22 November 2022

Wairakei Research Centre
114 Karetoto Road
RD 4
Taupō 3384
Private Bag 2000
Taupō Mail Centre
Taupō 3352
New Zealand
T +64-7-374 8211
F +64-7-374 8199
www.gns.cri.nz

Tēnā koe, e ngā mana, e ngā reo, rau rangatira mā, tēnā koutou

Ka ora te wai, ka ora te whenua

Ka ora te whenua, ka ora te tangata

Re: Outputs from GNS Science Groundwater Research programmes

This document reports on GNS Science's groundwater-related research outputs for the period November 2021 to October 2022. The aim of our groundwater research programmes is to build inter-generational wealth and wellbeing through wise custodianship of Aotearoa New Zealand's freshwater in a context of changing climate.

The first section of this report summarises each of our ongoing research programmes. The second section summarises the research outputs and provides email/web links for further information.

We hope that you will find this overview of our research useful. Please do not hesitate to contact us if you would like to give us feedback or comments.

Nāku noa, nā,

Magali Moreau	Stewart Cameron
Team Leader	Team Leader
Environmental Chemistry	Hydrogeology, Geophysics and Groundwater Modelling

On behalf of contributing authors:

Brioch Hemmings	Karyne Rogers	Mike Stewart	Rose Cantwell
Catherine Moore	Kate Robb	Mike Taves	Simon Cox
Conny Tschritter	Jay Curtis	Mus Hertoghs	Susana Guzman
Chris Worts	Lauren Coup	Nimthara Udawatta[1]	Thomas Brakenrig
Damon Clarke	Lee Chambers	Paul White	Tusar Sahoo
Diane Bradshaw	Lucjan Sajkowski	Paul Oluwumni	Uwe Morgenstern
Dominic Strogen	Maïwenn Herpe	Peter Gardner	Vanessa Trompetter
Estefania Santamaria	Marcus Vandergoes	Richard Kellett	Wes Kitlasten
Frederika Mourot	Martin Crundwell	Richard Levy	Zara Rawlinson
Karen Houghton	Matthew Coble	Rogier Westerhoff	

1 Now at Jacobs, Australia

Our hydrogeology research activities are undertaken as part of six research programmes funded by the Ministry of Business, Innovation & Employment (MBIE) (Figure 1):

- **Te Whakaheke o Te Wai (TWOTW):** This Endeavour programme supports better water management by improved understanding of flow sources, pathways and lags. Methods are being developed to produce the world's first nationally continuous maps of groundwater age, origin and flow paths, useable by all institutions involved in water management. We test and develop modelling methods to represent the origin of groundwater flow in New Zealand's 200 major aquifer systems and the baseflows in rivers that are connected to them. We measure age tracers, which integrate all flow velocities (of water and contaminants) above a measurement point. We use complementary hydrogeological, chemical and isotope data to understand the origin of recharge and flow pathways and effects of geology, seasonality and stream order. New modelling approaches will integrate tracers and other data across scales. Working with hapū, iwi and national Māori partners, we have incorporated mātauranga-a-iwi/hapū into our models alongside the tracers and other related data. This programme brings together GNS Science (GNS; lead organisation), the Institute of Environmental Science and Research (ESR) and the National Institute for Water & Atmospheric Research (NIWA) and is funded through the MBIE Contestable Fund. Duration: 2018–2023. An overview of the programme can be viewed in this short TWOTW video. For more information, you can access the TWOTW webpage or contact Catherine Moore or Uwe Morgenstern.
- **Groundwater (GW):** This programme includes fundamental hydrogeological research that underpins all projects at GNS. It aims to progress our understanding of Aotearoa New Zealand's groundwaters on multiple angles: what our aquifers are made of, where they are located, how water and key substances flow through them, how water quality changes along the flow paths, what are the current and future pressures on the resource and how science can better inform their management. The programme deliverables are multi-format, from digital maps, datasets and tools to environmental models and forecasts. In this programme, we work in close collaboration with stakeholders, including regional councils and iwi. It is funded through GNS's Strategic Science Investment Fund (SSIF) and also receives co-funding from stakeholder initiatives. Duration: 2019–2024. For more information, you can access the GNS GW Programme webpage or contact Conny Tschritter.
- **National Groundwater Monitoring Programme (NGMP):** This programme provides a national perspective on groundwater quality through the establishment of 'baseline' groundwater quality; associates groundwater quality with causes, such as anthropogenic influences; and provides best-practise methods for sampling and monitoring, as well as groundwater quality data interpretation. The NGMP consists of three components: operations (in collaboration with all New Zealand regional authorities), research and database. Duration: national coverage of the network was attained in 1998; research activities started in 2002. This programme is a collaboration between all regional authorities and the Tūwharetoa Māori Trust Board. It is funded as part of GNS's SSIF infrastructure programme. For more information, you can access the NGMP webpage or contact Magali Moreau (programme) or Lauren Coup (operations).

- **New Zealand Water Model (NZWaM):** This programme aims to improve national-scale simulation of surface- and groundwater processes across New Zealand using a framework designed to facilitate the coupling of hydrologic models. In this programme, our role is to contribute national-scale models of groundwater flow, groundwater age and hydraulic properties of the subsurface. We also use tools, methods and models developed in our other programmes (GW and TWOTW) to facilitate the use of surface water (TopNet) model outputs in the groundwater models (MODFLOW6) via the HydroDeskNZ framework. We are currently developing techniques for tight coupling of the TopNet surface water model with the MODFLOW6 groundwater model. Combining these models allows better representation of surface water to groundwater interactions. Case study areas include catchments located in the Gisborne, Horizons and Southland regions. This programme brings together NIWA (lead organisation), Manaaki Whenua – Landcare Research and GNS. Duration: 2016–2023. For more information, you can access the NIWA NZWaM webpage (for the full project) or the GNS NZWaM webpage or contact Wes Kitlasten for more details on the groundwater component.
- **NZ SeaRise:** The primary aim of the NZ SeaRise programme was to generate new sea-level projections at high spatial resolution for New Zealand to include the latest science from the Intergovernmental Panel on Climate Change (IPCC) Assess Report 6 and details regarding local vertical land movement. New sea-level projections can be accessed through an online tool that allows users (public and planner interface) to click on a location along the coast and see how much the sea level is expected to rise, and by when, under different climate-change scenarios. These projections are now being used to assess the potential impact of sea-level rise around New Zealand's coastal zone, including changes in groundwater inundation. NZ SeaRise was funded through the MBIE Endeavour Programme and included researchers from Victoria University of Wellington (lead organisation), GNS, NIWA and other New Zealand and international institutions. This five-year programme finished in September this year, but new work that builds on outputs and outcomes will continue through the new Our Changing Coasts Endeavour (2022–2027) | Te Ao Hurihuri; Te Ao Hou Programme. For more information, you can access the NZ SeaRise website or contact Richard Levy.
- **Lakes380**: This programme enriched the understanding of the environmental, social and cultural histories of around 10% of New Zealand's 3800 lakes (>1 ha) by collecting and analysing lake sediments and water samples, as well as conducting interviews and field visits. Lake sediments are natural archives that continuously record environmental history, providing measures of current and historical aquatic communities and water quality that is equivalent to centuries of environmental monitoring. Currently, environmental data exists for fewer than 5% of our 3800 lakes, and these datasets are typically only 20–30 years long. This programme captured up to 1000 years of lake history, contributing new knowledge to ensure that our lakes are valued and protected – now and for generations to come. It documented when and why changes occurred and established natural conditions throughout a cross-section of New Zealand lakes. It interweaves scientific data with mātauranga Māori to provide a richer understanding of the value and health of our lakes. This programme is funded through the MBIE Contestable Fund and is co-led by the Cawthron Institute. Duration: 2017–2023. For more information, you can access either the Lakes380 website; the Moana Pūrākau Kete portal, a digital storytelling portal associated with the Wairarapa case study that weaves ecological, cultural and social knowledges; or contact Marcus Vandergoes.

- **Future Coasts Aotearoa:** This programme is a collaborative NIWA-led Endeavour that aims to assess impacts of sea-level rise on coastal communities and wetlands, including the investigation of adaptation measures. GNS leads the work that provides biophysical data to the rest of the project team. The output of the GNS component will quantify, at the nationwide scale, changes in freshwater for different sea-level rise scenarios, e.g. increase in groundwater table, groundwater salinity and flooding. The sea-level rise data input feeding into this project originates from the NZ SeaRise programme (see above). Duration: 2021–2026. For more information on the groundwater component, contact Lee Chambers.

In addition to the aforementioned programmes, GNS's research is also funded from, or via, regional councils (e.g. Envirolink grants) and from programmes led by collaborators.

