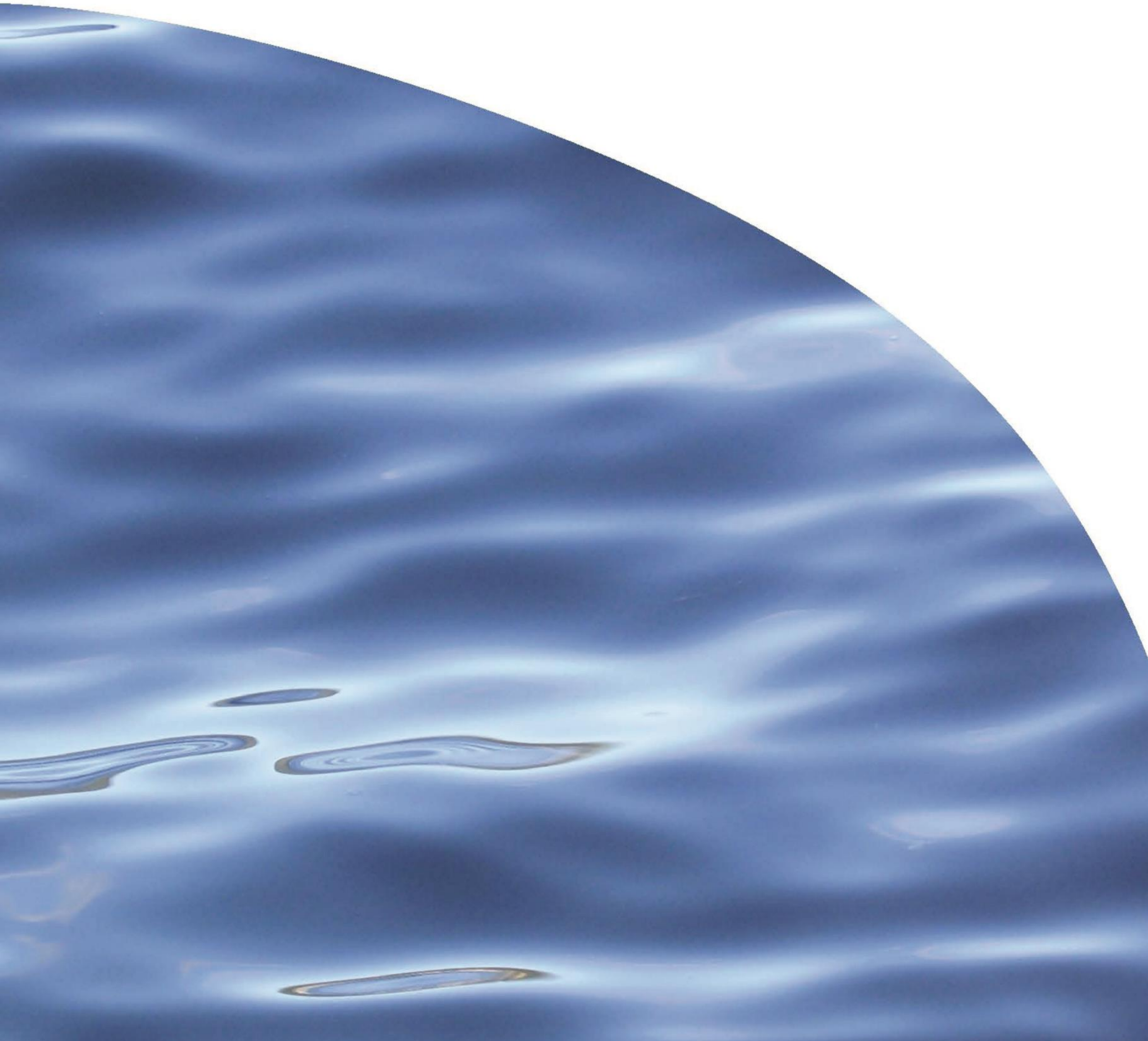
REPORT NO. 2949

ECOSYSTEM HEALTH OF TE WAIKOROPUPŪ



ECOSYSTEM HEALTH OF TE WAIKOROPUPŪ

ROGER YOUNG[1], GRAHAM FENWICK[2], ANDREW FENEMOR[3], MAGALI MOREAU[4], JOSEPH THOMAS[5], GRAHAM MCBRIDE[2], JOHN STARK[6], CHRIS HICKEY[2], MARK NEWTON[1]

1. CAWTHRON INSTITUTE
2. NATIONAL INSTITUTE OF WATER AND ATMOSPHERIC RESEARCH (NIWA)
3. LANDCARE RESEARCH
4. GNS SCIENCE
5. TASMAN DISTRICT COUNCIL
6. STARK ENVIRONMENTAL LTD

Prepared to support decision making by the Takaka Freshwater Land Advisory Group

CAWTHRON INSTITUTE
98 Halifax Street East, Nelson 7010 | Private Bag 2, Nelson 7042 | New Zealand
Ph. +64 3 548 2319 | Fax. +64 3 546 9464
www.cawthron.org.nz

Reviewed by:
Joanne Clapcott

Released by:
Chris Cornelisen

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EXECUTIVE SUMMARY

The freshwater springs at Te Waikoropupū are part of a wider system comprising much of the Takaka River catchment including the surface waters, the underlying aquifer and coastal waters in Golden Bay. The springs are New Zealand's largest and the spring water is among the clearest in the world.

The Tasman District Council (TDC) set up the Takaka Freshwater and Land Advisory Group (FLAG) to seek greater involvement from the community and stakeholders in developing the water quantity and quality management provisions for water resources in the eastern part of Golden Bay. The FLAG and TDC recognised a need to have more information relating to Te Waikoropupū to assist the FLAG in developing its recommendations. A panel of relevant scientists from throughout New Zealand was selected and asked to address a set of specific objectives. The objectives were to:

1. summarise the existing physicochemical and biological data time series for Te Waikoropupū and connected water bodies to improve understanding of the current state of the springs and changes over the last 10-20 years,
2. assess ecosystem health of the springs and highlight the major anthropogenic risks to spring health based on results of (1) and expert knowledge, and
3. provide recommendations on relevant attributes (and bands) that can be used in objective-setting.

The panel held a workshop and brought together some data relevant to these objectives. Further data collection, collation and analyses have subsequently been conducted. This report provides a summary of the outcomes of the workshop and subsequent work.

A wide range of water quality and biological data has been collected from Te Waikoropupū since 1970. It is important to recognise that Te Waikoropupū incorporates at least 3 linked groundwater-dependent ecosystems: the aquifers, the spring basin and the downstream riverine ecosystem. The majority of the data has been collected from within the spring basin itself. Some data collected close to the Main Spring vents reflect water quality within the aquifer. Data collected in the Springs River downstream are also potentially relevant, although the relationships between health of the aquifer, the spring basin and the downstream riverine ecosystems are complex.

Over the full length of the data record (1970–2017) there has been an increase in the concentration of nitrate nitrogen by about 0.1 mg NO_3-N/L. However, concentrations of nitrate nitrogen have decreased over the last 3-4 years. The median concentration over the last 10 years is 0.41 mg NO_3-N/L.

Water clarity is extremely high in Te Waikoropupū, but has only been measured directly once at the Main Spring (63 m underwater visibility on 11 February 1993). Water clarity in the Springs River upstream of the salmon farm (but downstream of the confluence with Fish

Creek) has been measured more frequently and data indicate a decline in clarity at that site. However, it is not known if water clarity at the Main Spring has declined over the same period because clarity downstream in the Springs River is affected by a variety of factors independent of the Main Spring. There are significant logistical and technical issues with precisely measuring the clarity of such clear water in the spring basin. Trials are currently underway to determine if there is a suitable approach to clarity measurement for regular monitoring in the future.

Dissolved oxygen levels within Te Waikoropupū are relatively low and reflect the groundwater-dependent nature of this system. There was a small decrease in DO concentrations between spot measurements at the Main Spring vents in the early 1970s (range 58-64% saturation) compared with continuous data collected near the Main Spring vent in April/May 2016 (range 50–53% saturation), although the difference is only slightly larger than typical DO measurement uncertainty (test variability).

Spot measurements in the spring basin indicate a small increase in pH over the sampling period. There is no evidence for any long-term changes in dissolved reactive phosphorus concentrations or water temperature within Te Waikoropupū.

Macroinvertebrate community data collected in the Springs River downstream of the spring basin (but upstream of the salmon farm) suggest that the health of the upper reaches of the Springs River has not changed noticeably from 1986 to 2015.

Data are limited on faecal indicator bacteria concentrations, but indicate that faecal indicator bacteria are absent or at very low concentrations in aquifer water and levels meet drinking water guidelines. Concentrations are slightly higher further downstream (e.g. in Springs River), but are still well below contact recreation guidelines.

There are records of four introduced aquatic plants within Te Waikoropupū. Their presence is not ideal, but fortunately none of these plants is strongly invasive, so they are likely to have had minimal effects on the Te Waikoropupū aquatic ecosystem.

After considering the available data and the potential threats to the health of Te Waikoropupū, the science panel considered that water clarity, DO, and the concentrations of nitrate nitrogen and dissolved reactive phosphorus were critical water quality parameters for ongoing monitoring and for managing Te Waikoropupū's values. Maintenance of flows through the system is also considered very important. Information on invertebrates, macrophyte cover, conductivity, pH, temperature and the concentrations of manganese, dissolved organic carbon, ammoniacal nitrogen, chloride and iron will also be important for guiding management.

