ* being $\ln(2)/T_{1/2}$ (radioactive decay of tritium with a half-life $T_{1/2}$ = 12.32 years); and *g(τ,f)* is a system response function (Maloszewski and Zuber 1982, 1991; Zuber et al. 2005; Cook and Herczeg 2000). The response function describes the distribution of ages within the water sample, for example, arising from mixing of groundwater of different ages within the aquifer or at the well. The two most commonly employed response functions are the dispersion model and the exponential piston flow model (Zuber et al. 2005). The exponential piston flow model is a combination of the piston flow model, which assumes piston flow in a single flow tube with minimal mixing of water from different flow lines at the discharge point (e.g. a confined aquifer), and the exponential model, which assumes full mixing of water from different flow paths with exponentially distributed transit times at the groundwater discharge point (e.g. mixing of stratified groundwater at an open well in an unconfined aquifer).

The various response functions are described in Zuber et al. (2005) and Cook and Herczeg (2000). Stewart et al. (2017) showed that the exponential piston flow model covers the age distributions of typical groundwater discharges. The exponential piston flow model response function is given by:

$$g(\tau) = 0 \qquad \text{for} \quad \tau < (1-f) \qquad \text{Equation 3.2}$$

$$g(\tau) \quad = (f t_t)^{-1} exp\left[-\left({}^{\tau}/_{f t_t}\right) + \left({}^{1}/_{f} - 1\right)\right] for \qquad \tau < (1-f) \qquad \text{Equation 3.3}$$

where t_t is the Mean Residence Time (MRT), *f* is the ratio of the volume of exponential flow to the total flow volume at the groundwater discharge point and $t_t(1-f)$ is the time water takes to flow through the piston flow section of the aquifer (Maloszewski and Zuber [1982] use the variable η; η=1/*f*). The model with *f*=0 becomes equivalent to the piston flow model and, with *f*=1, becomes equivalent to the exponential model.

The two parameters of the response functions, t_t specifying the mean and *f* the distribution of transit times, are determined by convoluting the input (tritium concentration in rainfall) to simulate passage through the hydrological system in such a way as to match the output (e.g. tritium concentration in wells or springs).

3.1.1 Age Tracers

Tritium is produced naturally in the atmosphere by cosmic rays. In addition, large amounts of tritium were released into the atmosphere in the early 1960s during the atmospheric thermonuclear weapons testing, giving rain and surface water significantly higher tritium concentrations at that time (Figure 3.1). Surface water becomes separated from the atmospheric tritium source when it infiltrates into the ground; subsequently the tritium concentration in the groundwater then decreases over time due to radioactive decay and is therefore a function of time that the water has been underground (age).

Tritium, with its pulse-shaped input, is a particularly sensitive tracer for identifying two unique age distribution parameters via the delay and dispersion of the bomb-pulse in the groundwater compared with the rain input. This approach is particularly useful for the age interpretation of wells with little other information on mixing of groundwater from varying depths and of different ages. The superimposed bomb-tritium can accurately and precisely identify water recharged between 1960 and 1975, enabling identification of complicated age distributions in groundwaters, e.g. from multi-screen wells, if tritium time-series and/or multi-tracer data are available.

Tritium has now become the most robust groundwater dating tool in New Zealand. It is part of the water molecule and has no sources or sinks in the groundwater system through chemical processes. The relatively small amount of bomb-tritium that mixed from its northern hemispheric sources into the southern hemisphere (Taylor 1968) has now decayed and, since about 2010, no longer results in ambiguous age interpretations for New Zealand hydrologic systems. Figure 3.2 shows the tritium output of a typical transfer function for New Zealand in comparison with that of Vienna, which is typical for the mid-latitude continental northern hemisphere. Dashed lines show the tritium output 10 years ago, when still-significant levels of bomb-tritium were still present in New Zealand's groundwater systems. In New Zealand, a monotonous decline in tritium output versus MRT was already observed 10 years ago, allowing determination of unambiguous groundwater ages with a single tritium measurement. In the northern hemisphere, there is still a significant amount of bomb-tritium present in the groundwater systems, requiring complementary age tracers (SF_6, helium-3) or tritium time-series data to find unique ages. However, from Figure 3.2, it can be derived that, in the coming years, bomb-tritium will have declined sufficiently in the northern hemisphere, similar to the situation in New Zealand in 2010, to allow determination of unique ages from single tritium measurements, including surface water dating where no complementary age tracers are available.

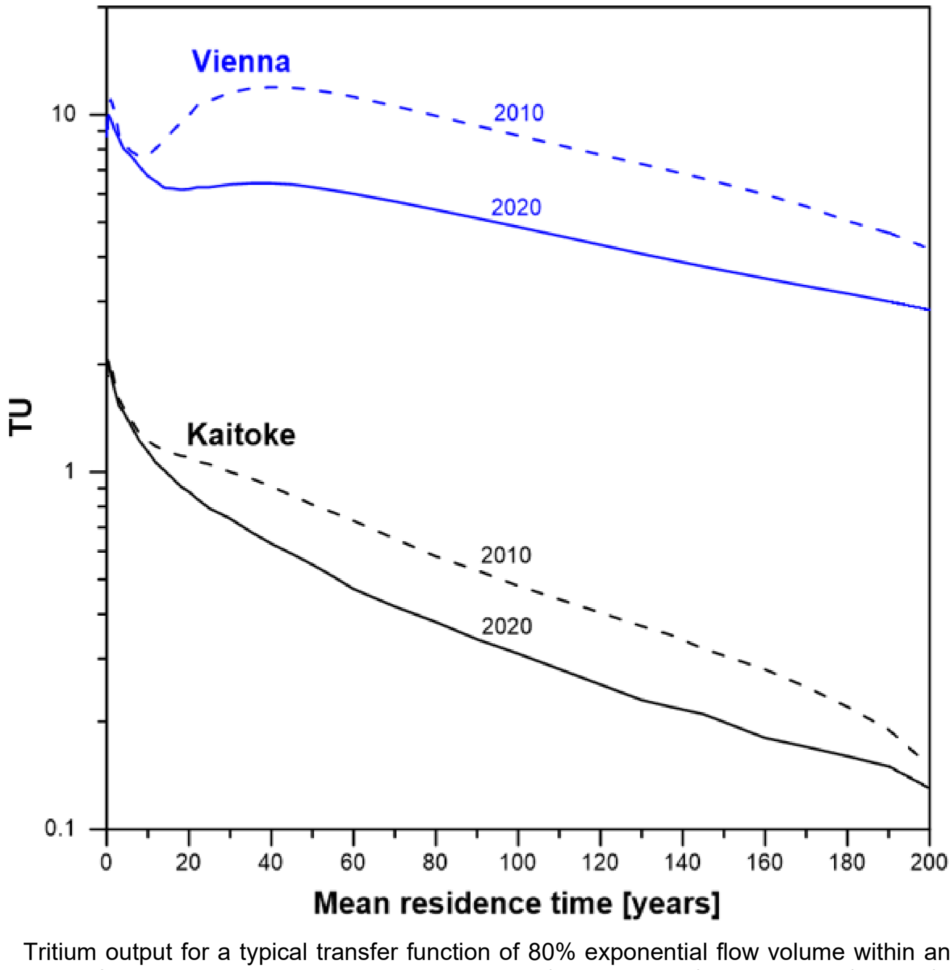

Figure 3.2 Tritium output for a typical transfer function of 80% exponential flow volume within an exponential piston flow model, calculated using the Kaitoke (New Zealand) and Vienna (Europe) tritium input. Solid lines are current tritium output; dashed lines are previous tritium outputs from 10 years ago for comparison to show the decline of bomb-tritium.

Tritium is now used to date river and stream water over timescales of years and decades. No other readily available tracer is able to date surface water, as other tracers are significantly altered when the groundwater is exposed to air. In other parts of the world, the application of accurate and robust groundwater dating to understand hydrological systems on large scales, with respect to groundwater lag times, storage, recharge, hydrochemical evolution and land use versus geologic impact on groundwater quality, is still more complicated as bomb-tritium remains present. Therefore, these new opportunities offered by the tritium method in New Zealand are currently leading to increased understanding of hydrologic systems (McDonnell et al. 2021).

To provide the tritium input into New Zealand hydrologic systems, tritium concentrations are measured in rainfall at Kaitoke, 40 km north of Wellington (monthly values, Figure 3.1). This data is applicable for any location around New Zealand by applying a scale factor to adjust for latitude, altitude and coastal influence. The scale factor is deduced from an additional eight New Zealand rain records of at least two years in length.

Chlorofluorocarbons (CFCs) are entirely man-made contaminants. They were mostly used for refrigeration and pressurising of aerosol cans, and their concentrations in the atmosphere gradually increased until the mid-1990s (Figure 3.1). CFCs were then phased out of industrial use because of their destructive effects on the ozone layer. Thus, atmospheric CFC concentrations rapidly reduced in the 1990s and concentrations continue to decrease, meaning that CFCs are not as effective for dating water recharged after 1990. CFCs are relatively long-lived and slightly soluble in water, therefore they enter groundwater systems with groundwater recharge. Their concentration in groundwater records the CFC atmospheric concentration from when the water was recharged, allowing determination of the recharge date of the water.

Another chemical compound, Halon-1301 ($CBrF_3$), shows promise to remain a more useful age tracer, due to its still slightly increasing concentrations in the atmosphere (Figure 3.1) and absence of local contamination sources that could interfere with dating (Beyer et al. 2017). Halon-1301 has been used as a refrigerant gas and fire suppressant agent in the mid-1990s, but also faces production restriction due to its ozone-depleting effect.

SF_6 is primarily anthropogenic in origin but can also occur in some volcanic and igneous fluids. Significant production of SF_6 began in the 1960s for use in high-voltage electrical switches, leading to increased atmospheric concentrations (Figure 3.1). The residence time of SF_6 in the atmosphere is extremely long (800–3200 years). It holds considerable promise as a dating tool for post-1990s groundwater because, unlike CFCs, atmospheric concentrations of SF_6 are expected to continue increasing for some time (Busenberg and Plummer 2000), as evidenced by the recent more-than-linear increase, which makes SF_6 a very sensitive tool for dating young groundwater.

3.1.2 Radon

Radon-222 (^{222}Rn) gas is a radioactive decay product of uranium, which is ubiquitous in almost all rocks and soils. Groundwaters, in a closed system in contact with these rocks, accumulate ^{222}Rn released from the minerals, resulting in elevated ^{222}Rn concentrations in groundwater. These concentrations are a result of the equilibrium between ^{222}Rn delivery and radioactive decay (half-life 3.8 days) and can vary considerably depending on the uranium content and ^{222}Rn emanation potential of the aquifer material. In surface waters, ^{222}Rn concentrations are low because of limited contact with its source and because of decay and degassing into the air. This tracer informs on the presence of young (up to weeks) groundwater.

The contrast between high ^{222}Rn concentrations in groundwater and low concentrations in surface water allows the identification of fresh groundwater discharges into surface water, as indicated by elevated ^{222}Rn concentrations in river water (Martindale et al. 2018). Conversely, fresh river water recharge into groundwater systems is indicated by low ^{222}Rn concentrations in groundwater, as it takes approximately three weeks (five to six half-lives) for the ^{222}Rn to equilibrate to the ambient concentration of groundwater.

3.2 Stable Isotopes

The stable isotope signature of meteoric water depends on the history of the water masses with regard to temperature-dependent kinetic processes, such as evaporation of the water from the sea and re-precipitation. For example, rivers from colder, higher-altitude catchments usually have a more negative isotope signature than local, low-altitude rain near the coast, allowing us to distinguish whether groundwater recharge is derived from river or from local rainfall.

The stable isotope ratios $^{18}O/^{16}O$ and $^{2}H/^{1}H$ are expressed as δ values and represent the difference in parts per thousand between isotope ratios in water relative to those in Vienna Standard Mean Ocean Water (V-SMOW): $\delta^{18}O$ (‰) = $[(^{18}O/^{16}O)_{sample}/(^{18}O/^{16}O)_{VSMOW} - 1] \times 1000$. $\delta^{2}H$ is expressed in a similar way. Stable isotope analysis was carried out in the Rafter Stable Isotope Laboratory at GNS Science using isotope ratio mass spectrometry.

3.3 Hydrochemistry

The hydrochemical composition of groundwater reflects its recharge conditions and evolutionary flow pathways. Various land-use activities or geological formations can result in specific groundwater chemistry signatures that can be traced back to a recharge source or origin. Increasing ion concentrations of water due to water-rock interaction within the aquifer can indicate flow pathways and groundwater processes.

3.3.1 State and Trend Analysis

To reflect the natural variability of groundwater chemistry, state and trends of groundwater quality are described using the following statistical metrics, which are consistent with previous SoE and national reporting (Moreau and Daughney 2015):

- **Median and median absolute deviation (MAD):** the median is a measure of central tendency. It is a more robust measure than mean values because it is not affected by outliers. The MAD gives an indication of the data spread around the median; it is likewise more robust than the standard deviation, particularly to long distribution tails (Helsel et al. 2020).
- **Percentiles (5th, 25th, 75th, 95th):** these inform the data spread around the median (Helsel et al. 2020).
- **Trend magnitude:** the rate of change in each parameter. In this report, the trend magnitudes are based on Sen's slope estimator, which is commonly used for environmental reporting (Helsel et al. 2020).
- **Trend category:** a descriptive category based on the sign of Sen's slope. A symmetric confidence interval around the trend is calculated. If this interval contains zero, the trend is described as 'uncertain'. If this interval does not contain zero, it is 'established with confidence' and assigned either a 'decreasing' or 'increasing' descriptor. This method was recently developed and applied to river quality state and trend assessments (Larned et al. 2016; McBride 2019).

- **Trend type:** this class is somewhat indicative of the confidence in the ability to detect the trend over the natural range of variability in measured concentrations, measured through the MAD (Moreau and Daughney 2021). A trend is classed as 'perceptible' if the change calculated using Sen's slope over the time period is greater than the median plus two MADs, and as 'imperceptible' elsewhere.
- **Statistical test p-values:** in this report, several statistical tests were conducted to assess either the statistical significance of a trend, seasonality or distribution difference. For each test, a hypothesis is formulated, and test statistics are calculated. An acceptable error rate is arbitrarily set to reject or accept the hypothesis, based on a data-calculated probability value (*p*-value). For this report, the significance level was arbitrarily set as $\alpha=0.05$ for all tests, which is a common threshold used in environmental statistics reporting. Detailed information about the use of hypothesis tests in general and the tests used in this report can be found in Helsel et al. (2020).

3.3.2 Hierarchical Cluster Analysis

Hierarchical cluster analysis (HCA) is a multivariate statistical method that categorises the chemistry data based on similarities in selected characteristics. We used HCA to assess variations in the hydrochemical composition of groundwaters within the region and their potential for distinguishing between different recharge sources (e.g. local rain versus river recharge) and identification of flow-evolutionary processes. HCA requires the use of complete cases, i.e. at least one analytical result (below or above detection limit) per parameter per site. The parameter selection represents a compromise between suitable data for processing and interpretation, including spatial coverage.

3.4 Recharge Temperature and Excess Air

Recharge temperature and excess air, derived from argon and nitrogen concentrations, can provide insight into the mechanisms controlling recharge. Ingram et al. (2007) found that excess air concentrations are linked to the magnitude of fluctuations in groundwater level and used this relationship to delineate recharge sources and rates. River-recharged groundwaters, in areas where groundwater levels can be expected to show small fluctuations, usually have lower excess air concentrations than rainfall-recharged groundwater in areas with large groundwater level fluctuations.

Recharge temperature and dissolved excess air have been derived from dissolved argon and nitrogen concentrations using the total dissolution model of Heaton and Vogel (1981). In this model, small bubbles of air entrapped in soil pores are completely dissolved into the groundwater under favourable recharge conditions, thus forming an excess air component. In other areas of New Zealand, this method enabled assessment of recharge sources and identification of paleo-groundwaters recharged during previous colder climates (Morgenstern et al. 2017).

3.5 Analytical Techniques

Tritium concentrations were determined at GNS Science using liquid scintillation in Quantulus™ ultra-low-level counters following vacuum distillation and electrolytic enrichment (Morgenstern and Taylor 2009). Tritium is expressed in tritium units (TU), in which 1 TU represents a $^{3}H/^{1}H$ ratio of 1×10^{-18}. Tritium enrichment by a factor of 95 yields a detection limit of 0.02 TU at GNS Science, and deuterium calibration of each sample ensures a 1% reproducibility of tritium enrichment. Relative precision (1 SD) of routine individual analyses is 1.8–2.3%.

Concentrations of CFCs (CFC-11, CFC-12, CFC-113), argon, nitrogen and methane (CH_4) were analysed using an analytical system similar to Busenberg and Plummer (1992); the analytical system for SF_6 is described in van der Raaij (2003). The CFC and SF_6 concentrations in Figure 3.1 represent southern hemispheric air (where 1 ppt is one part per trillion by volume of CFC, SF_6 or Halon-1301 in air, or 10^{12}).

Detection limits in terms of gas dissolved in water were 5 x 10^{-14} mol kg-1 water for CFCs, 1 x 10^{-16} mol kg-1 water for SF_6 and 3 x 10^{-16} mol for H-1301. Dissolved argon and nitrogen concentrations (analytical accuracy 1% and 3%, respectively) were measured to estimate the temperature at the time of recharge and the excess air concentration, as described by Heaton and Vogel (1981), and calculate the atmospheric partial pressure (ppt) of CFCs and SF_6 at the time of recharge.

Radon-222 samples from groundwater and river water were collected in 20 mL glass vials with metal-lined lids. Due to the short half-life of radon, the samples were measured within a few days after sampling. Liquid scintillation spectroscopy was used with 10 mL of sample water transferred into counting vials and mixed with a mineral-oil-based scintillant and radon absorber, followed by decay counting in a Quantulus™. Detection limits were typically <0.1 Bq/L. The Radon-222 analytical technique was validated by an inter-laboratory comparison organised by Flinders University (Adelaide, Australia) in 2018.

For the measurement of dissolved oxygen in the field, optical probes were used that produce more robust data than membrane probes.

Groundwater chemistry samples were collected following the 2006 standardised sampling protocol for SoE monitoring, consistent with the current National Environmental Standards (Daughney et al. 2006; Milne 2019). The NGMP samples have been analysed at the New Zealand Geothermal Analytical Laboratory since 1993. The NGMP analytical suite includes: sodium (Na), calcium (Ca), magnesium (Mg), potassium (K), carbonate (CO_3), bicarbonate (HCO_3), chloride (Cl), sulphate (SO_4), nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), dissolved iron (Fe), manganese (Mn) and dissolved reactive phosphorus (DRP) (Table 3.1). Hydrochemical analyses integrity of the NGMP samples is checked by calculating the charge balance error and/or ionic sum to ensure that the electroneutrality of the sample is verified (Moreau-Fournier and Daughney 2010). A historical reconstruction (starting from 1993) of changes in analytical methods used for each of the selected parameters monitored as part of NGMP is available elsewhere (Moreau and Daughney 2021). A temporal map of analytical methods and laboratories employed for the SoE network is not currently available.

Table 3.1 Current list of parameters monitored at National Groundwater Monitoring Programme (NGMP) sites. APHA stands for American Public Health Association, which is a reference for analytical methods (Baird et al. 2017).

Parameter	Units	NGMP Analytical Method
HCO_3, CO_3	mg/L	Titration APHA 2320B
Ca, Mg, K, Na, Fe, Mn, SiO_2	mg/L	Induced Coupled Plasma-Optical Emission Spectrometry, APHA 3120B
DRP	mg/L	Flow Injection Analyser APHA 4500-P G (modified)
Cl, NO_3-N, SO_4, Br, F	mg/L	Ion Chromatography APHA 4110B
NH_3-N	mg/L	Flow Injection Analyser APHA 4500-NH_3-N

3.6 Data Processing

3.6.1 Datasets

In total, the Tairāwhiti Gisborne aggregated dataset consisted of groundwater chemistry collected at 152 wells, with time series ranging from one-off measurements to spanning the full 1982–2022 time period (Table 3.2; Figure 3.3) from the following sources:

- Current monitoring datasets (SoE, NGMP, NTS).
- GNS Science Water Dating Laboratory dataset – this dataset consists of historical data accumulated throughout the years by the laboratory as part of its operations. To reflect the sensitivity of some of this data, exact coordinates were removed from the provided dataset.
- Published brine spring locations, chemistry and stable isotope data (Reyes et al. 2022)

Water level data comprises levels recorded at 90 sites, largely overlapping with the chemistry sites, with a time period spanning from December 2011 to March 2023 (Jeune 2022).

The location of the sites is provided in Appendix 1 (Figure A1.1 and Figure A1.2).

Table 3.2 Dataset summary for hydrochemistry and groundwater age.

Network	Type	Bore	Spring	River
NGMP	Hydrochemistry plus age measurements	6	0	0
SoE	Hydrochemistry only	38	0	0
	Hydrochemistry plus age measurements	37	0	0
	Age measurements only	6	0	0
NTS	Hydrochemistry plus age measurements	5	0	0
	Age measurements only	3	0	0
No network	Hydrochemistry only	4	0	0
	Hydrochemistry plus age measurements	10	0	0
	Age measurements only	44	2	2
	Brines	1	11	0
Total		**154**	**13**	**2**

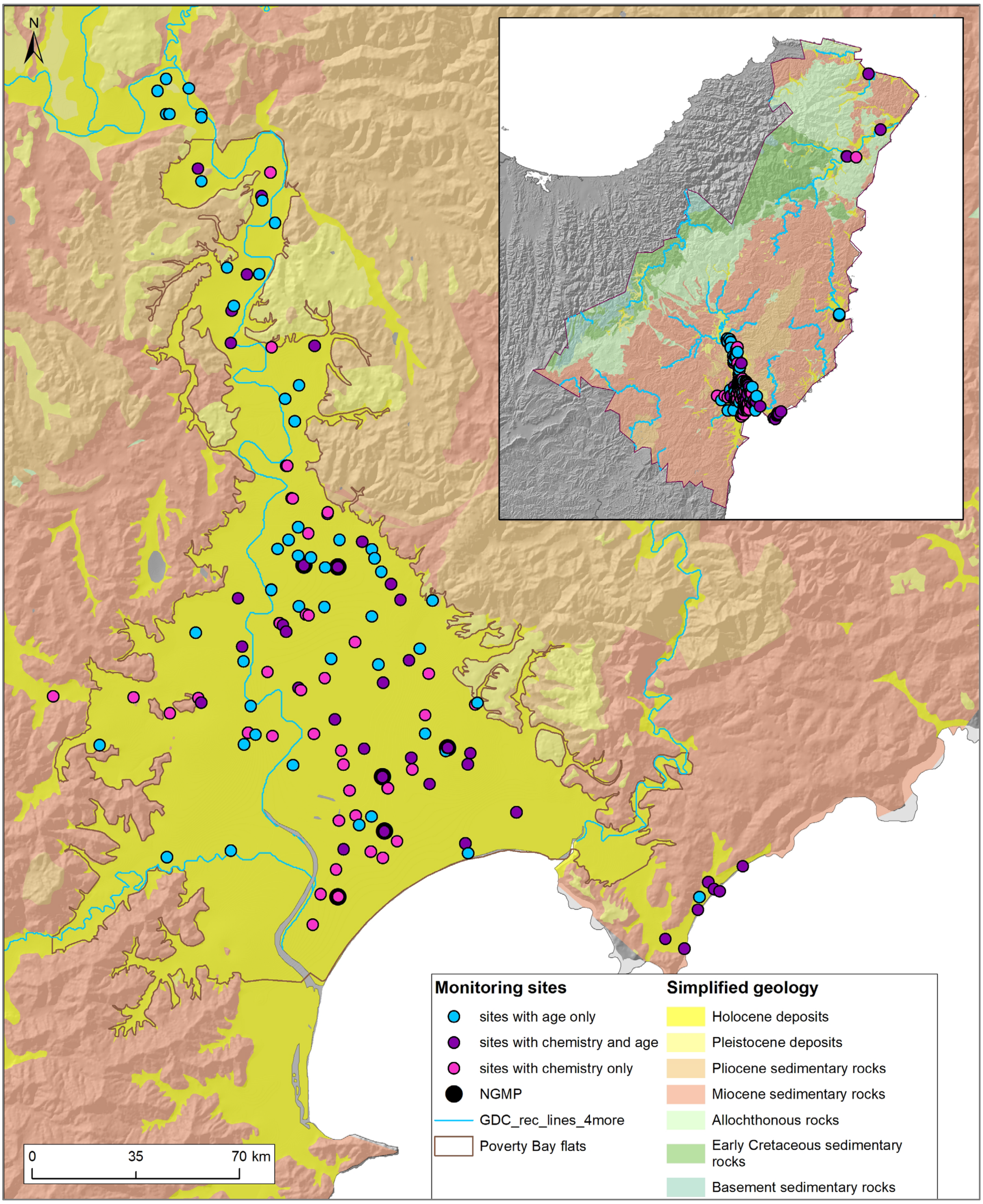

Figure 3.3 Location of sites with groundwater chemistry and/or age with an indication of the monitoring network where applicable in the Tairāwhiti Gisborne district. Three sites are not shown, as coordinates were not available.

While processing data, it was noted that dissolved oxygen (DO) concentrations for sites with long time series (>20 measurements) exhibited larger noise (>2 mg/L) variations between sampling events post-2015. These variations are mostly uncorrelated by changes with redox indicators, such as dissolved Fe and Mn concentrations (Figure 3.4). It is unlikely that such a change in oxygen conditions in the aquifer would not be accompanied by changes in chemistry. This suggests that there may be data quality issues for this parameter, either limited data capture or possible data collection issues, e.g. calibration.