Our research programmes are structured into five high-level Research Questions (RQs), each of which is addressed through specific activities and relate to the current[2] national research priorities (Figure 1) of the New Zealand Groundwater Forum Special Interest Group, which represents groundwater scientists and technical staff from regional authorities. The Forum is under the umbrella of Te Uru Kahika, which is the newly formed entity that represents the collective effort of the 16 regional authorities.

For your convenience, all outputs are listed in Table 1; clicking on individual outputs or questions will take you to the relevant content.

2 Morris R, Fernandes R, Hadfield J, Thomas J, Tidswell S, Fenemor A, Robb C. 2021. Guiding groundwater resource management: Groundwater Forum Science and Technology Strategy 2021. [Lincoln] (NZ): Manaaki Whenua Landcare Research. Prepared for Groundwater Special Interest Group; [accessed 2022 Nov]. https://www.envirolink.govt.nz/assets/Guiding-groundwater-resource-management-Groundwater-Forum-RST-strategy-2021-v2.pdf

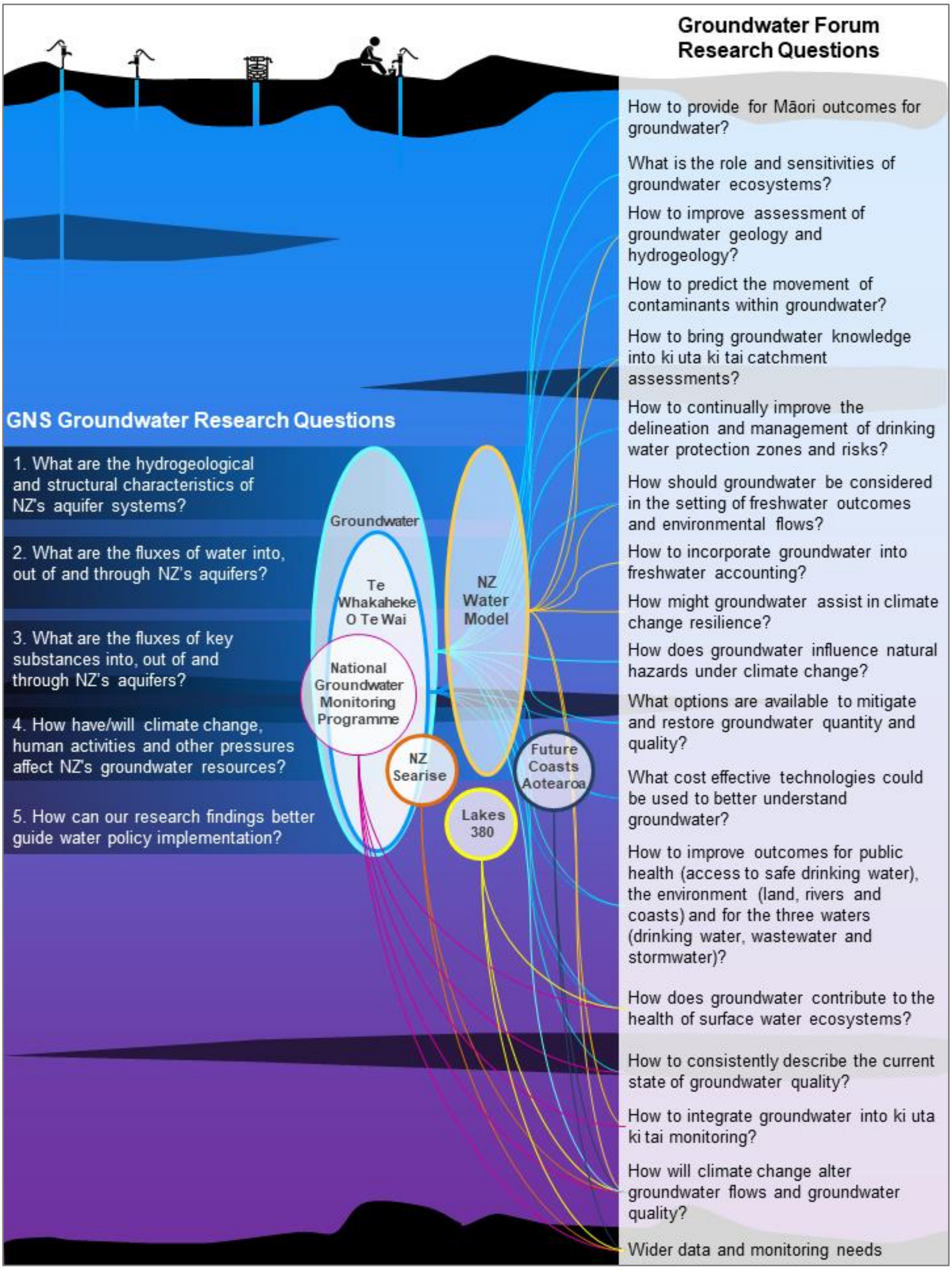

Figure 1 Schematic mapping of current GNS research programmes against research priority areas identified by the Groundwater Forum Special Interest Group in 2021. Each programme is represented by a circle; overlapping circles indicate alignment between programmes.

Table 1 GNS Groundwater Research Questions and science outputs (clicking on a question or output will take you to the relevant section in the report).

GNS Groundwater Research Questions	Research Output (November 2021 to October 2022)	Why is it Important?
1. What are the locations and properties (structural, hydrogeological and fluid) of New Zealand's aquifer systems?	1.1 Airborne Electromagnetic (AEM) data modelling in Hawke's Bay	Understanding the 3D aquifer geometry, hydraulic properties and distribution to improve freshwater management tools, such as groundwater models
	1.2 Summer of airborne-aquifer mapping begins	Same as 1.1
	1.3 3D facies modelling of the Wairau Plains	Developing a seamless, nationally consistent map and classification of New Zealand aquifers to improve water policy development and environmental reporting
	1.4 Updated New Zealand Hydrogeological-Unit Map now available	Same as 1.2
2. What are the fluxes of water into, out of and through New Zealand's aquifers?	2.1 Advanced modelling techniques	To support groundwater management
	2.2 Using tritium to understand intermittent streams	Improved understanding of catchment processes, storage and release
	2.3 Stable isotopes as a proxy for travel time and storage	Same as 2.2
	2.4 Age tracers to inform the response of the Christchurch groundwater system to exploitation	Same as 2.2
3. What are the fluxes of key substances into, out of and through New Zealand's aquifers?	3.1 National monitoring of groundwater quality	Supports characterisation of the state and trends of New Zealand groundwaters
	3.2 Hydrochemistry to infer groundwater age distribution	Same as 2.2
4. How have/will human activities, climate change and other pressures affect New Zealand's groundwater resources and receiving environments (e.g. springs, rivers and lakes)?	4.1 Potential impacts of climate change on groundwater	Informs adaptive management
	4.2 Sensitivity of microbial communities to seawater intrusion and geothermal re-injection	Maintaining groundwater ecosystem health requires knowledge on the effect of human-induced effects
	4.3 Hydrochemistry to inform groundwater restoration	Same as 3.2
	4.4 Impacts of sea-level rise on shallow coastal urban groundwater systems	Same as 4.1
	4.5 Monitoring shallow coastal urban groundwater systems	Same as 4.1

GNS Groundwater Research Questions	Research Output (November 2021 to October 2022)	Why is it Important?
5. How can our research findings better guide water policy implementation?	5.1 DNA and paleo-environmental based tools	Improved understanding of lake and ecosystem change and resilience to support lake management
	5.2 Improved use of monitoring technologies	To improve water management and policy
	5.3 Lower Waihemo / Shag River Valley case study	Same as 5.2
	5.4 Science and policy workshops	Direct exchange with stakeholders to ensure relevance and facilitate science uptake
	5.5 Workshops and outreach activities	Same as 5.4

RQ1. What are the locations and properties (structural, hydrogeological and fluid) of New Zealand's aquifer systems?

Output 1.1 Airborne Electromagnetic (AEM) data modelling in Hawke's Bay (Provincial Growth Fund, Hawke's Bay Regional Council and GW-funded)

Close to 8000 km of airborne Transient ElectroMagnetic (SkyTEM) data were collected in early 2020 over the Heretaunga and Ruataniwha plains and Poukawa and Ōtāne basins as part of the Hawke's Bay 3D Aquifer Mapping project. SkyTEM data processing and resistivity modelling has been completed for all 8000 km. To collect additional supporting datasets, a drilling programme was completed and reported in the Ruataniwha and Heretaunga plains areas. Hydrogeological interpretations and numerical groundwater model revisions are underway. The project completion date has been extended to June 2023. Contact: Zara Rawlinson.