In keeping with the philosophy of the National Policy Statement for Freshwater Management (2014) to maintain and improve the overall quality of freshwaters, the FLAG is considering a wide range of quantity and quality management provisions that will apply straight away to help maintain the values identified for Te Waikoropupū. The science panel has recommended triggers to initiate further action relating to the four critical water parameters mentioned above. The goal behind these recommended triggers is to maintain Te Waikoropupū in its current state. Recommendations from the science panel on water quality triggers to initiate further management action are:

- water clarity[1]—50 m
- dissolved oxygen—45-50% saturation
- nitrate nitrogen—0.40-0.50 mg/L
- dissolved reactive phosphorus—0.006-0.010 mg/L.

We recommend that an annual median of monthly samples is the appropriate statistic to compare with these triggers. An important point to consider in relation to these recommended triggers is the identification of further actions that should take place if they are exceeded. Further monitoring to identify mechanisms and potential solutions for the trigger breach will be part of the likely actions required, but the science panel emphasises that this is not the only action that should be implemented. Depending on the parameter of interest, potential actions could include controls on stock access to waterways, improvements to wastewater management, additional riparian restoration efforts, further controls on the operation of the Cobb Power Scheme, further controls on water abstraction and further investment in best management practices on farms within the catchment—especially in identified aquifer recharge areas connected to Te Waikoropupū and adjacent properties with potential runoff pathways towards Te Waikoropupū.

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[1] This should be considered as an interim trigger to potentially be revised if regular clarity monitoring is possible, since short-term variability in clarity, although expected to be low, is currently unknown.

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GLOSSARY

Most definitions are from Land Air Water Aotearoa: https://www.lawa.org.nz/

Term	Definition
Adsorbed	When molecules of a dissolved substance have adhered to the surface of a solid.
Anoxic	Depleted of oxygen.
Aquifer	A geological layer of sand, gravel, or fractured rock that contains groundwater. Confined aquifers are underneath impermeable layers of silt or clay (also called aquitards) so they don't receive water and pollutants from land directly overlying them.
Black disc	Black disc is a kind of water clarity observation that measures how far away a black target ("black disc") can be seen horizontally through the water. The further away the disc can be seen, the clearer the water.
Chlorophyll-*a*	Chlorophyll-*a* is a green pigment in plants that is used for photosynthesis and is a good indicator of the total quantity of algae present
Conductivity	An indirect measure of charged particles (electrolytes) in water. For example, salt water has high, and freshwater low, conductivity.
Dissolved oxygen (DO)	The oxygen content of water. Dissolved oxygen is important for fish and other aquatic life to breathe.
Dissolved reactive phosphorus	The dissolved phosphorus compounds that are available for use by plants and algae.
Faecal indicator bacteria	Bacteria such as *E. coli* that can be measured to estimate the amount of faecal contamination in water.
Geohydrological	Relating to the distribution and movement of groundwater in soil and rocks.
Macroinvertebrates	Any organisms without a backbone or internal skeleton large enough to be visible to the naked eye, such as insects, worms, and snails.
MCI	MCI stands for Macroinvertebrate Community Index which is an index where macroinvertebrates are used for monitoring and reporting on stream health in New Zealand. The MCI assigns a score to each species or taxon (from 1 to 10), based on its tolerance or sensitivity to organic pollution, and then calculates the average score of all taxa present at a site.
Macrophytes	Large water plants and algae that live in freshwater and are visible to the naked eye, as opposed to the microscopic periphyton and phytoplankton. Macrophytes can be either submerged, floating or emergent.
Median	The midpoint of a series of observed values, such that a new value has an equal chance of being above or below it. An average may be skewed high or low in the series depending on extreme values.
mg/L	Milligrams per litre.
Nitrate nitrogen	A highly soluble compound of nitrogen and oxygen with the chemical formula NO_3-N
Ammoniacal nitrogen	Covers two forms of nitrogen: ammonia and ammonium. Animal waste (particularly from humans and farmed animals such as sheep and cows) is the major source of ammoniacal nitrogen in New Zealand waterways.
Periphyton	The mix of algae, fungi, and bacteria that grow on the beds of our rivers, lakes and streams.
Physicochemical	Relating to both physical and chemical properties. Water is a liquid (physical), and is a solvent carrying dissolved substances (chemical).
Transmissometer	An instrument for measuring light transmission by using a source and detector.
Venturi effect	A reduction in fluid pressure after passing through a narrow passage that can result in turbulence and mixing

1. INTRODUCTION

Te Waikoropupū is a wāhi tapu (sacred place) of great significance to tangata whenua. It is also treasured by the wider Golden Bay community and is a popular tourist attraction. The freshwater springs at Te Waikoropupū are part of a larger system comprising much of the entire Takaka River catchment and connected with surface waters up-valley from the Waingaro River, the underlying aquifer and coastal waters in Golden Bay (Figures 1, 2, 3 and 4). The springs are New Zealand's largest (mean flow from the Main Spring of 10 m^3/s; Thomas & Harvey 2013) and the spring water is among the clearest water in the world (Davies-Colley & Smith 1995). The springs issue at an elevation of 50 m above sea level from the confined, karstic Arthur Marble Aquifer. The underlying aquifer is very large (total volume 3.4 km^3 and at least 500 m thick in places). Recharge of the aquifer is through rainfall in the areas where the marble is outcropping, and from flow loss from the upper Takaka River, parts of the Waingaro River, and creeks draining into the upper Takaka Valley and a small input from seawater (0.5%; Stewart & Thomas 2008). A mean residence time of eight years was calculated based on tritium and CFC-11 measurements (Stewart & Thomas 2008). Spring water includes a mix of young water contributed through the river losses and valley rainfall and older karstic waters (Stewart & Thomas 2008).

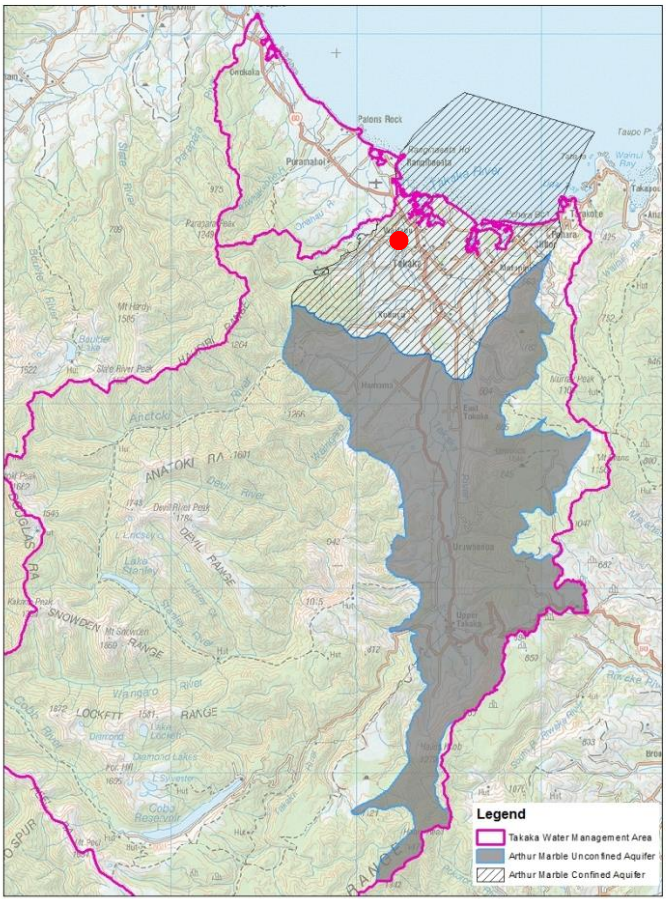

Figure 1. Map of the Takaka Valley showing the location of Te Waikoropupū (●) and the contributing aquifer within the catchment boundaries (source: Tasman District Council).

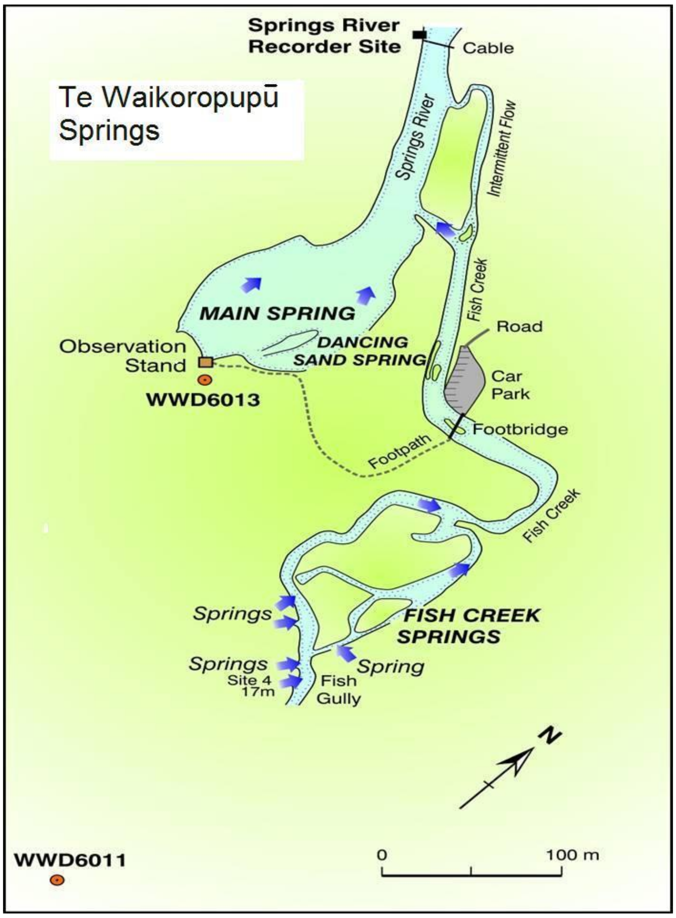

Figure 2. Schematic map showing the location and connections between different parts of the Te Waikoropupū Springs. Source: Tasman District Council.