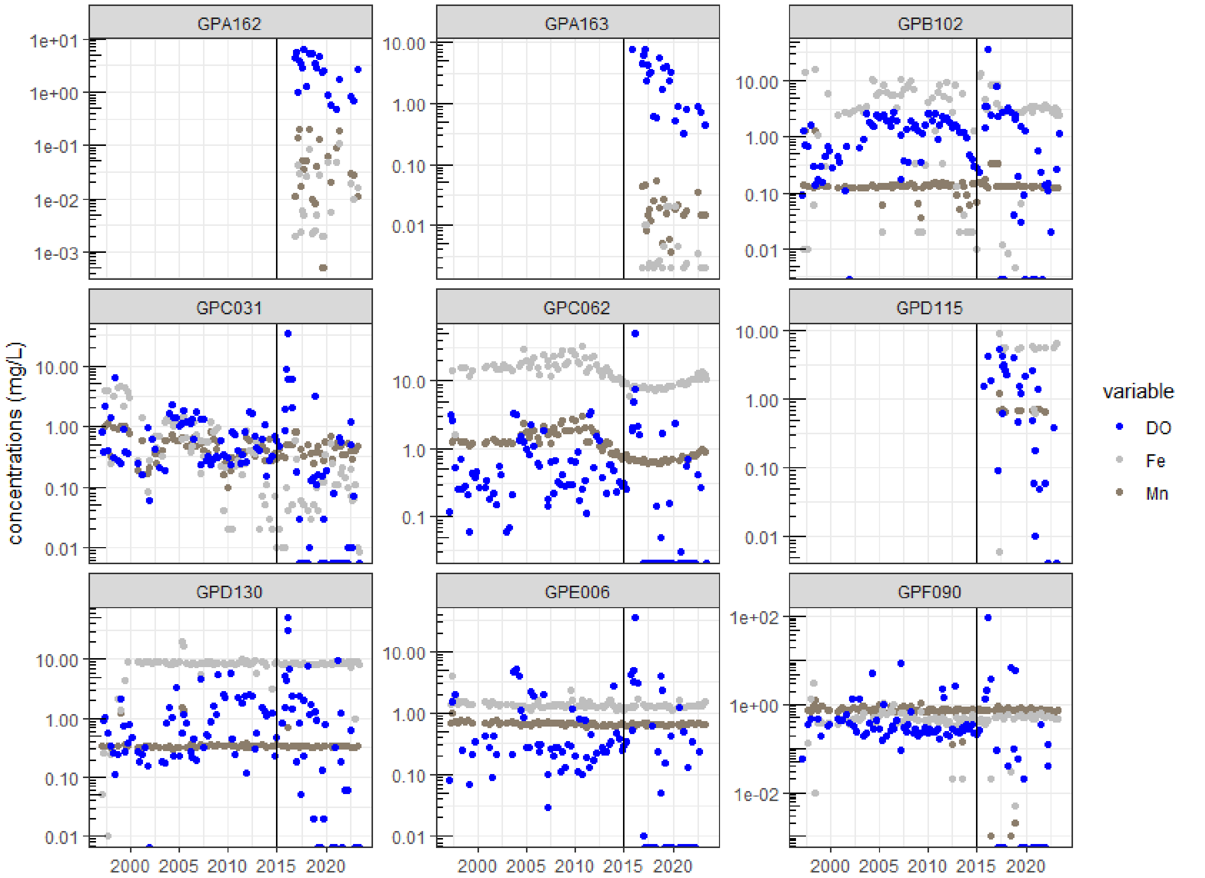

Figure 3.4 Dissolved oxygen time series at sites where more than 20 data points are available for dissolved oxygen (DO). The vertical line indicates 1/01/2015.

3.6.2 Age Interpretation

For age interpretation, exponential piston flow models were used with a percentage exponential age distribution within the total flow volume ranging from 10% to 100%, with 70% used at most sites. The age distribution parameters, MRT and the fraction of exponential flow (EPM fraction) within the total flow volume for the lumped parameter model for age interpretation are listed in the digital data file *GNS SR2021-44_Data_Output.xlsx* attached to the PDF version of this report. There were only a few cases where sufficient time series data were available to measure the mixing fraction. Usually, the tritium data were used as the most robust age tracer data.

Groundwater model ages determined using ^{3}H and ^{14}C depend on their individual characteristics. ^{3}H has a much shorter radioactive half-life than ^{14}C (12.32 years for ^{3}H versus 5730 years for ^{14}C), so ^{3}H is useful for dating younger waters (up to 210 years with f=0.75), while ^{14}C is good for older waters (about 1000 up to 40,000 years). When the ^{3}H and ^{14}C indicated ages are approximately the same, or the ^{3}H concentration is indistinguishable from zero and the ^{14}C age is equal to or greater than 210 years, then the two methods are in agreement (i.e. concordant in age). However, when the sample has a relatively old ^{14}C age (greater than 210 years) but contains ^{3}H, then the ages are not concordant, and the sample must contain some younger water that has ^{3}H in it (Stewart et al. 2017).

3.6.3 Hydrochemistry Data Processing

3.6.3.1 State and Trend Aanalysis

The hydrochemistry data for the Tairāwhiti Gisborne district consisted of time series ranging from less than a year to 36 years, some of the longest groundwater quality monitoring in New Zealand. State and trend analysis were performed with R software (version 3.6.2) using the LWP-Trends (version 2101) and NADA (version 1.6-1.1) libraries. The LWP-Trends library was used to compute the Mann-Kendall trend test (seasonally adjusted or not), Sen's slope estimations and Krukall-Wallis seasonality tests on censored and uncensored time series that have been processed with Non-Detects and Data Analysis (NADA) methods[1] (Helsel et al. 2020).

To calculate meaningful state and trend metrics, minimum data requirements were set as follows:

- **Descriptive statistics (indicative of state over the 2012–2017 time period):** Where there was no censoring, median, MAD and percentiles were estimated using statistical formulas. For time series affected by less than 25%, median and MAD were estimated using Regression on Order Statistics (ROS) models, and percentiles were calculated using statistical formulas. Above 25% and below 80% censoring, no percentiles were calculated; median and MAD were computed using ROS models. Above 80% censoring, there is no estimate of median, MAD or percentiles; values are shown as below the highest detection limit.
- **Kruskal-Wallis test (includes seasonal and trend time periods):** the number of seasons considered for the analysis is four (autumn, winter, spring and summer). The annual time period commences on 1 March of the first year (start of autumn). To enable seasonality state and trend assessments, all seasons must have at least one observation, and individual seasons require at least two data points.
- **Mann-Kendall test and Sen's slope estimator (includes seasonal and trend time periods):** the time series must contain at least 10 data points, the maximum censored values must be smaller than the maximum observed values, and at least five unique observations must be required for each time series.

3.6.3.2 Hierarchical Cluster Analysis

Hierarchical cluster analysis (HCA) was undertaken using the calculated site-specific median values of nine different parameters: Ca, Mg, Na, K, HCO_3, Cl, SO_4, NH_3-N and field pH. In total, 91 groundwater sites had data for the selected parameters and were included in the HCA. Data for other parameters, such as DRP, were not included in the analysis. Total forms were not used as the dissolved and total forms are not directly comparable, as demonstrated by the reported significant decrease in Fe concentrations observed following a change in sampling protocol, specifically field-filtering, in the Wellington region in 2004 (Daughney and Randall 2009). NO_3-N in groundwater is mainly a reflection of the land use in the recharge area and is considered separately for assessment of the recharge source. Excluding NO_3-N from the HCA better helps to focus on groundwater evolutionary processes.

1 The NADA library implements the statistical methods to handle censored values (i.e. concentrations measured below the detection limit). It is used here to calculate medians and median absolute deviations for time series with left-censored values. For heavily censored datasets (i.e. more than 50% of results are recorded below the detection limit for a given parameter), a Regression on Order Statistics model was used to calculate the median value. Above 80% censoring (i.e. more than 80% of results for a given parameter are below the detection limit), medians were not estimated. Sites that had been sampled only once were still included in the hydrochemical assessment to maximise the number of sites available.

Approaches for HCA were based on best practice from previous experience in New Zealand and overseas (Güler et al. 2002; Daughney and Reeves 2005). HCA was initially conducted on log-transformed and normalised median concentrations, temperatures or conductivity using the nearest-neighbour linkage rule. This approach identifies sites where hydrochemistry is most different from other sites. Following this, HCA was then conducted using Ward's linkage rule (Ward 1963). Ward's method is based on an analysis of variance and produces smaller distinct clusters than other linkage rules, in which each site in a cluster is more similar to other sites in the same cluster than to any site assigned to a different cluster. The square of the Euclidean distance was used in the HCA as the measure of similarity for both linkage rules.

4.0 RESULTS AND DISCUSSION – GROUNDWATER PROCESSES AND FLOW DYNAMICS

In this section, the water tracer results are interpreted with respect to: (1) groundwater dynamics from recharge to discharge, (2) interaction with surface water, (3) recharge sources, and (4) understanding of the processes that control groundwater hydrochemistry, including sources and expected loads of nutrients. The techniques are complementary, and the results improve significantly by integrating all techniques.

4.1 Data Outputs

The chemistry and age tracer dataset used in this report is provided in the digital data file *GNS SR2021-44_Data_Output.xlsx* attached to the PDF version of this report, with the following worksheets:

- *Read_me*: caveat on the data.
- *Site_information*: site details (ID, site type, area, coordinates, monitoring network, well depth, screen top and length) for the sample locations. Aquifer attribution is shown within three columns ("aquifer_gdc", "aquifer_gns", "aquifer_wga"), which indicate the aquifer attribution based respectively on a 2021 extract of GDC's borehole database, GNS Science reattribution performed as part of this work and aquifer attribution from the geological model currently undertaken for GDC by Wallbridge Gilbert Aztec (WGA). The last column ("aquifer_gns_attribution_comment") highlights the rationale for aquifer reattribution where the GNS Science value differs from either the GDC or WGA dataset.
- *Units*: detailed information (acronym, units, form) for both chemistry and age tracer parameters.
- *Chemistry*: aggregated analytical results from sources detailed in Section 3.6.1.
- *Age*: aggregated age tracer measurements and interpretation from sources detailed in Section 3.6.1.
- *State_Trend*: groundwater chemistry state and trend metrics calculated over the time period available at each site, on a per site per parameter basis. Reported metrics are: median and MAD, percentiles (5^{th}, 25^{th}, 75^{th}, 95^{th}), trend magnitudes and categories, and p-values for the Mann-Kendall and Kruskal-Wallis tests (Section 3.6.3).
- *Trend_categories*: summary of groundwater chemistry long-term trends calculated over the full time period are available at each site highlighting the trend category, the number of statistically significant trends above natural variability and a list of trending parameters grouped as increases or decreases (Section 4.5.6).
- *HCA*: HCA cluster attribution, where applicable (Section 3.6.3).

4.2 Water Levels

Water level data is currently only available within the Poverty Bay flats and exhibits strong seasonal variations (high in winter and low in summer) ranging from a metre up to a few metres (Figure 4.1). The higher amplitudes observed in the deeper aquifers suggest limited recharge for overlying layers. Localised groundwater level lows demonstrate the impact of summer abstraction, with some significant drawdown (>5 m) recorded in the deeper aquifer. In the coastal THS, trigger levels are set at 0.5 m above sea level (asl); however, water levels are measured frequently below sea level, which emphasise the aquifer's vulnerability to seawater intrusion. Both the MKG and MTK aquifers have been associated with long-term declining water levels, and recommendations to manage these through trigger levels and monitoring were made in 2016 (Moreau et al. 2017).

Spatially, median water levels in the Poverty Bay flats range from close to sea level near the coast to 33 m asl at Te Karaka, the northernmost part of the Poverty Bay flats. Water levels decrease closer to the coast in the shallower aquifers (THS, WPG, SFD). Water levels from the deeper aquifers (MKG, MTK) are higher than those of the shallower aquifers, suggesting limited hydraulic connectivity or downward vertical flow.

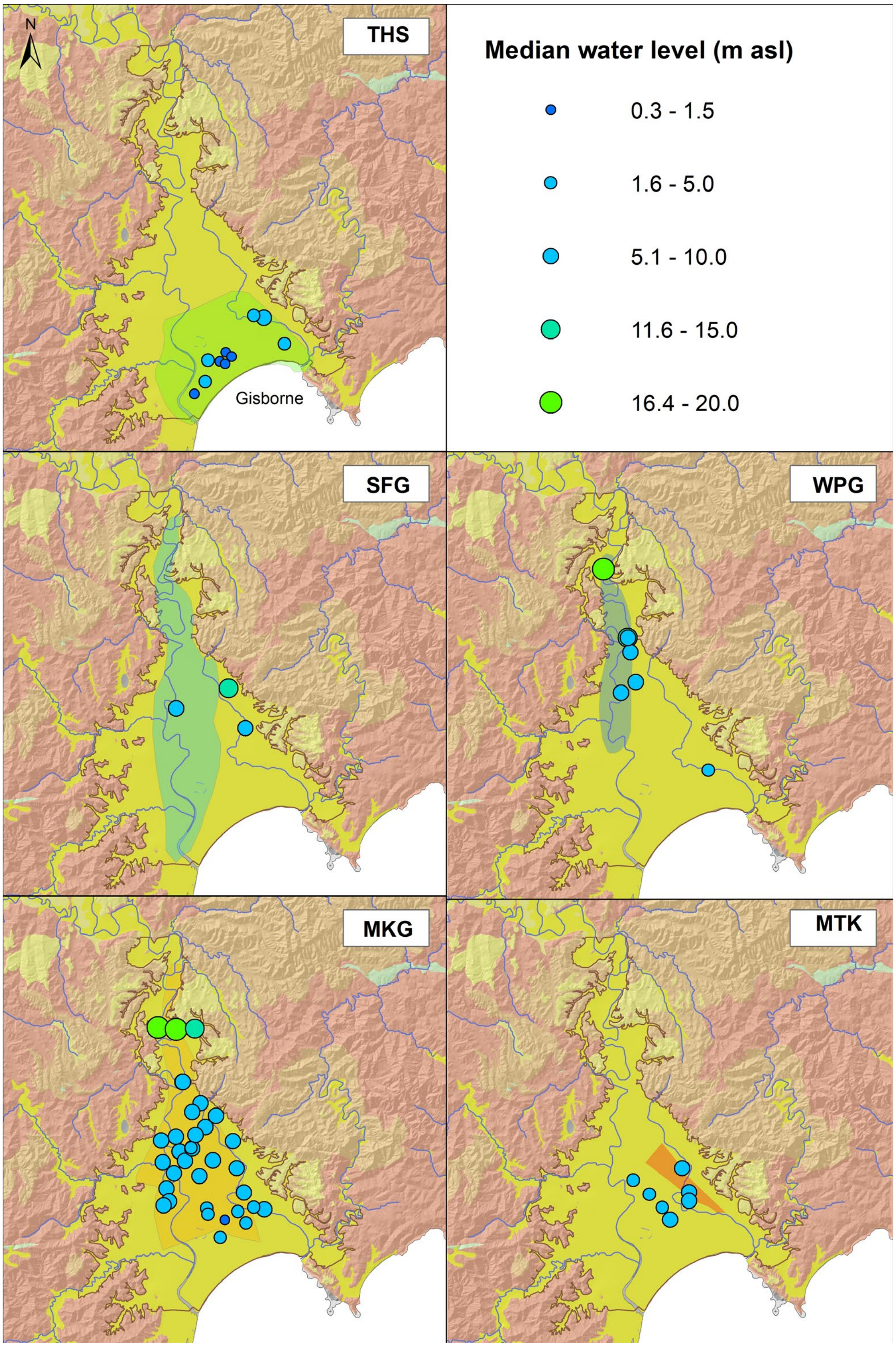

Figure 4.1 Spatial distribution of groundwater elevations in metres above sea level (m asl) in the Tairāwhiti Gisborne aquifers.

4.2.1 Temporal Variability

In shallow aquifers, most wells display increases in groundwater elevation (Table 4.1). In the WPG, a range of temporal patterns were observed, from groundwater elevation increases (GPB111, GPD019) to decreases (GPE026, GPE040, GPG058. GPG059) over the full time period (>25 years). Trend magnitudes range from 0.06 to 0.2 m/yr for increases and -0.01 to 0.05 m/yr for decreases. In the SFG, three wells exhibit increasing water levels over the long-term with magnitudes between 0.02 and 0.04 m/yr. In the THS, most wells exhibit rising water levels, with a magnitude ranging from 0.001 to 0.05 m/yr. At three wells (GPA003, GPB099, GPC030), a short-term groundwater elevation decrease in the early 1990s preceded the long-term increase. In contrast, in the deeper aquifer, water levels are mostly decreasing (Table 4.1). In the MKG, most sites exhibit either a long-term water level decrease at a rate ranging from -0.01 to -0.1 m/yr (n=25) or no statistically significant trends (n=21). In the MTK, water levels have been consistently decreasing over the last 25 years across most wells at rates ranging from -0.01 to -0.04 m/yr (9 out of 12 wells).

In all aquifers, multiple wells record a sharp water level increase in early 2023, likely to be a pressure response to Cyclone Gabrielle (Figure 4.2). It should be noted that although the pressure response is almost immediate, the chemistry response may be significantly slower, if perceptible due to aquifer storage.

Table 4.1 Summary of long-term (full record) water level trends in Poverty Bay flats wells.

Aquifer	Number of Wells	Decreasing	Increasing	Uncertain
Shallow – WPG	10	4	2	4
Shallow – SFG	5	0	3	2
Shallow – THS	30	4	13	13
Deep – MKG	50	25	4	21
Deep – MTK	12	9	0	3

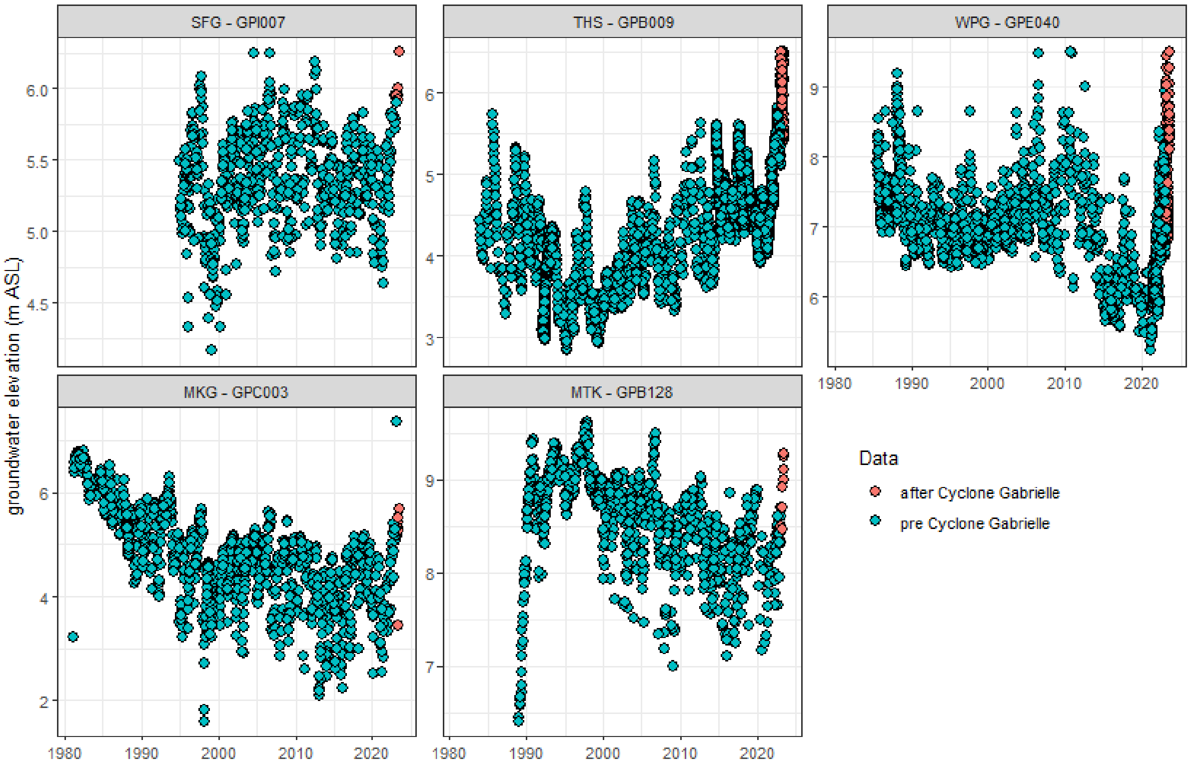

Figure 4.2 Water level time series in metres above sea level (m asl) at selected locations in the Poverty Bay flats.

4.3 Water Age

4.3.1 Groundwater Residence Time

In this section, four types of long-term tracers are used to establish groundwater residence times. Age tracers and MRTs are provided as a digital attachment to this report, along with published ^{14}C derived age (Taylor 1994; Reyes et al. 2022).

4.3.1.1 Age Tracer Results

Shallow aquifers within the Poverty Bay flats (THS, WPG, SFG) and in the ECAs exhibited tritium ratios similar to those of rainwater (*c.* 2 TR), indicating very young water sources dotted in the Poverty Bay flats and the ECAs (Figure 4.3). These higher tritium ratios and associated assumed ages suggest that groundwater flow dynamics in these shallow aquifers are dominated by rapid flow. Deeper groundwaters in the deeper aquifers of the Poverty Bay flats (MKG, MTK) and also in the Wainui ECAs, exhibited low to very low tritium ratios (<0.2 TR), indicating older water (Figure 4.3).

Gas tracer samples were only recently (between 2017 and 2022) collected in the district at 29 sites. For the interpretation of age tracers, it is important to keep in mind that gas tracers in groundwater samples can be contaminated due to air contact during sampling, or in the well head and in the aquifer, due to anthropogenic sources in the recharge area (Section 3.1). Of these 29 sites, only four sites show CFC contamination, indicating the presence of localised contamination sources in the MKG and the Wainui and Waiapu ECAs (Table 4.2). These elevated point source CFC concentrations can be used to identify recharge from local rain, as elevated CFC concentrations do not occur in river water. There were no instances of contaminated samples for SF_6 or Halon-1301.

Generally, groundwaters are older in the Poverty Bay flats than the ECAs, which is consistent with the relative size (and depositional record) of the flats (Figure 4.4). In the Poverty Bay flats, the groundwater gets older (>100 years) as the well depth/aquifer depth increases (Figure 4.5), as depicted in the current conceptual model of deeper aquifers with limited hydraulic continuity with the sea and the groundwater level pattern. In the shallow Poverty Bay aquifers, the THS exhibits the narrowest range, with MRTs between 10 and 80 years (for well depths of 4–11 m). This is followed by the WPG, SFG and MKG, with both MRTs between 20 and 100 years. Wells screened in the MTK exhibit older groundwaters, with MRTs ranging from 110 to 140 years. It is worth noting, however, that repeated age tracer measurements at two THS wells (GPC031 and GPC062) indicate significant local changes in age tracer concentrations, suggesting change in the well's recharge areas or capture zones. These changes are also visible in the groundwater chemistry (see Section 4.5.6).

In the ECAs, most sites are shallow (<10 m deep) with MRTs varying between one year and 35 years. This variability is consistent with the heterogeneous nature of the sediments in these areas. Increased silt content within the sediments results in slower groundwater flow and longer MRTs, whereas the presence of former river channels in the flats creates zones of higher permeability and younger MRTs (Section 2.1). Two sites were measured with significantly older water (150–200 years) – GRB031 (Waiapu, 12 m deep) and GPA119 (Wainui, 19.2 m deep). At both sites, the long residence time is associated with a strong Na/Cl signature compared with other ECA groundwater. This is likely due to mixing with deeper and older brines.

Table 4.2 Age tracer measurements for groundwaters in the Tairāwhiti Gisborne district at sites where gas tracers were collected. The quoted measurement error is the combined statistical standard uncertainty from all processes contributing to the measurement uncertainty, expressed as one standard deviation (Ellison et al. 2000). Ar, N2 and excess air concentrations are expressed in mL of gas at standard temperature and pressure (STP) per kg of water. Negative values indicate degassing has occurred. Partial pressures are calculated from the measured concentrations via Henry's Law using recharge temperatures after correction for excess air. Modern atmospheric concentrations of these gases are around 225 ppt, 510 ppt, 72 ppt, 3.5 ppt and 9.5 ppt, for CFC-11, CFC-12, CFC-13, halon-1301 and SF6, respectively. Concentrations above these levels are considered to be contaminated with other sources of these tracers (highlighted cells in grey).