An online ESRI StoryMap and webmap were developed as a public outreach tool to provide access to 3D datasets and reports as they become publicly available. The first and current released is dated from June 2022 and includes results from the Poukawa and Ōtāne basin surveys (Figure 2). Subsequent releases are planned for 2023 as the Heretaunga and Ruataniwha plains survey results become available. The webmap utilises online data-access developments funded by GNS since 2014 through multiple projects.

GNS is a contributor to the official Hawke's Bay Regional Council webpage for updates on the 3D aquifer mapping project. Publications are available online.

Foged N. 2022. Hawke's Bay 3D Aquifer Mapping Project: Heretaunga Plains, 3D hydrostratigraphic modelling. Aarhus (DK): Aarhus University HydroGeophysics Group. Prepared for Hawke's Bay Regional Council; [accessed 2022 Nov]. https://www.hbrc.govt.nz/assets/Document-Library/HSM-Report-Heretaunga-June2022-HBRC-Cover.pdf

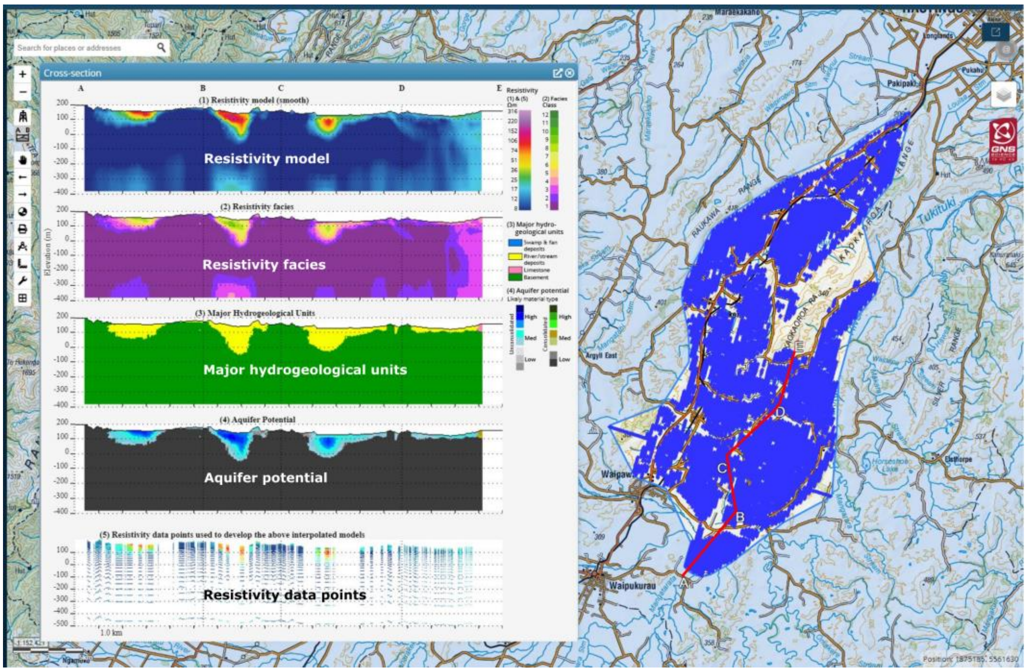

Figure 2 Example screenshot from the embedded webmap showing a cross-section through the Poukawa and Ōtāne basin 3D models. The cross-section shows the resistivity model and derived geophysical and hydrogeological interpretations.

Output 1.2 Summer of airborne-aquifer mapping begins (Provincial Growth Fund)

The summer of skyTEM aquifer mapping work has begun and will take place in different parts of the country. The Northland survey was completed in mid-November and the Southland survey is now underway. These aerial surveys are just one component of data collection, and it will take time for our scientists to interpret and analyse the raw data, but the ultimate aim is to provide the information in a useful format for councils, tangata whenua and the community. The next step for this programme is skyTEM mapping in Gisborne in February. As part of this programme, initiatives to collect complementary datasets, such as high flow harvesting, surface-water flow monitoring and groundwater drilling, are being explored. This mapping is undertaken as part of Aqua Intel Aotearoa (AIA), a partnership between Kānoa (the delivery arm of the Provincial Growth Fund) and GNS. It is a national science platform on regional water availability and storage and complements our GW programme. Contact: info@aquaintel.co.nz.

Output 1.3 3D facies modelling of the Wairau Plains (GW-funded)

Identification of aquifer characteristics continues with development of methods to model, in 3D, geological facies and their properties. Methods for facies identification utilise Boolean operators on well log descriptions, following White et al. (2021). Currently, this approach is showing promise. For example, in Figure 3, the new facies model of the Wairau Plains indicates that aquifers (H1, P1 and P2?) have two marine incursions near the current coastline (MI1 and MI2). Contact: Paul White.

White PA, Crundwell MP, Davidson P. 2021. Three-dimensional model of sedimentary facies in the lower Wairau Plain: new insights into Holocene coastal aquifer development. In: *60th Annual Conference: NZHS 2021: oral abstracts*; 2021 Nov 30 – Dec 3; Te Whanganui a Tara / Wellington, Aotearoa New Zealand. Wellington (NZ): New Zealand Hydrological Society. p. 214–215.

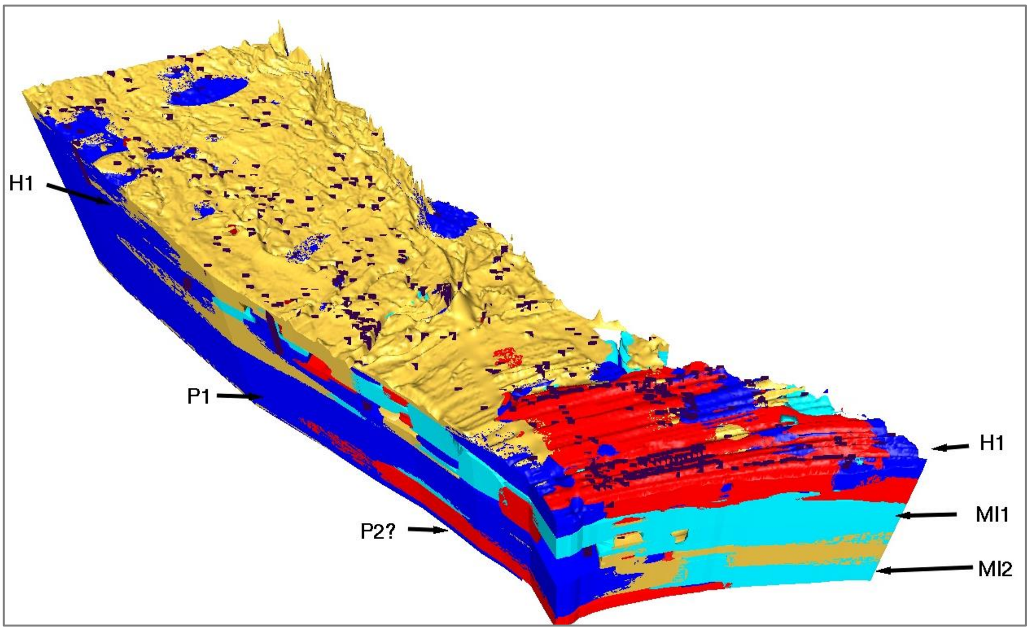

Figure 3 New facies model of the northern Wairau Plains, to a depth of 60 m below sea level. The model shows locations of Holocene aquifers (i.e., terrestrial gravels and beach gravels in royal blue and red), terrestrial sediments (ochre) and shallow marine/estuarine sediments (teal). The location of the well log data used in this analysis are shown in black.

Output 1.4 Updated New Zealand Hydrogeological-Unit Map now available (GW-funded)

The New Zealand Hydrogeological-Unit Map (HUM) is a GIS dataset (overlapping, stacked polygons) that represent hydrogeological units (i.e. aquifers, aquitards, aquicludes and basement) developed in a nationally consistent manner. The HUM framework is a long-term programme to map our aquifers in 3D, currently through facies mapping. Geological and depositional facies are a key component of this mapping, as they enable connection of their spatial distribution with hydraulic properties. Surface facies are propagated in the sub-surface using the HUM units. This mapping is used in conjunction with facies 3D modelling and will be sequenced using the New Zealand hydrogeological systems from the coastal to inland to basement systems.

Geological and depositional facies are now available for the first time in the North Island's coastal systems as part of the 2022 New Zealand Hydrogeological-Unit Map. This version features increased consistency with QMAP and the hydrogeological systems and the current status of facies mapping. Modifications to the previous version include creation and removal of HUM units, revised sub-surface extents to reflect regional geology and new attributes to accommodate facies model information (Figure 4). Further releases are pending as mapping progresses in other hydrogeological systems. Contact: Stew Cameron.