Tasman District Council (TDC) is the regulatory authority in Golden Bay responsible for managing land and water. The government is encouraging a move toward more collaborative decision making on water management through the National Policy Statement for Freshwater Management (2014) (NPSFM). Following this lead, TDC has set up the Takaka Freshwater and Land Advisory Group (FLAG) to seek greater involvement from community, stakeholders and iwi in developing the water quantity and quality management provisions for water resources in the eastern part of Golden Bay. This area includes the Takaka River and its tributaries, ground waters and adjacent coastal streams. Ultimately, the group will prepare and recommend draft planning provisions to TDC.

Given the importance of Te Waikoropupū to all parties, the FLAG and TDC recognised a need for more scientific information relating to Te Waikoropupū to assist the group in developing its recommendations. Previous reports (Fenwick 2015; Stark 2015a) only considered certain aspects, or reviewed only a subset of the available information. With financial support of DairyNZ, a panel of relevant scientists from throughout New Zealand was selected and asked to address a set of specific objectives. The objectives were to:

1. summarise the existing physicochemical and biological data time series for Te Waikoropupū and connected water bodies to improve understanding of the current state of the springs and changes over the last 10–20 years,
2. assess ecosystem health of the springs and highlight the major anthropogenic risks to spring health based on results of (1) and expert knowledge, and
3. provide recommendations on relevant attributes (and management bands) that can be used in objective-setting.

The panel held a workshop in March 2016 and brought together some data relevant to these objectives. Further data collation, collection and analyses have subsequently been conducted. This report provides a summary of the outcomes of the workshop and the subsequent work.

Figure 3. The main spring basin at Te Waikoropupū.

2. METHOD

The selected group of scientists participated in a workshop held at the Cawthron Institute on 31 March 2016. The goal of the workshop and subsequent efforts was to discuss and find agreement on each objective in order to assist FLAG with its deliberations. The meeting was attended by eight scientists with a range of expertise that included freshwater resources, invertebrate monitoring, groundwater and surface water hydrology, groundwater biodiversity/ecology, nitrate modelling, toxicology, trend analyses and water quality (Table 1). The agenda for the workshop can be found in Appendix 1. DairyNZ provided funding to convene the workshop, but DairyNZ staff were not active participants in the workshop or involved with subsequent data analyses and discussion.

Table 1. Participants at the Te Waikoropupū science workshop held at Cawthron Institute.

Name	Organisation	Role/Expertise
Roger Young	Cawthron	Workshop convenor, Freshwater ecology
Joseph Thomas	TDC	Takaka water resources
John Stark	Stark Environmental Ltd	Invertebrate monitoring
Magali Moreau	GNS Science	National groundwater monitoring network
Graham Fenwick	NIWA	Groundwater biodiversity/ecology
Andrew Fenemor	Landcare Research	Nitrogen modelling, hydrology
Graham McBride	NIWA	Trend analyses water quality
Chris Hickey	NIWA	Toxicology water quality
Justin Kitto	DairyNZ	Observer

An initial presentation on the outcomes of the workshop was made to the FLAG in April 2016. Several questions were raised by the FLAG and have subsequently been addressed through collation of additional datasets and collection of new data. A more detailed presentation was given to the FLAG and Takaka Valley farmers in late July 2016.

Figure 4. Dancing Sands spring at Te Waikoropupū.

3. EXISTING PHYSICOCHEMICAL AND BIOLOGICAL DATA

Functionally, Te Waikoropupū comprises three distinct, but linked, groundwater-dependent ecosystems[2] (GDEs): the subsurface aquifer GDE within the aquifers, the spring basin GDE (the vents and associated basins: Main, Dancing Sands and Fish springs), and the downstream riverine GDE (Springs River and lower Takaka River). The ecological processes and physicochemical transformations within each differ significantly; these processes modify physicochemical factors and influence the health of successive ecosystems within the overall Te Waikoropupū system. Because each of these ecosystems differs in key drivers and processes, the ecological health of each is best assessed individually using criteria relevant to each specific GDE, while recognising the strong connections between the ecosystems. Importantly, the spring basin GDE is a transition between the dark subsurface aquifer GDE and the photosynthetically-driven riverine GDE where aquifer water mixes and equilibrates with surface waters.

3.1. Physicochemical data

Physicochemical data have been collected at Te Waikoropupū from 1970 onwards by a variety of parties. See Appendix 2 for a table containing an overview of physicochemical attributes measured, by whom, and when.

Physicochemical data for Te Waikoropupū was first collected in 1970 by Frances Michaelis (1974; 1976) as part of her PhD research project. Over the course of 15 sampling occasions during 1970–1971, Michaelis took a comprehensive range of physicochemical measurements at both the Main Spring and Dancing Sands spring. Stewart and Downes (1981) next collected physicochemical data from the Main Spring and upper Fish Creek Spring as part of their isotope hydrological study on a single occasion in 1979. Mueller (1992) measured a smaller range of physicochemical properties, including calcium, magnesium, nitrate, potassium, sodium, and sulphate at the Main Spring and Fish Creek as part of his geohydrological study of the Takaka Valley for the regional council. TDC monitored physicochemical elements at the Main Spring irregularly between 1986 and 2008; and at three monthly intervals at Fish Creek between September 2014 and the present day. The Council also maintain a continuous water temperature logger in the Main Spring, deployed since November 2015.

Since 1991, the Main Spring at Te Waikoropupū has been monitored quarterly as part of the National Groundwater Monitoring Programme (NGMP) by GNS Science (GNS).

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[2] This ‘groundwater-dependent ecosystem’ framework and terminology is adopted here following its wide use in Australia (see Hatton and Evans 1998) and utility for distinguishing inter-linked ecosystems that rely on groundwater (see also Fenwick 2016).

Sampling for this programme, carried out by TDC staff, provides the most comprehensive physicochemical dataset to date. The dataset includes water temperature, conductivity and the concentrations of arsenic, calcium carbonate, sodium, magnesium, manganese, potassium, iron, chloride, fluoride, bromide, nitrate, nitrite, ammonium, sulphate and silicon dioxide. Dissolved reactive phosphorus sampling and analyses were initially undertaken annually, and then quarterly since 2015.

Cawthron measured physicochemical properties at the Main Spring and Dancing Sands Spring on a single sampling occasion in 1999 and recently deployed a continuous DO logger in the Main Spring in April–May 2016.

Lastly, Friends of Golden Bay have conducted weekly monitoring of temperature, conductivity, and the concentration of nitrate, dissolved reactive phosphorus, and, on occasion, chloride at two sites along Fish Creek and at the Main Spring since late 2015.

The majority of the samples collected by Michaelis (and samples collected by TDC in 1998) were collected by divers directly at the Main Spring vents and thus represent water quality within the aquifer. Subsequent samples have been collected by wading into the Main Spring along the path that was used by divers, and more recently samples have been collected from the viewing platform as close as possible to the Main Spring vent.

3.1.1. Nitrate nitrogen

Nitrate nitrogen (NO_3-N) concentrations can influence the growth and abundance of aquatic plants and, at higher concentrations, can have direct toxic effects on some aquatic invertebrates and fish.

Over the full sampling record the nitrate nitrogen concentrations in the Main Spring have ranged between 0.12 and 0.92 mg/L (Figure 5). However, there are several outliers in the data. For example, seven samples with particularly low nitrate concentrations (< 0.2 mg/L) were reported in the early 1990s compared with samples collected before and afterwards. Further investigation of the original data records indicates that nitrate concentration measurements returned to more representative values when water quality analyses were moved to the GNS lab at Wairakei from December 1992. We believe that the low concentrations observed in the seven samples collected in the early 1990s were an artefact of changes in the analytical method used by different laboratories, and are considered outliers in the dataset.

There are also six anomalous values indicating nitrate nitrogen concentrations greater than 0.6 mg/L. There is no indication of a correlation between these spikes and spring flows or any other parameters. Therefore, the veracity and likely cause of these higher nitrate values remain uncertain. They may relate to rare issues of sample contamination and are also considered as outliers.

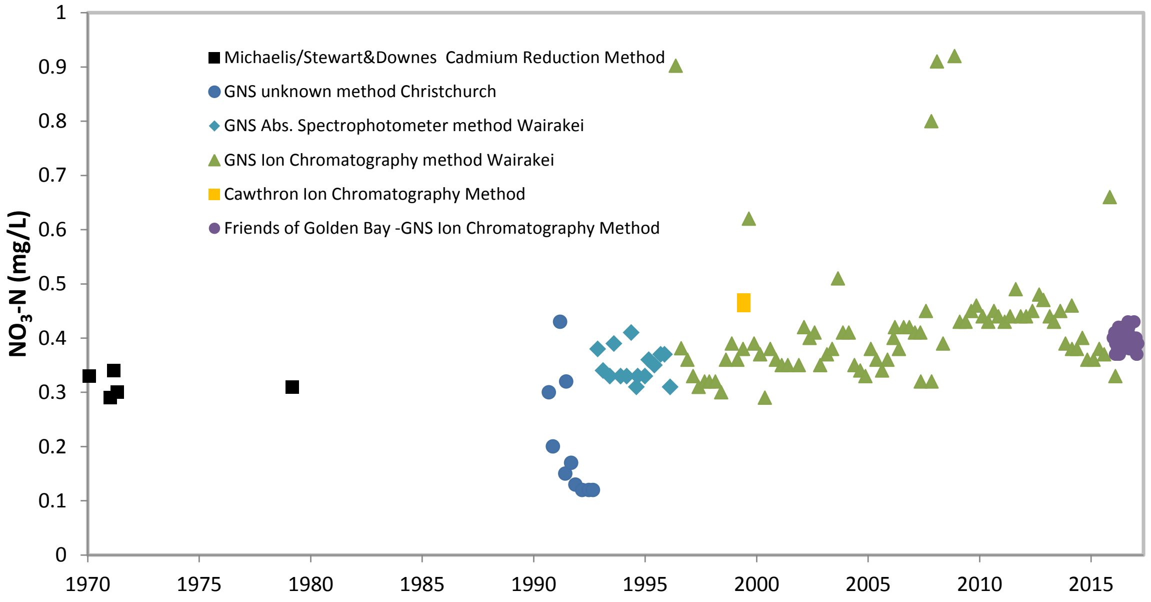

Figure 5. Nitrate nitrogen concentrations in the Main Spring at Te Waikoropupū. Data from Michaelis (1974) for 1970-71, Stewart and Downes for 1979, TDC/GNS data from 1990 to 2016, and Friends of Golden Bay data in 2016/17. Any changes in laboratory or laboratory method are also shown.