Aquifer	Well ID	Date	Tr (TU)	± Tr (TU)	SF_6 (pptv)	± SF_6 (pptv)	Halon (pptv)	± Halon (pptv)	CFC 11 (pptv)	±CFC 11 (pptv)	CFC 12 (pptv)	±CFC 12 (pptv)	CFC 113 (pptv)	±CFC 113 (pptv)
WPG	GPB111	4/03/2020	0.008	0.013	0.06	0.19	0.06	0.02	0.5	2	3.3	2.6	4.6	4.2
MKG	GPE067	3/03/2020	1.153	0.032	5.93	0.31	1.49	0.12	227	17	226	16	15.6	4.6
MKG	GPE068	3/03/2020	0.875	0.027	4.77	0.3	1.13	0.11	3.1	2	197	15	15.2	4.5
MKG	GPF090	4/03/2020	0.195	0.019	0.36	0.13	0.09	0.1	0.6	3	4.3	4.3	1.9	5.8
MKG	GPF095	3/03/2020	0.022	0.016	0.5	0.17	0.05	0.07	0.3	2	1.9	3.5	0	2.9
THS	GPA004	3/03/2020	1.093	0.031	3.51	0.22	0.14	0.1	6.2	5	22.1	3.6	5.4	5.4
THS	GPC028	4/03/2020	0.602	0.024	0.32	0.13	0.1	0.13	14	7	17	4.9	3.3	7.4
THS	GPC031	4/03/2020	2.127	0.045	7.49	0.46	0.15	0.11	7.5	3	40.4	5.4	4.1	5.5
ECAs – Karakatuwhero	GAR007	5/03/2020	1.372	0.036	8.36	0.36	1.51	0.09	1.9	4	133	49	0	4.7
ECAs – Ūawa	GTA005/014	23/03/2017	1.304	0.032	4.17	0.48	0.16	0.04	1.8	1	61.6	7.9	0.9	14.5
ECAs – Ūawa	GTA36/37	23/03/2017	1.039	0.031	0.29	0.04	0.08	0.05	11.9	6	68.6	35.8	3	5.3
ECAs – Waiapu	GRB047	23/03/2017	4.462	0.08	7.41	0.75	2.32	0.26	15615	1892	-	-	94.4	14.4
ECAs – Waiapu	GRB048	23/03/2017	1.649	0.037	6.44	0.72	2.33	0.21	144	15	448	43	44.1	7.1
ECAs – Waiapu	GRC013	5/03/2020	1.311	0.034	8.52	0.37	1.98	0.12	554	117	1056	67	45.9	6
ECAs – Wainui	GPA162	22/03/2017	0.646	0.024	-	-	-	-	2	3	37.4	5.6	5.3	6.8
ECAs – Wainui	GPA163	23/03/2017	1.072	0.031	6.7	0.7	2.59	0.25	84.9	9	431	49	34.9	7.1
ECAs – Wainui	GPA164	22/03/2017	1.084	0.031	-	-	-	-	22.9	10	109	36	13.5	8.2
ECAs – Wainui	GPA302	5/03/2020	1.218	0.032	3.96	0.24	1.54	0.1	73.9	7	414	26	28	8.6
ECAs – Wainui	GPA305	4/03/2020	0.972	0.03	2.8	0.19	0.66	0.05	15.6	4	109	12	11.8	7
ECAs – Wainui	GPA307	18/03/2020	1.304	0.034	7.08	2.6	1.93	0.44	97.3	14	382	44	43.1	10.9
ECAs – Wainui	GPA310	18/03/2020	1.492	0.037	5.81	0.89	2.84	0.45	295	31	598	53	86.1	11.1

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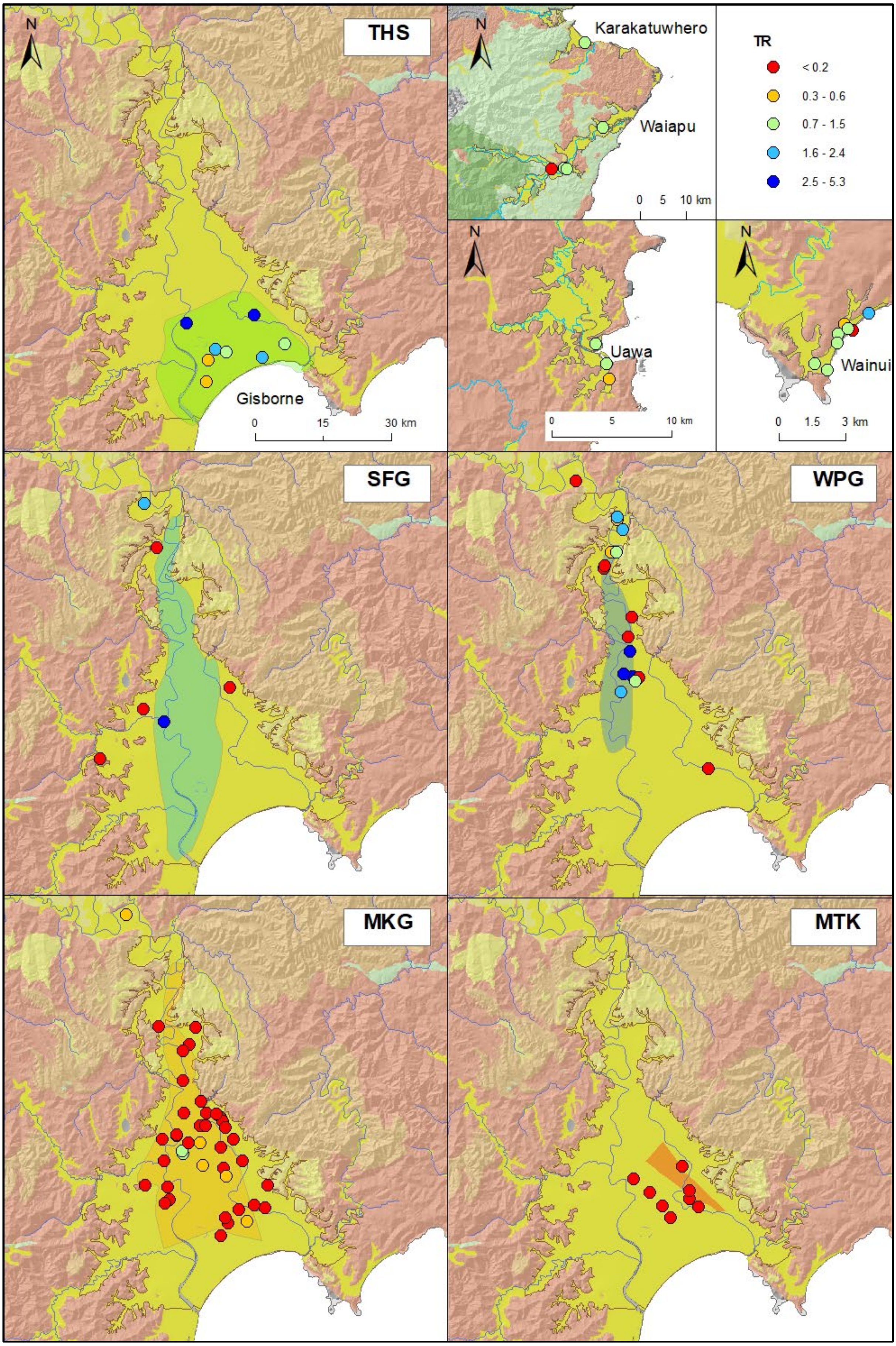

Figure 4.3 Raw tritium ratios (TR), displayed in tritium units for groundwaters in the Tairāwhiti Gisborne district.

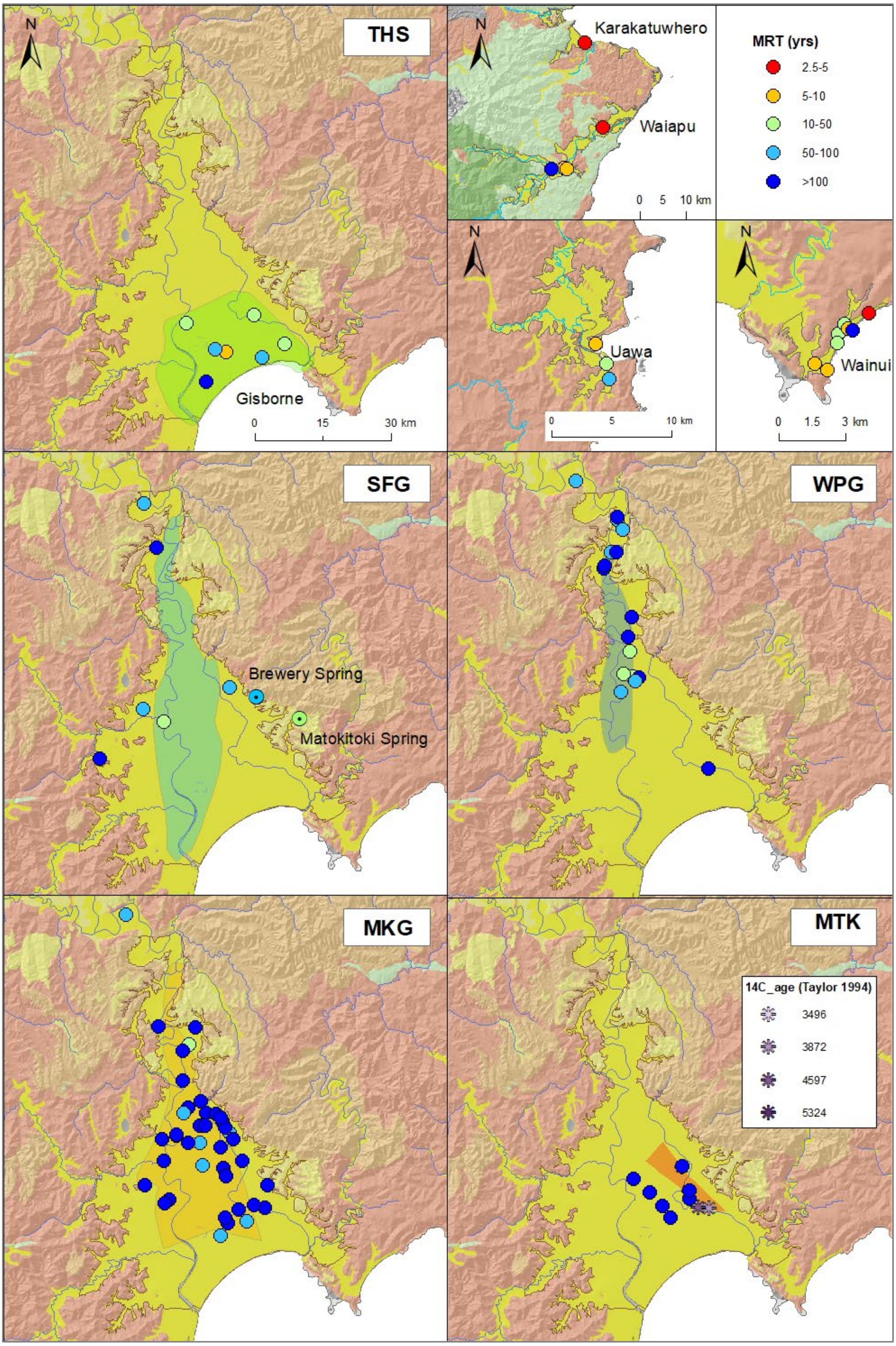

Figure 4.4 Map of groundwater mean residence time (MRT) in years. Note that GPB039 was interpreted as sourced by MTK in Taylor (1994).

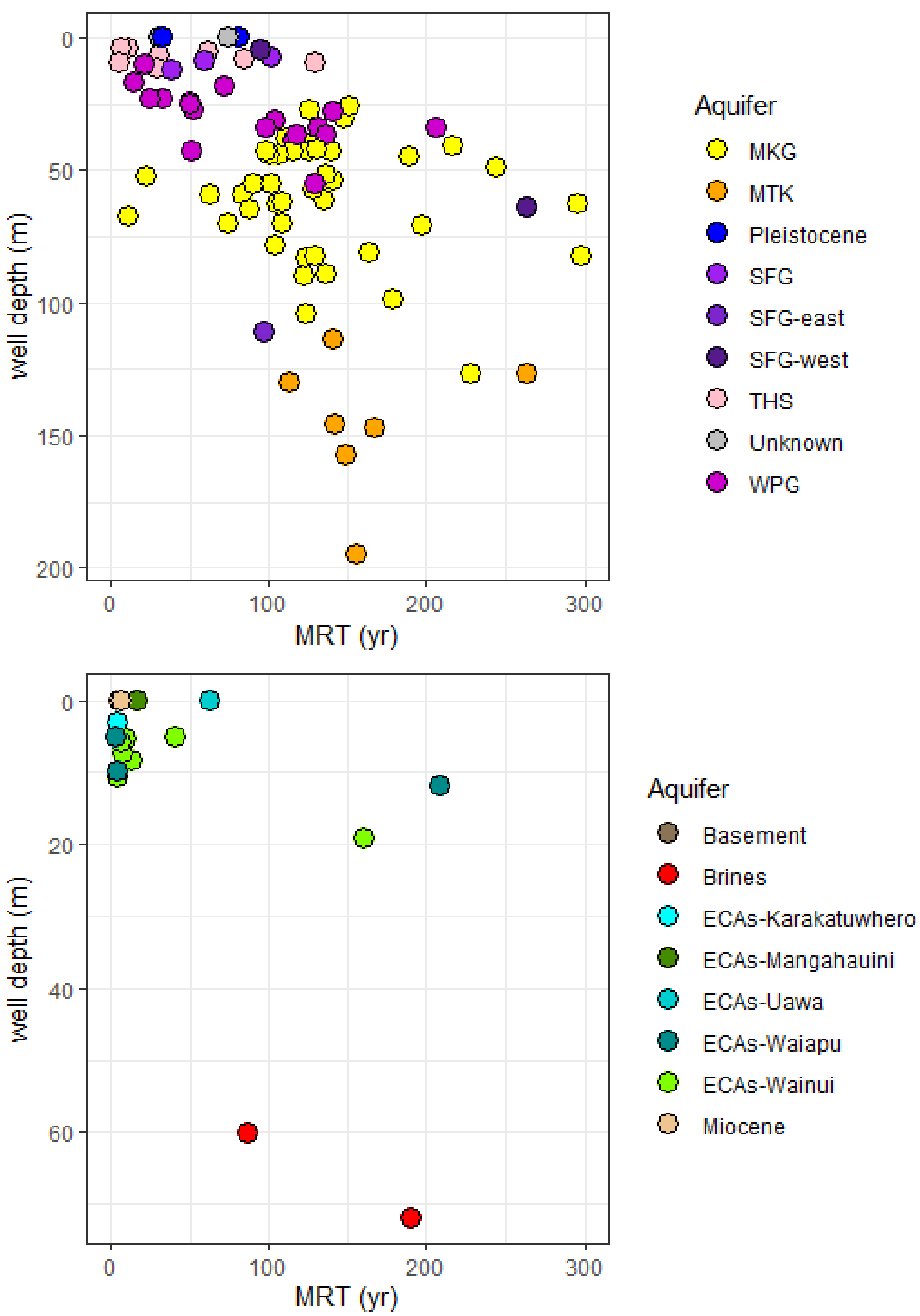

Figure 4.5 Mean residence time (MRT) (year) versus well depth (m) for wells located in the Poverty Bay flats (top) and elsewhere in the district (bottom).

4.3.1.2 Results from Radon-222

Measurements of ^{222}Rn were collected over the 2017 and 2020 sampling rounds at 33 sites (Table 4.3). Groundwater ^{222}Rn concentrations range between 3.1 and 30.1 Bq/L, which is significantly higher than ^{222}Rn measured in surface water along a 20 km reach of the Te Arai River (<0.1–0.9 Bq/L) (Martindale et al. 2018). The concentration range suggests limited recharge from surface water, and there is no correlation with age or well depth (Figure 4.6). The wide range of ^{222}Rn concentrations is likely to be due to the radon transfer from geological minerals into the water, which is not a uniform process. Other conditions, such as the radium concentration of the minerals and the ability to release ^{222}Rn, appear to result in a high variability of ^{222}Rn concentrations. In addition, ^{222}Rn can also be absorbed by organic matter, which limits the use of ^{222}Rn-ingrowth as an age tracer.

Table 4.3 Field parameters, radon concentration and radon error in Tairāwhiti Gisborne groundwaters.

Aquifer	ID	Date	DO (mg/L)	Rn (Bq/L)	± Rn (Bq/L)	T (ºC)	EC (uS/cm)	pH (pH unit)
Basement	Puketiki spr.	02/11/22	-	30.1	1.7	16	94.2	
Karakatuwhero	GAR007	5/03/20	0.00	4.73	0.34	18.2	242	6.58
Ūawa	GPA162	22/03/17	2.86	7.30	0.53	18.9	1398	6.78
	GRB048	23/03/17	0.53	12.27	0.81	16.7	153	6.26
	GTA047	03/11/22	-	6.98	0.5	-	352	-
	GTA044	03/11/22	-	3.47	0.3	16.7	450	-
	GTC005	03/11/22	-	10.1	0.66	16.5	21280	-
	GTC004	03/11/22	-	13.1	0.84	15.2	24100	-
	GRB007	02/11/22	-	20	1	15.9	257	-
	Titirangi spr.	03/11/22	-	13.7	0.86	15.5	547	-
Waiapu	GPC028	4/03/20	0.80	3.83	0.28	16.5	722	6.93
	Racecourse spr.	02/11/22	-	11.3	0.68	16	273	-
Wainui	GPA305	4/03/20	0.20	3.48	0.26	17.9	1010	7.02
	GRB047	23/03/17	-	8.05	0.57	18.7	221	5.96
	GPA302	5/03/20	0.00	7.16	0.47	20.0	1304	7.03
	GPA164	22/03/17	3.73	22.53	1.40	19.0	793	7.21
	GTA36/37	23/03/17	0.76	7.42	0.53	17.1	819	7.18
	GPA163	23/03/17	0.01	15.41	0.97	17.6	1303	7.17
	GPF095	3/03/20	0.00	5.58	0.38	16.2	800	6.91
Mangahauini	Enihau spr.	02/11/22	-	11.9	0.72	16.5	472	-
Miocene	Waipiro spr.	02/11/22	-	8.81	0.55	16.3	676	-
MKG	GTA005/014	23/03/17	0.00	7.24	0.53	17.5	603	6.83

Aquifer	ID	Date	DO (mg/L)	Rn (Bq/L)	± Rn (Bq/L)	T (ºC)	EC (uS/cm)	pH (pH unit)
THS	GRC013	5/03/20	1.60	10.15	0.65	16.6	414	6.2
	GPF090	4/03/20	0.00	8.26	0.52	15.2	849	7.04
	GPA004	3/03/20	0.42	3.10	0.24	19.3	546	7.5
	GPC031	4/03/20	0.01	3.36	0.26	18.5	979	7.041
Pleistocene	Brewery spr.	03/11/22	-	8.94	0.6	14.9	633	-
	Matokitoki spr.	03/11/22	-	6.94	0.49	16.3	607	-
WPG	GPE067	3/03/20	2.40	3.63	0.27	16.1	772	7.24
	GPE068	3/03/20	0.52	5.09	0.35	15.0	866	7.23
	GPB111	4/03/20	0.01	9.26	0.57	16.4	1111	7.31
	GPE006	3/03/20	-	4.42	0.30	16.1	635	7.03
	GPH030	3/03/20	-	11.16	0.61	15.9	804	6.76

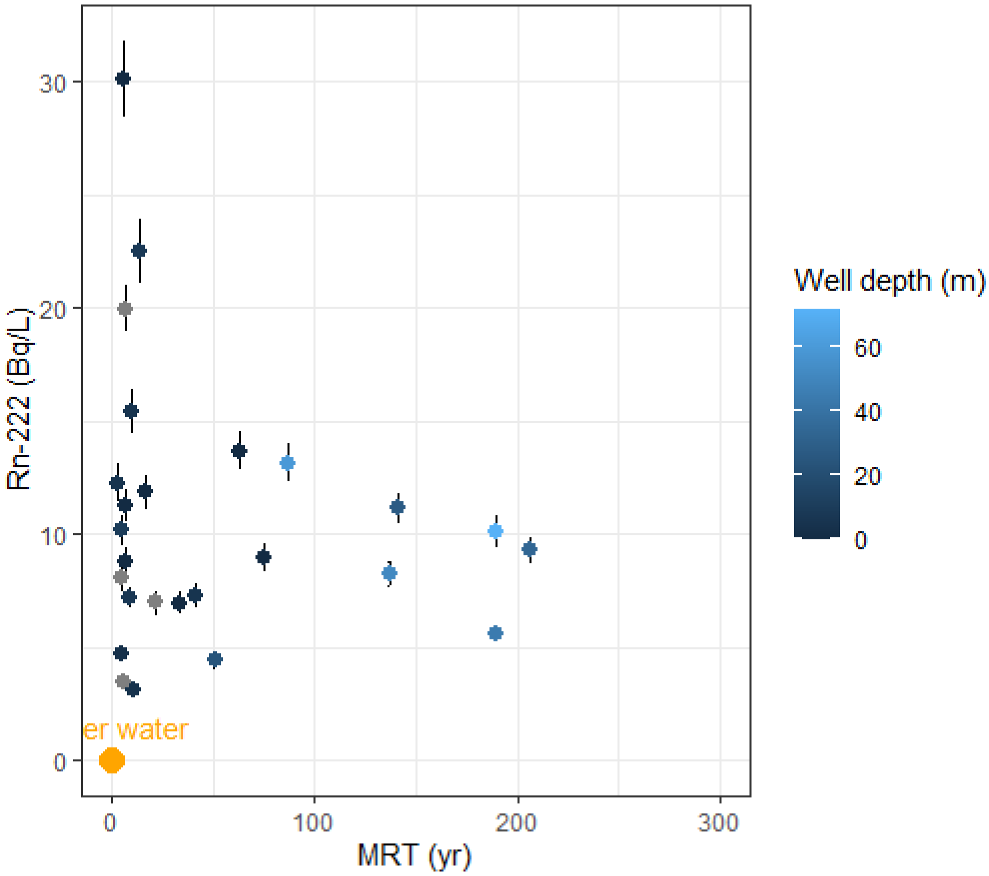

Figure 4.6 Radon-222 concentrations versus mean residence time (MRT) depicted against well depth (top) and area (bottom). Note data from GPC031 and GPC062 collected in 2020 were excluded from this graph due to recent significant changes in chemistry and age.

4.4 Stable Isotopes

Water stable isotopes measured in the region can distinguish between freshwater (characterised by more negative $\delta^{18}O$ values below -4 ‰) and brines which depart from the New Zealand river water line North Island sites (Yang et al. 2020) (Figure 4.7). There is a wider scatter in isotope values amongst the brines, which is not correlated with the spatial distribution.

Focussing on the fresh groundwaters, stable isotope values are generally consistent with the natural trend for increasing values as elevation decreases (Figure 4.8). In the Poverty Bay flats, the more positive values are observed in the coastal THS, suggesting local rainfall recharge or possibly recharge by smaller tributaries. In the ECAs, although there is overlap with Poverty Bay samples, the $\delta^{2}H$ and $\delta^{18}O$ values also tend to be more positive, which is consistent with smaller catchments and a stronger coastal precipitation influence, similar to the THS values.

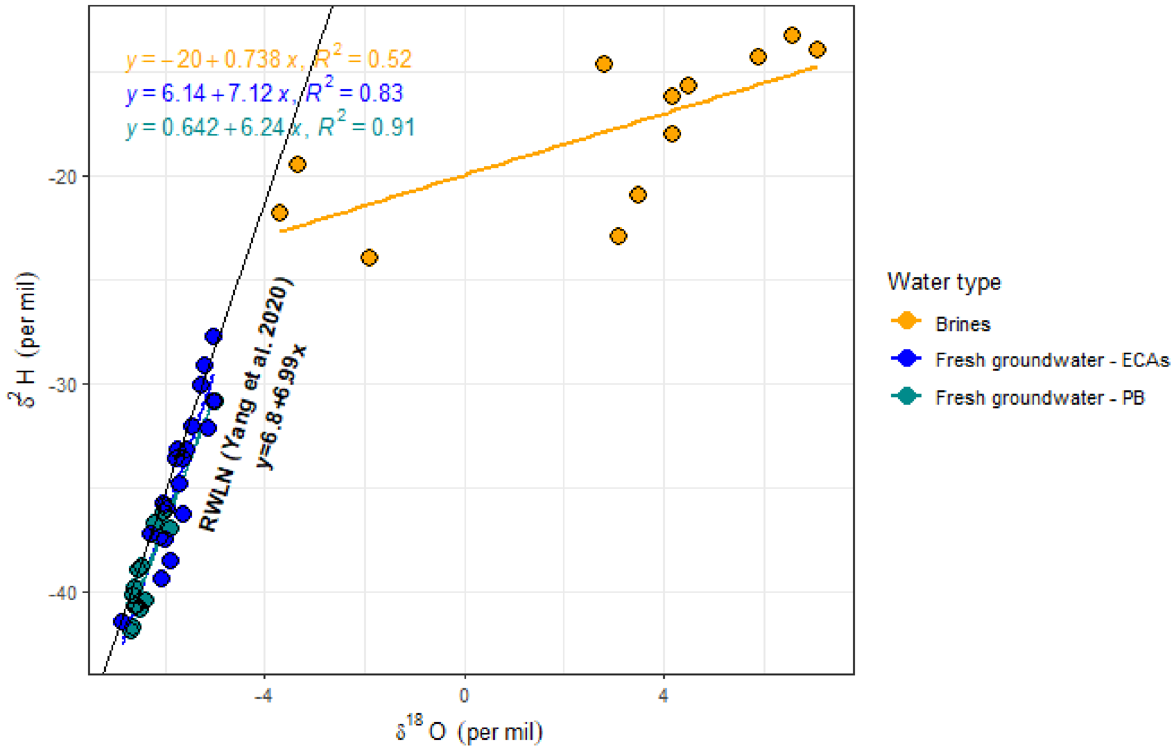

Figure 4.7 Water stable isotope measurements in Tairāwhiti Gisborne groundwaters, with data coloured by water type. Note that some sites have multiple measurements over time.

In the Poverty Bay flats, the δ^{18}O values were used to investigate recharge mechanisms between aquifers (Taylor 1994). The SFG, WPG and MKG are hydraulically connected to the river (-6.6 ‰ in winter, -5.9 ‰ in summer). The wide distribution of δ^{18}O values in the MKG was interpreted as bimodal, with one group exhibiting lower values (x to y ‰), similar to winter values of the Waipaoa River, and a second group showed more positive values (>-6.5 ‰), consistent with those recorded on the eastern margins of the flats, and likely to reflect tributaries (Figure 4.9). Data acquired since 1994 are consistent with the findings, with the widest δ^{18}O range observed in the WPG and the MKG. The wide spread of values from the ECAs, despite most samples being located close to the coast, suggest that recharge mechanisms may be similar to the Poverty Bay flats, with local river-recharge and possible seasonal influence.

In the Poverty Bay flats, samples were collected in 2022 at Matokitoki Spring (-6.01 ‰) and Brewery Spring (-6.46 ‰). The locations and elevations of both springs suggest that these are draining from either fractured Pleistocene limestone and sandstones or gravels derived from these, rather than SFG – δ^{18}O differences indicate distinct sources. In Taylor (1994), similarities between Brewery Spring and GPF056 were drawn. GPF056 is an artesian well, which is an oddity for the SFG in this area. Although originally drilled to 111 m in 1981, the well log indicates that the screened interval is between 14 and 17 m below the ground, with a water strike between 15.2 and 19.5 m below ground. The available lithological description is predominantly clay, which is consistent with the absence of MKG and MTK in this area noted by Taylor (1994). The well was not sampled in 2022 as this site was decommissioned in 2018. The water level record indicates values ranging from 9.14 to 13.27 m asl. In comparison, Brewery Spring emerges at an elevation of *c.* 40 m above ground level, which means there is a significant water level difference between the sites and therefore the two features are unlikely to be hydaulically connected.

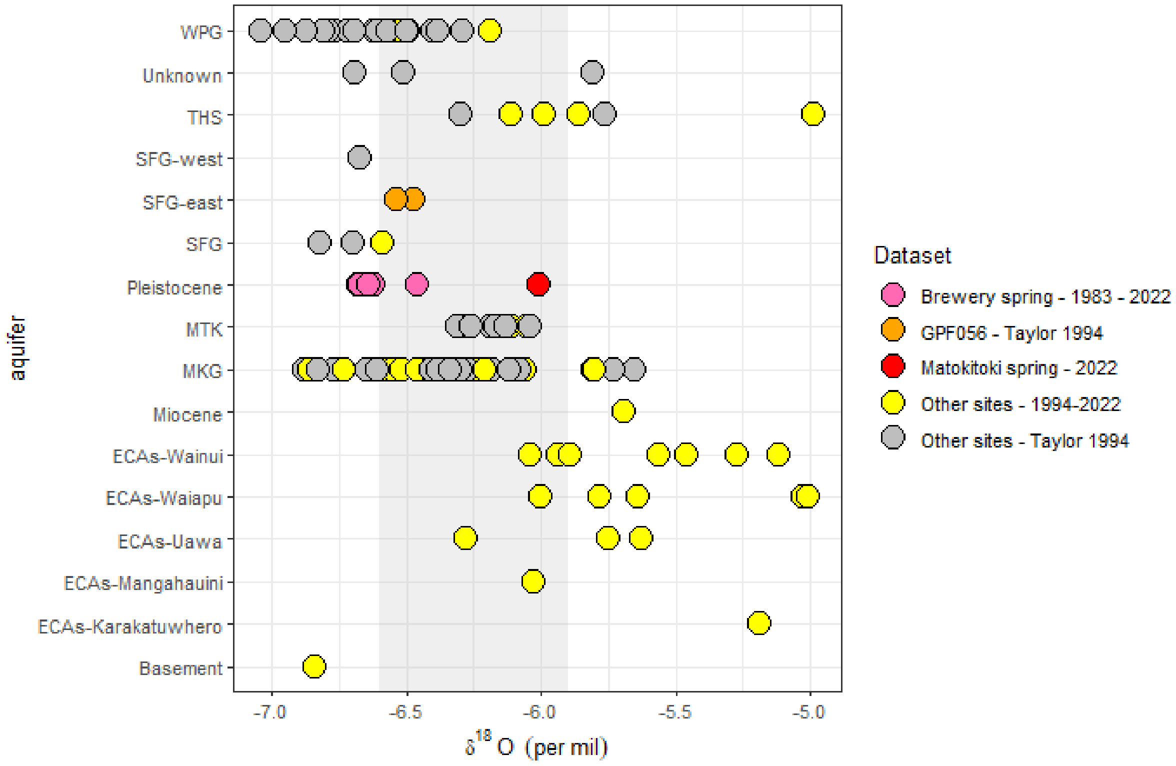

Figure 4.8 Groundwater $\delta^{18}O$ values in Tairāwhiti Gisborne, with data grouped by aquifer. Note that some aquifer reclassification was performed on the 1994 data.