Moreau M, White P, Udawatta N, Strogen D, Crundwell M, Cameron S, Chambers L, Mourot F, Santamaria E, Tschritter C. Forthcoming 2022. Building New Zealand's 3D aquifer map: facies mapped at the national scale for coastal systems. In: *NZHS MSNZ 2022 Joint Conference 2022*; 2022 Dec 6–9, Dunedin, New Zealand.

White PA, Moreau M, Mourot F, Rawlinson ZJ. 2019. New Zealand Groundwater Atlas: hydrogeological-unit map of New Zealand. Lower Hutt (NZ): GNS Science. 96 p. Consultancy Report 2019/144. Revised November 2022.

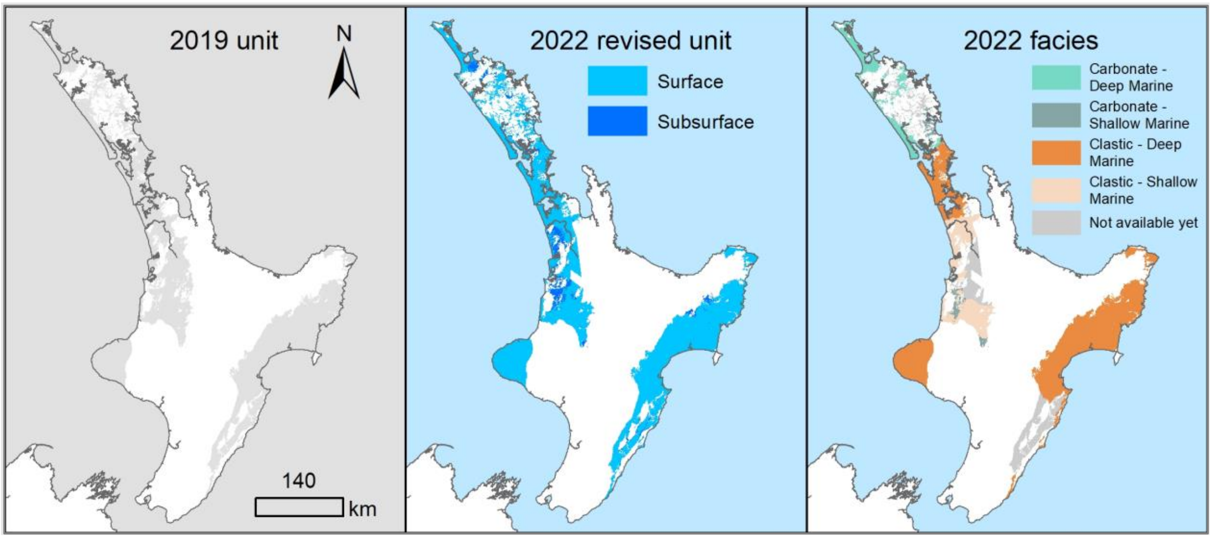

Figure 4 Comparison of the 'Oligocene_NI_sediments' HUM unit extent between the 2019 (left) and 2022 datasets (middle), and the new facies attribute in the 2022 dataset (right).

RQ2. What are the fluxes of water into, out of and through New Zealand's aquifers?

Output 2.1 Advanced modelling techniques (TWOTW and GW co-funded)

This output also addresses RQs 3, 4 and 5 and builds on the findings of the Smart Models for the Aquifer Management programme (SAM).

2.1.1 Theoretical exploration and numerical techniques implementation

Rapid transmission of contaminants in groundwater can occur in alluvial gravel aquifers via highly conductive small-scale Open Framework Gravels (OFGs). The OFG structure is complex, so assessments of contamination risks in these aquifers are highly uncertain. Geostatistical models, based on lithological data, can be used to quantitatively characterise this structure. These models can support analysis of the risks of contamination in groundwater systems. Geostatistical model uncertainty can be reduced by assimilating information from hydraulic system response data but is computationally challenging. We developed a method (Transition Probability) to address these challenges. The results demonstrate that the common modelling practice of adopting a single geostatistical model may result in realistic predictions being overlooked and significantly under-estimate the uncertainties of groundwater transport predictions. The work highlights the need to explore the uncertainty of geostatistical models in the context of the predictions being made. Contact: Catherine Moore.

Moore C, Scott D, Burbery L, Close M. 2022. Using sequential conditioning to explore uncertainties in geostatistical characterization and in groundwater transport predictions. *Frontiers in Earth Science*. 10. doi:10.3389/feart.2022.979823.

The paper by Johnson et al. (2022) explores the impact of common model boundary condition assumptions on the uncertainty of key geothermal model predictions. This is a key issue for robustly assessing the risks of managing both geothermal and groundwater systems. The findings are an important step along the path of implementing appropriate model boundary conditions between the geothermal and groundwater systems. Contact: Catherine Moore.

Johnson PJ, Stauffer PH, Omagbon J, Moore CR. 2022. Implications of rootless geothermal models: missing processes, parameter compensation, and imposter convection. *Geothermics*. 102:102391. doi:10.1016/j.geothermics.2022.102391.

2.1.2 Developing modelling capability

Our groundwater modelling team continues to develop capability in the modelling community through project partnering. These projects aim to enhance technical capability and provide guidance for modellers and decision-makers. They include contributions to the development of international industry-standard groundwater modelling tools and next-generation model construction and deployment software. The software developed are primarily platform-independent and either contribute to existing open-source libraries or exist as stand-alone, open-source tools. These tools are designed for specialist numerical modellers to support model construction, rapid and re-producible uncertainty quantification and data assimilation. They facilitate more effective model-based decision support for GNS's groundwater and geothermal numerical modelling activities. The following outputs were delivered this year:

- Participation to a series of webinars and workshops on decision-support modelling viewed through the lens of model complexity. These workshops were linked to a recent co-authored, open-source monograph 'Groundwater Modelling for Decision Support

Initiative' (gmdsi.org) on this theme. The report builds on work from the SAM programme, funded by MBIE (grant no. C05X1508).

Doherty J, Moore C. 2021. Decision support modelling viewed through the lens of model complexity. Adelaide (AU): Flinders University, National Centre for Groundwater Research and Training. 77 p. (GMDSI monograph). doi:10.2597/p25g-0f58.

- Ongoing refinements to the rapid-writing tool for the MODFLOW/MT3D surface-water routing packages (most recently the SWN package). The latest addition is the Python package 'gridit', which facilitates rapid re-sampling of spatial data to groundwater models, was released. This tool is much faster than existing tools and allows modellers to quickly explore the implications of spatial input data and grid resolution on numerical groundwater models. It is downloadable from this GitHub site. Contact: Mike Taves.
- Contributions and enhancements to the model-independent pyEMU Python suite, including faster calculations of factors for geostatistical interpolation and improved techniques for construction of model-independent PEST interface files. Find out more about these modules from this GitHub site. Contact: Brioch Hemmings.

2.1.3 Application of advanced decision-support modelling

The aforementioned tools have been applied to:

- The national-scale New Zealand groundwater model, which is used to simulate groundwater age across New Zealand as part of the TWOTW research programme (Figure 5). This groundwater model is also being incorporated into the NZWaM model to inform groundwater contributions to surface water. This MODFLOW6-based model can be used as an advanced model to specifically simulate the groundwater system or to inform and parameterise the simplified representation of groundwater in TopNet-GW. Contact: Wes Kitlasten.
- Local-scale models are being used to support joint enquiry processes that incorporate groundwater and surface-water mātauranga. Contact: Catherine Moore.
- Source protection zone delineation, including providing robust descriptions of underpinning aquifer heterogeneity. This work has also been extended to work on recently released delineation guidelines with Aqualinc and the development of a microbial risk assessment tool for discharges near drinking water wells with ESR. Contact: Catherine Moore.

