From: Graham Fenwick
To: Plan Hearings
Subject: Re: Proposed Plan Change 7 to the Canterbury Land and Water Regional Plan - Webpage Updates
Date: Friday, 17 July 2020 2:19:55 pm
Attachments: Submitter 339 Evidence of Graham Fenwick.docx

Hi Tavisha & team.

Please find attached my evidence for PPC7.

Please let me know if you require anything further from me as part of
this process.

Thank you.

Cheers

Graham.

Graham Fenwick

On 2020-07-16 14:35, Plan Hearings wrote:
> Tena koe
>
> There have been a number of documents added to the website for
> Proposed Plan Change 7 to the Canterbury Land and Water Regional Plan
> [1], additional documents are regularly added to the webpages for the
> Plan Changes.
>
> The following documents have been added under the “Council
> Documents” tab:
>
>   * Memo on Consolidated Officer Recommendations on PC7 10 July 2020
> [2]
>   * Consolidated Officer Recommendations on PC7 10 July 2020 (PDF) [3]
>   * Consolidated Officer Recommendations on PC7 10 July 2020 (word) [4]
>   * Memorandum of Counsel on behalf of Canterbury Regional Council
> regarding the Explanatory Note - Orari FMU Land Use Attributes [5]
>
> The following document has been added under the “Independent Hearing
> Commissioner Documents” tab:
>
>   * Decision 2 of the Hearing Commissioners [6]
>
> The following documents have been added under the “Additional
> information released by Council” tab:
>
>   * GIS information of Officer recommendations to amend the proposed
> PC7 planning maps of ‘Indigenous Freshwater Species Habitat' [7]
>   * Well data used to generate Figures 2-6, 2-8 and 2-9 in the Nitrate
> Management report (Kreleger and Etheridge, 2019) (CCC wells.csv) [8]
>   * Well data used to generate Figures 2-6, 2-8 and 2-9 in the Nitrate
> Management report (Kreleger and Etheridge, 2019)
> (CCC_wells_all_nitrate.csv) [9]
>   * Data referred to in Figure 6-3 of the Waimakariri Land and Water
> Solutions Programme (Etheridge and Hanson, 2019) (SC vs depth inland
> vert grad area.xlsx) [10]
>   * Memo - Data that provides the Environment Canterbury Soil Types
> Layer on Canterbury Maps [11]
>   * Orari FMU Land Use Attributes [12]
>
> Statements of evidence-in-chief are being uploaded under the
> “Submitters Documents” tab and will be uploaded over the course of
> the next week.
>
> Should you have any questions, please do not hesitate to get in touch
> with me.
>
> Nga mihi
>
> Tavisha
>
> PLAN HEARINGS
>
> Environment Canterbury
>   [13]
>
> [14]
> [14]
> planhearings@ecan.govt.nz PO Box 345, Christchurch 8140
> Customer Services: 0800 324 636 [15]
> 24 Hours: 0800 76 55 88 [16]
> ECAN.GOVT.NZ [13]
>
> [17] [18] [19] [20]
>
>   [21]
>
>
>
> Links:
> ------
> [1] https://apc01.safelinks.protection.outlook.com/?url=http%3A%2F%2Fwebmail.orcon.net.nz%2Fecan.govt.nz%2Flwrppc7&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936888745&sdata=1tTYp8K0lqwqk8Slz0EoZA%2FmcbR9pPuHC8C1RmYq6C0%3D&reserved=0
> [2] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.ecan.govt.nz%2Fdocument%2Fdownload%3Furi%3D3903382&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936888745&sdata=H7PghN62HGalctrPgdx7PBvTjOScllAKmUAl%2FD2cq%2F0%3D&reserved=0
> [3] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.ecan.govt.nz%2Fdocument%2Fdownload%3Furi%3D3903379&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=7NvZEDHz0b7JIGIn0Eg59WGaXXouM102dW9rRuOOkXg%3D&reserved=0
> [4] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.ecan.govt.nz%2Fdocument%2Fdownload%3Furi%3D3903370&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=iGmBWUmavcVVJS8eXuCoyhYFkAunUNK4fc%2FojO4gXBs%3D&reserved=0
> [5] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.ecan.govt.nz%2Fdocument%2Fdownload%3Furi%3D3906674&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=eFs3YE8nu897d3gC8WtB%2FBgpKXtxHNuNEwodjZVL4GU%3D&reserved=0
> [6] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fecan.govt.nz%2Fdocument%2Fdownload%3Furi%3D3906641&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=%2Byzm4GuKE2MR9aECtEVIN7GrLOwYwscH06hq9c7psxo%3D&reserved=0
> [7] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fopendata.canterburymaps.govt.nz%2Fsearch%3Fq%3D_amendment&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=a4N9n7CymPgIBc%2Bb%2FOadFN2G1McVZhhSDHy5pQjEdnw%3D&reserved=0
> [8] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.ecan.govt.nz%2Fdocument%2Fdownload%3Furi%3D3904552&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=biP9UoVN32xA5aUZmkj1HfrE0T9TtNGvbyUU44e9Bwc%3D&reserved=0
> [9] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.ecan.govt.nz%2Fdocument%2Fdownload%3Furi%3D3904554&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=h5FhD9BYKHEdo4GBMPBXoom8eXUrP9Go58VOx9Pz28w%3D&reserved=0
> [10] https://apc01.safelinks.protection.outlook.com/?
url=https%3A%2F%2Fwww.ecan.govt.nz%2Fdocument%2Fdownload%3Furi%3D3904558&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=ReUUJOtQG%2BhoJAQRYTs%2FCc%2Bda1BGf%2Bo1pbWSerw8bNA%3D&reserved=0
> [11] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.ecan.govt.nz%2Fdocument%2Fdownload%3Furi%3D3906174&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=NHJZIAORd%2BB9hKxtr7SO%2Fe4D7qCubi7meDC%2FyDxr168%3D&reserved=0
> [12] https://apc01.safelinks.protection.outlook.com/?
url=https%3A%2F%2Fwww.ecan.govt.nz%2Fdocument%2Fdownload%3Furi%3D3906673&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=HH4%2FAnYh8cJVhOn6Mz3ycG3wDmaBGQwyUrOn%2BC78fCM%3D&reserved=0
> [13]
> https://apc01.safelinks.protection.outlook.com/?
url=https%3A%2F%2Fwww.ecan.govt.nz%2F%3Futm_source%3Demail%26amp%3Butm_medium%3Demail%26amp%3Butm_campaign%3Dsignature&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=fy%2FgyxLYFuk8a0H7uxpzFDxe%2FF9SnETNY9yviGrBEvc%3D&reserved=0
> [14] tel:
> [15] tel:0800324636
> [16] tel:0800765588
> [17] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.facebook.com%2FEnvironmentCanterbury%2F&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936898740&sdata=XlVurjDw1SVjihHiaqCZXONmnbdvzL4nxBj%2BbRqs1g0%3D&reserved=0
> [18] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Ftwitter.com%2FECan&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936908737&sdata=ZQ0QS9srgGt%2BhSd3aLuhNfZypvN0QOhoquOCmFX08dE%3D&reserved=0
> [19] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.youtube.com%2Fuser%2FECanGovt&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936908737&sdata=TglSFBwRam4CRpZHXX6fJGkISb8qiplub9uKMx%2Be0KA%3D&reserved=0
> [20] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.instagram.com%2Fenvironment_canterbury%2F&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936908737&sdata=aVUR5CutbLRhf8FJ9s7A9hNtkwbniRK13GfsNOAe9Qo%3D&reserved=0
> [21] https://apc01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fcovid19.govt.nz%2F&data=02%7C01%7C%7Cfeb9a45d217a41457bd308d829f79c51%7C984befeac12e454e91117b8d8da5e7e1%7C0%7C0%7C637305491936908737&sdata=ZHKPBnWz8b07PG9QrlerITvu9TwRdVGS485d%2BPZ4qIc%3D&reserved=0