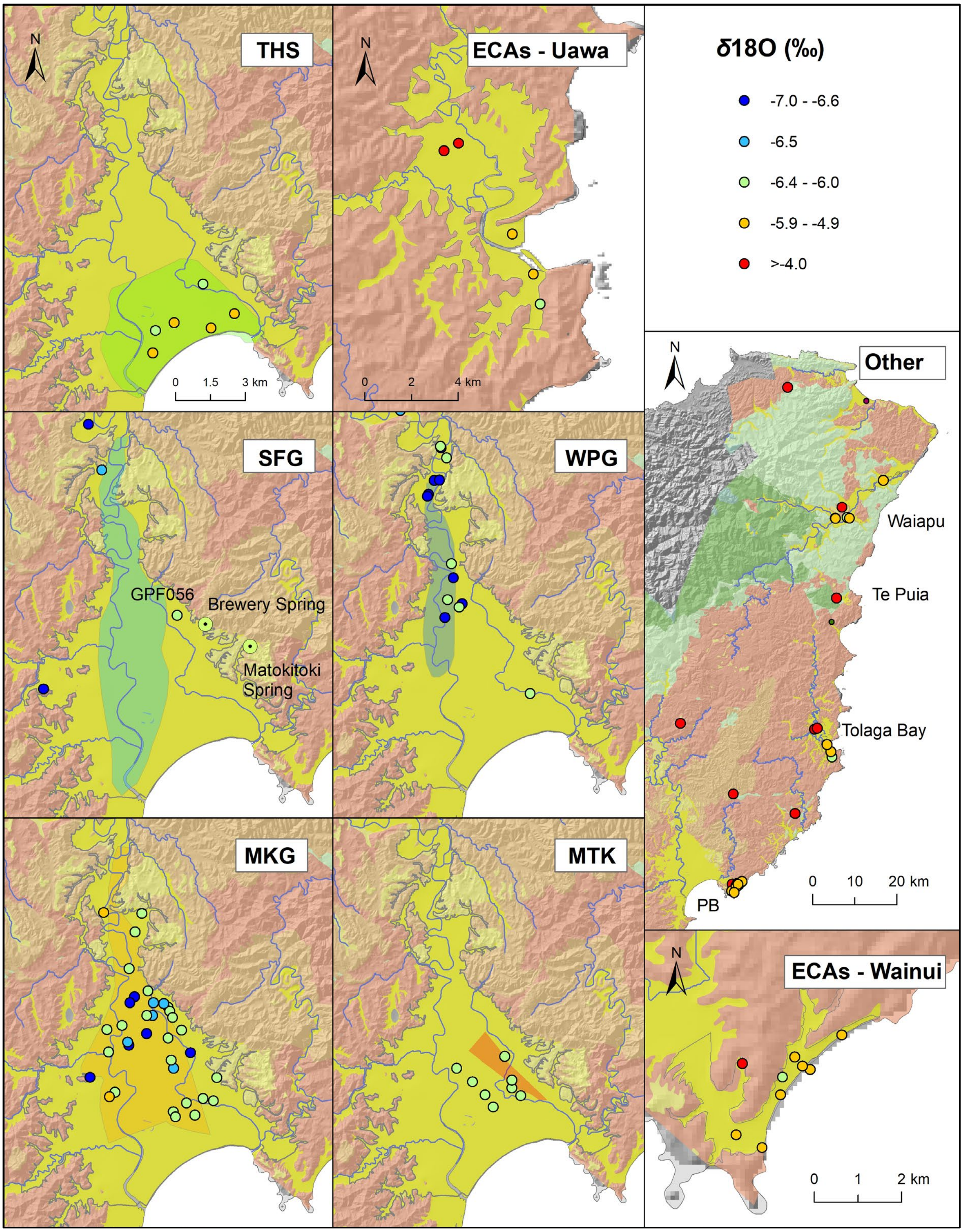

Figure 4.9 Spatial distribution of $\delta^{18}O$ values in Tairāwhiti Gisborne groundwater samples.

4.5 Hydrochemistry

In the following figures, groundwater hydrochemistry parameters are shown versus MRT to identify drivers of hydrochemistry and the impacts of land use versus natural processes on groundwater quality. Note that all MRTs >100 years result from data close to the tritium detection limit and may be significantly older (potentially thousands of years). The numbers only indicate the estimated minimum MRT.

During the process of natural groundwater evolution, aquifer matrix minerals are progressively dissolved over time and increasing ion concentrations with groundwater age indicate a geological source due to leaching from the aquifer material. In contrast, high concentrations (in particular nutrients) in young groundwaters indicate contamination from anthropogenic land-use activities. An overview of the hydrochemical composition of the groundwater from Tairāwhiti Gisborne in comparison with the average New Zealand groundwater composition is listed in Table 4.4. Overall, Tairāwhiti Gisborne district groundwaters have significantly higher solute concentrations relative to average concentrations of New Zealand groundwaters. The presence of brines associated with the HSZ is demonstrated in some of the maximum concentrations.

Table 4.4 Hydrochemistry statistics, showing number of wells, minimum and maximum concentrations and the 25th, 50th and 75th percentiles for all hydrochemistry data from wells with groundwater age-tracer data. The New Zealand percentiles, shown for comparison, are for groundwater quality data obtained from over 1000 sites collected as part of State of the Environment (SoE) monitoring programmes run by regional authorities and compiled by the Ministry for the Environment (Daughney and Wall 2007).

Parameter	Units	Gisborne Data						New Zealand Percentiles		
		No.	Min.	25%	50%	75%	Max.	25%	50%	75%
Ca	mg/L	121	7.0	123	123	150	1220	9.6	15.5	30.0
Cl	mg/L	120	2.0	56	56	255	9860	7.3	15.3	30.1
HCO_3	mg/L	112	35	545	545	686	3200	40.0	62.7	144.6
K	mg/L	120	0.99	7.0	7.0	9.4	80	1.0	1.6	3.7
Mg	mg/L	118	1.4	16	16	24	420	2.6	4.6	8.5
Na	mg/L	120	1.00	87	87	190	6020	9.4	15.0	29.6
NO_3-N	mg/L	104	0.0009	0.0043	0.0043	0.021	19	0.00	1.3	4.4
SiO_2	mg/L	22	5.0	21	21	31	50	13.5	17.0	29.5
SO_4	mg/L	120	0.020	5.0	5.0	23	132	3.0	6.5	13.0
DRP	mg/L	101	0.0040	0.013	0.013	0.047	1.8	0.01	0.02	0.07
Fe	mg/L	75	0.0020	2.4	2.4	6.6	62	0.01	0.03	0.23
Mn	mg/L	25	0.0030	0.097	0.097	0.69	1.4	0.00	0.01	0.24
NH_3-N	mg/L	110	0.00005	0.65	0.65	3.0	28	0.00	0.01	0.06
Cond.	µS/cm	105	174	1000	1000	1347	19514	144.8	210.0	371
pH	pH unit	109	6.3	7.1	7.1	7.3	9.0	6.4	6.8	7.2

4.5.1 Hierarchical Cluster Analysis

HCA (Section 3.3) was performed on the hydrochemistry dataset to group sites with similar hydrochemistry. HCA results are displayed as a dendrogram (Figure 4.10). Each vertical line ends at a single sample site. Horizontal lines join hydrochemical groups. The similarity between sites and groups of sites is indicated by the height up the y-axis (distance) of the respective connecting horizontal line. Low horizontal lines join sites with the most similar chemistry. HCA interpretation required the selection of appropriate horizontal thresholds, dividing sites into clusters with similar chemistry.

At the highest threshold, the data (n=99) is divided into three clusters: A, B and C (Figure 4.10). Cluster A consists of diluted shallow groundwaters mostly of Ca-HCO_3 type; Cluster B comprises more evolved groundwaters with a range of oxidation levels; and Cluster C consists of Na-Cl type brines, originating from saltwater welling up from the subduction zone (Figure 4.13). At the second threshold, clusters A and B can be divided into two sub-clusters, each reflecting a range of aquifer systems and hydrochemical evolution, and Cluster C can be separated into three sub-clusters. These sub-clusters are described as follows (Figure 4.10 to Figure 4.13; Table 4.5):

- Cluster A1 (n=31) is the second largest cluster, characterised by relatively low total dissolved solids content and a Ca-HCO_3 water type (Ca and HCO_3 centroid concentration of 92 and 335 mg/L, respectively). Na and Cl concentrations are low (28 and 30 mg/L, respectively). Aquifer conditions range from reducing to oxygenated, and in the latter case, elevated NO_3-N concentrations (up to 19 mg/L) are present. Wells are mostly shallow in depth and comprise a range of aquifers in the Poverty Bay flats and ECAs.
- Cluster A2 (n=3) is the smallest cluster, with dilute chemistry (centroid concentrations for Ca, HCO_3 and Na are 25, 50 and 13 mg/L, respectively). Wells are screened in ECAs – Waiapu or basement – and MRT indicates young waters (five to six years).
- Cluster B1 (n=10) comprises evolved Ca-HCO_3 type waters (Median HCO_3 concentrations range from 415 to 1300 mg/L, respectively). High concentrations for a range of solutes suggest prolonged residence times enabling extensive water-rock interaction. Fe, Mn and NH_3-N concentrations range from below detection limit to a few mg/L, suggesting a range of oxygenation conditions. Wells are sourced from the SFG, THS and Wainui aquifers (depth range of 5.3 to 26.5 m). MRT is young, between six and 11 years. The exception is Well GPC062. At this site, age tracer samples collected in 2005 and 2022 indicated a change in groundwater age, which is correlated with a change in chemistry (see Section 4.5.6).
- Cluster B2 (n=37) is the largest cluster with similarly evolved groundwaters within reducing conditions. Fe concentrations range from 0.5 to 18 mg/L. All wells are located within the Poverty Bay flats (WPG, MKG and MTK), and MRTs range from 44 to over 100 years.
- Cluster B3 (n=11) is characterised by highly evolved, strongly reducing groundwaters (HCO_3 concentrations range from 775 to 1500 mg/L, Fe concentrations between 4.2 and 19 mg/L). Most sites are located in the Poverty Bay flats and screened in deeper aquifers (MKG and MTK) with MRTs greater than 120 years, except for Well GPJ078 (SFG) and Well GTC003 (brines, located in Tolaga Bay). The latter exhibits a markedly different chemistry from the remainder of the cluster (Na-Cl water type), yet significantly lower concentrations of Ca, Cl, K, Mg and NH_3-N than the other Tolaga Bay brines (GTC004 and GTC005).
- Cluster C (n=7) consists of Na-Cl water types characterised by very high total dissolved solids content (median Cl concentration of 7200 mg/L), elevated Br concentrations (21 to 36 mg/L) and more positive $\delta^{18}O$ values typical of the saline groundwaters. Sub-cluster C1 (n=3) includes Well GPE012, a 68-m-deep well located in Waerengaahika, near Patutahi in the Poverty Bay flats. Sub-cluster C2 (n=2) consists of active, warm features (Te Puia Springs, Otopotehetehe respectively 67 and 25°C) with comparatively much lower Ca and HCO_3 concentrations, saline signature (Br, Na, Cl) and significantly more positive $\delta^{18}O$ values. Sub-cluster C3 (n=2) mainly differs from C1 by their lower Ca concentrations.

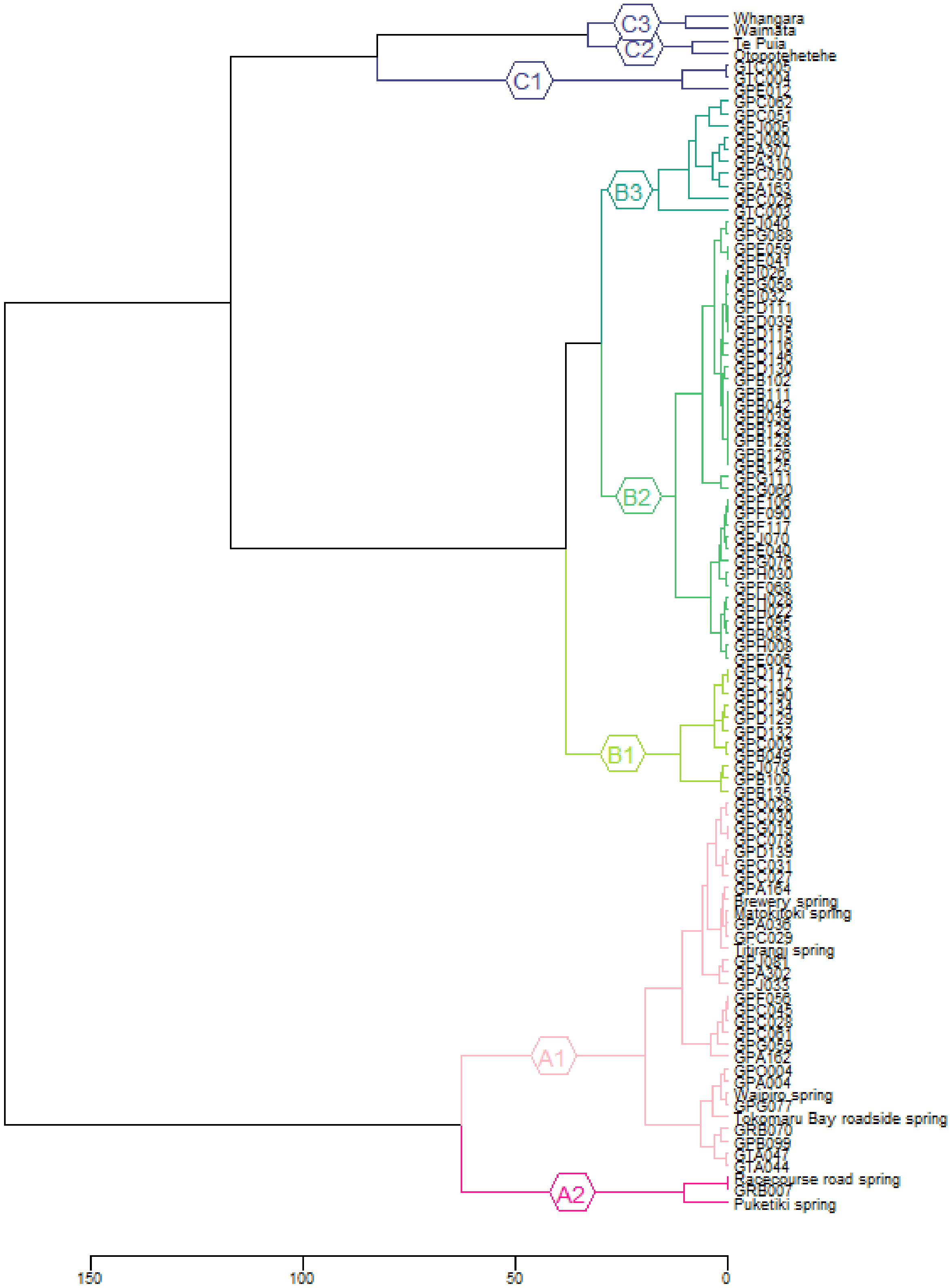

Figure 4.10 Dendrogram produced by hierarchical cluster analysis (HCA).

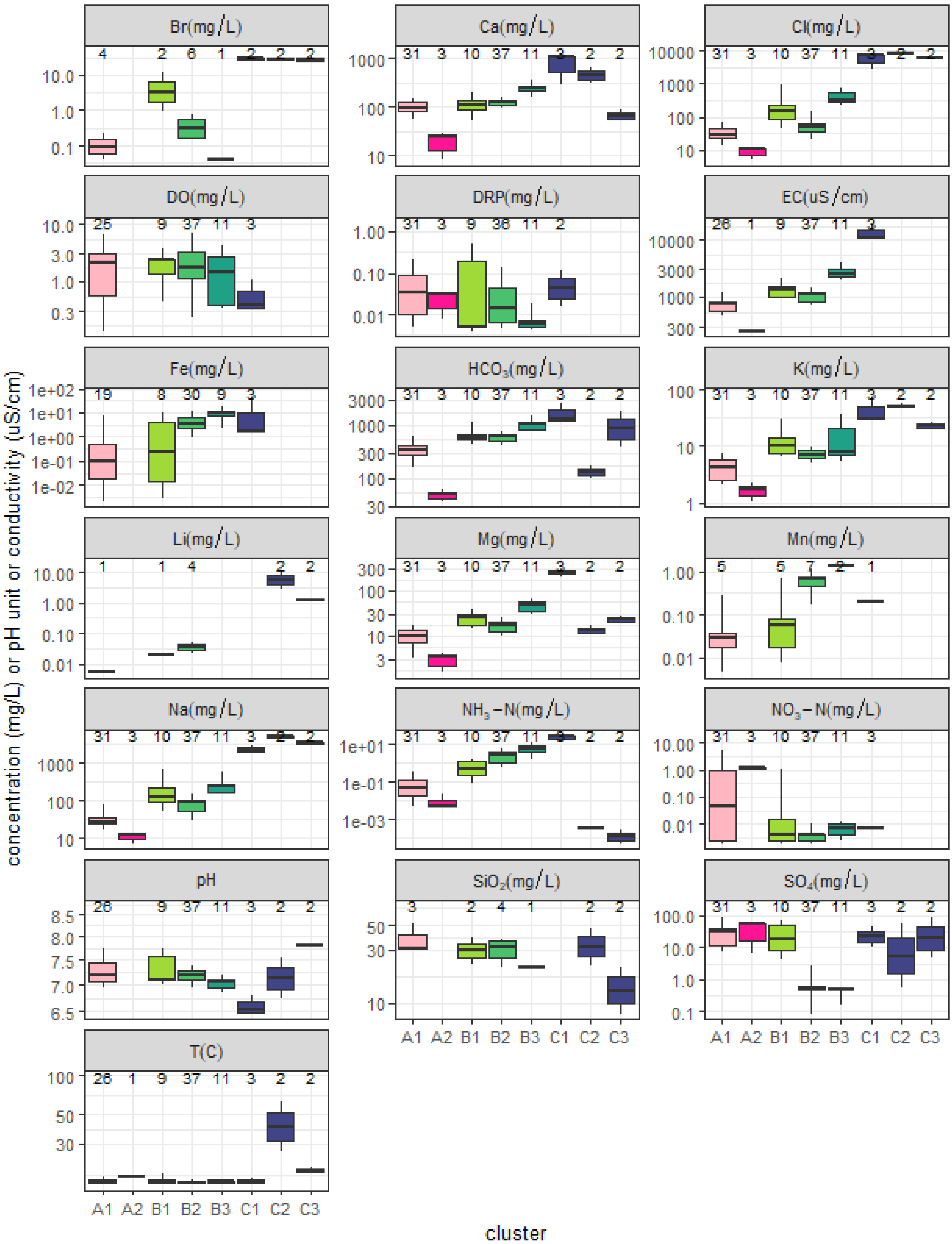

Figure 4.11 Box plots of hydrochemistry parameters organised by second threshold cluster. The numbers displayed above each box indicates the sample size. Colours relate to the sub-clusters as shown in Figure 4.10.

Table 4.5 Hierarchical cluster analysis (HCA) showing water type and a summary description of notable hydrochemistry and well depths from each cluster.

Cluster	Water type	Number of Sites	Description
A1	Ca HCO_3	31	Dilute. Second largest cluster. Sites are from mostly shallower depths and a range of aquifers in the Poverty Bay flats and ECAs.
A2	Mixed Ca Mg HCO_3 Ca Mg HCO_3SO_4	3	Dilute. Lowest EC, oxidised, low NO3-N. Sites screened in ECAs – Waiapu or basement. Young waters.
B1	Ca Mg HCO_3	10	Moderate conductivity. Oxic to anoxic. Sites are sourced from SFG, THS and Wainui. Young waters.
B2	Ca Mg HCO_3	37	Evolved, reducing. This is the largest cluster. Intermediate EC, second-highest HCO_3, Ca, Mg, Fe and NH3-N, suggesting reduced conditions and occurrence of nitrogen. Sites sourced from WPG, MKG and MTK. Old waters from the Poverty Bay flats.
B3	Ca Mg HCO_3	11	Evolved, strongly reducing. Highest non-brine EC, highest HCO_3, Ca, Mg, Fe and NH3-N, suggesting reduced conditions. Sites screened in MKG and MTK aquifers. Old waters from the Poverty Bay flats.
C	Na Cl	2	Brines. Highest Li concentrations, lowest δ^2H and $\delta^{18}O$ values, strong Na, Cl signature. Range of cold to warm springs. Linked to subduction zone.

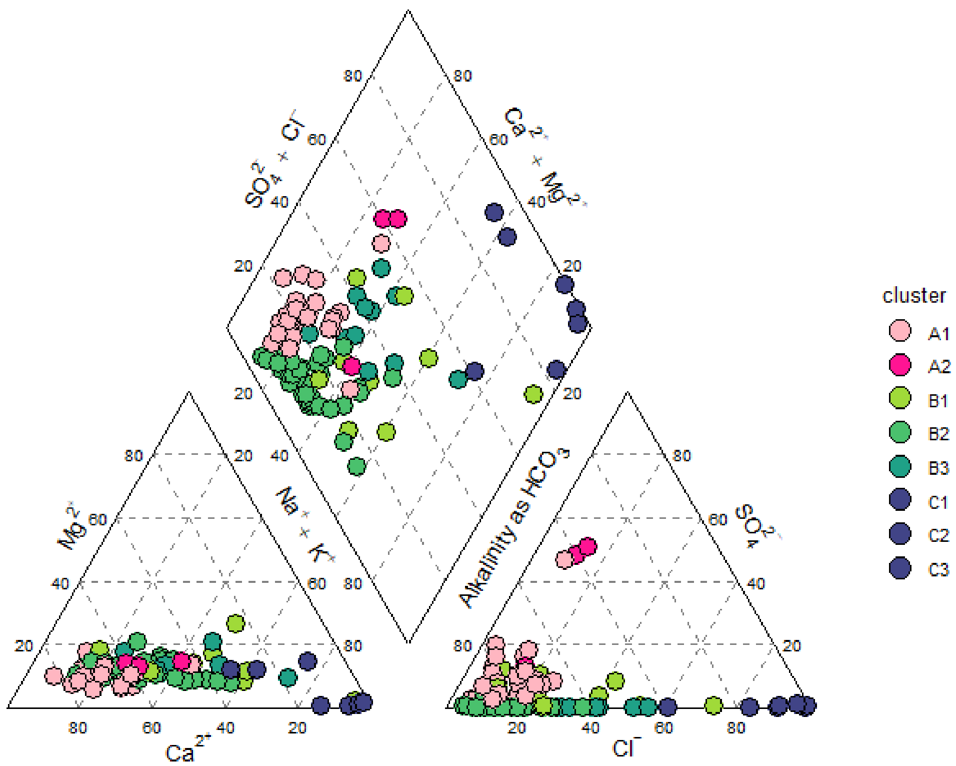

Figure 4.12 Piper diagram showing the variation of major ion chemistry by sub-cluster. The left and right triangles show the major cation and anion ratios on an equivalence basis, respectively, and the centre diamond plots projections based on the two triangular plots. Sites are grouped into sub-clusters assigned by hierarchical cluster analysis (HCA).

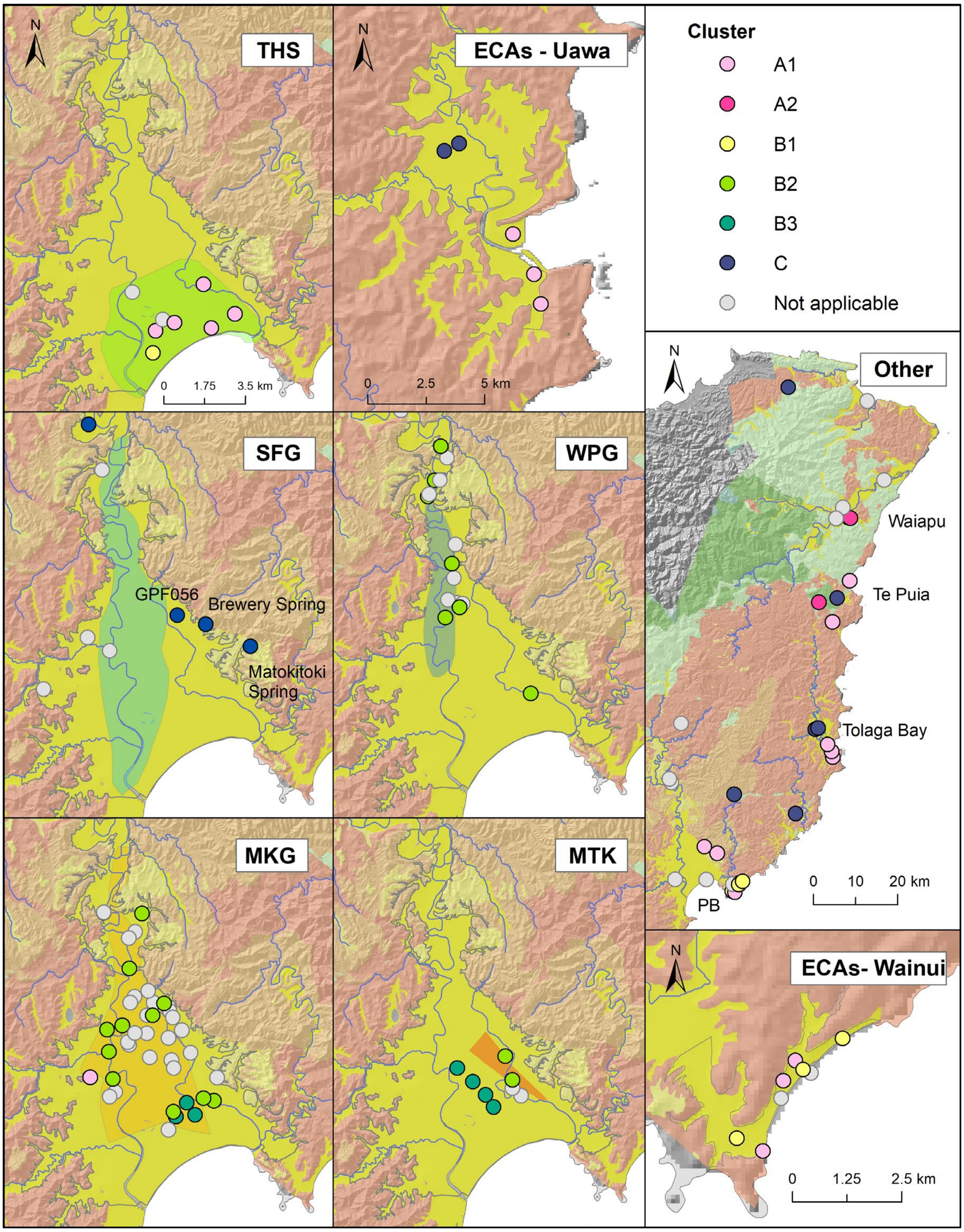

Figure 4.13 Geographic distribution of sites assigned to sub-clusters using hierarchical cluster analysis (HCA).