Rutter H, Moore C. 2021. Guidelines for modelling source water risk management areas. Christchurch (NZ): Aqualinc Research Limited. 48 p. Prepared for the Ministry for the Environment; [accessed 2022 Nov]. https://environment.govt.nz/assets/publications/guidelines-for-modelling-source-water-risk-management-areas.pdf

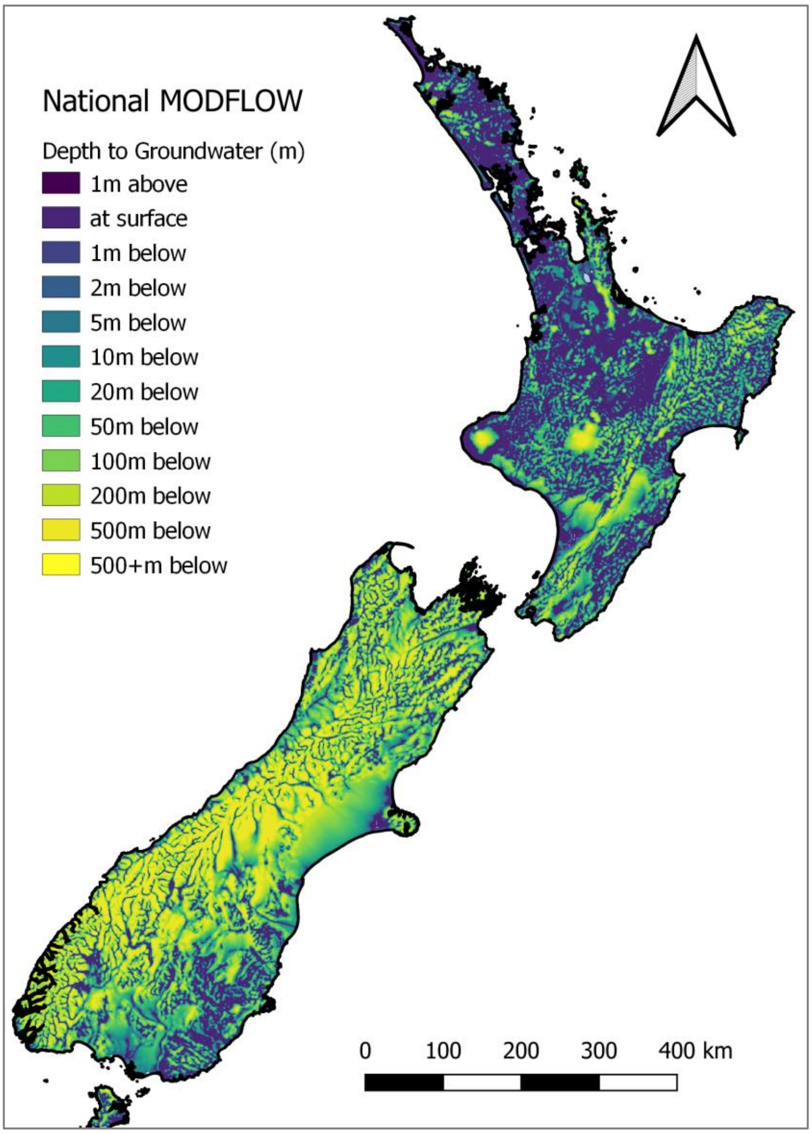

Figure 5 Depth to groundwater as simulated by the national-scale MODFLOW6 model of New Zealand, used to simulate groundwater age (TWOTW) and characterise the representation of groundwater in the NZWaM project.

Output 2.2 Using tritium to understand intermittent streams (GW-funded)

In a Monash-University-funded project, we used tritium water dating to understand river functioning of intermittent streams. Such streams are not well understood but important for managing headwater catchments. Mean transit times (MTTs) of intermittent stream flows in headwater catchments from a semi-arid area in southeast Australia varied between years and decades and varied between catchments. Regional groundwater close to the stream with a residence time of several hundred years dominated in one catchment, whereas younger water stored in the riparian zone was the main source in the other catchments. The differences in MTTs between the catchments may reflect land-use differences. Overall, due to being less-well connected to the regional groundwater, the MTTs of these intermittent streams are far shorter than those for perennial headwater streams in southeast Australia, indicating that they are vulnerable to short-term variations in rainfall. Contact: Uwe Morgenstern.

Barua S, Cartwright I, Dresel PE, Morgenstern U, McDonnell JJ, Daly E. 2022. Sources and mean transit times of intermittent streamflow in semi-arid headwater catchments. *Journal of Hydrology*. 604:127208. doi:10.1016/j.jhydrol.2021.127208.

Output 2.3 Stable isotopes as a proxy for travel time and storage (GW-funded)

The combined use of deuterium and tritium to determine Travel Time Distributions (TTDs) in streams is an important development in catchment hydrology (Rodriguez et al. 2021[3]). A recent comment by GNS co-authors takes issue with Rodriguez et al.'s assertion that the truncation hypothesis may not hold for catchments in general; specifically, that the use of stable isotopes alone may not lead to under-estimation of travel times or storage compared to tritium. In this comment by Stewart et al. (2021), the authors discuss reasons why the truncation hypothesis could still apply to the majority of catchments despite not appearing to hold for the catchment studied by Rodriguez et al. (2021). They also discuss more generally future applications of tritium in Northern and Southern Hemisphere catchments. Contact: Mike Stewart.

Stewart MK, Morgenstern U, Cartwright I. 2021. Comment on "A comparison of catchment travel times and storage deduced from deuterium and tritium tracers using StorAge Selection functions" by Rodriguez et al. (2021). *Hydrology and Earth System Sciences*. 25(12):6333–6338. doi:10.5194/hess-25-6333-2021.

Output 2.4 Age tracers to inform the response of the Christchurch groundwater system to exploitation (GW-funded)

The Christchurch groundwater system is an exceptional water resource with very high drinking-water quality, supplying all of the water requirements of the city. Using ^{14}C and ^{3}H dating, we demonstrated changes in the groundwater system over the years because of increasing groundwater abstraction due to increasing population and development. The new data revealed slightly older ^{14}C ages and increasingly steep west–east age gradients compared to the earlier work from 1976 to 2006, showing continued upflow of deep water into the exploited aquifers that is much older on the east (coastal) side than on the west (inland) side. In addition, the ^{3}H ages for wells on the west side of the system are often much younger than their ^{14}C ages, showing that there is input of young shallow water to the wells in addition to the deep water input, with the young component becoming younger, although smaller, as a proportion of the flow, and the old component from depth becoming larger. In the future, slowly increasing chemical input to the Christchurch aquifers on the west side of the system is to be expected as abstraction from the old deep groundwater increases, which, on the western side of the Christchurch system, is derived from rainfall recharge on the developing Ashley-Waimakariri Plains. Contact: Mike Stewart.

Stewart MK, van der Raaij RW. 2022. Response of the Christchurch groundwater system to exploitation: carbon-14 and tritium study revisited. *Science of The Total Environment*. 817:152730. doi:10.1016/j.scitotenv.2021.152730.

3 Rodriguez NB, Pfister L, Zehe E, Klaus J. 2021. A comparison of catchment travel times and storage deduced from deuterium and tritium tracers using StorAge Selection functions. *Hydrology and Earth System Sciences*. 25(1):401–428. doi:10.5194/hess-25-401-2021.

RQ3. What are the fluxes of key substances into, out of and through New Zealand's aquifers?

Output 3.1 National monitoring of groundwater quality (NGMP-funded)

Quarterly groundwater samples were collected and analysed for major ion and dissolved metals at 107 sites this year (Figure 6). Groundwater quality data collected as part of NGMP can be accessed through the Geothermal and Groundwater Database.

Geothermal and Groundwater Database. 2005–. Release 3.2.5. Lower Hutt (NZ): GNS Science; [updated 2022 Jun 21; accessed 2022 Oct]. https://ggw.gns.cri.nz/ggwdata/

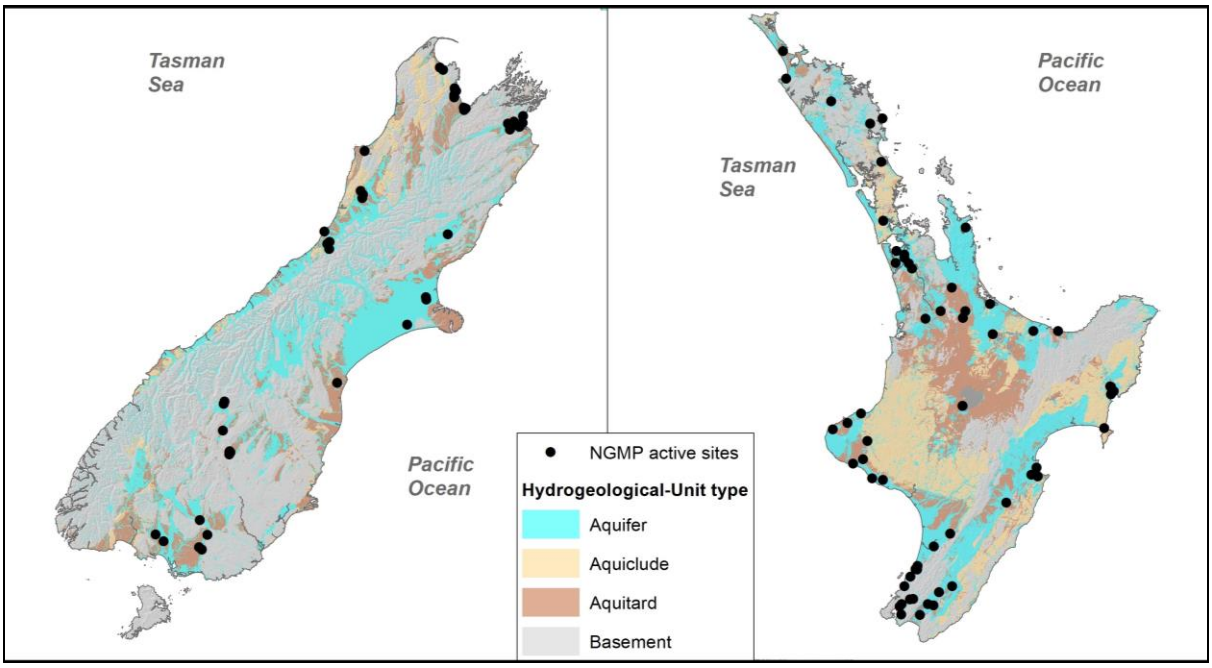

Figure 6 NGMP site locations relative to New Zealand hydrogeological units. Data source: Hydrogeological-unit Map, Ministry for the Environment web portal.