There are indications of a further anomalous series of values. Ten to 15 values from around 2009 to 2013 are notably less variable and slightly greater than preceding and subsequent values (Figure 5). Thus, we are cautious in interpreting them.

Using the full 47-year data record (including outliers), there was an overall increase of about 0.1 mg/L in the concentration of nitrate nitrogen (Mann-Kendall trend test, Z = 5.5, increase of 0.6% per year). This upward trend is still evident when the outliers in the data are excluded, although the increase was 0.5% per year without outliers (Mann-Kendall trend test, Z = 5.0, Figure 6). The upward trend of nitrate nitrogen concentration over the last 20 years was 0.3% per year (Mann-Kendall trend test, Z = 2.0, Figure 6). However, data for the last 10 years indicate a decrease of about 0.04 mg NO_3-N/L or 1.5% per year (Mann-Kendall trend test, Z = -4.1, Figure 6), although this decrease is driven by the consistently high values recorded over 2009–2013. In an analysis of a subset of these data, Mead (2016) found a similar increasing trend in nitrate nitrogen from 1990 to 2015.

Assuming a worst case with an annual increase of 0.6% per year continuing indefinitely, then it would take until 2178 for concentrations of nitrate nitrogen to reach

1.0 mg NO_3-N/L, the transition point between A-band and B-band waterbodies for nitrate toxicity outlined in the National Policy Statement-Freshwater Management (NPSFM; Ministry for the Environment [MfE] 2014) for surface water systems with conservative levels of water hardness (i.e., low water hardness, < 30 mg $CaCO_3$/L). Nitrate toxicity is reduced by increasing water hardness. Water from Te Waikoropupū has relatively high concentrations of calcium carbonate (i.e., high hardness, 190 mg $CaCO_3$/L), therefore the site-specific value relevant to nitrate toxicity for Te Waikoropupū is increased to 13 mg/L (Hickey 2015). Note, however, that the effects of nitrate concentrations on stimulation of algal growth also need to be considered. The ratio of nitrogen to phosphorus in water from Te Waikoropupū (around 40:1) suggests that phosphorus concentrations, rather than nitrogen concentrations are more likely to be limiting plant growth. Nevertheless, it is important to monitor and manage both nitrogen and phosphorus concentrations.

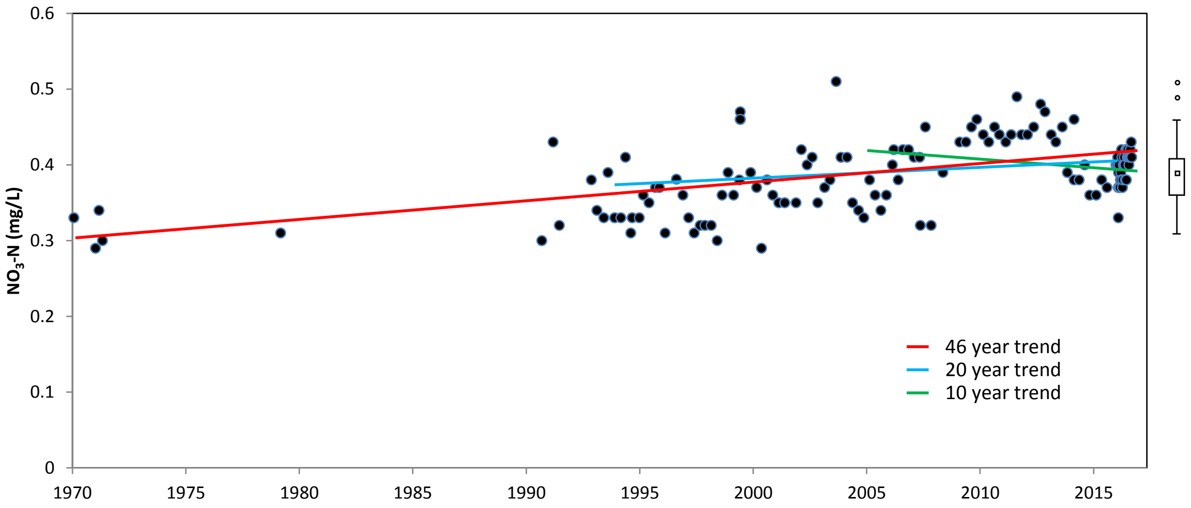

Figure 6. Nitrate nitrogen concentrations in the Main Spring at Te Waikoropupū with outliers omitted, 1970-2017. Data from Michaelis (1974) for 1970-71, Stewart and Downes for 1979, TDC/GNS data from 1990 to October 2016, and Friends of Golden Bay data to Mar 2017. A box and whisker plot showing the distribution of the data (median, 5th, 25th, 75th and 95th percentiles) is also shown to the right of the graph.

3.1.2. Clarity

Water clarity has only been measured directly once at the Main Spring, on 11 February 1993 by Davies-Colley & Smith (1995). A subsequent indirect measurement on 10 March 1995 using a transmissometer (Martek 1 m path length) confirmed their findings, and determined that water clarity was 63 m, which was ‘the highest yet reported for any fresh water, and close to the theoretical maximum for optically pure water… [which ranked Te Waikoropupū] among the very clearest waters in the world’ at that time (*ibid.* p. 251).

No water clarity monitoring has been undertaken since then at the Main Spring. However, water clarity monitoring has been undertaken regularly since 1997 at sites in the Springs River (the riverine GDE) downstream of the confluence with Fish Creek and upstream of the salmon farm discharge, for resource consent monitoring purposes (downstream monitoring data are not considered here). Two methods were used to measure water clarity. The black disc method (200 mm disc) was used between 1997 and 2012, and the indirect transmissometer method (Wetlabs 250 mm path length) has been used from 2012 onwards. Recent records from the latter are highly variable, probably due to measurement uncertainty rather than changes in water clarity. Excluding outliers, the range of water clarity measurements over the entire data record at the upstream site was 10–40 m, with clarity declining between 1997 and 2014 from about 30 m to about 20 m (Figure 7). It should, however, be remembered that this dataset does not represent Main Spring water clarity as monitoring occurred downstream of the confluence (and influence) of Fish Creek, and is also affected by sediment and organic matter entrainment processes occurring within the Springs River. Nevertheless, this downward trend demonstrates a strong need to monitor water clarity in the Main Spring more regularly in the future.

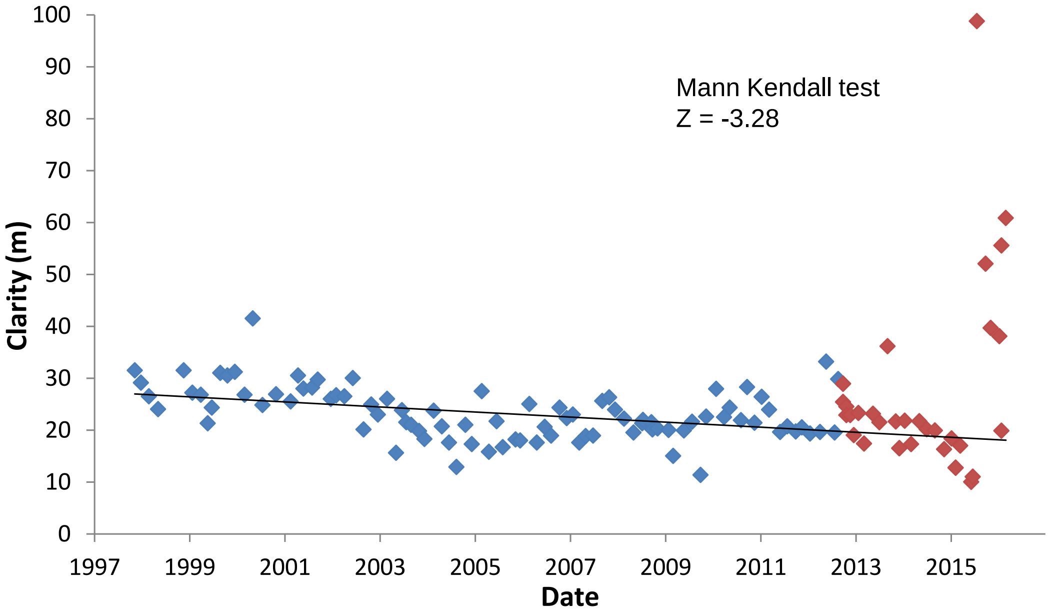

Figure 7. Water clarity in the upper Springs River downstream of Fish Creek. Note that the blue data points represent water clarity as measured using the black disc method, while the red data points used the transmissometer method. Data courtesy of NZ King Salmon Ltd and supplied by Envirolink Ltd.

