8.4 Groundwater depletion

Author, affiliation: Channa Rajanayaka (NIWA)

Citation for this chapter: Rajanayaka, C. (2024). Groundwater depletion. *In:* Lohrer, D., et al. *Information Stocktakes of Fifty-Five Environmental Attributes across Air, Soil, Terrestrial, Freshwater, Estuaries and Coastal Waters Domains*. Prepared by NIWA, Manaaki Whenua Landare Research, Cawthron Institute, and Environet Limited for the Ministry for the Environment. NIWA report no. 2024216HN (project MFE24203, June 2024). [https://environment.govt.nz/publications/information-stocktakes-of-fifty-five-environmental-attributes]

State of knowledge of the "Groundwater depletion" attribute: Excellent / well established – comprehensive analysis/syntheses; multiple studies agree.

Part A—Attribute and method

A1. How does the attribute relate to ecological integrity or human health?

Groundwater depletion, primarily caused by excessive extraction for agricultural, industrial, and domestic purposes [1-4], presents significant challenges to both ecological integrity [5-7] and human well-being [8,9], despite its susceptibility to natural phenomena such as prolonged low precipitation.

Ecologically, depleting groundwater affects interconnected surface water systems because they form a single, hydraulically connected resource [10,11]. Consequently, groundwater depletion can lead to the drying up of wetlands, streams, and rivers, disrupting habitats and endangering species reliant on these vital water sources. Furthermore, it adversely affects vegetation health, resulting in diminished biodiversity and altered ecosystems within groundwater aquifers [12] and above ground environments alike. Additionally, depleting fresh groundwater resources increases the potential for seawater intrusion in coastal areas, and the consequences of contamination can be detrimental, requiring lengthy remediation processes through careful management.

Groundwater depletion is the primary cause of land subsidence, which poses a potential threat to the ecological integrity of the area due to loss of support or underground caving in certain geological settings [13-15]. The repercussions of groundwater depletion extend to human health, as lowered groundwater levels often result in the cessation or reduction of access to groundwater extraction from shallow drinking water wells [16], leading to physical health issues (e.g., kidney stones, urinary tract cancers and some colon cancers) due to inadequate water consumption [17,18] and mental health concerns [19,20].

Groundwater depletion also frequently results in diminished water quality within aquifers and surface water bodies, particularly pronounced during periods of low rainfall when these resources heavily rely on groundwater recharge [1,21]. This heightened vulnerability to pollutants in the remaining groundwater exacerbates health risks.

A2. What is the evidence of impact on (a) ecological integrity or (b) human health? What is the spatial extent and magnitude of degradation?

There is a substantial body of international and national literature that demonstrates the impact of groundwater depletion on ecological integrity and human health. Studies have shown that reduced water levels in some streams, both in Aotearoa-NZ [22,24] and overseas [25-28], have compromised ecological integrity due to depleted groundwater levels. Recent evidence also highlights the effects on groundwater-dependent ecology caused by decreasing groundwater levels [27,29,30]. Ecological impacts due to land subsidence, resulting from excessive groundwater abstraction and consequently depleted groundwater levels, have been reported in Auckland [31], Wairakei [32,33] and potentially in Canterbury [15], and is a significant problem in many countries, including populated areas such as California, Florida, Arizona, Helsinki, Bangkok, Mexico City, and Jakarta [13,14,34-37].

Nationally, the depletion of groundwater wells has impacted human physical and mental health. Shallow wells in the Canterbury region began to run dry in the 1970s [16], and Environment Canterbury identified that the situation worsened over the last two decades, particularly around the Ashburton and West-Melton area [38]. There is also substantial international evidence showing health issues related to groundwater depletion [39-44]. Groundwater depletion is linked to increased concentrations of pollutants, due to lower water volumes available for dilution, which heightens health risks. These risks include gastrointestinal illnesses [45-46], reproductive disorders [47], and neurological ailments [46], especially in communities reliant on groundwater for drinking and irrigation purposes.

The spatial extent and magnitude of degradation caused by depleting groundwater vary considerably due to factors such as geology, aquifer characteristics, heterogeneity of the aquifer, recharge rates (due to both natural [precipitation] and anthropogenic influence [irrigation]), groundwater abstraction volumes and their patterns, as well as surface-groundwater interactions. Therefore, it is crucial to consider aquifer or site-specific properties to minimise degradation resulting from groundwater depletion [48].

A3. What has been the pace and trajectory of change in this attribute, and what do we expect in the future 10 - 30 years under the status quo? Are impacts reversible or irreversible (within a generation)?

The pace and trajectory of groundwater depletion varies significantly in Aotearoa-NZ and overseas. Typically, humans tend to access surface water, if available, before developing groundwater resources, as it is generally cheaper to abstract surface water than to pump from deep aquifers. Globally, the pace of groundwater depletion is most rapid in arid and semi-arid regions, as well as in highly populated areas [49-52].

Similar trends can be seen in regions such as Canterbury in Aotearoa-NZ due to the high demand for groundwater resources. In Canterbury, groundwater abstraction for domestic and stock water purposes started in the early 1900s. Environment Canterbury data show a significant increase in consents for groundwater use for domestic supply and industrial purposes around 1970.

Since the early 1990s, consents for groundwater use have increased considerably, mainly for irrigation [53]. With the current trend of high demand for groundwater, it is predicted that groundwater depletion will continue over the next 10 to 30 years. Increased temperatures and more drought-prone conditions are projected under climate change scenarios for many parts of the world.

Along with associated longer growing seasons, it is likely that groundwater demand for irrigation will increase, resulting in further groundwater depletion [54-56], unless interventions are taken to remedy the adverse trend. The reversal of impacts can be achieved through appropriate management of groundwater abstractions and approaches such as managed aquifer recharge (MAR) [1]. However, the rate of reversal is dependent on many factors, including aquifer properties.

A4-(i) What monitoring is currently done and how is it reported? (e.g., is there a standard, and how consistently is it used, who is monitoring for what purpose)? Is there a consensus on the most appropriate measurement method?

There are several methods for monitoring groundwater depletion. The most widely used methods in Aotearoa-NZ are groundwater level measurements using observation wells or piezometers. Piezometers are specialised wells used to measure the pressure head at specific depths, providing detailed information about groundwater levels in different aquifer layers. Regional authorities maintain strategically positioned groundwater level networks to monitor groundwater levels [57]. These networks are typically installed in areas of high groundwater demand and different hydrogeological units to support predicting trends, identifying potential risks linked to excessive extraction, and supporting sustainable water use. The monitoring is usually conducted according to the National Environmental Monitoring Standards (NEMS).

Historically, groundwater levels were measured manually using a dipping device (inserting a metal tape into the well until it contacts water). However, the majority of councils now utilise automated methods for continuous measurements (telemetered sites). The telemetered data should be cross-checked periodically against manual measurements to ensure accuracy. The groundwater level measurements are typically reported relative to the New Zealand Vertical Datum 2016 for meaningful comparison between sites and other water bodies (e.g., rivers and lakes). Groundwater levels are generally reported as time series plots for each well or a combination of wells within a cluster such as a hydrogeological unit.