3.1.1 Quarterly samples and data curation

Work has commenced to make laboratory analysis transcripts for NGMP samples publicly accessible. Transcripts in PDF format are now archived and are available upon request. Upload of the transcripts onto the database will be scheduled next year. This change will contribute to the transparency of our environmental data. To access these records directly from the web interface will require some back-end modification of the Geothermal and Groundwater Database, scheduled for next year due to staff movements. Our Sensor-Observation-Service (52° North) remains available.

3.1.2 Research activities

An update on the age interpretation at all NGMP sites has now been completed. Water dating is undertaken as part of NGMP, with irregular sampling due to the nature of the tracers. The first national overview was achieved in 2009 and repeat sampling has been undertaken to investigate possible change with time or to refine interpretation. This update represents a significant amount of work behind the scenes and is the result of strategic sampling alignment between programmes. The revised age interpretation has been uploaded onto our database and is used to re-visit the relationship between age and chemistry. Contact: Magali Moreau.

3.1.3 First results from the groundwater ecosystem monitoring network (GW, NGMP co-funded)

This recently developed project will characterise microbial communities in groundwater, and the range of ecological functions that they can carry out, as an indicator of ecosystem health. Over the long-term, this information will be used to develop a microbial community health index linked to groundwater quality. Samples are currently collected as part of NGMP and State of the Environment (SOE) monitoring, analysed for groundwater chemistry and microbial analysis (taxonomic and metagenomic sequencing to identify potential functions). The analytical results, taxonomic classification and metagenomic predictions of the first 40 groundwater samples collected nationwide are now available. Sequencing of DNA extracted from these samples confirmed high microbial diversity with microbial communities capable of ecosystem services, including denitrification. Contact: Karen Houghton.

Houghton KM, Santamaria Cerrutti ME. In press. Groundwater ecosystem monitoring: microbial diversity and function, annual report 2022. Lower Hutt (NZ): GNS Science. (GNS Science report; 2022/54). doi:10.21420/E0ZE-N191.

Output 3.2 Hydrochemistry to infer groundwater age distribution (TWOTW-funded)

Groundwater age or residence time is important for identifying flow and contaminant pathways through groundwater systems; however, there usually are a lot more groundwater chemistry data available than groundwater age-tracer data. For the first time, two meta-modelling methods were tested to derive groundwater age distributions from hydrochemistry. We selected the Symbolic Regression (SR) and Gradient-Boosted Regression (GBR) techniques based on the amount of available data, ease of use and adaptability and/or proven potential in similar research. Both methods generally work well for predicting groundwater age distributions from hydrochemistry and can be used to assist with the interpretation of lumped parameter models where age tracers have been sampled. They can also be applied to predict groundwater age distributions for wells that have hydrochemistry data available but no age-tracer data. This output is a collaboration between GNS and NIWA. Contact: Conny Tschritter.

Tschritter C, Daughney CJ, Karalliyadda S, Hemmings B, Morgenstern U, Moore C. 2022. Estimation of groundwater age distributions from hydrochemistry: comparison of two metamodelling algorithms in the Heretaunga Plains aquifer system, New Zealand [preprint]. *Hydrogeology and Earth System Sciences*; [accessed 2022 Nov]. doi:10.5194/hess-2022-258.

RQ4. How have/will human activities, climate change and other pressures affect New Zealand's groundwater resources and receiving environments (e.g. springs, rivers and lakes)?

Output 4.1 Potential impacts of climate change on groundwater

A methodology was developed to assess the climate-change impacts on rainfall recharge to groundwater. This methodology provides mean seasonal and annual values of net infiltration, rainfall recharge and water table elevation under multiple climate-change scenarios. It uses available national datasets and models and regional climate data (Figure 7). This methodology was applied to two regional studies with contrasting landscapes, climate and hydrogeology (Otago and Hawke's Bay). The results highlighted strong local and seasonal variations in rainfall recharge patterns and water table elevation in both regions. This methodology can be applied in other New Zealand regions and is expected to support the initiation of adaptation actions. It is now available as an open-access publication.

The publication includes a literature review of groundwater and climate-change issues and challenges. It also discusses uncertainties and difficulties to untangle climate change and land-use effects and climate-change adaptation. Contact: Frederika Mourot.

Mourot FM, Westerhoff RS, White PA, Cameron SG. 2022. Climate change and New Zealand's groundwater resources: a methodology to support adaptation. *Journal of Hydrology: Regional Studies*. 40:101053. doi:10.1016/j.ejrh.2022.101053.

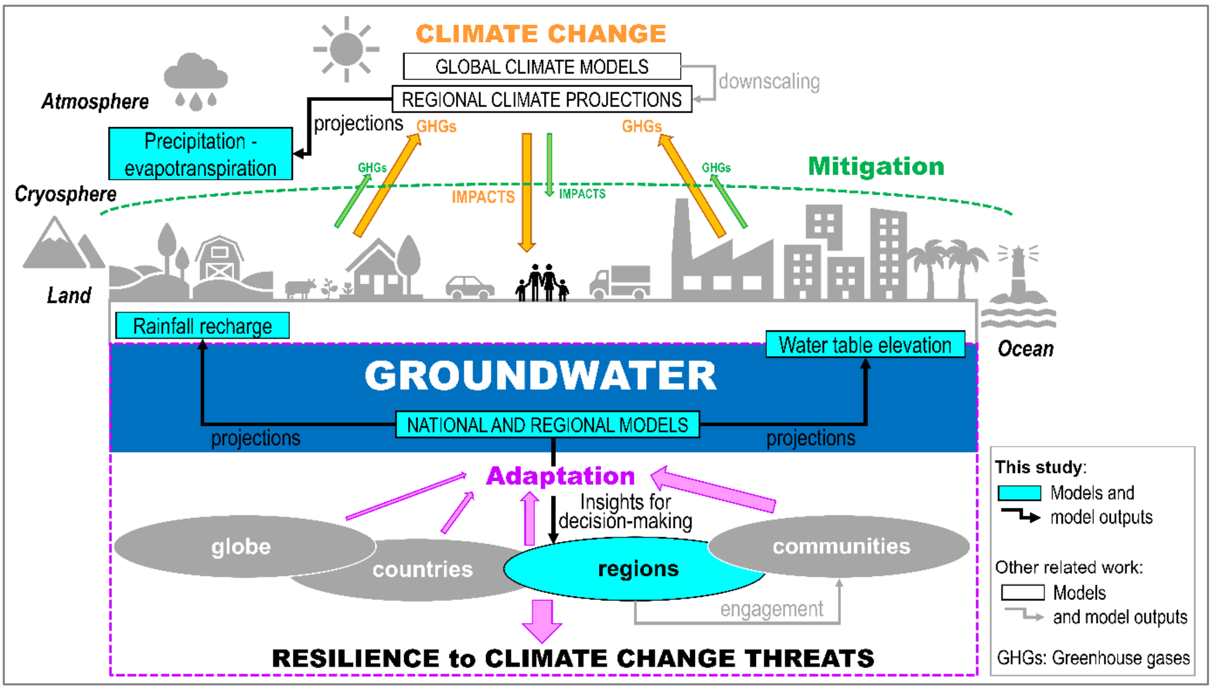

Figure 7 Methodology to assess the potential impacts of climate change on New Zealand's groundwater resources and develop adaptation actions (Mourot et al. 2022).

Output 4.2 Sensitivity of microbial communities to seawater intrusion and geothermal re-injection (Global Change through Time SSIF-funded)

Two studies examining the impact of groundwater pressures on microbial communities are now available: a pilot study on the effect of seawater intrusion and another on the effects of geothermal re-injection. The seawater intrusion study used a combination of culture-dependent (growth curves, isolation of bacteria) and culture-independent (marker gene sequencing, functional gene quantification) methods to identify the potential effects of saltwater intrusion on groundwater microbes and their functions. Some groundwater microbial communities were negatively impacted by increasing chloride concentrations, including declines in bacteria responsible for nitrate and ammonia removal. Identification of keystone species affected by saltwater in these ecosystems will enable management decisions to be made about future abstraction limits or if defences against sea-level rise are needed. The assessment of the effect of geothermal re-injection on groundwater microbial communities highlighted the need to monitor bathing water for the presence of micro-organisms, which may be pathogenic or induce chemical changes to the receiving environment, and provided recommendations for treatment options. Contact: Karen Houghton.

