Groundwater Ecosystems:
Functions, values, impacts and management

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Abby Matthews
Science & Innovation Manager

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Prepared by:

Graham Fenwick, Michelle Greenwood ,Erica Williams, Juliet Milne, Erina Watene-Rawiri

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For any information regarding this report please contact:
Michelle Greenwood
Freshwater Ecologist
Freshwater Ecology
Telephone +64-3-343 8061
michelle.greenwood@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
PO Box 8602
Riccarton
Christchurch 8011
Phone +64 3 348 8987

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Juliet Milne	Formatting checked by:	[signature]
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Cover photo image: Phreatoicus typicus, a 20 mm long isopod from Canterbury's groundwater. Nelson Boustead, NIWA.

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Executive summary

New Zealand's groundwaters are important sources of drinking water for people and livestock, support diverse agricultural and industrial activities, and culturally are highly significant. Groundwater is closely interconnected with surface waters, at times providing the primary source of fresh water in rivers and streams, especially over summer – while in other physiographic and climatic settings, surface waters may lose flow to groundwater. Groundwater also underpins many surface water ecosystems (e.g., wetlands, lakes, rivers) and supports some vegetation types via these interconnections. These linkages with surface water bodies, and the realisation that aquifers are dynamic ecosystems, not just underground reservoirs of water, has led to the concept of groundwater dependent ecosystems. This report is concerned with one type of groundwater dependent ecosystem, subsurface groundwater dependent ecosystems (hereafter, groundwater ecosystems or GEs). Groundwater ecosystems inhabit water within aquifers below the water table and beyond the hyporheic zone underlying rivers.

Regional plans across New Zealand have shifted increasingly over the last decade to recognise and manage surface water and groundwater as a single resource, with a focus on management of the physical resource water and protection of groundwater-dependent ecosystems on the land surface. However, recognition of the importance of GEs and the services they provide is now also increasing, as is the case in countries such as Australia and the United States. For example, Greater Wellington Regional Council (GWRC) included objectives in its Proposed Natural Resources Plan for water quality and water quantity to safeguard aquatic ecosystem health values of both GEs and connected surface water ecosystems.

This report draws on published or otherwise publicly accessible literature to assess what is currently known about GEs in New Zealand to inform future freshwater policy development and groundwater management by regional (and potentially central) government. The focus is on ecosystems within true groundwater (phreatic or permanently saturated zone), mostly within alluvial aquifers,[1] which are the largest and most widespread aquifers across New Zealand. Specifically, this report covers:

- GEs, including the types of life present in aquifers and the key factors that affect GEs,
- The ecosystem services and values supported by GEs,
- An overview of Māori values, beliefs and practices associated with GEs,
- Key threats to GEs,
- The current legislative context for groundwater management, and
- GE-related research priorities.

This report is based on a desktop literature review of publicly available written material. It reviews much of the available information on GEs and extrapolates from fundamental ecology and research on similar ecosystems to fill gaps in presently available groundwater research knowledge. Although the science required to inform sustainable groundwater management continues to advance, it is still very imprecise in New Zealand. Therefore, this report draws on groundwater ecosystem research and policy documents from other countries (e.g., Australia and the USA) and international agencies (e.g., the World Bank and the Council of Europe), which are more advanced in GE research and policy development.

[1] Note that karst and fractured rock aquifer systems function in very much the same way.

Groundwater ecosystems

Alluvial aquifers provide complex and diverse physical habitats for GEs, which are heterotrophic, relying on organic carbon and dissolved oxygen (DO) supplied in recharge water. Organic carbon (mostly in dissolved form, DOC) and DO are generally more abundant (concentrated) closer to recharge sources and at shallower depths within an aquifer, and less abundant farther from recharge sources and/or after more time within the GE.

Groundwater contains numerous dissolved substances, both from the land surface and produced by dissolution of aquifer minerals and reactions within the aquifer. Dissolved oxygen is one key substance derived from recharge (surface) water that is essential for most GEs. Its availability determines bacterial community composition, biogeochemical processes, establishes the reduction-oxidation (redox) potential of the water, and influences the water's suitability for human uses.

Natural microbial communities within biofilms are the main component in GE chemical transformations. They mediate important biogeochemical reactions to influence groundwater chemistry, including the transport and fate of organic compounds and metals, the amounts and nature of organic carbon and nitrogen in groundwater, degrading contaminants and enhancing groundwater quality.

As well as microbes and biofilms, groundwater supports a diverse range of aquatic invertebrates (Protozoa and Metazoa), collectively known as stygofauna. Alluvial aquifer stygofaunal communities are dominated by crustaceans, notably amphipods, copepods and ostracods. Water mites also are common, along with other crustaceans (isopods, syncarids), gastropod snails, flatworms, nematode worms, annelid worms and beetles. Stygofaunal communities appear more abundant and diverse within 1-2 m of the groundwater surface compared with deeper in groundwater.

Although poorly known, New Zealand's stygofauna appears to be remarkably rich and diverse compared with that known for the British Isles, a similar sized group of islands. In New Zealand there are over 100 named species with another c. 700 collections of groundwater amphipods and isopods awaiting analysis. With the exception of some copepods, all named species are endemic to New Zealand and several are probably restricted to single aquifers or discrete aquifer systems.

Stygofauna are important to groundwater ecosystem functioning just as aquatic invertebrates are important to surface water ecosystem functioning. Stygofauna can consume large amounts of bacteria and biofilm. Through their movement and feeding activities, stygofauna browse biofilms and re-work finer sediment within the GE, ingesting and defecating sediment particles, as well as burrowing into and through the sediment. The magnitude of this bioturbation and its ecological effects can be very substantial, albeit poorly understood.

Groundwater values and ecosystem services

Traditionally aquifers and their associated GEs have been thought of as primarily physical systems that supply a valued resource, such as potable or irrigation water. Groundwater ecosystems actually provide four types of important ecosystems services. Provisioning services include water supply (e.g., for drinking, stock, irrigation and industry) and genetic resources (the pool of microbial and stygofaunal genotypes, which may include genes useful for humans). Regulatory services delivered by GEs include water purification and disease control through (natural or managed) bioremediation, maintaining hydraulic conductivity through stygofauna movement and feeding activities (bioturbation), and buffering of floods and drought through the assimilation and storage of water with GEs. Cultural services are non-material benefits arising from GE functioning (e.g., spiritual values, such as connection with springs or puna, and surface water recreational values, such as through providing water seasonally to sustain base flows in rivers that are valued for fishing). Supporting services are services that are essential to delivering other types of ecosystem services (e.g., nutrient recycling and habitat provision).

Currently, there are few methods that decision makers can use to compare the values of one groundwater use with an alternative (including leaving groundwater in place). Estimating the economic values of GEs is complicated by the physical interconnectedness of GEs with surface waters and our incomplete understanding of GE functioning. For these reasons, multiple assumptions and estimates are usually involved in ecosystem valuation. Despite their tentative nature, estimates of ecosystem value and an improved understanding of the many values provided by GEs are likely to assist sustainable management of groundwaters.

Māori values, beliefs and practises associated with groundwater ecosystems

Māori have a range of values, beliefs and practices associated with GEs that are underpinned by the intergenerational Māori worldview and a holistic and integrated understanding of the water cycle and the environment as a whole. Recent research is starting to improve our understanding of groundwater-dependent Māori values, beliefs and practices that 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.

Land use activities that may adversely affect Māori values associated with groundwater include land development, water abstraction, poor water resource management practices, and mixing of waters.

Māori have identified research required to support their aspirations for improved management of GEs. Common priority themes of iwi and hapū include: the protection of puna, addressing the threats of artificially augmenting aquifers with water from adjacent catchments (i.e., mixing of waters), the protection of cultural landscapes and all the components this entails (e.g., watercourses, groundwaters, buffers, wetlands, revegetated areas, irrigation practices, runoff pathways, wāhi taonga), and the protection of groundwaters from contaminants.

Key threats to groundwater ecosystems

The main threats to GEs from human activities are changes in organic carbon and DO concentrations, changes to the groundwater hydrological regimes, and the introduction of contaminants.

Slight increases in organic carbon from land-use activities may stimulate bacterial biofilms and stygofauna. Excessive organic carbon inputs to groundwater result in increased biofilm biomass that can reduce DO concentrations through respiration, and clog finer pore spaces, which may further reduce DO concentrations. Increased organic carbon concentrations result in larger populations of fewer stygofaunal species and, as DO concentrations diminish, can suppress stygofauna activity. Sustained low or no DO concentrations may eliminate stygofauna grazing, allowing biofilms to block more pore spaces within the aquifer, creating an increasingly anoxic environment, which can alter water quality.

Many activities can affect groundwater hydrological regimes. Changes in hydrological regimes due to water abstraction can alter stygofauna community richness, abundance and/or functioning.

Abstraction from coastal aquifers can result in saltwater contamination of groundwater as seawater replaces abstracted freshwater, potentially making parts of the aquifer habitat unsuitable for its stygofauna and for delivering groundwater ecosystem services.

Numerous contaminants from land use activities (e.g., nitrate, ammonium, agrichemicals, metals, hydrocarbons, emerging contaminants) can contaminate groundwater. Nitrate contamination of groundwater is relatively widespread in New Zealand, but the concentrations that are harmful are unknown for any groundwater species or for GEs overall.

Many activities, including agriculture and water abstraction, have multiple effects on GEs, and the combined effects may be cumulative or act synergistically. Further, adverse effects on GEs may take decades to appear and even longer to be remediated because of the usually slow movement of groundwater from recharge to discharge.

Current regulatory context for managing GEs

The Resource Management Act (RMA) 1991 provides the primary component of New Zealand's legislative framework for managing freshwater ecosystems, much of which can be applied directly to managing GEs. Two regulatory instruments under the RMA, the National Policy Statement for Freshwater Management (NPS-FM 2014) and proposed National Environmental Standard on Ecological Flows and Water Levels, explicitly reference groundwater or aquifers in an ecosystem health context. The NPS-FM provides an overarching structure for managing freshwater resources that recognises the national significance of freshwater and Te Mana o te Wai (the integrated and holistic wellbeing of a freshwater body).

The New Zealand Conservation Act 1987 and the New Zealand Biodiversity Strategy require regional councils to ensure that the intrinsic and other values of all biodiversity – including that of "underground aquifers" – are adequately maintained and safeguarded for future generations.

The first water conservation order for an aquifer in New Zealand is presently in progress. Although focussed on protecting the diverse values associated with Te Waikoropupū Springs (near Tākaka), the proposed order seeks to ensure that GEs in contributing aquifers are protected to sustain the springs' remarkable water clarity and substantial cultural, social, economic and biodiversity values.

Only a few regional plans, notably those of the Tasman District and the Wellington Region, explicitly acknowledge GEs. Internationally, the European Union and Australia (where the concept of GEs originated) provide the strongest recognition and measures to sustain GEs. Groundwater management in Australia was driven by the National Water Initiative (NWI).

Research priorities

Our ability to manage groundwater as valuable ecosystems is currently limited by the very incomplete knowledge of these ecosystems, how they function and how human activities affect them. Internationally and in New Zealand, research into GEs is relatively recent, lacks the body of descriptive science that underpins today's ecological management models and tools, and is complicated by difficulties in accessing GEs and adequately sampling stygofauna (restricted geographic ranges and low population densities).

Research that would bring the most immediate benefits to GE management includes a national survey of GE state and function (including hydrological and water chemistry attributes), development of standard sampling methods and indicators for measuring and reporting on GE health, and identification of toxicity thresholds of key GE taxa or communities for key contaminants such as nitrate. Investigating the influence of multiple contaminants and environmental modifiers (e.g., DO) and developing methods to construct environmental flows (abstraction and recharge rules) for GEs (and surface water bodies dependent on water from GEs) would also be beneficial.

1 Introduction

Groundwater is a very substantial component of New Zealand's fresh water resource, with approximately 200 known aquifers underlying 26.3% of the country's land surface (White 2001); Figure 1-1). Groundwater provides an important source of drinking water for people and livestock, and supports a range of agriculture, horticulture and industry. Water, including groundwater, is a taonga (treasure) of paramount importance to Māori with attendant rights, interests and responsibilities.

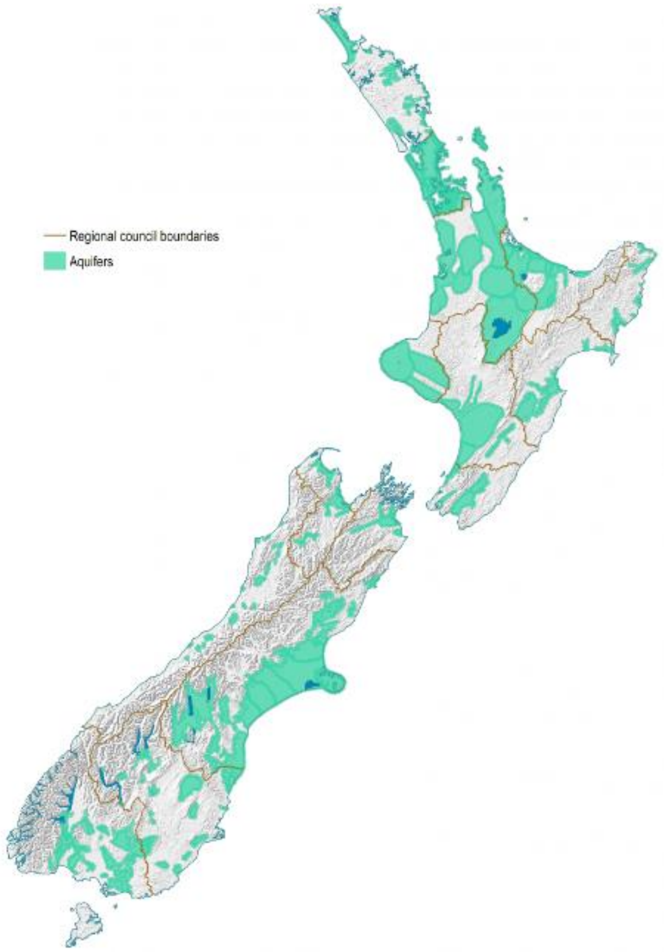

Figure 1-1: Geographic locations and extents of aquifers in New Zealand. Source: GNS Science, reproduced in MfE and Stats NZ (2015).

Groundwater is closely interconnected with surface waters. At times groundwater provides the primary source of freshwater in rivers and streams – especially over summer – while in other physiographic and climatic settings, surface waters may lose flow to groundwater. Groundwater also underpins many surface water ecosystems (e.g., wetlands, lakes, streams and some vegetation types via these interconnections). These linkages and exchanges with surface water bodies, and the realisation that aquifers are dynamic ecosystems and not just underground water storage, has led to the concept of groundwater dependent ecosystems (GDEs; Sinclair Knight Merz 2001, LWC 2002, Murray et al. 2003).

This report focusses on one type of groundwater dependent ecosystem, subsurface groundwater dependent ecosystems (hereafter groundwater ecosystems or GEs), which inhabit water within aquifers, usually below the water table, and beyond the hyporheic zone underlying active channels in rivers. Like above-ground ecosystems, a groundwater ecosystem comprises a biological community of organisms, including bacteria, fungi and meio- and macro invertebrates, interacting with each other and their physico-chemical environment. The organisms and ecosystem functioning within groundwater ecosystems provide significant biodiversity values and important ecosystems services (e.g., Fenwick 2016).

WHAT ARE GROUNDWATER ECOSYSTEMS?

Groundwater ecosystems (GEs), more formally termed subsurface groundwater dependent ecosystems (SGDEs), can be defined as "an aquatic ecosystem occurring below the surface of the ground that would be significantly altered by a change in the chemistry, volume and/or temporal distribution of its groundwater supply" (Tomlinson and Boulton 2008). GEs include the shallow mixing zone between surface and ground water (hyporheic zone) down to the dark depths of saturated ground water. In this report we focus on the deeper groundwater ecosystems, (phreatic or saturated zone, where all interstitial spaces are filled with water) as this is the area lacking most knowledge.

Alluvial aquifers are the largest and most widespread water bodies in New Zealand and are the focus of this report.[2] Alluvial aquifers are significant in most regions, especially in Hawke's Bay, Tasman, Marlborough and Canterbury. While New Zealand's alluvial aquifers are reasonably well known hydrologically, very little is known about their ecology. Diverse microbial communities are reported for some regions (Van Bekkum et al. 2006, Sirisena et al. 2013) and groundwater fauna (stygofauna) are known from most regions (Fenwick 2000). Thus, GEs are expected to occur within most of the shallower, oxygenated (oxic) alluvial aquifers throughout New Zealand. Similar GEs also are likely to occur within karst (eroded or karstified limestone and marble) aquifers and fractured rock aquifers (Juberthie 2000, Pipan and Culver 2007, 2013), although there is even less known about these systems in New Zealand.

Internationally, there has been a move towards greater recognition of the intrinsic values of GEs, including in Australia, Europe and the U.S. (e.g., Thompson 2011, Serov et al. 2012, Griebler and Avramov 2015). While regional plans across New Zealand have increasingly shifted over the last 10 or so years to recognise and manage surface water and groundwater as a single resource (e.g., Hughes and Gyopari 2011), this was largely to improve management of water as a *physical* resource and protect groundwater-dependent ecosystems on the land surface. However, in New Zealand recognition of the importance of GEs and the services they provide is now also increasing. For example, Greater Wellington Regional Council (GWRC) included objectives in its Proposed Natural Resources Plan (GWRC 2015) for water quality and water quantity to safeguard aquatic ecosystem health values of both GEs and connected surface water ecosystems. These objectives are consistent with recent national policy initiatives such as the New Zealand Biodiversity Strategy[3] (DoC and MfE 2000) and the National Policy Statement for Fresh Water Management (NPS-FM; NZ Govt 2014, 2017). The latter explicitly includes aquifers as a type of freshwater and sets ecosystem health as a mandatory value for managing all freshwater.

[2] Other aquifer types include those in volcanic sediments or fractured basalt, and limestone (karst aquifers). While this report focuses on alluvial aquifers, it is clear that karst aquifer systems (e.g., as found in the Tasman District) function in very much the same way (e.g., Holsinger 1966, Simon et al. 2003).

[3] http://www.doc.govt.nz/nature/biodiversity/nz-biodiversity-strategy-and-action-plan/new-zealand-biodiversity-strategy-2000-2020/

1.1 Report purpose

This report seeks to draw together and summarise the readily available information on human values associated with groundwater and how GE services and biodiversity may support these values in New Zealand. The report also seeks to provide an overview of Māori values, beliefs and practices associated with GEs, key threats to GEs, and key research priorities to assist with GE management. Overall, this report aims to provide a resource to inform and support future groundwater policy development and monitoring by regional (and potentially central) government.

1.2 Report scope and structure

This report draws on available published, or otherwise publicly available, literature to assess what is currently known about GEs and, where international material is included, its relevance to New Zealand. The focus is on ecosystems within groundwater[4], mostly within alluvial aquifers, however, karst and fractured rock aquifer ecosystems function similarly (e.g., Holsinger 1966, Simon et al. 2003). We focus on true groundwater (phreatic or permanently saturated zone) ecosystems. In doing this, we recognise the intergradation between this zone, the vadose (unsaturated) zone and the hyporheic zone (sub-stream bed zone where river and groundwater mix), and understand that many of the organisms and processes are common, at least between the phreatic and hyporheic zones.

A partially drafted version of this report was originally prepared to support the development of groundwater policy in GWRC's Natural Resources Regional Plan. Recognising its value to New Zealand overall, preparation of this more comprehensive version was instigated by Horizons Regional Council and GWRC in conjunction with the regional sector's Groundwater Forum. The report was funded through MBIE Envirolink Contract No. C01X1716.

The main body of the report is structured as follows:

- Section 2 provides an overview of GEs, including the types of life present in aquifers and the key factors that affect GEs and GE functioning.
- Section 3 identifies the values associated with GEs using three main approaches; ecosystem services, the concept of natural capital, and economic valuation.
- Section 4 provides an overview of Māori values, beliefs and practices associated with GEs.
- Section 5 examines key environmental factors that affect GEs, notably changes to dissolved substances important for life within GEs, changes to the groundwater hydrological regime, and the introduction of harmful substances.
- Section 6 provides an overview of the current national and regional regulatory context for groundwater management in New Zealand. International regulatory approaches are also briefly outlined.
- Section 7 discusses priorities for groundwater research to support managing groundwaters from a GE perspective.
- Section 8 presents conclusions and recommendations.

[4] We deliberately distinguish the aquifer (the variously porous and permeable rock or sedimentary deposit that holds and/or transmits groundwater) from the groundwater and ecosystem that inhabits the aquifer, much as the river bed is distinguished from the river ecosystem.

Short summaries are presented at the end of sections 2 to 6 to highlight the key points. A glossary of the scientific terminology and Te Reo used in this report are provided in Section 10 and Section 11, respectively.

1.3 Methodology and limitations

This report is based on a review of publicly available literature (e.g., client reports, journal papers, statements of evidence, statements of association, statutory acknowledgements, regional plans, iwi/hapū environmental management plans, cultural impact assessments) from New Zealand and international sources. New knowledge gathering (e.g., interviews), interpretation and analysis were outside of the scope of this report.

This report does not represent a comprehensive state of our knowledge about how Māori value and use GEs throughout New Zealand. To the best of our knowledge, very few targeted research studies have investigated Māori groundwater-dependent values, uses and practises. The Te Reo, Te Ao Māori concepts, and examples of Māori groundwater-dependent values, uses and practises introduced in this report are examples to help illustrate various contexts, concepts and behaviours.

Although the science required to inform sustainable groundwater management continues to advance, it is still very imprecise in New Zealand where many of our c. 200 aquifers are hydro-geologically complex (White 2001). This report therefore draws on groundwater ecosystem research and policy documents from other countries (e.g., Australia and the USA) and international agencies (e.g., the World Bank and the Council of Europe), which are more advanced in their GE research and policy development.

1.4 Finding a common language for evaluating and protecting groundwater biodiversity

Numerous terms are used to describe the various components of GEs. The language used varies with the discipline, the discipline-specific methodologies, the physico-chemical processes involved, the resource use(rs), and/or application of planning and policy to the evolving management context.

In situations where different knowledge systems, using different terminologies, are brought together (e.g., mātauranga Māori, hydrogeology, ecology, speleology, volcanology, modelling, planning and policy), it is useful to develop common language dictionaries, or glossaries, so that each knowledge holder is respected and the various parties can communicate with each other more effectively (e.g., Williamson et al. 2016) (Table 1-1).

Table 1-1: Examples of terminology that may be used by various parties when talking about groundwaters and their associated ecosystems. Please note that the lists are in alphabetical order. In terms of the mātauranga Māori held by whānau, hapū, rūnanga and iwi, this is not meant to be a complete and exhaustive list of the different terminology used across New Zealand.

Language	Examples of terminology
Common	gravel aquifer, bore, caves, groundwater, hot springs, seepages, sink holes, soda springs, springs, spring heads, underground aquifers, underground waters, water table, well
Te Reo	ngā wai rarowhenua, ngawha, puia, puna, puna manawa whenua, puna wai, puna waiariki, wai manawa whenua, wai rongoā, Wai tapu, waiariki, waipuna
Technical	alluvial aquifer, artesian spring or well, carbonated springs, cave resurgences, emergent springs, fractured rock aquifer, gravel aquifer, hypogean systems, hyporheic zone, karst aquifer, low temperature geothermal energy resources, risings or resurgences, subterranean rivers and lakes, shallow groundwater, surface groundwater aquifer, spring-fed streams, unconfined or confined aquifer

2 Groundwaters as ecosystems

New Zealand's alluvial aquifers are reasonably well known hydrologically, however, very little is known about their biodiversity and ecology. Diverse microbial communities are reported for some regions (Van Bekkum et al. 2006, Sirisena et al. 2013) and groundwater fauna (stygofauna) are known from most regions (Fenwick 2000), but numbers of species and their distributions are poorly known. Traditionally, with access into groundwater systems only through wells, caves or springs, groundwater ecosystems (GEs) were regarded as dark, uniform environments with limited biodiversity, simple food webs and restricted productivity. However, a growing body of evidence depicts GEs as physically and biologically diverse and potentially productive ecosystems.

This section provides an overview of GEs, including the physical and chemical characteristics of groundwater habitats, the types of life present in aquifers and GE functioning.

2.1 Aquifers as physical habitats

Habitat heterogeneity is important in any ecosystem, because a diversity of physical spaces provides habitat for a diversity of organisms and ecosystem processes. The physical habitat (substrate size and composition, interstitial or crevice size, water velocity) within an aquifer is likely to vary at several scales[5].

At the fine scale (sub-millimetres to 100 mm) the physical habitat for organisms living within all types of aquifers is likely to be heterogeneous, at least in terms of aquifer mineral composition, surface texture and particle size (in alluvial systems). The size of interstices between particles and within crevices, and water velocities within these spaces are also likely to vary widely, adding further habitat heterogeneity and potential niche differentiation for microbes and invertebrates.

There is additional physical heterogeneity at local scales (1 to >100 m). For example, parts of some Canterbury alluvial aquifers include preferential flow-paths, each comprising a longitudinal "pipe", lens or underground stream of well sorted gravels that meander horizontally and vertically through the subsurface alluvium (Figure 2-1) (Davey 2006). These pipes (irregular in cross-section, some 2 m wide, 10-40 cm high) lie within a matrix of poorly sorted alluvium (Davey 2006). Some probably fill and flow only seasonally as water levels rise in response to recharge events.

2.1.1 Groundwater hydrology

Groundwater ecosystems lack light and, hence, photosynthetically active plants that create energy and oxygen in most other ecosystems. Thus, GEs depend on oxygen, organic matter and nutrients that are carried into the aquifer by recharge water (see Section 2.4 for further details). Some microbes and biofilms function in damp, static media, but free water is essential for most, if not all, groundwater fauna for respiration and to enable movement. Thus, an aquifer's water regime has a strong influence on its GE composition and functioning, but the relationship between a GE and its aquifer's water regime is poorly understood. Eco-hydraulics is a well-established and important research field for managing surface waters and has recently received some attention for groundwaters (Hancock et al. 2009, Humphreys 2009).

[5] Toth (1963) identified three scales of groundwater flow within drainage basins from a hydrological perspective: local, intermediate and regional. Our ecological focus is principally at local and sub-local scales, although intermediate and regional flows may also be important.

Figure 2-1: Groundwater preferential flow path within the Canterbury Plains exposed within sea cliffs at Lowcliffe. From Davey (2006), Fig. 8.

While the relationship between GEs and their hydrological regime is poorly understood, we can make some generalisations of likely effects based on knowledge from other dynamic aquatic ecosystems. The groundwater level or upper boundary of a GE migrates vertically through the zone of intermittent saturation[6] (ZIS) (e.g., Scarsbrook and Fenwick 2003, Larned et al. 2014), which, like the intertidal zone on coasts, may be very active biologically, due to its dynamic conditions. The ZIS is an ecotone, a transitional habitat between the vadose zone[7] and the true groundwater (phreatic zone), through which key resources (organic carbon, oxygen and nutrients) transit. As such, it is likely to be rich in biodiversity and ecosystem function, with some components perhaps more active when unsaturated within the ZIS's damp, humid matrix. Organic carbon and other nutrients percolating through the vadose zone from the land surface (Humphreys 2009, Korbel and Hose 2015) may be concentrated via evaporation or become more bioavailable after desaturation or during re-wetting (e.g., Vázquez et al. 2015), driving continued, if not enhanced, ecological activity. Biofilms readily recover from dewatering (Weaver et al. 2015). Conceivably, life histories of some stygofauna may be linked to seasonal recharge events (Scarsbrook and Fenwick 2003), some migrating into the ZIS seasonally to feed on its biofilms that become more active when this zone is saturated (Baker et al. 2000). Other stygofauna may use unsaturated, damp sediments of the ZIS to escape predation during a critical life-history stage or to aestivate seasonally. However, there is no empirical information on such fundamental aspects of stygofaunal biology to evaluate this speculation on stygofaunal use of the ZIS.

[6] The vertical zone through which the upper limit of groundwater saturation migrates and, hence, is saturated with water intermittently.

[7] The unsaturated zone or zone between the land surface and the water table (or the groundwater "surface").

2.1.2 Water velocity

Groundwater velocity, driven by piezometric or water level gradients (Figure 2-2), is an important factor at all scales (i.e., sub-millimetre to kilometres). Velocity drives replenishment rates for key substances and nutrients not generated with the GE. Velocity also influences the groundwater chemical environment and removal rates of carbon dioxide and other potentially important toxicants or products of ecosystem functioning.

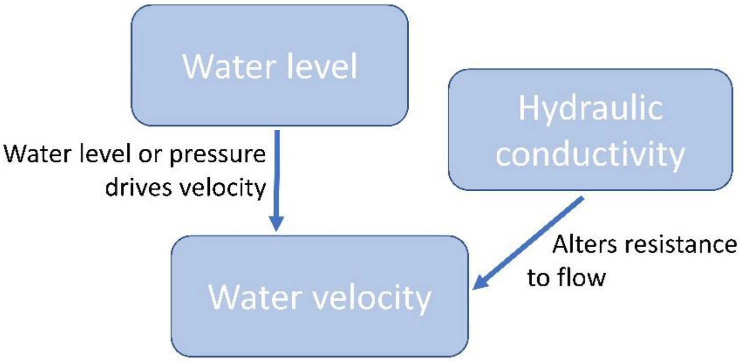

Figure 2-2: Groundwater velocity is determined by water level or pressure differences and aquifer conductivity or resistance to flow. Open arrow, recharge water; blue arrows, direct effects.

Meaningful measures of groundwater velocity are practical only over larger (> 100 m) scales, whereas hydraulic heads or relative groundwater levels, usually determined over distances of 10 to > 1000 m, provide indications of relative velocities. Tracer experiments also can determine velocities over scales of tens to hundreds of metres (e.g., Sinton et al. 2005). However, relationships between velocities at these scales and GE ecology and functioning are tenuous.

Within an aquifer, the flow of groundwater is driven by differences in water level elevation, which create differences in water pressure (e.g., as may develop in the vicinity of a pumped abstraction well) and hydraulic conductivity[8], essentially the aquifer medium's resistance to flow through its pore spaces[9]. A given gradient in groundwater elevation or pressure will lead to a flow rate that is proportional to the aquifer's hydraulic conductivity.

Aquifers with relatively large and well-connected pore spaces have a high hydraulic conductivity (groundwater moves through them with little resistance). Other aquifers (or parts of the same aquifer) with very small or poorly connected pore spaces or fractures resist water movement, so have a low hydraulic conductivity. Alluvial aquifers with reasonably high hydraulic conductivity predominate in New Zealand (White 2001), but conductivities within an aquifer vary widely. Pore spaces in parts of an alluvial aquifer may be largely or partially filled with silt or clay, which substantially reduces or prevents groundwater flow. Karst aquifers in New Zealand also vary in their conductivities. The Arthur Marble Aquifer, which supplies Te Waikoropupū Springs, is highly karstified (eroded to become highly porous) in places and its water averages 8-10 years from recharge to discharge, yet it discharges a very large volume via the springs, indicating extremely high conductivities (and artesian pressures) immediately upstream (Williams 1977, Thomas and Harvey 2013).

[8] See USGS on-line glossary: http://or.water.usgs.gov/projs_dir/willgw/glossary.html#H .

[9] Transmissivity refers to the rate of flow across a whole aquifer (i.e., depends on aquifer cross sectional width and height), whereas conductivity refers to a flow across a unit area of an aquifer.

2.2 Groundwater chemistry

The major dissolved substances found in groundwater are similar to those found in surface water (Golterman and Kouwe 1980), and include calcium, magnesium, sodium, potassium, carbonate, chloride and sulphate from recharge water and weathering of aquifer materials (Rosen 2001). Various forms of organic carbon are also typically dissolved in groundwater (Artinger et al. 2000). Other substances that often represent a minor, but significant, fraction of the dissolved content of groundwater include nitrogen (mostly as nitrate or ammonium), phosphorus (typically as phosphate), silica, iron, manganese, fluoride and bromide (Rosen 2001). Several trace substances will also be present in groundwater (e.g., arsenic). The total and relative concentrations of these major, minor and trace dissolved substances vary from place to place and from time to time, even within a single aquifer, and on small spatial scales (Rosen 2001, Davidson and Wilson 2011).

Groundwater chemistry is strongly influenced by dissolved substances that originate from:

- Uncontaminated or natural recharge water (e.g., sodium and chloride from rain water; calcium and phosphorus from the land surface and soils). Concentrations of these substances may remain stable or increase along an aquifer’s flow path, depending on the aquifer’s lithology.
- Recharge water contaminated by human activities (e.g., agrichemicals, organic matter and pathogens, cadmium from phosphate-rich fertilisers). Concentrations of these substances tend to increase along an aquifer’s flow-path, as contaminants from overlying land leach into the groundwater.
- Natural microbial metabolism and respiration within the aquifer (e.g., dissolved oxygen, nitrogen, organic carbon, bicarbonate). Concentrations of these substances tend to decrease along the aquifer flow path (Figure 2-3), unless they are replenished via recharge water.
- Chemical and microbial weathering of aquifer minerals (e.g., potassium, magnesium, calcium, arsenic). Concentrations of these substances vary with weathering rates of the minerals and groundwater residence time (Bennett et al. 2000). Consequently, their concentrations increase along the aquifer flow-path (Figure 2-3).

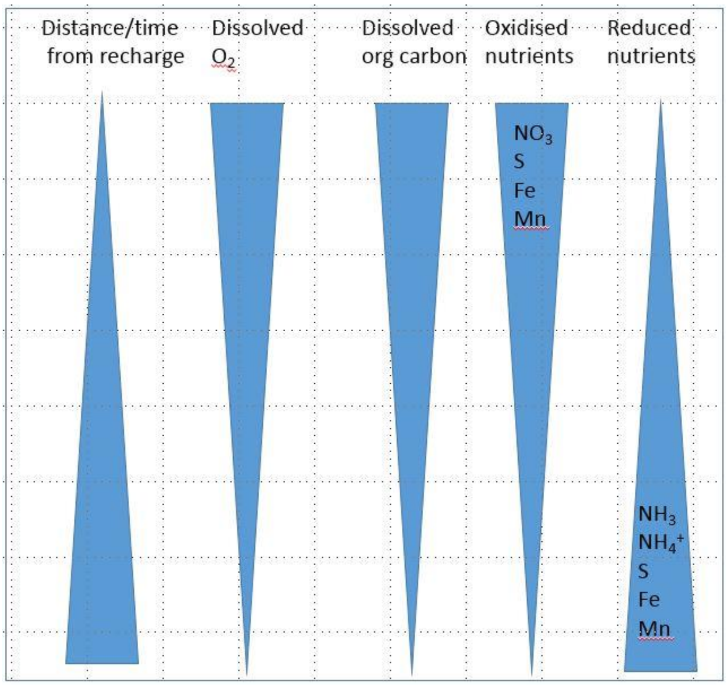

Figure 2-3: Schematic representation of changes in concentrations (width of bars) due to microbial transformations that occur within groundwater with distance from recharge and/or time underground. Assumes no recharge after initial entry into the aquifer. Modified after Boulton et al. (2008).

2.2.1 Dissolved oxygen and implications for chemical transformations

Oxygen is essential for aerobic life, especially for most stygofaunal invertebrates (Malard and Hervant 1999) that play a key role in GE functioning (see Section 2.4.2). Oxygen enters surface water from the air and from aquatic plant photosynthesis, and cooler water usually has higher dissolved oxygen (DO) concentrations than warmer water. Unpolluted, gravel-bed, stream water is usually close to 100% saturated (i.e., c. 10 mg/L, depending on its temperature) (Davies-Colley and Wilcock 2004), although natural processes and human impacts can deplete oxygen, especially where higher temperatures and organic carbon enrichment increase chemical and biological demand for oxygen beyond its replenishment rate. Recharge water, mainly from rivers and precipitation (rain, snow), usually has higher DO concentrations and increases groundwater DO concentrations (Baker et al. 2000, Griebler and Leuders 2009). Water flowing through an aquifer usually has minimal or no re-oxygenation from lack of contact with air for long periods (weeks, months, years, decades).

Oxygen is consumed within an aquifer by biochemical and geochemical processes. Consequently, groundwaters tend to contain less oxygen with increasing distance from their recharge zones and, typically, are 5-45% saturated (i.e., DO 0.5-4.0 mg/L) (e.g., Danielopol and Pospisil 2001, Hancock et al. 2005). However, karst aquifers may contain structures (e.g., tunnels, chambers, drip holes, etc.) that expose groundwater to air and facilitate some re-oxygenation within the aquifer. Groundwater velocity, which determines the rate of DO replacement, can be an important influence on groundwater chemistry.

Dissolved oxygen concentrations fluctuate naturally in many undisturbed GEs. These fluctuations can be very wide where aquifers are closely connected to surface waters, which experience large seasonal differences in flows (i.e., low stream water levels and flows are replicated within the aquifer). In other cases, fluctuations may result when there are seasonal peaks in recharge and/or nutrient arrival.

Although aerobic metabolism is the norm, some GEs are almost entirely and persistently anoxic, so that anaerobic and/or chemoautotrophic[10] metabolism predominates. Anoxic ecosystems include not only Archaea, bacteria and fungi (discussed in Section 2.3), but also some cave crustaceans (e.g., amphipods), which may obtain their energy via symbiotic bacteria on their cuticles that oxidise sulphur (Dattagupta et al. 2009, Flot et al. 2014). Most shallower aquifers are largely oxic (Rosen 2001), but both oxic and anoxic conditions are expected, at least at microscales (<1-100 mm). Bacteria with diverse metabolic pathways usually co-exist simultaneously within most GEs (Krumholz 2000, Kovacik et al. 2006), because heterogeneous aquifer porosity leads to micro-scale variations[11] in oxygen availability (Flynn et al. 2013, Handley et al. 2014). This diversity of co-existing bacterial metabolic pathways allows a GE to continue to function when DO availability changes: aerobically metabolising species will dominate when conditions are more oxic, and anaerobes will dominate as conditions become anoxic. In turn, the dominant microbial pathways influence concentrations of dissolved elements (nitrogen, manganese, iron, sulphur, etc.) and nutrients (e.g., nitrate, nitrite, ammonium, sulphate, etc.) within groundwater (see Section 2.2.1) (Downes 1985, Madsen et al. 1991, Chapelle 2000, Bethke et al. 2008, Wrighton et al. 2014).

Dissolved oxygen concentrations in groundwater control important biochemical processes, notably the reduction-oxidation (redox) potential of the groundwater, which determines the chemical state of key substances (e.g., nitrogen) and groundwater quality. As DO becomes scarce in an aquatic environment, different microbial metabolic pathways predominate. These pathways differ in the terminal electron accepting processes (TEAPs) used by organisms to utilise organic carbon for energy and generate respiratory end-products. The metabolic pathway that provides greatest energy requires oxygen as the electron acceptor and favours microbes that utilise that pathway (EPA 2014). As oxygen becomes depleted, nitrate, becomes the electron acceptor (TEAP) yielding the next most energy, and microbes that utilise this pathway are favoured. Each TEAP, using different electron acceptors, produces different metabolic end products (see Figure 2-4). The sequence of TEAPs utilised, termed the redox ladder (Figure 2-4), involves a progressive change in the chemical environment from oxidising to reducing (low DO or no DO environment). This change alone results in some important redox reactions proceeding without microbial involvement (Grundl et al. 2011).

Dissolved oxygen concentrations and redox conditions probably vary at quite fine spatial scales (<1 mm - >10 m), so that a three-dimensional mosaic of redox conditions exists at any time. Changes to redox conditions may occur across this mosaic, and probably rarely develop uniformly within large volumes of an aquifer. However, the balance of oxic versus reducing conditions within any part of an aquifer is likely to be very important to GE health and its ability to deliver ecosystem services. For example, these changes in water chemistry affect its quality – especially suitability for potable purposes – and its suitability for supporting many stygofauna (e.g., nitrate is reduced to nitrite, ammonia, ammonium and nitrogen gas and ammonia is highly toxic to most invertebrates – so too is hydrogen sulphide (e.g., Oseid and Smith 1974), which results from reduction of sulphates). Reduction of manganese oxide and iron hydroxide result in soluble metal compounds, which taint water rendering it unpotable (Downes 1986).

[10] Chemoautotrophic species use inorganic energy sources, such as hydrogen sulphide, elemental sulphur, ferrous iron, molecular hydrogen, and ammonia (rather than sunlight or organic carbon), to synthesize all necessary organic compounds (proteins, carbohydrates, etc.) from carbon dioxide.

[11] All sedimentary or interstitial habitats are heterogeneous at scales of less than millimetres. Alluvial aquifers comprising cobbles to clay-sized particles and incorporating substantial sub-surface preferential flow paths (as in Canterbury and probably the Wellington region also), are very heterogeneous at such scales.

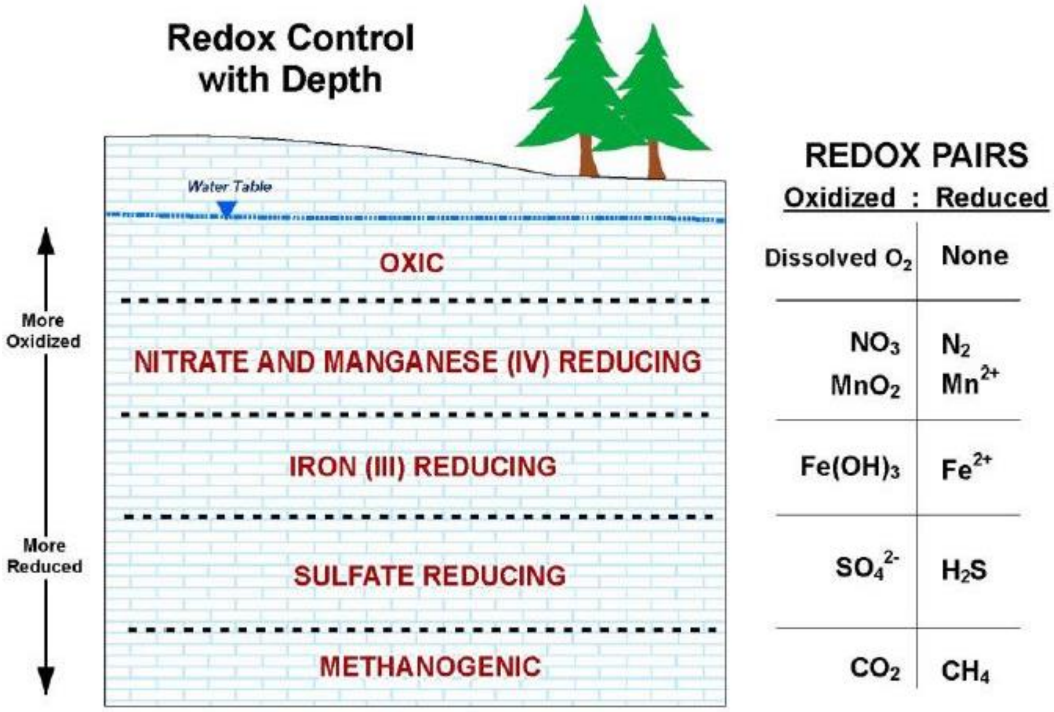

Figure 2-4: Sequence of terminal electron acceptors (redox ladder) favoured by microbial metabolism within different oxidised-reduced environments, such as with increasing depth within an aquifer. Redox pairs: oxidised and reduced forms of each electron acceptor within the sequence. From: EPA (2014).