BEFORE THE PROPOSED NATURAL RESOURCES PLAN HEARINGS PANEL

IN THE MATTER	of the Resource Management Act 1991
AND	
IN THE MATTER	Proposed Plan Change 7 to the Canterbury Land and Water Regional Plan

---

STATEMENT OF EVIDENCE OF GRAHAM DAVID FENWICK

SUBMITTER 339

17 July 2020

TABLE OF CONTENTS

1. INTRODUCTION

1.1 My name is Graham David Fenwick. I am a biologist with over 40 years' experience as a practicing researcher. My academic qualifications are a BSc, MSc and PhD, all in aquatic ecology, and a post-graduate Diploma of Business Administration. I have worked for NIWA as a scientist for 20 years (since 1998), latterly in the role of Assistant Regional Manager, Christchurch, and now mostly retired. I have also worked as a biodiversity scientist involved in environmental investigations for Memorial University of Newfoundland (Canada), the Australian Museum (Sydney), and the University of Canterbury. My specialist areas are aquatic invertebrate biodiversity and the ecology of aquatic sediments.

2. CODE OF CONDUCT

2.1 I have read the Environment Court of New Zealand Practice Note 2014 and have prepared this evidence in accordance with it. My evidence in this statement is within my area of expertise. I have not omitted to consider all material facts known to me that might alter or detract from the opinions which I express. I have qualified my opinions wherever I consider there is uncertainty.

3. SCOPE

3.1 I have provided evidence on the following specific matters:

(a) Technical background on groundwater biodiversity and ecosystems, and

(b) National directives for protecting groundwater ecosystems.

(c) Responses to the Section 42A Officers' Report.

4. TECHNICAL BACKGROUND ON GROUNDWATER

Definition of groundwater

4.1 **Groundwater** is all water that occurs below the ground surface for either brief times or longer durations (Fenwick 2016). Groundwater can occur in the pore spaces between the grains of unconsolidated sediments, such as sand or gravel. Groundwater also occurs in the fractures of consolidated rock. Geological formations (e.g., sedimentary deposits, fractured bedrock, eroded limestone) that hold or transmit groundwater are termed **aquifers**. For the purposes of this evidence, groundwater is all water within an aquifer.

4.2 Groundwater originates from the passage of surface water into aquifers, a process referred to as **recharge**. A significant fraction of groundwater is recharged from rainfall that seeps through soil into aquifers. Another significant fraction of groundwater is recharged from rivers, where river water seeps through the river bed into an underlying aquifer. Groundwater can also be recharged during irrigation or other agricultural or industrial land-use practices.

4.3 Groundwater within the **saturated zone** (part of an aquifer filled with water) flows through small or large spaces (interstices, pores, cracks, cavities, etc., <1 mm to >100 mm) from higher to lower elevations and pressures (i.e., along **hydrostatic gradients**). In some cases, groundwater may be trapped in an aquifer and remain underground indefinitely.

4.4 The process by which water from an aquifer enters or becomes a surface water body is known as groundwater **discharge**. Human extraction of groundwater from aquifers, for example for irrigation or water supply, is also a form of discharge that is often termed **abstraction**.

Groundwater attributes

4.5 Groundwater and surface water are best regarded as dynamically interconnected parts of a single water resource, but interactions between the two vary widely in timing, rate, volume and location, even within small sub-catchments (Hatton & Evans 1998, Winter et al. 1998).

4.6 Groundwater can be dramatically affected by human interventions. For instance, groundwater or surface water abstraction can affect groundwater pressure gradients and alter groundwater flow rates and directions. Also, as in rivers, groundwater velocities decrease when water levels are lowered.

4.7 As water moves over the land surface and through soils and rock, including through an aquifer, it picks up numerous dissolved substances and fine particulate matter, including bacteria and other microscopic organisms. Although there may be some physical filtration and chemical transformations *en route* to and within an aquifer, most of these substances enter the groundwater.

4.8 Thus, land-use activities can markedly change the quantities and types of dissolved and fine particulate matter entering groundwater, and these substances may have important effects on groundwater quality.

4.9 Unlike surface water bodies, there are no photosynthetic plants in aquifers because there is no sunlight for their growth. Most life in aquifers, therefore, depends upon energy from surface environments, mostly imported as **dissolved organic carbon** (**DOC**). In special situations, plant roots may contribute organic carbon directly to groundwater.

4.10 Oxygen is another dissolved substance important for sustaining healthy aquatic ecosystems in many aquifers, as well as strongly influencing biogeochemical processes within an aquifer. It is carried into an aquifer by recharge water. Without photosynthesis and direct mixing with air, there is little or no re-oxygenation of groundwater within an alluvial aquifer. Consequently, dissolved oxygen concentrations tend to decrease with groundwater's time underground and along an aquifer's flow path (Griebler 2001, Helton et al. 2012) (except in limestone (or karst) systems). Deeper aquifers containing older groundwater tend to have little (**hypoxic**) or no (**anoxic**) dissolved oxygen.

Groundwater biodiversity and groundwater-dependent ecosystems

4.11 Most shallow aquifers support significant biodiversity. Bacteria, Fungi and Archaea (microbes) are amongst the most universal forms of life, and inhabit almost all aquatic habitats, including both oxic and anoxic aquifers.

4.12 Aquifers throughout New Zealand, including within the Canterbury Region, contain significant biodiversity. Research shows a high microbial biodiversity (>250 likely species) in New Zealand aquifers (Van Bekkum et al. 2006, Sirisena 2014, Sirisena et al. 2014).

4.13 Bacteria and other microbes in groundwater are mostly closely associated with **biofilms**, thin layers of bacteria and self-produced organic (polymeric) substances (Brunke & Gosner 1997) that coat essentially all surfaces (clay grains to boulders) within an aquifer.

4.14 The composition of these microbial communities appears determined primarily by the availability of dissolved oxygen within the aquifer (Griebler 2001). These different microbial communities profoundly affect groundwater quality by transforming dissolved substances into different chemicals, depending on oxygen availability (Chapelle 2000, Griebler 2001).