Given the high cost associated with installation, most monitoring is targeted in high-demand areas, and the monitoring network can potentially be insufficient to provide adequate information about the complete groundwater level dynamics within a large area, such as an entire catchment or region. This limitation arises because groundwater flows in the "downhill" direction, similar to surface water, and due to the potential energy associated with pressure [11] (hydraulic head). Excessive abstractions in one area can potentially impact other areas of the aquifer to which they are hydraulically connected due to the pressure differential.

Other approaches used to support understanding groundwater depletion include Water Budget Analysis [58] (calculating the balance between inputs [recharge, inflow] and outputs [extraction, outflow]), Geochemical Methods such as isotope analysis [59] and water quality monitoring [60]. Additionally, remote sensing techniques are increasingly used to understand groundwater depletion, especially over large geographical areas. The most common remote sensing approaches are the NASA's Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) [61,62], and InSAR (Interferometric Synthetic Aperture Radar) [63,64]. The GRACE satellites measure changes in Earth's gravity field, which can be used to infer changes in groundwater storage over large regions (approximately 400 km by 400 km). InSAR uses satellite radar data to detect ground surface deformation, which can be related to groundwater extraction.

There is no consensus on the most appropriate measurement method, as the spatiotemporal scale of accuracy and cost associated with each method vary significantly. For example, a monitoring well, which involves considerable investment, is more appropriate for assessing groundwater depletion at a single location, while remote sensing provides information for a larger area at relatively low cost, but lower accuracy for any single location. Therefore, the monitoring method needs to align with the decision-making needs. However, by combining the above methods, along with scientific approaches such as trend analysis of groundwater levels [65] and considering the dynamics of interconnected systems (e.g., climate, river flow, water abstractions, land use changes, tidal effects), a detailed and accurate picture of groundwater depletion can be obtained.

A4-(ii) Are there any implementation issues such as accessing privately owned land to collect repeat samples for regulatory informing purposes?

The implementation issues of monitoring and reporting are primarily dependent on the approach used. For example, using 'invasive' methods such as groundwater wells or piezometers requires obtaining permission from landowners to install the well or piezometer and ensuring ongoing access for monitoring and maintenance. It may also require compliance with privacy laws to use or publicise information, if relevant. The cost of telemetry approaches for monitoring depends on the availability of telecommunication options for the site. Using satellite technology for data transfer in areas without mobile coverage can be expensive.

In addition, the performance of wells can be compromised due to sedimentation and damage from natural events (e.g., earthquakes) or vandalism. Therefore, it is important to take necessary precautions and implement QA-QC measures to ensure the data is reliable. Failing to use consistent measurement standards and a common datum can impact the ability to accurately utilise monitored data for regulatory and management purposes.

While this is not a significant issue for assessing groundwater level changes, which are typically slower than surface water level changes, temporal resolution of data availability and cloud cover and weather conditions may hinder the use of remote sensing data for high temporal resolution analysis. Similarly, remote sensing methods like GRACE only offer coarse spatial resolution (e.g., 400 km by 400 km), which may not be suitable for detailed local or regional analysis [66,67].

A4-(iii) What are the costs associated with monitoring the attribute? This includes up-front costs to set up for monitoring (e.g., purchase of equipment) and on-going operational costs (e.g., analysis of samples).

The costs associated with monitoring groundwater depletion vary significantly depending on the approach used and site-specific conditions. The up-front cost of monitoring wells, commonly used by regional councils to measure location-specific groundwater levels, depends on factors such as the well's depth and diameter, screen length, site accessibility for drilling, and the time required to develop the well (to remove sediment and clean the well). The cost can range from less than $10,000 to more than $100,000 per well.

The capital cost for data transmission also depends on the medium used, such as cellular or satellite, and ranges from less than $10,000 to more than $20,000. The ongoing costs can be considerable for manual sites due to staff time requirements. For automated sites, the ongoing cost may range from less than $100 to more than $250 per year, depending on whether it uses cellular networks or satellite. However, the cost can increase to more than $5,000 if the temporal resolution of data transfer is high, such as 15-minute intervals. Additionally, ongoing costs include data storage, QA-QC of data, and data analysis.

The costs associated with the use of remote sensing data also vary with many factors. For example, while the raw data from GRACE is freely accessible, the total cost of using GRACE data can vary significantly depending on the user's specific needs and resources, including software, computational resources, expertise, and potential consulting services.

A5. Are there examples of this being monitored by Iwi/Māori? If so, by who and how?

The author is not aware of any groundwater depletion monitoring being specifically undertaken by iwi/hapū/rūnanga. However, several organisations use groundwater level data for their research (e.g., Te Rūnanga o Ngāi Tahu, Te Kura Taka Pini research unit) and business operations (e.g., Ngāi Tahu Farming).

A6. Are there known correlations or relationships between this attribute and other attribute(s), and what are the nature of these relationships?

Groundwater depletion has known correlations or relationships with attributes including riparian margin establishment/protection, surface water flow alteration, catchment permeability and groundwater nitrate [3,27,68-71].

Part B—Current state and allocation options

B1. What is the current state of the attribute?

Understanding the current state of groundwater depletion varies significantly between and within regions. For example, monitoring by Environment Canterbury indicates that groundwater levels have been affected by abstraction [72]. In the Kaituna catchment in the Bay of Plenty, where the demand for groundwater is the highest in the region, trend analysis of groundwater levels reveals mixed results. Among the 22 groundwater level time series analysed, only two showed statistically significant long-term decreasing trends. Additionally, the study found that climate (i.e., natural factors), rather than groundwater use, is the primary factor controlling groundwater levels [65].

Based on these examples, it is reasonable to conclude that while understanding the current state and trends in groundwater depletion is crucial for freshwater management, this attribute should be assessed in conjunction with interconnected systems such as climate, land surface recharge, stream flows, and water abstractions to accurately ascertain changes in state.

B2. Are there known natural reference states described for New Zealand that could inform management or allocation options?

Typically, currently available monitoring does not inform the natural reference states in Aotearoa-NZ for two main reasons: (1) most groundwater level monitoring sites are located in high-demand areas where groundwater levels are affected by abstractions, and (2) current land cover and use do not represent natural conditions. Measurements would need to be taken in wilderness areas such as Fiordland which would be difficult and expensive. Due to these challenges, it is generally not feasible to directly develop natural reference states of groundwater levels through monitoring in most areas.

An alternative approach to develop natural reference states for groundwater levels is to utilise hydrological modelling approaches [3,73] to support management and allocation options, including the limit-setting process under the NPS-FM. However, these modelling approaches can only represent a “pseudo-natural state”, such as no water abstractions and no irrigation, and typically simulate the current land cover rather than a "pure" natural state due to a lack of detailed information about the former natural state. The accuracy of these models may also be affected by other anthropogenic influences such as dams, diversions, and discharges, which impact groundwater level dynamics.

Nevertheless, these models can provide a useful tool for informing groundwater management by simulating conditions that approximate natural states as closely as possible given existing constraints.