4.5.2 Redox Conditions

Fully oxygenated water in equilibrium with air has a DO concentration of *c.* 10.5 mg/L. In groundwater systems, water is separated from the atmosphere and, in the presence of organic matter or other electron donors (e.g. pyrite), DO is consumed by microbial oxidative reactions. Reduction of DO is energetically the most favourable reaction that micro-organisms use, with the result that other reduction reactions (including denitrification) typically do not occur until most of the DO has been consumed. These reactions take time and usually old waters become increasingly anoxic (Böhlke et al. 2002).

Gisborne aquifers exhibit a range of redox conditions from oxygenated to anoxic. Most sites (n=120) are classed as oxic with DO>0.5 mg/L (55%), and 18% of the sites exhibited anoxic or anoxic-mixed with DO<0.5 mg/L, and 23% of the sites were indeterminate (McMahon and Chapelle 2008). Reducing conditions prevail in clusters A and B, and are consistent with older, more evolved groundwaters (Figure 4.14).

Generally, the shallower aquifers (THS, ECAs) are oxic to sub-oxic, with low concentrations of Fe, Mn and NH_3-N, and the deeper aquifers exhibit a wider range of redox conditions. In the WPG, localised elevated CH_4 and Fe concentrations occur, indicating highly anoxic aquifer conditions up to the stage of methane fermentation (Morgenstern and Daughney 2012). In the Wainui ECAs, localised CH_4 measurements in excess of 500 μmol/L are not associated with longer MRT (>100 years), suggesting active denitrification possibly facilitated by the occurrence of organic material (e.g. Well ID GPA164, Wainui ECAs, MRT 10 years, CH_4 concentration of 827 μmol/L) (Figure 4.15).

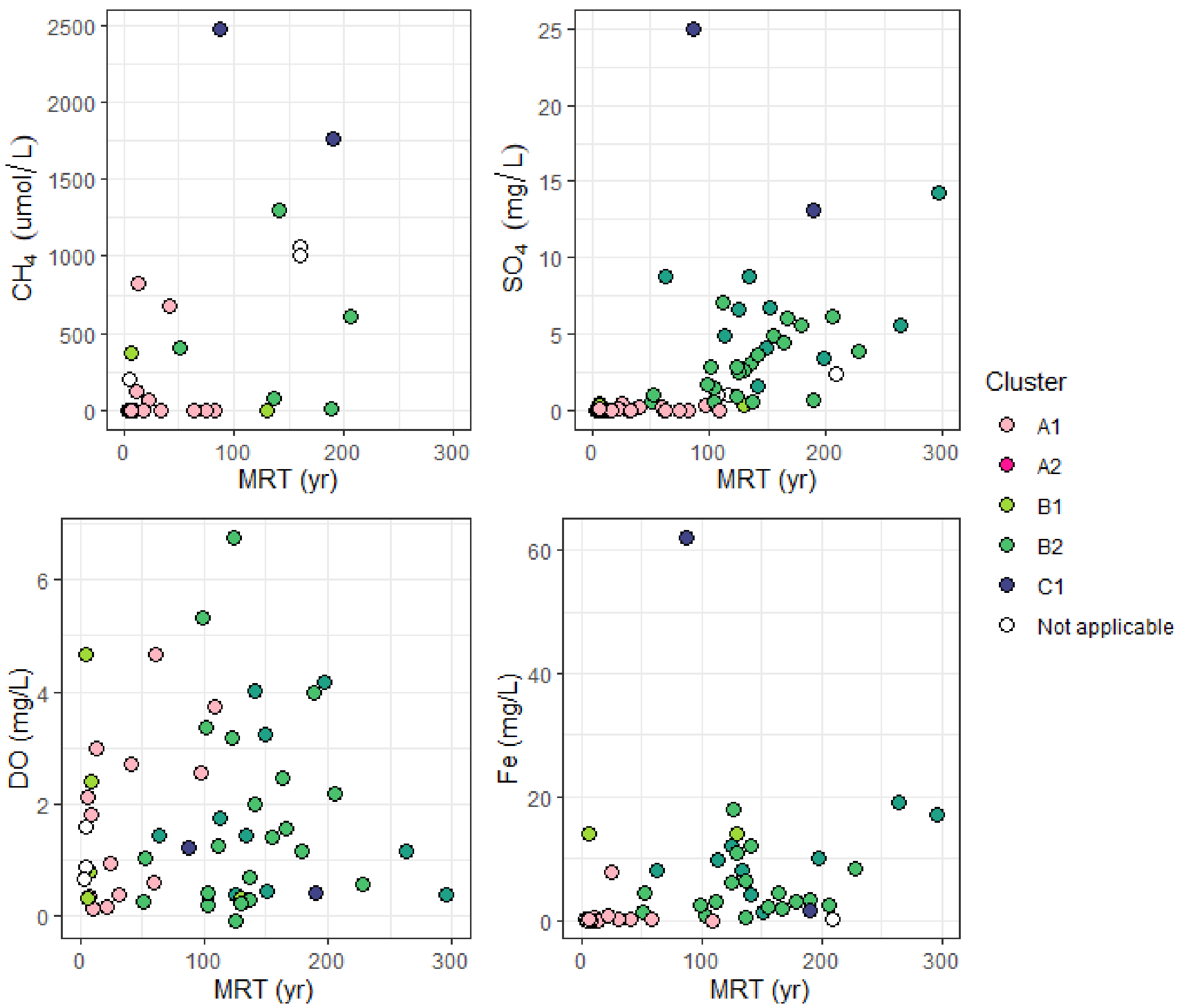

Figure 4.14 Dissolved oxygen, Fe, CH_4 and NH_3-N concentrations versus mean residence time (MRT) for Tairāwhiti Gisborne groundwater. This hydrochemistry data originates from various sources over time. Note that this figure only includes sites at which both chemistry and age-tracer data were available, not the entire dataset.

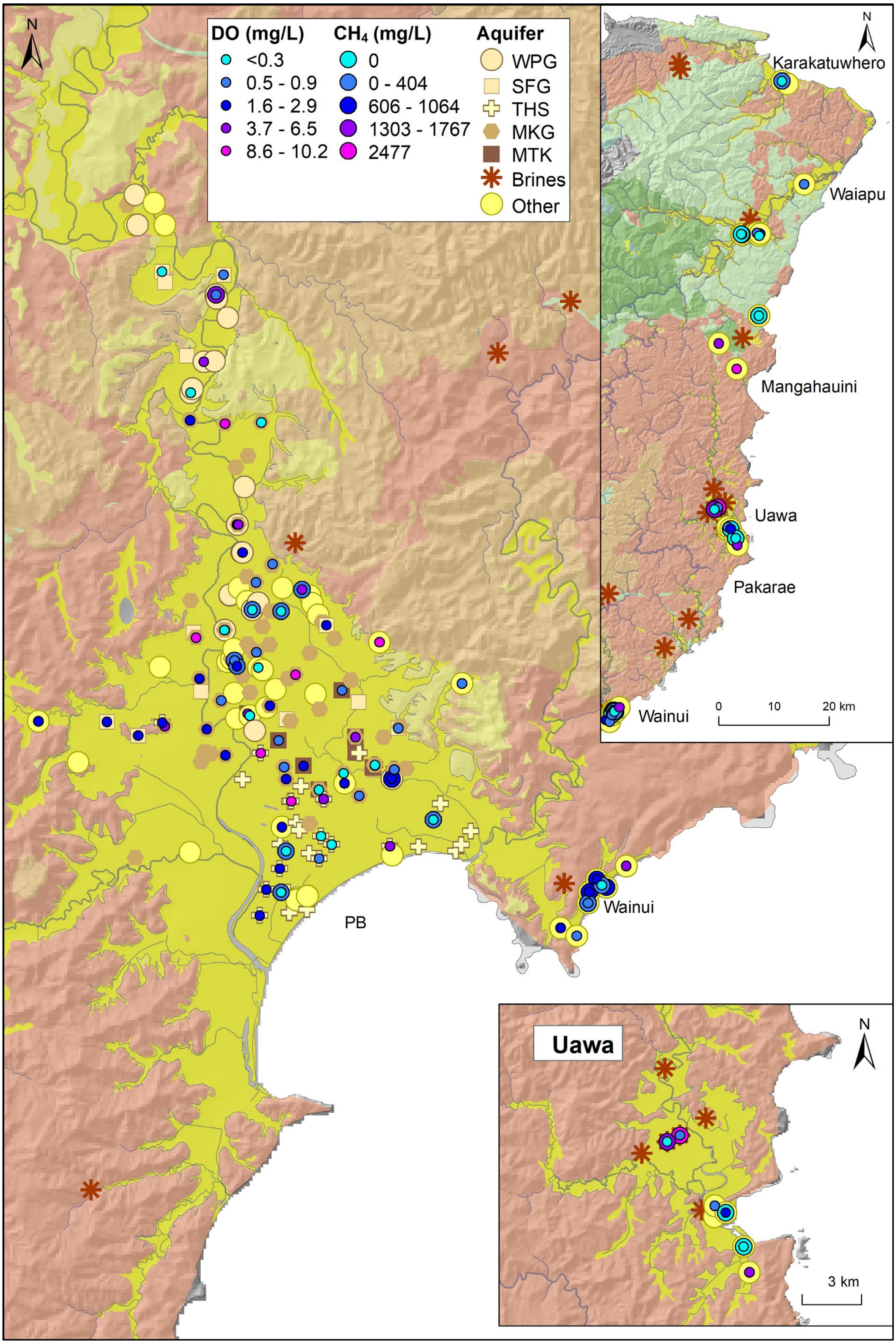

Figure 4.15 Map of dissolved oxygen (inner circle) and CH_4 (outer circle) in Tairāwhiti Gisborne groundwaters.

4.5.3 Nutrients

The main anthropogenic impacts on groundwater quality in New Zealand started with the onset of industrial agriculture in the 1950s, as deduced from the dataset of the NGMP of New Zealand (Morgenstern and Daughney 2012). Comparison of ion concentrations of recently recharged groundwater, and groundwater that was recharged before 1950, allowed the baseline identification of the pre-industrial groundwater quality and the impacts of land-use activities on groundwater quality. In 2012, the NGMP dataset enabled the identification of agricultural contaminants (mostly nutrients) from high-intensity land use, listed in Table 4.6.

Table 4.6 Agricultural indicators for high-intensity land use (modified from Morgenstern and Daughney 2012), showing concentration range prior to high-intensity land use, threshold concentrations that indicate high-intensity agricultural land use, and observed maximum concentrations. Threshold concentrations in brackets can be ambiguous. *Brine chemistry data was removed.

Agricultural Indicator	Concentration Range Prior to High-Intensity Land Use (mg/L)	Threshold Concentration (mg/L)	Observed Maximum Concentration in New Zealand (NGMP, 2012) (mg/L)	Observed Maximum Concentration in Gisborne* (All Data up to 2023) (mg/L)
NO_3-N	0–2.5	2.5	34	19
SO_4	0–12	12	94	132
Cl	0–60	(60)	100	916
Br	0–0.2	(0.2)	1.3	31
Ca	0–50	(50)	110	407
Mg	0–15	(15)	54	65.9
Cr	0–0.0015	0.0015	0.006	0.003

Comparison of the Tairāwhiti Gisborne data to the NGMP data only allows identification of anthropogenic versus geological sources and determination of the impact from high-intensity land use where oxygenated conditions prevail, which represent *c.* 51% of the monitoring sites. At highly reduced sites, land-use indicators, such as NO_3-N and SO_4, will naturally be converted into other forms, such as NH_3-N and sulphur gas as part of the microbiologically facilitated reduction processes.

In Tairāwhiti Gisborne oxic groundwaters, the NO_3-N, SO_4, Cl, Ca and Mg thresholds for impact by high-intensity land use in New Zealand were exceeded at 5%, 33%, 34%, 98% and 0% of the sites (n=61), respectively. However, the long MRTs, consistent with high total dissolved solids content, are likely contributing to some of the exceedances for Cl, Ca and Mg concentrations due to geogenic sources. There were no exceedances of the aforementioned thresholds for NO_3-N or Cr recorded at sites where the redox status was unknown (n=89).

Most oxic sites (88%) exhibit low NO_3-N concentrations within the range 0.002–2.1 mg/L, which is below the threshold for high-intensity land use (Morgenstern and Daughney 2012). Two sites (GPA302, Wainui and GPJ081, THS) exhibited concentrations above 11.3 mg/L, the maximum acceptable value for drinking water supplies (Water Services [Drinking Water Standards for New Zealand] Regulations 2022). A third site (GPA310) located in the Wainui aquifer exceeded the land impact threshold. The remaining sites are well below these thresholds. This highlights that, to date, no major legacy nitrate loads were identified in the district.

SO_4 concentrations of greater than 12 mg/L (indicative of high-intensity land use) and up to about 79 mg/L occur across the entire age range of the sampled groundwaters (Figure 4.16). The rare instances of elevated NO_3-N are matched with high SO_4 concentrations, but not the highest. Older groundwaters have low SO_4 concentrations, which is consistent with anoxic conditions.

DRP concentrations do not show any trend with groundwater age, whereas K concentrations increase with groundwater age, which is consistent with increasing rock-water interactions under low flow conditions (Figure 4.16).

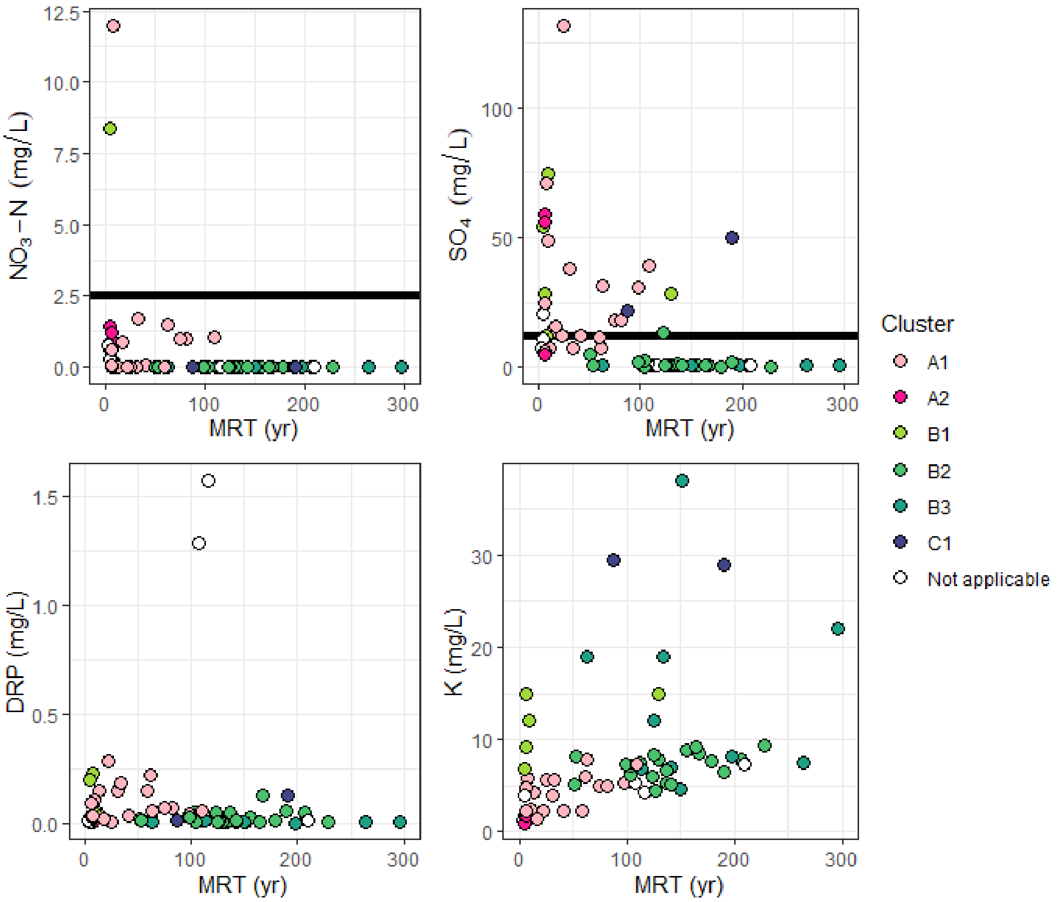

Figure 4.16 NO_3-N, SO_4, DRP and K concentrations versus mean residence time (MRT) for Tairāwhiti Gisborne groundwaters. Colour code refers to HCA sub-clusters (Section 4.3.1). Bold horizontal lines indicate thresholds for high-intensity land use based on Morgenstern and Daughney (2012). Hydrochemistry data originates from various sources over time. Note this figure only represent sites at which both chemistry and age-tracer data were available.

Hydrochemistry Evolution

Hydrochemical parameters include mineral concentrations and are usually dissolved from the aquifer material (Figure 4.17). Microbial redox processes can impact on mineral dissolution, resulting in different trends of ion concentrations with MRT in many groundwaters of New Zealand (Morgenstern and Daughney 2012). The dataset is separated by HCA clusters, which reflect variations in the redox status of groundwaters.

The Gisborne hydrochemical data is consistent between aquifers, despite a range of age and redox conditions. This is likely to be reflecting the homogenous geology of the district. Ca, Mg, Na and HCO_3 concentrations increase as MRT increases, due to increased water-rock interaction over time. Brines are markedly different from most of the district's groundwater, with significantly higher concentrations of hydrochemical parameters. Ca and HCO_3 data plot between the 1:1 line, indicating a calcium carbonate dissolution source, and the 50% line, indicating that for those groundwaters 50% of the HCO_3 is derived from decaying organic matter. There are no data that plot above the calcium carbonate 1:1 dissolution line, which would be indicative of excess-Ca, often associated with high-producing exotic grass areas (lime application is the likely source of this excess Ca). The Poverty Bay flats are significantly larger and deeper than the ECAs, and the corresponding data spread between calcium carbonate and decaying organic matter is larger than elsewhere. Tairāwhiti Gisborne's aquifers are all associated with the Poverty Bay flats, whose development is linked to the associated river(s) size, which influences the development of gravel lenses where most groundwater will be hosted. The Poverty Bay flats' aquifers major ions data display scatter, which may be linked to variations in source rock material, and large spatial and depth variations in connectivity between gravels likely to lead to a range of hydrochemical reactions and rates of reaction. Although SiO_2 concentrations generally increase with Cl content (not shown), the limited MRT data do not support the use of SiO_2 as a proxy for groundwater age, observed in other regions of New Zealand (e.g. Morgenstern et al. 2015).

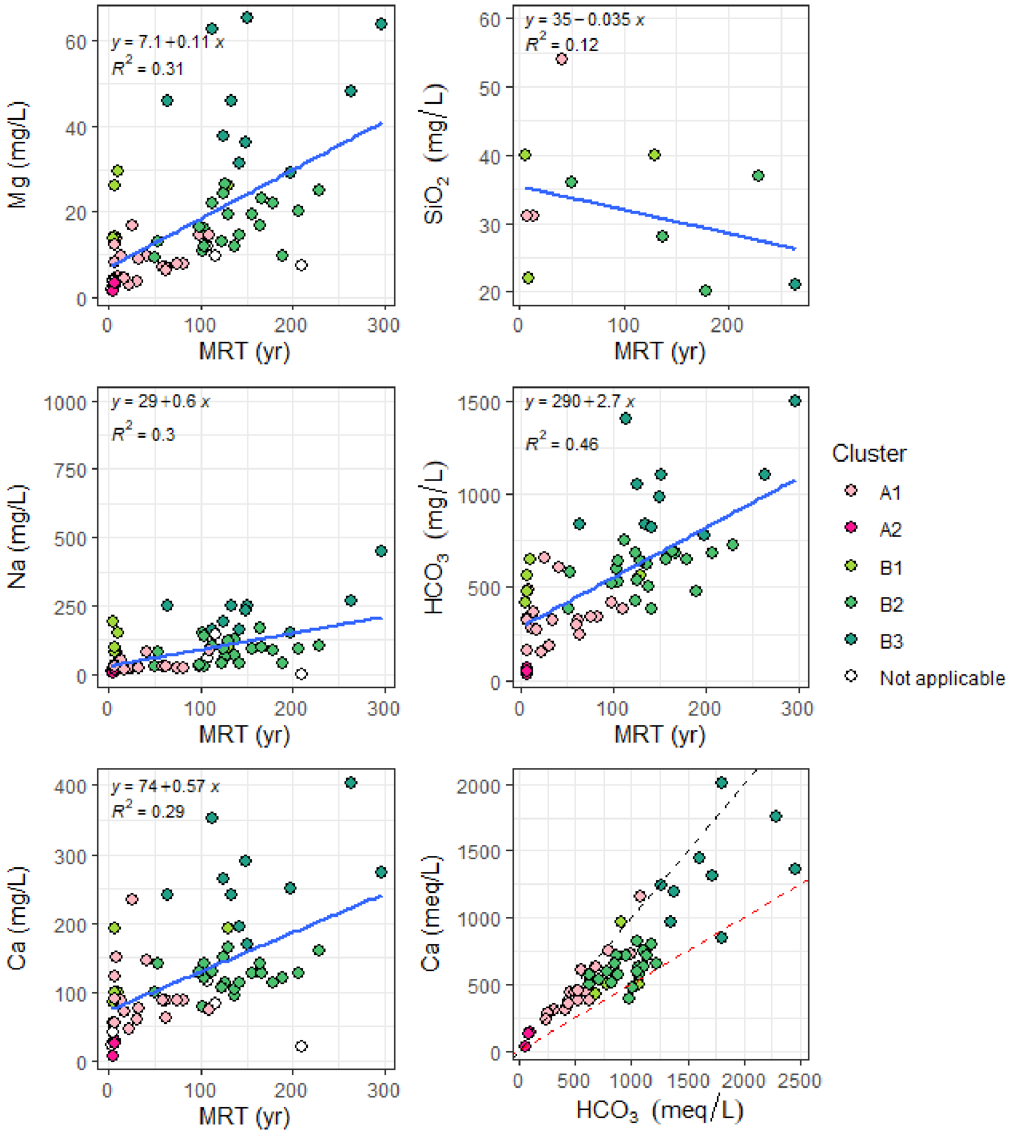

Figure 4.17 Mg, SiO_2, Na, HCO_3 and Ca concentrations versus mean residence time (MRT) for Tairāwhiti Gisborne groundwaters, excluding brines. The bottom-right plot shows Ca versus HCO3 on a milli-equivalent basis, with the black dashed line indicating the 1:1 calcium-carbonate dominated dissolution line and the red dashed line the equilibrium when 50% of HCO3 is derived from decay of organic matter.

4.5.5 Spatial Distribution of Selected Chemistry Parameters

In this section, spatial distributions of chemistry parameter examples are shown that can inform recharge sources and flow patterns for the Gisborne groundwater systems.

4.5.5.1 Chloride and $\delta^{18}O$

Chloride (Cl) and oxygen isotope ($\delta^{18}O$) values are conservative groundwater tracers, without significant sources and sinks in the aquifer, and can be used to track natural flow patterns. Inland rain is characterised by significantly lower Cl concentrations and $\delta^{18}O$ values compared with coastal rain. Low Cl and $\delta^{18}O$ values in groundwater therefore indicate recharge from higher elevations via inland rivers or ice melt.

Low Cl concentrations (<100 mg/L) occur in all aquifers (Figure 4.18 – cyan symbols) although higher values are limited to the Poverty Bay flats and Wainui, and extremely high Cl values (>1000 mg/L) are typical of brines. The Cl concentration range in the Poverty Bay flats occurs across multiple aquifers, with the higher values seen in the MTK and MKG. One Poverty Bay well located in Waerengaahika (GPE012) presents an anomalously high Cl content consistent with the major ion signature of a brine. There are no $\delta^{18}O$ data measured in this well. In multiple catchments, brines occur within an aquifer system either as springs or at depth.

In the Poverty Bay flats, concurrently low Cl and $\delta^{18}O$ values occur in the WPG, suggesting river recharge. In the ECAs, almost all sites exhibit lower Cl and more positive $\delta^{18}O$ values, suggesting little recharge from the river. Lower Cl combined with intermediate $\delta^{18}O$ values occur in ECAs, which is consistent with smaller river-recharged aquifer systems, located close to the sea.