3.1.3. Dissolved oxygen

The data record for dissolved oxygen (DO) spans 1971–2016. Michaelis’s (1976) first measurements of DO in 1971 using divers at the spring vents found a mean concentration of 6.6 mg/L (range 58–64% saturation). These records probably represent DO concentrations within the aquifer. Spot measurements have since been undertaken at Main Spring between 1998 and 2015, but often at the edge of the spring and represent conditions within the spring basin rather than the aquifer (Figure 8). The measurements, taken as part of the NGMP, ranged from 2.4 to 9.5 mg/L.

Dissolved oxygen concentrations are likely to increase markedly when aquifer water is aerated as it reaches the water surface above and distant from the spring vents, and as DO derived from photosynthesis of aquatic plants in the spring basin is mixed with the aquifer water. DO concentrations in surface waters (such as beyond the spring outflow itself) can vary widely within a 24 hour period, increasing as a result of photosynthesis of aquatic plants during daylight hours and decreasing due to respiration at night. No diurnal variation in DO concentrations or photosynthesis-related effects is expected to occur in groundwater or in spring water at its point of emergence (unless its residence time underground is brief). Therefore, with the exception of Michaelis's (1976) measurements directly at the spring vents, these data reflect conditions in the Main Spring basin and are not a measure of the DO concentrations in upwelling groundwater from the aquifer.

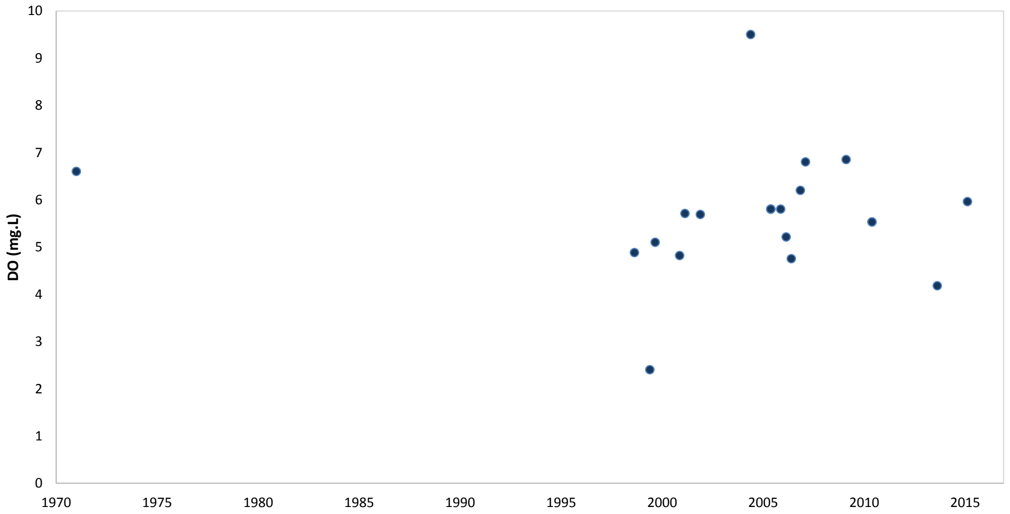

Figure 8. Spot measurement of dissolved oxygen at Te Waikoropupū Main Spring, 1971–2015.

The widely varying DO concentrations measured in the Main Spring basin prompted the deployment of a continuous DO logger in Te Waikoropupū (on the outside edge of the viewing platform and above the largest spring vent) in early 2016. Continuous monitoring from the data logger provides much more certainty around the range of DO concentrations experienced in upwelling groundwater from the aquifer, although the logger was close to the surface and presumably still measuring a mixture of water directly from the aquifer along with some water that had been resident in the spring basin for some time. During April–May 2016, DO saturation consistently ranged between 50–53%, which is equivalent to 5.5–5.7 mg/L (Figure 9). Small diurnal variations in DO concentration (around 0.1 mg/L) were observed in the data, suggesting that some of the water being measured was influenced to a small extent by aquatic plant photosynthesis in the Main Spring basin (spring basin GDE), not just water directly from the aquifer (aquifer GDE), even though the logger was deployed close to the Main Spring vent.

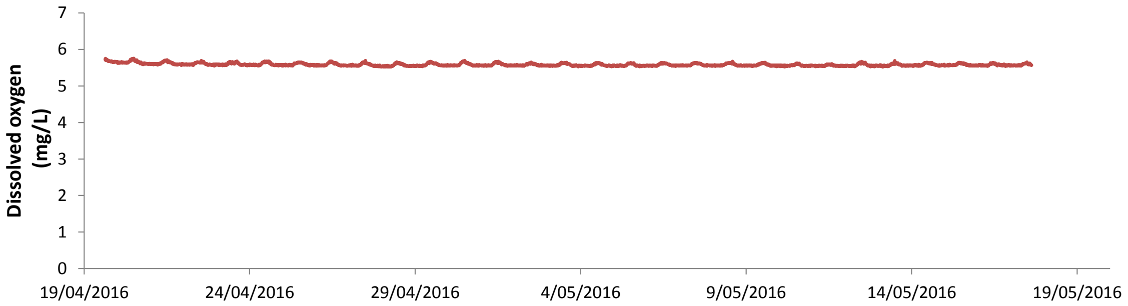

Figure 9. Continuous levels of dissolved oxygen in Te Waikoropupū Main Spring, April and May 2016. Data from Cawthron.

A comparison of the measurements of DO saturation collected from near the Main Spring vents in the early 1970s (6.4–7.0 mg/L, 58–64% saturation) with the continuous data collected close to the Main Spring vents in April–May 2016 (5.5–5.7 mg/L, 50–53% saturation) suggests a decrease of about 1.0 mg/L or about 10% saturation since the 1970s. Calibration of DO meters is complex and measurement errors of at least 5% are common, even among high quality loggers calibrated by the same person at the same time (Roger Young, unpublished data). The 10% change observed here is only slightly greater than typical DO measurement uncertainty.

Further, we note that the DO measurements within the upwelling water are an average for water sourced from different parts of the aquifer. Given the nature of karst and alluvial aquifers, it is likely that there will be lower DO concentrations in some parts of the aquifer. Equally, water in some parts of the overall aquifer system, probably along higher velocity, preferential flow paths, almost certainly will contain more DO.

3.1.4. Phosphorus

There are fewer data on phosphorus concentrations at Te Waikoropupū than there are for nitrate and DO. 'Available' phosphorus was first measured by Michaelis in the Main Spring and Dancing Sands Spring in 1970 and 1971. During 1994–2015 GNS sporadically measured dissolved reactive phosphorus (DRP) in the Main Spring as part of the NGMP. Since March 2015, DRP concentrations have been measured once every three months at the Main Spring by GNS as part of the NGMP; while Friends of

Golden Bay have measured DRP weekly in the Main Spring and at two sites on Fish Creek since December 2015. Over the data record, most phosphorus values are in the range 0.001–0.01 mg/L (Figure 10). These are relatively low concentrations and unlikely to cause excessive periphyton growth (Biggs 2000; Matheson et al. 2016). These concentrations are also relatively close to the analytical detection limits for phosphorus concentrations (recent Hills Laboratories detection limit 0.001 mg/L). It is important that future monitoring specifies low analytical detection limits so any changes over time can be identified.

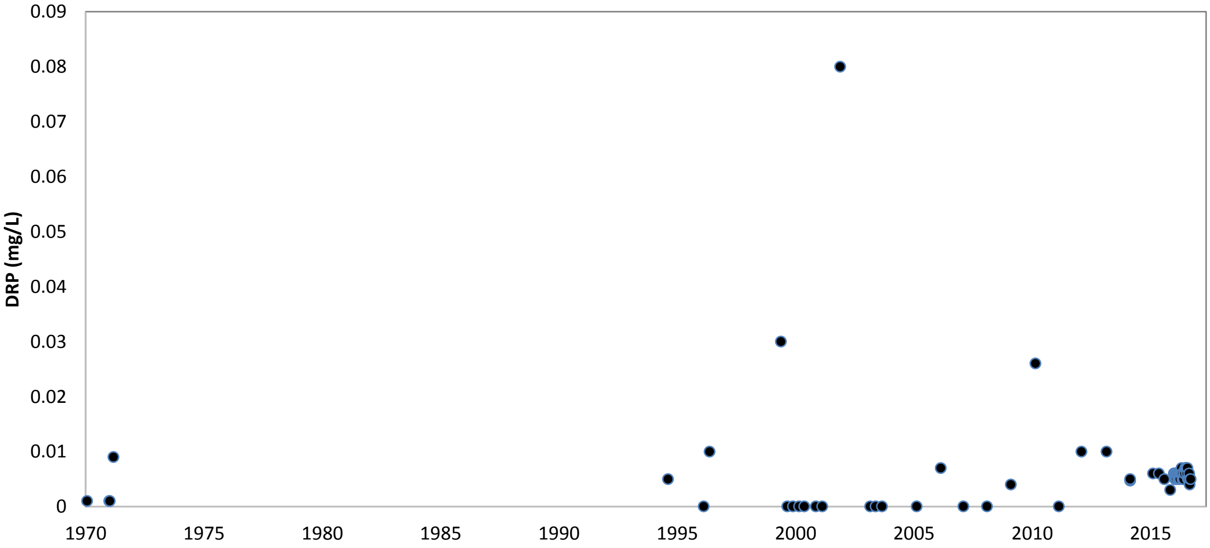

Figure 10. Dissolved reactive phosphorus at Te Waikoropupū Main Spring, 1971-2016. Data from Michaelis for 1970-1971, TDC/GNS data from 1990 to October 2016, and Friends of Golden Bay data to March 2017.