4.15 Animal life (unicellular Protozoa and multicellular metazoan invertebrates) also inhabits aquifers world-wide (Griebler & Lueders 2009). Groundwater metazoans, referred to as **stygofauna** (Humphreys 2000), are invertebrates adapted to life underground (i.e., no body pigments, no or reduced eyes, elongated bodies, elongated antennae) (Gibert et al. 1994, Coineau 2000, Gibert 2001). Small body size is another adaptation to subsurface, interstitial life, but some New Zealand stygofaunal macroinvertebrates grow to 20 mm long (Wilson & Fenwick 1999).

4.16 New Zealand's stygofauna is widespread and diverse. Exploratory collecting revealed stygofauna in aquifers throughout the country (Fenwick 2000). More than 50 species are known from one intensively investigated shallow alluvial aquifer (the Selwyn) in Canterbury (Fenwick 2016). Several species are known from the Waimea aquifer near Nelson and the five known collections from the Wellington Region contained four species of stygofaunal amphipods.

4.17 Soon to be published research funded under the New Zealand's Biological Heritage National Science Challenge used genetic techniques to explore the extent and spatial scale of two groups of common stygofauna. Results showed that most species are short-range endemics, restricted to individual aquifers. Large numbers of different stygofaunal invertebrate species new to science were identified in the three Canterbury aquifers investigated (Ashley-Waimakariri, Central Canterbury, Rangitata-Hinds), as well as in aquifers in the other three regions investigated (Southland, Tasman, Hawkes Bay).

4.18 New Zealand's stygofauna comprises genera and species mostly endemic to this country (Scarsbrook et al. 2003). It includes some remarkable, ancient lineages (e.g., Barnard & Barnard 1983) moulded by our land's unique geological history, similar to those of weta, tuatara and kiwi.

4.19 Stygofauna appears restricted to oxygenated (oxic to hypoxic) aquifer habitats. The presence of macroinvertebrate stygofauna in anoxic aquifers in New Zealand is poorly known.

4.20 Groundwater life is rarely seen because these environments are difficult to access and because wells or bores are usually designed to exclude all but water. Because groundwater biodiversity is largely hidden and difficult to access, there is limited understanding of the extent of groundwater biodiversity and its contribution to the ecology of fresh waters (Gibert et al. 1994).

4.21 Despite this very incomplete knowledge, it is now well-established that life in an aquifer comprises a natural, functioning ecosystem, termed a **subsurface groundwater-dependent ecosystem** (**GE**)(DLWC 2002, Serov et al. 2012, Fenwick et al. 2018). GEs are communities of microbes and stygofauna that interact with each other and with their non-living environment, performing natural ecological processes in the absence of light.

Groundwater ecosystem services

4.22 As part of their natural functioning, these GEs modify their environment, providing **ecosystem services** that benefit the wider environment and humans. Biofilms within alluvial aquifers capture and process dissolved and fine particulate organic matter (including bacteria)(DOC), a vital part of natural bioremediation or cleansing that occurs in aquifers (Chapelle 2000, Handley et al. 2013, 2015, Wrighton et al. 2014). These biofilms utilise DOC and other substances, resulting in net losses of carbon from the ecosystem via aerobic respiration (Williamson et al. 2012, Di Lorenzo & Galassi 2013, Wrighton et al. 2014).

4.23 Biofilm bacteria also transform several other substances that would otherwise degrade water quality (e.g., polyaromatic hydrocarbons, such as naphthalene, from coal, tar and incomplete combustion of organic matter (Madsen et al. 1991)). In particular, they also facilitate denitrification, the transformation of nitrate into nitrogen. Bacterial denitrification appears to occur principally at hypoxic to anoxic microsites within aerobic aquifers (e.g., Koba et al. 1997, Gold et al. 1998, Rivett et al. 2008), and can result in significant (mean 50%, range: 29-75%) nitrate attenuation within some aquifers (e.g., Stenger et al. 2013, Elwan et al. 2015).

4.24 The stygofauna delivers additional ecosystem services. Stygofauna ingest biofilm and digest bacteria (Sinton 1984, Fenwick et al. 2004), keeping finer aquifer pore spaces open and water flowing through these pore spaces (Boulton et al. 2008).

4.25 While grazing biofilm and moving within an aquifer, stygofauna mechanically tills or disturbs the aquifer particles, turning them, eating and abrading adhering biofilm, reworking and repositioning finer particles, and probably altering sediment matrices (Fenwick et al. 2004). This process, termed **bioturbation** and widely known in aquatic ecosystems (e.g., Mermillod-Blondin 2004, Wilkinson et al. 2009, Kristensen et al. 2012), is akin to the role of earthworms in healthy soils. In groundwater, bioturbation both stimulates microbial activity, which biogeochemically transforms contaminants, and reduces any clogging, which facilitates water flows (bioirrigation) that replenish dissolved oxygen (bioaeration) (Boulton et al. 2008) and maintain aerobic, oxidising conditions and higher water quality.

4.26 The overall effects of these GE processes, termed **ecosystem services**, include improving groundwater quality and its suitability for human uses, and maintaining an aquifers' ability to conduct water and its yield of water for abstraction. These effects sustain many of the human values associated with groundwater, notably human health and economic values. These effects also contribute to the natural and human values associated with many rivers and streams, which receive smaller to larger contributions from groundwater.

Threats to GEs and groundwater values

4.27 Surface water quality is well-known to affect **aquatic ecosystem health** (**AEH**), with numerous dissolved and suspended substances degrading AEH when beyond critical limits (shortages and over-supplies) (e.g., Hynes 1972, Davies-Colley & Wilcock 2004). This applies equally to groundwater and GE AEH (e.g., Notenboon et al. 1994, Korbel et al. 2013, Korbel & Hose 2015, Espanol et al. 2017).

4.28 As with surface water ecosystems, there is good evidence that human land-use activities frequently affect GE health by changing water quality and/or groundwater hydrology (e.g., Sinton 1984, Boulton et al. 2008, Stein et al. 2010, Hartland et al. 2011, Di Lorenzo & Galassi 2013, Korbel et al. 2013).

4.29 Harmful concentrations of common freshwater pollutants are known for many surface water organisms and habitats, and there are established limits or guideline concentrations for several common contaminants for sustaining the ecological health of surface water ecosystems.

4.30 Such limits have not been determined for GEs because harmful concentrations of common pollutants (e.g., nitrates) are unknown for any stygofauna world-wide and in New Zealand. One study indicated that stygofauna were more sensitive to some pollutants than their surface water equivalents (Mosslacher 2000), but robust evidence is largely lacking.

4.31 Surface water ecosystem health limits, guideline or trigger concentrations (concentrations above which harmful effects are likely, and the converse for other substances, e.g., dissolved oxygen) are based mostly on toxicities of individual substances to readily accessible species, and usually include some species known to be more sensitive than others (e.g., Hickey 2016). They tend to overlook sublethal effects, some of which interfere with natural reproduction and other important physiological or behavioural processes (e.g., Hickey 2016).

4.32 Surface AEH guideline concentrations usually overlook any combined or synergistic effects of contaminants on individual species, although there is some recent information on the effects of some substances in reducing toxicity (e.g., nitrate toxicity is reduced in hard water or when chloride is present) (Hickey 2016).

4.33 Guideline or trigger concentrations based on toxicities for selected species have unknown relationships to ecosystem health. However, a conservative approach dictates that ecosystem health is best assured by maintaining ambient contaminant concentrations well below known toxic concentrations, and below those known to induce sublethal effects on any of its species.