As an example, groundwater in the Hutt Valley aquifer system was oxic near the aquifer recharge area and contained low concentrations of nitrate and sulphate, but little ammonium or hydrogen sulphide, and undetectable concentrations of dissolved iron (Downes 1986). Further along the flow path (near the foreshore), DO concentrations were lower and nitrate concentrations higher (due to leaching from land surface). Further still along the flow path, there was even less DO, most nitrate had disappeared, and dissolved iron concentrations were well above detectable limits (Downes 1986).

The relationship between groundwater hydrology, DO and water chemistry is summarised in Figure 2-5.

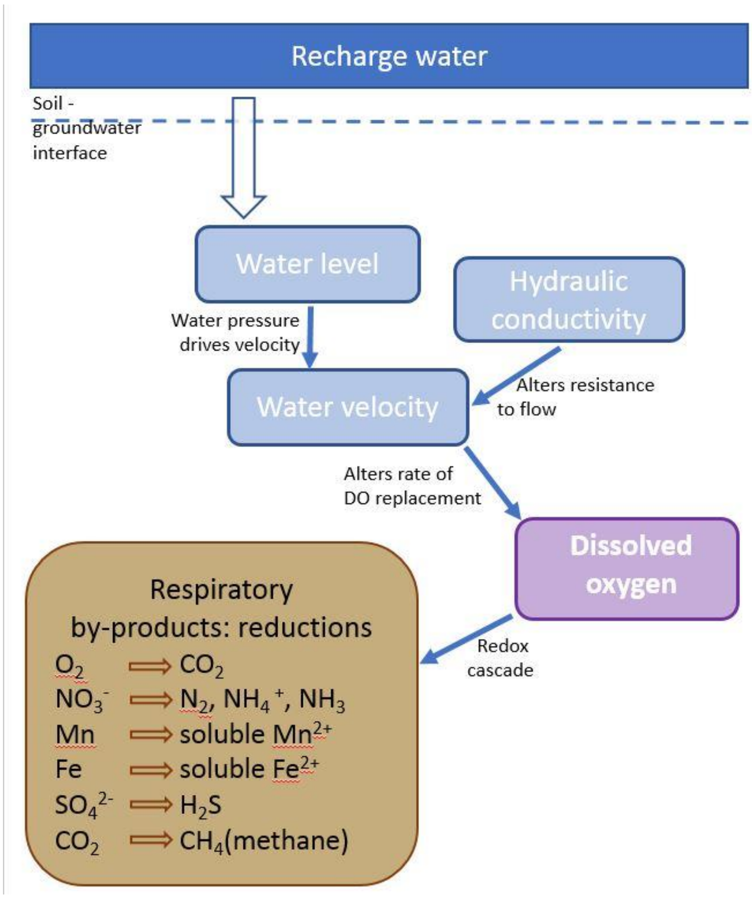

Figure 2-5: Interactions between aquifer hydrological properties and groundwater chemistry. Open arrows, inputs with recharge water; solid blue arrows, direct effects.

2.2.2 Groundwater quality

The term groundwater quality refers to the overall amount (concentration) of dissolved substances (including contaminants such as agricultural and industrial chemicals) and other contaminants (notably viruses, bacteria, protozoans) in water, with the connotation of fitness for a particular use. For example, groundwater from a particular aquifer may contain some dissolved substances at concentrations that render it suitable for stock water, but not for human consumption (White 2001). The main guidelines used to interpret groundwater quality in New Zealand are the Drinking-water Standards for New Zealand (Ministry of Health 2008) and the Australia and New Zealand Guidelines for Fresh and Marine Water Quality (ANZECC and ARMCANZ 2000).

Groundwater quality is dynamic, often varying in time and space over quite small scales, even within a single aquifer (Gunatilaka et al. 1994, Larned et al. 2014). For example, dissolved organic carbon (DOC) concentrations varied from undetectable to 7.5 mg/L and DO concentrations ranged from c. 3 to 16 mg/L in a Canterbury aquifer (6-10 m depth, 50-100 m to nearest river) over several years, and concentrations varied almost as widely within single wells (Larned et al. 2014). Such spatial and temporal changes in groundwater quality can be driven by both natural processes, like climatic variations between seasons, and human activities, such as changes in land use and management (Davidson and Wilson 2011). Shallower GEs may be more susceptible to contamination than deeper systems, depending on the overlying soil or substrate type, as they are closer to potential sources of contaminants and have shorter water retention times. GEs that have particularly long retention times may show time lags between historic land use and current water quality depending on water flow rates and where contamination occurred relative to water abstraction points.

2.3 Life in groundwater ecosystems

Bacteria, fungi and Protozoa are amongst the most universal forms of life, inhabiting almost all aquatic habitats, and are consistent components of GEs. Metazoan life (multicellular animals, more advanced than bacteria and Protozoa) inhabits most groundwater habitats worldwide (e.g., Australia, Papua-New Guinea, Korea, China, India, Oman, Morocco, Europe, UK, Canary Islands, North America, South America), except where limited by higher water temperatures (i.e., above c. 50 °C) (Borgonie et al. 2011, Ravaux et al. 2013). Some metazoan invertebrates are known from aquifers 3.6 km below the land surface (e.g., Borgonie et al. 2011, Edwards et al. 2012). Stygofauna are rarely seen because our only means of accessing them are wells or bores which are usually designed to exclude all but water. Also, many of the species involved are small (although larger invertebrates are known, including crustaceans in New Zealand that grow to over 25 mm in length). Therefore, because groundwater is largely hidden and difficult to access, few biologists worldwide have explored stygofauna and its biodiversity (Gibert et al. 1994).

2.3.1 Microbes and biofilms

Microorganisms (or microbes), including bacteria, fungi and yeasts, are the most abundant and diverse group of living organisms on Earth, in terms of habitats occupied and metabolic functional capability (Griebler and Leuders 2009, Lategan et al. 2012). Microbes are ubiquitous in groundwater systems all over the world, often to significant depths (>3600 m below land surface) and extreme physico-chemical conditions (low DO, high temperatures, etc.) (Parkes et al. 1994, Stevens and McKinley 1995, Borgonie et al. 2011). Although typically less abundant and less diverse than bacteria in groundwater, fungi and yeasts are significant contributors to natural transformations of dissolved substances in shallow aquifers (Lategan et al. 2012).

Bacteria are the most abundant and diverse type of organism in groundwater (Griebler and Leuders 2009, Lategan et al. 2012). More than 2,500 different kinds (probable species or operational taxonomic units (OTUs[12])) occur in some aquifers overseas (Flynn et al. 2013) and in New Zealand (e.g., Van Bekkum et al. 2006, Sirisena et al. 2013). Using advanced DNA-based techniques, 6579 OTUs were distinguished from 35 hydrologically-isolated GE sites across New Zealand (Sirisena 2014). Most (65 %) OTUs occurred at single sites, few of these OTUs were very abundant, and the 35 OTUs detected in 10 or more samples comprised 73.6% of total abundance (Sirisena 2014). This indicates many unique bacterial species (OTUs) are present in New Zealand groundwater and that the community comprises mostly rare and locally endemic species, with fewer geographically widespread and abundant species (Sirisena 2014).

Groundwater microbial communities appear to differ in composition and ecological functioning in response to changing physical and chemical conditions between and within locations (Griebler and Leuders 2009, Flynn et al. 2013, Sirisena et al. 2014). New Zealand studies have shown that water chemistry, especially redox potential, is correlated with bacterial species composition, and that geological factors (e.g., geographic region, aquifer lithology, recharge zone land use, well depth, residence time) are a secondary influence (Sirisena et al. 2014).

[12] OTUs are probable, but unconfirmed species.

The majority of microbes in groundwater systems are attached to substratum (i.e., benthic, not free in the water or planktonic), closely associated with biofilms (Harvey et al. 1984, Brunke and Gonser 1997). Biofilms comprise any group of microorganisms in which the cells stick to each other and to a surface. These adherent cells become embedded within a slimy extracellular matrix that is composed of extracellular polymeric substances (EPS) produced largely by the cells themselves. Biofilms develop naturally in any wet or aquatic environment[13], such as rock and sediment particles that comprise the aquifer matrix (Figure 2-6). Given the vast volume of the world's aquifers and the enormous surface areas present on mineral and rock surfaces within these aquifers, the habitat for biofilms and microbes is huge, containing an estimated 40% of the earth's terrestrial prokaryotic biomass (Griebler and Leuders 2009).

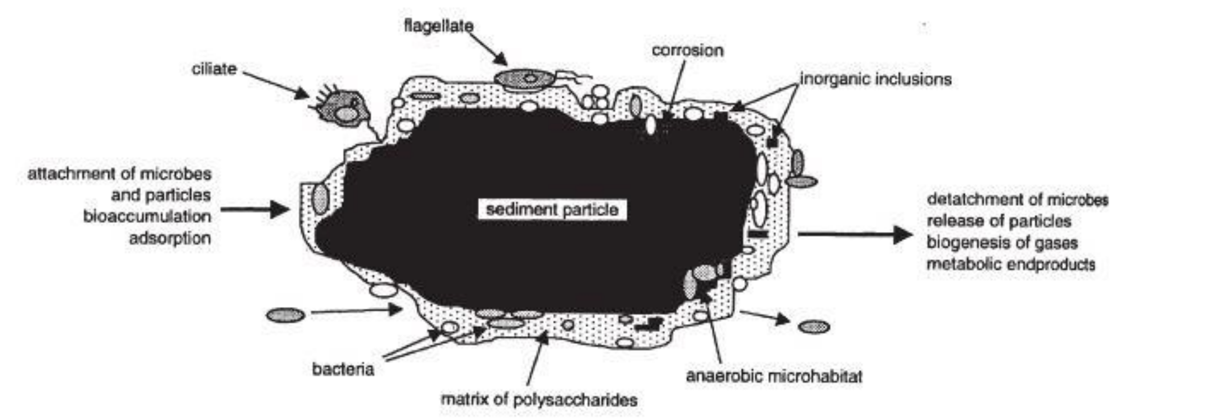

Figure 2-6: Alluvial groundwater biofilm composition and function. Source: Griebler (2001).

Biofilms are active, metabolising organic carbon and other nutrients in hyporheic environments (Robertson and Wood 2010), streams (e.g., Parkyn et al. 2005), caves (e.g., Simon et al. 2003), wastewater (e.g., Tanji et al. 2006) and groundwater (e.g., Langmark et al. 2004). Most studies concur that biofilms are a key functional component in GEs and this is true for biofilms in New Zealand's alluvial aquifers (e.g., Fenwick et al. 2004, Boulton et al. 2008). Alluvial aquifer biofilms take several months to develop (Williamson et al. 2012). They are more active (i.e., uptake of organic carbon) closer to upper catchment recharge sites where there is more dissolved organic carbon, compared with lower in the catchment, where organic carbon availability is usually lower, and nitrate (and total nitrogen) concentrations higher (Williamson et al. 2012). Groundwater chemistry, particularly its reducing oxidising properties, strongly influences bacterial community structure and biochemical transformations within New Zealand aquifers (Van Bekkum et al. 2006, Sirisena et al. 2014). This suggests that these communities and their natural ecological processes may be altered or at risk from changes in groundwater chemistry and/or DO availability, whether human-induced or natural.

2.3.2 Archaea

Archaea are single-celled organisms that, like bacteria, lack nuclei and other internal membranous structures. Similar in size to many bacteria, they are biochemically and genetically distinct from the other two major divisions of life: Bacteria and Eukarya (Eukaryota) (fungi and plants, Protozoa and other animals, mammals). There is scant information on Archaea in New Zealand, but they are likely

[13] Biofilms appear universal wherever bacteria occur on surfaces in wet or broadly aquatic environments. This includes natural habitats such as river and lake sediments, marine environments, and within man-made habitats, such as water supply and wastewater pipes.

to be an important component of New Zealand's GE composition and functioning (e.g., Griebler and Leuders 2009). For example, international studies have demonstrated that methanogenesis and other important processes in groundwater environments are driven by archaeal communities (Flynn et al. 2013, Castelle et al. 2015).

2.3.3 Stygofauna

Protozoa (Protista)

Protozoa are single celled organisms. More than 50,000 species have been described, most of which are free-living. Protozoa are found in almost every possible habitat and feed on organic matter, such as other microorganisms or organic debris (Barnes 1980).

WHAT ARE STYGOFAUNA?

Stygofauna is a collective term for aquatic invertebrate (protozoan and metazoan) organisms that live in groundwater within aquifers. The term is derived from the mythical River Styx, which flows into the Greek Underworld. Stygofauna inhabit interstices within alluvial aquifers, crevices and tunnels within limestone and cracks and crevices within other fractured rock. Larger animals inhabit larger spaces, and stygofauna include fishes in other countries.

Amoebae and flagellates, two types of Protozoa are common in groundwater, whereas ciliates, a third type, are less common. Protozoans consume bacteria and provide food for other larger invertebrates occupying higher trophic levels (Novarino et al. 1997). They tend to be present, but sparse in pristine groundwater, and much more abundant where there is organic contamination (e.g., Fusconi and Godhino 1999). Greatest densities are usually within the upper aquifer and the unsaturated zone immediately above the water table in both uncontaminated and contaminated aquifers, whereas bacteria tend to be more evenly distributed with depth in the aquifer (Madsen et al. 1991). Communities of these small bacterial grazers reproduce very quickly to control bacterial abundances, and modify the rates and nature of some biogeochemical processes via their selective feeding (Madsen et al. 1991, Kinner et al. 1998, Andrushchyshyn et al. 2007). For these reasons, bacterial grazers are considered to be very important in ecosystem functioning (Madsen et al. 1991, Andrushchyshyn et al. 2007).

Very little is known about New Zealand's Protozoa, apart from some studies on human pathogens, such as *Cryptosporidium* and *Giardia* (Collins et al. 2007). These disease-causing protozoans are widespread and abundant in New Zealand, and our groundwaters are vulnerable because overlying soils and the aquifers themselves are typically porous (White 2001). Other protozoans seem likely to be widespread and abundant, especially where groundwater is enriched by land use activities.

Metazoa

A wide diversity of metazoan organisms inhabits New Zealand groundwater environments, notably alluvial aquifers. These range from miniscule ostracods and copepods through to amphipods and isopods up to 25 mm

METAZOA

Metazoan animals are multicellular, heterotrophic animals that develop from embryos. This group encompasses all animals with differentiated tissues, including nerves and muscles, ranging from sponges to humans.

(Barnes 1980)

long. The fauna of New Zealand's alluvial aquifers is still poorly known, but collections held by NIWA include (Scarsbrook et al. 2003):

- Cnidaria or Coelenterata (small, unpigmented, *Hydra* or anemone-like animals),
- Nematoda (nematode worms),
- Platyhelminthes (flatworms, see Figure 2-7),
- Mollusca (snails),
- Annelida (worms),
- Tardigrada (water bears),
- Hexapoda or Insecta (water beetles),
- Crustacea (ostracods, copepods, syncarids, amphipods, isopods), and
- Acari (water mites, see Figure 2-10 later in this section).

Other groups (e.g., sponges, hydroids, nemertean worms, rotifers, leeches) are also likely to be present in New Zealand's alluvial aquifers. Smaller organisms, frequently referred to as meiofauna to distinguish them from microbes and macrofauna[14], are an under-studied component of groundwaters, yet likely to be significant because of their small size, short generation times and the high volumes of small interstitial habitat space for them in most alluvial aquifers.

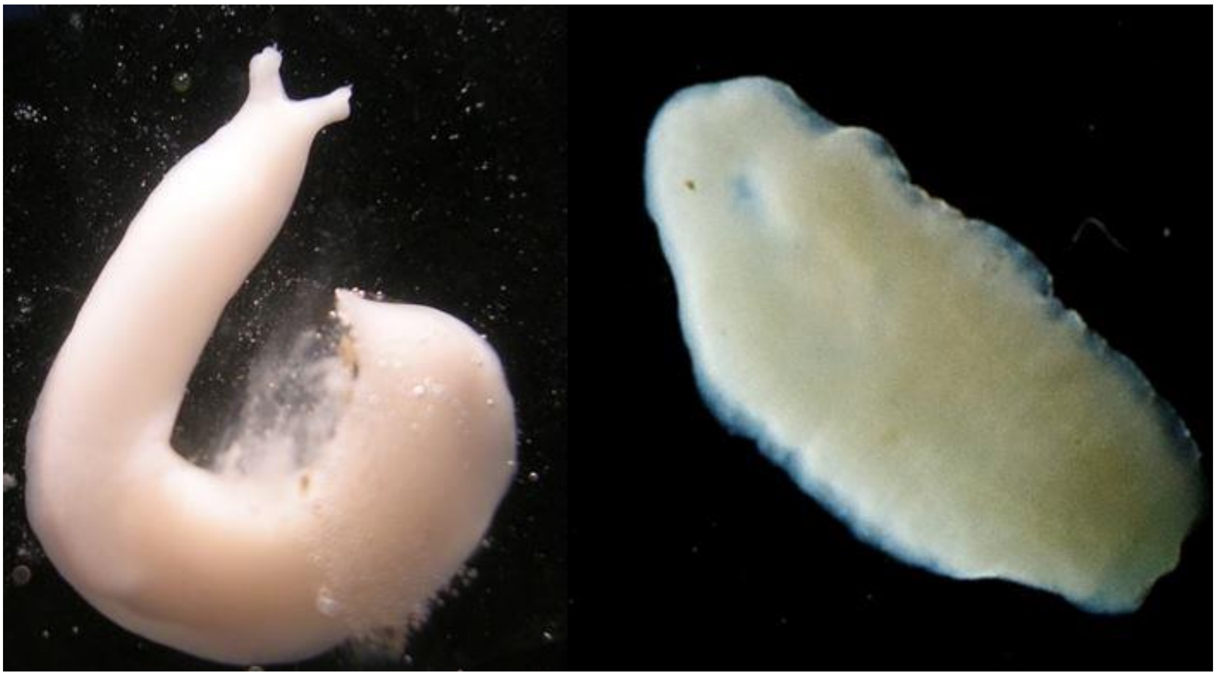

Figure 2-7: Two flatworms, examples of stygofauna from New Zealand aquifers. Left, *Prorhynchus* sp. (c. 35 mm long) from alluvial groundwater adjacent to the Selwyn River, Canterbury (image G. Fenwick, NIWA). Right, unknown flatworm (c. 7 mm long) collected by divers from the wall of the Pearse Resurgence, (image N. Boustead, NIWA).

[14] These three groups of organisms are distinguished on size (macro-, retained on 500 µm mesh; meio-, passing through 1 mm and retained on 64 µm mesh; micro-, passing through 64 µm mesh).

2.3.4 Richness and endemism of New Zealand stygofauna

An abundant stygofauna of large crustaceans (up to 20 mm long) was discovered within Canterbury's alluvial aquifers in the 1880s (Chilton 1882, 1894). Further investigations by Chilton added more species and genera, all endemic to New Zealand. Subsequent investigation of our stygofauna was sporadic, with a few workers adding to our knowledge from time to time. One scientist, G. (Willy) Kuschel, intrigued by crustaceans found in Waimea Plains groundwater, pumped wells throughout much of New Zealand, discovering a rich fauna, largely of crustaceans. These collections contain c. 25 undescribed species (Fenwick 2000) awaiting formal description and naming. Research into the biodiversity and functioning of these ecosystems continues to be hindered by the poor state of taxonomic knowledge, specifically the means to identify and define the numerous species comprising GEs.

DO FISH LIVE IN AQUIFERS?

Some Māori report historical accounts of large white tuna, or eels, coming out of groundwater in springs. In Canterbury, these tuna are said to have stomachs bulging with creatures resembling snails and some larger crustaceans known from the region's aquifers.

Stygofaunal fish are otherwise unknown from New Zealand, but do occur in some other countries.

Seven rivers walking - Haere Mārire 2017. Gaylene Barnes and Kathleen Gallagher (directors), Raynbird-Wickcandle Co-production, 84 mins. NZ International Film Festival (19 August 2017). http://www.wickcandle.co.nz/index.html

There are very few detailed investigations of New Zealand groundwater biodiversity. Some insights come from the above historical collections and more recent collections, but the overall biodiversity is very poorly resolved. In part, this is due to the inaccessibility of alluvial, karstic and fractured rock groundwater habitats, the inadequate sampling techniques, the generally low densities, small body sizes and cryptic nature of many groundwater invertebrates (Coineau 2000), and difficulties in distinguishing species. Historically, New Zealand's stygofauna received scant attention by taxonomists and the advanced taxonomic expertise essential for establishing and reliably identifying these challenging organisms is scarce. Molecular (DNA) methods are currently being used in a two-year research project, through the New Zealand's Biological Heritage National Science Challenge, aimed specifically at determining scales of stygofaunal and bacterial biodiversity within shallow alluvial aquifers [15]. However, substantial taxonomic work will be necessary to distinguish and name the new taxa that are being discovered.

Data available to date from existing collections and investigations of stygofauna indicate that stygobitic invertebrates occur universally and consistently in alluvial sediments and karstic aquifers (Juberthie 2000, Ward et al. 2000), including throughout New Zealand (Scarsbrook et al. 2003). Although poorly known, New Zealand's stygofauna appears to be remarkably rich and diverse, compared with that found elsewhere, with many species awaiting formal naming and many more species awaiting discovery. Some 112 named species are reported from New Zealand (Table 2-1) (Scarsbrook and Fenwick 2003, unpublished data). Another c. 700 collections of groundwater amphipods and isopods await analysis, but preliminary examination revealed >50 new species (Fenwick 2000). All species (except some copepods) are endemic to New Zealand, most completely new, and several are probably restricted to single aquifers or discrete aquifer systems (Fenwick 2001a, Haase 2008).

[15] See: http://www.biologicalheritage.nz/programmes/assessment/groundwater .

New Zealand's endemic stygofauna includes species belonging to families known only from New Zealand and only from aquifers. For example, our six described stygofaunal amphipod species (Figure 2-8) belong to three endemic families. Two of the four endemic genera comprise species that are strictly stygobitic (Fenwick 2001a). Some of these genera represent ancient lineages (e.g., *"the amazing Phreatogammarus, … which may be the most primitive living Crangonyctid [sic], now a perfect relict"* (Barnard and Barnard 1982). Stygofaunal isopods[16] belonging to the ancient (morphologically unchanged for >300 million years) Gondwanan suborder Phreatoicidea are further examples of New Zealand's remarkable, ancient biodiversity (e.g., Wilson 2008). At least three species, plus another undescribed one (Fenwick et al. 2009), are stygobites, each apparently endemic to separate regions of New Zealand. Their conservation status was considered data deficient in 2013 (Grainger et al. 2014).

Table 2-1: New Zealand's known stygofauna biodiversity. Numbers of described (scientifically named) and confirmed new to science (undescribed) species from springs, caves and alluvial groundwater. † excludes species known only from riverine and hyporheic habitats; ‡ additional species also known.

	Numbers of species		Number endemic	
Group	**Described**	**Undescribed**	**Genera**	**Families**
Cnidaria† (Hydra)		>1	?	?
Nematoda (round worms)	0	>1	?	?
Platyhelminthes†*(flatworms)	2	?	0	0
Gastropoda†*(snails)	43	?	15	0
Oligochaeta†* (worms)	2	?	0	0
Polychaeta† (bristle worms)	1	?	0	0
Tardigrada (water bears)	0	>1	?	?
Ostracoda† (seed shrimps)	0	>6	?	?
Copepoda† (water fleas)	10	>11	0	0
Syncarida	7	7	0	0
Isopoda† (scuds)	6	2	>4	
Amphipoda†‡ (sand hoppers)	6	>28	>4	4
Acari† (water mites)	32	?	21	1
Coleoptera† (water beetles)	3	0	2	3
TOTAL	**112**	**>57**	**>46**	**8**

New Zealand's stygofauna appears to include some non-indigenous or cosmopolitan species (copepods) (Karanovic 2005). Some of these copepods were apparently translocated by early European settlers via drinking water barrels, and their establishment may explain the low endemism reported for New Zealand's stygofaunal copepods (see Karanovic 2005).

[16] Three of New Zealand's nine described phreatoicids live in Canterbury's aquifers, and one undescribed species is known from groundwater in Southland. The other six described and 1-2 undescribed phreatoicids live in habitats inundated by groundwater at least seasonally (Wilson and Fenwick 1999).

New Zealand's total stygofaunal biodiversity is likely to be substantially greater than the c. 170 species indicated in Table 2-1, because some stygofaunal groups (e.g., ostracods) have not been examined by experts, and because there are few or no collections from many parts of New Zealand (e.g., Northland, Gisborne, Taranaki, Manawatu-Wanganui, Otago). Extrapolation from the composition of the world's stygofauna biodiversity (Botosaneanu 1986) indicates that the country's stygofauna comprises >420 species. This is likely to significantly under-estimate the true species richness (Scarsbrook and Fenwick 2003).

Figure 2-8: ***Phreatogammarus fragilis*, a large (body up to 20 mm long) amphipod crustacean from Canterbury's alluvial aquifers.** Image: N Boustead, NIWA.

Another reason for expecting high diversity in New Zealand's stygofauna is that many stygofaunal species appear restricted in their geographic ranges. Short-range endemism is likely because, unlike freshwater insects and many other organisms, stygofauna lack dispersal stages in their life histories, so appear unlikely to migrate between catchments. Also, hydrogeochemical (Rosen 2001) and microbial (Sirisena et al. 2013) diversity of New Zealand's aquifers indicates that populations isolated within a catchment are likely to adapt differently over time from those in adjacent catchments. Continued isolation means populations are likely to evolve into new species, as with New Zealand's hydrobiid snails (Haase 2008).

Molecular techniques are revealing genetic differences between populations and unrecognised species in groundwaters internationally, and are particularly useful because many stygofauna are difficult to distinguish based on appearance (i.e., they are morphologically conservative and cryptic) (Lefebure et al. 2007, Camacho et al. 2011). For example, Australian stygofaunal research continues to reveal remarkable biodiversity and short-range endemism of morphologically very similar species inhabiting subterranean habitats (e.g., Cooper et al. 2007, Bradford et al. 2010, Guzik et al. 2011a, Guzik et al. 2011b, Bradford et al. 2013).

2.3.5 Stygofauna communities

Alluvial aquifer stygofaunal communities[17] are best known for their macro stygofauna, which is typically dominated by crustaceans, notably amphipods, copepods, ostracods. Water mites also are common, along with representatives of other crustacean groups (isopods, syncarids), gastropod snails, flatworms, annelid worms and beetles. Larger animals (e.g., lobsters, shrimps, fishes and salamanders) inhabit some limestone or karst aquifers in some parts of the world (Elliott 2000), but are unknown for New Zealand. Despite the size of some macro stygofauna, most stygofaunal communities are numerically dominated by smaller micro and meiofaunal invertebrates (principally protozoans, nematodes, rotifers), but these are very poorly studied.

Groundwater invertebrates differ in the extent to which they inhabit subsurface habitats and are classified accordingly (Figure 2-9) (Gibert et al. 1994), with specific terms for clarity. The term stygofauna is a more general descriptor, mostly referring to stygophiles and stygobites, but it may encompass stygoxenes when they are found in groundwater (see the box for definitions).

Stygofauna appear longer lived than equivalent surface-water dwellers, seem adapted to periodic food scarcity, with lower metabolic rates (reduced oxygen consumption) that can be reduced further when food is scarce, as well as a greater tolerance of low oxygen availability (Spicer 1998, Mosslacher 2000, Wilheim et al. 2006). Morphologically, they tend to share several characteristics (Gibert 2001):

- small body sizes,
- elongated bodies and antennae,
- poorly developed or no eyes,
- and bodies and eyes are colourless.

SHORT-RANGE ENDEMICS IN OUR GROUNDWATERS

Some examples of short-range endemism in New Zealand include stygobitic hydrobiid snails (Haase 2008) and some stygofaunal amphipods.
The large amphipod *Paracrangonyx compactus* is reported only from the lower Waimakariri-Selwyn catchments over an area of c. 550 km^2, whereas *P. winterbourni* is known only from around Templeton (<2 km^2) (Fenwick 2001b).
The three described species of stygobitic phreatoicid isopods appear to inhabit different Canterbury catchments (Scarsbrook et al. 2003): *Phreatoicus typicus* is known only from the Waimakariri-Selwyn catchments. *Phreatoicus orarii* is known only from adjacent to the Orari River (South Canterbury). *Neophreatoicus assimilis* is recorded from tributaries to the adjacent Opihi River only.

Records of other New Zealand groundwater amphipods and isopods indicate some with wider distributions, but more detailed studies using molecular techniques will confirm the scale of stygofaunal endemism.

[17] An ecological community (= biocoenosis) is a group or association of species populations concurrently living in the same place, which may or may not be functionally inter-dependent.

TYPES OF FRESHWATER INVERTEBRATES BASED ON HABITAT PREFERENCES (see Figure 2-9):

Epigean species are ones which characteristically live above the ground surface or above ground within surface (epigean) waters.

Hypogean species typically dwell underground in subterranean or hypogean environments.

Hyporheic species live mostly within the permeable bed of surface streams and rivers. Collectively they comprise the hyporheos of a stream.

Stygofauna are animals (predominantly invertebrates) that live in groundwater. Three main types of stygofauna are recognised based on their use of hypogean habitats:

a. **Stygoxenes** are epigean dwelling species, with no affinities for groundwater habitats, although they may occur in groundwaters or caves accidentally.
b. **Stygophiles** actively use groundwater habitats at times, but mostly live in epigean habitats. Three types of stygophiles are distinguished:
    - **occasional hyporheic dwellers** (benthic species, perhaps larvae stages that live below the sediment surface temporarily);
    - **amphibite species** (obligate users of both epigean and hypogean habitats as part of their life histories);
    - **permanent hyporheos** (all life stages are benthic and/or hypogean dwellers).
c. **Stygobites** are obligate hypogean dwellers at all life history stages, usually with specialised adaptations to life in groundwater. Two types are distinguished:
    - **ubiquitous species** occur from hyporheic to deep groundwater habitats;
    - **phreatobitic species** live only in deeper groundwaters.

From: (Gibert et al. 1994).

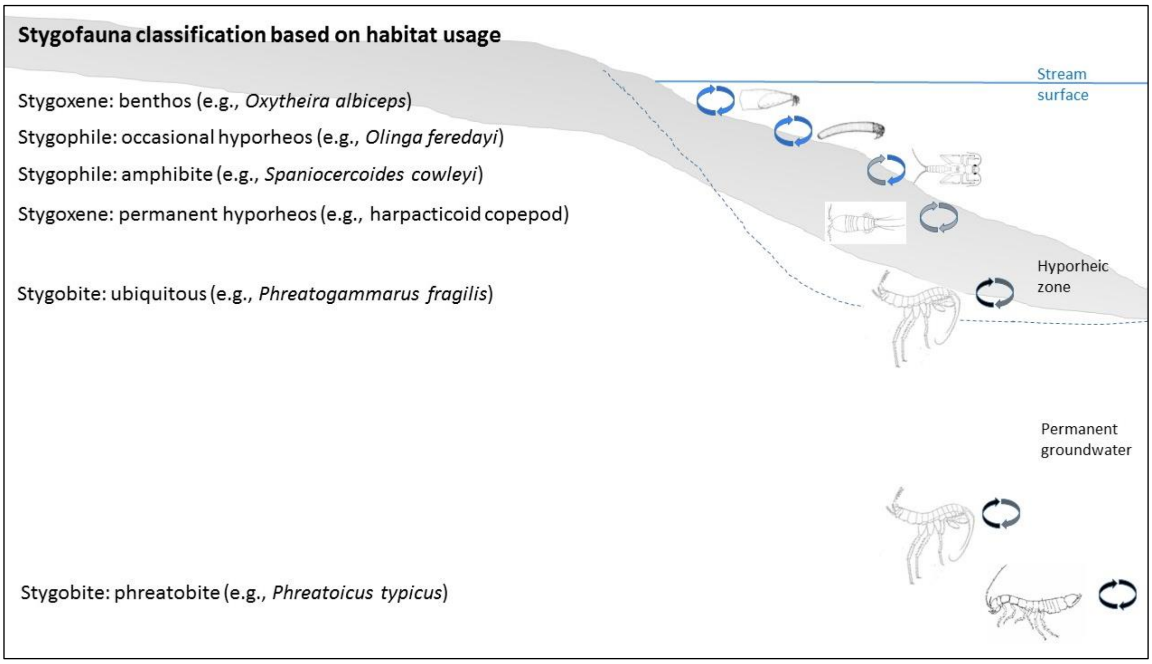

Figure 2-9: Classification of stygofauna based on habitats used. Modified after (Gibert et al. 1994, Scarsbrook et al. 2003).

Stygobite life histories typically involve delayed maturity, less frequent breeding, longer life times, produce fewer larger eggs than related/equivalent surface-living species, and their life-histories lack dispersal stages (Gibert et al. 1994). At least some stygofaunal species, notably amphipods, appear pre-adapted to living in food-scarce environments, having lower metabolic rates and oxygen demand (compared with epigean or non-stygofaunal species), which reduce even further when starved (Spicer 1998, Wilheim et al. 2006). Their lower metabolic rates and lower DO requirements further enhance the abilities of stygobites to inhabit interstitial spaces where oxygen availability can fluctuate (Wilheim et al. 2006).

Stygofauna tend to have low population densities and community compositions vary with seasonal recharge events, especially close to rivers or other areas of recharge, with the magnitude of community response decreasing away from the recharge source (e.g., Danielopol 1992, Pospisil et al. 1994, Mösslacher 1998, Hancock and Boulton 2008). Although reported as a response to increases in DO concentrations (Mösslacher 1998), these seasonally increased abundances could equally be a direct response to elevated water levels (any species aestivating within the zone of intermittent saturation (ZIS) become active in the GE community) and increased food from the pulses of newly recharged water.

Stygofaunal communities are more abundant and diverse within 1-2 m of the groundwater surface and the ZIS than deeper within the aquifer (Pospisil 1994, Mauclaire and Gibert 2001, Datry et al. 2005a, Hancock and Boulton 2008). Some species migrate deeper only when DO concentrations increase above sub-oxic levels (Pospisil 1994). Increased densities closer to the surface in both recharge and non-recharge locations appear to be a response to greater food (organic carbon and microbial biofilm) availability where oxygen is not limiting (Holsinger 1966, Sinton 1984, Mosslacher 2000, Fenwick et al. 2004, Hartland et al. 2011). Species present at shallower depths tend to be more stygophilic and, regardless of food availability, are replaced by more stygobitic ones with increasing depth into an aquifer, usually with no net change in species richness (Brunke and Gosner 1999, Datry et al. 2005a).

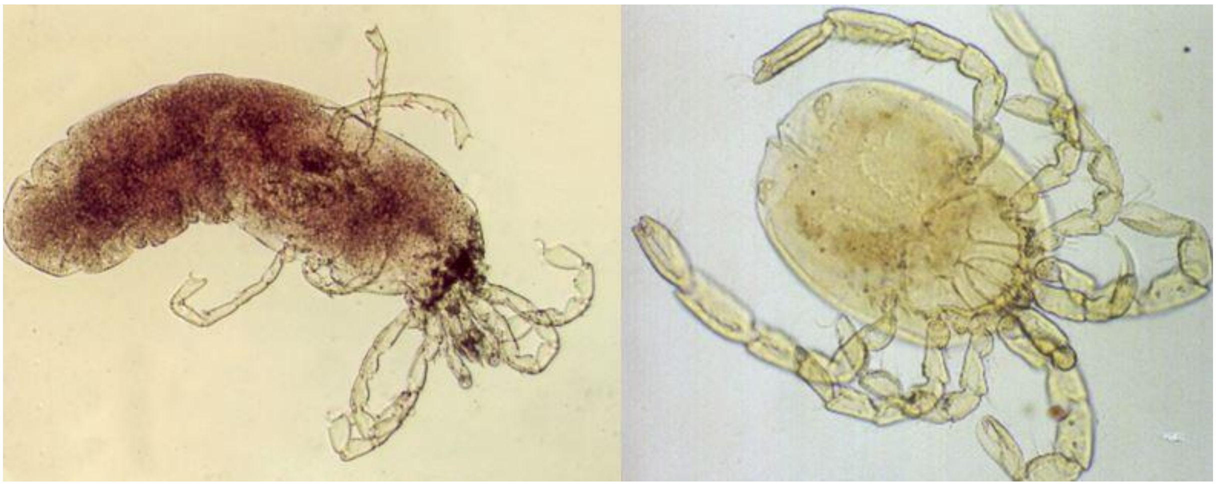

Figure 2-10: Two water mites from Canterbury groundwater: left, *Euwandesia tenebrio*; right *Schminkea* sp.
Images: D. Olsen, Cawthron Institute.

Roots of trees that penetrate aquifers also are associated with higher GE taxon richness, providing food (directly and indirectly as dissolved and fine particulate carbon), habitat, shelter and a substrate for fungi that may be consumed by stygofauna (Jasinka et al. 1996, Hancock and Boulton 2008). Several stygofaunal amphipods (*Phreatogammarus* sp.) were on large pieces of ancient wood exhumed from below the water table (4-8 m below ground) during construction in Christchurch (Duncan Gray, Environment Canterbury, pers. comm.).

Groundwater physico-chemistry appears to influence stygofaunal community compositions in some studies (e.g., Notenboom et al. 1994, Malard and Hervant 1999, Galassi et al. 2009), but not in others (e.g., Notenboom et al. 1995, Plenet et al. 1996, Dumas and Lescher-Moutoue 2001, Di Lorenzo and Galassi 2013). Low densities, low richness and heterogeneous spatial distribution are considered characteristic of relatively unimpacted GEs (Notenboom et al. 1995, Galassi et al. 2009, Hahn and Fuchs 2009, Martin et al. 2009), but the low richness and heterogeneity may be more a consequence of low densities.

2.4 Groundwater ecosystem functioning: dependence on external resources

As noted in Section 2.1, GEs are heterotrophic because they rely on imported organic carbon[18] as the primary energy source in the absence of light and photosynthetic plants (they also rely on imported oxygen). Organic carbon occurs predominantly as either dissolved (DOC) or, less commonly, as very fine particulate organic carbon (POC). Both forms of organic carbon are carried into aquifers with inflowing recharge water in the upper catchment, where it is incorporated into biofilms and bacteria (Fenwick et al. 2004, Boulton et al. 2008, Hartland et al. 2011). Biofilms and/or microbes are grazed by stygofauna and their organic carbon becomes incorporated into stygofauna tissues, as well as lost via respiration, excreta, death and decay (Figure 2-11) (Fenwick et al. 2004, Boulton et al. 2008, Hartland et al. 2011).

Within GEs, organic carbon and nutrients from other ecosystems move between trophic levels (e.g., biofilms, heterotrophs, predator) and detritus (i.e., non-living organic matter), with losses due to respiration within each trophic level (Sinton 1984, Fenwick 2001c, Boulton et al. 2008, Hartland et al. 2011, Williamson et al. 2012, Fenwick 2016). Much of the organic carbon (energy) within such ecosystems is recycled repeatedly between living and dead organic matter, and between dissolved, biofilm, living and particulate states, with losses due to respiration and carbon dioxide production at every step (Hartland et al. 2011).

HETEROTROPHIC ECOSYSTEMS & ORGANIC CARBON

Almost all ecosystems, including aquatic ecosystems, rely on organic carbon and dissolved oxygen (DO) produced by photosynthetic plants as their fundamental energy source and to support life. Heterotrophic ecosystems lack photosynthetic plants, depending entirely on organic carbon and DO imported from photic ecosystems. Hyporheic environments, heavily shaded streams, deep lake beds, coastal sediment habitats and deep seafloor ecosystems are among the better known heterotrophic ecosystems.

Organic carbon occurs naturally in diverse physical (living, dead and variously decayed plants, detritus, bacteria, fungi, animal tissue, etc.) and chemical forms, which are transformed as organic carbon is consumed, respired and recycled through an ecosystem. Organic carbon's availability in the right form often limits populations within heterotrophic ecosystems.

[18] Most groundwater ecosystems appear to utilise organic carbon as their primary energy source (i.e., bacteria and invertebrate animals), although some extreme microbes may utilise other energy sources.

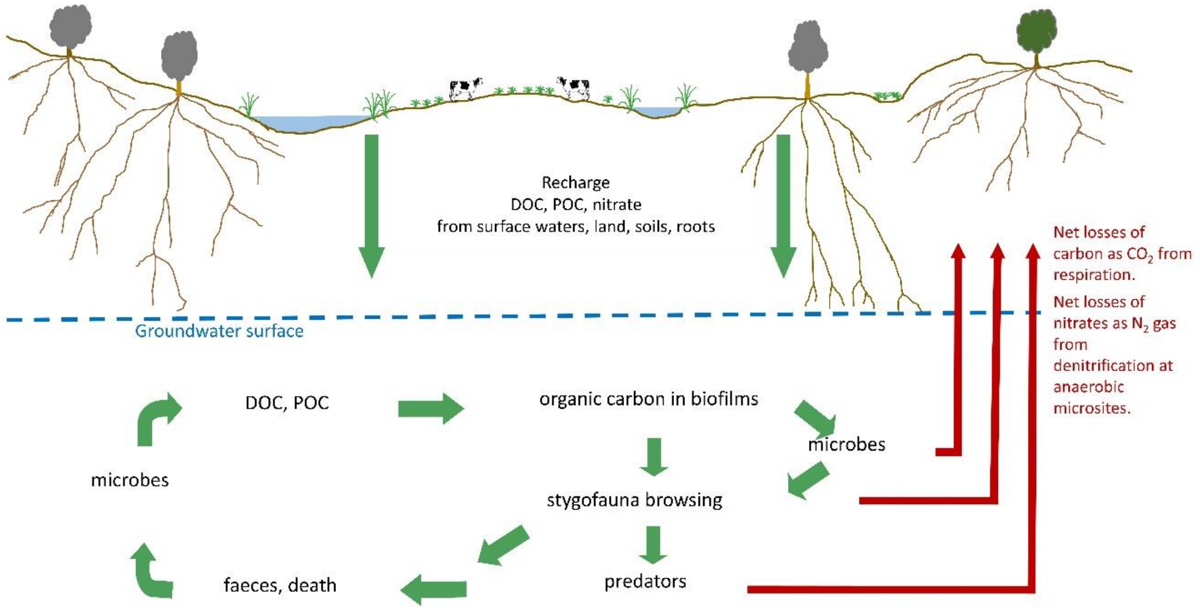

Figure 2-11: Simplified representation of organic carbon flows into and within groundwater ecosystems. DOC = dissolved organic carbon, POC = particulate organic carbon. After Fenwick (2016).