3.1.5. pH

The pH was first measured at Te Waikoropupū Main Spring and Fish Creek by Michaelis in 1970, by Stewart and Downes in 1979, in the Main Spring by Cawthron in 1999; and in the Main Spring by TDC in 2000, 2002, and 2008. The pH was also sampled in the Main Spring quarterly as part of the NGMP. Throughout the monitoring record, pH has ranged from 6.87 to 8.44 (Figure 11). The pH is also affected by aquatic plant photosynthesis and the relatively high range of variability observed probably reflects conditions in the Main Spring basin (spring basin GDE) rather than the pH of recent water upwelling from the aquifer (aquifer GDE).

Over the full data record, there was an overall increase of about 0.5 pH units (Mann-Kendall trend test, Z = 5.1, increase of 0.1% per year).

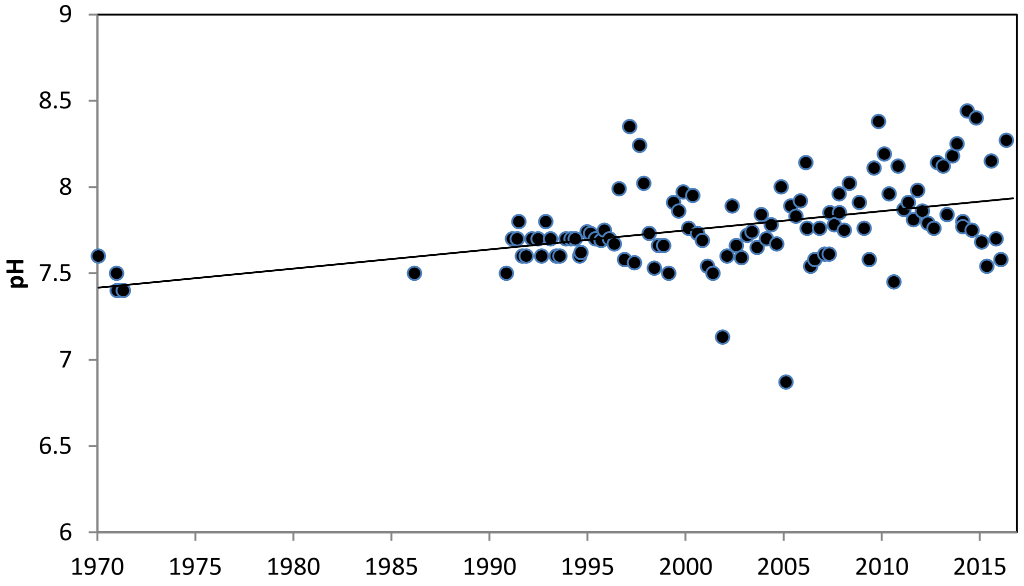

Figure 11. Field pH at Te Waikoropupū Main Spring, 1970–2016. Data from Michaelis for 1970–71, TDC/GNS data from 1990 to October 2016.

3.1.6. Chloride

Chloride concentrations have been measured at the Main Spring over the period from 1970–2016, and occur within a range of 16–125 mg/L. There is a strong positive correlation between flow and chloride concentration (Figure 12) suggesting that dense saline waters found within the lower levels of the aquifer are drawn upwards and discharged out of the springs during high flow periods (possibly through a venturi effect) (Stewart & Thomas 2008).

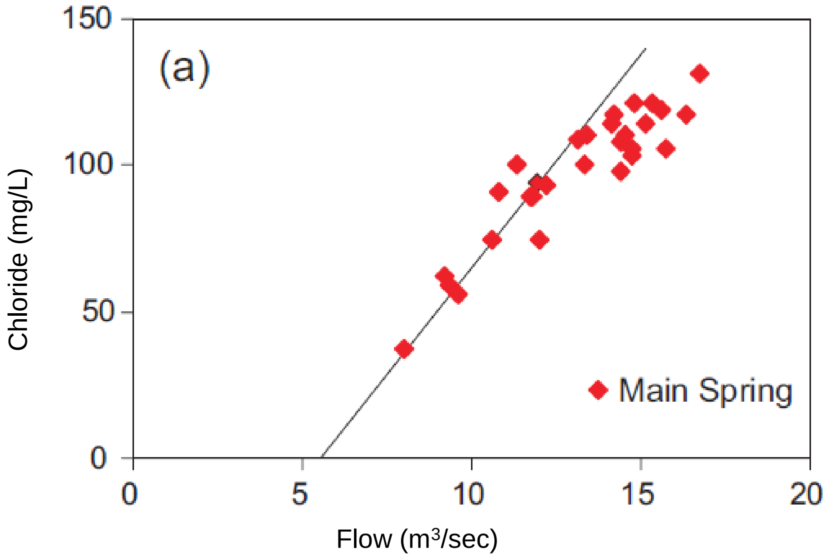

Figure 12. Chloride concentration as a function of flow in the Main Spring at Te Waikoropupū (from Stewart & Thomas 2008).

3.1.7. Temperature

Water temperature was first measured in the Main Spring and at the Dancing Sands Spring by Michaelis in 1970–1971, during which time a near constant temperature of 11.7 °C was recorded at the spring vents by divers (Michaelis 1976). These measurements represent conditions in upwelling water from the aquifer GDE. Spot measurements of water temperature in the Main Spring were undertaken by TDC staff from 1994 to 2015 as part of the NGMP, but sampling often was done at the edges of the Main Spring and so the dataset reflects the temperature of the water in the Main Spring basin (spring basin GDE) rather than water coming directly from the aquifer (aquifer GDE). Spot temperature measurements from the Main Spring basin ranged from 11.2 °C to 13.3 °C (Figure 13).

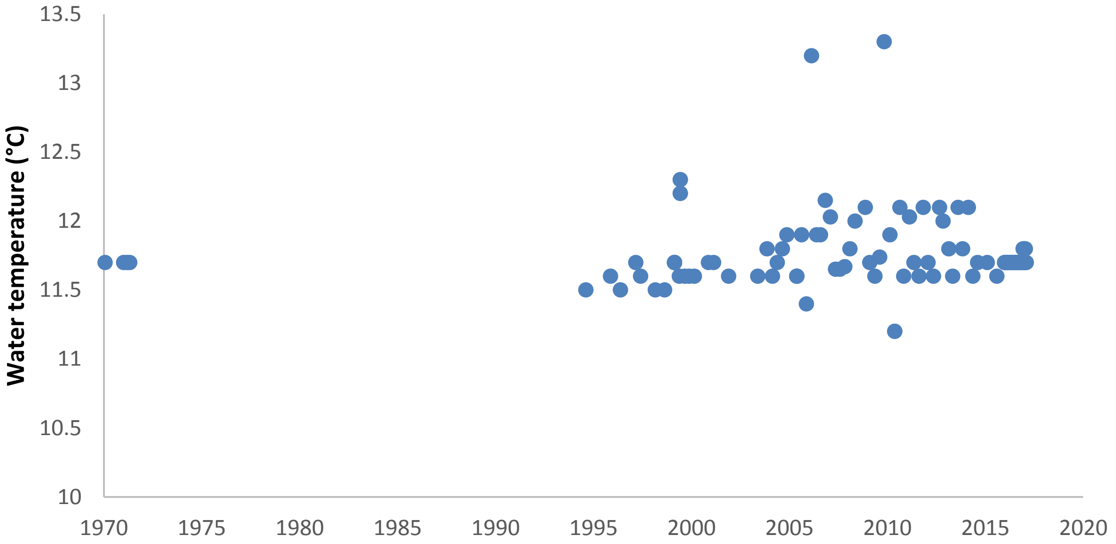

Figure 13. Spot measurements of water temperature at Te Waikoropupū Main Spring, 1994 to March 2017.

A continuous water temperature logger was deployed in the Main Spring basin (spring basin GDE) by TDC in October 2015 to better resolve water temperatures. Daily changes in water temperature are not expected for water upwelling from the aquifer. To date, water temperature measurements within the Main Spring basin have typically been 11.7 °C with occasional spikes up to 15.4 °C (Figure 14). The logger was installed initially at the edge of the Main Spring at the viewing platform, so the small diurnal temperature variations and occasional spikes in temperature featured in the dataset represent a mixture of water from the Main Spring basin (spring basin GDE) and water directly from the Main Spring vent (aquifer GDE). The logger was moved to the outside of the viewing platform and closer to the Main Spring vent in May 2016 in an effort to gather data on water temperatures of upwelling water and avoid any effects of solar heating of surface water and the remote possibility of overland flow on water temperature measurements. Some small daily fluctuations were still present in the data (Figure 14), probably reflecting some mixing of spring basin water with water upwelling from the aquifer, despite the logger being placed close to the Main Spring vent.

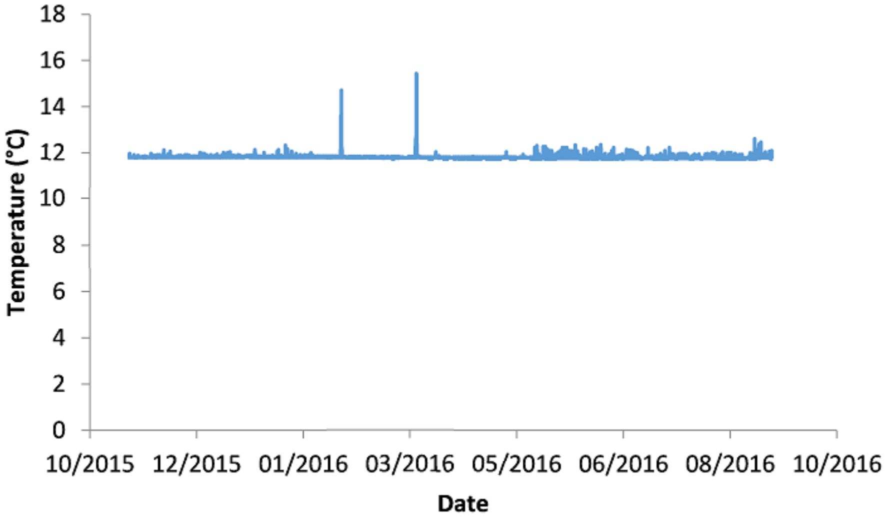

Figure 14. Continuous water temperature monitoring at Te Waikoropupū Main Spring, October 2015–September 2016.