4.34 Nitrate is a key contaminant of aquifers in the Canterbury Region, where high concentrations of nitrate can occur in groundwater over large areas (Hayward & Hansen 2004) and persist for decades (Stewart et al. 2011).

4.35 Although there is no unequivocal evidence that nitrate is harmful to stygofauna and GEs, its widely known toxicity to surface water invertebrates at low concentrations (e.g., Hickey 2013b, MfE 2017) almost certainly means that nitrate is similarly harmful to GE health.

4.36 The physiology of crustaceans, the dominant invertebrates in most GEs, is impaired by nitrate (and its other hypoxic states: nitrite and ammonia) (Alonso & Camargo 2003, 2006, Soucek & Dickinson 2012, Hickey 2013a). Some evidence indicates that crustaceans are more sensitive than other invertebrate groups to nitrate, whereas other evidence suggests the opposite (e.g., Soucek & Dickinson 2012).

4.37 Reduced oxygen concentrations appear to act synergistically with nitrite and with ammonia (NH_3) (nitrate is generally reduced to these substances in low oxygen environments) to affect the physiology crustaceans in acute, six-hour exposure (Broughton et al. in prep.). Thus, low dissolved oxygen concentrations in groundwater probably exacerbate the effect of chronic exposure to nitrite and ammonia on at least some stygofauna.

4.38 This information indicates the need for conservative limits for nitrate (and nitrite) in groundwater, as well as managing groundwater to sustain near-natural dissolved oxygen concentrations.

4.39 Dissolved oxygen is essential for sustaining most stygofauna and aerobic GE health. Its concentrations differ naturally between aquifers, are typically moderate to low in most aquifers, and some groundwaters lack dissolved oxygen (i.e., are anoxic) (Rosen 2001). Concentrations within most shallower aquifers vary seasonally and spatially (e.g., Larned et al. 2015) and generally decrease along an aquifer’s flow-path.

4.40 Because there is very limited re-oxygenation of water within an aquifer (Boulton et al. 2008), changes in groundwater velocity will affect ambient dissolved oxygen concentrations (Hoehn 2001).

4.41 Water level differences or hydrostatic gradients drive velocities of water movement through an aquifer. Thus, reduced groundwater levels, caused by reduced recharge and/or groundwater abstraction, can result in slower replenishment and lower dissolved oxygen (and DOC) concentrations, potentially compromising GE health.

4.42 Most groundwater is naturally low in available food (DOC) (e.g., Coineau 2000, Poulson & Lavoie 2000, Williamson et al. 2012, Larned et al. 2015). Beyond some undefined limits, increased DOC and/or reduced oxygen availability will affect the ability of stygofauna to control biofilm development (Boulton et al. 2008). Uncontrolled growth of biofilm may clog progressively larger pore spaces within an aquifer, reducing water velocities and dissolved oxygen replenishment, at least at finer scales (Baveye et al. 1998, Seifert & Engesgaard 2007, Bottero et al. 2013).

4.43 A shift towards hypoxic and anoxic conditions will change microbial communities (e.g., Cheung et al. 2014), favouring bacteria that use different metabolic pathways and produce different respiratory end-products (i.e., from CO_2 to H_2S) (Chapelle 2000). Such changes may significantly degrade water quality, initially at smaller (<10-100 mm) scales. Conceivably, this process, unchecked, may compromise the health of larger parts of a GE, degrade water quality further and reduce groundwater yield from the aquifer (Boulton et al. 2008, Fenwick 2016, Fenwick et al. 2018).

4.44 Figure 1 illustrates the ecological functioning of GEs and how different land-use activities may affect this functioning and its delivery of ecosystem services.

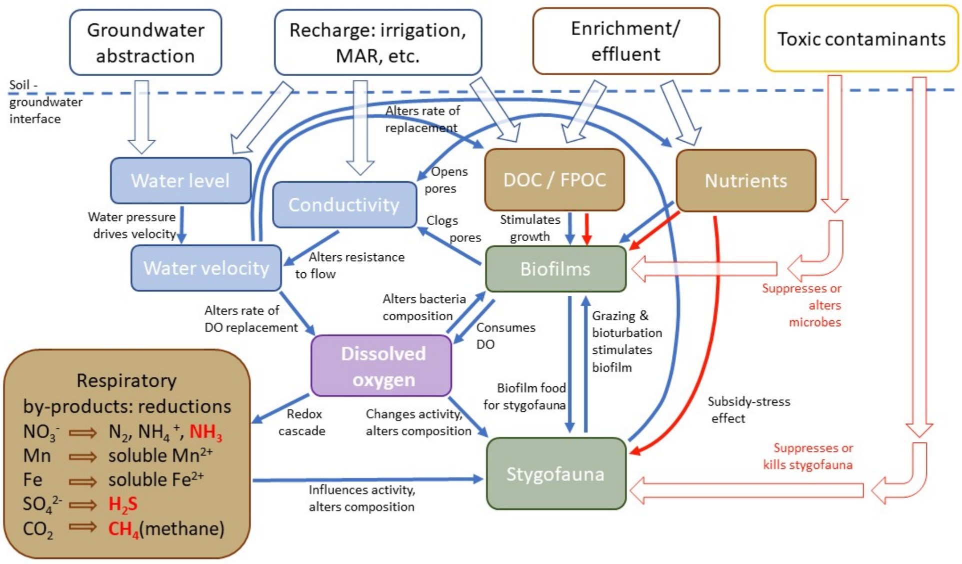

Figure 1. Potential direct and indirect effects of human activities on groundwater ecosystem functioning. Blue boxes, ecohydraulic effects; violet box, dissolved oxygen (DO); brown boxes, dissolved nutrients; green boxes, ecosystem biota. Blue arrows, direct effects; orange arrows, negative effects; paired red-blue arrows indicate potential subsidy-stress effects. Respiratory by-products in red, toxic at low concentrations. From: Fenwick et al. (2018).

5. NATIONAL DIRECTIVES FOR PROTECTING GROUNDWATER BIODIVERSITY AND ECOSYSTEMS

5.1 New Zealand's groundwater biodiversity has a high intrinsic value because of its global uniqueness and it ancient origins (e.g., Barnard & Barnard 1983). Although poorly known, Canterbury's groundwater biodiversity is a significant subset of this globally important groundwater biodiversity.

5.2 Even though the biodiversity within New Zealand's aquifers is poorly known, 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 (DoC 2000: 45).

5.3 The ecosystem services delivered by groundwater biodiversity are integral to sustaining groundwater and surface water resources, cultural identities and economies at local, regional and national levels (e.g., Boulton et al. 2008, Fenwick 2016, Robertson et al. 2017).

5.4 The Resource Management Act 1991 (and amendments) requires regional councils to ensure the sustainability of these ecosystem services (safeguard “the life-supporting capacity of air, water, soil, and ecosystems” by “avoiding, remedying, or mitigating any adverse effects of activities on the environment” to ensure that the needs of future generations are met (NZG 1991: Section 5).