Houghton KM, Fournier M, Tschritter C. 2022. Effects of saltwater intrusion on groundwater microbial community diversity. Lower Hutt (NZ): GNS Science. 45 p. (GNS Science report; 2021/39). doi:10.21420/HDB3-FJ35.

Sajkowski L, Houghton KM, Mountain BW, Burnell JG. 2022. Effects of reinjecting diluted mineral pool water into the Rotorua Geothermal System. Wairakei (NZ): GNS Science. 60 p. Consultancy Report 2022/18. Prepared for Bay of Plenty Regional Council.

Output 4.3 Hydrochemistry to inform groundwater restoration

To support the restoration programme of the Te Hoiere / Pelorus catchment (Marlborough), we interpreted previous baseline data to provide detailed understanding of the catchment functioning. The current environmental quality of the catchment is good but deteriorating. This is evident in some of the sub-catchments, where water quality is degrading. Marlborough District Council, Ngāti Kuia, the Department of Conservation and the wider community are part of the way through the restoration programme in the Te Hoiere / Pelorus catchment, with the aim to holistically manage the entire catchment from the mountains to the sea (ki uta ki tai). TWOTW provides the understanding of the flow of groundwater and associated contaminants (nitrate) through the catchment. Similar projects have already provided important insights into the groundwater and surface-water flow systems in other New Zealand catchments. Contact: Uwe Morgenstern.

Morgenstern U, Davidson P. 2022. Groundwater tracers for improved understanding of water and nitrate flow through Te Hoiere / Pelorus Catchment to inform decision making in restoration programme. Lower Hutt (NZ): GNS Science. 21 p. (GNS Science report; 2022/50). doi:10.21420/937F-H779.

Output 4.4 Impacts of sea-level rise on shallow coastal urban groundwater systems (SeaRise-funded)

The spatial and temporal likelihoods of groundwater inundation have been estimated on the basis of the IPCC sea-rise projections. This required the development of a Bayesian modelling workflow, incorporating both history matching and uncertainty quantification. The outputs of this work include spatial and temporal predictions of groundwater-level rise and their likelihoods, but also a graphical user interface, designed for Otago Regional Council, to improve the communication of these complex modelling results to stakeholders and decision-makers. This enhances not only the understanding of the likely impacts, but also allows further questions to be explored and decisions to be made around adapting to climate-change-induced sea-rise impacts on groundwater. Contact: Lee Chambers.

Chambers L, Hemmings B, Moore C, Cox S, Levy R, Knowling M. 2022. Decision-support modelling for an uncertain future: developing forecasts of sea level rise impacts on groundwater [abstract]. In: *EGU General Assembly 2022*; 2022 May 23–27; Vienna, Austria. Göttingen (DE): European Geosciences Union. EGU22-10747. doi:10.5194/egusphere-egu22-10747.

Output 4.5 Monitoring shallow coastal urban groundwater systems (GW, SeaRise and STRAND Marsden co-funded)

To understand the behaviour of groundwater in urban areas, we continue to maintain a monitoring network and collect data on shallow groundwater in South Dunedin in a partnership with Otago Regional Council. Recent work has focused on QA/QC of monitoring data and updating the groundwater surfaces and geometric models with recent observations. In July 2022, two rainfall events of >90 mm were just below the threshold of intensity to cause flooding (Figure 8). These records now provide a valuable reference for modelling how groundwater influences surface ponding and flooding.

Find out more about the STRAND project here. This project continues to involve multiple outreach and stakeholder interactions in South Dunedin, including Dunedin City Council. Our contributions include peer review of the programme, input into the hazards planning, installing new transducers in piezometers in the network, logging and dating drill-core, providing recommendations into the design of an urban stormwater monitoring network and helping with future scenario planning.

Cox SC, Ettema MHJ, Mager SM, Glassey PJ, Hornblow S, Yeo S. 2020. Dunedin groundwater monitoring and spatial observations. Lower Hutt (NZ): GNS Science. 86 p. (GNS Science report; 2020/11). doi:10.21420/AVAJ-EE81.

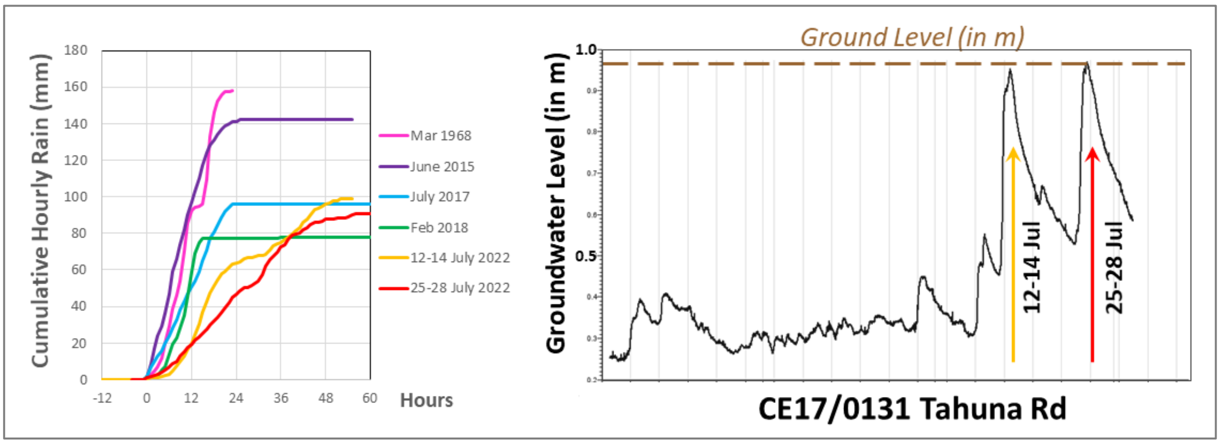

Figure 8 Methodology to assess the potential impacts of climate change on New Zealand's groundwater resources and to develop adaptation actions.

RQ5. How can our research findings better guide water policy implementation?

Output 5.1 DNA and paleo-environmental based tools

A new, robust DNA-based tool provides a rapid and cost-effective method that will allow a greater number of lakes to be monitored and more effectively managed in New Zealand and globally. This tool uses eDNA analysis of sediment bacteria to determine the Trophic Level Index (TLI) of the lake, using a one-off measurement (or model prediction) to give understanding of the current lake TLI. Combined with sediment trap monitoring, this could be used to detect early improvement. Contact: Marcus Vandergoes.

Pearman JK, Wood SA, Vandergoes MJ, Atalah J, Waters S, Adamson J, Thomson-Laing G, Thompson L, Howarth JD, Hamilton DP, et al. 2022. A bacterial index to estimate lake trophic level: national scale validation. *Science of The Total Environment*. 812:152385. doi:10.1016/j.scitotenv.2021.152385.

Output 5.2 Improved use of monitoring technologies (Our Land and Water National Science Challenge)

The New Zealand government has prescribed freshwater restoration actions (wetland restoration, riparian planting, etc.) in their national freshwater management legislation. However, efforts to monitor the effectiveness of these restorations are limited. We explored barriers and solutions to better understand what is needed for successful integration of innovative monitoring technologies into user practices. Expert surveys in our study revealed that interpretation of what 'success of freshwater restoration' means differs among groups. Expert scenario testing revealed that, rather than further innovations in technology, change in the practice of environmental monitoring is limited by the development of defensible and accepted guidelines on the application and effective deployment of existing sensors and methods. Our project initiated the development of a comprehensive dictionary of monitoring technologies to assess freshwater restoration. Contact: Rogier Westerhoff.

Westerhoff R, McDowell R, Brasington J, Hamer M, Muraoka K, Alavi M, Muirhead R, Lovett A, Ruru I, Miller B, et al. 2022. Towards implementation of robust monitoring technologies alongside freshwater improvement policy in Aotearoa New Zealand. *Environmental Science & Policy*. 132:1–12. doi:10.1016/j.envsci.2022.01.020.