It appears that the water temperature within the Te Waikoropupū aquifer is very stable over time at ~11.7 °C and there is no indication that water temperature has changed since the 1970s.

3.2. Biological data

All biological sampling to date has focussed entirely in either the spring basin GDE (Michaelis 1974, 1976, 1977; Doehring 2012; Department of Conservation [DOC] 2000), or the downstream riverine GDE (Stark 1993, 1999-2015; Stark & Pugsley 1986). No investigation of Te Waikoropupū's aquifer GDE has been undertaken, but, as indicated by Fenwick (2015) it almost certainly comprises a unique biodiversity that delivers ecosystem services which sustain many of the values associated with Te Waikoropupū.

3.2.1. Macroinvertebrates

As part of her PhD thesis, Michaelis (1974, 1977) conducted a thorough analysis of the macroinvertebrates found in Te Waikoropupū's large spring basin GDE (i.e., the basin into which the Main Spring and Dancing Sands spring discharge) and found 42 different kinds of macroinvertebrates. Insects were the most diverse group, with 21 different species (including 10 species of caddis flies), followed by flatworms (three species), crustaceans (six species) and molluscs (three species). The snail (*Potamopyrgus antipodarum*) was numerically dominant and represented more than 85% of the organisms collected at nine of the ten sampling sites (Michaelis 1974, 1977). Most of the macroinvertebrates found are widely distributed throughout New Zealand, and include organisms that are found in surface water systems and a few that inhabit groundwaters (e.g., a white eyeless flatworm *Dugesia* sp.). Most species found in Te Waikoropupū are native to New Zealand, apart from the snail (*Lymnaea columella* now called *Pseudosuccinea columella*) and the worm (*Lumbriculus variegatus*) (Michaelis 1974). Subsequent consent biomonitoring in association with the salmon farm indicates that the Springs River and nearby Bell's Creek provide habitat for at least 139 different macroinvertebrate taxa (Stark 2015b).

An analysis of available information found records of 54 benthic invertebrate taxa from within Te Waikoropupū's spring basin GDE (Fenwick & Smith unpublished data). In comparison, at least 139 different macroinvertebrate taxa (types) were reported from shallower stream beds of Fish Creek and the Te Waikoropupū River below the springs basin identified from more than 20 yearly monitoring surveys (Stark & Pugsley 1986; Stark 1993, 2015b) and other biodiversity investigations. Although Michaelis's (1974, 1977) study differed considerably from subsequent surveys (Stark various) in specific sampling locations, the types of habitats sampled, sampling effort, duration of sampling and taxonomic resolution; some of the differences in biodiversity almost certainly are due to the very different habitats present in the spring basin GDE, compared with the Springs River (the downstream riverine GDE). Two species found in the spring basin GDE (a flatworm, *Spathula alba*; an amphipod *Paraleptamphopus* sp.) are unknown from elsewhere in New Zealand (Fenwick & Smith unpublished data). The spring basin is also the northern-most known location for two caddisflies, *Hydrobiosis chalcodes* and *H. johnsi*, both typically associated with cold-water, alpine streams (Fenwick & Smith unpublished data). The nearest populations of these species are 400 km away for *H. johnsi* and 100 km for *H. chalcodes*. Te Waikoropupū's spring basin is close to the northern limit for another caddisfly (*Rakiura vernale*), known from scattered locations along the West Coast, northwest Nelson and Stewart Island. Conversely, Te Waikoropupū supports the only known South Island population of an abundant, North Island amphipod, *Paracalliope karitane*.

Overall, total invertebrate biodiversity for Te Waikoropupū spring basin GDE (54 taxa) was moderately high relative to that at other New Zealand springs (21 species in Waitaki to 61 in Southland and Waikato (Scarsbrook et al. 2007)). Actual biodiversity in Te Waikoropupū's spring basin GDE may be considerably higher than the 54 reported species because some habitats were poorly or not sampled and because improved collection practices and identification tools (including molecular DNA) are now available.

The combined freshwater invertebrate biodiversity of the spring basin GDE and the riverine GDE totalled 134 taxa (Fenwick & Smith unpublished data). As with most other springs, Te Waikoropupū spring basin GDE supports surface water and groundwater species. Several additional groundwater, spring and surface water species (notably smaller crustaceans, Tateidae (formally Hydrobiidae; snails) are likely to be discovered within the aquifer GDE, since several species are known from other springs in the Takaka catchment (e.g., Haase 2008).

Different kinds of macroinvertebrates have different habitat preferences and pollution tolerances. The macroinvertebrate community index (MCI) reflects the range of types of macroinvertebrate found at a site and is considered to be a useful general measure of river ecosystem health (Stark & Maxted 2007). The MCI approach gives sensitive species high scores while tolerant species get low scores. Therefore, a site with a high overall MCI score is dominated by pollution-sensitive species (and likely to be unpolluted), whereas a site with a low score is dominated by pollution-tolerant species and likely to be affected by pollution or fine sediments. MCI scores can be interpreted in the following way: over 119 = excellent; 100-119 = good; 80-99 = fair; and less than 80 = poor. Alternatively, MCI scores can be subjected to temporal trends testing to determine whether river health has improved, deteriorated, or shown little change over time.

Macroinvertebrate community index scores were calculated from samples collected just downstream of the Main Spring basin (and at sites further downstream) (i.e. riverine GDE) from 1986 to 2006 as part of the resource consent requirements for the NZ King Salmon Company Ltd farm (data collected by Stark Environmental Limited). Monitoring sites are shown in Figure 15. Sampling at Site 1 was discontinued after the March 2006 survey when the potential threat of *Didymosphenia geminata* was identified[3]. Site 3 was moved downstream to Site 3a where the habitat was similar, but access was better. In future, monitoring is to be restricted to Sites 3a and 5 (above and below the salmon farm discharge).

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[3] *Didymosphenia geminata* is a diatom (type of algae), sometimes called “rock snot”, that was first reported in New Zealand in 2004.

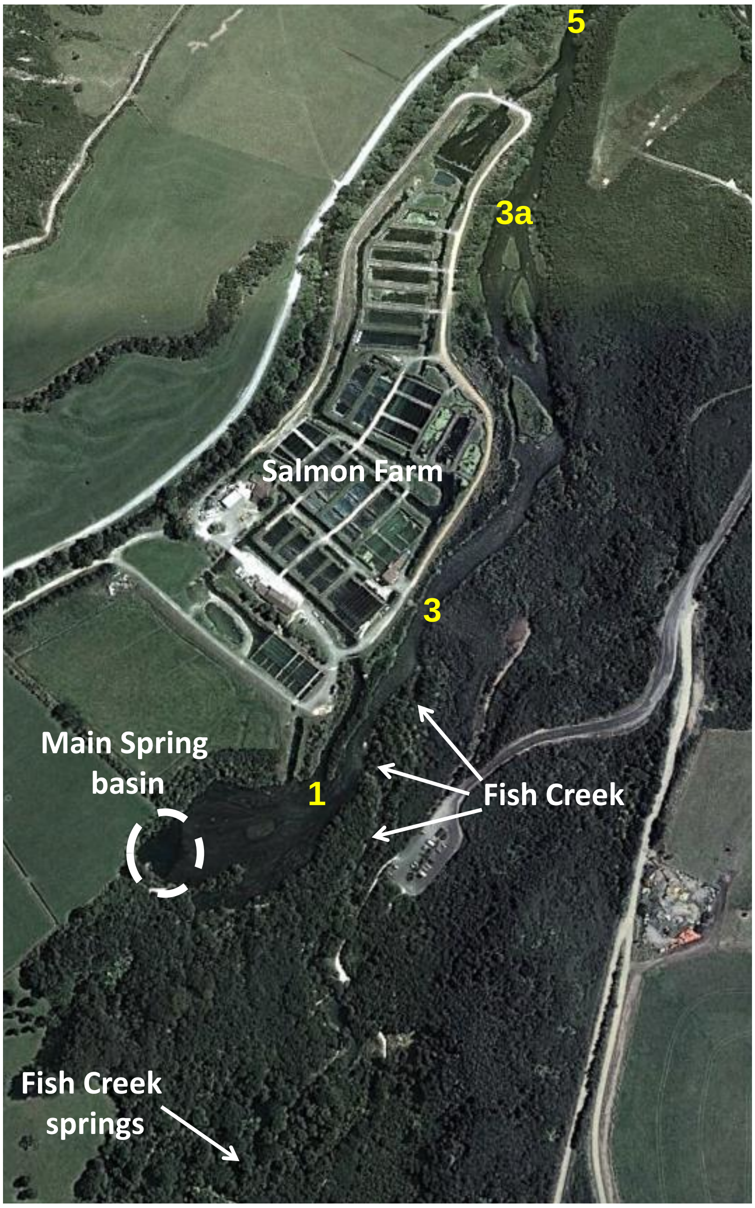

Figure 15. MCI monitoring sites at the Springs River, relative to the Main Spring basin, Fish Creek and Fish Creek springs.

Macroinvertebrate communities can show considerable variability from time to time and from place to place. This is reflected in biomonitoring data. However, based on MCI data from sites 1, 3, and 3a (all upstream of the salmon farm), the health of the Springs River upstream of the salmon farm discharge (riverine GDE) has shown expected levels of short term variation between sampling events, but not changed noticeably in a consistent way from 1986 to 2015 (Figure 16). These data do not provide a direct measure of the health of the Main Spring basin (spring basin GDE) or the aquifer (aquifer GDE).