5.5 Currently, there are no national numerical directives (defined concentrations) specifically for managing GEs for aquatic ecosystem health (AEH). However, the Ministry for the Environment’s National Policy Statement for Freshwater Management 2017 (MfE 2017)(and its precursor (MfE 2014) explicitly includes aquifers as “freshwater” (p. 4) and implicitly throughout the NPS-FM as “water”, “fresh water”, “freshwater resources”, “the resource”, “water body”, “waterway”, “freshwater management unit” (MfE 2017: 4, 5, 7-10). The repeated use of “associated ecosystem” (or similar) within Objectives A1, B1, C1 and D1, and their associated policies, is a clear signal that GEs are within the scope of this policy statement, and no less important than surface water bodies. Certainly, there is no exclusion of aquifers, groundwaters or GEs, either explicit or implied.

5.6 The NPS-FM Appendix 1 sets out national values and uses for freshwater, which explicitly includes “aquifer” as one “freshwater body type” (MfE 2017: 26). These compulsory national values for ecosystem health are:

- *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.

6. REGIONAL DIRECTIVES FOR PROTECTING GROUNDWATER BIODIVERSITY AND ECOSYSTEMS

6.1 The Vision Statement for Canterbury's biodiversity strategy states that the "Canterbury community values and cares for the region's biodiversity and accepts the shared responsibility to work together to ensure it is sustained and enhanced, both now and into the future" (ECan 2008: 4). Its stated outcome is that "there is a full range of healthy ecosystems stretching from the mountains to the sea, reflecting the unique and diverse natural character of the Canterbury region" (ECan 2008: 4). No exception is made for aquifers or groundwater biodiversity or GEs.

6.2 Goal 1 of the region's biodiversity strategy ("Protect and maintain the health of all significant habitats and ecosystems", ECan 2008: 5) similarly requires that aquifers and groundwater ecosystems are protected and their ecological health sustained.

6.3 These aspirations and goals are entirely appropriate, yet there is no evidence that they have been considered for groundwater in PPC7. There also is scant evidence that this vision and outcome have been considered for groundwaters within the Canterbury Land and Water Regional Plan generally.

7. CONCLUSIONS

7.1 For these reasons, I consider that groundwater biodiversity and ecosystems in the Canterbury Region require specific consideration and protection in Proposed Plan Change 7, as well as in the Land and Water Regional Plan, as a whole. Groundwater is the region's largest freshwater body, comprises the region's largest freshwater ecosystem. Continuing to manage it without due regard to its rich and largely endemic biodiversity, and to the substantial ecosystem services that it delivers is untenable.

7.2 The changes sought within my submission are a start to redressing this major oversight in management of Canterbury's water.

8. RESPONSES TO OFFICER'S SECTION 42A REPORT

Definitions: 2.9

8.1 Section 2.9: I am comfortable with the Section 42A report's response to my concerns on definitions.

8.2 Section 4, Table 1: I accept that the addition of a table of Freshwater Outcomes for Canterbury Groundwater is beyond the scope of PPC7.

Managed Aquifer Recharge: 4.99-100, 5.191

8.3 Because PPC7 will establish MAR as a discretionary activity within the region, it should seek to protect and sustain groundwater biodiversity and GE function, in order to be consistent with and implement the New Zealand and Canterbury biodiversity strategies.

8.4 **Section 42A Report, 7.56:** The concern is for direct or indirect connections between hydraulically separated aquifers. The analysis notes that "the proposed MAR provisions do not provide for the transfer of groundwater from one aquifer to another" (i.e, direct transfer or direct connection). The matter of indirect connections (i.e., via surface waters) is not addressed.

8.5 Most shallower aquifers in Canterbury are directly connected to adjacent surface streams or rivers. Thus, any diversion of surface water from above one shallow aquifer to a hydraulically separate aquifer will create an indirect connection between the two aquifers. Because most organisms migrate to inhabit all available habitat (many land plants and animals even cross oceans), some stygofauna species from the aquifer beneath the source stream inevitably will migrate along the surface water channel, probably within the bed, to colonise the recipient aquifer.

8.6 For this reason, proposed policy 4.99 should include a further condition, such as that in my submission: "*h. Adverse effects on the biodiversity and/or ecosystem functioning within the recharged aquifer from potentially invasive (exotic or indigenous) species are eliminated*".

8.7 Similarly, the exercise of discretion under proposed Rule 5.191 should include protection of groundwater biodiversity and ecosystems. A condition similar to that suggested in my submission seems entirely appropriate: "*16. Any adverse effects on groundwater biodiversity,* *endemic groundwater biodiversity and/or on groundwater ecosystem functioning*".

8.8 I acknowledge that the science of assessing groundwater biodiversity, groundwater ecosystems and their ecological health is poorly developed (S42A: 7.59). The note that "*there is no plausible direct means to evaluate or quantify the positive or negative 'effects' on groundwater ecosystems relative to the use of MAR*" (7.59) is open to debate. I believe that there are methods available that could be readily tested and adapted by appropriately skilled researchers with modest resourcing (e.g., detailed biological water quality profiling, DNA barcoding, environmental DNA, Groundwater Health Index (Korbel & Hose 2017)). At the least, some expert, desk-top assessment by a qualified (some experience with groundwater biodiversity and/or ecology) biologist/ecologist seems prudent.

8.9 Water quality measurement and monitoring (S42A: 7.60) can assist with assessing potential and actual effects, but, by no means, can it usefully quantify effects on biodiversity or ecosystem functioning (unless there are very large changes in water quality). The usual substances measured in groundwater must be expanded to include dissolved oxygen and dissolved organic carbon, as well as those other substances typically monitored for stream health assessment.

8.10 **Schedule 32.2.b.iv:** Agreed, mapping boundaries between separate aquifers can be deleted.

8.11 **Schedule 32.5:** An explicit requirement to assess the actual and potential effects on biodiversity and ecosystem functioning seems essential under the New Zealand and regional biodiversity strategies, as well as under clauses of the Land and Water Regional Plan (see Section 1.3.3 of PPC7).

9. REFERENCES

Alonso A, Camargo J. 2003. Short-term toxicity of ammonia, nitrite, and nitrate to the aquatic snail *Potamopyrgus antipodarum* (Hydrobiidae, Mollusca). Bulletin of Environmental Contamination and Toxicology 70: 1006-1012.

Alonso A, Camargo JA. 2006. Toxicity of nitrite to three species of freshwater invertebrates. Environmental Toxicology 21: 90-94.

Alonso, Á, Camargo, JA. 2015. Ammonia toxicity to the freshwater planarian Polycelis felina: contrasting effects of continuous versus discontinuous exposures. Archives of Environmental Contamination and Toxicology 68: 689-695.

ANZECC, ARMCANZ. 2000. The Guidelines. Australia and New Zealand guidelines for fresh and marine water quality. http://www.environment.gov.au/system/files/resources/53cda9ea-7ec2-49d4-af29-d1dde09e96ef/files/nwqms-guidelines-4-vol1.pdf

Barnard JL, Barnard CM. 1983. Freshwater Amphipoda of the world. 1. Evolutionary patterns. Hayfield Associates, Mt Vernon, Virginia. 358 pp.