Biological activity in GEs is frequently limited by organic carbon availability (Jones Jr 1995, Baker et al. 2000) and many stygobitic species are adapted to living in aquifers where food is scarce, with their metabolic (and reproductive) rates and oxygen requirements generally appreciably lower than those of equivalent epigean or stygophilic species (Spicer 1998, Wilheim et al. 2006). Variability in organic carbon availability strongly influences GE community composition and abundance (e.g., Sinton 1984, Baker et al. 2000, Fenwick et al. 2004, Datry et al. 2005b, Hancock and Boulton 2008), including bacteria that utilise other energy sources (Wrighton et al. 2014). DOC concentrations tend to be greater in upper catchment recharge areas than lower in the catchment (Williamson et al. 2012), and recharge at any other point along a catchment, including from overlying land use activities, can add to DOC concentrations (Jones Jr 1995, Baker et al. 2000, Scarsbrook and Fenwick 2003). Concentrations of DOC are usually lower deeper within an aquifer (Mauclaire and Gibert 2001, Datry et al. 2004, Helton et al. 2015). DOC also varies in concentration and composition (relative concentrations of different sugars) seasonally (Gunatilaka et al. 1994, Chapelle et al. 2013).

Different sources of organic carbon occur in some aquifers. Buried ancient wood and other recalcitrant organic material within some alluvial aquifers had associated stygofauna, including crustaceans (D. Gray, Environment Canterbury, pers. comm.). Plant roots and their associated mycorrhizal (symbiotic) fungi are potentially important sources for shallow GEs. In Western Australia, some tree roots penetrate >30 m to enter the groundwater where root mats support a diverse stygofauna (c. 25 species, some 10 cm long, including fish, crayfish, leeches, amphipods) (Jasinka et al. 1996). Organic carbon inputs to New Zealand aquifers may occur from plant roots that penetrate groundwater (e.g., Matagouri: *Discaria toumatou*, Calder 1961).

Figure 2-12 is a simplified representation of our understanding of organic carbon flows in GEs, both oxic and anoxic.

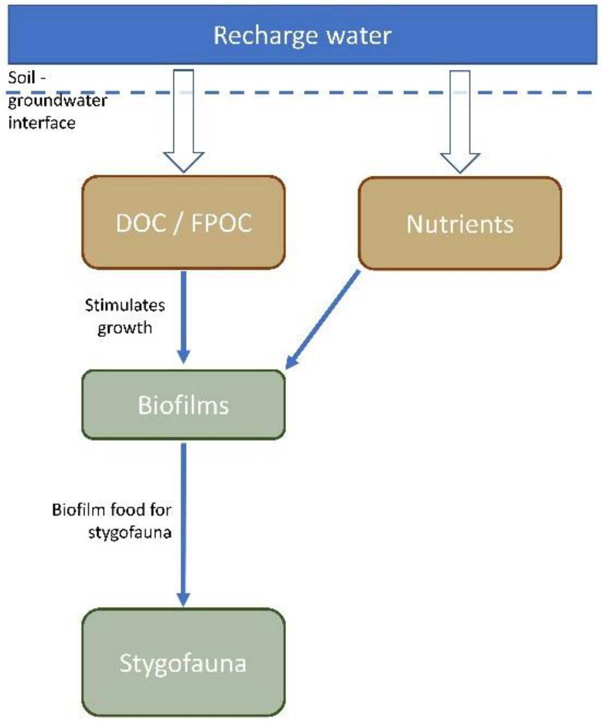

Figure 2-12: Simplified organic carbon flow path in oxic and anoxic groundwater ecosystems. DOC, dissolved organic carbon; FPOC, fine particulate organic carbon; open arrows, inputs via recharge water; solid arrows, direct effects of one component on another.

The supply of DO to GEs is also fundamentally important to their ecosystem health and functioning. As well as influencing chemical transformations by altering redox conditions (see Section 2.2.1, Figure 2-13), DO is consumed by most bacteria and aquatic organisms as they live, feed, grow and reproduce. DO availability is essential for most stygofaunal invertebrates (Malard and Hervant 1999), and may be the dominant, direct, effect on stygofaunal community composition and abundance (Mosslacher et al. 1996). Aerobic organisms use oxygen for respiration, although species differ in their oxygen consumption rates and abilities to withstand hypoxia[19]. True stygobitic species consume less oxygen than their stygophilic and epigean counterparts (Spicer 1998, Mosslacher 2000, Wilheim et al. 2006), enabling survival at the lower (<3 mg/L) DO concentrations generally found in subterranean interstitial habitats (Malard and Hervant 1999). Under such hypoxic conditions, some stygobites switch to anaerobic metabolism to fuel their energy needs (Hervant et al. 1996), but probably cannot survive such conditions indefinitely. Other species actively move towards and into higher DO concentrations, independent of flow direction, or migrate vertically, and may congregate at or above the water surface (Henry and Danielopol 1999).

There is usually a balance between DOC and DO concentrations. Small additions of DOC stimulate GE ecosystem functioning, but stimulation by excessive inputs can drastically reduce available DO concentrations, forcing the ecosystem towards anoxia (Sinton 1984, Fenwick et al. 2004, Boulton et al. 2008). This scenario favours species that metabolise anaerobically, notably bacteria which produce by-products (e.g., ammonia, sulphur dioxide) that degrade water quality and ecosystem health. This subsidy-stress effect of organic carbon on aquatic, heterotrophic ecosystems is well known (Sinton 1984, Boulton et al. 2008, Aristi et al. 2015).

[19] Hypoxic means low oxygen concentrations. Although a relative term, hypoxic conditions usually refer to DO concentrations between 0 (anoxia) and c. 2 mg/L.

Organic carbon and DO interact with each other and other properties (e.g., water level, velocity, nutrients), including the traits, structure and functioning of the biological communities to sustain the ecosystem. Figure 2-13 provides a simplified summary of these interactions.

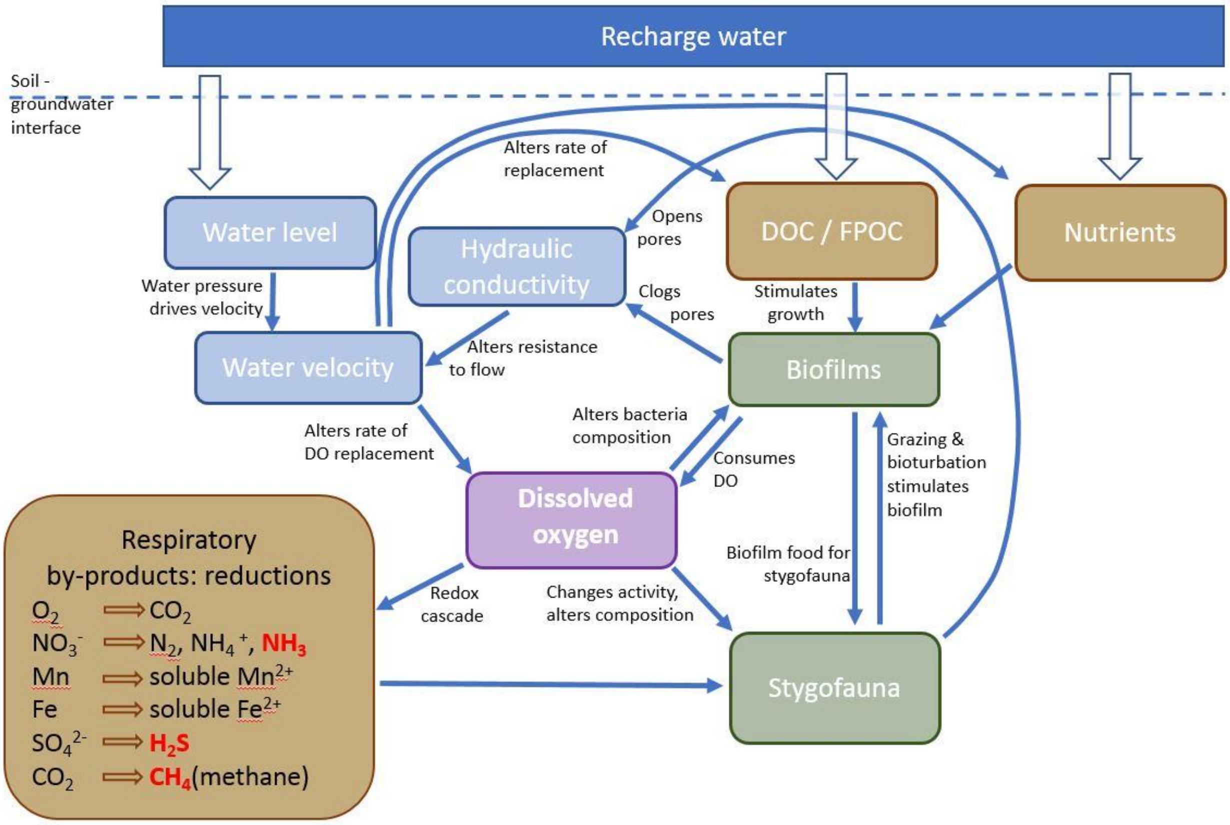

Figure 2-13: Simplified diagram of groundwater ecosystem functioning. Water, nutrients and organic matter (as dissolved organic carbon, DOC, and fine particulate organic carbon, FPOC) are transported into the GE. Blue boxes, hydrological effects; violet box, dissolved oxygen (DO); brown boxes, dissolved nutrients; green boxes, ecosystem components. Open arrows, inputs via recharge water; blue arrows, direct effects. Red text, respiratory by-products that are toxic to stygofauna.

2.4.1 Functional role of microbes and biofilms

Biofilm bacteria are the major functional component of GEs, concentrating organic carbon, nutrients and other substances, converting this into organic compounds essential to invertebrates (e.g., amino acids), degrading contaminants and enhancing groundwater quality, driving groundwater's natural bioremediation processes (Di Lorenzo and Galassi 2013, Wrighton et al. 2014). Most of the organic carbon carried into groundwaters with recharge water becomes integrated into biofilms and variously converted into microbial and biofilm biomass (Taylor and Jaffé 1990, Hartland et al. 2011, Liu et al. 2017). The bacteria and biofilms are browsed by invertebrates, themselves consumed by predators, scavengers or by heterotrophic microbes when they die. The cycle repeats endlessly: organic carbon in faeces and dead invertebrates is recycled via microbes and dissolution, incorporation into biofilms, browsed again, and so on, with net losses of carbon from the GE as carbon dioxide during respiration in all stages within oxic environments (Boulton et al. 2008, Fenwick 2016).

Numerous, specialist bacteria are involved in cycling organic carbon, each capable of only a small transformational step in the overall degradation process (Wrighton et al. 2014). Figure 2-13 provides a simplified representation of GE functioning in oxic environments. This qualitative representation does not emphasise the importance and complexities of microbial (mostly biofilm bacteria) activity (Malard and Hervant 1999).

Natural microbial communities in aquifers influence other important biogeochemical reactions and groundwater chemistry, including the transport and fate of organic compounds and metals (Flynn et al. 2013). With time and distance from recharge locations, reduced oxygen concentrations result in increased microbial reduction of nitrate to its reduced forms (nitrite, ammonium and ammonia) (Chapelle 2000) (Figure 2-4). Known as denitrification, this is one of the most important pathways for natural removal of nitrate from groundwater and is directly relevant to the functioning and value of GEs.

Persistent low to anoxic conditions favour co-occurring microbial populations of species that produce different metabolic end products (Krumholz 2000, Kovacik et al. 2006). Stygofaunal activity will be reduced or eliminated in these conditions because most metazoan stygofauna are constrained by oxygen availability (Malard and Hervant 1999) and the toxic nature of some microbial respiratory by-products. Thus, protozoan stygofauna probably dominate biofilm gazing and organic carbon cycling under persistent anoxic conditions.

2.4.2 Functional role of invertebrates: feeding and bioturbation

Stygofauna are important to GE functioning, as are invertebrates in many aquatic ecosystems (Lohrer et al. 2004, Mermillod-Blondin and Rosenberg 2006, Navel et al. 2012). They consume biofilm and bacteria, and contribute to natural bioremediation, as found in a seminal investigation of GE functioning in New Zealand Sinton (1984):

- Organic enrichment led to increased stygofaunal community density in an alluvial aquifer in reponse to organic enrichment from land use activities.
- Some stygofauna consumed coliform bacteria derived from wastewater disposal on upstream land.
- Using some crude assumptions, the three main stygofauna species were estimated to collectively assimilate approximately 20% of the calorific value of effluent applied to the site.
- There were periodic mass kills of stygofauna in the most contaminated wells due to anoxic conditions (sulphur smell and blackened sediments), coinciding with high organic carbon concentrations and seasaonal low water levels.

Through their movement and feeding activities, stygofauna (e.g., Figure 2-14, Figure 2-15, Figure 2-16) essentially till or re-work the sediment, ingesting and defecating selected sediment particles, as well as burrowing into and through it. Direct evidence for the importance of bioturbation (sediment re-working by animals, principally invertebrates) by groundwater invertebrates is increasing (e.g., Sinton 1984, Datry et al. 2003, Fenwick et al. 2004, Stumpp and Hose 2017). For example, at one site in Templeton (Canterbury), the most abundant invertebrate (mean 207 per well, SD = 241.7, n = 4), a large (c. 20 mm long) phreatoicid isopod (*Phreatoicus typicus*) (Wilson and Fenwick 1999), fed by ingesting fine, clay-sized particles and digesting the associated live bacteria and organic matter from these. The population was estimated to process 0.7-2.8 kg/m^2/yr of sediment (Fenwick et al. 2004, Boulton et al. 2008).

Figure 2-14: Two stygofaunal amphipods: left, *Paracrangonyx compactus* from Canterbury's alluvial aquifers (body up to 8 mm long), and *Paraleptamphopus* sp. from deep within the karstic Pearse Resurgence (Nelson region). Images: N. Boustead, NIWA.

Similarly, the importance of bioturbation by marine, river, hyporheic and lake benthic invertebrates as ecosystem engineers[20] is now well established (e.g., Mermillod-Blondin et al. 2003, Lohrer et al. 2004, Mermillod-Blondin et al. 2004, Mermillod-Blondin and Rosenberg 2006, Nogaro et al. 2009) and suggests that bioturbation in GE is an important function fulfilled by stygofauna. In GEs, this bioturbation and grazing activity removes potentially harmful microbes, reduces biofilm, stimulates organic carbon uptake by biofilms (Gibert and Deharveng 2002, Mauclaire et al. 2006), disaggregates and aerates finer sediments, and helps to maintain water flow through fine pore spaces (Fenwick et al. 2004, Boulton et al. 2008), as well as creating new flow paths. The specific effects of bioturbation appear to differ with aquifer hydrodynamics (Mermillod-Blondin and Rosenberg 2006), nutrient status, and sediment characteristics, as well as feeding modes of the organisms involved (Nogaro et al. 2009). Five functional bioturbation modes (Table 2-2) identified for stream-hyporheic habitats (Nogaro et al. 2009) seem directly applicable to alluvial groundwater habitats and stygofauna. The bioturbation activities can occur at the groundwater surface (i.e., boundary of saturated and unsaturated zones), between a large pore and a sediment deposit within the saturated zone (i.e., the interfaces of any preferential flow paths and the finer grained aquifer matrix), or elsewhere in the saturated zone (e.g., within a crevice). Bioturbation probably is similarly important in the functioning of karst aquifers and fractured rock aquifers, where finer pore spaces may become occluded by fine sediments and/or biofilm.

In diffusion-dominated (i.e., minimal water movement) habitats, sediment re-working by ecosystem engineers (species with disproportionally large effects on their abiotic environments) stimulated aerobic microbial activity and organic carbon mineralisation by 'irrigating' biofilms (animals' movements and respiratory water currents create fine-scale currents), increasing biofilm surface area exposed for solute exchanges and releasing nutrients from consumed biofilm and organic particles via excretion (Lohrer et al. 2004, Mermillod-Blondin and Rosenberg 2006). Bioturbation within advection- or flow-dominated, heterogeneous sediment habitats can lead to preferential flow paths of coarser sediment developing, with finer particles removed by flowing water, so that sediments overall become coarser and pore spaces increase, in turn reducing nutrient availability for biofilms on the surface area of finer sediments at and beyond the margins of the flow paths (Mermillod-Blondin and Rosenberg 2006).

[20] Ecosystem engineers are *"organisms that modify the physical structure of the environment through non-trophic activity and act on resource availability for other species"* (Nogaro et al. 2009), p 126.

Table 2-2: Functional types of bioturbators in subsurface groundwater-dependent ecosystems. After Nogaro et al. (2009), with functional activities redefined for aquifers.

Functional group	Functional activity
Bio-diffusers	Organisms that randomly move diffuse sediments at an interface.
Upward conveyers	Consumers at an interface ingesting/egesting material into larger pore spaces.
Downward conveyors	Consumers at an interface ingesting/egesting material into deeper sediments.
Regenerators	Species that excavate open burrows that remain part of the sediment matrix when abandoned.
Gallery-diffusors or bio-irrigators	Species that dig or build extensive, interlinked tubes or burrows that are irrigated by biotic activity.

Figure 2-15: *Cruregens fontanus*, a large (c. 25 mm long) isopod crustacean from Canterbury's alluvial aquifers. Image: N. Boustead, NIWA.

Stygofauna influence the porosity and permeability of shallow GEs, breaking down organic matter, modifying nutrient regimes and facilitating net losses of material from the GE (Mermillod-Blondin et al. 2004, Nogaro et al. 2006, Nogaro et al. 2009, Navel et al. 2012). Several groundwater species selectively ingest fine particles (Boulton et al. 2008), as well as burrowing through these and larger grained sediments, creating and altering fine-scale flow paths (Torreiter et al. 1994, Danielopol et al. 2000b, Datry et al. 2003). In the process, stygofauna almost certainly influence the composition and development of biofilms, essential for cycling organic carbon and for mineralising nitrogen (Costerton et al. 1995, Butturini et al. 2000) through their grazing and bioturbation activities in much the same ways as hyporheic communities do this (Boulton et al. 2007).

The magnitude of bioturbation and its ecological effects can be very substantial, albeit poorly understood for GEs and stygofauna. Populations of a large ecosystem engineer inhabiting Canterbury's large alluvial aquifer near Christchurch were estimated to ingest 7-28 tonnes of clay-sized sediment particles per hectare per year for a site contaminated by wastewater (see Boulton et al. 2008). Even at the low end of this calculated range, the ecosystem and geological implications for this amount of sediment processing are significant.

Stygofauna also ingest bacteria and other organisms, conceivably reducing populations of some potentially harmful bacteria (e.g., coliform bacteria) and protozoans (e.g., *Cryptosporidium*) that may persist or even reproduce within biofilms (Wingender and Flemming 2011). However, there is also some evidence that stygofauna may actually transport harmful organisms throughout aquifers, potentially increasing the extent of contamination (Smith et al. 2016).

Figure 2-13 summarises the physical, chemical and ecological processes and interactions within GEs that are described above.

Figure 2-16: A large (up to 20 mm body length) bioturbator from Canterbury's alluvial aquifers: *Phreatoicus typicus* feeds on clay-sized particles, digesting biofilms and bacteria from these. Image: N. Boustead, NIWA.

2.5 Engineered heterotrophic ecosystems

Humans have used natural soil (vadose zone) and GE bioremediation processes via septic tanks for centuries. Bioremediation or treatment using naturally occurring organisms to break down hazardous substances into less toxic or non-toxic substances (EPA 2012) is a widely used engineered equivalent of the ecological processes occurring in many freshwater ecosystems, including GEs. The five applications outlined here illustrate that managing groundwaters sustainably requires us to recognise that GE health is important in order to maintain its ecological functioning, especially the remediation capacities of natural GEs (see Section 3.1.2).

2.5.1 Drinking water treatment

Biofiltration is a well-established engineered approach to improving water quality for urban domestic supplies of potable water and for partial remediation of wastewater prior to discharge to the environment. Sand or slow sand filters, traditionally one of the most commonly used means of purifying municipal water supplies (Huisman and Wood 1974), function in the same way as GEs. Physical filtration removes most fine inorganic particulates and most microbes are trapped or removed in the fine sand matrix. Biological activity is important. The upper layer of sand filters usually comprises a very active meshwork of filamentous algae, diatoms, fungi, bacteria, protozoans and other small invertebrates. This layer initiates the biological breakdown of contaminants (Mauclaire et al. 2006). Further biological activity, along with physical adsorption of small particles and macromolecules onto particles and into biofilm, continues through the entire filter matrix, with bacterial densities reducing by factors of 1000-10,000 in the process (Huisman and Wood 1974). Biofilm is very important in this process, with the fine matrix presenting vast surface areas (estimated at 1.5 ha/m^3 of sand) for its development and uptake of contaminants (Huisman and Wood 1974). Periodic backwashing and/or replacement of upper layers of sand is required to remove accumulated deposits to maintain the filter's aerobic conditions and effectiveness (Clark et al. 1971, Huisman and Wood 1974).

2.5.2 Wastewater treatment: trickling or percolating filters

Trickling or percolating filters also are functionally similar to GEs and frequently involve both biofilms and invertebrates. These filters, commonly large (>10 m diameter) cylinders packed with natural or manufactured media or substratum (selected because of its high surface area: 80 m^2/m^3 for some manufactured media), oxidise organic compounds as wastewater trickles over biofilm developed on the media within the cylinder or column. Generally, the biofilm includes not only bacteria and fungi, but also protozoa, worms, insect larvae and other small invertebrates. Aerobic conditions are maintained by diffusion and splashing as water trickles down through the filter. Forced air may be used in some applications. Thus, aerobic conditions persist at the biofilm surface, but conditions within the biofilm may be variously anaerobic towards the substratum (<1 mm scales). Thick biofilms typically slough off to form a secondary sludge, which is trapped by a downstream sedimentation tank or clarifier. Clogging and flow channelling within the column are usually managed using physical (e.g., back-washing) and/or chemical (e.g., peroxide, ozone) methods to maintain vertical percolation rates of 0.1-0.4 m^3/hr per m^2 of surface area (Huisman and Wood 1974).

Experimental introductions of metazoans (oligochaete worms; Naidaidae and Tubificidae) into trickling filters significantly reduced sludge production (by 10-50%) (Rensink and Rulkens 1997, Wei et al. 2003), removed considerably more organic carbon, reduced blocking to keep the system aerated, digested potentially harmful bacteria, protozoans and other organisms, and stimulated microbial activity (Baker 1975, Learner 1975, Solbe 1975). Further, filters with moderate biofilm resulted in diverse communities, which controlled biofilm development better and eliminated nuisance swarms of adult flies (Baker 1975, Learner 1975).

Slow sand and trickling biofilter technologies resemble processes occurring naturally within GEs. The biggest difference is that human interventions are required to keep these engineered ecosystems functioning efficiently. Not only is it critical to manage flow rates, effluent qualities and aeration, but backwashing is required to remove accumulations of biofilm and other material that impede flows and reduce aerobic conditions within the filter matrix, because these lead to anaerobic conditions that, in turn, can accelerate clogging (Mauclaire et al. 2006). Also, trickling filters produce large quantities of organic sludge that presents a substantial disposal problem due to the high water content and potentially harmful constituents of sludges (heavy metals, pathogens, and persistent organic pollutants) (e.g., Clark et al. 1971, Wei et al. 2003).

2.5.3 Wastewater treatment: constructed treatment wetlands

Constructed subsurface-flow treatment wetland (CSFTW) systems use ecosystem processes to remediate wastewater, with wetland plants above ground and stygobitic organisms inhabiting porous media (soils, gravels, alluvium, etc.) below ground. They have received significant attention for their potential to remediate wastewater from smaller, dispersed sources (e.g., rural domestic and industrial sources), primarily using rooted plants. However, clogging (reduced hydraulic conductivity) of subsurface media is a significant problem with these CSFTW systems, with porosities reduced by >50% in some cases (e.g., Nivala et al. 2012). Originally predicted to be effective for 50-100 years (Knowles et al. 2011), their effectiveness is reduced within 8-15 years and half of all constructed wetlands clog after five years of operating (Zhao et al. 2009).

Biofilms that develop within interstices of CSFTWs appear to be the key agents responsible for rapidly reduced hydraulic conductivity (Caselles-Osorio et al. 2007, Nivala et al. 2012). Studies have shown that biofilm growth is greatest closest to the water source or inlet, re-routes flow, markedly reducing the effective porosity and increasing entrapment of particulate matter, thus, further accelerating clogging pores within the media and rapidly reducing infiltration rates (Dupin and McCarty 1999, Zhao et al. 2009). The rate of this clogging may be further increased with higher nutrient concentrations, notably organic carbon, especially in forms that are more bioavailable.

Adding earthworms to a clogged system restored much of the hydraulic conductivity within ten days in one experiment (Li et al. 2011) and appeared to be the lowest cost of seven remediation approaches trialled (Nivala et al. 2012). Although this clogging was mostly above the water table and the earthworms effecting restoration were not aquatic organisms, this example demonstrates the capacity of biofilms to dramatically alter the hydraulic regime of a porous system and the extent to which invertebrates can control biofilm development and maintain hydraulic conductivity. Both points have important implications for natural GEs and their management.

2.5.4 Bio-clogging

Biological clogging, or reduced hydraulic conductivity within a porous medium due to biofilm development, occurs in diverse engineering situations, including drinking water filtration systems, wastewater trickling filter beds, urban fire water supply systems, domestic water supply reticulation systems, wastewater collection networks (Thullner 2010), and constructed treatment wetlands (Knowles et al. 2011). Bio-clogging in a few situations is summarised briefly below to illustrate that it is a common phenomenon and that it can be substantial in magnitude and spatial extent (Mays and Hunt 2005).

Bio-clogging of aquifers for containing and remediating contaminated groundwater has received considerable attention, with more recent focus on achieving this by stimulating indigenous microbial populations. Hydraulic conductivities of experimental sand columns appear to halve when their porosity is reduced by 20% due to bacterial growth and biofilm development (Seki 2013). The clogging causing these large reductions in hydraulic conductivity appears due more to bacterial colonies growing preferentially in high permeability sites, aggregations of them blocking pore spaces (Ross et al. 1998, Ross et al. 2001, Seifert and Engesgaard 2007, Seki 2013), rather than to biofilms and EPS accumulating evenly on substratum grains (e.g., Figure 2-17) (Vandevivere and Baveye 1992, Mauclaire et al. 2006).

Engineered recharge of aquifers (also known as managed aquifer recharge or MAR) with surface waters may also be compromised by bio-clogging. Artificial recharge, especially from harvesting river water during floods, is an important water management approach in some places and is under active investigation on the Canterbury Plains. Although conceptually simple, clogging is the main impediment to recharge via injection bores (wells), with clogging occurring within minutes to years after commencement (Rinck-Pfeiffer et al. 2000). Physical clogging by suspended solids appears to be the main factor, but bio-clogging (Figure 2-17) associated with polysaccharides and bacterial colonies was the second most important factor in lab experiments, and a significant issue for artificial recharge via ponds and natural infiltration systems (Rubol et al. 2014).

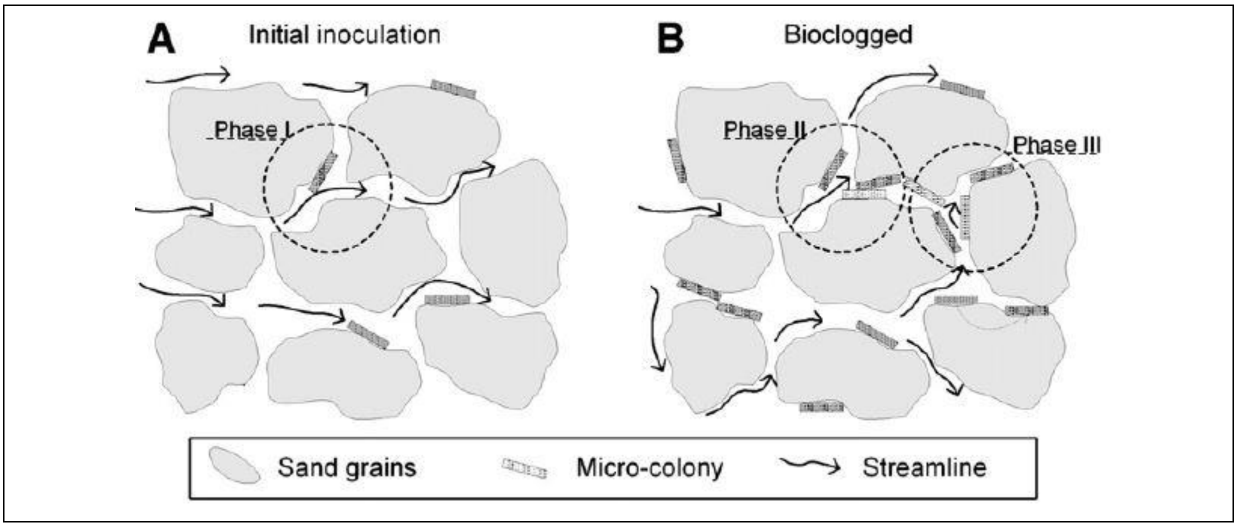

Figure 2-17: Schematic illustration of porous medium with sparse micro-colonies and little biofilm development (phase I) (A) and (B) with denser micro-colonies and more extensive biofilm restricting pore spaces and reducing hydraulic conductivity (phases II and III). From Seifert and Engesgaard (2007), Fig. 1).

2.5.5 *In situ* groundwater bioremediation

Engineered remediation of contaminated groundwater is now well established for some chemicals via:

- Bioremediation: bacteria naturally present at the site break down the contaminant under ambient conditions),
- Biostimulation: adding nutrients to stimulate natural bacterial populations, and/or
- Bioaugmentation: adding bacteria not present or common at the contaminated site (e.g., see Semprini et al. 1990, Löffler and Edwards 2006, Yabusaki et al. 2007).

Chlorethylenes (oil derivatives widely used in diverse industrial applications) (Aulenta et al. 2005, Löffler and Edwards 2006, Vainberg et al. 2009), perchlorate (industrial applications) (Löffler and Edwards 2006), petroleum hydrocarbons (BTEX: benzene, toluene, ethylbenzene, xylene (Chapelle 1999), PAHs (polycyclic aromatic hydrocarbons) (Schmitt et al. 1996), and uranium (Löffler and Edwards 2006, Yabusaki et al. 2007) are among the groundwater contaminants managed at field scales using one or more of these methods.

Creating permeable reactive zones or barriers within an aquifer is an extension of this *in situ* bioremediation. Contaminants in groundwater moving passively or along an induced hydraulic gradient are adsorbed, precipitated or chemically or biologically degraded (Kao and Lei 2000). The process involves installing a wall or zone of reactive material (e.g., peat, pecan shells, etc. containing biologically-available organic carbon) perpendicular to flow direction. The organic carbon stimulates natural (or introduced) bacterial populations that metabolise the contaminant as the groundwater passes. Another approach involves inoculating the aquifer with cultures of bacteria known to produce EPS, along with a suitable soluble carbon source (e.g., molasses) (e.g., Ross et al. 2001).

2.6 The importance of surface water – groundwater connections

As heterotrophic ecosystems, GEs depend on their connectivity with surface water bodies for supplies of DO and organic carbon[21], resources that affect the chemical and biological conditions within the GE (see Sections 2.2 and 2.4). Likewise, the hydrological regime of GEs is influenced by recharge and discharge of groundwater, often through connections with surface water bodies.

Aquifers differ naturally in their hydrological connectivity to surface waters, which determines the rate of delivery of organic carbon, DO and other nutrients. Thus, hydrological connectivity exerts a substantial influence over a GE's structure and function (e.g., see Dumas et al. 2001, Malard et al. 2003, Bork et al. 2009, Mencio et al. 2014). Three types of GEs are recognised based on their hydrological connectivity (Hahn 2006):

- Weak hydrological exchange (oligo-alimonic GEs): low DO and low organic carbon supply; typically few or no stygofauna.
- Moderate hydrological exchange (meso-alimonic GEs): organic carbon and oxygen supplies are moderate to high; stygofauna dominated by stygobites (obligate groundwater dwellers).
- Strong hydrological exchange with surface waters (eu-alimonic GEs): moderate to high DO and food supplies; rich, abundant stygofauna comprising stygobites and stygoxenes.

Many surface ecosystems depend on water and dissolved nutrients carried to them by groundwater. These groundwater dependent ecosystems (GDEs) include wetlands, many rivers at base-flow, some types of terrestrial vegetation, coastal groundwater ecotones[22] and coastal ecosystems (Tomlinson 2011). Therefore, it is more appropriate to think of groundwater and surface water as a single water resource (Winter et al. 1998).

2.7 Summary

- Groundwater level and the hydrological conductivity of the aquifer matrix determine groundwater velocity and rates at which key substances (energy/food, oxygen, nutrients, etc.) are replenished.
- Groundwater contains numerous dissolved substances, both from the land surface and from interactions within the aquifer. Dissolved oxygen in one key substance that is essential for some of the important life in groundwater. Its availability drives key biochemical processes, establishes the reduction-oxidation (redox) potential of the water, and the water's suitability for human uses.

[21] Lithotrophic or otherwise chemoautotrophic bacteria are known to be an important source of organic matter in some situations, but apparently not in shallower (<50 m depth) groundwater ecosystems.

[22] An ecotone is a transitional zone or area between two adjacent ecosystems. Ecotones typically share attributes of adjacent ecosystems and may have their own unique attributes.

- Groundwater ecosystems (GEs) occur in most aquifers. These are usually energy limited, so GEs tend to be more productive closer to recharge sources and at shallower depths within the aquifer.
- Groundwater ecosystems are heterotrophic, relying on organic carbon imported with recharge water. They also rely on recharge water to replenish dissolved oxygen.
- Natural microbial communities in aquifers influence important biogeochemical reactions and groundwater chemistry, including the transport and fate of organic compounds and metals, as well as the amounts and nature of carbon and nitrogen in groundwater.
- Biofilms are the major functional component of groundwater, degrading contaminants and enhancing groundwater quality, so that natural GEs self-purify or bioremediate groundwater.
- As well as microbes and biofilms, groundwater supports a diverse range of aquatic invertebrates (Protozoa and Metazoa), collectively known as stygofauna. Alluvial aquifer stygofaunal communities are dominated by crustaceans, notably amphipods, copepods, ostracods. Water mites also are common, along with other minor crustaceans (isopods, syncarids), gastropod snails, flatworms, nematode worms, annelid worms and beetles.
- Stygofaunal communities tend to be more abundant and diverse within 1-2 m of the groundwater surface and the zone of intermittent saturation. Roots of trees that penetrate aquifers also are associated with higher taxon richness, providing food, habitat, shelter and a substrate for fungi that may be consumed by stygofauna.
- Although poorly known, New Zealand’s stygofauna appears rich and diverse, compared with that found elsewhere. There are over 100 named species with another c. 700 collections of groundwater amphipods and isopods awaiting analysis. With the exception of some copepods, all species are endemic to New Zealand and several are probably restricted to single aquifers or discrete aquifer systems.
- Groundwater ecosystems are strongly influenced by groundwater chemistry (in particular, concentrations of dissolved oxygen and organic carbon) and groundwater levels and velocity. However, the relationship between an aquifer’s hydrological regime and GE health is poorly understood.
- Stygofauna are important to groundwater ecosystem functioning just as aquatic invertebrates are important to surface water ecosystem functioning. Stygofauna can consume large amounts of bacteria and biofilm, potentially acting as bioremediators in contaminated systems, but they need certain conditions to maintain healthy communities.
- Through their movement and feeding activities, stygofauna, like many aquatic invertebrates, essentially till or re-work the sediment, ingesting and defecating selected sediment particles, as well as burrowing into and through the sediment. The magnitude of bioturbation and its ecological effects can be very substantial, albeit poorly understood for GEs and stygofauna.

- Groundwater ecosystems provide a natural bioremediation function that is similar to human engineered bioremediation applications, such as the use of sand filters for drinking water treatment, and the use of trickling filters and constructed subsurface-flow wetlands for wastewater treatment.
- Aquifers are open systems, dynamically interconnected with surface waters such that groundwater and surface water should be regarded as a single water resource which variously passes from one habitat to another.

3 Groundwater values and ecosystem services

Groundwater ecosystems and the services they provide support a diverse range of human values and are of fundamental importance to many societies and economies worldwide (Stanford et al. 1994; Thompson 2011). For example, groundwater is an important source of drinking water for people and livestock, and supports many industries, particularly agriculture and horticulture.

Our understanding of GE functioning is very incomplete, and the systems themselves are hydrogeologically and ecologically complex (Davey 2006, Boulton et al. 2008, Thomas and Harvey 2013). Traditionally GEs have been thought of as physical systems that supply a valued resource (i.e., a supply of water for industrial, agricultural and domestic use). Major advances in understandings of groundwaters during the past decade have resulted in stakeholder and regulatory authorities, at least in Europe and Australia, recognising the ecological and social values of groundwaters. This includes accepting that GEs deliver ecosystem services (the benefits people obtain from ecosystems) that are fundamental to supporting human values (Danielopol et al. 2004, MEA 2005, Griebler and Avramov 2015).

In this section we identify human values associated with GEs using three main approaches designed to assist in integrating human values associated with ecosystems into stakeholder thinking, conversations and evaluations (e.g., cost-benefit analyses) at all levels (e.g., de Groot et al. 2010, Harrison et al. 2010).

One of the main approaches to identifying ecosystem values is the concept of ecosystem services (Costanza et al. 1997, MEA 2005). The ecosystem services approach provides a framework for identifying the many values associated with GE services (or those of other ecosystems; see inset box).

A second, emerging approach, is the concept of natural capital (e.g., OECD 2015). Natural capital can be defined as the stock of natural ecosystems from which ecosystem services (or the benefits people gain from ecosystems) flow. A GE is a component of natural capital, and water storage is one of the ecosystem services that it provides.

A third approach, often in conjunction with either the ecosystem services framework (e.g., MEA 2005), or the natural capital framework (e.g., van Ayl and Au 2018) is to undertake an economic valuation to define the ecosystem components and assign monetary values. Economic valuation can give new insights and estimates of the monetary values of what is at stake that usefully inform decision-making (e.g., de Groot et al. 2010), but may involve using some creative approaches to establishing monetary values.

We apply the ecosystem services approach to identify components of value that GEs provide, discuss the concept of GE natural capital, and review the application of economic valuation to GEs.

ECOSYSTEMS SERVICES CONCEPT FACILITATES BETTER DECISIONS

"People find themselves confronted with ever starker tradeoffs [sic] in the allocation of resources to competing uses and users. … These tradeoffs [sic] are becoming increasingly vexing and difficult to resolve, from both ethical and practical perspectives. The Ecosystem Services Framework integrates biophysical and social dimensions of environmental protection in a way that holds great promise for addressing the environmental crisis that will likely peak in the 21st century."

From: (Daily 2000): 333

3.1 Ecosystem services

Ecosystem services are the benefits people obtain from ecosystems, and ecosystem health is often defined as an ecosystem's ability to provide the services people desire. The ecosystems services approach is a framework that assists in assessing ecosystem condition, the provision of services and their value to humans. The framework, used widely for the last 30 years (Costanza et al. 1997, MEA 2005), is a method to identify and categorise ecosystem services. Individual studies often make variations to framework, particularly to the groupings of components of ecosystem services (see Figure 3-1). In our application to GEs, we follow the ecosystem services framework of MEA (2005), which grouped ecosystem services into four main categories (recognising that some of the categories overlap):

- *Provisioning services*: the products obtained from ecosystems (e.g., food, freshwater, fuel).
- *Regulating services*: benefits obtained from regulation of ecosystem processes (e.g., disease regulation, pollination, water purification).
- *Cultural services:* non-material benefits obtained from ecosystems (e.g., recreation, cultural heritage, sense of place).
- *Supporting services:* services necessary for the production of all other services (e.g., soil formation, nutrient cycling, primary production).

Here we apply the ecosystem services framework to GEs to identify the range of ecosystem services GEs provide (see Figure 3-1 for a summary). We note that many of these services are largely derived from physical processes (e.g., hydrological conductivity), but they are included as ecosystem services because their continued performance appears closely tied to biodiversity and ecosystem functioning.

Some of the ecosystem services provided by GEs, especially provisioning services (e.g., water sources for domestic and industrial uses), are generally well quantified and documented (White 2001). A few overseas studies have highlighted the potential regulating services that stygofauna may provide (Nogaro et al. 2006, Boulton et al. 2008, Nogaro et al. 2009), although empirical research specific to New Zealand is very limited. Other ecosystem services, especially cultural and supporting services are largely unquantified for GEs. Thus, our discussion of GE services below is largely based on ecosystem services identified elsewhere in the world (Figure 3-1). The ecosystems services are likely to be delivered in much the same way by New Zealand's GEs, because our knowledge indicates that GEs, especially alluvial GEs, function in a similar manner in different countries, even though the species involved differ (Mermillod-Blondin et al. 2003, Mermillod-Blondin et al. 2004, Boulton et al. 2008).

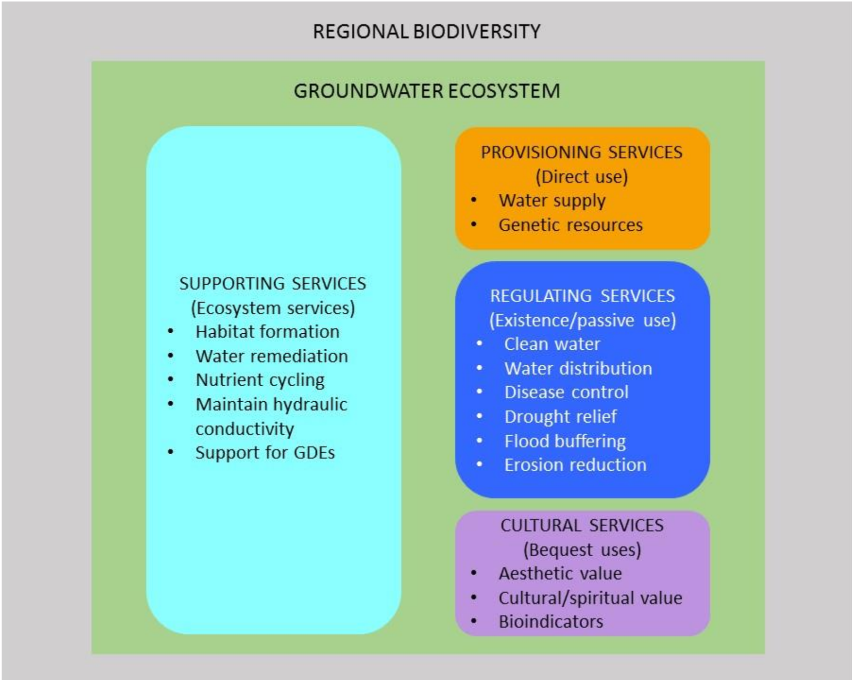

Figure 3-1: Ecosystem services provided by subsurface groundwater ecosystems. Orange, very important for human well-being; blue moderately important; violet, important; turquoise, services essential to the others. Framework modified after MEA (2005) and Griebler and Avramov (2015).