B3. Are there any existing numeric or narrative bands described for this attribute? Are there any levels used in other jurisdictions that could inform bands? (e.g., US EPA, Biodiversity Convention, ANZECC, Regional Council set limit)

There are no globally accepted default numeric or narrative bands for groundwater depletion levels to ensure sustainable water resource management, ecological integrity, and human health. This is primarily due to the spatial heterogeneity in aquifer dynamics, where the same absolute or proportional change in groundwater levels can produce different outcomes in different locations. For example, surface-groundwater interactions vary spatially, and the rate of outflow from an aquifer through groundwater discharge to surface water features will spatially differ if the same level of change is applied. Sustainable groundwater management ideally requires a location-specific balance of recharge, discharge, and extraction.

Regional councils typically develop location-specific numeric or narrative bands based on water balance assessments or modelling approaches. In the absence of a detailed assessment, adaptive management thresholds can be used in groundwater management. This approach allows for responding to changing conditions and new information through appropriate monitoring and a review process.

B4. Are there any known thresholds or tipping points that relate to specific effects on ecological integrity or human health?

As described above in B3, there are no universal numeric or narrative bands to determine thresholds or tipping points that specifically affect ecological integrity or human health. The most effective approach is to develop location-specific abstraction limits that maintain a sustainable level of groundwater depletion. This ensures an appropriate level of outflow to surface water bodies (baseflow) and oceans, which is crucial for reducing the potential risk of seawater intrusion. These measures support long-term ecological integrity and human health by maintaining the natural hydrological balance and preventing adverse environmental impacts.

B5. Are there lag times and legacy effects? What are the nature of these and how do they impact state and trend assessment? Furthermore, are there any naturally occurring processes, including long-term cycles, that may influence the state and trend assessments?

In general, groundwater dynamics are associated with lag times. However, lags are widely variable due to many factors including geology, surface-water interaction, climate and water abstraction patterns. For example, a recent study of radiocarbon dating of groundwater samples estimated that the groundwater in some coastal South Canterbury areas is up to 11,000-21,000 years old [74], indicating a very slow flow through the aquifer. In contrast, other sites contain younger groundwater [75,76], implying more rapid flow rates through the aquifer. Consequently, lag time of impact of groundwater abstraction from an aquifer and climate cycles, and subsequent effect of groundwater depletion, varies between and within aquifers [77,79].

B6. What tikanga Māori and mātauranga Māori could inform bands or allocation options? How? For example, by contributing to defining minimally disturbed conditions, or unacceptable degradation.

Māori have a range of values, beliefs and practices associated with groundwater ecosystems that are underpinned by a holistic and integrated understanding of the water cycle and the environment as a whole [90]. Groundwater-dependent cultural values, beliefs and practices encompass cultural landscapes and settlements, wāhi ingoa (place names), wāhi tapu (sacred places) and wāhi taonga (treasured places), rongoā (healing) and ceremonies (e.g., burials), mahinga kai (e.g., spring-fed streams), tuhitera neherā (rock art), marae water supplies and indigenous biodiversity (e.g., [91-93]).

There are examples of where groundwater features have been afforded the status of wāhi tapu and wāhi taonga. For example, Ōmaru puna wai in the Canterbury region was registered with the New Zealand Historic Places Trust as a wāhi tapu in 2005 [94]. Ratana et al. (2017)[95] developed an approach for Ngā Tai o Kāwhia whānau to express their aspirations for wetlands and puna, and the enhancement of important taonga species that utilise them. A framework was developed to support whānau prioritisation of sites for restoration based on their uses and associations with repo (swamps) and puna (springs) in the Kāwhia rohe.

As explained in B3 and B4, it is not feasible to develop universal spatial thresholds to limit groundwater depletion and achieve uniform outcomes. However, determining location-specific levels of allowable groundwater depletion due to human activities should consider the impact on surface water bodies and, consequently, on tikanga Māori and/or mātauranga. This approach supports cultural flow preference studies (or adaptation of this published method), such as those developed for harvesting mahinga kai from various freshwater habitats [80,81].

Part C—Management levers and context

C1. What is the relationship between the state of the environment and stresses on that state? Can this relationship be quantified?

There is a well-understood direct relationship between stressors and groundwater depletion. These stressors can be divided into two main groups: natural and anthropogenic. Natural stressors primarily include low precipitation, increased evaporation, and low river flows in areas that recharge groundwater. Anthropogenic stressors include groundwater abstractions, river flow alterations (e.g., surface water abstraction, diversions, impoundments), and changes in land use and management.

Although there is a relationship between stressors and groundwater depletion, it is generally challenging to quantify and attribute the influence of each stressor due to the complex interconnections within the system, as well as lags and legacy effects. To better understand these relationships, process-based distributed hydrological models can be used. However, developing such models is resource-intensive and often prohibitive for many areas. Additionally, these models are often developed to be specific to particular sites and cannot easily be applied to different spatial locations [82]. To overcome these limitations, several statistical modelling approaches have been developed to estimate the relative contributions of changes in natural systems and human activity to groundwater depletion [38,83,84].

C2. Are there interventions/mechanisms being used to affect this attribute? What evidence is there to show that they are/are not being implemented and being effective?

Key management interventions used to address groundwater depletion include developing sustainable water allocation limits for aquifers using cumulative impact assessments and restricting water abstractions when groundwater levels fall below certain thresholds, based on predefined rules and groundwater level monitoring of a reference well. The former can be specified for each aquifer in the regional or freshwater management unit plan. The latter can be implemented by including conditions in each water take resource consent to restrict water abstractions.

However, there are many barriers to setting sustainable limits and implementing water abstraction restrictions to achieve the desired outcomes. For example, determining sustainable water allocation limits may be challenging due to limitations in available data needed for a robust assessment. Similarly, the impact of restrictions on water abstraction from different spatial locations, even within the same aquifer, can vary due to the heterogeneity of the aquifer and its hydraulic connection to surface water [48]. Therefore, designing an accurate restriction regime with variable spatial restriction limits with the same aquifer is challenging and can be perceived as an unfair management strategy by some water users.

Given the complexity and resource-intensive nature of developing sustainable water allocation limits and water restriction management plans, the uncertainty associated with the developed numerical values (for both allocation limits and restrictions) can be significant. Therefore, it is advisable to utilise an adaptive management plan with appropriate monitoring and a review process. Such adaptive management should also include the ability to alter the developed numeric values for limits and water restrictions as soon as new knowledge is gained to avoid environmental degradation, as some aquifer systems may take years to recover from prolonged adverse activities.

Both the regional plan and consent conditions should refer to separate schedules that can be altered through adaptive management for allocation limits and restriction triggers, rather than specifying them directly in the regional plan and consent, if legally allowed. For example, specifying water take restriction conditions as numeric values in the resource consent ("hard coded") may prevent changes until the consent is due for renewal, even if adaptive management findings illustrate that the consented water take regime is unsustainable.

C2-(i). Local government driven

Regional councils and unitary authorities set allocation limits for each groundwater aquifer or Groundwater Allocation Zone (GAZ) using a variety of approaches. These approaches include percentages of average annual rainfall, soil-crop-water balance modelling, water balance assessments, field investigations (e.g., use of lysimeters), mathematical or statistical modelling, and physically based modelling.