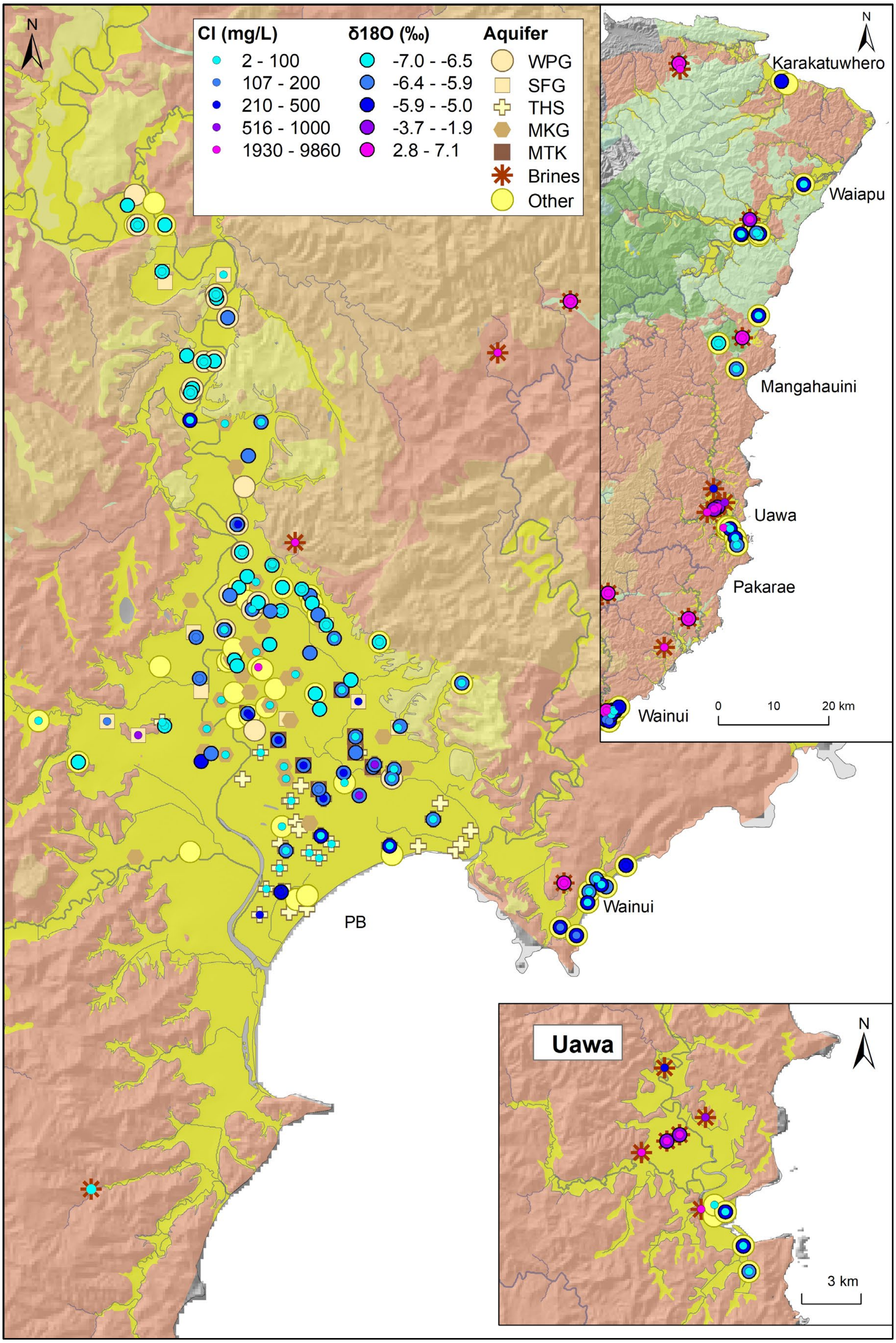

Figure 4.18 Spatial distribution of chloride (Cl) and $\delta^{18}O$ values in Tairāwhiti Gisborne's groundwaters. The figure shows that in the Poverty Bay flats, low Cl concentrations occur locally within the THS, SFG, MKG and MTK aquifers. The ECAs exhibit higher Cl, suggesting limited river recharge.

4.5.5.2 Nutrients

Nitrogen in its nitrate form is the most pervasive agricultural contaminant in New Zealand's groundwaters. However, in Tairāwhiti Gisborne, most sites exhibit low to below-detection concentrations (Figure 4.19), which could be the result of natural denitrification processes (loss of NO_3-N) or simply natural mineralisation from nitrate to ammonia. By conjunctively displaying both nitrogen forms, it becomes apparent that in the shallow aquifers, NO_3-N and NH_3-N concentrations are low, save for local nitrate hotspots. These hotspots occur in Pahutahi (Well GPJ081, THS consistently measured between 2017 and 2023) and in the Wainui ECA (Wells GPA302 and GPA310, both showing high variability and NO_3-N peaks above 20 mg/L between 2017 and 2023). It is more likely that at these locations, nitrate is sourced from human activities. In the deeper Poverty Bay flats' aquifers, however, nitrogen can present in significant concentrations as ammonia, with increasing concentrations close to Te Hapara (MKG, MTK). Considering the aquifer depth and residence time, the source of nitrogen is likely to be organic material within the aquifer itself. Nitrogen is absent from the brines.

Phosphorous is essential for the development of life forms. It can be present in groundwater as orthophosphate ion, but also in cellular material. Phosphorous is naturally derived from rock interaction or decomposition of plant and animal tissue, or waste. It is also a land-use impact indicator, as fertilisers, manure and composted material contain phosphorous. DRP is the form of phosphorous that is mobile in groundwater. Figure 4.20 shows the spatial distribution of DRP in Tairāwhiti Gisborne's groundwaters. In the Poverty Bay flats, DRP concentrations are generally low, with slightly higher concentrations along the Taruheru River (SFG, THS and MKG aquifers) and on wells located close to the basement on the eastern side of the Poverty Bay flats. The high DRP concentrations are measured in the Wainui and Ūawa ECAs, whilst low concentrations occur in Waiapu.

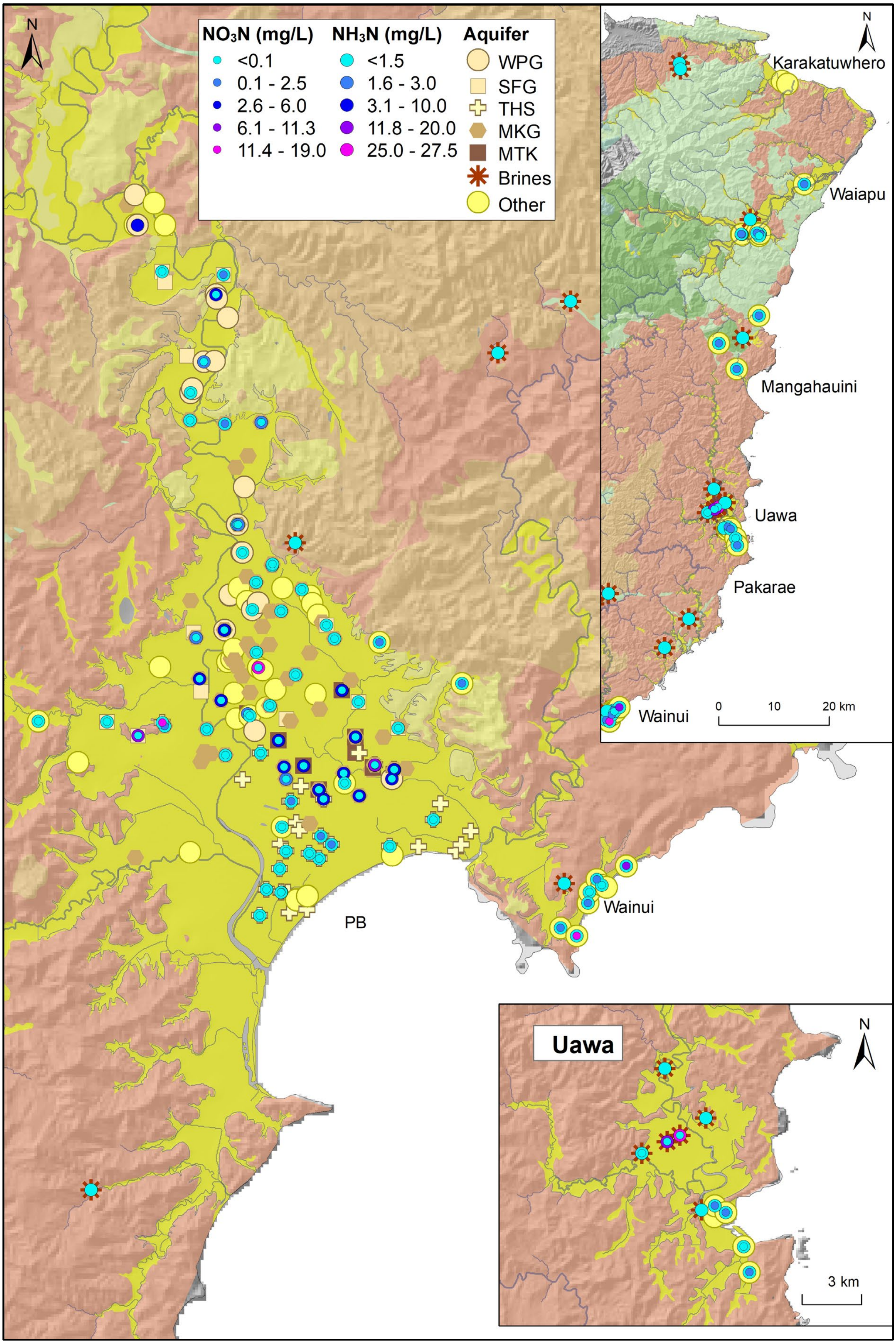

Figure 4.19 Spatial distribution of nitrogen (NO_3-N and NH_3-N) in Tairāwhiti Gisborne groundwaters.

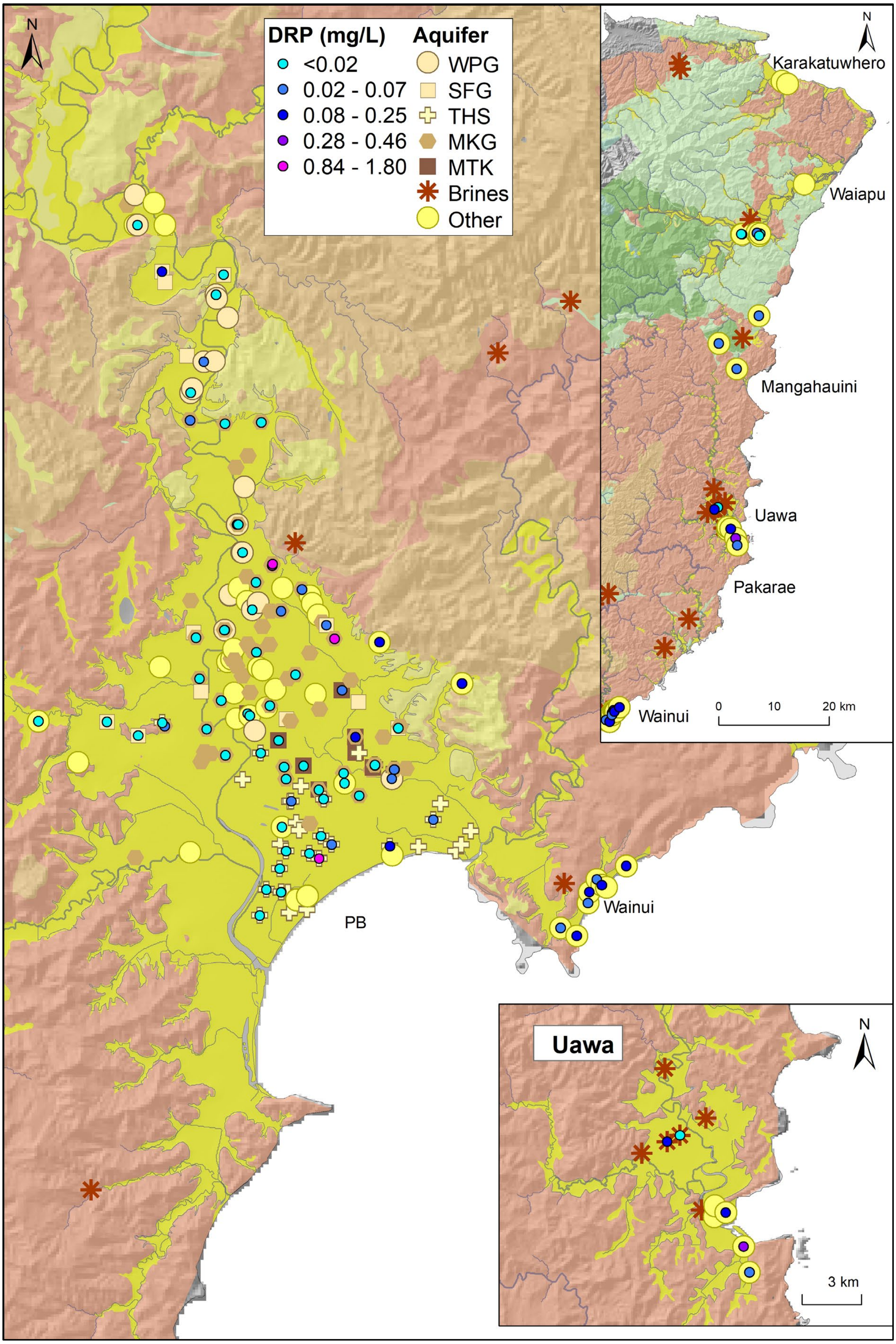

Figure 4.20 Spatial distribution of dissolved reactive phosphorus (DRP) in Tairāwhiti Gisborne groundwaters.

4.5.5.3 Bicarbonate

The main sources of bicarbonate (HCO_3) in groundwater are uptake of CO_2 from the atmosphere, uptake of CO_2 in the soil zone from microbial and plant root respiration, reduction reactions of organic matter and sulphate in the groundwater system, and dissolution of carbonate rocks. The main sources of elevated HCO_3 in groundwater are reduction reactions of organic matter and dissolution of carbonate rocks in the groundwater system.

There are large variations in HCO_3 concentrations in the district (Figure 4.21). In the Poverty Bay flats, the lowest HCO_3 concentrations occur in the THS, with the lowest value towards Gisborne city. This is consistent with the silica-rich, as opposed to carbonate-rich, aquifer material. Moderate HCO_3 concentrations occur in the WPG and SFG, and the highest concentrations are found in the lower parts of the flats in the deeper MKG and MTK. The HCO_3 concentration distribution is consistent with increases along the flow path. There are isolated occurrences of HCO_3 concentrations (>1000 mg/L) similar to that of brines in the Poverty Bay flats (SFG, MKG, MTK). In the ECAs, there are variations in HCO_3 concentrations: Karakatuwhero, Ūawa and Waiapu exhibit low concentrations. In the Wainui aquifer, low to moderate HCO_3 concentrations occur along the coast.

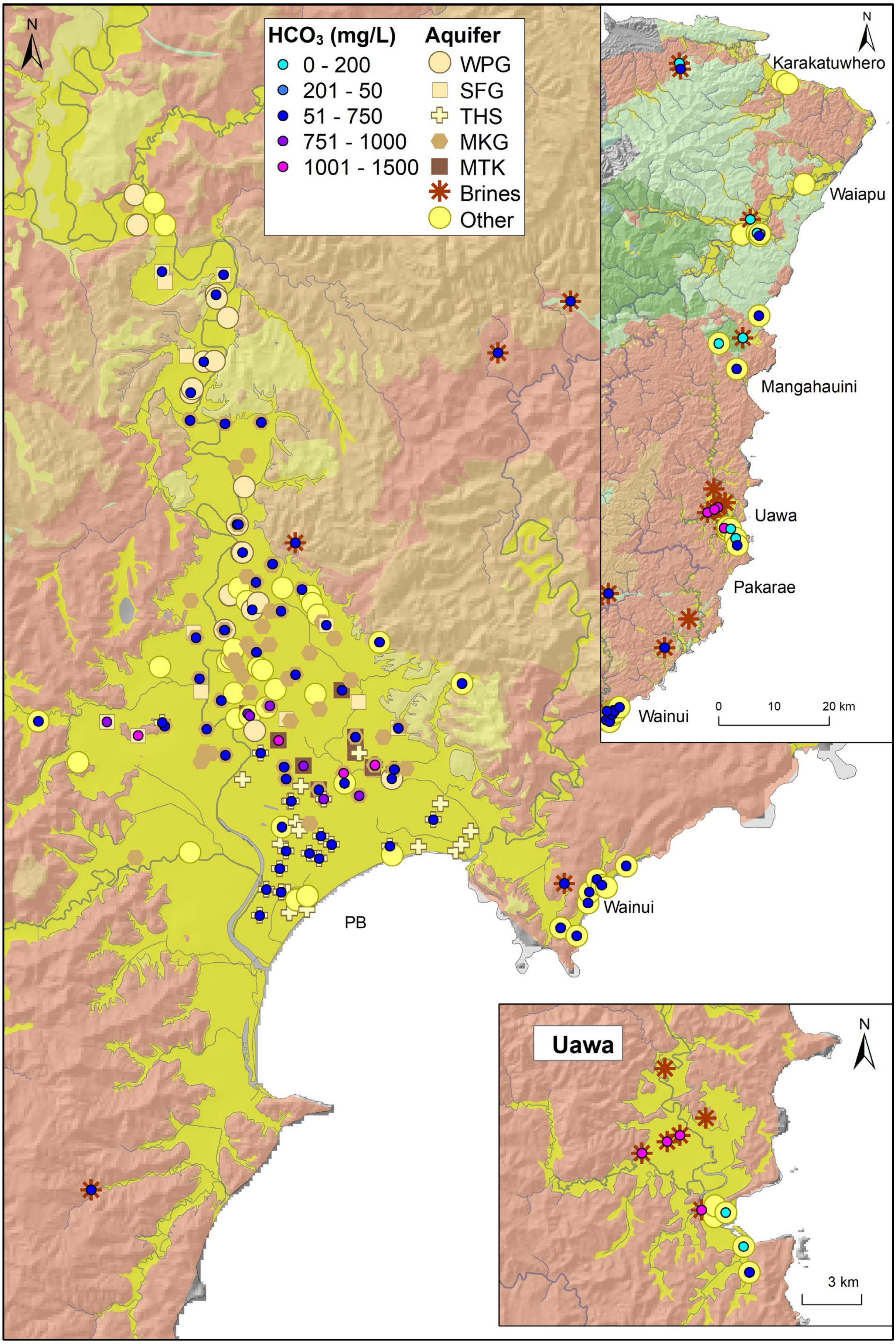

Figure 4.21 Spatial distribution of bicarbonate (HCO_3) in Tairāwhiti Gisborne groundwaters.

4.5.5.4 pH

Potential hydrogen or pH is a measure of the activity of hydrogen in groundwaters, which is a controlling factor of the solubility and biological availability of chemical constituents, such as nutrients (phosphorus, nitrogen and carbon) and heavy metals (lead, copper, cadmium, etc.). Low pH is generally associated with more soluble or mobile metals, but also decaying organic matter. New Zealand groundwaters exhibit pH ranging from 6 to 8.5 and Tairāwhiti Gisborne's groundwaters fit this pattern. Most Tairāwhiti Gisborne groundwaters (excluding brines) exhibit a pH between 6.6 and 7.5 spatially and between aquifers (Figure 4.22). In the Poverty Bay flats, the lowest pH (of X and Y) occurs in the THS towards the Waipaoa River mouth and in the WPG north of Ormond in the headwaters. There is no clear spatial distribution pattern for field pH in the MKG. The lowest MKG pH values (6.4 and 6.7) were recorded at sites located in the Waiapu ECA (GRB047 and GRC013) and are associated with very low DO, but not with elevated Fe and Mn, suggesting that decaying organic matter may be the dominant process. Brines exhibit a wide range of pH from X to Y.

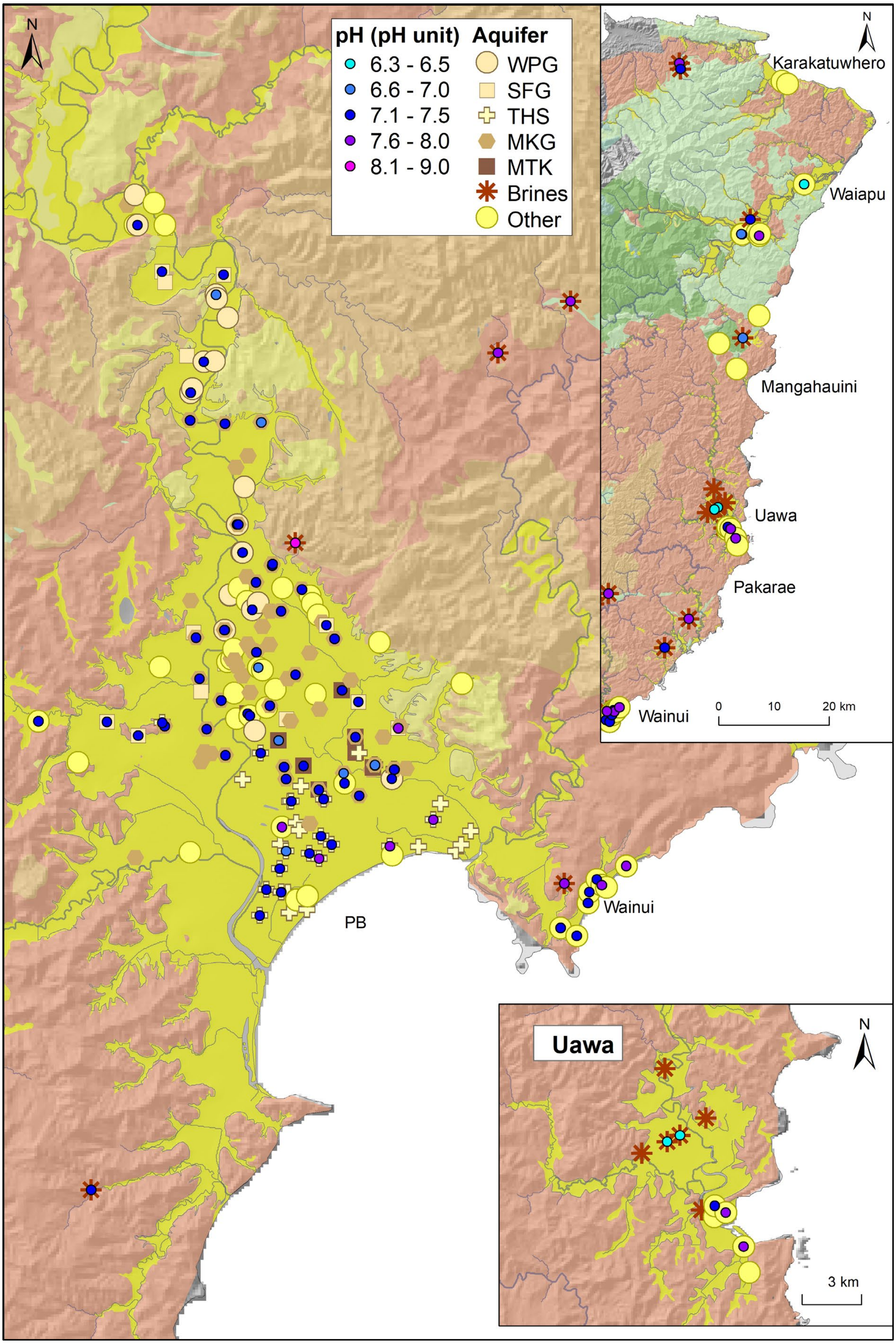

Figure 4.22 Spatial distribution of laboratory measured pH in Tairāwhiti Gisborne groundwaters.

4.5.5.5 Electric Conductivity

Conductivity is a measure of the total dissolved solids content for groundwaters. There are a range of processes that may lead to increased conductivity, including water-rock interactions due to long residence time, and mixing between groundwaters and seawater intrusion. The range of conductivity in the district is wide (173–19,514 μS/cm). As an indicative, New Zealand rainwater has a conductivity between 20 and 150 μS/cm (Nichol et al. 1997) and rivers range between 100 and 200 μS/cm (Vant and Smith 2004).

Generally, EC values are lower in the ECAs than in the Poverty Bay flats (Figure 4.23) and, where measured, brines show significantly higher EC (>10,000 uS/cm). Shallow Poverty Bay flats' aquifers have lower total dissolved contents (THS, WPG, SFG). The spatial coverage available for the MKG shows a gradation of conductivity, increasing from the headwaters towards the coast. The highest EC values measured in the MKG (X) are similar to those measured in the MTK. In the ECAs, low conductivity values are recorded in Karakatuwhero, Ūawa and Waiapu (<600 μS/cm) contrasting with moderate values (1000 to 1500 μS/cm) in Wainui. In this area, higher conductivities arise from high concentrations for most major ions, except for Mg. This suggests prolonged rock-interactions with low Mg rock material, which is consistent with the geology (sand overlying estuary deposits).

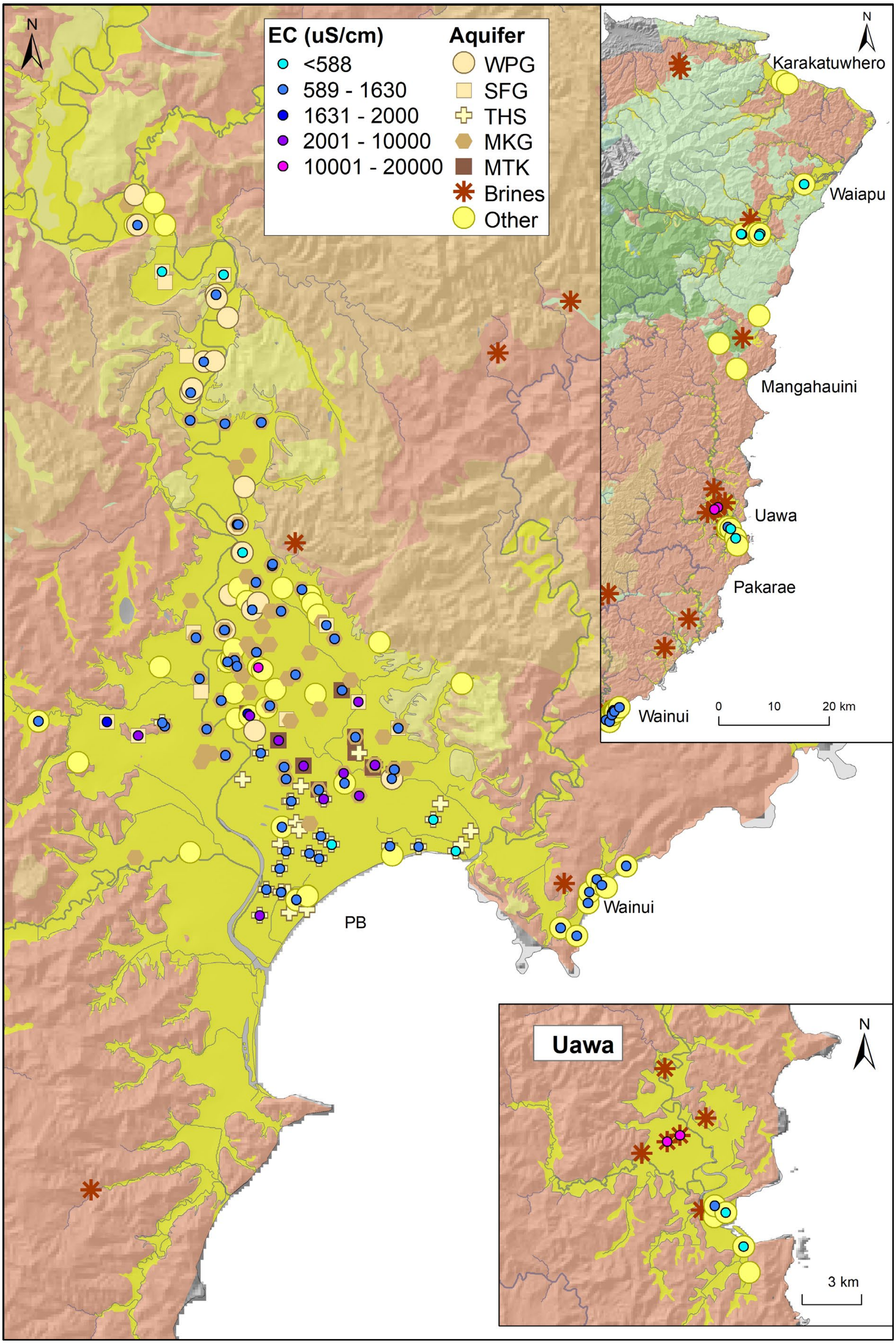

Figure 4.23 Spatial distribution of field electrical conductivity (EC) in Tairāwhiti Gisborne groundwaters.