3.1.1 Provisioning services: products delivered by the ecosystem

Two important provisioning services are water supply and genetic resources.

Water supply

The main service provided by GEs for human use is water for drinking, domestic uses, irrigation, stock water and for industrial uses. About half of New Zealand's drinking-water is sourced from groundwater[23], with reliance on groundwater differing appreciably between regions (Rajanayaka 2010). Our economy is also dependent on groundwater (White 2001, Robb and Bright 2004, Daughney and Reeves 2005), and, even with tighter management constraints imposed by regional councils (e.g., through implementation of the NPS-FM 2014), will likely be increasingly so in the future as irrigation-dependent land uses expand and climate change reduces precipitation in many of New Zealand's prime agricultural areas (e.g., Canterbury, Wairarapa, Taranaki, Hawke's Bay, Waikato; Reisinger et al. 2010). Water exports (bulk or bottled), although a very small component of the overall abstractive demand, are an increasingly important and valuable product from these provisioning services.

Genetic resources

Groundwater biodiversity, both microbial and stygofaunal, presents a pool of unique organisms, some of which may be useful for human purposes. Groundwater biodiversity remains unexplored for potentially high value processes (enzymes, biochemical transformations) and compounds for industrial and medical applications (Kristie et al. 2017). See Section 2.3 for details of GE biodiversity.

[23] http://www.drinkingwater.esr.cri.nz/general/nzprocesses.asp, accessed 15 Jun 2018.

3.1.2 Regulating services: purification, buffering, maintaining conductivity

Water purification and disease control

Bioremediation (natural or managed transformation of contaminants by living organisms into less harmful products, Chapelle 2000) is an important supporting ecosystem service delivered by GEs. Natural microbial communities in uncontaminated and in variously contaminated aquifers, through their diverse metabolic activities, are the primary agents directly involved in these biogeochemical transformations along an aquifer's flow path. They can remove and/or transform organic (e.g., acetate, naphthalene, benzene, toluene; Andreoni and Gianfreda (2007)) and inorganic (e.g., uranium, nitrate, ammonium; Mouser et al. (2009)) contaminants via their metabolic pathways (Flynn et al. 2013). Stygofauna are involved indirectly through consuming and digesting biofilm (organic carbon), bacteria, viruses and other potentially harmful pathogenic organisms (e.g., *Cryptosporidium*) that may be immobilised or consumed variously within GEs.

Such bioremediation occurs naturally and spontaneously, sometimes at slow rates, and is generally self-sustaining. Natural microbial communities can be stimulated to remediate contaminated groundwater (Anderson and Lovley 1997, Aulenta et al. 2005, Löffler and Edwards 2006, Vainberg et al. 2009) by increasing the availability of scarce nutrients (e.g., organic carbon), by introducing specific bacteria, or a combination of both (Aulenta et al. 2005). Engineered systems frequently use a combination of physical filtration, biofilms and, in some instances, invertebrates to treat water for drinking and wastewater prior to disposal (e.g., Huisman and Wood 1974). These, however, require interventions for manage bioclogging or accumulations of sludge (Clark et al. 1971). Refer to Section 2.5 for a comparison of GE functioning with engineered bioremediation systems.

Disease control, another element of bioremediation, seems very likely. Many potentially harmful bacteria, including coliform bacteria, enteric viruses, and free-living opportunistically pathogenic (e.g., *Naegleria*, *Acanthamoeba*) and obligate parasitic protozoans (e.g., *Cryptosporiduim*) probably become bound into groundwater biofilms, surviving periods of weeks or months (Wingender and Flemming 2011) or indefinitely. Some of these pathogens are also eaten and digested by stygofaunal crustaceans (Sinton 1984, Boulton et al. 2008, Smith et al. 2016). However, biofilm mats can protect pathogens from desiccation during drying periods, enhancing their survival (Wingender and Flemming 2011) and dispersal of some pathogens may also be enhanced by stygofauna (Smith et al. 2016).

Maintaining hydraulic conductivity

Groundwater ecosystems variously affect the hydraulic conductivity of aquifers (Griebler and Avramov 2015), or their capacity to conduct and supply water to bores or other abstraction points (aquifer transmissivity). As noted in Section 2.4.2, through their movement and feeding activities, many invertebrates essentially till or re-work the sediment, ingesting and defecating selected biofilm and sediment particles, as well as burrowing into and through it (Datry et al. 2003, Mermillod-Blondin et al. 2003, Mermillod-Blondin et al. 2004, Mermillod-Blondin et al. 2008). This bioturbation reduces accumulations of biofilms, opens fine pore spaces, creates new flow paths, aerates the matrix, and stimulates biofilm activity. In engineered applications of biofilms for remediating water quality, the lack of larger invertebrates and their significant bioturbation may contribute to the need for relatively frequent interventions to unclog the system.

Buffering of floods and droughts

GEs also provide regulating services by assimilating and storing water, effectively reducing run off to lessen soil erosion and surface flooding, releasing stored water gradually to support other ecosystems, and transporting water to other points within the aquifer (Brunke and Gonser 1997, Tomlinson and Boulton 2008). Both physical and biological effects on aquifer transmissivity are involved in this buffering effect. Water stored in aquifers generally does not degrade, but rather tends to increase in quality over time, including over decades and centuries (Griebler and Avramov 2015), so long as the water remains oxic. GEs also release water during drier periods, contributing substantial base flow to ephemeral rivers or seasonal low flows (Tomlinson and Boulton 2008, Larned et al. 2014, Griebler and Avramov 2015).

3.1.3 Cultural services: non-material benefits

Social values

Groundwater is an essential component of everyday life for many communities. However, by virtue of being underground, the social values of groundwater seem largely unrecognised and unknown, other than the fact that groundwater supports a range of water needs that contribute to social well-being. However, most of the social values associated with surface freshwaters are relevant to groundwaters because groundwaters are variously connected to and feed most surface freshwater bodies (refer Section 2.6).

Indigenous cultural values

Wai is a taonga that underpins Māori wellbeing and economy. Water is the basis of life without which nothing would exist. From a Māori perspective, waterways are the life-blood of the whenua (land) and, therefore, the people themselves (e.g., Te Manaaki Taiao Te Taiwhenua o Heretaunga. 2012). The connection between mauri (life force), water and people is a basic tenet for Māori. From the beginning, Māori lived on, around, and in tune with their waterways, which were a source of sustenance, transport, mātauranga (knowledge) and recreation. The inherent connection with water is expressed in Te Reo (the Māori language) where the term 'wai' is used to describe and evince the status of water across all Māori society. This connection is seen as intrinsic and divine (e.g., Te Manaaki Taiao Te Taiwhenua o Heretaunga. 2012). An overview of some of the Māori values, beliefs and practices associated with GEs is presented in Section 4.

Spiritual values

Springs are widely recognised as providing spiritual experiences or services, not only to indigenous cultures, but also to western people (Bergkamp and Cross 2006). These services clearly are inextricably linked to groundwater and essentially attributable to GEs. For example, *"The spiritual realm is reflected in the legend of Huriawa the Kaitiaki Taniwha who was called forth to reside and clear the caves and caverns of the underground realm. She is the keeper, Kaitiaki and the giver of purity and pristine water Ngā wai ora o Huriawa. The Ngāti Tama kaitiaki ethic is to ensure the purity of the waters of Te Waikoropupū Springs are maintained as one of the purest waters ever measured in the World"* (Little 2018). This spiritual experience appears to be a significant element of the experience sought by tourists visiting large springs, such as Te Waikoropupū Springs near Tākaka.

3.1.4 Supporting services: ecosystem services essential to delivering other services

Nutrient cycling

GE processes concentrate and transform organic carbon, nutrients and other substances that are re-used by the GE and essential for its continued functioning. This alters the form, amount, and timing of delivery of substances to surface waters and wells.

Provision of habitat

Both biofilms and stygofauna provide and maintain the habitat required for GE functioning. Stygofauna provide habitat by creating and maintaining the physical habitat space, and maintaining the hydraulic conductivity and hydrological connectivity that is required both for healthy GEs (Fenwick et al. 2004, Boulton et al. 2008b). Biofilms deliver concentrated energy and nutrients, which are essential to stygofauna in delivering their ecosystem services.

3.2 Natural capital

Natural capital is another way of defining the benefits (or ecosystem services) humans derive from ecosystems. Natural capital includes individual assets, such as minerals, energy resources, plants and wildlife, as well as the services that ecosystems provide, such as crop pollination (OECD 2015, van Ayl and Au 2018). The natural capital concept establishes an asset class that is comparable to financial, social and intellectual capital classes.

While natural capital can generally be thought of as the stock of natural ecosystems from which ecosystem services (or the benefits people gain from ecosystems) occur, there are multiple specific definitions including:

- The Organisation for Economic Cooperation and Development's (OECD) "*How's Life?*" (OECD 2015), also adopted by the New Zealand treasury (van Ayl and Au 2018): "*Natural capital refers to critical aspects of the natural environment. It can include individual assets such as minerals, energy resources, land, soil, water, trees, plants and wildlife. However, it also includes broader ecosystems – i.e., the joint functioning of, or interactions among, different environmental assets, as seen in forests, soil, aquatic environments and the atmosphere.*"
- The UK's Natural Capital Committee (2017) (NCC 2017): "*those elements of the natural environment which provide valuable goods and services to people, such as the stock of forests, water, land, minerals and oceans*".
- The Global Nature Fund (2018): *"the world's stocks of natural assets both renewable and non-renewable which include soil, air, water, minerals and all living things, beneficial and crucial to the survival of mankind"*.

One example of a component of GE natural capital is the biodiversity[24] within them. GE biodiversity is important and valuable to humans primarily because ecological processes, mediated by the organisms (bacteria, fungi, Archaea, invertebrates), deliver ecosystem services or outcomes that benefit human life. Groundwater biodiversity also has the same intrinsic value associated with all life,

[24] Biodiversity (or biological diversity) is "the variety of all biological life — plants, animals, fungi, and microorganisms — the genes they contain and the ecosystems on land or in water where they live. It is the diversity of life on earth" (UN 1992; NZBS 2000). In addition to the organisms present, biodiversity encompasses the interactions between species and their environments, their ecological processes and the ecosystem services that these organisms deliver to benefit human life.

the uniqueness of those species inhabiting New Zealand's groundwaters (primitive, Gondwanan affinities, endemic, highly restricted distributions) and their unknowable future role and potential applications for human kind.

> **ECOSYSTEMS ARE CAPITAL ASSETS**
>
> *"[W]e must recognize that … ecosystems are capital assets; if properly managed, they yield a flow of vital services. Ecosystem services include … basic life-support processes (such as pollination, water purification, and climate regulation), life-fulfilling conditions (such as serenity, beauty, and cultural inspiration), and preservation of options (such as conserving genetic and species diversity for future use)".*
>
> (Daily 2000)

Accounting for the value of natural capital was defined as *"measurement and valuation of nature's benefits in terms of ecosystem goods and services — like fresh water, flood control and forest products — to be incorporated into a general standard format consistent with conventional national accounts"*[25]. New Zealand has developed accounts for its key freshwater resources (see Statistics New Zealand), but these are focussed entirely on the country's groundwater volumes, treating these systems simply as physical resources (Moreau-Fourier and Cameron 2011). The New Zealand Treasury recently released a discussion document (van Ayl and Au 2018) intended as a starting point for determining how to measure and evaluate the value of New Zealand's natural capital, including ecosystem services and physical resources.

3.3 Economic valuation

Economic valuation is often used in conjunction with methods such as natural capital or ecosystem services to value the identified benefits that ecosystems provide in a more comprehensive and objective way, and to allow more specific cost-benefit analyses of different management scenarios.

One way to define the economic value of groundwater is to trace the direct market use of the water. In this way, the monetary benefits of using the water for industrial or agricultural purposes can be calculated, often alongside estimates of the number of full-time jobs created by expansion of the industry. For example, the value of water used for irrigation (from combined surface and groundwater sources) on the Poverty Bay Flats was estimated at approximately $11.3 million dollars per year in 2012 (The AgriBusiness Group. 2012). Such evaluations can be used to assess impacts of different water management scenarios, for example, water allocation limits (The AgriBusiness Group. 2012) or an increase in irrigable land area (Saunders and Saunders 2012) on industry revenue and employment rates.

Direct use value is only one component of the total economic value (TEV) generated by any ecosystem. Estimating the value of the non-direct use (or non-market) services provided by GEs, such as cultural values, or regulating services (e.g., the buffering of floods, maintenance of a reliable water supply, protection against saltwater intrusion into an aquifer) and biodiversity values, is much harder than tracing market value of water use (Bergkamp and Cross 2006). Estimating total economic values (i.e., quantifying both use and non-use services) provides useful insights to support management decisions and policy (Pearce and Moran 1994, Edwards and Abivardi 1998), even if the process

[25] See http://www.conservation.org/projects/Pages/Valuing-and-Accounting-for-Natural-Capital.aspx?gclid=CI3c_J7CmsYCFQxwvAodTi0A0A .

involves multiple assumptions and estimates. For example, the valuation process highlights the fundamental value of biodiversity and its ecosystem services to decision-makers (Edwards and Abivardi 1998).

A generic framework for TEV of natural resources identifies five use and non-use values and subcomponents within each (Pearce and Moran 1994, Edwards and Abivardi 1998). These value categories are listed and defined below (following Pearce and Moran 1994):

- Use values have three categories:
  - direct value: actual uses, such as water abstracted for industrial or domestic uses
  - indirect value: benefits derived from GE functions: e.g., GEs use as a drought buffering system
  - option value: approximates an individual's willingness to pay to safeguard an asset for the option of using at a future date.
- Non-use values are usually divided into two categories:
  - bequest value: the benefit accruing to any individual knowing that others in the future will benefit from the resource
  - existence value: the value an individual gains from knowing something exists, even though he or she may never have used or seen it. For example, an individual's concern to protect the giant panda, even though they have never seen one, and likely never will.

Although there is a significant debate around this framework and the validity and utility of its components for resource valuation (Pearce and Moran 1994), it does reveal the complexities of natural resource economic valuations, and provides a structure for attempts to quantify TEV (e.g., Edwards and Abivardi 1998).

Below we adapt a variation of this framework[26] (Qureshi et al. 2012) for valuing alluvial GEs (Figure 3-2). The revised framework re-structures the key components of TEV to be more ecologically meaningful. In the terminology of Pearce and Moran (1994), indirect use values have been renamed 'ecosystem services values'. Note also, in this modified framework, we regard ecosystem services values as non-use values, because use of the GE resources (i.e., water) generally impacts the values of these ecosystem services, even if only marginally.

The revised framework emphasises the dynamic interaction between use/extraction values and non-use values. Generally, these oppose each other, with any increase in direct use reducing non-use values. Non-use values comprise existence or passive use value, plus bequest value, and ecosystem services value. The option value for groundwater is the potential future value of the water. Option values (value of potential future uses) are part of non-use values (as part of bequest values), and include the flexible/reversible extractive uses of use values. Any use now is likely to reduce future options (Pearce and Moran 1994), because any existing use tends to take precedence over a new use when the resource becomes scarce. Estimating option value is extremely difficult, at least for the medium to longer term future.

[26] We note that subsequent variations of this breakdown of total economic value (e.g., Qureshi 2012, DAE 2013) identify essentially equivalent components simply arranged slightly differently.

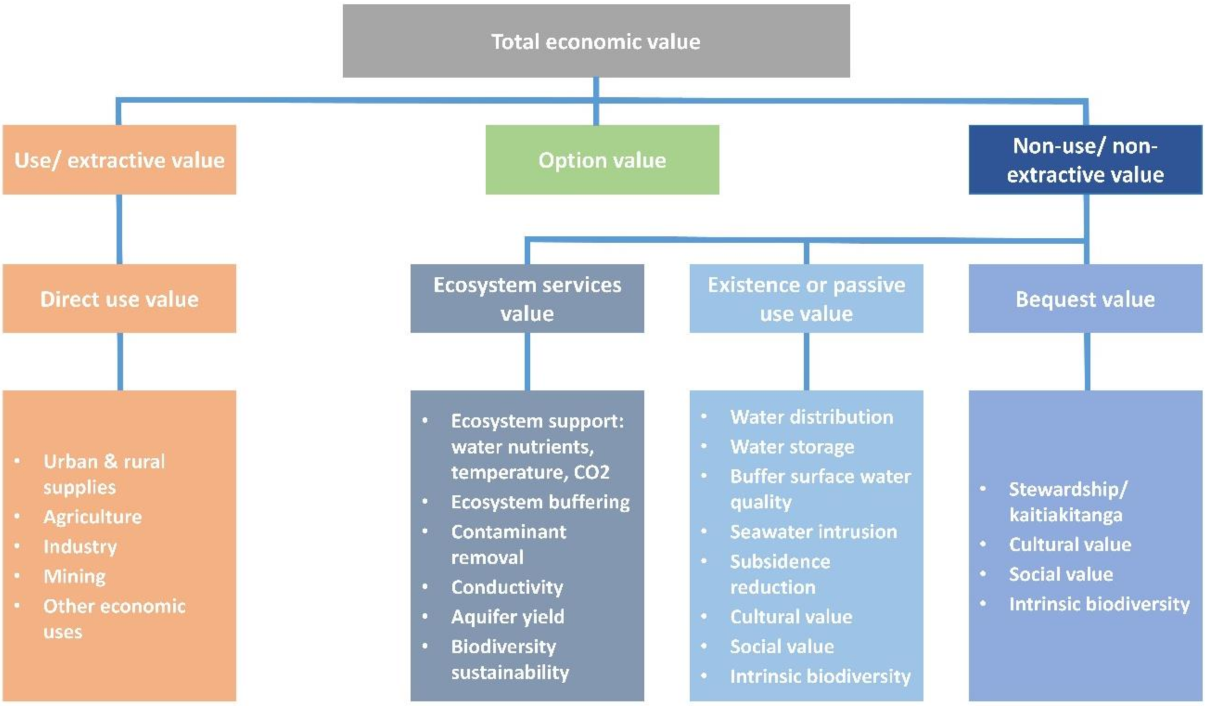

Figure 3-2: Components of total economic value of alluvial groundwater. Modified from (Pearce and Moran 1994, Edwards and Abivardi 1998, Qureshi et al. 2012, Deloitte Access Economics 2013). In the terminology of Pearce and Moran (1994), orange indicates direct use values, turquoise the indirect use values, green the option values, dark blue the existence values, and purple the bequest values.

The value of ecological function can be estimated, based on the cost of alternative ways of delivering equivalent benefits (Pearce and Moran 1994, Edwards and Abivardi 1998). For example, ecological function value could be estimated from the costs of treating the community's water supply if it became contaminated (assuming that, as previously in Christchurch City, it is supplied to users directly from underlying aquifers without any treatment).

The utility of this conceptualisation of total economic value is illustrated by a list of some component values that we identified for Christchurch's domestic groundwater supply (Table 3-1). Even this detailed list does not capture all values for the Christchurch City aquifers (and other ecosystems), such as, the overall alluvial aquifer geology and hydrology that facilitate the ecosystem services. Other workers have noted similar shortcomings, which often mean that some quite substantial economic values are not considered (Pearce and Moran 1994).

Table 3-1: Examples component values for the aquifer ecosystem supplying Christchurch City. Structure (and colours) follows that shown in Figure 3-2. Note: the list of values in this table is incomplete but illustrates the benefits and difficulties in this approach.

Extractive or use values	Option values	Non-extractive or non-use values		
Direct use values	**Future use values**	**Ecological function values**	**Existence/passive use values**	**Bequest values**
Clean water for domestic use	Realised only in future?	Water remediation	Security of natural self-purifying processes	Future value of all other values
Industry use: consumption & non-consumption	Manaakitanga	Aquifer yield	Living ecosystem	Whakapapa
Water distribution	Future ecosystem services management	Water distribution	Ecosystem resilience	Kaitiakitanga
Water storage		Mahinga kai	Biodiversity values	Whanau ora
Supplying surface & coastal waters		Supplying surface & coastal ecosystems	Biodiversity conservation (genotypes, species)	Wairuatanga

3.3.1 Examples of total economic value of groundwater ecosystems

A few New Zealand studies estimated the economic value of groundwater, but they are dated, fragmentary, small-scale and/or not directly applicable to the rest of the country (Mosley 1990, White et al. 2001) A total of 35 non-market (non-use) valuation studies for freshwater ecosystems in New Zealand were found in a review by Marsh and Mkwara (2013). Only three of these directly involved groundwater (White et al. 2001, Kerr et al. 2003, White 2011). In addition, even in direct use valuations of water, (e.g., the economic valuation of irrigation), surface and groundwater sources may not be separated in the analysis due to the hydraulic linkages between them (Saunders and Saunders 2012, The AgriBusiness Group. 2012, NZIER 2014). In the section below, we summarise examples of economic estimates for the use and non-use values of groundwater in New Zealand.

A Direct use value

One of the earlier attempts to value New Zealand's freshwater (Mosley 1990, citing Mosley 1988) arrived at the figure of $2.34 billion (in 1988; equates to $4.6 billion in 2018[i]), based on some of the direct uses of water. That study noted that this estimate did not include *"the more intangible, but nonetheless real"* other values associated with water, especially its cultural values to Māori (Mosley 1990: 133). Subsequently, New Zealand's total direct use of groundwater was valued $24-25 billion (in 2001, or $34.3-35.7 billion in 2018) by extrapolating from estimates groundwater's value to industry and agriculture in the Nelson area (White et al. 2001). These estimates differ appreciably, showing that economic valuation is frequently compromised by available information.

Nelson case study

The total economic value of groundwater in the Waimea Plains area (7,500 ha; 43% irrigated) of Nelson was assessed for agricultural irrigation, industry and bulk supply (domestic and smaller industrial users) (White et al. 2001). The value of groundwater to irrigators (260 irrigators, 3,226 ha irrigated by 615 m^3/day on average) was assessed by two methods based on the effect of irrigation water availability on property values. First, scaling irrigators' perceived loss in value for their properties if groundwater was lost, valued the resource at $38 million annually, which is equivalent to [2001] $0.65/$m^3$ of groundwater allocated. Second, quantitative modelling of farm rateable (government) valuations as a function of land, water, labour and capital attributes, indicated a marginal value of [2001] $0.82/$m^3$ for groundwater allocated, which, extrapolated to the total area, estimated the value of groundwater for irrigation at $48 million (White et al. 2001).

Applying the first (loss of business value if water access ceases) approach to industry businesses, produced an estimated annual value of this resource to the area's industry of $173 million. This equates to [2001] $81.05/$m^3$ for groundwater allocated to businesses in the Waimea area (White et al. 2001). Groundwater's value for bulk supply purposes was assessed at $33 million, based on the likely cost of accessing equivalent volumes of water from alternative sources (White et al. 2001). Similarly, this overall value equates to [2001] $3.48 – 13.48/$m^3$ (depending on the estimate of municipal/bulk supply used).

Subsequent changes in land-use practices (mostly to higher revenue or more efficient water-use activities) and product prices, resulted in revenue from irrigation water in part of this area increasing from an average of $4.9/$m^3$ in 2004/05 to $16.7/$m^3$ in 2007/08 (White 2011). Adjusting the value of groundwater for irrigation use in Table 3-2 for this increase indicates a valuation of groundwater for irrigation at ~$184 to 234 million (or ~$263 to 334 million in 2018), a combined use valuation of $478 to 527 million ($682 to 752 million in 2018) and overall total value of $480 to 529 million ($685 to 755 million in 2018). This valuation is incomplete, however, because the research approach did not explore option values fully (White et al. 2001).

Standardised valuations of groundwater ($/$m^3$) for irrigation in the Waimea area estimated here (Table 3-2) differ appreciably from those estimated by White (2011): 2007/08 revenue $6.40 – $30.70/$m^3$ of groundwater applied. Part of this difference is due to estimates in Table 3-2 being based on White et al.'s (2001) work, which focused on water allocated, whereas White (2011) examined revenue/m^3 of water applied over a six-month growing season. However, doubling the estimates in Table 3-2 as a correction for the six-month irrigation season still leaves our estimates well below White's (2011) more recent figures.

Also, our estimated revenue/m^3 of groundwater for industrial use seems anomalously large. We were unable to check either volumes allocated or the valuation but suspect that the method used to derive the value (i.e., loss of businesses' values if water was unavailable) over-estimated the value of groundwater to those businesses. Other economic analyses on supplementary water sources (i.e., the Waimea Community Dam proposal) (e.g., Clough & Corong 2014, Fenemor et al. 2015, Bermeo et al. 2015) provided no directly comparable information on the value of groundwater.

This example illustrates some approaches used in direct use valuation and that the values obtained can vary widely with the quality of assumptions, data, and estimates or other values used in the calculations.

Table 3-2: Value (NZ$ million in 2001 and 2018) of groundwater to main user groups and overall value of groundwater within Waimea, Nelson. Data from White et al. (2001)[27]; 2018 $ values derived using the Reserve Bank of New Zealand's online calculator (https://rbnz.govt.nz/monetary-policy/inflation-calculator). Bulk use/reticulated volumes from: a, White et al. (2001); b, Fenemor (2013); c, McCormack (2017). *, includes 3.408 times increase in revenue from irrigation due to land-use changes, following White (2011).

Component values	Volumes allocated 000 m³/day	Groundwater resource value			
		Total resource: 2001 $ millions/year	2001 $/m³	Total resource: 2001 $ millions/year	2018 $/m³
Irrigation use	160	38 – 48	0.65 – 0.82 (2.22 – 2.80)*	184 – 233.5	**3.17 – 4.00**
Industry use	5.85	173	81.05	246.9	**115.66**
Bulk use[a]	197	33	12.43	47	**17.74**
Bulk use 16.3% of irrigation use[b]	26	33	3.48	47	4.97
Bulk reticulated use[c]	6.7	33	13.49	47	19.25
Subtotal	*174 – 363*	*244 – 254*	*[31.12]**	*477.9 – 527.4*	*[44.41]*
Non-use total (minimum only)	?	1.2	?	1.7	?
Overall total	**174-363**	**245.2 - 255.2**		**479.6 – 529.1**	**-**

B Ecosystem, existence and bequest values

The non-use value of groundwater (e.g., spring flows, water quality, prevention of saltwater intrusion) for Waimea-Nelson was estimated at $1.2 million by surveying the community's willingness to pay for protection, assuming that reducing industrial and agricultural extraction by 20% (1.8 billion m^3) would deliver the protection (White et al. 2001). This estimate probably significantly under-estimates the non-use values of groundwater. We note that White et al.'s (2001) valuation of *in situ* groundwater (or non-use value) explored three dimensions: spring flow, water quality and salt-water intrusion. Our understanding of non-use values resolves several more dimensions, which, although not necessarily recognised by most stakeholders, are significant components of overall non-use value of groundwater. An Australian investigation considered that "*under some circumstances they* [environmental and option values] *are arguably … just as important as extractive use values*" (Deloitte Access Economics 2013, p 18-19). Based on these observations, the GE TEVs for Waimea probably exceed $1 billion per year.

Equivalent calculations for the value of groundwater, including ecosystem services, to all sectors (excluding mining) across Australia indicated a A$6.8 billion direct contribution to GDP (based on use of 3,530 gigaL/year[28]) and, applying a direct-indirect multiplier, a TEV of production dependent on groundwater of A$9.4 billion (Deloitte Access Economics 2013, p 38). That study noted that non-use value could be as high as direct use values, suggesting an overall TEV approaching A$18 billion (Deloitte Access Economics 2013).

[27] We note that White et al.'s (2001) volumes allocated differ appreciably from those shown in McCormack (2017), notably Figure 3-4. That figure shows TDC metered demand only and excludes irrigation and other abstraction from non-council bores.

[28] One gigalitre (gigaL) = 1 billion (1,000 million) litres = 1 million cubic metres.

Estimates of the value of benefits that four European cities derived from "water treatment due to natural treatment from the ecosystems" of adjacent, variously protected areas are comparable (ten Brink et al. 2013, p 32). For the cities of Berlin, Vienna, Oslo and Munich, the annual values (economic benefits) of natural water purification (i.e., ecosystem services) were between €7-16 million and of water provision (i.e., use value) between €12-91 million per city. These translate into average benefits of €15-45 per capita per year for both water purification and provision (ten Brink et al. 2013).

These examples show that the total economic value (TEV) of groundwater in the Waimea area, including its biodiversity and ecosystem services, is undoubtedly very substantial, but difficult to determine with any degree of accuracy (e.g., as described and used by Deloitte Access Economics (2013)). Nonetheless, these estimates indicate that both use and non-use components have a high value to the economy, regional and national. Ecosystem services are perhaps the most significant part of non-use values, because these services are considered essential to perpetuate the supply of water in quantity and quality required to generate direct and indirect economic value.

3.4 Summary

- Traditionally, GEs are treated as physical systems that supply a valued resource (i.e., supply of water for various uses). Groundwater ecosystems actually provide far reaching ecosystems services covering four main areas: provisioning, regulating, cultural and supporting.
- Two important provisioning services are water supply (e.g., for drinking, stock, irrigation and industry) and genetic resources arising from the unique pool of microbial and stygofaunal species present in groundwater.
- Regulatory services include water purification and disease control through (natural or managed) bioremediation, maintenance of hydraulic conductivity through the movement and feeding activities of stygofauna (bioturbation), and buffering of floods and drought through the assimilation and storage of water with groundwater ecosystems.
- Cultural services include non-material benefits arising from social values (e.g., reliance on groundwater as an essential component of everyday life for many communities), spiritual values (e.g., connection with springs or puna) and support for surface water recreation values (e.g., through provision of cooler water seasonally to support based flows of depleted rivers that are valued for recreational activities).
- Supporting services relate specifically to ecosystem services and include biodiversity values, nutrient recycling and habitat provision (see Section 2.7 for a summary of these services).
- The concept of natural capital involves establishing asset classes for components of ecosystems (and other aspects of the natural environment which benefit humans, such as the biodiversity of groundwater ecosystems) within a country's national accounts.
- Estimating the economic values of GEs is complicated by their physical interconnectedness with surface waters, our lack of understanding of GE functioning and inadequate data to support the multiple assumptions and estimates involved in ecosystem valuation.

4 Māori values, beliefs and practises associated with groundwater ecosystems

This section overviews Māori values, beliefs and practices associated with GEs. There are common principles and values that establish and reinforce whānau, hapū, rūnanga and iwi identity, and their responsibilities and rights to manage and use natural resources, including GEs. The Māori worldview requires an inter-generational focus; resources must be protected and enhanced for those generations not yet with us and in respect of those that have passed. We encourage readers to source the cited references for a more in-depth understanding of Māori cosmology, principles, concepts and the tribal and catchment histories touched on in this section.

4.1 Overview

The Māori relationship with the environment and natural resources, water more specifically, is founded upon whakapapa (connections, genealogies) and whānaungatanga (relationships, kinship). From a Māori worldview water appears early in the whakapapa, emerging while Ranginui (Sky father) and Papatūānuku (Earth mother) are still locked in loving embrace:

Ā, ko Rū-nuku, ko Rū-rangi, ko Rū-papa,
ko Rū-take, ko Rū-kerekere,
Ko Rū-ngātoro ko koukou mataero, koi runga
Koai ū-whāio, Ko Rū-ngātoro,
Ko Wai-o-nuku, Ko Wai-o-rangi,
Ko Wai-papa, Ko Wai-take, ko Manatu.

And, the Earth trembles, the Sky trembles, the Ground trembles,
the Source trembles, the intense trembles,
the resounding trembles, annoint the thin surface above,
Then numerous trembles, resounding ko Manatu, tremble, the ebbing,
the Waters of the Earth, the Waters of Heaven,
the **Waters of the ground**, the Source of Waters, the ebbing.
(Source: Wiremu Maihi Te Rangikaheke, adapted in Hikuroa (2017)

Māori seek to understand the total environment or whole system and its connections through whakapapa, not just part of these systems, and their perspective is holistic and integrated (Harmsworth and Awatere 2013). These relationships often manifest themselves in inherited rights that are accompanied by responsibilities, as kaitiaki, to care for ecosystems. The rights and responsibilities of iwi, hapū and whānau are therefore seen in the context of a wider Māori world-view based on Māori kaupapa (philosophy). Hapū have direct relationships to puna (springs), other water bodies that are reinforced in their pepeha (tribal sayings), whakataukī (proverbs) and waiata (songs) (e.g., Morgan 2006, Ngāi Tūāhuriri Rūnanga et al. 2013). For example, the Waikoropūpū waiata:

Waikoropūpū, Waikoropūpū,
Pūpū ake te whenua,
Pūpū ake ko ngā waiora,
Waikoropūpū,
Ngā puna wai o Tākaka,
Ngā puna roimata wairua,
Waikoropūpū, Waikoropūpū.

Bubbling waters from the throat of the spring,
Bubbling waters from the throat of the spring,
Forever bubbling from the land,
Forever bubbling for the health of the people and the spring waters,
The spring waters of Tākaka,
The tears of the spirit ancestors,
Waters bubbling from the throat of the spring,
Waters bubbling from the throat of the spring[29]*.*

Mātauranga Māori (Māori knowledge system) is a holistic perspective encompassing all aspects of knowledge and seeks to understand the relationships between all component parts and their interconnections to gain an understanding of the whole system. Similar to western knowledge, mātauranga Māori is a dynamic and evolving knowledge system and has both qualitative and quantitative aspects. Kaupapa Māori research, based on Māori approaches and ethical frameworks, is often used to generate mātauranga Māori. It is based on its own principles, frameworks, classification systems, explanations and terminology (Tipa et al. 2016). For example, a general classification of Māori terms for water is shown in (Douglas 1984), where waters are also ranked – from the sacred puna wai to the water in common use (wai māori) and those of very limited use such as wai kino (Te Wai Māori 2008).

When referring to groundwater-dependent features or characteristics (excluding thermal systems), some of the terminology used by different hapū and iwi around the country includes: ngā wai rarowhenua, puna, puna manawa whenua, puna wai, puna waiariki, wai manawa whenua, wai rongoā, wai tapu and waipuna.

[29] https://www.doc.govt.nz/Documents/parks-and-recreation/places-to-visit/nelson-marlborough/te-waikoropupu-interpretation-panels.pdf

Table 4-1: General Māori classifications of water from various iwi/hapū groups. Adapted from Douglas (1984) and Tipa et al. (2016).

Te Reo	Description
Wai ora	The purest form of water, such as rain-water, it is the spiritual and physical expression of Ranginui's long desire to be re-united with Papatūānuku. Pure water is termed "te waiora a tane" and to Māori it contains the source of life and well-being. Contact with Papatūānuku gives it the purity as water for human consumption and for ritual. Traditional water could only remain pure without being mixed and was protected by ritual prayer. Traditionally wai ora had the potential to give life, sustain well-being, and counteract evil.
Waitohi	Areas of pure water
Wai puna	Spring water
Wai māori	Freshwater water, water for normal consumption – water becomes wai māori when it comes into unprotected contact with human beings (e.g., running streams, lakes). It therefore becomes normal, usual, or ordinary and no longer has any particularly sacred associations. Wai māori is often used to describe water that is running, unrestrained, or to describe water that is clear or lucid. Wai māori has a mauri (which is generally benevolent) and was controlled by ritual.
Waiwera	Hot water used for healing purposes, bathing, recreation.
Waipuna	Generally pure spring water that comes from the ground (e.g., hillside or underground springs)
Waitapu	Sacred waters used in rituals. Rituals used running water, sometimes termed wai matua o Taupapa (virgin water as it flows from the earth). Water was applied using certain plants, not human-made vessels.
Wai whakaika	Ritual waters, pools, ceremonial
Wai whakaheketūpāpaku	Water burial sites
Wai kino	Literally means bad or impure water (e.g., stagnant pools). Often associated with past events, polluted or contaminated water. Includes water that is dangerous, such as rapids
Wai mate	Water that has lost mauri, degraded, and is no longer able to sustain life. Mate is associated with death, and wai mate may have been used in places of contamination and tapu, historic battles, dead, damaged or polluted water, where water has lost the power to rejuvenate itself or other living things. Wai mate, like wai kino, has the potential to cause ill fortune, contamination or distress to the mauri of other living things or spiritual things including people. The subtle difference between wai kino and wai mate seem to be based on a continued existence of mauri (albeit damaged) in the former, its total loss in the latter. Wai mate also has geographical meaning: to denote sluggish water, a backwater to a mainstream or tidal area, but in this sense the wai mate retains its mauri.
Wai tai	Seawater, saltwater, the surf or the tide – used to describe any water that is tidal, influenced or related to the sea (the domain of Tangaroa) and includes waves, surf, estuaries, tidal channels, river mouths (e.g., salt water). It is used to distinguish sea water from freshwater (wai māori, wai ora). Wai tai was water that was returned to Tangaroa. Māori often thought in cycles and processes of generation, degradation, and rejuvenation. It had uses for seafood (kaimoana), bathing and healing.
Waimātaitai	Significant estuarine or brackish waters

For generations Māori have emphasised the need to consider and manage our environment in its entirety, as an undivided entity, and this specifically includes GEs. For example:

- To Maniapoto, the Waipā River [Waikato region] is a single indivisible entity that flows from the spring Pekepeke to its confluence with the Waikato River and includes its waters, banks, bed (and all minerals under it) and its streams, waterways, tributaries, lakes, fisheries, vegetation, floodplains, wetlands, islands, springs, geothermal springs, water column, airspace and substratum as well as its metaphysical elements with its own mauri. The Deed in Relation to Co-Management of the Waipā River describes it in this way (Ngā Wai o Maniapoto (Waipā River) Act 2012)[30]:
    - *"Te Awa o Waipā is a taonga to Maniapoto. Maniapoto have a deep-felt obligation and desire to restore, maintain and protect all of the waters that flow and/or fall within the Maniapoto rohe (Ngā Wai o Maniapoto),* ***whether the waters are above, on or underground.*** *Te Mana o Te Wai (The quality and integrity of the waters) is paramount. The obligation includes the waters that flow into and form part of the Waipā River."*
    - *"Waipā River, Waiwaia and all natural fresh water resources, other rivers, streams and tributaries that feed into the Waipā,* ***and the aquifers*** *(including fresh and salt water) are essential to sustainability and longevity of the environment from which we gain sustenance and wellbeing."*
- *"Although there is separation in management and policy regimes, within tikanga Māori terms,* ***connected groundwater systems are regarded as part of the main river*** *in accordance with "Te Mana ki Te Wai" and the 'Ki Uta Ki Tai" principles."*[31]
- *"Our rivers,* ***groundwater****, lakes, and wetlands have provided our people with food, spiritual nourishment, cleansing, modes of transport, and communication as well as medicinal, building, and weaving materials. Water is a sensitive and complex taonga that Raukawa has a duty to respect, protect, and restore. Our mana whakahaere is balanced by the inherent responsibilities that come as guardians of our waterbodies. This places the expectation that each generation leaves our waterbodies in a healthy and balanced state for future generations"* (Raukawa Charitable Trust 2015).
- *"We see the springs as part of the wider system of the Tākaka River catchment – everything from the* ***underground source*** *to the sea, all the small tributaries and all the springs that bubble up into the ocean. Because the physical and the spiritual are inseparable, the health of the whole system reflects the well-being of our community"* (Little 2018).

Concepts such as (but not limited to) Ki Uta Ki Tai and Ma Uta Ki Tai (e.g., Te Rūnanga o Ngāi Tahu. 2003, Henwood and Henwood 2011) are used by Māori to describe their holistic understanding of aquatic ecosystems and how the health and wellbeing of the people is intrinsically linked to that of the natural environment. Ki Uta Ki Tai recognises the movement of water through the landscape and the numerous interactions it may have on its journey and **acknowledges the connections** between

[30] http://www.legislation.govt.nz/act/public/2012/0029/latest/DLM3335204.html

[31] https://www.epa.govt.nz/assets/FileAPI/proposal/NSP000041/Board-minutes-directions-and-correspondence-Correspondence-to-decision-maker/Mauri-Protection-Authority-Views-on-procedural-matters-25092017.pdf

the atmosphere, surface water, **groundwater**, land use, water quality, water quantity, and the coast. It also acknowledges the connections between people and communities, people and the land, and people and water (NZ Govt 2017). This Māori resource management framework reflects that resources are connected, from the mountains to the sea, and must be managed as such (Ngāi Tahu ki Murihiku 2008) as reflected in the whakataukī "*He taura whiri kotahi mai ano te kopunga tai no i te pu au*" (From the source to the mouth of the sea all things are joined together as one). Recent examples of the use of this principle in iwi freshwater policy and planning includes: Ngāi Tahu ki Murihiku Natural Resource and Environmental Iwi Management Plan, Te Rūnanga o Kaikōura Environmental Management Plan, Mahaanui Iwi Management Plan, Orari River Catchment Management Strategy and Whakaora Te Waihora Restoration Plan (Tipa et al. 2016).

4.2 Māori-driven groundwater research

To the best of our knowledge few targeted studies have been completed to increase understandings of groundwater-dependent Māori values, beliefs and practises and hapū/iwi priorities for groundwater management. However, over the last five or so years, the research needs of hapū and iwi are driving the delivery of research which will provide new knowledge and methods of benefit to other groups around the country. These research studies include:

- **Groundwaters of Te Wai Pounamu (South Island) with a focus on Murihiku (Southland):** This Southland-based study was designed to address five objectives: (1) consider groundwater and surface water resources in terms of the cultural values associated with such resources; (2) describe the cultural values and assess the significance of these; (3) identify any registered historic places / sites linked to groundwater dependent features and processes; (4) identify how cultural values could be affected by hydrological change; and (5) make specific recommendations on avoidance of negative impacts on the water dependent cultural values. The results of this study are published in Tipa & Associates (2013b).