Full or partial groundwater abstraction restrictions are implemented by regional authorities through consent conditions to achieve various outcomes, such as preventing groundwater level depletion, supporting sufficient groundwater discharge to surface water bodies to prevent ecological degradation, and preventing saltwater intrusion. In addition to using consent conditions for water take restrictions, regional authorities can also use Section 329[1] of the RMA to issue water shortage directions.

When implemented appropriately, full or partial groundwater abstraction restrictions can be an effective intervention. For example, Tasman District Council (TDC) identified seawater intrusion into the coastal areas of the Hau Plains during low rainfall periods (droughts) through their monitoring network. TDC implemented water restrictions in the affected area for droughts exceeding a 1-in-10 year event, as stipulated in their Resource Management Plan, which has proven to be an effective means of reducing the risk of seawater intrusion.

C2-(ii). Central government driven

The central government policies related to this attribute are outlined in the NPS-FM 2020, which applies to all freshwater (including groundwater) and, to the extent they are affected by freshwater, to receiving environments such as estuaries and the coastal marine area.

NPSFM clause 3.16 (3) states that "Environmental flows and levels must be expressed in terms of the water level and flow rate, and may include variability of flow (as appropriate to the water body) at which: (c) for levels of groundwater: any taking, damming, or diversion of water meets the environmental outcomes for the groundwater, any connected water body, and receiving environments."

Under Te Tiriti o Waitangi, it is the duty of the partnership to manage freshwater [85], including groundwater, in a manner that meets the cultural values of mana whenua.

C2-(iii). Iwi/hapū driven

Iwi/hapū/rūnanga provide input into the development of regional plans and have developed their own iwi environmental management plans that include objectives, policies and/or methods to support the groundwater-related outcomes they are seeking. For example, the Mahaanui Iwi Management Plan [Canterbury region] policy WM8.6 requires that: "aquifers are recognised and protected as wāhi taonga. This means: (a) The protection of groundwater quality and quantity, including shallow aquifers; (b) The protection of aquifer recharge; (c) Ensuring a higher rate of recharge then abstraction, over the long term; (d) Continuing to improve our understandings of the groundwater resource, and the relationship between groundwater and surface water" [94].

There are examples of where groundwater features have been afforded the status of wāhi tapu or wāhi taonga. For example, Ōmaru puna wai in the Canterbury region was registered with the New Zealand Historic Places Trust as a wāhi tapu in 2005 [94].

C2-(iv). NGO, community driven

It is difficult for NGOs or community-driven organizations to implement large-scale interventions to address groundwater depletion beyond contributing to resource management planning. However,

---

[1] Under s329 of the RMA, regional councils and unitary authorities can issue water shortage directions at any time there is a serious temporary shortage of water in its region or any part of its region. The direction may apportion, restrict, or suspend the taking, use, damming, or diversion of water.

many NGOs, community groups, and conservation organisations have voiced concerns about environmental degradation due to depleting groundwater levels. For example, the Environment and Conservation Organisations of New Zealand, a non-profit network of over 45 organisations concerned with conservation and the environment, works with international networks and engages with central and regional governments to advocate for environmental issues. Another example is Fish & Game, which has reported several instances of water shortages in some Canterbury streams and considers there to be a link between low stream flows and groundwater abstractions in inland Canterbury [22].

Interventions currently being employed by NGOs, community groups (including iwi/hapū/rūnanga) and conservation organisations in New Zealand to improve freshwater quality can also conceivably help to increase water availability in catchments including groundwater. These interventions include creation of new hard or soft infrastructure to increase water storage and surface water/aquifer recharge in catchments (e.g., reservoirs, ponds, wetlands, plantings and organic soils.

C2-(v). Internationally driven

From an international perspective, the United Nations General Assembly has recognised the human right to safe and clean drinking water and sanitation. Groundwater depletion undermines this human right. The UN-Water Summit on Groundwater 2022 called on governments for accelerated actions towards sustainable groundwater development.

In 2005, the UN's Educational, Scientific and Cultural Organisation, along with the Food and Agriculture Organisation, developed a landmark document titled “Groundwater in International Law - Compilation of Treaties and Other Legal Instruments” to highlight the importance of groundwater resources in international law [86].

Another international initiative is the Groundwater Project, a non-profit organisation committed to advancing education by creating and providing free high-quality groundwater educational materials online for everyone (https://gw-project.org/).

Other international obligations to prevent adverse groundwater depletion include climate change commitments under the Paris Agreement and conditions under Free Trade Agreements.

Part D—Impact analysis.

D1. What would be the environmental/human health impacts of not managing this attribute?

Failing to manage long-term groundwater depletion can have significant environmental and human health impacts. Environmentally, many ecosystems depend on groundwater. Wetlands, rivers, and lakes that rely on groundwater inputs can dry up, leading to the loss of biodiversity and the degradation of aquatic habitats. Over-extraction of groundwater can cause land subsidence, resulting in permanent loss of aquifer storage capacity and damage to infrastructure such as buildings, roads, and pipelines. In coastal areas, reduced groundwater levels can lead to saltwater intrusion, contaminating freshwater aquifers with seawater, making the water unusable for drinking and irrigation.

Human health is also significantly impacted by groundwater depletion. Depleted groundwater resources mean less availability of water for drinking, sanitation, agriculture, and industrial use, leading to water scarcity and associated health issues such as dehydration, poor sanitation, and food shortages, and mental health issues. Lower groundwater levels can lead to the concentration of contaminants like arsenic, fluoride, and nitrate in the remaining water, posing serious health risks such as poisoning, dental and skeletal fluorosis, and other chronic illnesses. Reduced agricultural productivity due to water scarcity can lead to food insecurity, malnutrition, and increased poverty, further exacerbating health problems. Effective management of groundwater is crucial to prevent these adverse environmental and human health impacts. Sustainable practices and policies should be implemented to ensure the long-term availability and quality of this resource.

D2. Where and on who would the economic impacts likely be felt? (e.g., Horticulture in Hawke's Bay, Electricity generation, Housing availability and supply in Auckland)

The economic impacts groundwater depletion would likely be felt across various sectors and communities, with significant repercussions for both rural and urban areas due to adverse levels of groundwater depletion.

- Agricultural sector: The agricultural sector, particularly viticulture, horticulture, and dairy farming, relies heavily on groundwater for irrigation across the country. Depletion would lead to reduced water availability for irrigation, resulting in lower crop yields, reduced crop quality, and decreased productivity. Insufficient water for other needs, such as produce processing, stock water, milk cooling, and dairy shed washing, would directly affect farmers' incomes. While pastoral farmers (e.g., dairy) may be able to purchase supplementary feeds (e.g., seeds) for animals, potentially at a higher cost, to mitigate the effects of a drought, this option is not feasible for horticulture or vegetable production [87]. Such impacts on horticulture are likely to be severe in areas like Pukekohe, Heretaunga Plains in Hawke's Bay, and Poverty Bay Flats in Gisborne. Businesses that supply agricultural inputs, such as seeds, fertilizers, and equipment, would also suffer as farmers cut back on spending due to reduced revenues. Lower agricultural output could increase the cost of raw materials, impacting food processors and manufacturers.
- Communities: Communities in rural areas often depend on groundwater for drinking water and domestic use. Depletion could lead to water shortages, necessitating costly alternatives like water trucking or infrastructure investments to access alternative sources. Reduced agricultural productivity can have a ripple effect on local economies, leading to decreased spending in rural towns and potentially causing job losses in agricultural and supporting sectors.
- Hydropower generation: Groundwater depletion reduces river baseflows, particularly during summer, leading to lower water levels in reservoirs. This decreases the availability of water for hydropower generation, reducing electricity output and potentially causing energy shortages. Consequently, reliance on alternative, often less sustainable energy sources may increase, impacting both the economy and environment.
- Tourism sector: Impacts can threaten the tourism sector by diminishing water resources essential for hospitality services and outdoor activities. It undermines the

country's "clean and green" image, deterring visitors attracted to pristine natural environments and potentially leading to economic losses in tourism-dependent communities.