Baveye P, Vandevivere P, Hoyle BL, DeLeo PC, de Lozada DS. 1998. Environmental impact and mechanisms of the biological clogging of saturated soils and aquifer materials. Critical Reviews in Environmental Science and Technology 28: 123-191.

Bottero S, Storck T, Heimovaara TJ, van Loosdrecht MCM, Enzien MV, Picioreanu C. 2013. Biofilm development and the dynamics of preferential flow paths in porous media. Biofouling 29: 1069-1086.

Boulton AJ, Fenwick GD, Hancock PJ, Harvey MS. 2008. Biodiversity, functional roles and ecosystem services of groundwater invertebrates. Invertebrate Systematics (Special Issue) 22: 103-116.

Broughton RJ, Marsden ID, Hill JV, Glover CN. (in prep.). Interactive effects of hypoxia and dissolved nutrients on the physiology and biochemistry of the freshwater crayfish, *Paranephrops zealandicus*. Submitted to Marine and Freshwater Research (November 2017).

Brunke M, Gonser T. 1997. The ecological significance of exchange processes between rivers and groundwater. Freshwater Biology 37: 1-33.

Camargo J, Alonso A, Salamanca A. 2005. Nitrate toxicity to aquatic animals: a review with new data for freshwater invertebrates. Chemosphere 58: 1255–1267.

Canadian Council of Ministers of the Environment (CCME). 2012. Canadian water quality guidelines for the protection of aquatic life: nitrate ion. In: Canadian environmental quality guidelines, Canadian Council of Ministers of the Environment, Winnipeg. 17 pp. http://ceqg-rcqe.ccme.ca/download/en/197

Chapelle FH. 2000. The significance of microbial processes in hydrogeology and geochemistry. Hydrogeology Journal 8(1): 41-46.

Cheung SG, Chan CYS, Po BHK, Li AL, Leung JYS, Qiu TW, Ang PO, Thiyagarajan V, Shin PKS, Chiu JMY. 2014. Effects of hypoxia on biofilms and subsequently larval settlement of benthic invertebrates. Marine Pollution Bulletin 85: 418-424.

Close, M.; Abraham, P.; Webber, J.; Cowey, E.; Humphries, B.; Fenwick, G.; Howard, S.; Huynh, K.; Grace, T.; Dupont, P-Y.; Weaver, L. (2020). Use of sonication for enhanced sampling of attached microbes from groundwater systems. *Groundwater*. doi: 10.1111/gwat.12984

Coineau N. 2000. Adaptations to interstitial groundwater life. P. 189-210. In: Wilkens H, Culver DC, Humphreys, WF (eds), Subterranean ecosystems. Ecosystems of the World 30. Elsevier, Amsterdam. 791 pp.

Daughney CJ, Reeves R. 2003. Definition of hydrochemical facies for New Zealand's groundwaters using data from the National Groundwater Monitoring Programme. Institute of Geological & Nuclear Sciences Science Report 2003/18. 68 pp.

Davies-Colley R, Wilcock B. 2004. Water quality and chemistry in running waters. Pp. 11.1-11.7 In: Harding J, Mosely P, Pearson C, Sorrell, B. (eds), Freshwaters of New Zealand. New Zealand Hydrological Society and New Zealand Limnological Society, Christchurch.

Department of Conservation (DoC). 2000. The New Zealand Biodiversity Strategy. Department of Conservation, Wellington. 144 pp. http://www.doc.govt.nz/Documents/conservation/new-zealand-biodiversity-strategy-2000.pdf

Department of Land and Water Conservation (DLWC). 2002. The NSW State groundwater dependent ecosystems policy, a component policy of the NSW State groundwater policy framework. NSW Government. 40 pp.

Di Lorenzo T, Galassi DMP. 2013. Agricultural impact on Mediterranean alluvial aquifers: do groundwater communities respond? Fundamental and Applied Limnology 182(4): 271-282. 10.1127/1863-9135/2013/0398

ECan. 2008. A Biodiversity Strategy for the Canterbury Region. Environment Canterbury, Christchurch. 92 pp.

Elwan A, Singh R, Horne D, Roygard J, Clothier, B. 2015. Nitrogen attenuation factor: can it tell a story about nutrients in different subsurface environments? In: Currie LD, Burkitt LL (eds), Moving farm systems to improved attenuation. Fertilizer and Lime Research Centre (Massey University) Occasional Publication No. 28 12 pp. http://flrc.massey.ac.nz/publications.html

Español C, Comín FA, Gallardo B, Yao J, Yela JL, Carranza F, Zabaleta A, Ladera J, Martínez-Santos M, Gerino M, Sauvage S, Sánchez-Pérez JM. 2017. Does land use impact on groundwater invertebrate diversity and functionality in floodplains? Ecological Engineering 103: 394-403, http://dx.doi.org/10.1016/j.ecoleng.2016.11.061

Fenwick GD. 2000. Collections of New Zealand groundwater amphipods. NIWA Technical Report: 1-21.

Fenwick GD. 2016. Groundwater ecosystems. Pp. 345-355. In: Jellyman P, Davie TJA, Pearson CP, Harding JS (eds), Advances in New Zealand freshwater science. NZ Hydrological Society Inc. and NZ Limnological Society Inc., Christchurch. 696 pp.

Fenwick, G., Greenwood, M., Williams, E., Milnes, J., Watene-Rawiri, E. 2018. Groundwater ecosystems: functions, values, impacts and management. Prepared for Horizons District Council. NIWA Client Report 2018184CH. 155 pp. http://www.envirolink.govt.nz/assets/Uploads/1838-HZLC143-Groundwater-Ecosystems-Functions-values-impacts-and-management.pdf

Fenwick GD, Thorpe HR, White PA. 2004. Groundwater systems. Pp. 29.1-29.18. In: Harding J, Mosely P, Pearson C, Sorrell B. (eds), Freshwaters of New Zealand. New Zealand Hydrological Society and New Zealand Limnological Society, Christchurch.

Gibert J, Stanford JA, Dole-Olivier MJ, Ward JV. 1994. Basic attributes of groundwater ecosystems and prospects for research. Groundwater Ecology: 7-40.

Gibert J. 2001. Basic attributes of groundwater ecosystems. Pp. 39-52. In: Griebler C, Danielopol DL, Gibert, J, Nachtnebel HP, Notenboom, J (eds), Groundwater ecology: a tool for management of water resources. European Commission, Brussels. 367 pp.

Gold AJ, Jacinthe PA, Groffman PM, Wright WR, Puffer RH. 1998. Patchiness in groundwater nitrate removal in a riparian forest. Journal of Environmental Quality 27:146-155. doi:10.2134/jeq1998.00472425002700010021x

Greenfield S, Milne J, Perrie A, Oliver M, Tidswell S, Crisp P. 2014. Aquatic ecosystem health and contact recreation outcomes in the draft Natural Resources Plan: Technical guidance document. Greater Wellington Regional Council, Report GW/ESCI-T-greenfield14/91. 52 pp. http://www.gw.govt.nz/assets/Plans--Publications/Regional-Plan-Review/Proposed-Plan/Proposed-Natural-Resources-Plan-for-the-Wellington-Region-July-2015.pdf

Griebler C. 2001. Microbial ecology of the subsurface. Pp. 81-108. In: Griebler C, Danielopol DL, Gibert, J, Nachtnebel HP, Notenboom, J, Groundwater ecology: a tool for management of water resources. European Commission, Brussels. 367 pp.