- **Ka Tu Te Taniwha, Ka Ora Te Tangata:** This research programme, facilitated by Ministry of Business Innovation & Employment's (MBIE) Vision Mātauranga Capability Fund[32], was a collaboration between Ngāti Rangiwewehi, GNS Science, and Bay of Plenty Regional Council. The two primary objectives of the Ka Tu Te Taniwha Programme were: (1) to combine technical, scientific and mātauranga-a-iwi information for the Awahou groundwater catchment into an integrated data repository and knowledge resource; and (2) to allow Ngāti Rangiwewehi to incorporate traditional knowledge and understanding of cultural significance to inform and plan for future freshwater development in the Awahou catchment. Two reports (Ngāti Rangiwewehi 2015, Lovett and White 2016) and several presentations have been produced. More information can be accessed through the GNS website[33].

- **Ngā Repo o Maniapoto:** This project, funded by Te Wai Māori[34] and MBIE's Vision Mātauranga Capability Fund, developed out of the need to capture the mātauranga-ā-hapū surrounding wetlands and puna, and develop a new decision-support tool to help

[32] http://www.mbie.govt.nz/info-services/science-innovation/investment-funding/current-funding/2018-vmcf-investment-round

[33] https://www.gns.cri.nz/Home/Our-Science/Environment-and-Materials/Groundwater/Research-Programmes/Past-research-programmes/Ka-Tu-Te-Taniwha-Ka-Ora-Te-Tangata

[34] http://www.waimaori.maori.nz/research/purpose.htm

prioritise the order of restoration. This project provided space 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 (Figure 4-1). The results of this study are published in Ratana et al. (2017).

- **Ngā Kete o Te Wananga[35]:** This NIWA-led research programme is the result of MBIE's 2013 Freshwater Management Sandpit. The programme is designed around the question "How can we develop and optimise synergies between science, mātauranga Māori and other relevant factors to improve freshwater management?". Since this programme began, rūnanga partnerships have further defined the culturally relevant spatial scales and refined the focal freshwater management priorities within the Southland and Canterbury regions. As a result, there are three main workstreams underway: (1) development of a Murihiku Cultural Water Classification System; (2) development of a Opihi Cultural Biography (which includes springs); and (3) investigation of ways to protect land-based taonga in freshwater management, using rock art as an example (which includes springs and groundwater management). The rock art component of this programme is expanded on in Section 4.3.6.

Figure 4-1: The Ngā Repo o Maniapoto project co-developed a strategic restoration framework with Ngā Tai o Kāwhia whānau for prioritising wetland and puna restoration efforts in their rohe. In this example the framework shows some of the mātauranga on fisheries, cultural significance, uses and associations of repo (swamps) and puna (springs) in the Kāwhia rohe. Source: Ratana et al. (2017).

[35] https://www.niwa.co.nz/te-k%C5%ABwaha/research-projects/ng%C4%81-kete-o-te-w%C4%81nanga-m%C4%81tauranga-science-and-freshwater-management-0

4.3 Māori values, beliefs and practices

In this section we have drawn the available literature (e.g., client reports, journal papers, Statements of Evidence, Statements of Association, Statutory Acknowledgements, Regional Plans, Iwi/Hapū Environmental Management Plans, Cultural Impact Assessments) to provide examples of the links between GEs and Māori values, beliefs and practices (Figure 4-2 and Figure 4-3). It is not the intention of this report to present everything that different iwi and hapū from around the country have written about GEs. Rather we aim to provide a range of examples from a range of hapū and iwi to help illustrate the key points presented. It is anticipated that many values associated with surface waters are also relevant to groundwaters, because groundwaters are variously connected to and feed most surface waters.

4.3.1 Cultural landscapes and settlements

In a Māori worldview all physical landscapes are inseparable from tupuna (ancestors), events, occupations and cultural practices. These dimensions remain critical to cultural identity and to the maintenance of a Māori sense of place (e.g., Ngāti Te Ata Waiohua 2012). To mana whenua, these cultural sites have a mauri that binds the current generations through mana, tapu and whakapapa to the whenua, the cultural sites and to the early ancestors. The landscape and cultural sites act as a repository for the whakapapa, mana, tikanga and traditions for the current and future generations (e.g., Hovell & Atkins Holm Majurey Limited 2012).

Settlement is only possible if there are sufficient resources (food, materials, drinking water) to sustain a community. The distribution of hydrological features such as aquifers, puna, repo and awa shaped the way whānau and hapū settled across New Zealand (e.g., kainga/kaika, pā, papakainga) and seasonally utilised catchments and trails (e.g., Te Wai Pounamu mahinga kai trails) (Tipa & Associates 2013b). For example:

- Tipa et al. (in prep) explain [Canterbury region] *"an interesting characteristic of the placement of these kaika is their proximity to rivers, **springs**, wetlands and backwaters. When Kai Tahu was granted reserves in the lower catchment following European settlement, it is interesting that the sites chosen were also near these. Today, this association remains very important."*
- *"This abundance of fresh water which was constantly being **replenished through Waipuna** (freshwater springs) was utilised by the tangata whenua who constructed Pā in the immediate area north-west of the confluence of Booths Creek and Parkvale Stream* [Wellington region]*"* (Ohau Plants Ltd 2011).

Generally, cultural landscapes are large areas with layers of interrelated values and features, and can have many connected communities, for example, *"Kā Papatipu Rūnaka value all waterways within the Waitaki Catchments. We consider three dimensions to a waterway: from the headwaters to the sea; from the river to the riparian/floodplains; and **from river to groundwater"*** (Kai Tahu Ki Otago 2005). Figure 4-4 illustrates the various components of one valued cultural landscape, Takiroa, on the south bank of the lower Waitaki River catchment. Many taonga are found at Takiroa including springs, spring-fed channels and swampy land, rock art, rock shelters, nohoanga and pā. To successfully protect this cultural landscape all ecosystem components (including springs, watercourses, buffers, wetlands, revegetated areas, rock art) need to be factored into management plans.

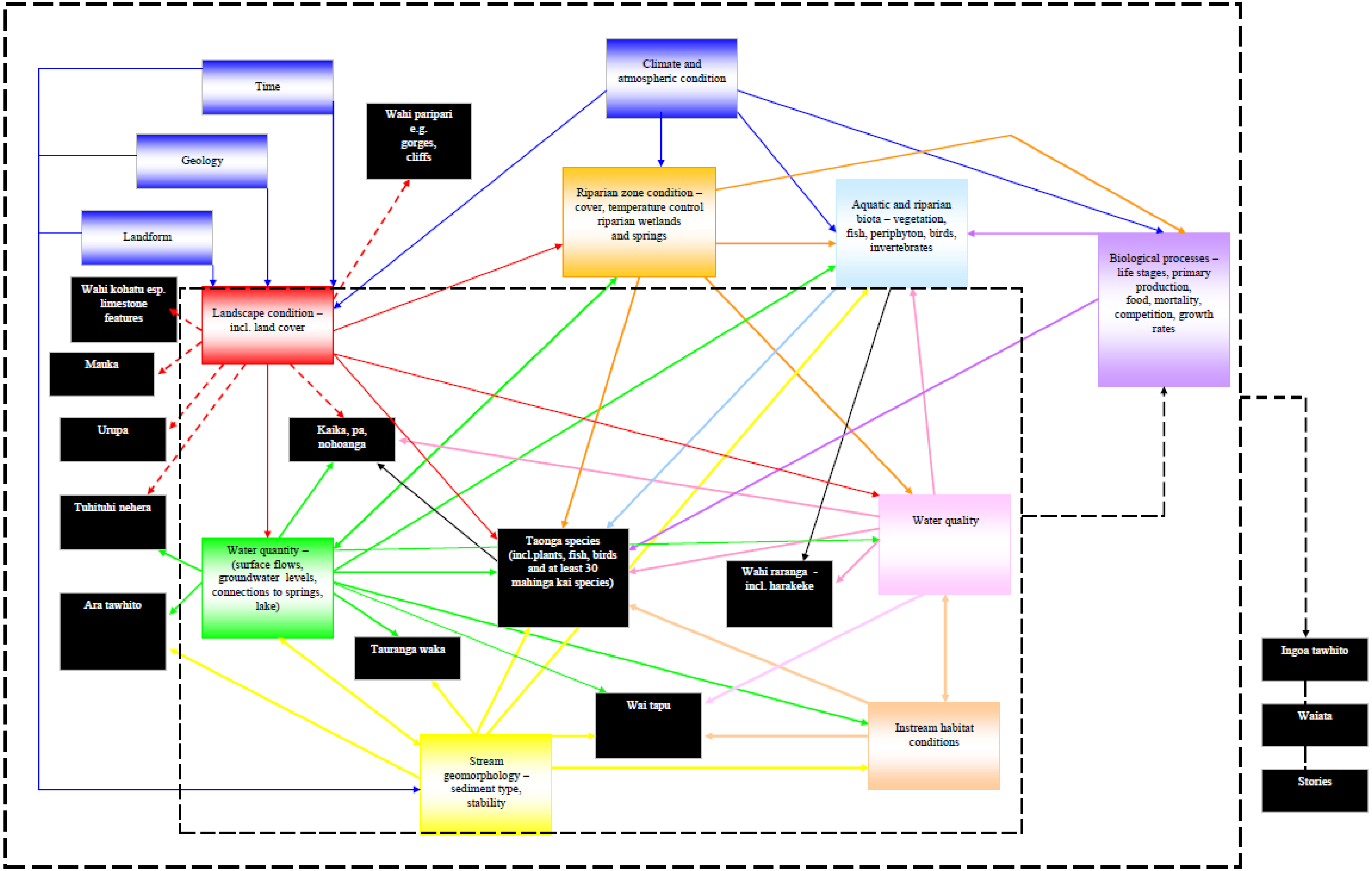

Figure 4-2: Conceptualisation of the inter-relationships between wāhi taonga in the Te Waihora catchment (Canterbury region) and how they are dependent on a healthy functioning ecological ecosystem, that includes groundwaters. Source: Tipa & Associates (2013a).

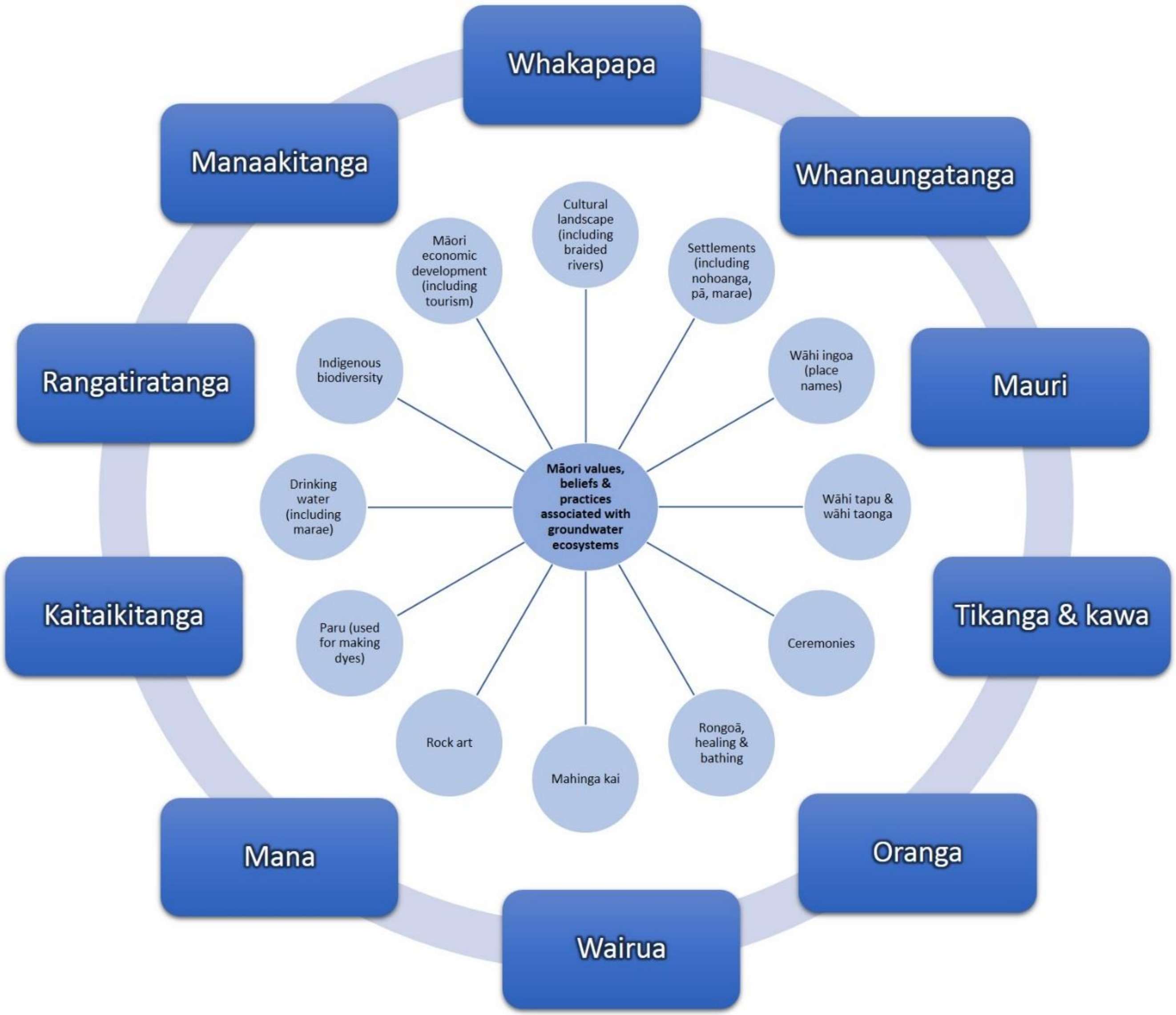

Figure 4-3: Examples of some of the Māori values, beliefs and practices associated with groundwater ecosystems. The "inner circle" expresses some of the more tangible uses and physical associations that Māori have with groundwater ecosystems; however, the "outer circle" recognises that these uses/practices are underpinned by beliefs/principles such as mauri, whakapapa, manaakitanga and kaitiakitanga.

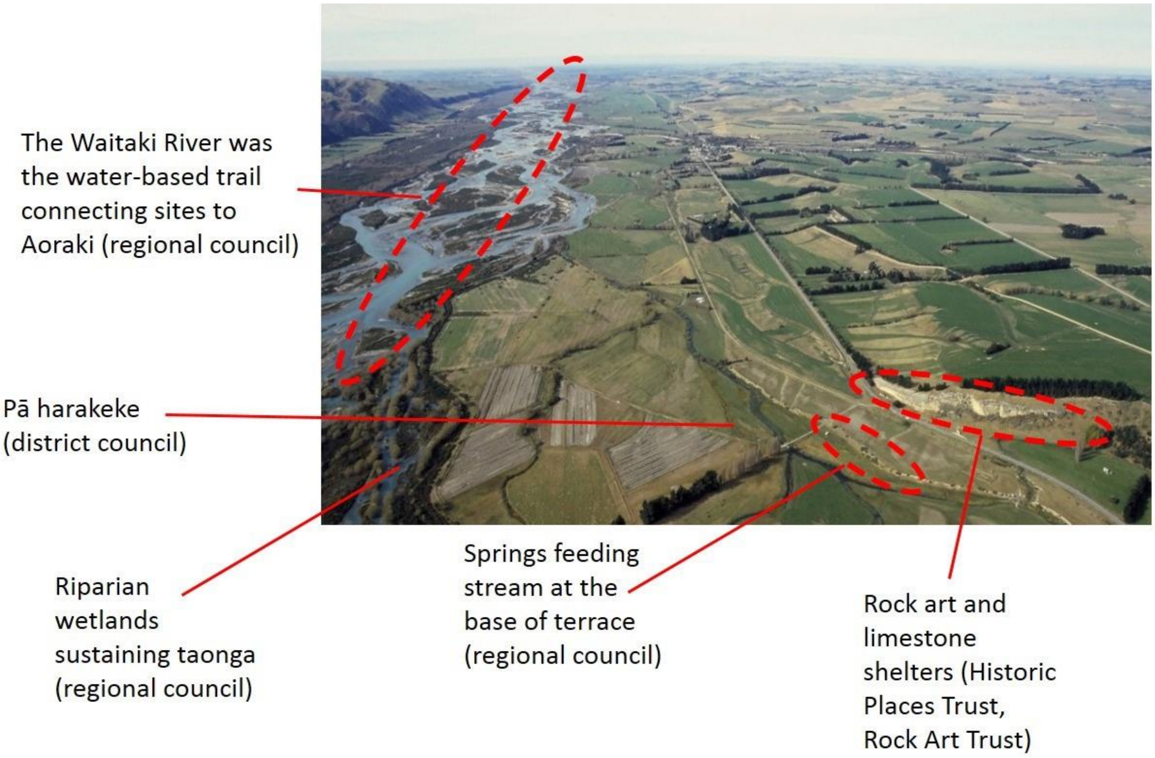

Figure 4-4: The cultural landscape of Takiroa (Waitaki catchment) showing taonga and management jurisdictions (in brackets). Source: Tipa & Associates (2013a). Please note that the Historic Places Trust has since changed its name to Heritage New Zealand.

4.3.2 Wāhi ingoa (place names)

The value Māori attach to waterways is evident from the fact that every part of a landscape was known and named. Not only were the larger mountains, rivers and plains named but every hillock, stream and valley. Some place names describe the state, features, or relationships in a catchment (Hughey and Baker 2010). Many groundwater features, such as springs and aquifers, have their own names, often related to the cultural landscape, a historical event, the hydrological complex, its physical characteristics (e.g., the sound), and/or how the feature was/is used by tangata whenua. For example:

- *"**Waiariki** is the name of a natural spring in the vicinity of Eden Crescent [Auckland region] meaning 'waters of the ariki (head chief)' or waters having a curative value"* (Ngāti Te Ata Waiohua 2012).

- *"The rangātira Ruapani, who embodied the whakapapa of Horouta, Takitimu and Paikea, had brought peace and prosperity to the people of Turanganui through his leadership. The treasured puna (fresh water spring) at the mouth of the Waikanae* [Gisborne region] *was given the name **Te Wai o Hiharore**, after the grandmother of Ruapani. A revered place of resource for Rongowhakaata, as it is the mauri for kaimoana such as kanae (mullet)"* (Gisborne District Council 2013).

- **Te Ipu Pākore** is a spring that used to be one of the main water wells that supplied the Maungawhau pā [Auckland region]. The name Ipu Pākore or 'Cracked Water Bowl' comes from two women who were ambushed after returning from the spring. It also refers to a later incident in Arch Hill involving a massacre of Waiohua women that took place when the pā and water spring were taken by a rival tribe (Ngāti Te Ata Waiohua 2012).

- Ngāti Kahungunu hi Heretaunga [Hawke's Bay region] held mana over a large water resource once represented in widespread wetlands supporting abundant fish and water fowl, the primary food source of Ngāti Kahungunu. It was particularly large and famous, and was recorded in a whakataukī: *Heretaunga ararau, Heretaunga haukūnui, Heretaunga haro te kahu, Heretaunga takoto noa.* Waitangi Tribunal (2012) interpret *Heretaunga ararau* to mean the myriad of waterways through the great swamps and the myriad of hapū that they linked together on shore and ***Heretaunga haukūnui*** to describe the waters as a system of repo, awa and puna, the life-giving **waters from deep in the earth** (Waitangi Tribunal 2012). Waitangi Tribunal (2012) illustrates the location of Te Haukūnui in a conceptual diagram of the water cycle (Figure 4-5).

Morgan (2006) further explains how the maintenance of the knowledge base for hapū is linked to the physical landscape and its appearance – as the whakapapa of hapū includes the place names within the rohe (tribal area). Many pepeha identify the origins of each hapū in association with geographic features such as mountains and areas of occupation, but also the water source and the significant water body to which the hapū have claimed rights. Marae (communal gathering places) sometimes take the name of the water supply that provides sustenance for a hapū. For example, the identity of the Ngāti Te Rangiunuora people [Bay of Plenty region] is inextricably tied to Lake Rotoiti and Puna Whakareia marae. A translation of the full name of the marae means the well or spring that sustained Rākeiao, an important ancestor of the Ngāti Te Rangiunuora people (Morgan 2001).

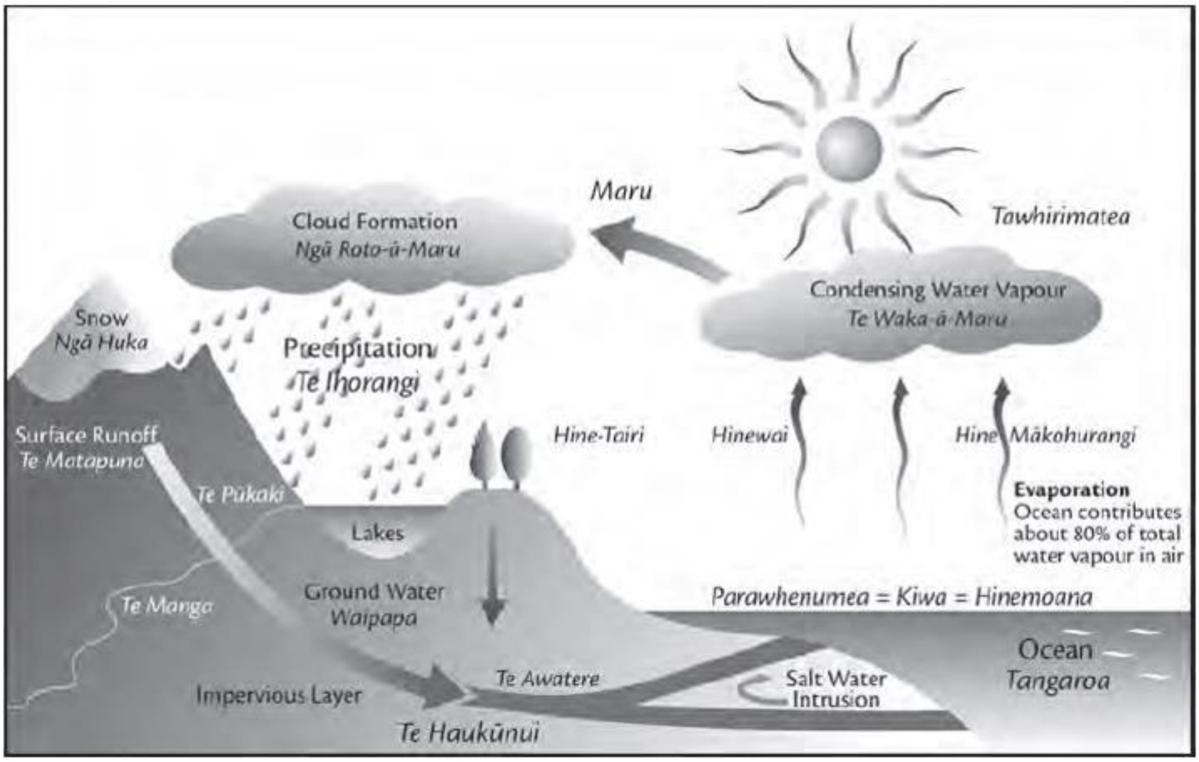

Figure 4-5: Conceptualisation of a water cycle, illustrating the location of Te Haukūnui. Source: Waitangi Tribunal (2012).

4.3.3 Wāhi tapu and wāhi taonga

Māori heritage (i.e., natural and physical resources that contribute to an understanding and appreciation of New Zealand's history and cultures) covers the full range of values and types of places – buildings, sites and areas. For example, Māori heritage may include urupā, water springs, pā, gardens, battle grounds, marae, flag poles and pou, wetlands, churches, hunting sites, rivers and mountains[36]. There are examples of where groundwater features have been afforded the status of wāhi tapu[37] and wāhi taonga, including:

- **Puna Waiariki**, Awa, Roto, Toka, Motu, Mahinga Kai, Ngaherehere, hot springs, rivers and waterways, rock features, islands, hunting grounds, forests and many other geographical features were **imbued with wāhi tapu status** dependent on ancestral association and activities. They were often recognised as holding such status but activities surrounding them were less restrictive. More people had greater access to them although some sites may have also been dedicated purely to one family or one chief (Potiki 2016).

- The **Ōmaru puna wai** [Canterbury region] is an example of a **spring registered** with the New Zealand Historic Places Trust as a **wāhi tapu** in 2005 (Ngāi Tūāhuriri Rūnanga et al. 2013).

- 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"* (Ngāi Tūāhuriri Rūnanga et al. 2013).

- *"The Waiau-uha River* [Canterbury region] *catchment is a cultural landscape. Tribal history is embedded in the river, and the lands that it flows through. There are multiple sites and places in the catchment considered wāhi tapu, and the river and associated tributaries, wetlands and **waipuna are considered wāhi taonga**."* .

4.3.4 Rongoā and ceremonies

Water plays a significant role in the spiritual beliefs and cultural practices of Māori. Waikato-Tainui classify waters into 'states' where *"Wai Ora – Life giving and sustaining. These waters are generally regarded as pristine, sanctified water, primarily used for "higher" purposes such as ceremonial use, blessings, cleansing of chiefs etc. These waters are generally **spring waters** (puna), or in areas specifically designated for higher purposes. These waters must be protected."* .

Many iwi and hapū around New Zealand have undertaken cultural mapping workstreams to record the location and narratives associated with cultural sites of significance, including groundwater-dependent features. Sites that were used for burials, rituals and ceremonial purposes are often managed as silent files where the true significance of a site may not be readily shared with the wider public. Tau et al. (1990) further explain that water was classified according to its nature and uses

[36] http://www.qualityplanning.org.nz/index.php/planning-tools/heritage

[37] Is defined in the Heritage New Zealand Pouhere Taonga Act 2014 as a place sacred to Māori in the traditional, spiritual, religious, ritual, or mythological sense.

which determined how they may, and may not, be used. Areas of water were set aside for various types of use, including by tohunga and chiefs, either because of their location or because the waters were considered to have special qualities. Examples include:

- Wai whakaheke tūpāpaku were places where human corpses were weighted down and placed in marshes, lagoons, rivers, **springs**, and in the ocean in certain secret places.
- Te Awahou and Kaikaitāhuna [Bay of Plenty region] are the waterways that emanate from the **sacred springs**, Te Puna a Pekehāua and Te Puna a Hangarua. These springs are protected by our kaitiaki Pekehāua and Hinerua (Te Maru o Ngāti Rangiwewehi Iwi Authority 2012).
- At Te Waikoropupū [Tasman region] *"The water coming from Te Waikoropupū Springs has long been seen to have cultural significance to Ngāti Rārua, hence the name Wai Ora, or Water of Life, given to it by our tūpuna. The Wai Ora was used in cultural traditions for cleansing and spiritual healing, and it was visited prior to, and after, significant journeys"* (Te Rūnanga o Ngāti Rārua 2018).
- At Te Waihora [Canterbury region] *"the numerous **waipuna** (springs) are important sites for mahinga kai and other tikanga (practises). Of particular note is Te Waiwhakaheketūpapaku – a **spring head water burial site** in which many significant tupuna are buried."* (Ngāi Tūāhuriri Rūnanga et al. 2013).
- The Waitangi Tribunal (2012) explains how the Poroti Springs [Northland region] are a taonga of great spiritual significance to Te Uriroroi, Te Parawhau, and Te Mahurehure, and indeed to the whole of Ngā Puhi. The springs were and are a highly prized resource, the **waters were used for rongoā** (healing) and also for ritual, and they provide physical sustenance in the form of watercress, tuna (freshwater eels), and kēwai (freshwater crayfish).

4.3.5 Mahinga kai

The definition of mahinga kai promoted by the NPS-FM is not as holistic as that applied by some tribal groups (e.g., Ngāi Tahu)[38]. Further although we use the terminology mahinga kai, we recognise that this terminology is not used by all hapū and iwi.

Mahinga kai species like tuna (freshwater eels), kanakana/piharau (lamprey), kōura/kēwai (freshwater crayfish) and kanae (mullet) are integral to Māori socioecological systems and sustained local and regional economies with food and resources. For many whānau there continues to be a direct reliance on traditional food sources to supplement nutritional needs in the household (Morgan 2006). In addition, these species support Māori wellbeing through on-going creation and maintenance of mātauranga Māori, intergenerational knowledge transfer, and strengthening connections between whānau>marae>hapū>iwi and with valued features of cultural landscapes. Many of these species are also vital for maintaining ecosystem integrity and function. Although mahinga kai activities generally occur above ground, there are many examples in the literature where

[38] (1) 'Mahinga kai' is referred to in the NPS-FM as indigenous freshwater species that have traditionally been used as food, tools, or other resources (NZ Govt 2014); (2) Mahika kai encompasses the ability to access the resource, the site where gathering occurs, the act of gathering and using resources, and ensuring the good health of the resource for future generations (KTKO 2017).

Māori have identified the dependencies of mahinga kai activities on groundwater ecosystems, including:

- **Springs** are a focal point within the cultural landscape of Waikawa [Southland region]. A range of cultural activities were possible given the supply of clean reliable water by spring-fed streams. The **spring-fed streams** feeding into the Waikawa Estuary were significant sources of mahinga kai, used for healing, and supported a number of nohoanga (settlements) in the vicinity (Figure 4-6). The spring-fed waters and the biodiversity that they sustain are essential to the future good health of the Waikawa and the gazetted Waikawa/Tumu Toka mātaitai. In the Waikawa catchment, groundwater resources are seen to be at risk because of an historic decision to bury dieldrin in the headwaters (Tipa & Associates 2013b).
- In the Makōura Stream [Wellington region] *"Prior to refrigeration, Māori would often store their shellfish and various food stuffs in freshwater pools and clean flowing streams. The Makōura was* ***perfect for this purpose due to being spring-fed*** *which reduced the likelihood floodwaters washing away the food supplies. Due to being sourced from a spring (or a series of springs) it consistently ran clear and was less likely to embed sand, mud and/or grit into the food in the stream. Marine Koura were also stored in the stream for eating at a later date. This was a delicacy known commonly as Kōura pirau – or rotten crayfish"* (Ohau Plants Ltd 2011).
- *"The naming of Waikanae* [Gisborne region] *is derived from Wai – the* ***fresh water springs*** *which attracted the treasured delicacy of Rongowhakaata, the fish mullet - Kanae. From the mouth of the Waikanae Stream to the headwaters at Te Kuri a Tuatai at various locations there are* ***puna fostering the kanae*** *and hapū Ngai Tawhiri, Ngai te Kete, Ngāti Ruawairau and others of Rongowhakaata"* (Gisborne District Council 2013).
- *"Before European settlement began in the 1850s, the lower reaches of the Waimakariri and Rakahuri* [Canterbury region] *connected with a maze of waterways and wetlands* ***fed by underground springs of the purest artesian water****, which* ***nourished a wealth of mahinga kai*** *rich in birdlife, eels, fish and natural vegetation"* (Ngāi Tūāhuriri Rūnanga et al. 2013).
- *"The Waipā river* [Waikato region]*, its tributaries,* ***puna****, swamp areas were* ***an important source of food****"* (Nehenehenui Regional Management Committee 2017).
- *"****Spring sourced water*** [within the Rangitata catchment, Canterbury region] *is especially valued because of its high quality, clarity, it reliability and its temperature. Whānau members described the importance of spring fed streams that provide cold water habitats [for mahinga kai] at times of low flow"* (Tipa & Associates 2015).

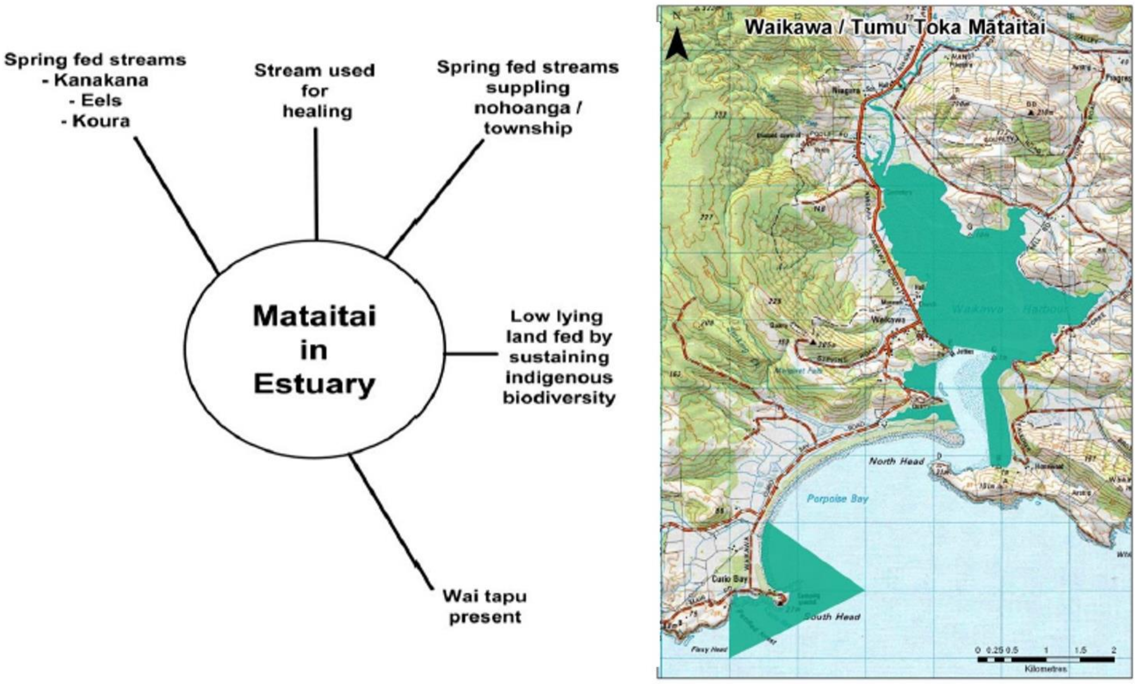

Figure 4-6: Some examples of groundwater-related, cultural value dependencies, in the Waikawa River catchment. Source: Tipa & Associates (2013a).

4.3.6 Rock art

Tuhituhi neherā or Māori rock art refers to the drawings and carvings of Māori people on both large and small rock surfaces. Tuhituhi neherā has been described as *"a priceless relic of the prehistory of our country."*[39] Tuhituhi neherā sites are found on limestone rock formations, sandstone and Schlitz formations all over the South Island, and in some places in the North Island.

Rock art sites are intimately associated with freshwater ecosystems; as these sites were based around providing mahinga kai and transport, in addition to cultural and spiritual uses. Many rock art sites are near streams, rivers, swamps and/or springs. While many sites remain in good condition, tuhituhi neherā sites in New Zealand are intrinsically fragile and they are threatened, in many cases seriously, by adjacent land use activities. In particular, water use activities in the vicinity of tuhituhi neherā sites can adversely affect both surface condition of vulnerable rock art pigments as well as nearby freshwater ecosystems which are an integral component of the cultural landscape. Existing IMPs for the South Canterbury region specifically mention the significance of the rock art and the need to protect it from inappropriate use and development.

The preservation and management of rock art sites, including the freshwater ecosystem within which it is intimately situated, requires a robust understanding of the sensitivity and vulnerability of each site to modifications and disturbances within the local hydrological and hydrogeological environment. Vulnerable tuhituhi neherā sites and related freshwater ecosystems are potentially sensitive to:

- Small changes in the local groundwater environment – changes in water table height (rises, declines or seasonal range in level),

[39] https://teara.govt.nz/en/maori-rock-art-nga-toi-ana

- Changes in the local microclimate (increased air moisture, irrigation spray drift),
- Changes in local drainage systems (diversions, new channels, ponding),
- Increased saturated weight of overburden above an overhang/cave, and
- Changes in water chemistry of natural seepages onto the rock surface and into freshwater ecosystems.

Activities which may induce local hydrological changes and impact on the vulnerability of tuhituhi neherā and associated freshwater ecosystems are fall into three categories:

- Irrigation,
- Groundwater abstraction, and
- Drainage diversions/water conveyance/other excavation activities.

The Ngā Kete o Te Wānanga research programme in collaboration with the Ngāi Tahu Rock Art Trust and Te Rūnanga o Arowhenua are developing a freshwater-focussed sensitivity mapping approach that will contribute to the preservation of sites and their associated ecosystems (Gyopari et al. 2017, Gyopari et al. In prep). Conceptual diagrams have enabled the sensitivities of rock art to water to be illustrated (Figure 4-7) and conveyed to resource managers[40]. This research is providing a valuable and unique opportunity to engage with an established specialist Māori team of experts (i.e., Rock Art Trust), to draw upon mātauranga Māori and complement the project team's scientific expertise, particularly around hydrogeology (groundwater-surface water interactions).

4.3.7 Paru

There are examples in the literature where certain puna are known for paru (muds) that had special characteristics and were used for dying items such as kete, piupiu and whāriki (e.g., Maniapoto, Tipa et al. 2014). Exposure of these muds (e.g., drainage of wet areas) causes oxidation, degrading the properties of this important cultural resource (Te Kanawa 2009).

4.3.8 Marae water supplies

The marae is central to Māori community life and culture, performing critical cultural, social and infrastructural roles for Māori and New Zealand society more generally. There are more than 900 ancestral marae throughout New Zealand[41]. The Department of Statistics and the Ministry of Culture and Heritage reports that visiting a marae is the primary Māori cultural experience for the majority of New Zealanders – involving 543,000 people, or one in five adults, over an annual period (Statistics New Zealand and Ministry for Culture and Heritage 2003). Marae facilities are used by both the Māori and non-Māori community for a wide range of events, of duration anywhere between two hours and a week, including community meetings, school camps, youth programmes, and conferences (e.g., NZFSA 2008). Marae also have an important, and in some locations critical, role in New Zealand's civil defence response and natural hazard emergency management (e.g., Ministry of Civil Defence & Emergency Management 2006, Department of Internal Affairs 2008). These points help illustrate the importance of marae infrastructure not only for Māori, but for all New Zealanders.

[40] e.g., presented by Amanda Symon, Manager of the Ngāi Tahu Rock Art Trust, to the Opihi, Temuka, Orari Pareora Zone Committee, a committee established by Environment Canterbury.

[41] For example, the Naumai place website lists 988 individual marae that have self-registered (as of 6 March 2012). http://www.naumaiplace.com/home/marae/search/directory/all/29/

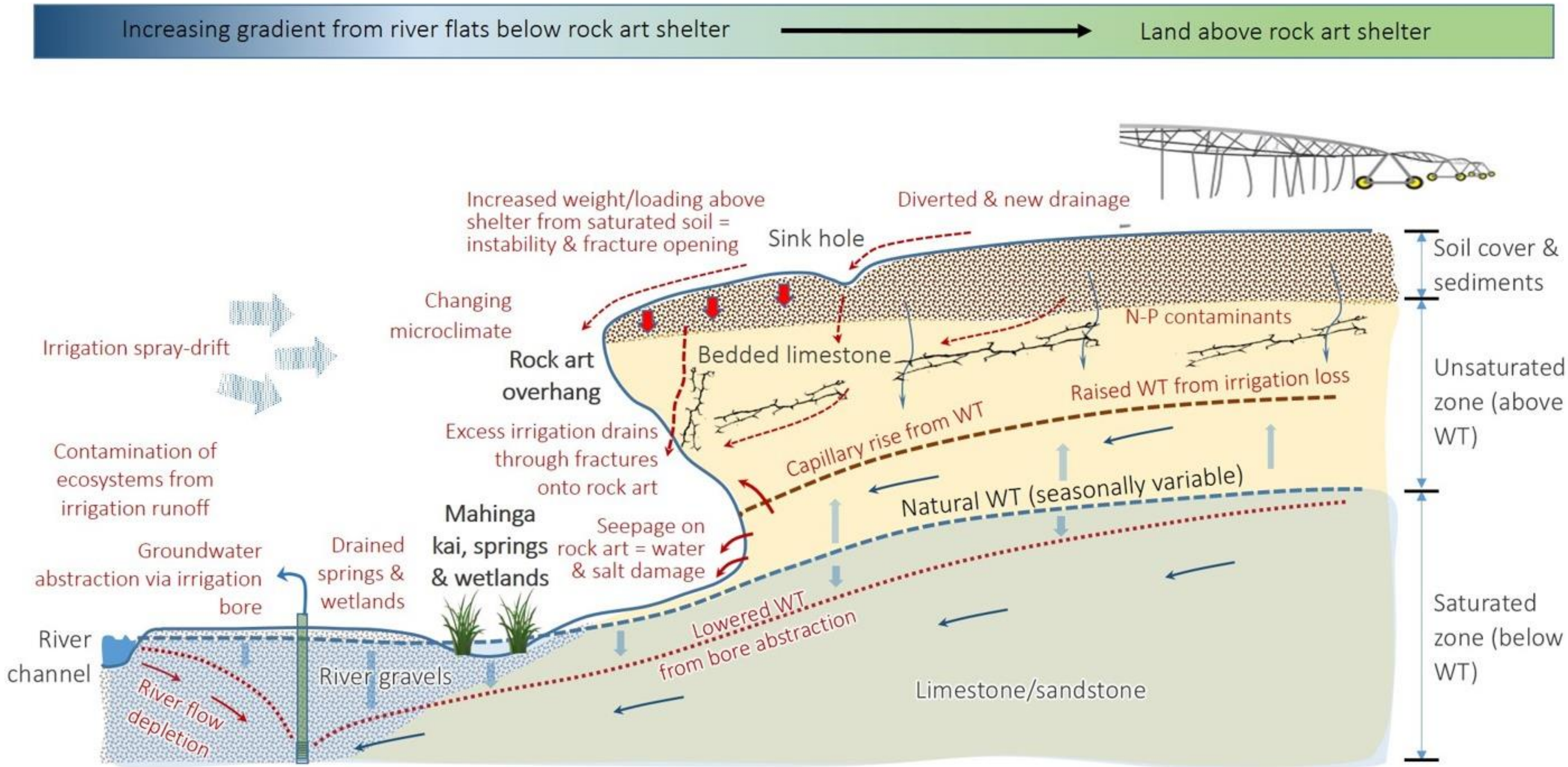

Figure 4-7: A conceptualisation of water-related dependencies that affect rock art, using Takiroa as an example. Source: Gyopari et al. (in prep).

The adequacy and quality of water supply are integral to the efficiency and safety of marae. Food safety, personal hygiene, effective waste disposal and fire protection systems all depend on water supply. The majority of marae (43%) surveyed by Te Puni Kōkiri in 2009 (Te Puni Kōkiri 2012) drew water from the mains supply. Amongst those not connected to the mains supply, **bore, spring, puna, or well** (20%), rainwater tanks (14%), and a combination of rainwater tanks and bore (9%) were generally used (Te Puni Kōkiri 2012). While the majority of marae reported having a reliable and safe supply of water, of marae with their own supply, 32% identified that they did not have a reliable supply and 14% did not have safe drinking water.