- Coastal areas: Groundwater depletion can lead to saltwater intrusion, affecting freshwater supplies and ecosystems that support fisheries and agriculture sector. This would impact businesses and communities reliant on these industries.
- Public health and environment: Degraded water quality due to groundwater depletion can increase the incidence of waterborne diseases and chronic illnesses, leading to higher healthcare costs for communities and the government. Costs associated with environmental degradation, such as loss of wetlands and decreased river flows, may require expensive restoration projects funded by taxpayers.
- Infrastructure: Groundwater depletion can cause land subsidence, damaging infrastructure such as roads, bridges, and pipelines, leading to costly repairs and maintenance.
- Government and policy: The government may face higher costs related to increased regulation, monitoring, and enforcement efforts to manage the remaining groundwater resources effectively. There may also be a need for economic support programs to assist affected farmers and communities, placing additional strain on public finances.

D3. How will this attribute be affected by climate change? What will that require in terms of management response to mitigate this?

Groundwater depletion will be significantly affected by climate change, as altered precipitation patterns, increased evaporation rates, and prolonged droughts are likely to reduce natural groundwater recharge, particularly in eastern parts in Aotearoa-NZ [88], and consequently reduce discharge to rivers [89]. Rising temperatures can exacerbate water scarcity by increasing demand for irrigation in agriculture [54], leading to more intensive groundwater extraction. In coastal areas, sea-level rise and reduced freshwater recharge can increase the risk of saltwater intrusion into freshwater aquifers, further degrading groundwater quality and availability. These changes necessitate a proactive management response to mitigate the impacts of climate change on groundwater resources.

Effective management strategies will need to include enhanced monitoring of groundwater levels and quality, coupled with adaptive management practices that can respond to changing conditions. This will involve the implementation of more robust water allocation frameworks that prioritise sustainable use and protect critical recharge zones. Additionally, the development and promotion of water-efficient technologies and practices in agriculture, industry, and domestic use will be crucial. Managed aquifer recharge (MAR) and water storage infrastructure projects (see Section C2 iv) can help augment natural recharge, and regulatory measures must be put in place to limit over-extraction and prevent contamination.

If no action is taken to address groundwater depletion, the consequences will be severe. Groundwater levels will continue to decline, leading to the deterioration of ecosystems, reduced agricultural productivity, and compromised water supply for communities. This will exacerbate water scarcity, potentially leading to conflicts over water resources. The increased concentration of contaminants in dwindling groundwater supplies will pose serious health risks, making the need for protection and sustainable management even more critical. Protecting groundwater resources is not just important but essential to ensure water security and environmental health in the face of climate change.

References:

(1) Konikow, L. F.; Kendy, E. Groundwater Depletion: A Global Problem. Hydrogeology Journal 2005, 13 (1), 317–320. https://doi.org/10/fp25hg.

(2) Mukherjee, A.; Scanlon, B. R.; Aureli, A.; Langan, S.; Guo, H.; McKenzie, A. Global Groundwater: From Scarcity to Security through Sustainability and Solutions. In Global groundwater; Elsevier, 2021; pp 3–20.

(3) Rajanayaka, C.; Weir, J.; Kerr, T.; Thomas, J. Sustainable Water Resource Management Using Surface-Groundwater Modelling: Motueka-Riwaka Plains, New Zealand. Watershed Ecology and the Environment 2021, 3, 38–56.

(4) Foster, S.; Chilton, J.; Nijsten, G.-J.; Richts, A. Groundwater—a Global Focus on the 'Local Resource.' Current opinion in environmental sustainability 2013, 5 (6), 685–695.

(5) Brunke, M.; Gonser, T. The Ecological Significance of Exchange Processes between Rivers and Groundwater. Freshwater Biology 1997, 37 (1), 1–33. https://doi.org/10.1046/j.1365-2427.1997.00143.x.

(6) Lapides, D. A.; Maitland, B. M.; Zipper, S. C.; Latzka, A. W.; Pruitt, A.; Greve, R. Advancing Environmental Flows Approaches to Streamflow Depletion Management. Journal of Hydrology 2022, 127447. https://doi.org/10/gpjp7w.

(7) Akhtar, F.; Nawaz, R. A.; Hafeez, M.; Awan, U. K.; Borgemeister, C.; Tischbein, B. Evaluation of GRACE Derived Groundwater Storage Changes in Different Agro-Ecological Zones of the Indus Basin. Journal of Hydrology 2022, 605, 127369.

(8) Rajasooriyar, L. D.; Boelee, E.; Prado, M. C.; Hiscock, K. M. Mapping the Potential Human Health Implications of Groundwater Pollution in Southern Sri Lanka. Water resources and rural development 2013, 1, 27–42.

(9) Jia, X.; O'Connor, D.; Hou, D.; Jin, Y.; Li, G.; Zheng, C.; Ok, Y. S.; Tsang, D. C.; Luo, J. Groundwater Depletion and Contamination: Spatial Distribution of Groundwater Resources Sustainability in China. Science of the Total Environment 2019, 672, 551–562.

(10) Lewandowski, J.; Meinikmann, K.; Krause, S. Groundwater–Surface Water Interactions: Recent Advances and Interdisciplinary Challenges; Multidisciplinary Digital Publishing Institute, 2020.

(11) Winter, T. C.; Harvey, J. W.; Franke, O. L.; Alley, W. M. Ground Water and Surface Water: A Single Resource. (Vol. 1139). US Geological Survey.; 1998; Vol. 1139.

(12) Griebler, C.; Avramov, M. Groundwater Ecosystem Services: A Review. Freshwater Science 2015, 34 (1), 355–367. https://doi.org/10.1086/679903.

(13) Galloway, D. L.; Burbey, T. J. Regional Land Subsidence Accompanying Groundwater Extraction. Hydrogeology Journal 2011, 19 (8), 1459.

(14) Leake, S. A. Land Subsidence from Ground-Water Pumping. US Geological Survey; 1997.

(15) Wilson, D. D. Hydrogeology of Metropolitan Christchurch. Journal of Hydrology (New Zealand) 1976, 101–120.

(16) Mandel, S. The Groundwater Resources of the Canterbury Plains; Lincoln College. New Zealand Agricultural Engineering Institute., 1974.

(17) Healthify. Water - How Much Do I Need to Drink Each Day? Https://Healthify.Nz › Hauora-Wellbeing › Water; 2022.