Griebler C, Lueders T. 2009. Microbial biodiversity in groundwater ecosystems. Freshwater Biology 45(4): 649-677.

Handley KM, VerBerkmoes NC, Steefel CI, Williams KH, Sharon I, Miller CS, Frischkorn KR, Chourey K, Thomas BC, Shah MB, Long PE, Hettich RL, Banfield JF. 2013. Biostimulation induces syntrophic interactions that impact C, S and N cycling in a sediment microbial community. ISME J 7: 800–816.

Handley KM, Wrighton KC, Miller CS, Wilkins MJ, Kantor RS, Thomas BC, Williams KH, Gilbert JA, Long PE, Banfield JF. 2015. Disturbed subsurface microbial communities follow equivalent trajectories despite different structural starting points. Environmental Microbiology 17(3): 622–636.

Hartland A, Fenwick GD, Bury S. 2011. Tracing sewage-derived organic matter into a shallow groundwater food-web using stable isotope and fluorescence signatures. Marine and Freshwater Research 62: 119-129.

Hatton TJ, Evans R. 1998. Dependence of ecosystems on groundwater and its significance to Australia. Land and Water Resources Research and Development Corporation Occasional Paper 12/98. 77 pp.

Hayward SA, Hanson CR. 2004. Nitrate contamination of groundwater in the Ashburton-Rakaia plains. Environment Canterbury Report No. R04/9. 45 pp.

Helton AM, Poole GC, Payn RA, Izurieta C, Stanford JA. 2012. Scaling flow path processes to fluvial landscapes: An integrated field and model assessment of temperature and dissolved oxygen dynamics in a river-floodplain-aquifer system. Journal of Geophysical Research: Biogeosciences 117(G00N14): 1-13. doi:10.1029/2012JG002025

Hickey C. 2002. Nitrate guideline values in ANZECC 2000. Memorandum to James Court, Ministry for the Environment, 30 September 2002. 10 pp.

Hickey CW. 2013a. Statement of evidence. Before the Board of Inquiry, in the matter of the Tukituki Catchment proposal. 40 pp.

Hickey CW. 2013b. Updating nitrate toxicity effects on freshwater aquatic species. NIWA Report No. HAM2013-009. Prepared for the Ministry of Business, Innovation and Employment. 39 pp.

Hickey CW. 2016. Guidelines for the protection of aquatic ecosystems, toxicant trigger values: nitrate – freshwater. Australian and New Zealand guidelines for fresh and marine water quality. Draft August 2016. Council of Australian Governments Standing Council on Environment and Water, Canberra, ACT, Australia. 26 pp.

Hickey C, Martin ML. 2009. A review of nitrate toxicity to freshwater aquatic species. Environment Canterbury Technical Report No. R09/57. 46 pp. ISBN 978-1-86937-997-1.

Hoehn E. 2001. Exchange processes between rivers and ground waters – the hydrological and geochemical approach. Pp. 55-68. In: Griebler C, Danielopol DL, Gibert J, Nachtnebel HP, Notenboom J, Groundwater ecology: a tool for management of water resources. European Commission, Brussels. 367 pp.

Humphreys W. 2000. Background and glossary. Pp. 3-14. In: Wilkens H, Culver DC, Humphreys, WF (eds), Subterranean ecosystems. Ecosystems of the World 30. Elsevier, Amsterdam. 791 pp.

Hynes HBN. 1972. The ecology of running waters. Liverpool University Press, Liverpool. 555 pp.

Keenan L, Thompson M, Mzila D. 2012. Freshwater allocation and availability in the Wellington region: State and trends. Greater Wellington Regional Council Publication No. GW/EMI-T-12/141. 117 pp. http://www.gw.govt.nz/assets/Our-Environment/Environmental-monitoring/Environmental-Reporting/Freshwater-Allocation-and-Availability-SoE-report.pdf

Koba K, Tokuchi N, Wada E, Nakajima T, Iwatsubo G, 1997. Intermittent denitrification: the application of a 15N natural abundance method to a forested ecosystem, Geochimica et Cosmochimica Acta 61(23): 5043-5050, https://doi.org/10.1016/S0016-7037(97)00284-6.

Kincheloe JW, Wedemeyer GA, Koch DL. 1979. Tolerance of developing salmonid eggs and fry to nitrate exposure. Bulletin of Environmental Contamination and Toxicology 32(1): 575-578.

Korbel KL, Hancock PJ, Serov P, Lim RP, Hose GC. 2013. Groundwater ecosystems vary with land use across a mixed agricultural landscape. Journal of Environmental Quality 42(2): 380-390.

Korbel KL, Hose GC. 2015. Habitat, water quality, seasonality, or site? Identifying environmental correlates of the distribution of groundwater biota. Freshwater Science 34(1): 329-343.

Korbel KL, Hose GC. 2017. The weighted groundwater health index: Improving the monitoring and management of groundwater resources. Ecological Indicators 75:164-181.

Kristensen E, Penha-Lopes G, Delefosse M, Valdemarsen T, Quintana CO, Banta GT. 2012. What is bioturbation? The need for a precise definition for fauna in aquatic sciences. Marine Ecololgy Progress Series 446: 285-302. https://doi.org/10.3354/meps09506

Larned ST, Unwin MJ, Boustead NC. 2015. Ecological dynamics in the riverine aquifers of a gaining and losing river. Freshwater Science 34(1): 1-19.

Madsen E, Sinclair J, Ghiorse W. 1991. In situ biodegradation: microbiological patterns in a contaminated aquifer. Science, 252(5007): 830-833. doi:10.1126/science.2028258

Mermillod-Blondin F, Gaudet JP, Gerino M, Desrosiers G, Jose J, Châtelliers MCd. 2004. Relative influence of bioturbation and predation on organic matter processing in river sediments: a microcosm experiment. Freshwater Biology, 49: 895–912. doi:10.1111/j.1365-2427.2004.01233.x

Ministry for the Environment (MfE). 2014. National Policy Statement for Freshwater Management 2014. Wellington. Ministry for the Environment. http://www.mfe.govt.nz/publications/fresh-water/national-policy-statement-freshwater-management-2014.

Ministry for the Environment (MfE). 2017. National Policy Statement for Freshwater Management 2014. Wellington. Ministry for the Environment. http://www.mfe.govt.nz/sites/default/files/media/Fresh%20water/npsfreshwater-ameneded-2017_0.pdf

Ministry of Health (MOH). 2008. Drinking water standards for New Zealand 2005, revised 2008. Wellington. Ministry of Health. https://www.health.govt.nz/system/files/documents/publications/drinking-water-standards-2008-jun14.pdf.

Mösslacher F. 2000. Sensitivity of groundwater and surface water crustaceans to chemical pollutants and hypoxia: implications for pollution management. Archiv fur Hydrobiologie 149: 51-66.