4.3.9 Indigenous biodiversity

The protection of indigenous biodiversity is an important value for many hapū and iwi across New Zealand. For Māori, GEs play a key role in the functioning of healthy surface water ecosystems, including the marine waters, and the associated taonga species they support. Examples include:

- *"While Te Waihora* [Lake Ellesmere, Canterbury region] *is primarily a brackish-water environment, there are areas of vegetation typical of more freshwater wetlands. These areas are almost independent of the lake and are a result of localised **groundwater springs** and tributaries flowing into Te Waihora and **provide habitat for species** that otherwise would not occur in the brackish lake waters"* (Te Rūnanga o Ngāi Tahu and Department of Conservation 2005).
- *"Repeated reference has been made to the significance of the lower Waitaki River* [Canterbury region]*, in particular side braids, riparian wetlands, **springs** and backwaters for their **biodiversity values**. They are also significant for their mahika kai" and "**Springs** occur predominantly along the wall on the north side of the lower valley. Some only moisten deep-rooted plants others bubble to the surface and are large enough for birds and humans to drink from. The network of waterways and springs, provided a patchwork of aquatic environments **supporting fish, bird and plant life** throughout an otherwise arid catchment"* (Kai Tahu Ki Otago 2005).
- "*For Kāi Tahu waterways are of the utmost importance. Kāi Tahu is concerned about water quantity and the **surface-groundwater interactions** that provide a range of freshwater habitats. Cultural values could be affected for example by changes to flow regimes creating adverse effects on taonga species/indigenous species/displacement species and their habitats, or by low flows compromising the ability of Kāi Tahu to use waterways for recreation or for gathering mahika kai. Kāi Tahu wish to see minimum flow levels and flow regimes that recognise and provide for their cultural values and relationships, and that support the healthy functioning of the full range of associated ecosystems*" (Kai Tahu Ki Otago 2017).

4.4 Pressures on groundwater-dependent Māori values, beliefs and practices

Hapū and iwi from all over New Zealand have identified a variety of pressures on GEs that in turn impact their values, beliefs and practices; including co-dependent ecosystems and associated taonga downstream of spring-fed waters. Some of the commonly occurring themes include raupatu (land confiscation), the inappropriate mixing of waters, contamination, water abstraction, compartmentalised management, and land development (Figure 4-8). Some examples follow.

Figure 4-8: Some of the pressures on Māori values, beliefs and practices associated with groundwater ecosystems.

4.4.1 Raupatu and land development

In less than a century it is estimated that Māori lost 95% of their lands, much of it by force or stealth, facilitated on behalf of the Crown[42]. The return of land and associated taonga is a large component of Treaty settlements; however, with the return of a small subset of their original assets typically comes a legacy of environmental issues as a result of decades of poor and inappropriate management. For example, over the past 100 years wetland extent has significantly reduced, with 10% across all of New Zealand remaining, when compared to pre-human extent (Ausseil et al. 2008). New Zealand's remaining wetlands are under threat from land modification and other human activities and Māori are becoming increasingly aware of the dire state of repo (swamps) and associated puna, resulting in many hapū- and iwi-led projects centred on the restoration of repo and puna within their rohe (Taura et al. 2017).

[42] http://www.maoriparty.org/raupatu_in_2016

One example of the loss of significant tribal assets and associated cultural values that were dependent on groundwater is the Lake Tāngonge wetland complex in Northland. Tāngonge, once a lake and wetland, was one of the most important mahinga kai of Te Rarawa and Ngāi Takoto iwi and hapū. This highly valued ecosystem was severely modified (Figure 4-9) as land development activities interfered with the hydrological system (including groundwaters), when areas were drained during a major government scheme from the 1930s to make way for Pākehā settlement. The Tāngonge experience of land alienation and environmental degradation created barriers to its use; loss of a food source, loss of kaitiakitanga knowledge and understanding, and loss of mana associated with the inability to assert rangatiratanga – all factors which link directly to the health and wellbeing of the people. This prevented and undermined Māori interaction with Tāngonge and impacted on their health and wellbeing. Consequently, now there is little shared understanding about the cultural and ecological connectivity (including hydrology, ecology, patterns of cultural use and activity) of the catchment (Te Rūnanga o Te Rarawa Iwi Research & Development 2013).

As a result of the Te Rarawa Treaty settlement[43], land is to be returned to the iwi. The collective vision of Te Rarawa is to restore the Tāngonge wetland system to regenerate the food and resource producing capacity of the area to in turn contribute health, social, economic, cultural and environmental gains and opportunities for tangata whenua. Aspirations for the restoration of the taonga are grounded in what it could be once more; its place in iwi futures are fundamental to current desires for iwi development and revitalisation (Te Rūnanga o Te Rarawa Iwi Research & Development 2013).

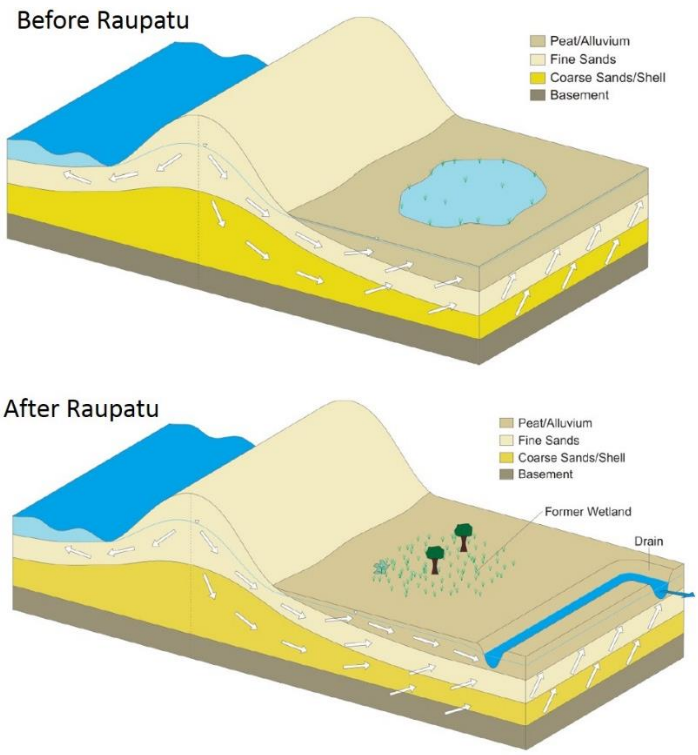

Figure 4-9: Simplified conceptual model schematic of the Tangonge lake complex and wetland area in Northland before (top) and after (bottom) the confiscation of the land from Te Rarawa and construction of drainage and flood protection works. As a result of the construction of the drainage and flood protection network, shallow groundwater is now directed into drains and out of the wetland toward the Awanui River, lowering the water table. Adapted from SKM (2013).

[43] https://www.govt.nz/treaty-settlement-documents/te-rarawa/

4.4.2 Water abstraction

The cumulative impacts of water abstraction from both surface and groundwater sources is commonly expressed as a concern by iwi and hapū (e.g., via iwi management plans and cultural impact assessments). In addition, the success (or otherwise) of mitigation actions focused in catchment surface waters, like restoring mahinga kai species, is intertwined with the health and wellbeing of GEs where groundwater flows and water quality are often identified as key attributes of healthy surface water ecosystems. For example:

- *"Over-abstraction of water can result in degradation of streams' and rivers' natural values and character"* (Kai Tahu Ki Otago 2017).
- *"One of the greatest concerns raised by tangata whenua and community members during the Waikato River Independent Scoping Study (NIWA 2010) was the risks of 'running out of clean water' to drink, decreased ability to undertake practices such as waka ama, and also the impacts of lowering river levels on the health and sustainability of key species (e.g., whitebait, and weaving plants like kutakuta/ngaawhaa and wiiwii)"* (Williamson et al. 2016).

There is also a commonly held view that the legacy of past/present management practises is having an impact on the ability of future generations to use and experience the freshwater environment in the ways their tūpuna were able to. For example:

- *"I've noticed at times there's not a lot of water available to do the things we did when we were kids. Most summers it's getting like that. The river doesn't have swimming holes any more that I can see. We take the younger ones there, but we don't go swimming. We use the Hawea River* [Otago region] *hole now. But my three sisters and I are more connected to the Cardrona than the Hawea River. If the river is totally depleted of water it's going into its reserves underground which isn't good. We can't just keep taking water, it's not good. It can't keep carrying on"* (Kai Tahi Ki Otago 2017).

The Mahaanui Iwi Management Plan (Ngāi Tūāhuriri Rūnanga et al. 2013) is an example of an IMP that suggests it is time for a new way of managing water in the Canterbury region and outlines in Wai Māori (WM) Issue 8, that *"Water quantity: Freshwater resources in the takiwā are over-allocated or under increasing pressure from abstractive use and this has resulted in significant effects on:*

a) Mauri;

b) Mahinga kai habitat, abundance and diversity;

c) The relationship of tāngata whenua with freshwater, including cultural well-being and the loss of customary use opportunities;

d) The flows of lowland spring-fed streams;

e) The ability of groundwater resources to replenish and recharge for ongoing use and future generations;

f) Resilience of waterways, or the ability to withstand stress or disturbance;

g) Natural variability and character of waterways, including floods and freshes;

h) Cultural health of hāpua (coastal lagoon), including duration and frequency of openings; and

i) Connectivity between waterways and their tributaries, associated wetlands and the sea".

4.4.3 Poor management

Several iwi management plans also raise the issue of how the Crown's approach to managing groundwater resources, particularly abstraction, has been biased towards supporting economic interests, at the expense of environmental and Māori values, often with very little understanding of the groundwater ecosystem (i.e., hydrology, recharge rates, connectivity). Ngāi Tūāhuriri Rūnanga et al. (2013) express this issue in the following way:

- *"The prevailing approach to water management has been to prioritise abstractive use over the mauri of the resource, and to commodify and compartmentalise water rather than manage it as a life sustaining taonga. Freshwater management has more often than not been driven by economic considerations to the detriment of the environment and cultural values associated with that environment",* and
- *"Over-allocation is a reflection of the lack of understanding of the freshwater resource, including the relationship between surface and groundwater, and of the lack of value given to the resource. Resolving over-allocation requires a fundamental shift of mindset: from maintaining reliability of supply for abstractors to recognising the value of water as essential to all life and respecting it for its taonga value ahead of all other values."*

Ngāi Tahu ki Murihiku believe that a precautionary approach is required:

- *"…regarding the cumulative impact of takes, and the sustainability of water supply. Uncontrolled abstractions from both surface and groundwater sources can have adverse effects on water quality and quantity, and on the mauri of the water source. In areas such as Riversdale, kaitiaki rūnanga have already identified a risk to the groundwater resources as a result of the cumulative effects of groundwater takes in the area"* (Ngāi Tahu ki Murihiku 2008).

4.4.4 Mixing of waters

Contemporary decision-making processes are considering a range of reactive freshwater management options that may not align with Māori values, beliefs and practises, including managed aquifer recharge (MAR – refer Section 5.5.1). Tau et al. (1990) explain that water was classified according to its nature and uses. The classifications of these waters determined how they may, and may not, be used – *and "Where water types are incompatible, the mixing of these waters is unacceptable to Ngāi Tahu"*. For example:

- *"For tāngata whenua, avoiding the unnatural mixing of waters is fundamental to the protection of mauri in waterways. Transferring water from one catchment to another or mixing different types of water through flow augmentation, tributary transfers and out-of-catchment transfers means that the life supporting potential of the receiving water is potentially compromised (i.e., it may no longer have the same life giving potential as it would if it were left in its original state)..."* (Ngāi Tūāhuriri Rūnanga et al. 2013).
- From the perspective of Kai Tahi Ki Otago (2005) the cross mixing of water from one catchment to another may adversely affect the mauri of both catchments. *"The mauri, or life force, of individual catchments is special and distinct, and the characteristics of each differ depending on whether the source is from snow-capped mountains, lakes, lowland runoff or **groundwater**. This is further influenced by the natural characteristics*

of the water body, soil type, structure of the river bed, flow, degree of pollution, and contamination from exotic weeds. Kai Tahi Ki Otago firmly believe that those extracting water from one catchment for eventual release to another, have failed to take into account effects on the health and vitality of the affected waters and habitat, or on Kai Tahu cultural and spiritual beliefs, values and uses."

4.4.5 Contamination

Iwi management plans are increasingly including objectives and policies to limit the impact of land-based contaminant inputs to GEs, particularly from farming. For example:

- The Raukawa Environmental Management Plan identifies the "*Impacts on soils and **groundwater** through increased animal numbers leading to a greater amount of animal waste (e.g. effluent through ponds and direct urine patches*)" (Raukawa Charitable Trust 2015).
- The Waikato-Tainui Environmental Management Plan expresses that *"Due to the large catchment area of the Waikato river, and the highly fertile farmland, historical agricultural activities expanded at an exponential rate. Consequently, water quality is often poor in areas where high levels of agricultural activity leach pollutants into groundwater. The nature of non-point source pollution, non-compliant discharges of urban run-off, and sewage effluent make it difficult to manage water quality, resulting in the accumulation of contaminants in sensitive environment"* and suggest that methods and tools are adopted to achieve higher water quality standards which ensure that contaminants do not reach groundwater (Waikato-Tainui Te Kauhanganui Inc 2013).

4.5 Māori-driven groundwater research and management needs

Increasingly, Māori are driving and directing research to gain new knowledge to support restoring and improved management of groundwater ecosystems. Further, iwi and hapū priorities for the improved health and wellbeing of catchments is driving the development of indicators and communication tools to increase awareness of the importance of groundwater ecosystems for water security and water quality (e.g., Waikato River Report Card, Williamson et al. 2016). Common themes that emerge from the identified research needs and management priorities of iwi and hapū include:

- **Protection of puna**: The protection of puna is one of the most commonly expressed priorities by hapū and iwi around New Zealand for improved management. For some, the protection of puna is related to the protection of surface water levels, flows and water quality to support Māori values, beliefs and practices throughout the year. For example, under the recently released Waikato and Waipā River Restoration Strategy (Neilson et al. 2018), the identification, fencing and planting of puna, including those used for marae water supplies, are of very high/high priorities (total estimated cost $2.83 M).
- **Recognition of the value of mātauranga Māori in the identification of groundwater-dependent ecosystems**: Ratana et al. (2017) illustrated how kaitiaki often hold the most reliable knowledge on the locations of puna. As part of the Ngā Kete o te Wānanga research programme, whānau from Arowhenua described the springs that are essential to provide flows to the lagoon and provide cold water inputs to the river

system that act as refugia during low flows and/or summer periods (Tipa et al., in prep).

- **Recognition of the specificity of mātauranga Māori available to enhance management of freshwater systems:** One of the key findings from Ratana et al. (2017) was the level of specificity provided by mātauranga Māori as evidenced by the numerous puna sites mapped with hapū participants. Puna, in particular, are often missed in council wetland mapping projects because the scales of GIS methods and satellite imagery are too coarse (usually around 1:10,000).
- **Mixing of waters**: Many lowland rivers and streams are now over-allocated and this has flow-on effects on the ability of the waterways to provide for iwi and hapū values. Many councils are evaluating managed aquifer recharge, or targeted stream augmentation as ways to help resolve declines in groundwater levels and storage. Some whānau are concerned with the threat of artificially augmenting aquifers with water from adjacent catchments and changing the characteristics of groundwaters, including its age and temperature.
- **Compartmentalised management:** Jurisdictional boundaries currently prevent management of a cultural landscape as a whole system. For example, as explained in Section 4.3.6, rock art may be viewed as being a land-based taonga and may not feature in water management discussions; however, its protection is equally dependent on appropriate freshwater management, including groundwater abstraction. To successfully protect cultural landscapes, all components (e.g., location of watercourses, groundwaters, buffers, wetlands, revegetated areas, irrigation practices, runoff pathways, wāhi taonga) need to be factored into management plans.
- **Ensure that contaminants do not enter groundwaters**: Leveraging the ability of waterways, including aquifers, to 'assimilate' the waste and contamination resulting from human activities does not align with Māori beliefs and practises. Kai Tahu Ki Otago (2005) further explains that the *"Degradation of any water body undermines the enduring cultural relationship iwi have traditionally enjoyed and seek to retain with their waters… Severance of the spiritual relationship with, and of the customary use of, a water body strikes at the very identity and well-being of the indigenous culture".* Some whānau have also identified threats associated with legacy contaminant issues, such as pesticides being dumped/buried near waterways.

4.6 Summary

- The Māori worldview requires an inter-generational focus, where resources must be protected and enhanced for those generations not yet with us, and in respect of those that have passed.
- For generations Māori have emphasised the need to consider and manage our environment in its entirety, as an undivided entity, and this specifically includes GEs.
- Concepts such as Ki Uta Ki Tai are used by Māori to describe their holistic understanding of aquatic ecosystems and how the health and wellbeing of the people is intrinsically linked to that of the natural environment.
- Ki Uta Ki Tai recognises the movement of water through the landscape and the numerous interactions it may have on its journey and acknowledges the connections

between the atmosphere, surface water, groundwater, land use, water quality, water quantity, and the coast. This Māori resource management framework reflects that resources are connected, from the mountains to the sea, and must be managed as such.

- Recent research is starting to improve our understanding of groundwater-dependent Māori values, beliefs and practices that 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.
- Land confiscations, land development, water abstraction, poor water resource management practices, contamination and inappropriate mixing of waters represent key pressures on groundwater-dependent Māori values, beliefs and practices.
- Māori have identified research that is required to support their aspirations for improved management of groundwater ecosystems. Common themes that emerge from the research needs and management priorities of iwi and hapū include: the protection of puna, addressing the threats of artificially augmenting aquifers with water from adjacent catchments (i.e., mixing of waters), the protection of cultural landscapes and all the components this entails (e.g., watercourses, groundwaters, buffers, wetlands, revegetated areas, irrigation practices, runoff pathways, wāhi taonga), and the protection of groundwaters from contaminants.

5 Key threats to groundwater ecosystems

The preceding sections outlined the substantial values associated with groundwater and the ecosystem services delivered by GEs. Sustaining GE health and their natural ecosystem services requires careful management of human activities to minimise these potential threats. Threats arise from activities which change primary resources (dissolved oxygen and organic carbon) concentrations within GEs, change groundwater hydrological regimes, and introduce harmful substances or contaminants.

Many human activities involve multiple factors (e.g., some agricultural activities involve groundwater abstraction fertilisers and effluent application which leach into groundwater). Figure 5-1 places these activities within our diagram of GE functioning presented in Section 2.4 so that direct and indirect effects can be readily visualised. This section discusses the three main types of threats based on available research knowledge and the fundamentals of ecology.

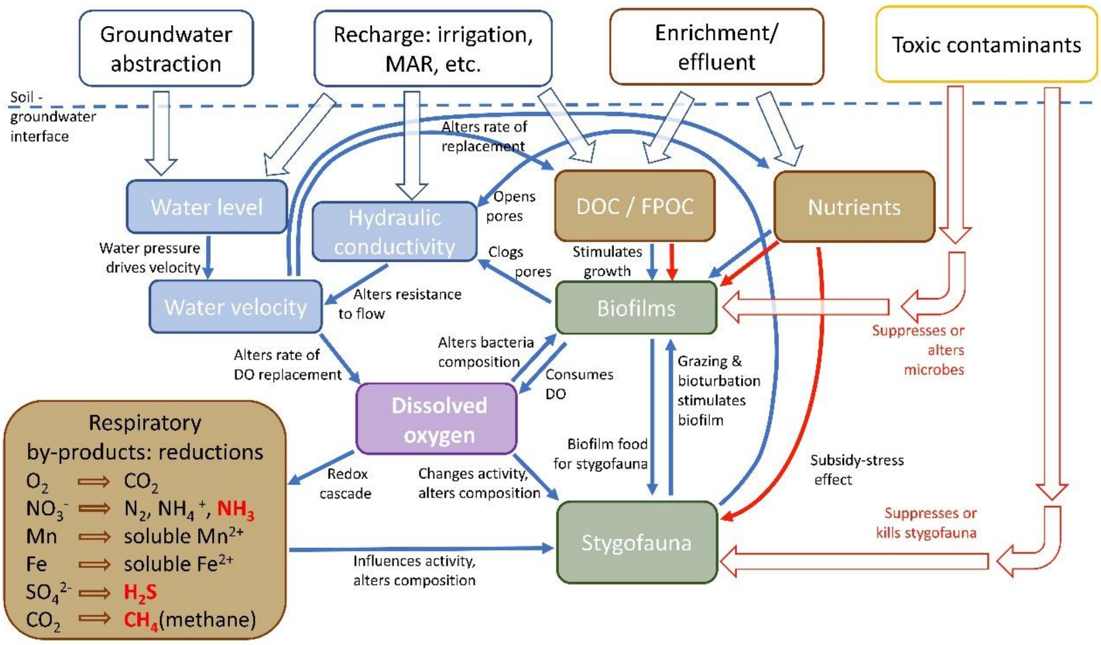

Figure 5-1: Potential direct and indirect effects of human activities on groundwater ecosystem functioning. Blue boxes, ecohydraulic effects; violet box, dissolved oxygen (DO); brown boxes, dissolved nutrients; green boxes, ecosystem biota. Blue arrows, direct effects; orange arrows, negative effects; paired red-blue arrows indicate potential subsidy-stress effects. Respiratory products in red, toxic at low concentrations.

An important point to recognise is that, although groundwater in parts of some New Zealand aquifers moves very fast compared with aquifers elsewhere (White 2001), the impacts of human activities on groundwater can take months to years or decades to become apparent, even in our faster moving aquifer systems. For example, nitrate-enriched water within the upper, unconfined aquifer in Waimea Plains differed in age in different bores and ranged from 6-50 years old (Stewart et al. 2011). Similarly, water emerging from Te Waikoropupū Springs averages eight years in age (Stewart and Williams 1981), so that potential contamination from upstream intensive agriculture will take considerable time to appear at the Springs. In the Lake Taupo catchment, groundwater ages of up to 80 years indicate that the effects of historical diffuse pollution may take decades to become apparent (Howard-Williams et al. 2010).

5.1 GE enrichment: organic carbon and dissolved oxygen

Activities that may result in increased organic carbon inputs into GEs include effluent leaching from intensive grazing or effluent or wastewater disposal. Leaching of irrigation water and managed aquifer recharge will generally be lower in organic carbon and may increase, decrease or have no impact on GE organic carbon depending on the concentration of carbon in the recharge water compared to the aquifer. The amount of organic carbon that enters the GE from surface-based activities will depend on the concentration of carbon in recharge water, the permeability of the aquifer to surface water recharge and the overlying soil type and processes within it that may either take up or release additional carbon.

Additions of organic carbon to GEs stimulate microbial activity and biofilm development and can have substantial effects on the GE health and ecosystem service delivery (Fenwick et al. 2004, Boulton et al. 2008, Hartland et al. 2011) because GEs are generally limited by organic carbon availability. In this way, organic carbon has a subsidy-stress effect in GEs: at lower concentrations, organic carbon subsidises stimulate bacterial biofilms and stygofauna, but creates stresses for both at higher concentrations (see Section 2.4 for details).

At low levels of enrichment, increased organic carbon facilitates increased biofilm activity and biomass, and increased stygofaunal densities. Increased biofilm biomass can reduce aquifer hydraulic conductivity by clogging fine pore spaces at small (<5 mm) scales and at progressively larger scales, if unchecked. Such clogging by biofilms can dramatically alter GE health and ecosystem service delivery. However, at low levels of enrichment, stygofauna may be able to increase grazing rates to suppress biofilm and keep the GE in balance, if the increased organic carbon is modest and sustained over weeks to months (e.g., Boulton et al. 2008). Relatively low levels of enrichment can alter GE community composition. In shallow groundwaters, where surface water organisms also occur, increased food availability potentially cancels the competitive advantages of stygobitic species, enabling stygophilic species with higher metabolic rates (and faster generation times) to out-compete and displace the natural stygobitic community (assuming DO is not limiting) (Taylor et al. 2003, Datry et al. 2005b, Wilheim et al. 2006).

Excessive enrichment of organic carbon has multiple impacts, both through altering competitive dominance of some organisms but also through reduced dissolved oxygen (DO) concentrations by stimulating microbial activity, which can, under certain conditions, use much or all of the available DO (e.g., Baker et al. 2000) (see Section 2.4 for details).

Excessive organic carbon generally results in increased biomass, usually of fewer species. Such a shift in community composition occurred within a large coastal aquifer contaminated by treated wastewater (increased nitrate, chemical oxidation demand, dissolved organic carbon) over 45 years, where one omnivorous species displaced others (including apparent extinction of one endemic stygobitic species) (Marsciopinto et al. 2006). An investigation in New Zealand revealed that wastewater disposal on land increased groundwater dissolved organic carbon, which increased abundances of some stygofaunal species, but reduced stygofaunal diversity (Hartland et al. 2011) (Figure 5-2).

Stygofauna within karst cave systems are similarly affected. For example, massive organic enrichment, resulting from sawdust dumped in a cave, exterminated the previously abundant and diverse stygofauna from a subterranean stream, resulting in biofilms >1 cm thick coating the gravel substrate, and huge populations of opportunistic stygophilic species (tubificid worms and chironomid flies)(Culver et al. 1992). Similar shifts in community composition in response to organic carbon enrichment are noted for several other GEs (e.g., Illife and Jickells 1984). These studies confirm similar reductions in diversity but increases in abundance found elsewhere for organic inputs from wastewater into karst caves (e.g., Holsinger 1966, Culver et al. 1992) and rivers (e.g., Scarsbrook and Fenwick 2003, Aristi et al. 2015).

Reductions in oxygen concentrations associated with organic enrichment have large impacts on GEs. Small reductions in DO may limit stygofaunal communities ability to increase in density in response to increased food (Mösslacher and Notenboom 1999). However, low oxygen conditions that approach anoxia (no DO) usually result in a massive community change with dominance by species adapted to living in near or completely anoxic conditions (predominantly heterotrophic (scavenging) bacteria proliferate) (e.g., Brune et al. 2000). Stygofauna appear variously adapted to hypoxia and anoxia, with most apparently unable to survive indefinite anoxia (Hervant et al. 1996, Spicer 1998, Mosslacher 2000). Their activity is likely to be suppressed under hypoxia and anoxia, and sustained low DO may reduce stygofaunal grazing, allowing biofilm biomass to increase and occlude finer pore spaces within the aquifer. In turn, this can reduce groundwater velocities at finer scales, slow replenishment of dissolved substances, leading to even lower DO concentrations or more persistent anoxia.

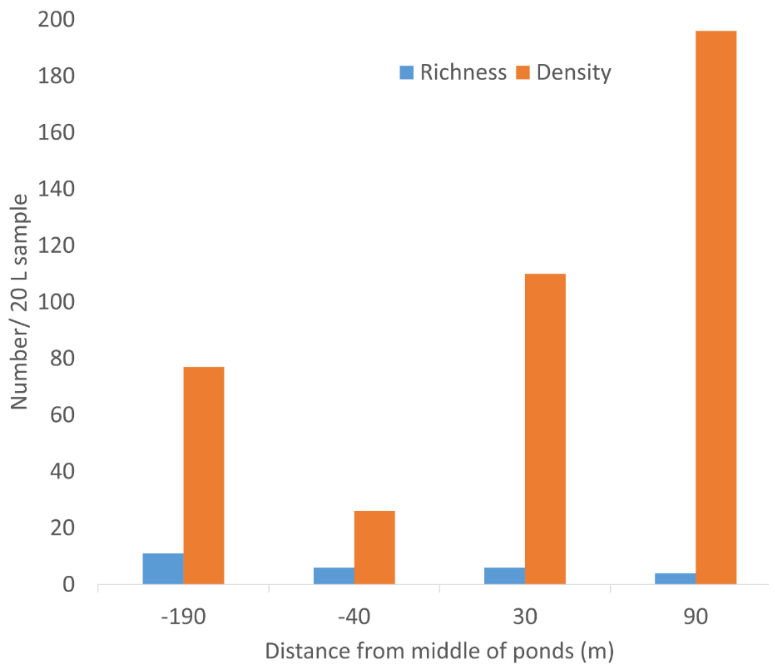

Figure 5-2: Effect of organic contamination on stygofaunal density (number of individuals) and richness (number of taxa) at a wastewater treatment facility in Canterbury. Distances from middle of ponds indicate relative contamination of each sampling well. Data from Hartland et al. (2011).

5.1.1 Example GE organic enrichment

Substantial changes in GE health were noted on five occasions in four different wells downstream of a wastewater disposal site in Canterbury's alluvial aquifer system. The naturally oxic GE became anoxic, killing the stygofauna (up to c. 300 individuals/well; all dead, blackened) (Sinton 1984, Fenwick et al. 2004) (Figure 5-3). Water from these wells smelled of hydrogen sulphide and sediments retrieved from them were dark grey, contained lots of crustacean fragments and retained water (i.e., clogged), unlike the clean, free-draining, brown sediments from nearby unaffected wells (Figure 5-4).

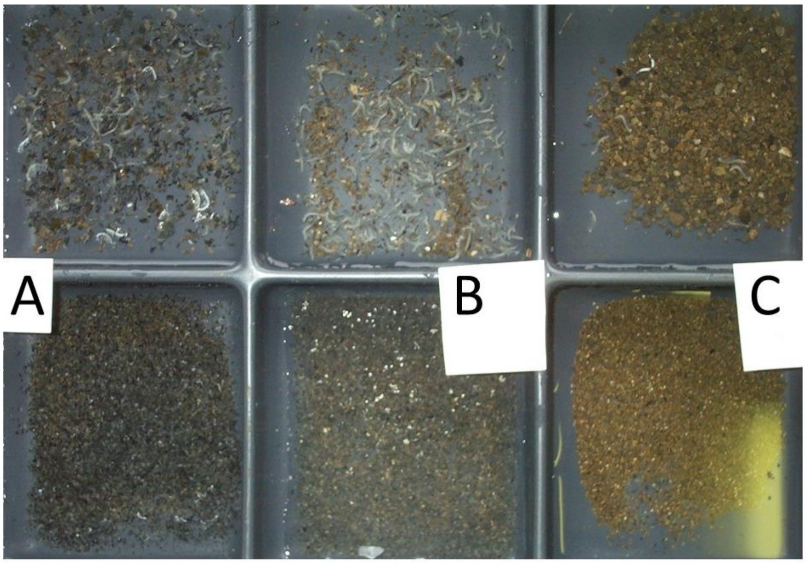

Figure 5-3: Contents of samples retrieved from groundwater wells at Templeton, Canterbury: A, heavily contaminated by wastewater, B, moderately contaminated; C, minimal contamination. Upper row, coarse fraction of sample contents; lower row, finer fraction of sample contents. Image: G. Fenwick, NIWA.

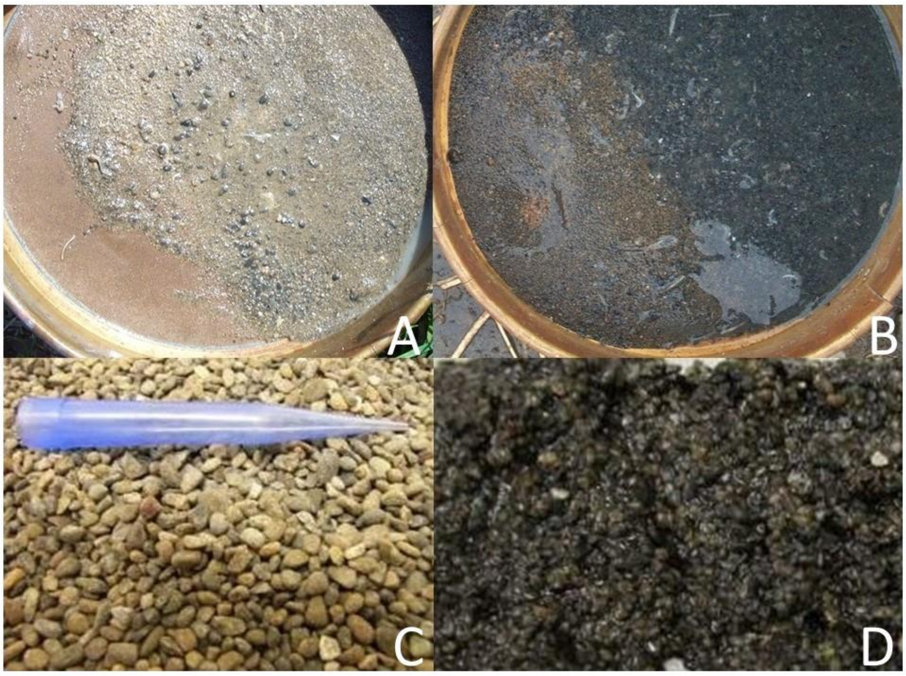

Figure 5-4: Sediment from bottoms of an uncontaminated (A) and a heavily contaminated (wastewater) (B) groundwater well from Templeton, Canterbury, and fine gravels before (C) and (D) after incubation of biofilms in high nutrients with stygofauna absent. Plastic item in C is 70 mm long. Images: A-B, G. Fenwick (NIWA); C-D, ESR.

These anoxic events coincided with two seasonal events: low groundwater levels (low velocities) and high organic inputs from the wastewater facility. The causes appear to be increased biofilm growth and biomass stimulated by the elevated organic carbon resulting in two potential effects. First, the biofilm consumed more of the available DO (Baker et al. 2000), which was already low due to seasonal low water levels and velocities. Second, the biofilm growth occluded finer interstitial spaces, further slowing water velocities and rates of dissolved oxygen replacement. A cascade of two further effects seem likely:

- the resultant low oxygen concentrations suppressed normal stygofaunal grazing and bioturbation, which had controlled biofilm clogging, and
- bioturbation was further reduced because anaerobic respiratory by-products (e.g., nitrate reduced to ammonia and sulphur dioxide, instead of carbon dioxide) from bacterial metabolism reached concentrations toxic to some stygofaunas.

5.2 Changes to the hydrological regime

Many activities significantly affect GE hydrological regimes. River diversions, dams or lake developments, irrigation developments, and direct groundwater pumping are the most common human activities directly affecting groundwater hydrology, changing groundwater pressure gradients and, hence, altering flow rates and directions (note, urban development does not necessarily reduce groundwater recharge rates (Lerner 2002). Alteration of river courses or sedimentation regimes can affect groundwater discharge rates. Forestry and urban land use activities may result in changes to water levels in underlying aquifers through increased evapotranspiration and interception of rainfall by tree crops (Fahey et al. 2004) and increased impervious surfaces (Walsh et al. 2005), respectively, reducing recharge via rainwater infiltration below the root zone (Boulton et al. 2003, Miyazawa et al. 2016). Alterations to spatial and temporal patterns in groundwater recharge and discharge rates will affect the physical environment of the GE by altering spatial heterogeneity and temporal fluctuations in water level and velocities, as well as replenishment rates of organic matter and DO.

Any changes in an aquifer's hydrological regime may affect its GE, depending on the nature, magnitude and duration of the change. Changes that affect recharge are potentially most important because recharge replenishes two critical dissolved substances: DO and organic carbon. Stygofaunal community abundances usually increase markedly with recharge water that introduces organic carbon and DO, and a succession in community composition usually results over a few (< 6) weeks (Mösslacher 1998) (Figure 5-5). Other investigations report no such relationships for stygofauna (e.g., (Larned et al. 2014, Korbel and Hose 2015). Bacteria respond directly to seasonal recharge, primarily to water quality (Korbel and Hose 2015).

5.2.1 Water level changes

Although groundwater velocity is an important factor in GE health and functioning, the relationship between velocity (or groundwater level) and GE condition is unknown. Any such relationship is likely to vary temporally and spatially. Changes in groundwater velocities within aquifers occur naturally with seasonal change in water levels (Mencio et al. 2014), other climatic events (e.g., El Niño and La Niña), and with earthquakes and other tectonic events. Local geology can result in some river reaches losing water into underlying aquifers, whereas other reaches of the same river may gain water (Larned et al. 2011). The volumes and locations of groundwater recharge from and discharge to these rivers may change over time in response to groundwater levels, river levels, river bed characteristics, and climatic conditions. Likewise, groundwater recharge from irrigation or other agricultural or industrial practices (e.g., land disposal of effluent) varies spatially, depending on land use, and temporally, depending on management practices.

Any activity that alters water level, such as water abstraction (Di Lorenzo and Galassi 2013), has the potential to stress a GE, changing stygofauna communities and/or abundance in some instances (Rouch et al. 1993, Dumas 2004, Hancock and Boulton 2008, Di Lorenzo and Galassi 2013), and/or altering conditions to favour different microbial communities (Chapelle 2000). Changes in water levels may strand some invertebrates above the water table, especially those preferentially inhabiting the upper saturated zone (Datry et al. 2005, Stumpp and Hose 2013).

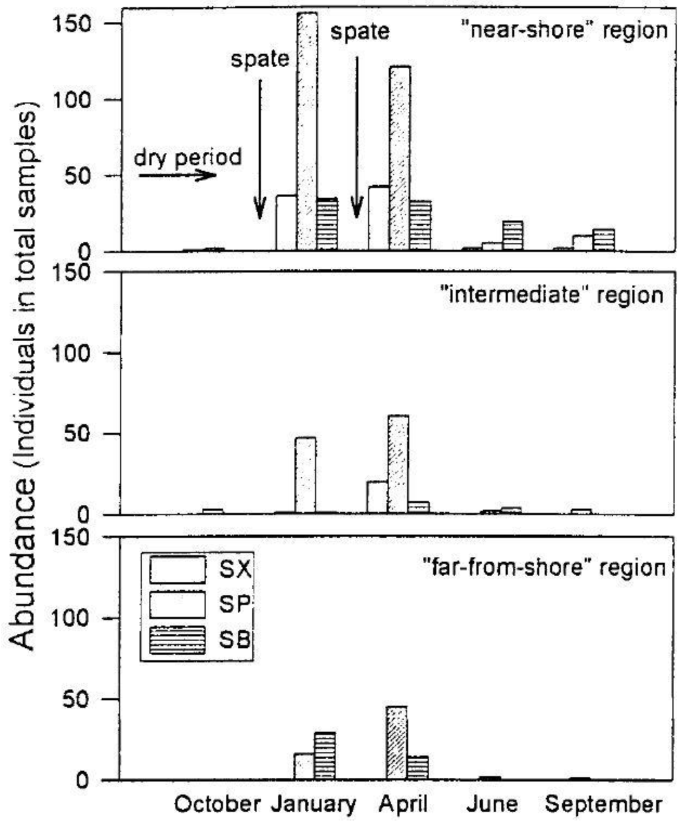

Figure 5-5: Changes in abundances of stygoxenes, (SX), stygophiles (SP) and stygobites (SB) in groundwater at three distances from recharge source (river) following a dry period and recharge events. Near-shore, 15-20 m from river; intermediate, 24-40 m; far-from-shore, 40-60 m. (From Mosslacher 2000, Fig. 5).

Invertebrates differ in their abilities to retreat with falling water levels, their abilities to escape stranding above the water table, and in their abilities to survive when stranded above the water table (Tomlinson and Boulton 2008, Stumpp and Hose 2013). Such stranding may be very substantial for invertebrates that actively migrate to and beyond the sediment-water interface when DO concentrations are very low (Henry and Danielopol 1999, Coineau 2000, Danielopol et al. 2000a), such as during irrigation peaks when seasonal water levels tend to be lowest.

Microbial biofilms can be relatively resistant to emergence due to lowered water table events, such as those that occur naturally within the zone of intermittent saturation (Weaver et al. 2015), but their recovery from longer term emersion and greater drying is unknown. Pathogenic microorganisms also may survive desiccation events because biofilms protect them from complete drying (Balzer et al. 2010, Wingender and Flemming 2011).

Sustained or permanent water table draw-down probably affects all components of the GE inhabiting the de-watered zone and the zone of intermittent saturation, from biofilms to invertebrates (Di Lorenzo and Galassi 2013; Stumpp and Hose 2013), as well as sediment structure, porosity and other physical characteristics (Mösslacher 1998, Paran et al. 2005), and biogeochemical processes, depending upon the aquifer's specific hydrogeology. These changes may be substantial and usually take place over many years, making them difficult to detect. Such changes probably are not readily reversible (Hancock et al. 2005) and climate change may exacerbate them in some areas.

Aquifer-wide water level changes due to abstraction could significantly reduce the suitable habitat available to any species restricted to small geographic areas (Robertson et al. 2009), putting some at risk of extinction (Boulton et al. 2003, Kremen 2005, Camacho et al. 2006, Majer 2009, Niemiller et al. 2013). Abstraction from aquifers that are adjacent to the coast can result in reduced groundwater pressures and saltwater intrusion into the aquifer. The resultant groundwater contamination, as seawater replaces abstracted freshwater (Fenemor and Robb 2001, Davidson and Wilson 2011), potentially makes parts of the aquifer unsuitable for stygofauna, affects microbial communities and GE services delivery, in addition to rendering the groundwater unsuitable for most human purposes.

Reduced water levels usually result in reduced velocities within the aquifer, just as in rivers. This indirect effect has important consequences for GE health. Reduced velocities result in slower replacement of essential substances at all scales within an aquifer. This means that DO concentrations may be reduced quite considerably during periods of low water levels. Dissolved organic carbon also may be replenished at lower rates, and carbon dioxide or other metabolic by-products may be more concentrated because their removal is slower. Thus, reduced water levels have the potential to initiate a cascade of effects on the GE: reduced DO leading to reduced stygofaunal control of biofilms, further reductions in groundwater velocity and DO, anoxic microbial metabolic pathways predominating, more chemically reducing conditions, and reduced metabolic by-products degrading water quality (see Section 2.2.1).

5.2.2 Connections to other waterbodies

The dependence on connection with surface waters for recharge makes GEs especially vulnerable to human-induced changes to surface water availability and quality. Reduced river flows, due to activities such as diversions and irrigation takes, may reduce surface water connectivity with groundwater, so that recharge is reduced, occurs intermittently and/or in different locations, or ceases completely. The effects of such changes on the aquifer and GEs depend upon the magnitude, timing, duration and nature of change in hydrological connectivity, changes to flow regimes, as well as on any concomitant water quality changes. There is inadequate empirical research evidence of the nature and magnitude of GE changes in response to changed connectivity.

5.3 Contaminants from land-use activities

As noted in Section 5.1, many substances applied to the land surface (e.g., fertilisers, effluent) are likely to enter underlying groundwater, via infiltration through the vadose zone and/or riverine recharge, and potentially affect GEs. While the list of potential contaminants of groundwater is very long, here we focus on three groups of substances known to adversely affect aquatic species and ecosystems: inorganic nitrogen, agrichemicals and emerging contaminants.