(18) Yongsi, H. B. N. Suffering for Water, Suffering from Water: Access to Drinking-Water and Associated Health Risks in Cameroon. Journal of health, population, and nutrition 2010, 28 (5), 424.

(19) Wutich, A.; Brewis, A.; Tsai, A. Water and Mental Health. WIREs Water 2020, 7 (5), e1461. https://doi.org/10.1002/wat2.1461.

(20) Kimutai, J. J.; Lund, C.; Moturi, W. N.; Shewangizaw, S.; Feyasa, M.; Hanlon, C. Evidence on the Links between Water Insecurity, Inadequate Sanitation and Mental Health: A Systematic Review and Meta-Analysis. Plos one 2023, 18 (5), e0286146.

(21) Farid, H. U.; Ahmad, I.; Anjum, M. N.; Khan, Z. M.; Iqbal, M. M.; Shakoor, A.; Mubeen, M. Assessing Seasonal and Long-Term Changes in Groundwater Quality Due to over-Abstraction Using Geostatistical Techniques. Environ Earth Sci 2019, 78 (13), 386. https://doi.org/10.1007/s12665-019-8373-2.

(22) Fish & Game. Rivers Run Dry In Christchurch. URL: Https://Fishandgame.Org.Nz/News/Rivers-Run-Dry-in-Christchurch/, Accessed on February 2021.; 2021.

(23) Boone, S.; Fragaszy, S. Emerging Scarcity and Emerging Commons: Water Management Groups and Groundwater Governance in Aotearoa New Zealand. Water Alternatives 2018, 11 (3).

(24) Larned, S. T. Phreatic Groundwater Ecosystems: Research Frontiers for Freshwater Ecology. Freshwater Biology 2012, 57 (5), 885–906. https://doi.org/10.1111/j.1365-2427.2012.02769.x.

(25) Esteban, E.; Calvo, E.; Albiac, J. Ecosystem Shifts: Implications for Groundwater Management. Environ Resource Econ 2021, 79 (3), 483–510. https://doi.org/10.1007/s10640-021-00569-7.

(26) Wang, W.; Yang, Z.; Kong, J.; Cheng, D.; Duan, L.; Wang, Z. Ecological Impacts Induced by Groundwater and Their Thresholds in the Arid Areas in Northwest China. Environmental Engineering & Management Journal (EEMJ) 2013, 12 (7).

(27) Saito, L.; Christian, B.; Diffley, J.; Richter, H.; Rohde, M. M.; Morrison, S. A. Managing Groundwater to Ensure Ecosystem Function. Groundwater 2021, 59 (3), 322–333. https://doi.org/10.1111/gwat.13089.

(28) Dangar, S.; Asoka, A.; Mishra, V. Causes and Implications of Groundwater Depletion in India: A Review. Journal of Hydrology 2021, 596, 126103.

(29) Erostate, M.; Huneau, F.; Garel, E.; Ghiotti, S.; Vystavna, Y.; Garrido, M.; Pasqualini, V. Groundwater Dependent Ecosystems in Coastal Mediterranean Regions: Characterization, Challenges and Management for Their Protection. Water research 2020, 172, 115461.

(30) Boulton, A. J. Conservation of Groundwaters and Their Dependent Ecosystems: Integrating Molecular Taxonomy, Systematic Reserve Planning and Cultural Values. Aquatic Conservation 2020, 30 (1).

(31) Samsonov, S.; Tiampo, K.; González, P. J.; Manville, V.; Jolly, G. Ground Deformation Occurring in the City of Auckland, New Zealand, and Observed by Envisat Interferometric Synthetic Aperture Radar during 2003–2007. Journal of Geophysical Research: Solid Earth 2010, 115 (B8).

(32) Allis, R. G. Review of Subsidence at Wairakei Field, New Zealand. Geothermics 2000, 29 (4–5), 455–478.

(33) Allis, R. G. Subsidence at Wairakei Field, New Zealand. In 1990 international symposium on geothermal energy; 1990.

(34) Zamanirad, M.; Sarraf, A.; Sedghi, H.; Saremi, A.; Rezaee, P. Modeling the Influence of Groundwater Exploitation on Land Subsidence Susceptibility Using Machine Learning Algorithms. Nat Resour Res 2020, 29 (2), 1127–1141. https://doi.org/10.1007/s11053-019-09490-9.

(35) Huang, P.; Ma, C.; Zhou, A. Assessment of Groundwater Sustainable Development Considering Geo-Environment Stability and Ecological Environment: A Case Study in the Pearl River Delta, China. Environ Sci Pollut Res 2022, 29 (12), 18010–18035. https://doi.org/10.1007/s11356-021-16924-6.

(36) Peng, M.; Lu, Z.; Zhao, C.; Motagh, M.; Bai, L.; Conway, B. D.; Chen, H. Mapping Land Subsidence and Aquifer System Properties of the Willcox Basin, Arizona, from InSAR Observations and Independent Component Analysis. Remote Sensing of Environment 2022, 271, 112894.

(37) Tang, W.; Zhao, X.; Motagh, M.; Bi, G.; Li, J.; Chen, M.; Chen, H.; Liao, M. Land Subsidence and Rebound in the Taiyuan Basin, Northern China, in the Context of Inter-Basin Water Transfer and Groundwater Management. Remote Sensing of Environment 2022, 269, 112792.

(38) Rajanayaka, C.; Yang, J.; Booker, D. Assessment of Potential Anthropogenic Impacts on Land Surface Recharge and Groundwater Levels in Canterbury. Prepared for Te Rūnanga o Ngāi Tahu, NIWA Report No. 2021173CH.; 2023.

(39) Jasechko, S.; Perrone, D. Global Groundwater Wells at Risk of Running Dry. Science 2021, 372 (6540), 418–421. https://doi.org/10/gjtsmc.

(40) Perrone, D.; Jasechko, S. Dry Groundwater Wells in the Western United States. Environmental Research Letters 2017, 12 (10), 104002.

(41) Li, P.; Li, X.; Meng, X.; Li, M.; Zhang, Y. Appraising Groundwater Quality and Health Risks from Contamination in a Semiarid Region of Northwest China. Expo Health 2016, 8 (3), 361–379. https://doi.org/10.1007/s12403-016-0205-y.

(42) Ženko, M.; Menga, F. Linking Water Scarcity to Mental Health: Hydro–Social Interruptions in the Lake Urmia Basin, Iran. Water 2019, 11 (5), 1092.

(43) Rieger, K.; Holm, R. H.; Sheridan, H. Access to Groundwater and Link to the Impact on Quality of Life: A Look at the Past, Present and Future Public Health Needs in Mzimba District, Malawi. Groundwater for Sustainable Development 2016, 2, 117–129.

(44) Chinnasamy, P.; Hsu, M. J.; Agoramoorthy, G. Groundwater Storage Trends and Their Link to Farmer Suicides in Maharashtra State, India. Front. Public Health 2019, 7, 246. https://doi.org/10.3389/fpubh.2019.00246.