4.5.5.6 Sodium and Magnesium

The main sources of sodium (Na) and magnesium (Mg) in groundwater are dissolution of carbonate and silica-rich rocks, occurrences of salt-bearing geological formations, deposition of sea-spray (Na only) and seawater intrusion (Na only).

There are strong similarities in the spatial distribution of Na and Mg in both the Poverty Bay flats and the ECAs (Figure 4.24 and Figure 4.25). There are large differences between individual brines in Mg concentrations and, although all brines are associated with elevated Na concentrations, some exhibit low Mg concentrations. This is not surprising because the brines are derived from seawater. The lowest Na and Mg concentrations (X and Y) occur in the ECAs and the THS (lowest towards Gisborne city) (Figure 4.24 and Figure 4.25). This is consistent with silica-rich, as opposed to carbonate-rich, aquifer material. Most of the Poverty Bay flats' shallow groundwaters have low concentrations of Na and Mg. These concentrations are higher in the deeper aquifers, likely due to increased water-rock interactions associated with longer MRTs.

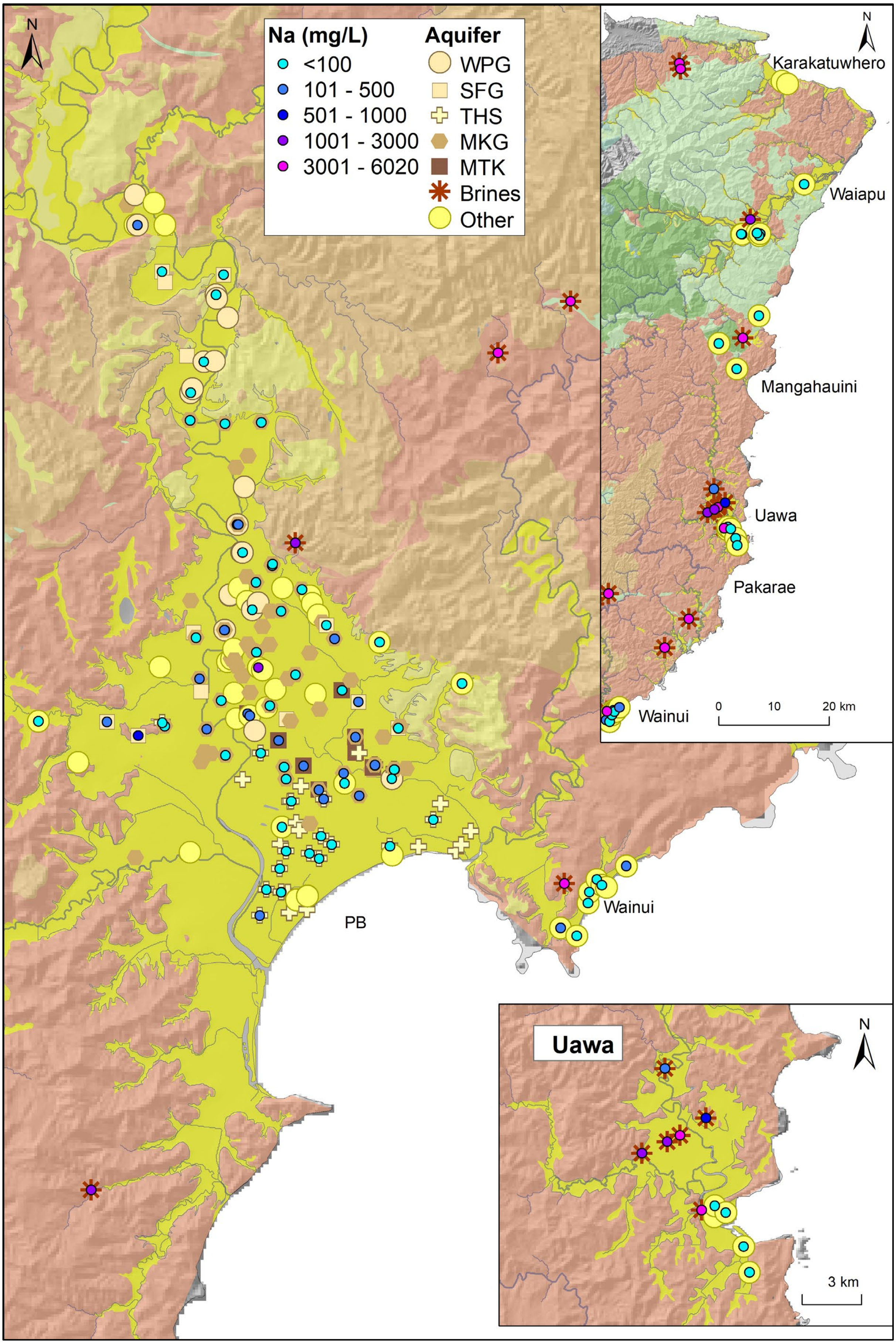

Figure 4.24 Spatial distribution of sodium (Na) in Tairāwhiti Gisborne groundwaters.

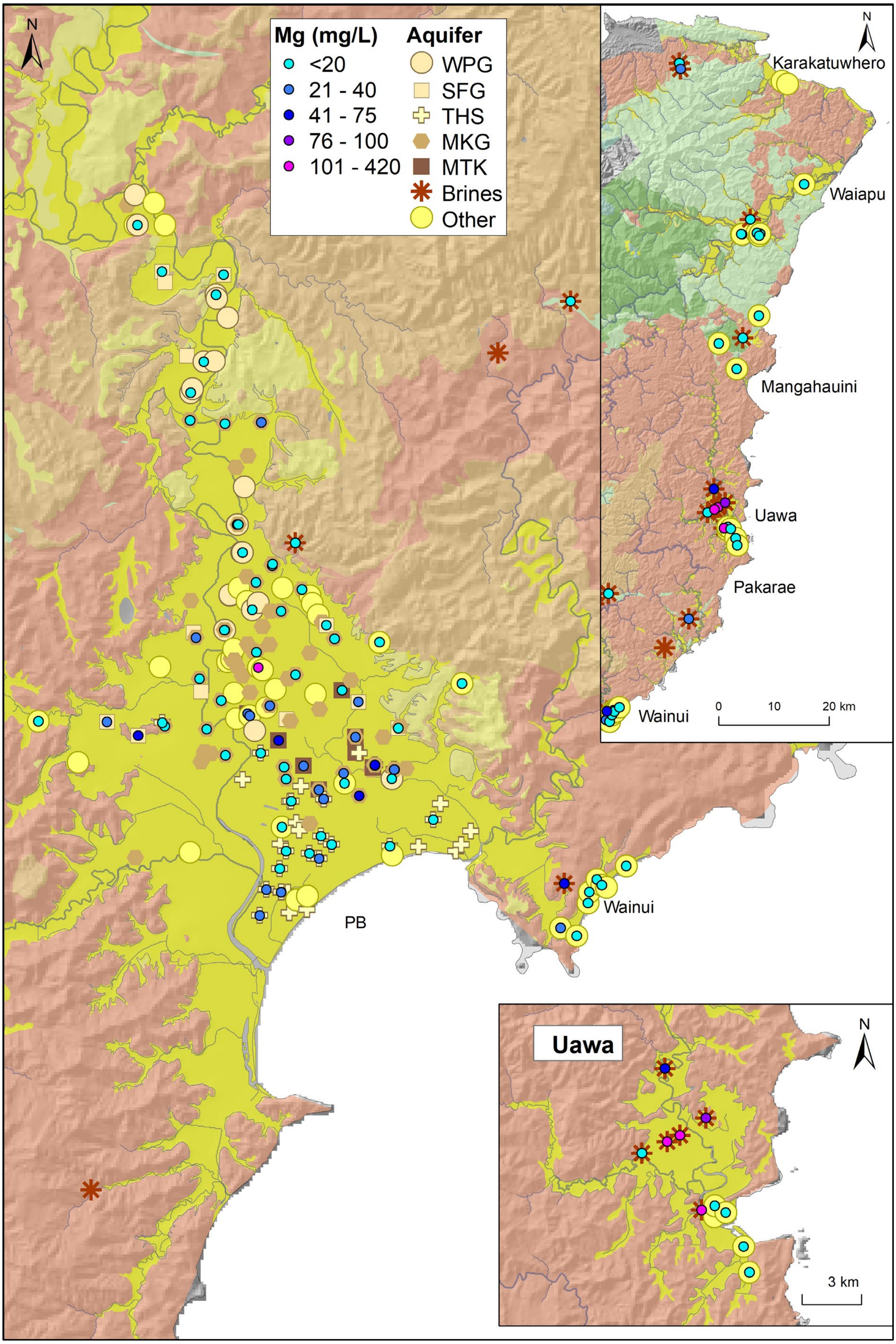

Figure 4.25 Spatial distribution of magnesium (Mg) in Tairāwhiti Gisborne groundwaters.

4.5.6 Temporal Variability

Where chemistry time series are available, half of the well sites demonstrated long-term trend patterns (n=93). Varying trend magnitudes were observed over the duration of the monitoring record across multiple aquifers. Chemistry time series were categorised into the following six patterns:

- **Minor trend (n=24)** comprises wells at which up to four minor parameters exhibit a perceptible trend magnitude (Figure 4.26). These changes are generally small. SO_4 is the most common trending parameter, however, statistically significant decreases may be explained by the lowering of detection limits through laboratory equipment and method upgrades. Only two sites exhibit increasing NO_3-N concentrations associated with high conductivity (>700 uS/cm). At Well GPJ033, there is a gap in nitrate measurements between 1986 and 2016, while other parameters have continuous records. At Well GPA305, hydrochemical data is only available between 2017 and 2023.
- **No trend (n=20)** consists of features exhibiting little variations over the time record (Figure 4.27). Wells in this category are mostly located in the Poverty Bay flats. At five sites, although there are no trends for chemistry, there are trends for water levels**.**
- **Freshening (n=17)** comprises sustained decreases in total dissolved content, which can be accompanied by increasing water levels and groundwater temperatures (Figure 4.28). Wells in this category are located in the Poverty Bay flats.
- **Limited recharge (n=14)** consists of wells exhibiting a sustained long-term increase in total dissolved content, which can be accompanied by stronger reducing conditions (Figure 4.29). This is likely to be the consequence of drawing older, more evolved groundwater, and is accompanied at some locations by declining water levels. Wells in this category are sourced from a range of Poverty Bay flats' aquifers, at a range of depths (11.3–80 m deep) and are spread across the flats.
- **Step change (n=9)** includes features that exhibit sudden changes in groundwater quality (Figure 4.30). There is a large variation within this category, with some step changes returning to previous conditions, whereas other wells exhibit abrupt changes in chemistry that are sustained (e.g. GRB048). Generally, there is no obvious correlation with water level changes. Some step changes occur at a similar time (e.g. 2010) and could be related to new sampling procedures.
- **Trend reversal (n=9)** includes features exhibiting trend reversals for multiple parameters (Figure 4.31). Wells in this category are located in the Poverty Bay flats.

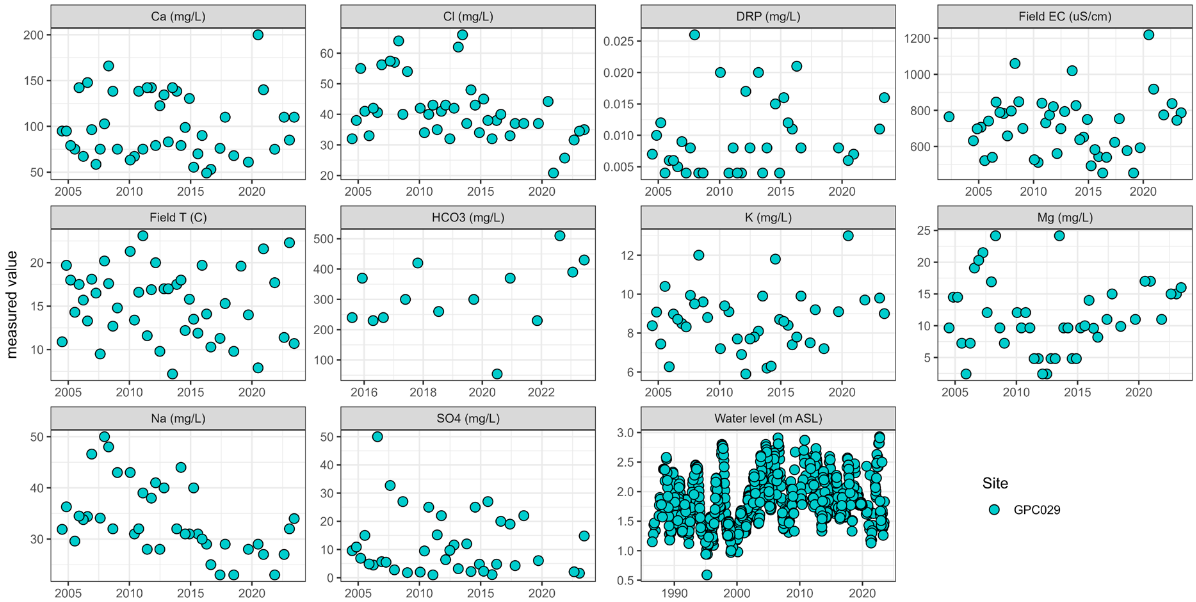

Figure 4.26 Monitoring time series for the ‘minor trend’ GPC029 well. Other sites in this category are: GPA162, GPA163, GPA302, GPA305, GPA307, GPA310, GPB128, GPC027, GPC029, GPC045, GPD116, GPB100, GPB102, GPB125, GPB129, GPB135, GPD111, GPD130, GPF106, GPH022, GPH028, GPJ033, GPB083, GRB047.

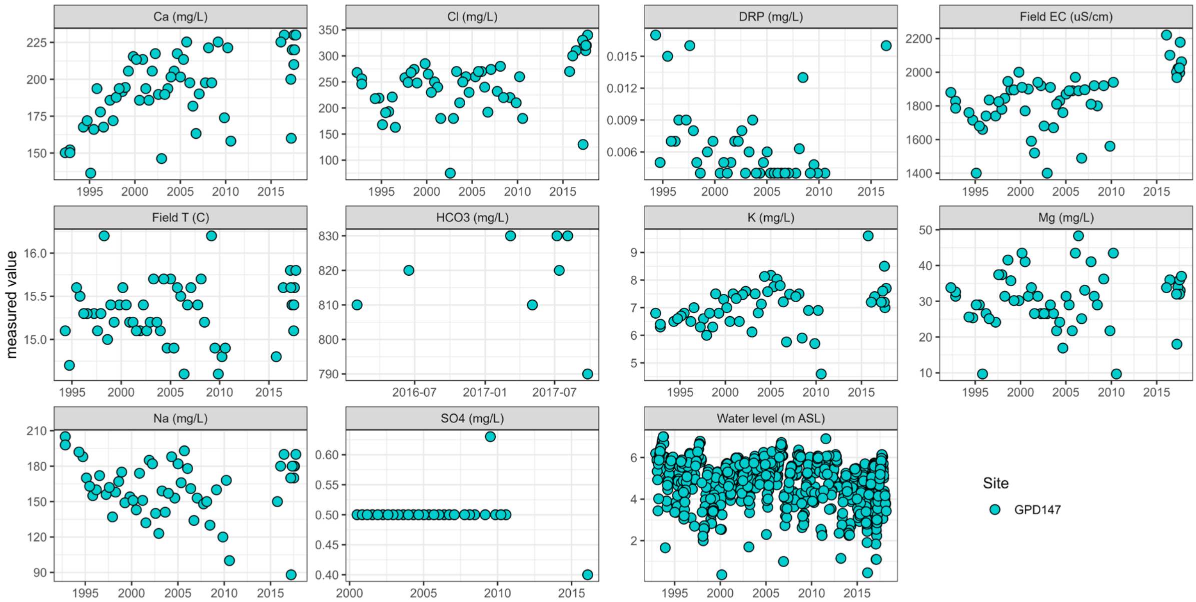

Figure 4.27 Monitoring time series for the ‘no trend’ GPD147 well. Other sites in this category are: GPB111, GPC036, GPC103, GPG111, GPC140, GPB126, GPD134, GPA164, GPC104, GPD129, GPD132, GPF068, GPG058, GPG076, GPG077, GPH030, GRB031, GRC013, GTA036.

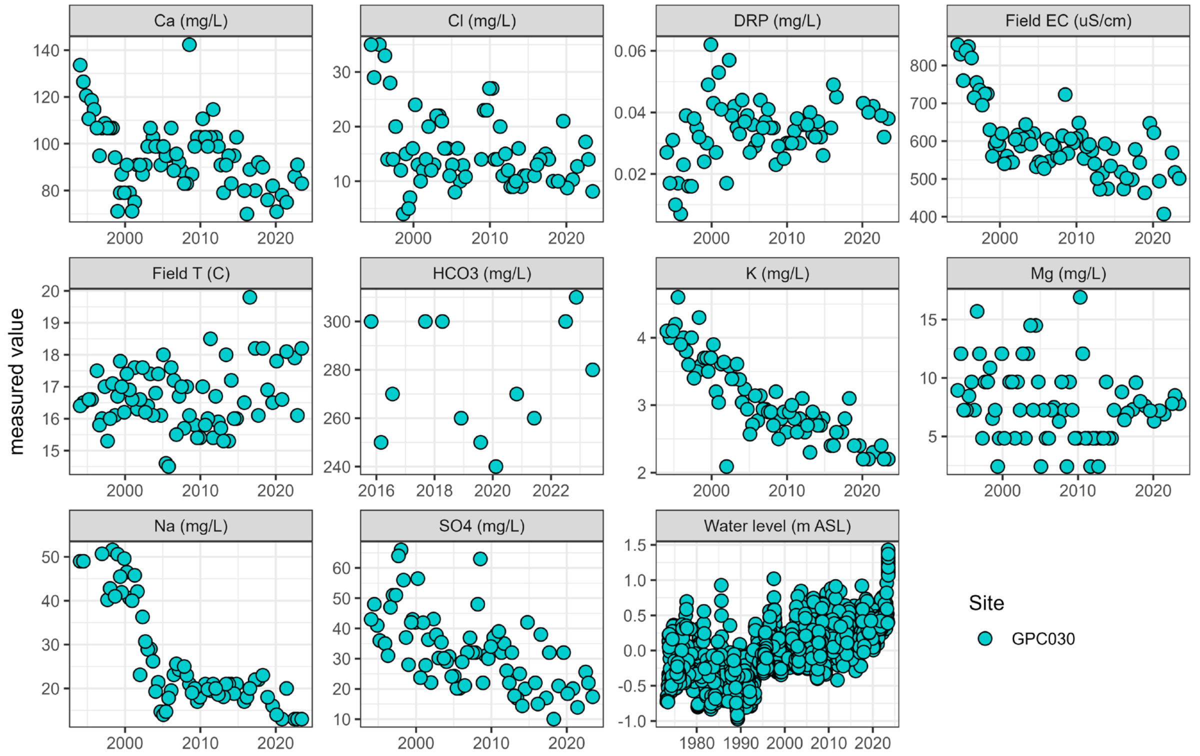

Figure 4.28 Monitoring time series for the 'freshening' GPC030 well. Other sites in this category are: GPB009, GPC112, GPE068, GPF056, GPB099, GPF090, GPF117, GPG088, GPI032, GPJ070, GPO052, GPE006, GPE040, GPF071, GPJ080, GPO004.

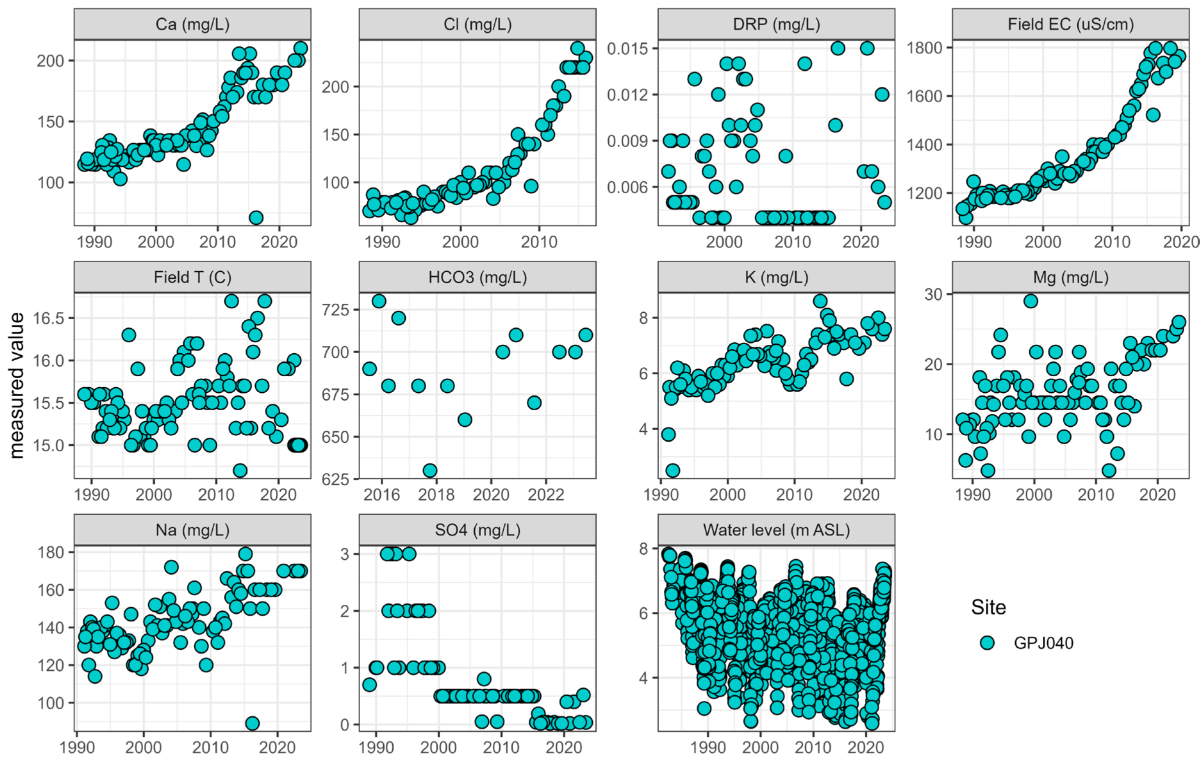

Figure 4.29 Monitoring time series for the 'limited recharge' GPJ040 well. Other sites in this category are: GPB042, GPC026, GPC028, GPC050, GPB039, GPB049, GPD039, GPD115, GPD146, GPF095, GPG026, GPG019, GPJ081.

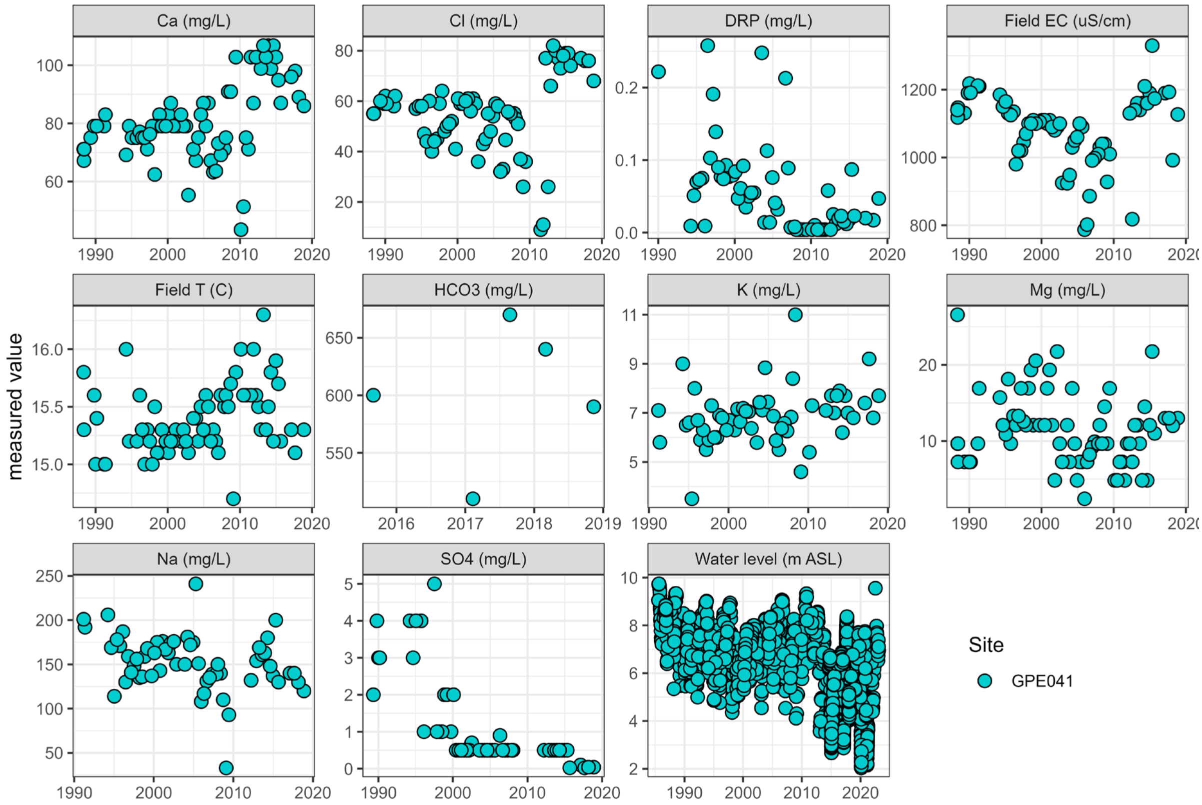

Figure 4.30 Monitoring time series for the 'step change' GPE041 well. Other sites in this category are: GPC031, GPC061, GPC078, GPC003, GPJ005, GPJ078, GPH008, GRB048.