5.3.1 Nitrate

Substantial amounts of nitrate enter many groundwaters from human sources (e.g., agriculture, various effluents, etc. (White and Close 2016), with concentrations frequently at potentially harmful levels for aquatic ecosystems (e.g., Tidswell et al. 2012). The primary concern of nitrate in groundwater is its toxicity to humans, farm and domestic stock, and to aquatic invertebrates, notably crustaceans, because it interferes with oxygen transport to body tissues (Camargo et al. 2005). Nitrates also are implicated as potential carcinogens for humans, adding to concern about drinking water nitrate concentrations. There are no useful data on nitrate toxicities for groundwater invertebrates (Mosslacher 2000), so information for equivalent surface water fauna (Hickey 2013, Hickey 2015) currently provides the best available understanding of the likely effects of nitrate on GEs.

Nitrate toxicity to aquatic animals increases with increasing nitrate concentrations and exposure times, and may decrease with increasing body size, water salinity and water hardness(Camargo et al. 2005). The effects of nitrate on biofilms and stygofauna *in-situ* from field studies are unclear, because several other factors varied with concentrations of nitrate in studies to date (Dumas et al. 2001, Dumas and Lescher-Moutoue 2001, Williamson et al. 2012, Di Lorenzo and Galassi 2013).

The maximum nitrate concentration for protecting freshwater biodiversity and ecological functioning has undergone successive reviews since the ANZECC (2000) guidelines were established. A revision of the ANZECC toxicity guideline concentration for nitrate was incorporated into National Objectives Framework (NOF) of the NPS-FM for nitrate concentrations in rivers (NZ Govt 2014). The NOF establishes a national bottom line of 6.9 mg/L and 9.8 mg/L of nitrate nitrogen as annual median and annual 95th percentile values, respectively. At these concentrations, which are much lower than the national drinking water guideline of 11.3 mg/L (Ministry of Health 2008), growth effects are likely for up to 20% of sensitive species, such as fish, but acute effects should be absent (NZ Govt 2014). According to the narrative in the NOF, annual median and annual 95th percentile values of ≤1 and ≤1.5 mg/L are required to avoid any adverse effects on riverine ecosystem health.

The NOF nitrate nitrogen concentrations were based on the best available compilation of relevant toxicity data for freshwater organisms in riverine ecosystems, not GEs. In preparing these data, Hickey (2013, p. 23) noted the continuing significant knowledge gaps in "*(i) the adequacy of native fish and invertebrate* [nitrate toxicity] *data for surface waters; (ii) absence of* [data on] *hyporheic* [and groundwater] *species; and (iii)* [nitrate] *toxicity modification in relation to water mineral content (measured by hardness)*". With respect to (iii), nitrate toxicity reduces with increasing water hardness (CCME 2012, Hickey 2015), with a given concentration of nitrate being less toxic in harder water.

Although toxicity information for surface water species is all that is currently available to guide interpretation of the effects of elevated nitrate concentrations on GEs, GEs differ from surface water ecosystems in some important ways:

- Groundwater invertebrate communities are dominated by crustaceans, notably copepods and amphipods. Crustaceans differ significantly in their physiologies, behaviours and life-histories from insects, fishes and molluscs, which predominate in river communities[44]. Of the 30 freshwater species for which useful toxic concentrations are known, only seven were crustaceans, and these did not include representatives of any New Zealand stygofauna families.
- A groundwater copepod was three times more sensitive to ammonium than a surface water species from the same family (Di Marzio et al. 2018), showing the potential for such differences across more stygofaunal species.
- Groundwater oxygen is typically <50% saturated, whereas surface waters usually contain more DO. Recent work revealed that reduced DO concentrations increased the sensitivity of New Zealand freshwater crayfish to nitrite and ammonia (Broughton et

[44] These groups predominate on lake beds, whereas crustaceans dominate within planktonic communities.

al. 2018). Synergistic interactions between oxygen, nitrate and other contaminants may be very important to stygofauna and GEs.

Presently used limits and guidelines for nitrate toxicity in surface water ecosystems were developed based on individual invertebrate species' responses to chronic exposures of up to 60 days. These experimental exposure durations are mostly less than the lifespans of many invertebrates, especially those inhabiting groundwaters. Thus, the science underlying these limits rarely examines whole of life effects on a species or the inter-generational effects of such exposures. Despite these limitations, the science underlying guideline concentrations continues to improve and the ANZECC (2000) guideline concentrations for nitrate-nitrogen decreased from 2000 to 2016 (i.e., earlier research results under-estimated toxic effects).

There is still much more to learn about nitrate toxicity in freshwater ecosystems generally, and on GEs in particular. For example, only recently has the ameliorating effects of water hardness on nitrate become known (Hickey 2016). Despite the inadequate knowledge, there is little doubt that nitrate contamination poses a significant risk to GEs. The principal uncertainties are over the concentrations at which chronic exposure poses a risk to biodiversity and ecosystem function, and the extent of potential synergistic and cumulative effects.

Recognising these shortcomings, and considering the need for protecting the very high conservation and ecological values within Te Waikoropupū Springs near Tākaka, two joint expert witness panels agreed that a safety factor of two should be incorporated into nitrate concentrations to protect these springs and GEs within their contributing aquifers (Fenwick et al. 2018, Hickey et al. 2018). This resulted in the experts agreeing that nitrate nitrogen concentrations in groundwater emerging in the springs should not exceed an annual median of 0.55 mg/L (Fenwick et al. 2018, Hickey et al. 2018). Such a low concentration was deemed appropriately precautionary given the springs' very high biodiversity, cultural, spiritual, economic and other values (Young et al. 2017).

5.3.2 Ammonia and ammonium

Ammonia (NH_3) and ammonium (NH_4^+) occur naturally in the environment along with nitrate (NO_3^-) and nitrite (NO_2^-) as the most common inorganic forms of nitrogen.[45] Ammonia is toxic to freshwater invertebrates at low concentrations, whereas ammonium (NH_4^+) is largely non-toxic (Russo 1985, Prenter et al. 2004). Lethal (LC50[46]) ammonia concentrations for three freshwater amphipod species were 0.36, 1.16 and 1.54 mg/L (96 h exposure, pH = 7.5), with sublethal effects (disruption of mating) occurring at 0.12 and 1.23 mg/L (Prenter et al. 2004). Another investigation of amphipods reported ammonia LC50 (96 h, pH = 8.5-10) concentrations at 0.71 mg/L and an LT50[47] of 21 h when exposed to 6 mg/L (McCahon et al. 1991), comparable to the 27 h LT50 for exposure to 3 mg/L from another study (Williams et al. 1986). Yet another study found 95 h LC50 concentrations (pH = 7.1=7.3) of 0.08

[45] Nitrate is usually reduced by bacteria as oxygen concentrations fall below c. 1 mg/L, so that inorganic nitrogen is predominantly ammonium and ammonia in hypoxic to anoxic environments (e.g., Camargo et al. 2005). Ammonium is the dominant reduced form and persists in equilibrium with unionised ammonia (NH_3) (Close et al. 2001), with relative concentrations of the two forms influenced by temperature and pH (Emerson et al. 1975).

[46] Lethal concentration (LC50): the concentration of a dissolved chemical that is estimated to kill 50% of the test organisms, and usually expressed as a time-dependent value (e.g., 24-hour or 96-hour LC50).

[47] Lethal time (LT50): median time from onset of exposure until death (or other condition).

mg/L[48] for a hypogean copepod and 0.3 mg/L for an epigean species belonging to the same family (Di Marzio et al. 2018).

In the NPS-FM, the NOF establishes a national bottom line for ammoniacal nitrogen (NH_4-N) in rivers and lakes of 1.3 mg/L and 2.2 mg/L (pH = 8), as annual median and annual 95th percentile values, respectively.[49] At these concentrations, impacts are expected on up to 20% of the most sensitive species, with acute effects expected on sensitive species above these concentrations (NZ Govt 2014).

Data on ammoniacal nitrogen concentrations in some New Zealand groundwater aquifers indicate the potential for ammonia to reach ecologically significant concentrations. Concentrations of ammonium (NH_4-N) as high as 1,568 mg /L were recorded in one region, although such extreme concentrations of ammonium are rare (Rosen 2001). At low DO concentrations (i.e., hypoxic to anoxic conditions, higher pH (>9.2) and higher water temperatures, ammonia concentrations in groundwater likely threaten GEs. Table 5-2 provides a summary of ammoniacal nitrogen concentrations in the Wellington region from Daughney and Randall (2009), along with calculated ammonia concentrations to indicate this substances potential importance in New Zealand GEs.

Table 5-2: Percentile concentrations of ammonium (Daughney & Randall 2009), ammonia (calculated) and total ammonia (calculated) in groundwater in the Wellington region (*n* = 70-71). Ammonia concentrations calculated from reported ammonium concentrations using from Thurston et al. (1979) equilibrium percentages, adjusted for water temperature and pH for each percentile (i.e., there is some unknown error here) (National Groundwater Quality Monitoring Programme "ammoniacal nitrogen (NH_4-N)" values assumed to be ionised ammonium (NH_4^+-N) concentrations).

Variable	Units	Percentile				
		5th	25th	50th	75th	95th
Ammonium	NH_4^+-N mg/L	<0.001	<0.001	0.02	0.29	4.86
pH	pH	5.7	6.1	6.4	6.8	7.2
Water temperature	°C	13.1	13.6	14.2	14.6	15.1
Ammonia	NH_3 %	1.2	3.1	11.2	24.3	43.9
Total ammonia (ammoniacal nitrogen)	NH_3 + NH_4^+-N mg/L	<0.001	<0.001	0.022	0.361	6.994
Ammonia	NH_3 mg/L	<0.001	<0.001	0.002	0.071	2.134

5.3.3 Agrichemicals, endocrine disruptors and nutraceuticals

A large suite of chemicals used on land enters freshwater and, from there, groundwater ecosystems. These include not only nutrients, but also heavy metals (e.g., cadmium in phosphate-rich fertilisers), pesticides (herbicides, insecticides), endocrine-disrupting compounds and hormones, pharmaceutically active compounds and organic micro-pollutants, such as disinfection by-products and perfluorinated compounds (Templeton et al. 2009). Many of these occur in New Zealand freshwater environments (Gaw et al. 2008, Scarsbrook et al. 2016, White and Close 2016) and, therefore, are assumed to be present in some aquifers.

[48] These authors tested the toxicity of NH_4^+, noted and measured NH_3, and did not distinguish between the toxic effects of these two forms, noting that "ammonium ion can contribute significantly to ammonia toxicity under some conditions" (Di Marzio et al. 2018): 77.
[49] Based on pH 8 and water temperature of 20° C.

Pesticides were present in groundwater at 17% of locations (*n*=165) within six of the 13 participating regions sampled for the 2014 national survey for these substances in groundwater (Humphries and Close 2014). Twenty-one different pesticides were detected, mostly at concentrations less than 0.0001 mg/L. Groundwater from 6% of wells containing two or more pesticides (Humphries and Close 2014). Comparison with previous four-yearly surveys since 1990 revealed that groundwater at most locations (55%; *n*=101) contained no pesticides during any survey, that there was no change in frequencies of bores contaminated with pesticides, and that there were approximately equal numbers of bores within which concentrations increased and decreased (7% and 8%, respectively) (Humphries and Close 2014). Thus, pesticides pose a threat to GEs and their ecosystem services, especially when present with other threats.

PROTECTING AQUATIC ORGANISMS FROM CHEMICALS

"Tens of thousands of man-made chemicals are in everyday use in developed countries. A high proportion of these, or their transformation products, probably reach the aquatic environment."
"However, we still know very little about the ecotoxicological effects of these".
"[I]t would be very foolish to downplay the threat that these chemicals pose to aquatic biodiversity".

(Sumpter 2009): 3877, 3891.

There is very limited information on these substances that is directly relevant to GEs. Lethal and sublethal effects of several of these substances on aquatic organisms are known (Templeton et al. 2009). Although most remain untested for adverse effects on biodiversity and ecosystem functioning, especially for GEs, their potential to adversely affects GEs is assumed as high and significant (Sumpter 2009). Further discussion of these common, toxic contaminants is beyond the scope of this report, but the scant knowledge suggests a precautionary approach should be adopted to protect GEs.

5.4 Human activities with multiple effects

5.4.1 Agriculture and other land-use activities

Agricultural and horticultural activities, ranging from dry land cropping and grazing to intensive, irrigation-based crop, market garden and dairy farming, generally result in multiple impacts on aquifers and their ecosystems. Certainly, one or two impacts frequently predominate, but others are less obvious and, in combination with other factors, may have synergistic impacts that substantially exceed the impacts of individual factors (see Section 5.6). Contamination by fertilisers and pesticides (Close et al. 2001), along with groundwater abstraction, is common in New Zealand (Humphries and Close 2014, Close and Humphries 2016).The individual effects of different elements of agriculture and horticulture are difficult to separate. For example, biofilms in an alluvial aquifer in Canterbury had a greater biomass and activity (i.e., uptake of organic carbon) in its upper reaches, compared to that lower in the catchment where land-use effects were greater (Williamson et al. 2012). However, the upper catchment groundwater, closer to primary recharge, contained more organic carbon and dissolved oxygen, much less nitrate and total phosphorus, and had lower temperatures and conductivities (Figure 5-6) (Williamson et al. 2012).

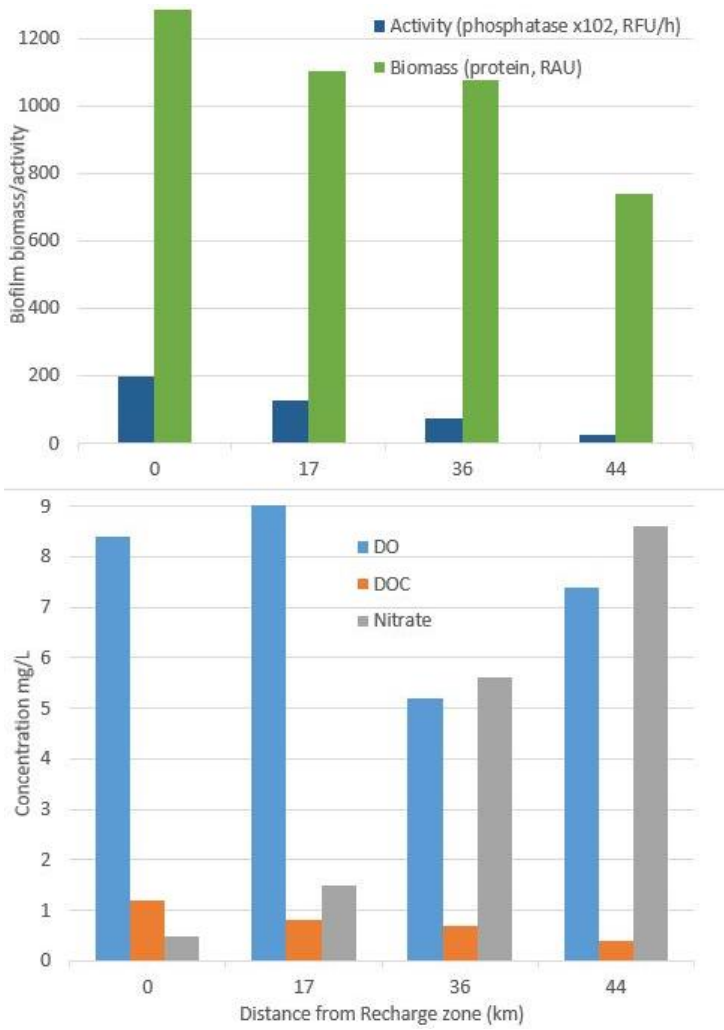

Figure 5-6: Changes in biofilm activity (top, left axis) and biomass (top, right axis), and water chemistry (lower graph) with increasing distance from recharge area (closest to site 1). Biofilm activity: phosphatase, units x 10^2 relative fluorescent units/hour. From: Williamson et al. (2012; Tables 2 and 4).

Studies of land-use activities on GEs elsewhere are similarly inconclusive due to multiple factors varying simultaneously. Some studies found that changes in alluvial aquifer stygofauna communities were weakly or not related to individual or combinations of environmental factors (including organic carbon, nitrate, conductivity) (Dole-Olivier et al. 2009, Stein et al. 2010, Tione et al. 2016), but stygofaunal community heterogeneity and low densities of sampling sites probably mask some effects (e.g., Korbel and Hose 2015). Other studies (Di Lorenzo and Galassi 2013, Lepure et al. 2013, Korbel and Hose 2015) identified reduced stygofaunal diversity (richness) and functionality (feeding modes) under farm land compared with natural forests or less intensive land-uses. Several environmental variables were involved (tree cover, soil characteristics, distance to surface water, temperature, conductivity, pH, DO, dissolved organic carbon, nitrate, phosphorus, sulphate, iron) and differed between these studies. The size of these effects on stygofauna may be quite substantial and marked (Plenet et al. 1996, Korbel and Hose 2015), but are presently unknown.

Forests of some tree species with high transpiration rates may alter groundwater levels, and potentially nutrient inputs into GEs. For example, water levels in a South Australian karst cave fell by almost one metre over five years as an overlying *Pinus radiata* forest established, and water levels in a nearby cave rose by about the same amount when its overlying forest was destroyed by fire

(Grimes et al. 1995 in (Boulton et al. 2003). Other examples highlight the effects of invasive exotic plants, notably trees, on overall water resource, but especially groundwater and groundwater levels. Shallow (0.5-2.5 m) alluvial groundwater levels along the Middle Rio Grande (New Mexico, USA) fluctuated daily by c. 10-15 cm in summer (Figure 5-7), largely due to transpiration by riparian plants, dominated by large, monotypic stands of invasive exotic salt cedar (Dahm et al. 2002). Similarly, exotic, invasive mesquite (*Prosopis* species) stands rely heavily on groundwater, with some species in Hawaii transpiring almost twice the annual precipitation by accessing groundwater (Miyazawa et al. 2016). Collectively, stands of this tree were estimated to use >134 million m^3 of groundwater annually in arid regions of South Africa, and were considered to threaten groundwater's ability to provide for future basic human needs in those regions (Gorgens and Van Wilgen 2004).

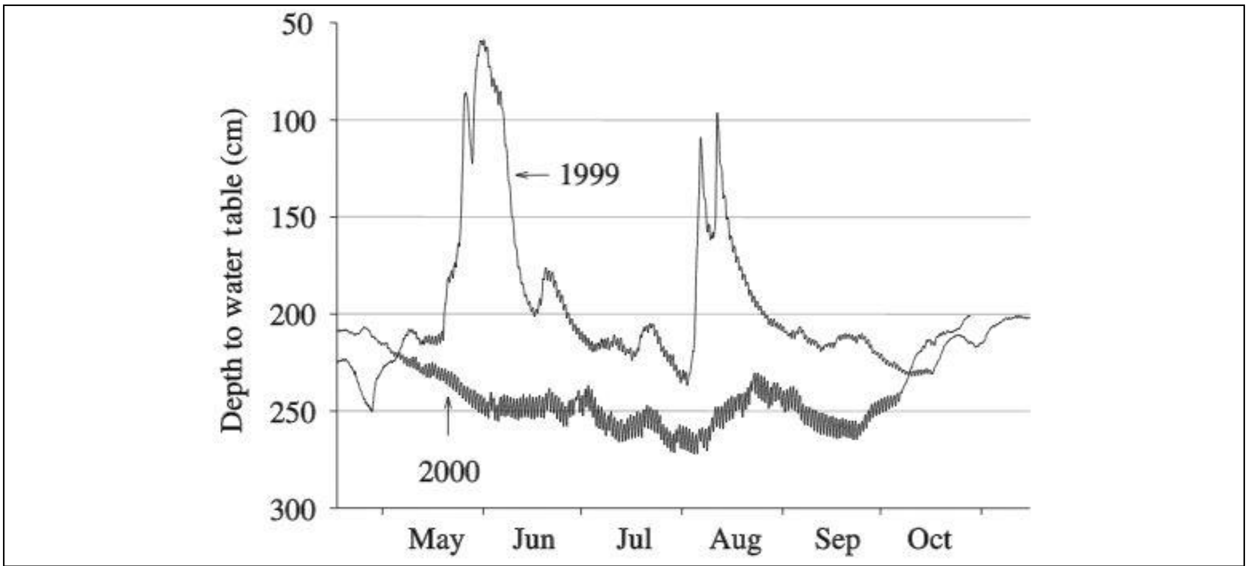

Figure 5-7: Water table fluctuations (cm below ground, 0.5 hour intervals) attributable to invasive salt cedar stands at southern Middle Rio Grande during 1999 and 2000 growing seasons. Daily fluctuations due to evapotranspiration first detectable in early May in both years; most pronounced in 2000 when riverine recharge was minimal. From Dahm et al. (2002), Fig. 5.

5.5 Water transfers

5.5.1 Artificial groundwater recharge (managed aquifer recharge or MAR)

Artificial groundwater recharge is a specific type of water transfer, often between aquifers, not necessarily between catchments or basins. This engineered replenishment of aquifers, usually by surface waters, offers opportunities to resolve increasingly common water problems arising from excessive groundwater abstraction. It involves delivering water onto or into ground that is sufficiently permeable for the new water to move into the aquifer and augment groundwater volumes (Bouwer 2002). The ground surface may be variously engineered to improve infiltration rates. Applications include storing water for future use, distributing water via an existing aquifer, and rejuvenating flows in spring-fed, lowland streams. Thus, MAR may hold the potential to alleviate these problems and/or overcome management limits on water abstraction aimed at sustaining surface water ecosystems to increase the viability of groundwater abstraction for productive purposes.

Although conceptually simple, MAR is not without its disadvantages, some of which may affect GEs. Artificial recharge can change water levels, pressure gradients and flow directions (at least at < 100 m scales) (Dillon et al. 2009). Depending on the scale of changes, this effect seems relatively benign for GEs, although other groundwater-dependent ecosystems may be more severely affected.

Localised clogging is a major problem with MAR (Bouwer 2002). Injection bores (wells) can become clogged within minutes to years after commencement (Rinck-Pfeiffer et al. 2000). Physical clogging of the infiltration medium by suspended solids appears to be the main factor, but clogging by biofilms (polysaccharides, bacterial colonies) was the second most important factor in experiments, and a significant issue for artificial recharge via ponds and natural infiltration systems (Bouwer 2002, Rubol et al. 2014). Clogging or reduced transmissivity within an aquifer by either biofilms or fine sediments from MAR can result in reduced groundwater velocities at smaller (10-100 m) spatial scales, leading to reduced dissolved oxygen concentrations and a concomitant cascade of effects (oxic to reducing chemical environment, changed microbial respiratory pathways and communities, reduced bioturbation, increased clogging, etc.). However, MAR operations are usually managed to minimise any clogging or other adverse effects (Bouwer 2002).

Another main effect of MAR on GEs is via changes in water quality (Dillon et al. 2009). In one study, spatial and temporal variability of DO, conductivity and temperature increased substantially with recharge and the averages of these variables and dissolved organic carbon within the aquifer changed to reflect the infiltration water (Datry et al. 2005b). The effects of this on GEs include increased stygofauna densities and changes in stygofaunal community composition (Datry et al. 2005b).

Mixing of waters via MAR also potentially erodes some Māori values, beliefs and practices associated with groundwaters. This was discussed in Section 4.4.4.

5.5.2 Inter-catchment (inter-basin) transfers: disrupting biogeographic boundaries

There is increasing concern over the threats to local biodiversity and ecosystem function posed by exotic species. This concern includes threats to freshwaters posed by accidental introductions of invasive species, which may displace endemic species or disrupt ecosystems (e.g., the freshwater diatom, *Didymosphaenia geminata* or didymo) (Kilroy and Unwin 2011)), compromising important values. GEs are not immune to this threat: invertebrates are particularly adept at migrating along any available pathway. Thus, many stygoxenes, if not stygobites, are expected to migrate along constructed pipes, race-ways and channels on the land surface.

There are several examples of freshwater invertebrate (as well as fish) invaders dramatically changing the biodiversity and ecosystem structure of northern hemisphere streams and lakes, particularly through loss of biodiversity loss (Dick et al. 2002, Kelly et al. 2003, MacNeil et al. 2004) and associated change to ecosystem functioning (Kelly and Dick 2005). These include invaders from the same land mass, which appear no less harmful than those from countries separated by seas (Pinkster 1988, Dick et al. 2002, Jazdzewski et al. 2004, Taylor 2004).

The increasing numbers and scales of engineered waterways for irrigation, water supply, hydropower generation, etc., within New Zealand risk breaching natural barriers to species dispersal. The resulting threats to GEs include biodiversity loss through inter-breeding of previously isolated populations and species, and stronger competitor species and predatory species reducing or eliminating some species and/or changing the composition of natural communities and their functioning (e.g., Dick et al. 2002, MacNeil et al. 2004). Changes to functioning are likely to compromise important ecosystem services (Pinkster 1988).

As described in Section 2.3, New Zealand's stygofauna appears to include many microbial and stygofaunal species with very restricted geographical ranges that diverged from adjacent populations and evolved into different populations, subspecies or species due to their physical separation. Short-range endemic species are regarded as having high biodiversity values and receive higher levels of protection.

5.6 Direct and indirect, cumulative and synergistic effects, and cascades of effects

Human effects on the environmental rarely occur alone. Generally, more than one stressor or factor is involved simultaneously with any human-induced environmental effect (e.g., Crain et al. 2008). Agriculture is an obvious example of a human activity with multiple stressors for GEs. Most agriculture today involves added nutrients and agrichemicals such as pesticides and herbicides to ensure production at financially sustainable levels. Some of these added nutrients and other agrichemicals leach into underlying groundwater, along with some organic carbon from the increased plant and/or animal production. Irrigation adds further effects, and these will be greater for GEs if groundwater is used; water levels will be reduced and fluctuate more, DO concentrations may be reduced, transport of dissolved and fine particulate matter from the land surface will increase (notably nitrate and organic carbon) with percolating recharge from irrigation water, etc. These multiple effects are cumulative.

One stressor acting alone may cause one or more direct effects on an ecosystem, as well as inducing indirect effects. Some of these direct and indirect effects, may involve synergistic effects where two or more stressors act together to cause an effect that is greater than the added individual effects of each stressor in isolation (e.g., low DO concentrations increase the toxicity of nitrate to some organisms) (see Section 5.3.1). We found no investigations of multiple stressors or synergistic effects of natural or human related stressors for GEs, and few for aquatic ecosystems generally. The best example is a recent study showing that low DO increases the toxicity of nitrate for a crustacean (Broughton et al. 2018). We also previously noted one important antagonistic effect; increased water hardness reduces the toxicity of nitrate to some freshwater organisms (CCME 2012, Hickey 2016).

Synergistic and antagonistic effects are very poorly understood in ecology generally (Crain et al. 2008), and in GEs in particular, because there has been very little research of such multiple factor effects. However, a detailed review of multiple stressor effects in marine ecosystems reported that *"cumulative stressor outcomes are … non-additive in specific comparisons 75% of the time and heavily weighted toward synergies when more than two stressors interact"* ((Crain et al. 2008): 1313). The effects of multiple stressors on groundwater ecosystems are likely to be similarly weighted towards synergistic effects, supporting a precautionary approach to managing New Zealand's GEs.

Most ecological research is focussed on understanding direct effects, simply because these effects are more easily determined. Indirect effects are increasingly identified, and frequently include multiple indirect or a cumulative sequence of effects. Perhaps the best examples are those termed trophic cascades. These occur where a reduced predator population leads to greatly increased densities of its prey. This increased population density decimates the prey's usual food species, in turn causing shifts in trophic relationships, ecosystem structure and nutrient cycling (Carpenter et al. 1985, Walsh et al. 2016). Trophic cascades are well described for several ecosystems, notably marine fisheries responses to excessive harvesting of predatory species, and for planktonic communities in the U.S. Great Lakes, where removal of piscivorous fishes led to increases in their prey (fishes that consumed zooplankton), reducing populations of zooplankton that fed on phytoplankton, so that phytoplankton populations increased substantially, making the previously clear, colourless lake water green and opaque (Carpenter et al. 1985). Key elements of these trophic cascades are changes to food webs that usually are initiated by human induced stressors (e.g., harvesting fishes) on higher trophic level predators, so that the changes are termed top-down, hence cascades.

Equivalent non-trophic, sequential cumulative (cascade), effects have received scant research attention, yet examples are common, and may start with changes in nutrients or to the base of food webs. For example, introduction of fine sediment into streams initiates a sequence of direct and indirect effects that change the ecosystem's functioning: fine sediment infiltrates the bed, clogging interstices, reducing or eliminating exchanges with the hyporheos and groundwater, gravel surfaces become coated with thickening layers of fines, and stream bed physico-chemical characteristics, notably dissolved oxygen concentrations, change (Wood and Armitage 1997). Ecological communities change as a result of this cumulative cascade of direct and indirect effects. The community composition shifts markedly to reduced diversity and densities; primary productivity declines as many benthic diatoms are excluded, suspension feeders are largely eliminated, sensitive invertebrates (notably Ephemeroptera, Trichoptera, Plecoptera) inhabiting crevices, interstices and hard surfaces disappear, and fish populations change in response to changed food types and bed characteristics (Wood and Armitage 1997).

IS BIODIVERSITY REDUNDANCY REAL?

"[T]here was no evidence for redundancy at high levels of diversity; the improvement in services [with increasing biodiversity] was continuous".

(Worm et al. 2006): 790.

Similar cascades of effects arising from human activities seem likely for GEs, especially at finer spatial scales (0.001-10 mm), within alluvial aquifers. For example, increased organic carbon in a GE may stimulate bacterial and biofilm activity that consumes much of the available dissolved oxygen, potentially reducing invertebrate populations and their bioturbation activities. This reduced grazing pressure and bioturbation is likely lead to biofilm accumulations, which clog finer pore spaces and reduce water velocities, in turn, lowering dissolved oxygen and increasing carbon dioxide concentrations. As microhabitats become increasingly anoxic, anaerobic bacterial activity will predominate, converting nitrate to nitrogen gas and toxic ammonia, further reducing invertebrate populations. As anoxic conditions and the resulting low redox potential extends to more microhabitats and more widely within the GE, bacteria metabolising manganese, iron and sulphur will become active within more of the aquifer, releasing these elements in soluble forms, tainting the groundwater. Further changes may ensue as the effects cascade until some significant, larger scale, event corrects these changes. We are not aware of studies demonstrating such cascades of effects at measurable scales in GEs. However, some of these changes (perhaps with other intermediate changes) almost certainly occur at microhabitat scales (at finer pore-space levels, < 1 mm) in most aquifers under natural conditions, and observations on contaminated GEs revealed such changes, at least temporarily at local scales (involving single wells or perhaps tens of metres) in response to stressors from human activities (Sinton 1984, Boulton et al. 2008).

Some biodiversity loss almost certainly has occurred in many of our GEs, and there is no way to know the degree to which this has compromised their ecosystem services. Most ecosystems have substantial apparent functional redundancy, so that they seem to function normally, at least in the short term, even with some loss of biodiversity (Pearce and Moran 1994). However, at some point of biodiversity loss, ecosystem functioning inevitably will be compromised, leading to reduced ecosystem service delivery. That critical point is unknown for most ecosystems (Reid and Miller 1989). It may be sooner if ecosystem engineers or keystone species (that have disproportionally large influences on an ecosystem; Reid and Miller 1989) are lost. One such stygobite is *Phreatoicus typicus* (a 20 mm long isopod, Figure 2-16), which consumes large quantities of clay particles in Canterbury's GEs (Fenwick et al. 2004, Boulton et al. 2008). Consequently, some apparently redundant or rare species are probably vital to the longer term resilience of ecosystems and they should be factored into ecosystem valuations (Humbert and Dorigo 2005, Hannes et al. 2011).

5.7 Summary

- Dissolved organic carbon and dissolved oxygen availability and interactions can significantly affect GEs. Organic carbon subsidises bacterial biofilms and stygofauna at lower concentrations but creates stresses at higher concentrations. Excessive organic carbon results in increased biomass, usually of fewer species that can reduce aquifer hydraulic conductivity by clogging fine pore spaces. While stygofauna appear variously adapted to low oxygenated conditions (hypoxia and anoxia), their activity is likely to be suppressed and sustained low dissolved oxygen concentrations may reduce grazing, allowing biofilm biomass to increase and block finer pore spaces within the aquifer.
- Many activities can significantly affect the hydrological regime within aquifers. Water abstraction generates potentially a significant disturbance for alluvial aquifer communities, changing community richness and/or abundance in some instances. Significant abstraction from coastal aquifers can result in saltwater contamination of groundwater as seawater replaces abstracted freshwater, potentially making parts of the aquifer habitat unsuitable for its stygofauna and for delivering groundwater ecosystem services.
- Nitrate, ammonium, agrichemicals and emerging contaminants can all enter groundwater from a range of land use activities. Nitrate toxicity probably represents the most significant current risk to GEs but there is a lack of toxicity data for groundwater species.
- Some activities, including agriculture, horticulture and water transfers, result in multiple impacts on groundwater and their ecosystems, some of which are cumulative or act synergistically.
- In some locations significant time lags (multi-decadal) occur between when water enters GEs and is either abstracted or reappears on the surface meaning that potential contamination may take considerable time to be observed. Conversely, the effects of any actions on the land to reduce potential contamination will take years to be realised.
- The overall paucity of information specific to GEs suggests that a precautionary approach is required to managing activities with the potential to threaten groundwater ecosystems.

6 Current regulatory context

This section provides an overview of the current national and regional regulatory context for groundwater management in New Zealand. International regulatory approaches are also briefly outlined.

6.1 National legislation and policy

New Zealand has a well-developed legislative framework for managing freshwater ecosystems, much of which can be applied directly to managing GEs. The primary component of this is the Resource Management Act (1991). The Conservation Act (1987) and New Zealand Biodiversity Strategy are also relevant to the management and conservation of groundwater biodiversity. Both the Resource Management Act and the Conservation Act are required to be interpreted and administered as to give effect to the principles of the Treaty of Waitangi.

6.1.1 Treaty of Waitangi

The Treaty of Waitangi (the Treaty) forms the underlying foundation of the Crown-Māori relationship regarding freshwater resources in New Zealand (Iwi Advisory Group [Freshwater] 2015). Water is a taonga (treasure) of paramount importance with attendant rights, interests and responsibilities. A series of Treaty principles specific to freshwater can be found in decisions of the Waitangi Tribunal, for example (Crengle 1993, Tipa et al. 2002):

- Non-Māori, in particular those who share the use of freshwater and those who are charged with its protection, need to be aware of the mental and spiritual values held by Māori in relation to water and the resources it supports (Waitangi Tribunal 1983, WAI6).

- The Māori conception of waterways is holistic and the rights that stem from the exercise of rangatiratanga over such resources will reflect this holistic perspective. The taonga value of freshwater encompasses the water itself, the resources within the waterbody, and its supporting environs. Rangatiratanga (right to exercise authority) with respect to water may include developmental interests (Waitangi Tribunal 1998, WAI212).

- The spiritual and cultural significance of a freshwater resource to Māori can only be determined by the tangata whenua (local people) who have traditional rights over the river (Waitangi Tribunal 1984, WAI4).

Iwi and government co-governance and co-management contexts are changing, which in turn should influence the way we manage and use GEs at local, regional and national scales. Treaty settlements are playing a critical role in providing the legislative foundation for a range of new co-governance and co-management institutional arrangements for the governance and management of fresh water and the active implementation of rehabilitation strategies and actions to meet Māori and community aspirations. Examples of policy drivers that seek to increase the influence of Māori in freshwater management and research include, for example, Te Ture Whaimana (Vision and Strategy for the Waikato River)[50], Te Awa Tupua (Whanganui River Claims Settlement) Act 2017[51], the National Policy

[50] https://waikatoriver.org.nz/wp-content/uploads/2011/07/Vision-and-Strategy.pdf

[51] http://www.legislation.govt.nz/act/public/2017/0007/latest/whole.html

Statement for Freshwater Management (NPS-FM, NZ Govt 2014), and the Vision Mātauranga Policy (MoRST. 2007).

In the case of the Waikato River, Te Ture Whaimana will prevail over any inconsistencies in other policies, plans, or processes affecting the Waikato River catchment. Relevant policies, plans, and processes (e.g., NPS-FM, Waikato Regional Policy Statement, district plans) cannot be amended so that they are inconsistent with Te Ture Whaimana and must be reviewed and amended, if required, to address any inconsistencies. The Statement of Significance in the Waikato Raupatu Claims (Waikato River) Settlement 2010[52] includes groundwater ecosystems:

> *"The Waikato River is our tupuna (ancestor) which has mana (spiritual authority and power) and in turn represents the mana and mauri (life force) of Waikato-Tainui. The Waikato River is a single indivisible being that flows from Te Taheke Hukahuka to Te Puuaha o Waikato (the mouth) and includes its waters, banks and beds (and all minerals under them) and its streams, waterways, tributaries, lakes, aquatic fisheries, vegetation, flood plains, wetlands, islands,* ***springs,*** *water column, airspace,* ***and substratum*** *as well as its metaphysical being. Our relationship with the Waikato River, and our respect for it, gives rise to our responsibilities to protect te mana o te Awa and to exercise our mana whakahaere (authority) in accordance with long established tikanga to ensure the wellbeing of the river. Our relationship with the river and our respect for it lies at the heart of our spiritual and physical wellbeing, and our tribal identity and culture."*

6.1.2 Resource Management Act 1991

The Resource Management Act 1991 (RMA), New Zealand's most important environmental legislation, establishes a hierarchical framework of policies, plans, rules and resource consents to manage the use, development and protection of natural and physical resources. National policy statements and national environmental standards developed and implemented at central government level direct regional council regional policy statements and plans, and district council district plans and rules.

The term "groundwater" (or "ground water") is absent from the RMA and "aquifer" appears just twice ("river(s)" and "lake(s)" appear throughout), although definitions of "water" and "water body" include specific mention of water below ground and water in aquifers. By omitting "aquifer" from listings of the other habitats within the definition of "water body", the RMA appears to imply that protection of the natural character of groundwater (including its biodiversity and ecosystem services) is not a matter of national importance. However, by adopting the Fisheries Act 1996's definition of aquatic life ("any species of plant or animal life that must inhabit any water body (fresh, brackish or marine) for part of its life"), the RMA implicitly includes and provides for consideration of groundwater.

6.1.3 National Policy Statement for Freshwater Management

The NPS-FM (NZ Govt 2014, 2017) provides an overarching structure for managing freshwater resources that recognises the national significance of freshwater and Te Mana o te Wai. Te Mana o te Wai is the integrated and holistic well-being of a freshwater body. By recognising Te Mana o te Wai as an integral part of the freshwater management framework it is intended that the health and well-

[52] http://www.legislation.govt.nz/act/public/2010/0024/latest/DLM1630105.html?search=sw_096be8ed80e3448a_Statement+Significance_25_se&p=1&sr=3

being of freshwater bodies is at the forefront of all discussions and decisions about freshwater, including the identification of freshwater values and objectives, setting limits, and the development of policies and rules. This is intended to ensure that water is available for the use and enjoyment of all New Zealanders, including tāngata whenua, now and for future generations (NZ Govt 2017).

The NPS-FM sets out objectives and policies that direct local government to manage water in an integrated and sustainable way, while providing for economic growth within set water quantity and quality limits. All regional and unitary councils are required to achieve compulsory national standards of "ecosystem health" (Table 6-1), and "human health for recreation" as minimum acceptable states for these two values, termed national bottom lines.

Table 6-1: NPS-FM compulsory national value for ecosystem health. (Source: NZ Govt 2017, Appendix 1).

NPS-FM definition of ecosystem health
Ecosystem health – The freshwater management unit supports a healthy ecosystem appropriate to that freshwater body type (river, lake, wetland, or **aquifer**). In a healthy freshwater ecosystem ecological processes are maintained, there is a range and diversity of indigenous flora and fauna, and there is resilience to change. Matters to take into account for a healthy freshwater ecosystem include the management of adverse effects on flora and fauna of contaminants, changes in freshwater chemistry, excessive nutrients, algal blooms, high sediment levels, high temperatures, low oxygen, invasive species, and changes in flow regime. Other matters to take into account include the essential habitat needs of flora and fauna and the connections between water bodies.

Seven other national values or uses are identified: the health and mauri of the environment, food gathering and places of food, cultivation, sacred waters, municipal and domestic water supply, economic or commercial development, and navigation. At least the first six of these depend on ecosystem services, making them directly relevant to GEs. The NPS-FM explicitly includes aquifers as "freshwater" and implicitly throughout the NPS-FM as "water", "fresh water", "freshwater resources", "the resource", "water body", "waterway", "freshwater management unit" (NZ Govt 2017). The repeated use of "associated ecosystem" (or similar) within Objectives A1, B1, C1 and D1, and their associated policies, signals that GEs are within the scope of the NPS-FM and no less important than surface water bodies. Certainly, there is no exclusion of aquifers, groundwaters or GEs, either explicit or implied. Table 6-2 lists key objectives from the NPS-FM that are relevant to managing groundwater ecosystems.

Table 6-2: Key objectives from the NPS-FM relevant to managing groundwater ecosystems. Source: NZ Govt (2017).

Objective Title	Objective No.	Description
Te Mana o Te Wai	AA1	To consider and recognise Te Mana o te Wai in the management of fresh water.
Water quality	A1	To safeguard: a) the life-supporting capacity, ecosystem processes and indigenous species including their associated ecosystems, of fresh water; and b) the health of people and communities, as affected by contact with fresh water; in sustainably managing the use and development of land, and of discharges of contaminants.
Water quality	A2	To safeguard: The overall quality of fresh water within a freshwater management unit is maintained or improved while: a) protecting the significant values of outstanding freshwater bodies; b) protecting the significant values of wetlands; and c) improving the quality of fresh water in water bodies that have been degraded by human activities to the point of being over-allocated.
Water quality	A4	To enable communities to provide for their economic well-being, including productive economic opportunities, in sustainably managing freshwater quality, within limits.
Water quantity	B1	To safeguard the life-supporting capacity, ecosystem processes and indigenous species including their associated ecosystems of fresh water, in sustainably managing the taking, using, damming, or diverting of fresh water.
Water quantity	B2	To avoid any further over-allocation of fresh water and phase out existing over-allocation.
Water quantity	B3	To improve and maximise the efficient allocation and efficient use of water.
Water quantity	B4	To protect significant values of wetlands and of outstanding freshwater bodies.
Water quantity	B5	To enable communities to provide for their economic well-being, including productive economic opportunities, in sustainably managing freshwater quantity, within limits.
Integrated management	C1	To improve integrated management of fresh water and the use and development of land in whole catchments, including the interactions between fresh water, land, associated ecosystems and the coastal environment.
National Objectives Framework	CA1	To provide an approach to establish freshwater objectives for national values, and any other values, that: a) is nationally consistent; and b) recognises regional and local circumstances.