(45) Bylund, J.; Toljander, J.; Lysén, M.; Rasti, N.; Engqvist, J.; Simonsson, M. Measuring Sporadic Gastrointestinal Illness Associated with Drinking Water–an Overview of Methodologies. Journal of water and health 2017, 15 (3), 321–340.

(46) Ravindiran, G.; Rajamanickam, S.; Sivarethinamohan, S.; Karupaiya Sathaiah, B.; Ravindran, G.; Muniasamy, S. K.; Hayder, G. A Review of the Status, Effects, Prevention, and Remediation of Groundwater Contamination for Sustainable Environment. Water 2023, 15 (20), 3662.

(47) Sampat, P. Groundwater Shock. World watch 2000, 13 (1), 10–22.

(48) Theis, C. V. The Source of Water Derived from Wells-Essential Factors Controlling the Response of an Aquifer to Development. Civil Engineering, Amer. Soc. Civil Engi. 1940.

(49) Huang, Z.; Pan, Y.; Gong, H.; Yeh, P. J. -F.; Li, X.; Zhou, D.; Zhao, W. Subregional-scale Groundwater Depletion Detected by GRACE for Both Shallow and Deep Aquifers in North China Plain. Geophysical Research Letters 2015, 42 (6), 1791–1799. https://doi.org/10.1002/2014GL062498.

(50) Jia, X.; Hou, D.; Wang, L.; O'Connor, D.; Luo, J. The Development of Groundwater Research in the Past 40 Years: A Burgeoning Trend in Groundwater Depletion and Sustainable Management. Journal of Hydrology 2020, 587, 125006.

(51) Famiglietti, J. S. The Global Groundwater Crisis. Nature climate change 2014, 4 (11), 945–948.

(52) Lancia, M.; Yao, Y.; Andrews, C. B.; Wang, X.; Kuang, X.; Ni, J.; Gorelick, S. M.; Scanlon, B. R.; Wang, Y.; Zheng, C. The China Groundwater Crisis: A Mechanistic Analysis with Implications for Global Sustainability. Sustainable Horizons 2022, 4, 100042.

(53) Booker, D.; Griffiths, J.; Henderson, R. Flow Regime Alterations in Canterbury Rivers. Prepared for Te Rūnanga o Ngāi Tahu, NIWA Draft Report No. 2021032CH, March 2021.; 2021.

(54) Cotterman, K. A.; Kendall, A. D.; Basso, B.; Hyndman, D. W. Groundwater Depletion and Climate Change: Future Prospects of Crop Production in the Central High Plains Aquifer. Climatic Change 2018, 146 (1–2), 187–200. https://doi.org/10.1007/s10584-017-1947-7.

(55) Döll, P. Impact of Climate Change and Variability on Irrigation Requirements: A Global Perspective. Climatic change 2002, 54 (3), 269–293.

(56) Harding, K. J.; Snyder, P. K. Modeling the Atmospheric Response to Irrigation in the Great Plains. Part I: General Impacts on Precipitation and the Energy Budget. Journal of Hydrometeorology 2012, 13 (6), 1667–1686.

(57) ECan. Environment Canterbury Groundwater Level Monitoring Sites. URL: Https://Opendata.Canterburymaps.Govt.Nz/Datasets/Ecan::Groundwater-Level-Monitoring-Sites-All/About; 2024.

(58) White, P. A.; Raiber, M.; Tschritter, C. Geological Model and Water Budget of the Hauraki Plains, Waikato Region. GNS Science: Willaki, New Zealand.; 2018.

(59) Dench, W. E.; Morgan, L. K. Unintended Consequences to Groundwater from Improved Irrigation Efficiency: Lessons from the Hinds-Rangitata Plain, New Zealand. Agricultural Water Management 2021, 245, 106530. https://doi.org/10/gjvdvj.

(60) Painter, B. Protection of Groundwater Dependent Ecosystems in Canterbury, New Zealand: The Targeted Stream Augmentation Project. Sustain. Water Resour. Manag. 2018, 4 (2), 291–300. https://doi.org/10.1007/s40899-017-0188-2.

(61) Landerer, F. W.; Flechtner, F. M.; Save, H.; Webb, F. H.; Bandikova, T.; Bertiger, W. I.; Bettadpur, S. V.; Byun, S. H.; Dahle, C.; Dobslaw, H.; Fahnestock, E.; Harvey, N.; Kang, Z.; Kruizinga, G. L. H.; Loomis, B. D.; McCullough, C.; Murböck, M.; Nagel, P.; Paik, M.; Pie, N.; Poole, S.; Strekalov, D.; Tamisiea, M. E.; Wang, F.; Watkins, M. M.; Wen, H.; Wiese, D. N.; Yuan, D. Extending the Global Mass Change Data Record: GRACE Follow-On Instrument and Science Data Performance. Geophysical Research Letters 2020, 47 (12), e2020GL088306. https://doi.org/10.1029/2020GL088306.

(62) Wiese, D. N.; Landerer, F. W.; Watkins, M. M. Quantifying and Reducing Leakage Errors in the JPL RL05M GRACE Mascon Solution. Water Resources Research 2016, 52 (9), 7490–7502. https://doi.org/10.1002/2016WR019344.

(63) Rosen, P. A.; Hensley, S.; Joughin, I. R.; Li, F. K.; Madsen, S. N.; Rodriguez, E.; Goldstein, R. M. Synthetic Aperture Radar Interferometry. Proceedings of the IEEE 2000, 88 (3), 333–382.

(64) Ferretti, A.; Prati, C.; Rocca, F. Permanent Scatterers in SAR Interferometry. IEEE Transactions on geoscience and remote sensing 2001, 39 (1), 8–20.

(65) Rajanayaka, C.; Kerr, T.; Ren, J.; Yang, J. Analysis of Groundwater Level Trends and Rainfall-Recharge Relationship of Lysimeters in Kaituna. Prepared for Bay of Plenty Regional Council, NIWA CLIENT REPORT No: 2023148CH, NIWA CLIENT REPORT No: 2023148CH, 105 p, June 2023.; 2023.

(66) Castellazzi, P.; Martel, R.; Galloway, D. L.; Longuevergne, L.; Rivera, A. Assessing Groundwater Depletion and Dynamics Using GRACE and INSAR : Potential and Limitations. Groundwater 2016, 54 (6), 768–780. https://doi.org/10.1111/gwat.12453.

(67) Rowlands, D. D.; Luthcke, S. B.; Klosko, S. M.; Lemoine, F. G. R.; Chinn, D. S.; McCarthy, J. J.; Cox, C. M.; Anderson, O. B. Resolving Mass Flux at High Spatial and Temporal Resolution Using GRACE Intersatellite Measurements. Geophysical Research Letters 2005, 32 (4), 2004GL021908. https://doi.org/10.1029/2004GL021908.

(68) Rajanayaka, C.; Weir, J.; Barkle, G.; Griffiths, G.; Hadfield, J. Assessing Changes in Nitrogen Contamination in Groundwater Using Water Aging: Waikato River, New Zealand. Journal of Contaminant Hydrology 2020, 234, 103686. https://doi.org/10/ghk4pp.