Output 5.3 Lower Waihemo / Shag River Valley case study (Envirolink-funded)

A review of a series of groundwater investigations initiated in the Lower Waihemo / Shag River Valley in 2017 was undertaken by Otago Regional Council to inform local freshwater management. Groundwater and surface water quantity and quality data indicate high spatial heterogeneity in this aquifer, with highly connected areas within clean alluvial sediments (mean residence time of up to two years) contrasting with less-connected parts associated with older, weathered alluvial sediments (mean residence time up to 20 years). High-frequency nitrate monitoring data demonstrate the influence of seasonal rainfall. For instance, high-rainfall events can cause nitrate pulses in groundwater (Figure 9), which can lead to increased river nitrate concentrations (and loads) where groundwater is discharged to the iver (e.g. upstream Shakey Bridge). This information can be used to review future monitoring, assist with refining aquifer delineation and increase understanding of nitrogen dynamics to ensure the sustainable management of the freshwater resources of the Lower Waihemo / Shag River Valley. Contact: Frederika Mourot.

Mourot F, Moreau M, Herpe M, Coble MA. In press. Synthesis of the groundwater investigations in the Lower Waihemo / Shag River Valley. Wairakei (NZ): GNS Science. Consultancy Report 2022/91. Prepared for the Ministry of Business, Innovation & Employment.

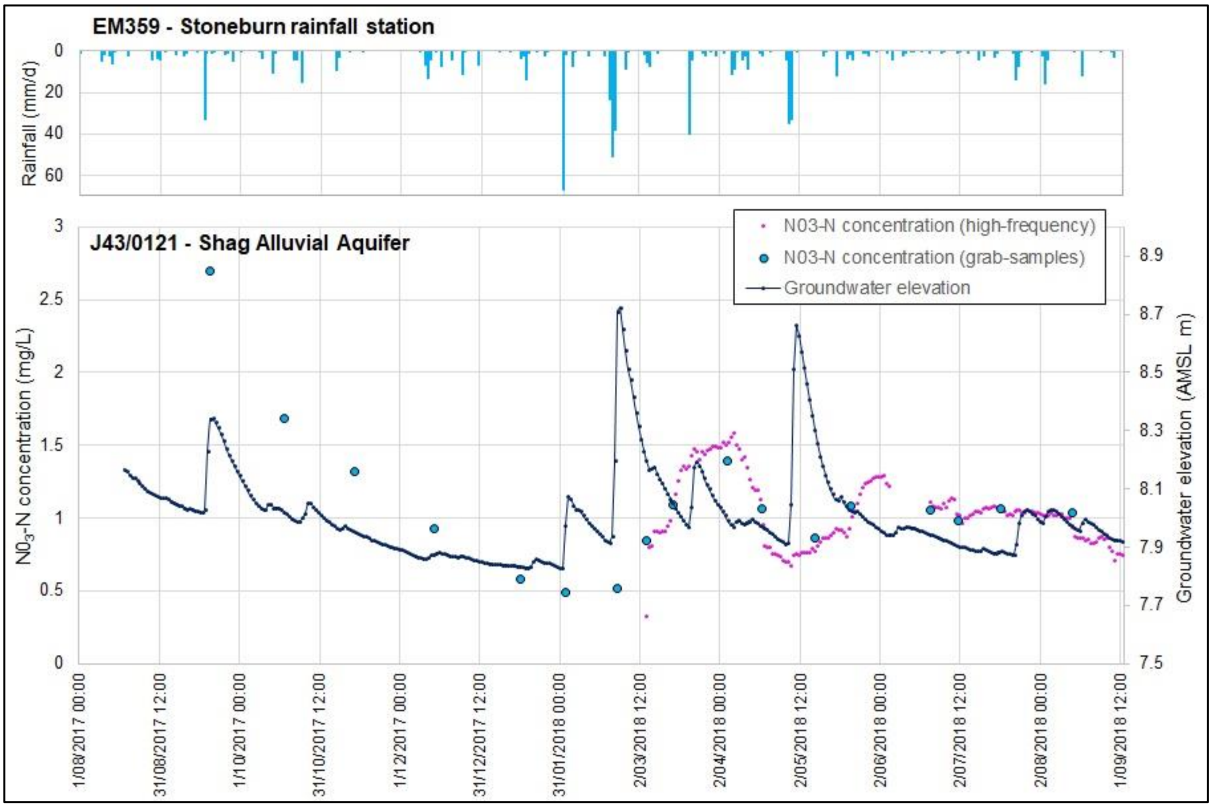

Figure 9 High-frequency nitrate sensing at bore J41/0121 (February–October 2018) in relation to groundwater levels at the same bore and rainfall at Stoneburn station (EM359). Missing nitrate data is due to sensor post-cleaning issues.

Output 5.4 Science and policy workshops (GW-funded)

To progress understanding of the groundwater science-policy nexus, a series of free workshops were provided as part of the GW programme. Four 2-hour video workshops were held in August 2022 to address four topics: (1) groundwater and the law; (2) records on engagement; (3) methods of iwi engagement (‘kaitiaki flow’ research and application) and (4) water budgets and groundwater allocation. These workshops were aimed at resource managers, policy-makers and researchers. Speakers included: Trevor Daya-Winterbottom (Associate Professor / Deputy Dean Te Piringa – Faulcty of Law, Waikato University); Pierre Glynn (Affilitated Scholar with Arizona State University and Scientist Emeritus Science and Decisions Center, USGS); Paul White and Frederika Mourot (GNS); and Te Rangikaheke Bidois, Kahuariki Hancock and Lee-Anne Rangimarie Bidois (Ngāti Rangiwewehi). This series attracted over 30 attendees per session from a wide audience (central and regional government, universities, CRIs, consultancies). The recordings are currently being edited and will be made available soon.

A fifth workshop will be held on 5 December 2022 (i.e. the day before the NZHS/MSNZ conference) in Dunedin. This workshop will cover three topics: climate-change adaption, water accounting and records of engagement. All are welcome to attend, and the workshop is free – to register, please contact Paul White.

Output 5.5 Workshops and outreach activities

Table 2 summarises the workshops and outreach activities to which we contributed this year.

Table 2 Knowledge transfer activities for the November 2021 to November 2022 period.

Event Type	Event Name, Organisation and Date	Event Description
Workshop *This relates to TWOTW and GW*	Groundwater Modelling Decision Support Initiative (November 21 to March 22)	• For regulators to lead an overhaul of the Groundwater Modelling Guidelines that are used in Australia and New Zealand. A report summarising the main themes of these workshops can be downloaded here.
Webinar *This relates to TWOTW and GW*	Scripted modelling workflows versus GUIs (August 3) Groundwater modelling for regulators (August 18)	• Webinars managed by the National Centre for Groundwater Research and Training (NCGRT) and administered by Flinders University.
Workshop	TWOTW Science Advisory Panel (February 22)	• Eight panel members from across regional councils, national science challenges, universities and iwi organisations provided lively and stimulating feedback to help shape the remaining stages of the programme.
Lecture *This relates to NGMP and GW*	Online Lecture (University of Canterbury – May 13)	• Invited lecture on state and trends in groundwater quality, including a groundwater-quality monitoring design practical as part of Canterbury's graduate Advanced Water Resources course.
Interviews *These relate to TWOTW*	Water underground talks	• Ocean Mercier (Victoria University of Wellington head of Māori studies and research supervisor of Amber Aranui in the TWOTW programme) discussed merging mātauranga-a-iwi/hapū with western science for better conceptual understanding with Tom Gleeson, who is an internationally well-known hydrologist. The interview can be viewed here.
Workshops *These relate to GW*	Groundwater Science and Policy Workshops (online): 1. Groundwater and Law (16/08/2022) 2. Records on engagement (18/08/2022) 3. Kaitiaki Flows: methods of iwi engagement (23/08/2022) 4. Water budgets and groundwater allocation (25/08/2022)	• This series of workshops tackled multiples facets of science to policy and is detailed in Section 5.4. • The series attracted over 30 attendees per session from a wide audience (central and regional government; universities; CRIs; consultancies).

Event Type	Event Name, Organisation and Date	Event Description
Multi-platform engagement with regional, district and city authorities *These relate to SeaRise, GW and STRAND*	NZ SeaRise South Dunedin case study – August 2021 to November 2022	• South Dunedin Community Hui to provide updates on research. These typically involved round-table conversations with the community about groundwater, plus off-record conversations with the Dunedin City Mayor and Otago regional councillors (11/08/2021, 1/06/2022, 9/11/2022). The significance of this work to the future of Dunedin City was noted in the 13/07/2022 editorial of the Otago Daily Times. • Simon Cox delivered a talk on groundwater-related hazards to about 100 people at a South Dunedin rate-payers meeting (26/11/2022). • Two lectures ('The geology and present hazard issues of South Dunedin' and 'Sea level rise, evolution of hazards and the future of South Dunedin') delivered for the U3A (University of the 3rd Age, 75 in attendance on 09/09/2022) as part of their 'A sustainable Dunedin' course.