Objective Title	Objective No.	Description
Monitoring plans	CB1	To provide for an approach to the monitoring of progress towards, and the achievement of, freshwater objectives and the values identified under Policy CA2(b).* * Policy CA2(b) relates to identification of values in each freshwater management unit.
Tāngata whenua roles and interests	D1	To provide for the involvement of iwi and hapū, and to ensure that tāngata whenua values and interests are identified and reflected in the management of fresh water including associated ecosystems, and decision-making regarding freshwater planning, including on how all other objectives of this national policy statement are given effect to.

6.1.4 Proposed National Environmental Standard on ecological flows and water levels

National Environmental Standards (NES) are developed by central government for regional and district councils to implement. The prescribed or stricter standards must be enforced by councils. The proposed NES on ecological flows and water levels has not yet been progressed as a national standard. Nonetheless, the proposed NES provides useful direction, including specific recognition for the need for environmental flows for groundwater, noting *"There remain some water bodies, principally small streams and groundwater systems, for which no specific environmental flows and water levels have been determined. The lack of an established environmental flow increases the potential for ecological (and other) values to be adversely impacted by water abstraction"* (MfE 2008, p2). Thus, the need for environmental flows for groundwater systems to protect groundwater biodiversity and ecosystems is recognised.

Draft guidelines for selecting methods to establish allocation limits for groundwater incorporate this interpretation of ecosystem protection (Beca 2008). The guidelines include GEs explicitly: *"Our approach concentrates on the aspects of groundwater systems related to ecological values (in the groundwater system and connected surface water systems) and physical properties of the aquifers such as structure and water quality"* (Beca 2008, p74). Further the guidelines note that *"an ecological flow regime [for groundwater] may include an allocation limit, water level or pressure limits, or other measures to ensure management objectives (such as adequate surface water flows or prevention of salt water intrusion) are met"* and included *"Maintenance of groundwater ecology (flora and fauna)"* among nine groundwater values or management objectives for aquifer systems (Beca 2008).

The discussion of flows in aquifers within these draft guidelines signalled a change in thinking about the management of aquifers as dynamic ecosystems. They state that it is *"often not possible to detect change in aquifer conditions as groundwater flows are reduced or the pattern of flows is changed… [due to] the high natural variability and the complexity of aquifer-surface water systems"* (Beca 2008, p75).

6.1.5 Water conservation orders

Water conservation orders (WCO) may be established under the RMA to protect waterways with significant amenity or intrinsic values. These may be applied to rivers, lakes, streams, ponds, wetlands, or aquifers, and can cover freshwater or geothermal water. If granted, a WCO can restrict or prohibit water takes, discharges and other uses of the water.

Fourteen of New Zealand's water bodies are currently protected by conservation orders because of their outstanding amenity or intrinsic values. Twelve of these orders protect rivers and two cover lakes. While there are no water conservation orders currently in place for aquifers in New Zealand, Te Waikoropupū Springs and associated water bodies (including the aquifers, Tākaka River, and tributaries) are currently the subject of a WCO application. This application was lodged with the Environmental Protection Authority by Ngāti Tama Ki Te Waipounamu Trust and Andrew Yuill in April 2017[53]. The springs, the largest freshwater springs in the southern hemisphere, are remarkable for their large discharge volume, very high visual clarity and blue-violet water colour. The springs also have very high cultural, biodiversity, social and other values (Young et al. 2017).

6.1.6 Conservation Act 1987

Promulgated to promote conservation of New Zealand's natural and historic resources (DoC 2008b), the Conservation Act provides for protection of aquifers and GEs in various ways, largely by implication. For example:

- The Act established the Department of Conservation (DoC) to, amongst other things, preserve all indigenous freshwater habitats. Groundwaters are encompassed within its definition of freshwater: *"other bodies of water whether naturally occurring or artificially made"*.
- Although stygofauna are not specifically identified, DoC's protective role explicitly includes crustaceans (the most abundant and diverse groups inhabiting GEs (Scarsbrook and Fenwick 2003): *"freshwater fish includes all species of … all shellfish of the Classes Mollusca and Crustacea, that must, at any time in the life history of the species, inhabit fresh water"*.

DoC's recent intended Natural Heritage Outcomes and objectives are relevant to groundwater biodiversity management (DoC 2008a, 2016, p10): *"The diversity of our natural heritage is maintained and restored"*. All five of the objectives set to achieve this are relevant to groundwater biodiversity and ecosystems:

- *"A full range of New Zealand's ecosystems is conserved to a healthy functioning state*
- *Nationally threatened species are conserved to ensure persistence*
- *Nationally iconic natural features and species are maintained or restored*
- *Locally treasured natural heritage is maintained or restored in partnerships*
- *Public conservation lands, waters and species are held for now and future generations"*.

6.1.7 New Zealand Biodiversity Strategy

The New Zealand Biodiversity Strategy (NZBS) (DoC and MfE 2000) gives effect to the United Nation's Convention on Biological Diversity (CBD), ratified by New Zealand in 1992. Two of the NZBS goals are relevant to managing groundwater biodiversity:

"Goal One: Community and individual action, responsibility and benefits

- Enhance community and individual understanding about biodiversity, and inform, motivate and support widespread and coordinated community action to conserve and sustainably use biodiversity; and

[53] https://www.epa.govt.nz/assets/FileAPI/proposal/NSP000042/Applicants-proposal-documents/WCW-Ngati-Tama-and-Andrew-Yuill-WCO-Application.pdf

- Enable communities and individuals to equitably share responsibility for, and benefits from, conserving and sustainably using New Zealand's biodiversity, including the benefits from the use of indigenous genetic resources", and

"Goal Three: Halt the decline in New Zealand's indigenous biodiversity

- Maintain and restore a full range of remaining natural habitats and ecosystems to a healthy functioning state, enhance critically scarce habitats, and sustain the more modified ecosystems in production and urban environments; and do what else is necessary to maintain and restore viable populations of all indigenous species and subspecies across their natural range and maintain their genetic diversity" (DoC and MfE 2000).

Regional biodiversity strategies, developed by regional councils in consultation with local stakeholder groups, guide biodiversity efforts towards achieving the NZBS goals regionally (e.g., GWRC 2012) and, collectively, New Zealand's obligations under the CBD.

6.2 Regional context

The primary focus of groundwater management across most regions to date has been the protection of groundwater as a physical resource for human use. Although there has been increasing recognition of the interconnectedness of surface and ground waters and the need to protect groundwater-dependent surface water ecosystems, few councils have explicitly sought to manage groundwater as an ecosystem with intrinsic biodiversity values. Two exceptions are Tasman District Council (TDC) and more recently, GWRC. There are also iwi management plans that have reference to groundwater ecosystems.

6.2.1 Tasman District Council

TDC's Regional Management Plan (TDC 2008) explicitly recognises the aquatic invertebrate fauna associated with the extensive karst systems present across the district, including the connectively between groundwater and surface waters. These karst systems include Te Waikoropupū Springs, near Tākaka, which are currently the subject of a WCO application (refer Section 6.1.5).

6.2.2 Greater Wellington Regional Council

In 2016, GWRC notified its Proposed Natural Resources Plan (PNRP) with objectives for both water quality and water quantity to safeguard aquatic ecosystem health values of both GEs and ecosystems in connected surface waters (Table 6-3). The PNRP distinguishes directly connected (i.e., abstraction has a direct and immediate effect on surface waters) from indirectly connected groundwater (i.e., abstraction has a lagged effect on surface waters) (Hughes and Gyopari 2014). Three potential stressors or threats are explicitly identified: nitrate concentrations, aquifer hydraulic conductivity and connectivity, and salt (sea) water intrusion.

The term "health" is defined within the PNRP as *"[t]he degree to which an aquatic ecosystem is able to sustains its ecological structure, processes, functions, and resilience within its range of natural variability"* (GWRC 2015). Thus, the intent to protect ecosystem function and services is clear and consistent with the NPS-FM. So too, is the intent to protect biodiversity, albeit, more implicitly. Biodiversity is specifically addressed (as *"aquatic plants, invertebrate or fish communities"* and *"stygofauna communities")* for nitrate effects in both categories of groundwater. Biodiversity is subsumed within *"groundwater-dependent ecosystems"* under water quantity outcomes (Table 6-3).

Table 6-3: Groundwater aquatic ecosystem health and mahinga kai outcomes listed in the Proposed Natural Resources Plan. Source: GWRC (2015).

Outcome	**Groundwater directly connected to surface water**	**Groundwater not directly connected to surface water**
Nitrate	Nitrate concentrations do not cause unacceptable effects on groundwater-dependent ecosystems or on aquatic plants, invertebrate or fish communities in connected surface water bodies.	Nitrate concentrations do not cause unacceptable effects on stygofauna communities or other groundwater ecosystems.
Quantity	The quantity of water is maintained to safeguard healthy groundwater dependent ecosystems.	
Salt intrusion	The boundary between salt and fresh groundwater does not migrate inland.	

6.2.3 Iwi management plans

An iwi management plan (IMP) is prepared by an iwi, iwi authority, rūnanga (tribal council) or hapū. IMPs are often holistic documents that cover more than resource management issues under the RMA. Much like council plans, IMPs may include issues, objectives, policies and methods relating to ancestral taonga, such as rivers, lakes, groundwaters, seabed and foreshore, mountains, land, minerals, wāhi tapu (scared place), wildlife and biodiversity, and places of tribal significance. These plans are often used by iwi/hapū to express how the sustainable management of natural resources can be achieved based on cultural and spiritual values. They often detail how the iwi/hapū expect to be involved in the management, development and protection of resources, and outline expectations for engagement and participation in RMA processes. These plans must be taken into account when preparing or changing regional policy statements and regional and district plans (Tipa et al. 2016). Some examples of how iwi and hapū aspirations for groundwater ecosystem management are being expressed as goals and objectives in IMPs were provided in Section 4.4. One example included Ngāi Tūāhuriri Rūnanga et al. (2013) which expressed over-allocation as *"…a reflection of the lack of understanding of the freshwater resource, including the relationship between surface and groundwater, and of the lack of value given to the resource."*

6.3 International approaches

We undertook a preliminary assessment of groundwater management in other countries to determine the extent to which groundwaters are recognised as containing unique biodiversity and valuable GEs. Our search identified that Australia (e.g., COAG 2004), the European Union (e.g., Griebler et al. 2010) and California recognised groundwaters as ecosystems and had established measures to sustain them. A preliminary review of water management processes in Canada (Saskatchewan River basin, Alberta), the USA (Great Lakes basin, Michigan) and South Africa (NWC 2012) indicated that these jurisdictions all recognise that surface water ecosystems depend upon groundwaters. However, none of these jurisdictions appear to recognise the existence of GEs or even life in groundwaters.

6.3.1 Australia

Groundwater management in Australia is driven by the National Water Initiative (NWI), agreed to by all states in 2006 as a consistent approach to managing water across Australia (NWC) [54]. The NWI

[54] See http://nwc.gov.au/nwi/nwi-10-year-anniversary .

established objectives, outcomes and actions, requiring each state to develop implementation plans to address these (COAG 2004, Tomlinson and Boulton 2008). Environmental allocations of water are one key element within the NWI, where an allocation of water within each water body is reserved specifically for the ecosystem to sustain its biodiversity and ecosystem values, among other values. Another important element is the consistent use of the term "groundwater system" ("groundwater resource" appears with similar frequency), perhaps an implicit reference to groundwater's ecosystem characteristics, and its hydrological and ecological linkages to other freshwater-dependent ecosystems.

The Australian NWI approach demonstrates a broad framework for managing groundwaters as ecosystems that are functionally connected to surface waters. Although our legislative context differs greatly from that of Australia, the approach appears to have considerable merit. An example objective and associated outcomes and actions are provided in Table 6-4. It is also worth noting the explicit acknowledgement of incomplete "science, socio-economic analysis and community input" (COAG 2004) because, like New Zealand, Australia's groundwater science knowledge, especially that concerning its ecosystems, is very incomplete and indigenous peoples' knowledge appears unrecognised. When the NWI concluded in 2014, it was considered to have halted declines in environmental quality of waterways, with significant gains in ensuring sufficient water to achieve environmental objectives (NWC 2014).

6.3.2 California

Groundwater comprises 33-50% of water use in California (CSG 2014) and the Sustainable Groundwater Management Act (SGMA) 2014 empowers local groundwater sustainability agencies (GSAs) to manage groundwater resources for current and future social, economic, and environmental benefits. The SGMA requires GSAs to balance achieving these diverse benefits as well as identifying and considering any effects on GEs. Its focus appears to be on sustaining human uses and GEs on the land surface; it defines "Sustainable groundwater management" as causing "*no undesirable results*" and the only undesirable result related to ecological effects is "*depletions of interconnected surface water that have significant and unreasonable adverse impacts on beneficial uses of the surface water* (CSG 2014, p 17-18).

The SGMA contains just one mention of groundwater dependent ecosystems, requiring that "*a groundwater sustainability plan shall include, where appropriate ... impacts on groundwater dependent ecosystems*" (CSG 2014, p30). To support implementing this requirement, the Nature Conservancy developed a guidance document, with tools and resources (Rohde et al. 2018). Although the SGMA contains no reference to GEs, the regulations for implementing groundwater sustainability plans defines them as "*ecological communities or species that depend on groundwater emerging from aquifers or on groundwater occurring near the ground surface*" (CSG 2016, p3). The focus on epigean (surface) GEs implied by this definition is the focus adopted by the Nature Conservancy; its guide does not consider GEs (Rohde et al. 2018), although stygofauna sampling is summarised in the GE assessment toolbox appendix.

Table 6-4: Example of an objective, outcomes and actions from Governments of Australia's National Water Initiative (NWI) that are directly relevant to sustainable management of GEs. Numbers refer to clauses and sub-clauses within the agreement document. Modified after Tomlinson and Boulton (2008) Table 5, from COAG (2004).

NWI objective	NWI outcome	NWI actions
23. Full implementation of this Agreement will result in a … system of managing surface and groundwater resources … that optimises economic, social and environmental outcomes by achieving the following:	**The Parties agree that, once initiated, their water access entitlements and planning frameworks will:**	
iii) statutory provision for environmental and other public benefit outcomes, and improved environmental management practices;	25 ii) provide a statutory basis for environmental and other public benefit outcomes in surface and groundwater systems to protect water sources and their dependent ecosystems; 25 iii) be characterised by planning processes in which there is adequate opportunity for productive, environmental and other public benefit considerations to be identified and considered in an open and transparent way; 25 iv) provide for adaptive management of surface and groundwater systems in order to meet productive, environmental and other public benefit outcomes; 25 x) identify and acknowledge surface and groundwater systems of high conservation value, and manage these systems to protect and enhance those values	35. Water that is provided by the States and Territories to meet agreed environmental and other public benefit outcomes as defined within relevant water plans … is to: i) be given statutory recognition and have at least the same degree of security as water access entitlements for consumptive use and be fully accounted for; ii) be defined as the water management arrangements required to meet the outcomes sought, including water provided on a rules basis or held as a water access entitlement; and iii) if held as a water access entitlement, may be made available to be traded … when not required to meet the environmental and other public benefit outcomes sought and provided such trading is not in conflict with those outcomes. 37. Broadly, water planning by States and Territories will provide for: i) secure ecological outcomes by describing the environmental and other public benefit outcomes for water systems and defining the appropriate water management arrangements to achieve those outcomes; and ii) resource security outcomes by determining the shares in the consumptive pool and the rules to allocate water during the life of the plan. 79 i) establish effective and efficient management and institutional arrangements to ensure the achievement of … f) any special requirements needed for the environmental values and water management arrangements necessary to sustain high conservation value rivers, reaches and groundwater areas.

6.4 Summary

- The Resource Management Act (RMA) 1991 provides the primary component of New Zealand's legislative framework for managing freshwater ecosystems, much of which can be applied directly to managing GEs.
- Both the National Policy Statement for Freshwater Management (NPS-FM) and proposed National Environmental Standard on Ecological Flows and Water Levels explicitly reference groundwater or aquifers in an ecosystem health context.
- The NPS-FM provides an overarching structure for managing freshwater resources that recognises the national significance of freshwater and Te Mana o te Wai (the integrated and holistic well-being of a freshwater body).
- The New Zealand Conservation Act 1987 and the New Zealand Biodiversity Strategy require regional councils to ensure that the intrinsic and other values of all biodiversity – including that of "underground aquifers" – are adequately maintained and safeguarded for future generations.
- Treaty settlements are playing a critical role in providing the legislative foundation for a range of new co-governance and co-management institutional arrangements for the governance and management of fresh water and the active implementation of rehabilitation strategies and actions to meet Māori and community aspirations.
- While there are no water conservation orders currently in place for aquifers in New Zealand, Te Waikoropupū Springs near Tākaka – a high-profile spring connected to a groundwater dependent ecosystem that supports significant cultural, social, economic and biodiversity values – are currently the subject of a water conservation order application.
- Only a few regional plans, notably those for the Tasman District and the Wellington Region, explicitly acknowledge groundwater ecosystems.
- Internationally, the European Union and Australia provide the strongest recognition and measures to sustain GEs. Groundwater management in Australia was driven by the National Water Initiative (NWI).

7 Research priorities

Despite the fundamental importance of groundwater to New Zealand, the science underpinning sustainable groundwater management is still very incomplete, in part reflecting the hydro-geological complexity of New Zealand's aquifers (White 2001), but also the difficulty in conducting research in such a difficult to access ecosystem. Similar to many other countries, our groundwaters are mostly managed as physical resources with chemical properties, despite an increasing recognition that aquifers comprise living ecosystems. Our ability to manage GEs is currently limited by this lack of knowledge and appropriate tools. This section outlines current research in New Zealand and future priorities for groundwater research from a GE perspective.

7.1 Current research

Two current research projects on GEs are relevant here:

- **Spatial scales of biodiversity (biofilm bacteria and stygofauna):** This NIWA-led project, involving the University of Waikato and ESR, is partially funded by NIWA and New Zealand's Biological Heritage National Science Challenge. It aims to (a) assess spatial scales of microbial and stygofaunal biodiversity within and between regions, (b) obtain preliminary data on variability of biodiversity with water quality and land use intensity, (c) establish a library of DNA for groundwater species (stygofauna and bacteria) to support future investigations, and (d) develop eDNA approaches for future groundwater ecosystem investigations. The project is due for completion in December 2018.
- **The influence of microbial processes on groundwater quality:** This is a University of Auckland-led MBIE Smart Idea research project that includes ESR. The three-year project commenced in October 2017 and is examining genomic novelty and functional capacity of a typical groundwater ecosystem. The impact of nutrient gradients on GE functioning and microbial diversity will be investigated, as well as the potential for changes in microbial diversity to affect the transport of pathogenic microorganisms.

7.2 Next priorities

We have identified four broad research areas[55], based on outcomes that will assist management of GEs (Figure 7-1):

A. Monitoring to establish baseline data to quantify GE biodiversity, function and health and to quantify impacts of threats to GEs.

B. Quantifying the effects of key threats/stressors on GEs (e.g., nitrate toxicity), particularly determining empirical relationships for limit setting.

C. Developing a preliminary predictive computer model and conceptual framework summarising the current state of understanding of relationships between GE state, functioning, key threats and human values that can be updated as knowledge develops. The

[55] Theme 5 (Integrated ecosystems and processes – fresh water) in the Conservation and Environment Roadmap (MfE & DoC 2017, pp46-47) identifies some research needs that align with what we outline, including *"gaps in our knowledge about the full extent of biota in our freshwater environments (especially aquatic invertebrates)"* and *"the complex relationships between land-use and the quality and quantity of surface and groundwater need further attention".*

model could create testable predictions relating to impacts of environmental conditions or threats on GE functioning and provision of human values.

D. Experiments run in conjunction with the three research areas above to test our understanding of how threats to GEs impact their functioning and support of human values, test tools developed for quantifying GE health, and investigate predictions developed under A-C above.

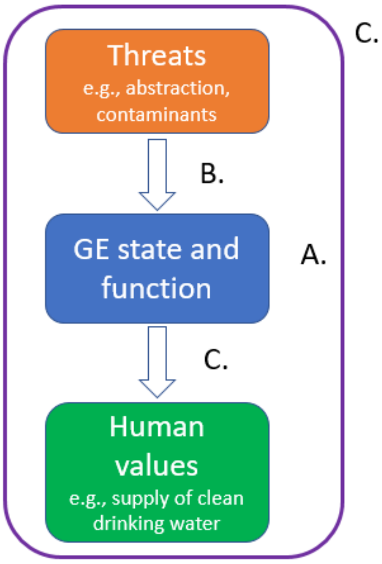

Figure 7-1: Relationship between GE state and functioning, threats and provision of human values with priority areas for research indicated. A = improved quantification and monitoring of GE state, functioning and health. B =development of tools and relationships to improve in limit setting to protect GEs. C = predictive modelling of GE threats, state and functioning on human values, including quantifying linkages between values and GE functioning.

Figure 7-2 provides an outline of the four key research areas and illustrates the relationships between them. Here we discuss only research areas A and B in more detail; these represent the higher priority areas.

7.1.1 A: Quantifying and monitoring groundwater ecosystems

A national survey of GE state and function is the first research priority. Along with GE state and function, hydrological and chemical attributes would be monitored in this survey to collectively provide information for:

- Determining what GE food webs look like,
- Linking GE food webs to key processes such as carbon and nutrient recycling, and services such as contaminant attenuation,
- Quantifying the degree of variability in physico-chemical and ecological conditions between GEs,
- Identifying potential indicators of healthy or impacted GEs,
- Improving knowledge of biodiversity patterns within GEs at local, regional and national scales, and
- Determining if GEs can be classified into management groups based on their hydrological, chemical or ecological properties.

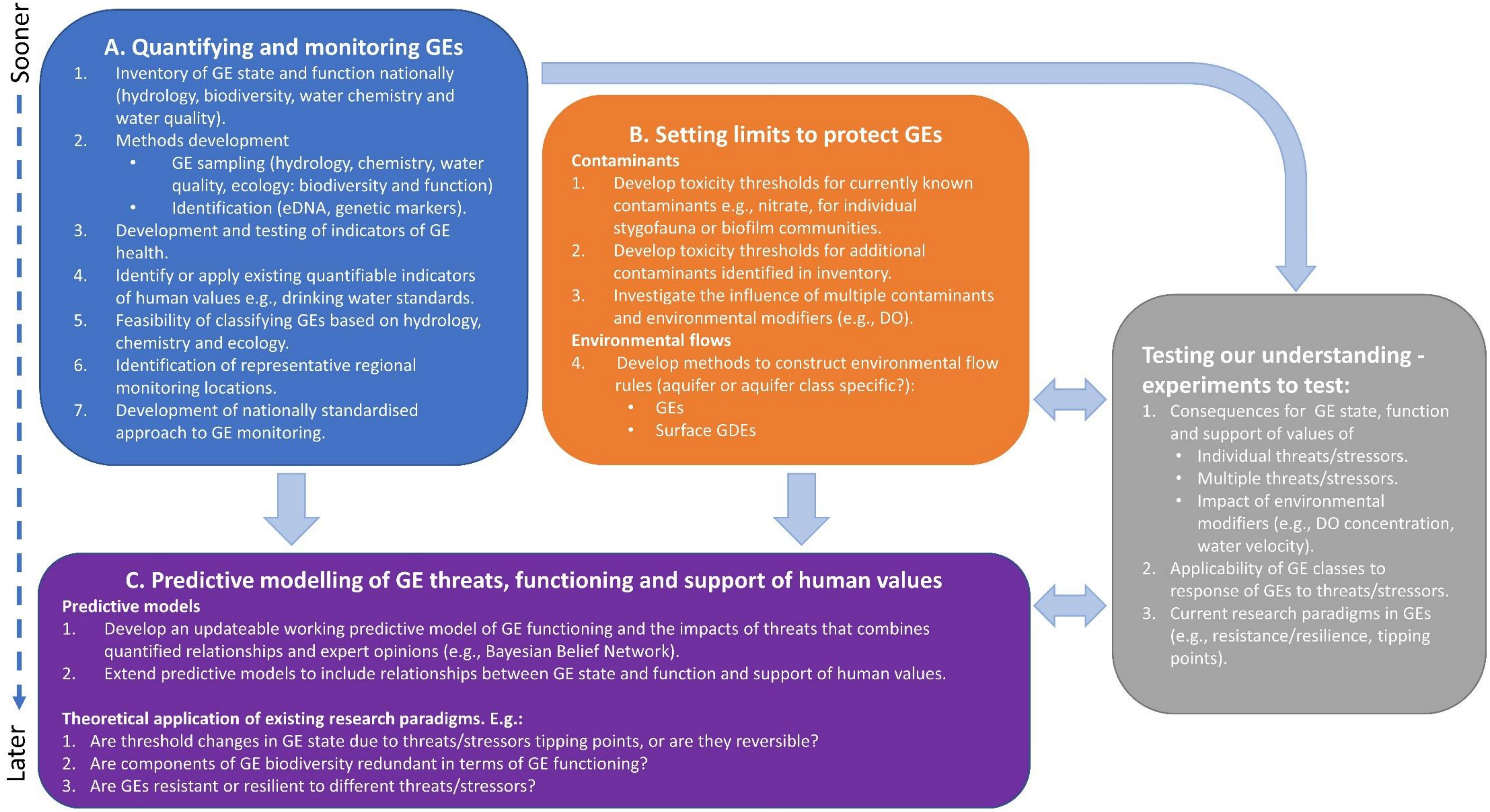

Figure 7-2: Relationships between key research areas. Research areas within each box are prioritised by number (top to bottom), however many numbered priorities will overlap between boxes. See text for additional details.

In conjunction with a one-off national survey, repeated surveys at a subset of sites would assist in quantifying the temporal variability in GE chemistry, water quality and ecology. This information would help inform recommendations as to timing of sample collections. Any survey or monitoring would use methods presently available, including emerging methods (e.g., environmental or e-DNA).

Other priority components of research area A include:

- Developing/standardising methods for GE sampling – ESR has recently completed an Envirolink advice project for Tasman District Council (TDC) that provides some guidance on sampling strategies for assessing the groundwater ecology of specific aquifers in the Tasman District (Weaver et al. 2018).
- Biodiversity identification methods – conventional taxonomic work has been completed for very few New Zealand groundwater stygofauna.[56] Work presently in progress under the NZ Biological Heritage National Science Challenge will deliver some ground work (e.g., exploration of eDNA approaches to microbial and stygofaunal sampling and monitoring).
- Developing and testing of indicators of GE health – for example, individual stygofaunal species or groups that are particularly sensitive to certain stressors, biofilm communities that develop under certain conditions, or measures of ecosystem functioning (e.g., decomposition rates of standard organic materials).
- Identifying types or classes of GEs based on hydrology, chemistry and ecology to assist in monitoring and managing GEs (e.g., in understanding responses to stressors or threats). The results of a national survey of GE state and functioning would provide the data required to develop a classification.
- Identifying representative regional monitoring locations – a classification system for New Zealand GEs, based on biodiversity, ecological, hydrological and chemical attributes, would facilitate developing representative regional and national GE monitoring networks. Regional networks are important because they may monitor more impacted or threatened systems to understand the speed of their responses. In contrast, national monitoring networks can monitor ecosystem health across a greater diversity of GEs to establish a representative national picture.

The ultimate goal from research component A would be the development of a nationally standardised approach (monitoring location selection, sampling methods, analytical methods, results presentation) to monitoring GE health (i.e., hydrology, chemistry, water quality, biodiversity and ecosystem functioning) for direct comparisons of GE state, function and response to threats within and between regions, as well as nationally. Ideally, a national GE health monitoring programme with repeated temporal sampling would be established, similar to GNS Science's National Groundwater Monitoring Programme (NGMP).

7.1.2 B: Setting limits to protect groundwater ecosystems

Research under this component would assist councils with setting guidelines and/or limits for contaminants and environmental flows to protect both GEs and the surface water ecosystems that depend on water from them. Some priority research areas include:

[56] Contemporary microbial methods mean that this type of work is not required for bacteria.

- Developing methods for determining environmental flows (abstraction and recharge rules) for GEs (as well as groundwater dependent surface ecosystems),
- Developing toxicity thresholds for currently known contaminants (e.g., nitrate for individual stygofauna or biofilm communities), and
- Investigating the effects of multiple contaminants and environmental modifiers (e.g., dissolved oxygen).

Understanding the role of biofilms and stygofauna in natural remediation processes (reducing or increasing concentrations and/or distribution) of contaminants is also an important research area. Key questions include:

- To what extent are contaminants removed through nutrient uptake by biofilms?
- Do stygofauna reduce pathogen numbers or transport them through the aquifer?

8 Conclusions

New Zealand's statutory and regulatory context provides the basis for managing groundwaters as functioning ecosystems, historically more by implication, but more explicitly with recent initiatives, notably the NPS-FM 2014. This review, therefore, provides the basis for moving from managing groundwater as a physical resource with some chemical properties, to a more explicit focus on managing groundwater biodiversity and ecosystem functioning to sustain water quality, aquifer porosity and conductivity, and the other important social, cultural and economic values associated with the New Zealand's groundwater resources.

Functionally, GEs resemble engineered systems designed to improve the quality of water for municipal supply or wastewater prior to disposal. However, unlike engineered systems, which require periodic interventions, natural alluvial GEs are self-perpetuating and self-sustaining, due to invertebrates which graze biofilms and disaggregate microbially-bound sediments to maintain the hydraulic conductivity of and water flow through the aquifer matrix.

Critical environmental factors for GEs appear to be organic carbon supply, dissolved oxygen, the hydrological regime and the interaction of these. Other important factors are concentrations of contaminants, notably nitrate, pesticides and herbicides. Agriculture and horticulture, especially where they rely on groundwater, tend to alter all of these factors within the underlying groundwater. Water transfers between catchments, including managed aquifer recharge, can also impact GEs (e.g., changes in stygofaunal densities and community composition), through altering groundwater levels, velocities, pressure gradients and chemistry. The overall paucity of information specific to GEs suggests that a precautionary approach may be required to managing activities with the potential to threaten groundwater ecosystems. This could potentially involve a framework of options for specific aquifers or classes of aquifers that vary depending on factors such as the target GE's current state and functioning (if known), magnitude and type of current and future threats, the types of values it provides, and the degree of hydraulic connectivity to other ground and surface waterbodies.

The major challenge facing regional and unitary councils is determining how to achieve an effective shift in aquifer and groundwater management focus to biodiversity and ecosystems to sustain the diverse values associated with groundwater. This will require a greater understanding of how GEs function, including the biogeochemical processes that occur within GEs, the linkages between these processes and key human values or ecosystem services, and the disruptive impacts of short- and long-term disturbances associated with activities such as groundwater abstraction and contaminant discharges into or onto land.

One small initial step that Horizons and other regional councils could take to promote the need for improved knowledge and management of GEs is to ensure that regional planning documents explicitly recognise that most groundwaters contain ecosystems that have significant values; and that these ecosystems provide important services which underpin human values associated with groundwater.

8.1 Priority research

Management of GEs would be improved with targeted research to:

1. Improve current GE knowledge through a national survey of GE state and function (using currently available methods), including hydrological and water chemistry attributes.

2. Develop standard methods for GE sampling and biodiversity identification.

3. Develop and test indicators to measure and report on GE health.
4. Identify toxicity thresholds of key GE taxa or communities for currently known contaminants, especially nitrate.
5. Investigate the influence of multiple contaminants and environmental modifiers (e.g., dissolved oxygen).
6. Develop methods to construct environmental flows (abstraction and recharge rules) for GEs (and surface water bodies dependent on water from GEs).

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10 Glossary of abbreviations and scientific terminology

Alluvial	Sand, silt, clay, gravel, or other matter deposited by flowing water, as in a riverbed, floodplain, delta, or alluvial fan. Alluvium is generally considered a young deposit in terms of geologic time
Amphipod	Amphipods belong to an order of malacostracan crustaceans with no carapace and generally with laterally compressed bodies. Amphipod range in size from 1 to 340 millimetres are mostly detritivores or scavengers
Aquifer	A body of permeable rock which can contain or transmit groundwater
Aquitard	A bed of low permeability along an aquifer which is a solid, impermeable area underlying or overlying an aquifer
Archaea	Microorganisms which are similar to bacteria in size and simplicity of structure but radically different in molecular organization. They are now believed to constitute an ancient group which is intermediate between the bacteria and eukaryotes
Autotroph/autotrophic	An organism that is able to form nutritional organic substances from simple inorganic substances such as carbon dioxide
Benthic/benthos	Of, relating to, or occurring at the bottom of a body of water/ organisms on the bed of a water body
Biodiversity/biological diversity	The variety of plant and animal life in the world or in a particular habitat
Biofilm	A thin but robust layer of mucilage adhering to a solid surface and containing a community of bacteria and other microorganisms
Bioremediation	The use of either naturally occurring or deliberately introduced microorganisms to consume and break down environmental pollutants, in order to clean a polluted site or waterbody
Bioturbation	The restructuring of sedimentary deposits (as in a lake bottom, aquifer or seabed) by moving organisms (such as worms and crustacea)
CBD	Convention on Biological Diversity
Chemoautotroph	An organism, typically a bacterium, which derives energy from the oxidation of inorganic compounds
Confining layer	See aquatard above
Copepod	A small or microscopic aquatic crustacean of the large class *Copepoda*.
Crustacea	A large group of mainly aquatic arthropods which include crabs, lobsters, shrimps, woodlice, barnacles, and many minute forms. They are very diverse, but most have four or more pairs of limbs and several other appendages
CSFTW	Constructed subsurface-flow treatment wetland
DoC	Department of Conservation
DOC	Dissolved organic carbon
Ecosystem	A biological community of interacting organisms and their physical environment

Ecosystem engineer	Any organism that creates, significantly modifies, maintains or destroys a habitat. These organisms can have a large impact on the species richness and landscape-level heterogeneity of an area
Ecosystem services	Benefits people obtain from ecosystems
Epigean	Living or occurring on or near the surface of the ground or in surface waters
EPS	Extracellular polymeric substances
Groundwater	Water held underground in the soil or in pores and crevices in rock
GDE	Groundwater dependent ecosystem
GWRC	Greater Wellington Regional Council
Hydraulic conductivity	property of soils and rocks that describes the ease with which a fluid (usually water) can move through pore spaces or fractures
Hypogean	Underground; subterranean
Hyporheic/hyporheos	Region beneath and alongside a stream bed, where there is mixing of shallow groundwater and surface water/ fauna occupying this zone
IMP	Iwi Management Plan
Invertebrate	Animal lacking a backbone, such as an arthropod, mollusc, annelid, coelenterate etc
Isopod	Crustacean having seven pairs of legs typically adapted for crawling, and a dorsoventrally flattened body
Karst	A topography formed from the dissolution of soluble rocks such as limestone, dolomite, and gypsum. It is characterized by underground drainage systems with sinkholes and caves
KTKO	Kai Tahu Ki Otago (now Aukaha). https://www.aukaha.co.nz
Lithotroph/lithoautotroph	Organism using inorganic substrate (usually of mineral origin) to obtain reducing equivalents for use in biosynthesis (e.g., carbon dioxide fixation) or energy conservation (i.e., ATP production) via aerobic or anaerobic respiration
MAR	Managed aquifer recharge
Metabolism/ metabolic	The chemical processes that occur within a living organism or community in order to maintain life
Metazoa/metazoan	Major division of the animal kingdom that comprises all animals other than protozoans and sponges. They are multicellular animals with differentiated tissue
mg/L	Milligrams per litre
Microbe/microbial	Organisms that are too small to see with the naked eye. found on every surface and in every habitat around the world, including inside the body. categorized into five major groups: bacteria, viruses, algae, fungi, and protozo

NES	National Environmental Standards. Regulations issued under the Resource Management Act by central government that prescribe technical standards, methods or requirements for environmental matters. Each local or regional council must enforce the same standard, although it can impose stricter standards if the NES explicitly allows for this. They may cover, but are not limited to: contaminants, water quality, level or flow, air and soil quality, noise, and standards, methods or requirements for monitoring. National environmental standards may specify qualitative or quantitative standards, standards for discharges, classification methods, methods and processes to implement standards, as well as exemption and transitional provisions. NESs can apply nation-wide or only to specific areas. Source: (MfE 2008)
NOF	National Objectives Framework
NPS-FM	National Policy Statement for Fresh Water Management
NWI	National Water Initiative (see http://www.agriculture.gov.au/water/policy/nwi)
NZBS	New Zealand Biodiversity Strategy
MBIE	Ministry of Business, Innovation and Employment
OUT	Operational Taxonomic Unit
Piezometric	The surface to which groundwater rises under hydrostatic pressure in wells or springs
Planktonic/plankton	Small and microscopic organisms drifting or floating in the sea or fresh water, consisting chiefly of diatoms, protozoans, small crustaceans, and the eggs and larval stages of larger animal
Protozoa/Protista	single-celled microscopic animals, which include amoebas, flagellates, ciliates, sporozoans, and many other forms
Recharge	deep percolation where water moves downward from surface water to groundwater
Redox potential	A measure of the tendency of a chemical species to acquire electrons and thereby be reduced
RMA	Resource Management Act
GEs	Sub-surface groundwater dependent ecosystems
SIG	Special Interest Group (see http://www.envirolink.govt.nz/assets/Uploads/Reg-SIG-Network-Sructure-Chart-Feb-2018.pdf)
Stygobite/ stygobitic	Obligate or strictly subterranean, aquatic animals and complete their entire life in this environment
Stygofauna	Fauna that live in groundwater systems
Stygophile/stygophilic	Stygofauna species that actively use groundwaters but also use surface waters
Syncarid	Crustacean of the superorder Syncarida – they have no carapace
TDC	Tasman District Council
TEV	Total economic value
Taxon/taxa	A taxonomic group of any rank, such as a species, family, or class.

Vadose zone	Also termed the unsaturated zone, is the area between the land surface and the top of the phreatic zone, the position at which the groundwater (the water in the soil's pores) is at atmospheric pressure ("vadose" is from the Latin for "shallow")
WCO	Water Conservation Order
ZIS	Zone of intermittent saturation. The upper part of the aquifer matrix through which the groundwater surface naturally fluctuates

11 Te Reo Māori used in this report

Aroha	Love, compassion, empathy
Hapū	Is a tribal grouping that consists of whānau who typically share descent from a common ancestor
Hāpua	Coastal lagoon
Ingoa wāhi	Place names
Iwi	Is an extended tribal grouping that consists of hapū or whānau who typically share descent from a common ancestor and associate with a distinct territory
Kaimoana	Seafood
Kaitiaki	Guardian
Kaupapa	Theme, philosophy, topic
Ki Uta Ki Tai (akin to Ma Uta Ki Tai)	From the mountains to the sea. Also see: https://www.mfe.govt.nz/publications/fresh-water/fresh-water-report-2017-introductionto-our-fresh-water/ki-uta-ki-tai-%E2%80%93
Mahinga kai / Mahika kai	(1) Is referred to in the National Policy Statement for Freshwater Management 2014 as indigenous freshwater species that have traditionally been used as food, tools, or other resources (2) To Ngāi Tahu mahinga kai is used to refer to their interests in traditional food and other natural resources and the places where those resources are obtained, i.e., food-gathering place
Mana	Prestige, authority, status
Mana o Te Awa	Seeks respect for: He tupuna awa (ancestral river); whakapapa and unity of the river tribes; the unique relationship of the people with the river; responsibilities of Waikato-Tainui and other river iwi to protect the mana of the river
Mana whakahaere	Refers to the authority iwi have established in respect of the river, over many generations
Manaakitanga	The process of showing respect, generosity and care for others. Ability of hosts to care for their visitors
Manawhenua	Refers to the mana held by local people who have 'demonstrated authority' over land or territory in a particular area demonstrated by possession and occupation of such land or territory over generations
Manaakitanga	The process of showing respect, generosity and care for others
Mātauranga	Knowledge
Mātauranga Māori	Is a holistic perspective encompassing all aspects of knowledge and seeks to understand the relationships between all component parts and their interconnections to gain an understanding of the whole system. It is based on its own principles, frameworks, classification systems, explanations and terminology. Mātauranga Māori is a dynamic and evolving knowledge system and has both qualitative and quantitative aspects
Maunga	Mountain
Mauri	Essential life force or principle, a quality inherent in all things both animate and inanimate
Murihiku	Southland

Papatūānuku	Earth mother
Pepeha	Tribal saying, tribal motto, proverb (especially about a tribe)
Puna	Spring or underground water
Rangatiratanga	Right to exercise authority, self-determination, self-management
Ranginui	Sky father
Rohe	Tribal area, district, region
Rūnanga / Rūnaka	Tribal assembly, council
Takiwā	Area, district, region
Tāne Mahuta	God of all living things
Tangaroa	God of the sea
Tangata whenua	Local people, the iwi or hapū who hold manawhenua over an area
Taonga	An object or natural resource which is highly prized or treasured
Tāwhirimatea	God of the winds
Te Mana o te Wai	Is a concept used in the National Policy Statement for Freshwater Management that encompasses several different aspects of the integrated and holistic health and well-being of a water body. When Te Mana o te Wai is given effect, the water body will sustain the full range of environmental, social, cultural and economic values held by iwi and the community. The concept is expressed in te reo Māori, but applies to freshwater management for and on behalf of the whole community. Also see: https://www.mfe.govt.nz/sites/default/files/media/Te%20Mana%20o%20te%20Wai.pdf
Te Reo	The Māori language
Te Ture Whaimana	The Vision and Strategy for the Waikato River
Te Wai Pounamu	South Island
Tikanga	procedure, custom, habit, lore, method, manner, rule, practice
Tupuna	Ancestor
Wai	Water
Waipuna	Spring
Wairua	Spirit
Wāhi taonga	Areas, places or sites that are treasured and valued
Wāhi tapu	Is defined in the Heritage New Zealand Pouhere Taonga Act 2014 as a place sacred to Māori in the traditional, spiritual, religious, ritual, or mythological sense
Wāhi tupuna	Is defined in the Heritage New Zealand Pouhere Taonga Act 2014 as a place important to Māori for its ancestral significance and associated cultural and traditional value
Waiata	Songs
Whakapapa	Connection, lineage, genealogy between humans and ecosystems and all flora and fauna

Whakataukī	Proverbs
Whānau	Families
Whanaungatanga	Refers to the reciprocal support relationship between members of the same whānau, hapū and iwi
Whenua	Land

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horizons
regional council

11-15 Victoria Avenue
Private Bag 11 025
Manawatu Mail Centre
Palmerston North 4442

T 0508 800 800
F 06 952 2929
help@horizons.govt.nz
www.horizons.govt.nz