New Zealand Government (NZG). 1991. Resource Management Act 1991 (reprint as at 18 October 2017). Parliamentary Counsel Office. http://www.legislation.govt.nz/act/public/1991/0069/latest/DLM230265.html

Notenboom J, Plenet S, Turquin M-J. 1994. Groundwater contamination and its impact on groundwater animals and ecosystems. Pp. 477-504. In: Gibert J, Danielopol D, Stanford JA (eds), Groundwater ecology. Academic Press, San Diego.

Poulson TL, Lavoie KH. 2000. The trophic basis if subsurface ecosystems. Pp. 231-249. In: Wilkens H, Culver DC, Humphreys, WF (eds), Subterranean ecosystems. Ecosystems of the World 30. Elsevier, Amsterdam. 791 pp.

Rivett MO, Buss SR, Morgan P, Smith JWN, Bemment CD. 2008. Nitrate attenuation in groundwater: a review of biogeochemical controlling processes. Water Research 42: 4215–4232.

Robertson AL, Griebler C, Malard F, Galassi D, Hose GC. 2017. Report on groundwater ecology. Summary report of the special session at the WFD CIS Groundwater Working Group meeting, Malta, 25-26 April 2017. 15 pp. https://circabc.europa.eu/w/browse/05171857-09cb-4e34-a9c5-3d98e3fd0a86

Rosen MR. 2001. Hydrochemistry of New Zealand's aquifers. Pp. 77-110. In: Rosen MR, White PA (eds), Groundwaters of New Zealand. New Zealand Hydrological Society, Wellington, New Zealand.

Scarsbrook MR, Fenwick GD, Duggan IC, Haase M. 2003. A guide to the groundwater fauna of New Zealand. NIWA Science & Technology Series 51. 59 pp.

Seifert D, Engesgaard P. 2007. Use of tracer tests to investigate changes in flow and transport properties due to bioclogging of porous media. Journal of Contaminant Hydrology 93: 58-71.

Serov P, Kuginis L, Williams JP. 2012. Risk assessment guidelines for groundwater dependent ecosystems, Volume 1 – the conceptual framework. Office of Water, NSW Department of Primary Industries, NSW Government: 48 pp. + App. 1-6.

Sinton LW. 1984. The macroinvertebrates in a sewage-polluted aquifer. Hydrobiologia 119(3): 161-169. 10.1007/BF00015207

Sirisena KA. 2014. Molecular characterization of bacterial diversity in New Zealand groundwater. PhD thesis, Victoria University of Wellington.

Sirisena KA, Daughney C, Moreau M, Ryan KG, Chambers GK. 2014. Relationships between molecular bacterial diversity and chemistry of groundwater in the Wairarapa Valley, New Zealand. New Zealand Journal of Marine and Freshwater Research 48: 524-539.

Soucek DJ, Dickinson A. 2012. Acute toxicity of nitrate and nitrite to sensitive freshwater insects, mollusks, and a crustacean. Archives of Environmental Contamination and Toxicology 62: 233-242.

Stenger R, Clague J, Woodward S, Moorhead B, Wilson S, Shokri A, Wöhling T, Canard H. 2013. Denitrification - the key component of a groundwater system's assimilative capacity for nitrate. Unpublished ms, 1-11 pp. https://www.massey.ac.nz/~flrc/workshops/13/Manuscripts/Paper_Stenger_2013.pdf

Stein H., Kellermann C, Schmidt SI, Brielmann H, Steube C, Berkhoff SE, Fuchs A, Hahn HJ, Thulin B, Griebler C. 2010. The potential use of fauna and bacteria as ecological indicators for the assessment of groundwater quality. Journal of Environmental Monitoring 12(1): 242-254.

Stewart, MK, Stevens, G, Thomas, JT, van der Raaij R, Trompetter V. 2011. Nitrate sources and residence times of groundwater in the Waimea Plains, Nelson. Journal of Hydrology (New Zealand) 50: 313-338.

Tidswell S, Conwell C, Milne JR. 2012. Groundwater quality in the Wellington Region: state and trends. Greater Wellington Regional Council, GW/EMI-T-12/140: 1-122. http://www.gw.govt.nz/assets/Our-Environment/Environmental-monitoring/Environmental-Reporting/Groundwater-Quality-SoE-report.pdf

Tomlinson M, Boulton AJ. 2010. Ecology and management of subsurface groundwater dependent ecosystems in Australia - a review. Marine and Freshwater Research 61(8): 936-949. doi 10.1071/mf09267

Van Bekkum M, Sainsbury JP, Daughney CJ, Chambers GK. 2006. Molecular analysis of bacterial communities in groundwaters from selected wells in the Hutt Valley and the Wairarapa, New Zealand. New Zealand Journal of Marine and Freshwater Research 40(1): 91-106. 10.1080/00288330.2006.9517405

Wellington Water. 2017: Waterloo wellfield water quality contamination investigations Part 1. Report to Wellington Regional Council. 52 pp. https://www.google.co.nz/search?source=hp&ei=dMgcWvvgPIeA8gXmpbGoAQ&q=Waterloo+Wellfield+Water+Quality+Contamination+Investigations+PART+1&oq=Waterloo+Wellfield+Water+Quality+Contamination+Investigations+PART+1&gs_l=psy-ab.3...1439.1439.0.1864.1.1.0.0.0.0.206.206.2-1.1.0....0...1c.1.64.psy-ab..0.0.0....0.mSoQEdW7BvM#

Wilkinson MT, Richards PJ, Humphreys GS. 2009. Breaking ground: pedological, geological, and ecological implications of soil bioturbation.

Earth-Science Reviews 97(1): 257-272. http://dx.doi.org/10.1016

Williamson WM, Close ME, Leonard MM, Webber JB, Lin S. 2012. Groundwater biofilm dynamics grown in situ along a nutrient gradient. Ground Water 50(5): 690-703. 10.1111/j.1745-6584.2011.00904.x

Wilson GDF, Fenwick GD. 1999. Taxonomy and ecology of Phreatoicus typicus Chilton, 1883 (Crustacea, Isopoda, Phreatoicidae). Journal of the Royal Society of New Zealand 29(1): 41-64.

Winter TC, Harvey JW, Franke OL, Alley WM. 1998. Ground water and surface water: a single resource. U.S. Geological Survey Circular 1139. 79 pp.

Wrighton KC, Castelle CJ., Wilkins MJ, Hug LA, Sharon I, Thomas BC, … Banfield J F. 2014. Metabolic interdependencies between phylogenetically novel fermenters and respiratory organisms in an unconfined aquifer. ISME Journal 8(7): 1452-1463. doi:10.1038/ismej.2013.249

Young RG, Fenwick GD, Fenemor A, Moreau M, Thomas J, McBride G, Stark J, Hickey C, Newton M. 2017. Ecosystem health of Te Waikoropupū. Cawthron Report No. 2949. 61 pp. http://www.tasman.govt.nz/environment/water/water-resource-management/water-catchment-management/water-management-partnerships-flags/takaka-fresh-water-and-land-advisory-group/flag-outputs-and-supporting-information/key-science-resources-takaka-flag/