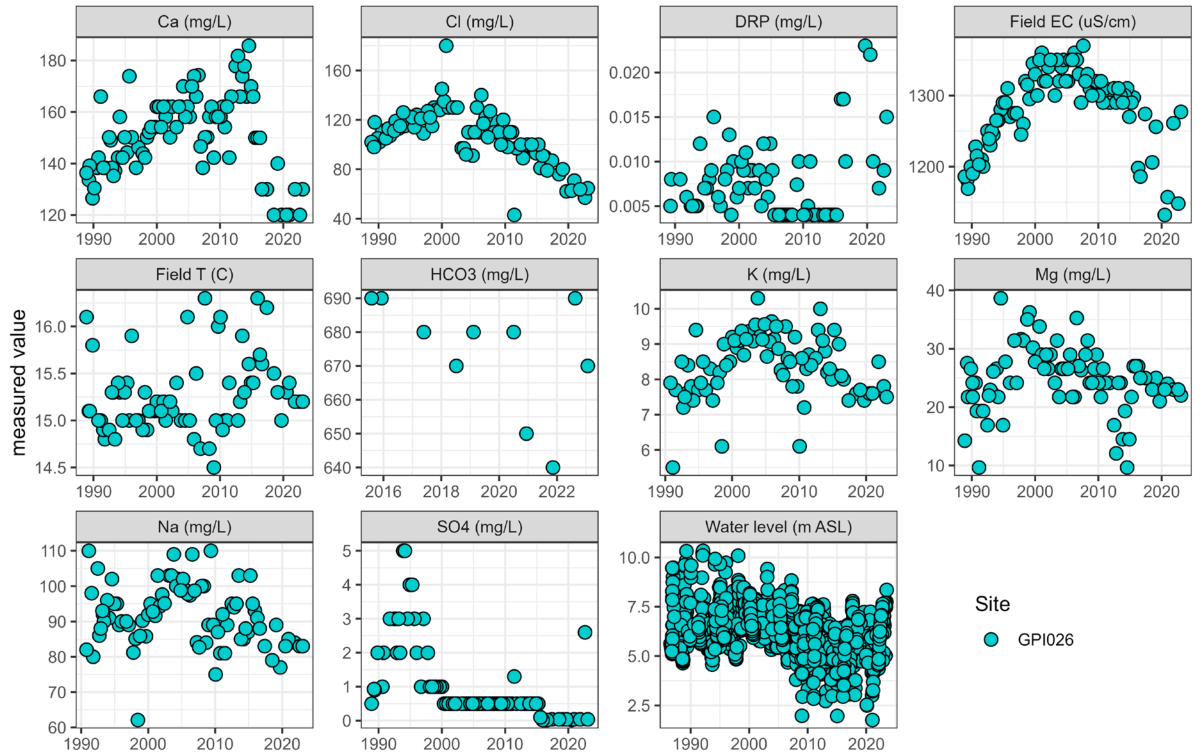

Figure 4.31 Monitoring time series for the 'trend reversal' GPI026 well. Other sites in this category are: GPA004, GPA036, GPC051, GPC062, GPD139, GPE059, GPG059, GPO028.

4.6 Groundwater Flow Dynamics

This section provides a summary of the information that can be derived from the previously discussed hydrochemistry, tracer concentrations and groundwater age regarding recharge source, recharge rates and flow connections.

4.6.1 Possible Drivers for Temporal Variations

In the THS, most wells show changes in chemistry with time, and closely located wells may exhibit a range of trend patterns (all six categories), which suggests local influences. At seven sites, groundwater is freshening, with five sites exhibiting trend reversals and two sites exhibiting monotonic trends (Figure 4.32). These trends indicate either increasing rainfall, river recharge, irrigation within the capture zone or a change in the capture zone. At two sites (GPC031 and GPC062), repeated age tracer measurements indicate a significant change in MRT from old (50–130 years) to less than 10 years, demonstrating a change in either recharge or flow within the capture zone. Six shallow sites exhibit a limited recharge pattern, with groundwater increasing in salinity. Three of these sites are located close to the Waipaoa River mouth (GPC026, GPC028 and GPC050) and, where recorded, water levels lie close to or below the ground surface. This salinity increase may have been caused by ingress of the tidal section of the river or saline intrusion. Further inland, at GPD146 (a well located on the edge of the mapped THS), an increase in salinity is associated with a rising water level, suggesting possible inflow from underlying gravels.

In the SFG, all sites with long-term chemistry are located on the margins of the Poverty Bay flats (east, west, north) and exhibit trend patterns. Freshening trends (GPB009, GPF056, GPJ080, GPO004) occur at locations close to rivers or tributaries, with likely hydraulic connections. Two occurrences of step changes (GPJ005 and GPJ078) coincide and occur in Patutahi, suggesting that the changes are linked to, and caused by, local conditions. A trend reversal at GPO028 occurred between 2000 and 2010, when more saline water was drawn. Groundwater level data were not available at these wells.

Trend patterns in the WPG are isolated occurrences of freshening in Waipaoa (GPE006, GPE040). Closely located contradicting trends (step change at GPG059; limited recharge at GPG019) suggest local conditions are affecting the wells.

In the MKG, 60% of the monitoring wells exhibit either a freshening, limited recharge, step change or trend reversal pattern. Freshening trends occur at nine sites across the Poverty Bay flats, with depths ranging from 44.8 to 170 m below ground level (GPC112, GPE068, GPF090, GPF117, GPF071, GPG088, GPI032, GPJ070, GPO052). It is unlikely that surface water would be drawn to these depths unless the well casing is compromised. It is therefore more likely that groundwater is drawn from the overlying gravel aquifers. Eight sites exhibit a limited recharge trend (GPB039, GPB049, GPD039, GPD115, GPD116, GPF095, GPG026, GPJ040) with varying magnitudes of salinisation (EC increase from 0.8 to 13.5 uS/cm/yr). At these sites, it is likely that increased salinity arises from pulling deeper waters from the MTK. The site depth range for this trend is 38–80 m below ground level and occurrence is widespread on the flats. Two sites (GPE059, GPI026) show trend reversals coinciding with either low groundwater levels or declining groundwater levels, suggesting that groundwater was pulled from the overlaying gravels. These three step changes (GPC003, GPE041 and GPH008) appear uncorrelated in both time and location, and are driven by local conditions. Instances of closely located occurrences of distinct trend patterns suggest lateral variability in the connection of MKG to overlying gravels.

In the MTK, no chemical trend patterns are observed in any of the six monitoring wells, despite decreasing water levels. This is consistent with the conceptual model by which the MTK is poorly connected to the overlying aquifers, and has a very limited and slow recharge.

In the ECAs, most trends are either minor (eight sites) or undetected (four sites). There is one occurrence of step change (GRB048), with a sharp increase in conductivity. The site is located inland, close to a landfill and a saline groundwater well (GBR031, 12 m deep). It is possible that either landfill leachate or saline water is seeping into GRB048.

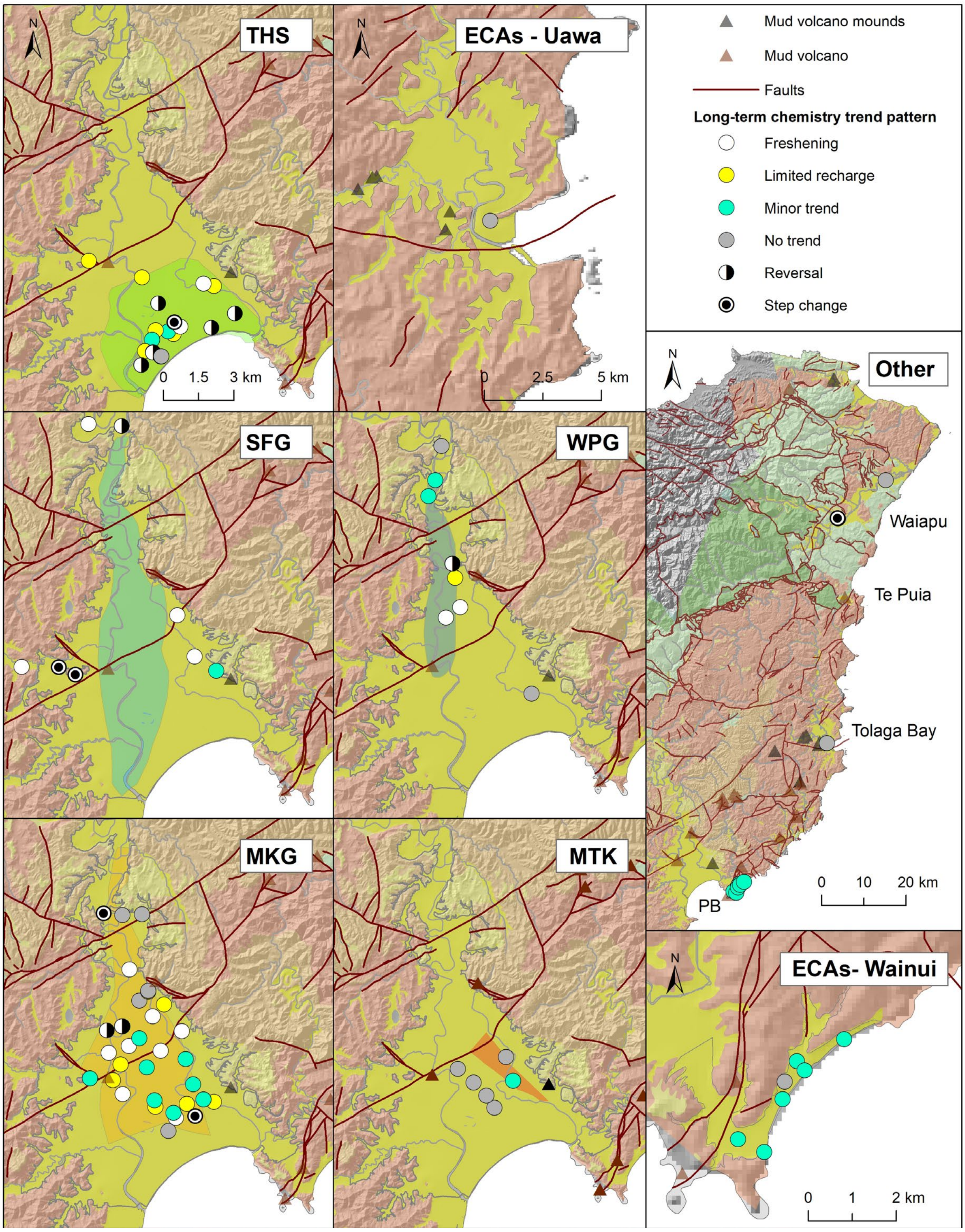

Figure 4.32 Spatial distribution of statistically significant trends. Only perceptible trends are shown where it was possible to perform the test.

4.6.2 Recharge Source of Groundwater and Connection to Surface Water

Shallow coastal aquifers, such as the ECAs and the THS, are recharged via rainfall or tributaries. It was noted, however, that in the Waiapu catchment, numerous local springs are reported, likely arising from fractures within hard rocks (Tertiary or older).

In the Poverty Bay flats, the shallow gravels (WPG and SFG) exhibit a strong connection with the Waipaoa River. On the margins of the flats, the SFG can be disconnected from the main rivers, as the gravels originate from tributary catchments (e.g. GPF056). On the eastern margin, Brewery Spring is sourced from fracture-flow from the nearby hills. Recharge to the deeper MKG is spatially and vertically heterogenous, with some areas recharged through the shallower gravels, and others exhibit limited surface recharge as deeper, more saline water is drawn upwards. The range of chemistry within the aquifer illustrates strong spatial controls on gravel connectivity. The continuing long-term decline in water levels in the MTK indicates storage depletion, which does not affect groundwater chemistry.

4.6.3 Vertical Flow and Recharge

Unconfined recharge situations result in stratified groundwater ages, and the related vertical recharge rates can be estimated from the age-depth relationship of the groundwater (Cartwright and Morgenstern 2012; Morgenstern et al. 2019). In the Poverty Bay flats aquifer, unconfined conditions are encountered in the WPG, some wells in the SFG and the THS. Outside of the flats, shallow porous aquifers are seen in the ECAs. Figure 4.33a shows groundwater age versus depth for shallow aquifers in Tairāwhiti Gisborne, separated into aquifers. Black dashed lines show estimated minimum and maximum recharge rates. Note that these recharge rates are associated with relatively high uncertainty because very little information is available as to the depth at which active groundwater flow into the wells occurs.

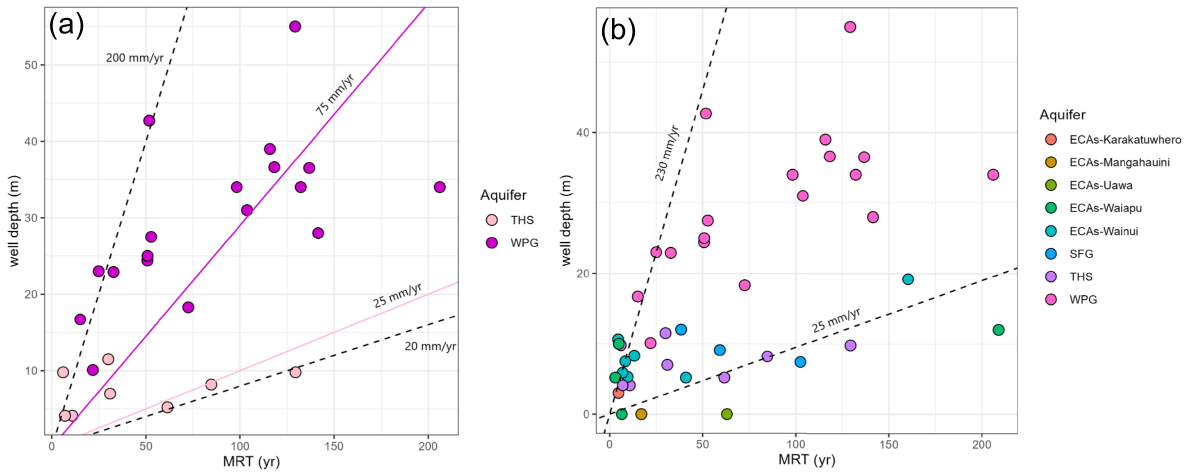

Figure 4.33 Groundwater mean residence time (MRT) versus depth for THS and WPG aquifers (a) and in the region, excluding Brines, MKG and MTK aquifers (b). Age versus depth trends are indicated by lines (assuming a porosity of 0.25). Coloured lines are indicative of a vertical recharge rate for a specific aquifer, dashed black lines indicate minimum and maximum recharge rates.

There is no unique overall trend between groundwater age and depth, indicating confined or disconnected groundwater system conditions throughout the flats. The range of calculated recharge rates is similar between flats for shallow unconfined aquifers (20–200 mm/yr). These values are relatively low, suggesting either low hydraulic conductivity or limited connectivity within the Holocene deposits. In the Poverty Bay flats, the recharge rate of the WPG is higher than the THS, where river recharge is expected to occur.

5.0 CONCLUSION

This collaborative project between GDC and GNS Science aimed to improve understanding of the water dynamics through the Tairāwhiti Gisborne aquifers to inform management and policy development. Specifically, this report addressed the following questions and problems:

1. Groundwater recharge, flow and discharge questions.

- How are groundwaters and surface waters connected in the Poverty Bay flats?
  - The shallow gravels of the Poverty Bay flats (WPG and SFG) exhibit strong connection with the Waipaoa River. On the margins of the flats, the SFG can be disconnected from the main river but connected to tributary catchments (e.g. GPF056). Brewery Spring is disconnected from surface water.
- Where does the river-recharged groundwater flow within the aquifers?
  - River recharge to groundwater occurs within the Poverty Bay flats' shallow aquifers at selected locations and within the ECAs. A recharge of 75 mm/yr was estimated for the WPG, with a possible maximum of 200 mm/yr.
- Where is groundwater recharged from local rain?
  - Rainfall is actively contributing to groundwater recharge in the THS and the ECAs, with an estimated rate of 25 mm/yr.
- What are the timescales of water flow through the aquifers?
  - Generally, groundwater flow in the district is slow compared with other areas in New Zealand, with long residence times. In the Poverty Bay flats, the youngest groundwaters were measured at six years in the shallow coastal THS. Although groundwater gets older (>100 years) as the well depth/aquifer depth increases (max estimated groundwater age is >5,000 years in the MTK), older groundwaters (>100 years) also occur in the shallow aquifers. This is accompanied by higher total dissolved solids in fresh groundwaters than elsewhere nationwide. This salinity is mostly through water-rock interaction. In the ECAs, MRTs varying between one year and 35 years were derived for most sites. The younger ages probably reflect the sizes and depths of the Holocene systems.

2. Groundwater chemistry questions.

- How do brines relate to fresher groundwaters in the district?
  - Brines associated with the HSZ occur throughout the district as springs or mud volcanoes. These features are generally not associated with active faults, and their hydrochemical and stable isotope values are distinct from freshwaters. Drilling reports suggest that the saline system is generally separated from the fresh groundwater systems by a caprock. Brine chemistry ranges from highly reducing and saline to relatively diluted within the Poverty Bay flats (e.g. GPE012).
- What are the drivers of long-term trends in chemistry in the Poverty Bay flats?
  - Long-term freshening or trend reversals involving more recent inflow of fresher groundwater in the THS may be driven by river-recharge induced by pumping, increased rain or irrigation. Some of the changes are rapid and significant, indicating a locally responsive aquifer.
  - Local conditions affect multiple wells in the WPG, SFG and MKG aquifers, with closely located wells exhibiting distinct trend patterns. Freshening may occur through river-recharge or drawing from overlying aquifers.

3. Groundwater management questions.

- Are there SoE monitoring wells influenced by local conditions?
  - The occurrence of isolated trend reversals or step changes in chemistry suggest local changes to the well's capture zone and therefore limitations at these locations to detect long-term changes. Note that where groundwater level information was available, it was valuable to use these data to investigate possible drivers of the changes observed in the chemistry data.

6.0 RECOMMENDATIONS

To support a review of GDC's monitoring network, we recommend the following investigations be undertaken:

- Continue monitoring groundwater for chemistry and water levels across the district. This has contributed to the understanding of temporal variations in hydrochemistry and will inform on the efficiency of freshwater management measures in the context of a changing climate.
- Long-term groundwater chemistry changes were identified in the Poverty Bay flats. In the short term, this information could be used to categorise GDC's current monitoring network within the Surveillance and Evaluative framework, which is currently being investigated by Waikato Regional Council (Hadfield 2023; Moreau 2024). At the same time, a reduction in sampling frequency (biannual to annual) for chemistry may be applied in the MTK, where limited changes in chemistry were detected. In the medium to long term, the existing network should be reviewed within this framework to optimise monitoring, including for the ECAs.
- Where ingress from deeper brines or nearby mud volcano fluids is likely, the analysis of stable water isotopes may provide useful data to test this hypothesis. Repeated stable isotope sampling may be valuable to assess any temporal changes.
- At two water quality monitoring sites (GPC029 and GPC078), chemistry time series are available; however, the aquifer information is unknown, likely due to a lack of a bore log. It may be worthwhile to replace these sites with nearby wells at which aquifer/depth information is available.
- Groundwater level, chemistry data and interpretations presented in this report should be considered when interpreting recently collected SkyTEM data.
- Step changes may be associated with time-bound changes in sampling procedures. By grouping sites by sampling run and field sampler, it may be possible to assess possible impacts from different sampling procedures. This information was not collected as part of this report.

7.0 ACKNOWLEDGMENTS

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APPENDICES

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APPENDIX 1 MAP OF THE TAIRĀWHITI GISBORNE DISTRICT SHOWING THE LOCATIONS OF CHEMISTRY AND AGE SITES

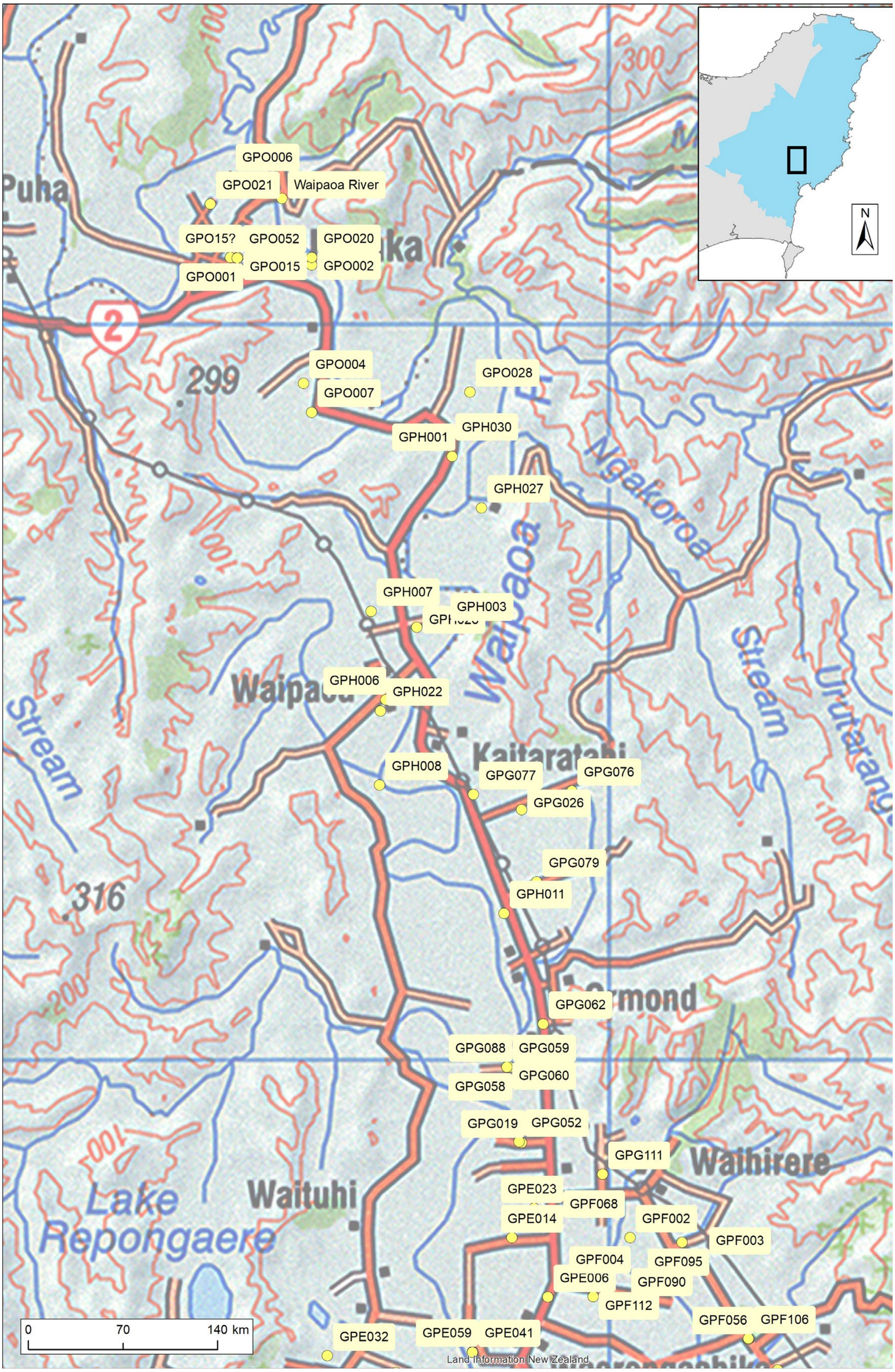

Figure A1.1 Location of chemistry and age-tracer sites, northern Poverty Bay flats.

Figure A1.2 Location of chemistry and age-tracer sites, southern Poverty Bay flats.

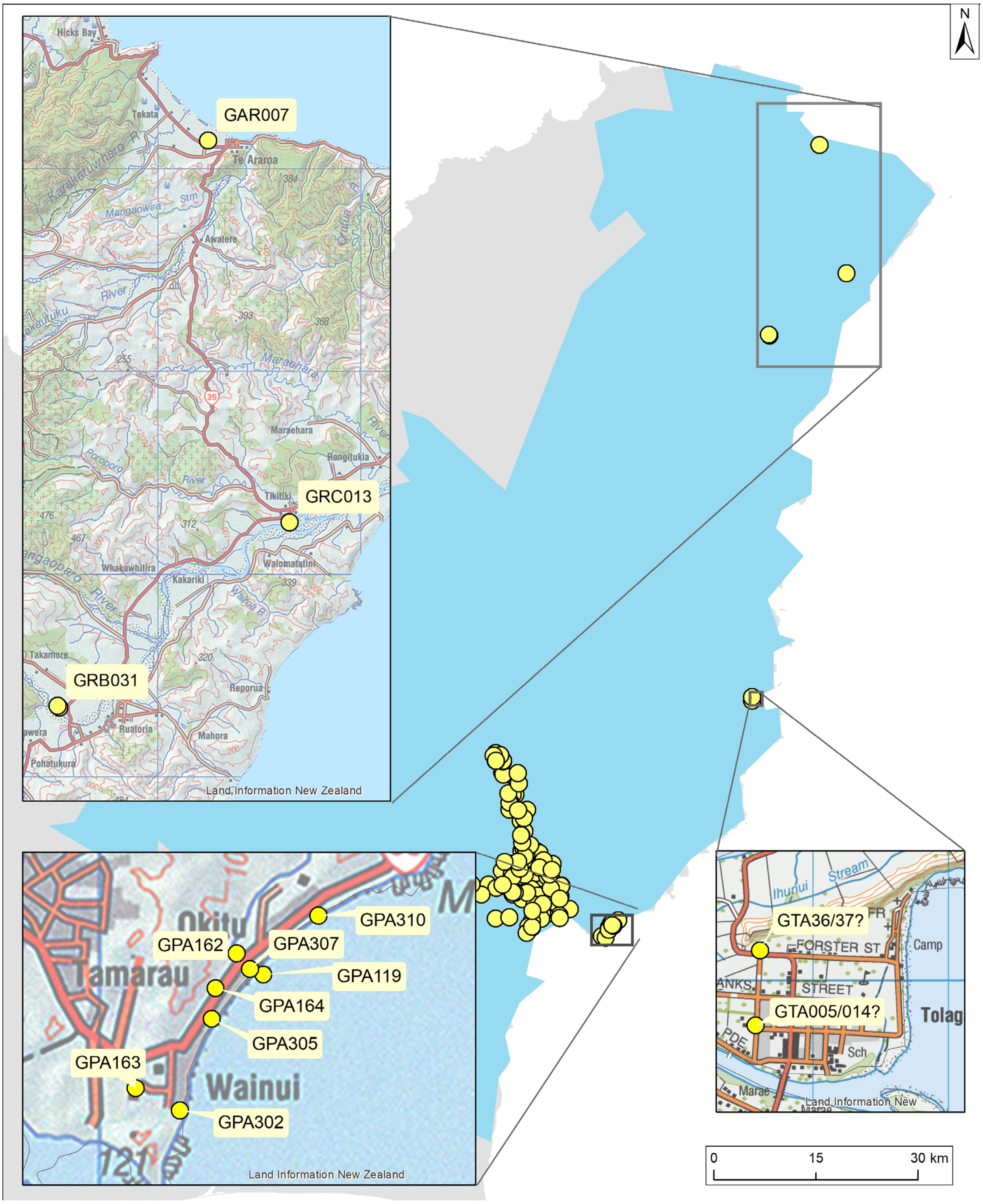

Figure A1.3 Location of chemistry and age-tracer sites, outside of the Poverty Bay flats.

www.gns.cri.nz

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