(69) Vautier, C.; Kolbe, T.; Babey, T.; Marçais, J.; Abbott, B. W.; Laverman, A. M.; Thomas, Z.; Aquilina, L.; Pinay, G.; de Dreuzy, J.-R. What Do We Need to Predict Groundwater Nitrate Recovery Trajectories? Science of The Total Environment 2021, 788, 147661.

(70) Rohde, M. M.; Stella, J. C.; Roberts, D. A.; Singer, M. B. Groundwater Dependence of Riparian Woodlands and the Disrupting Effect of Anthropogenically Altered Streamflow. Proc. Natl. Acad. Sci. U.S.A. 2021, 118 (25), e2026453118. https://doi.org/10.1073/pnas.2026453118.

(71) Harmon, R.; Barnard, H. R.; Singha, K. Water Table Depth and Bedrock Permeability Control Magnitude and Timing of Transpiration-Induced Diel Fluctuations in Groundwater. Water Resources Research 2020, 56 (5), e2019WR025967. https://doi.org/10.1029/2019WR025967.

(72) ECan. Water Quantity. Https://Www.Ecan.Govt.Nz/Your-Region/Plans-Strategies-and-Bylaws/What-We-Know/Water-Story/Plains-and-Urban-Areas/.

(73) Rajanayaka, C.; Singh, S.; Srinivasa, R.; Srinivasan, M.; Shiona, H. Hydrological Modelling of Taieri Catchment, Prepared for Otago Regional Council NIWA Client Report No. 2020299CH; 2023.

(74) Burbery, L.; Abraham, P.; Wood, D. South Canterbury Deep Groundwater Investigation (Revised 2020), Prepared for ECan by Institute of Environmental Science and Research Limited.; 2020.

(75) Stewart, M.; Trompetter, V.; van der Raaij, R. Age and Source of Canterbury Plains Groundwater. Environment Canterbury Report U02/30.; 2002.

(76) van der Raaij, R. Groundwater Age Determination along a Transect across the Central Plains, Canterbury, New Zealand. GNS Science Report 2012/16.; 2012.

(77) Zipper, S. C.; Gleeson, T.; Li, Q.; Kerr, B. Comparing Streamflow Depletion Estimation Approaches in a Heavily Stressed, Conjunctively Managed Aquifer. Water Resources Research 2021, 57 (2), e2020WR027591. https://doi.org/10/gk8hc5.

(78) Barlow, P. M.; Leake, S. A. Streamflow Depletion by Wells: Understanding and Managing the Effects of Groundwater Pumping on Streamflow; US Geological Survey Reston, VA, 2012; Vol. 1376.

(79) Rajanayaka, C.; Booker, D.; Yang, J. Estimating Cumulative Catchment Streamflow Depletion from Abstractions, EGU General Assembly 2021, Online, 19–30 Apr 2021, EGU21-1803, Https://Doi.Org/10.5194/Egusphere-Egu21-1803, 2021; 2021.

(80) Tipa, G.; Nelson, K. Identifying Cultural Flow Preferences: Kakaunui River Case Study. J. Water Resour. Plann. Manage. 2012, 138 (6), 660–670. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000211.

(81) Crow, S. K.; Tipa, G. T.; Booker, D. J.; Nelson, K. D. Relationships between Maori Values and Streamflow: Tools for Incorporating Cultural Values into Freshwater Management Decisions. New Zealand Journal of Marine and Freshwater Research 2018, 52 (4), 626–642. https://doi.org/10.1080/00288330.2018.1499538.

(82) Fienen, M. N.; Nolan, B. T.; Feinstein, D. T. Evaluating the Sources of Water to Wells: Three Techniques for Metamodeling of a Groundwater Flow Model. Environmental Modelling & Software 2016, 77, 95–107.

(83) Liu, M.; Nie, Z.; Liu, X.; Wang, L.; Cao, L. Change in Groundwater Table Depth Caused by Natural Change and Human Activities during the Past 40 Years in the Shiyang River Basin, Northwest China. Science of The Total Environment 2024, 906, 167722.

(84) Safeeq, M.; Fares, A. Groundwater and Surface Water Interactions in Relation to Natural and Anthropogenic Environmental Changes. In Emerging Issues in Groundwater Resources; Fares, A., Ed.; Springer International Publishing: Cham, 2016; pp 289–326. https://doi.org/10.1007/978-3-319-32008-3_11.

(85) Waitangi Tribunal. The Ngāi Tahu Report (Wai 27). GP Publications, Wellington: 174.; 1991.

(86) Burchi, S.; Mechlem, K. Groundwater in International Law: Compilation of Treaties and Other Legal Instruments; Food & Agriculture Org., 2005; Vol. 86.

(87) Rajanayaka, C.; McEwan, H.; Monahan, B. Field Verification of the Water Balance Model Used for Development of Irrigation Guidelines for the Waikato Region. Aqualinc Research Ltd Client Report, H12003/2 Prepared for Waikato Regional Council, April 2013.; 2013.

(88) Mourot, F. M.; Westerhoff, R. S.; White, P. A.; Cameron, S. G. Climate Change and New Zealand's Groundwater Resources: A Methodology to Support Adaptation. Journal of Hydrology: Regional Studies 2022, 40, 101053.

(89) Booker, D. J.; Snelder, T. H. Climate Change and Local Anthropogenic Activities Have Altered River Flow Regimes across Canterbury, New Zealand. Water Resour Manage 2023, 37 (6–7), 2657–2674. https://doi.org/10.1007/s11269-022-03233-x.

(90) Fenwick, G., Greenwood, M., Williams, E., Milne, J., Watene-Rawiri, E. 2018. Groundwater ecosystems: Functions, values, impacts and management. NIWA Client Report prepared for Horizons Regional Council. NIWA Client Report: 2018184CH. June 2018: 154.

(91) Tipa & Associates. 2013. Groundwaters of Te Wai Pounamu with a focus on Murihiku. Report prepared for Te Ao Marama Incorporated.

(92) Ngāti Rangiwewehi. 2015. Ka Tu Te Taniwha – Ka Ora Te Tangata: Understanding the impacts of development in the Awahou groundwater catchment to ensure the health and wellbeing of the Ngāti Rangiwewehi people: Report 1. Ngāti Rangiwewehi, GNS Science and Bay of Plenty Regional Council. Rāngiwewehi Charitable Trust, Ngongotaha.

(93) Lovett, A. P., and P. A. White. 2016. Ka Tu Te Taniwha - Ka Ora Te Tangat: Scientific repository for the Awahou catchment, Lower Hutt, N.Z. GNS Science report 2016/13. Available from: https://awahou.smart-project.info/materials/nrw-report

(94) Ngāi Tūāhuriri Rūnanga, Te Hapū o Ngāti Wheke (Rāpaki), Te Rūnanga o Koukourārata, Onuku Rūnanga, and Wairewa Rūnanga. 2013. Mahaanui Iwi Management Plan. 392 p. https://www.mkt.co.nz/iwi-management-plan/

(95) Ratana, K., N. Herangi, S. Te Huia, W. Tāne, and Ngā Tai o Kāwhia interview and wānanga participants. 2017. Prioritising wetland restoration efforts based on Mātauranga-ā-hapū in the Kāwhia rohe: A pilot study. NIWA Client Report: 2017124HN