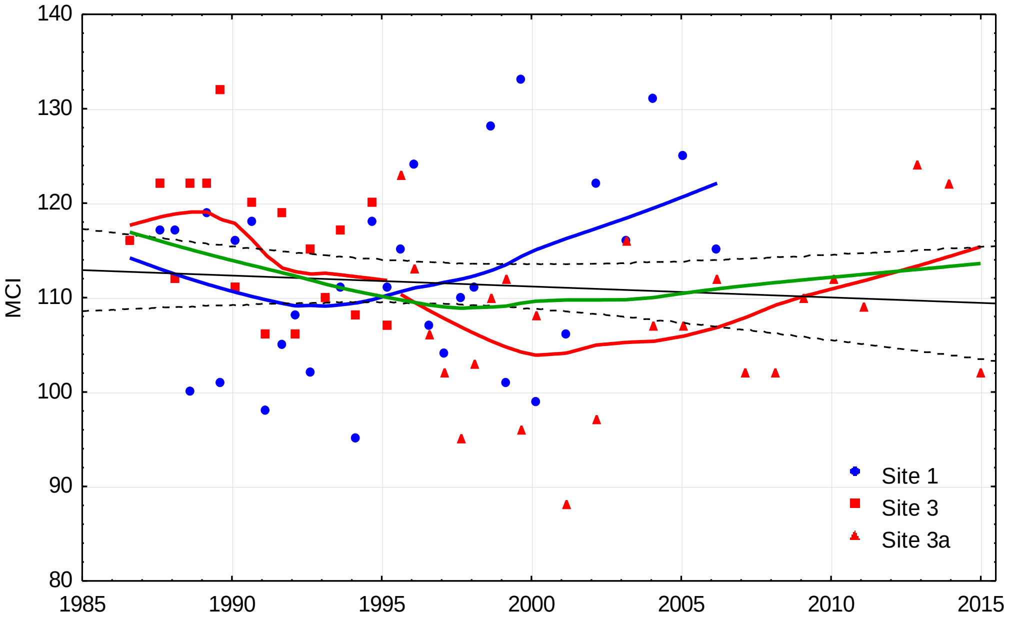

Figure 16. Macroinvertebrate community index (MCI) scores as measured at three sites in the Springs River downstream of the Main Spring basin, but upstream of the salmon farm, 1986–2015. See Figure 15 for site locations. The coloured lines are LOWESS smooth lines fitted to the data for each site. For more detail see Stark 2015b.

3.2.2. Faecal indicator bacteria

Faecal indicator bacteria such as *Escherichia coli* (*E.coli*) are measured to determine if it is safe to swim or collect kai from a site. Data on *E.coli* levels at Te Waikoropupū, come from a single sampling event (16 June 2014) only. On that occasion, samples were taken at several sites in and around the Main Spring, Fish Creek, and Dancing Sands springs.

E. coli concentrations near the vents of all three springs were less than 1/100 ml. A sample taken 100 m downstream of the Main Spring had an *E.coli* level of 1/100 ml. In comparison, water samples collected downstream of the Fish Creek Spring contained 16 to 23 *E.coli* per 100 ml, reflecting the influence of local surface runoff/inputs to Fish Creek upstream of the Fish Creek Spring. This single sampling suggests that aquifer GDE water emerging from all three springs is not contaminated by *E.coli*, whereas riverine GDE water short distances downstream from both sets of springs is affected by faecal contamination.

3.2.3. Aquatic plants

Michaelis (1974) also included a thorough study of the types of aquatic vegetation found within the Main Spring basin at Te Waikoropupū (spring basin GDE). Sixteen types of algae, seven species of moss, three species of liverwort and five species of aquatic vascular plant (angiosperms) were found. All of the algae, mosses and liverworts present were considered native to New Zealand, but three of the angiosperms (*Juncus microcephalus*–rush, *Rorippa microphylla*–watercress, *Callitriche stagnalis*–starwort) are introduced to New Zealand.

Subsequent annual monitoring of aquatic vegetation used underwater transects and photography (e.g., DOC 2000). This methodology was later changed to aerial photographs in conjunction with a single underwater transect (Strickland 2005; Figure 17). An additional non-native aquatic plant species, *Galium palustre,* was first recorded on that monitoring occasion. Strickland (2005) recommended removal of this plant and advised regular surveys to monitor regrowth and distribution. Repeat aquatic plant monitoring in 2012 found six species of aquatic plants in the main spring basin, including *G. palustre* which had 'changed from a few, large and localised patches to several, smaller, more wide-spread patches' (Doehring 2012 p. 9), and was the third most abundant species, in terms of cover, along the transect.

To our knowledge there is no information on patterns of periphyton/algal biomass in Te Waikoropupū over time because appropriate sampling has not been done. Biomass is likely to vary markedly from place to place and over time. Large accumulations of green algae are often seen on the rocks in unshaded patches within Fish Creek during summer, but this seems to be the exception rather than a common phenomenon throughout the spring basin GDE and riverine GDE.

Figure 17. Aerial photograph of Te Waikoropupū's spring basin from 2005 used for assessing aquatic plant cover. *Galium palustre* can be seen as the bright green growths at the bottom right hand side of the Main Spring.

3.2.4. Freshwater fish

Nine species of freshwater fish have been recorded in the vicinity of Te Waikoropupū (New Zealand Freshwater Fish Database – accessed March 2017). This includes eight native species (longfin eel, shortfin eel, torrentfish, giant kokopu, koaro, inanga, upland bully, redfin bully) and the introduced brown trout. On a national scale this is a relatively high diversity of native fish, but not as outstanding as neighbouring catchments like the Onekaka River where at least 14 different species of freshwater fish have been recorded.

4. ECOSYSTEM HEALTH AND ANTHROPOGENIC RISKS

The group of scientists who met in March 2016 considered the physicochemical and biological data presented above, and discussed the implications for management of Te Waikoropupū. The group subsequently identified any changes in water quality and biology and explored implications of these for each ecosystem. The health of visible surface water ecosystems (spring basin GDE and riverine GDE) is largely predetermined by the health of the upstream, connected aquifer and the waters feeding the aquifer. There are, however, few data on water quality and the composition of the aquifer GDE and the relationships between the health of these different ecosystems is unknown and likely to be complex. For these reasons, our evaluation of Te Waikoropupū is considered for the aquifers and surface water ecosystems separately.

Our review of all monitoring data showed that sampling and measurement within Te Waikoropupū was undertaken without explicit recognition that there are three linked ecosystems involved. Monitoring of the riverine GDE for consent compliance purposes was closely focussed on a single ecosystem, as was the aquatic plant monitoring within the spring basin GDE (DOC 2000; Strickland 2005; Doehring 2012). Michaelis's investigation was similarly focussed on the spring basin GDE, but monitored water quality at the Main Spring (and Dancing Sands spring) vents, and thus largely represented aquifer GDE water as it entered the spring basin GDE (Michaelis 1974).

Subsequent monitoring sought to determine water quality within the aquifer GDE by sampling, as far as practical, within the discharge from the Main Spring vent. Although the intent appears consistent, daily, photosynthesis-induced fluctuations in continuously monitored DO (Figure 9) illustrate the difficulties of sampling aquifer GDE water as it enters the spring basin. The variability in DO from this continuous measurement also illustrates that this and some other water quality parameters probably vary over small (< 1 m) spatial scales within the highly dynamic spring basin GDE. Turbulent mixing of aquifer GDE water with that in the spring basin probably contributes to the observed variability in some water quality variables.

4.1. Relevant guidelines

Guideline documents potentially relevant to Te Waikoropupū's surface water ecosystems include the *Australian and New Zealand Guidelines for Fresh and Marine Water Quality* (ANZECC) (ANZECC 1992; ANZECC & ARMCANZ 2000), the *Instream Plant and Nutrient Guidelines* (Matheson et al. 2016), the National Objectives Framework in the *National Policy Statement for Freshwater Management* (MfE 2014), the *Drinking Water Standards for New Zealand* (Ministry of Health [MoH] 2008), and the *Microbiological Water Quality Guidelines for Marine and Freshwater Recreational*

Areas (MfE 2003). Due to the unique characteristics of Te Waikoropupū, many of these guidelines are not necessarily relevant to Te Waikoropupū waters because they were based on data from rain-fed rivers where, for example, higher DO and lower water clarity would be expected.

The *ANZECC Guidelines* provide guidance on fresh and marine water quality management issues in both New Zealand and Australia (ANZECC & ARMCANZ 2000). This includes guidance on toxicants, physical and chemical stressors, sediment quality, agricultural water use and biological indicator methods. The ANZECC guidelines provides trigger values, not limits, meaning that if median water quality at monitoring sites exceed a trigger value, then some management response should be initiated. The ANZECC trigger values for ‘physicochemical’ parameters for New Zealand were derived statistically from a small set of rivers around New Zealand and do not necessarily reflect likely impacts on ecological values at levels higher than the trigger values (ANZECC & ARMCANZ 2000). For example, the lowland river trigger value for nitrate nitrogen (0.444 mg/L) was set based on the 80th percentile for data from a small subset of the 32 ‘baseline’ rivers sampled as part of the National River Water Quality Network (Davies-Colley et al. 2011). The value was not determined by looking at the toxicity of species to different concentrations of nitrate or by ecological changes in macroinvertebrate communities associated with elevated nitrate (e.g., such as enhanced periphyton abundance).

The *National Policy Statement for Freshwater Management* (NPSFM) sets out the objectives and policies for freshwater management under the Resource Management Act 1991. As part of the NPSFM, the National Objectives Framework (NOF) describes states for different attributes in relation to bands (A, B, C and D) and national bottom lines (the transition from C to D) in respect of compulsory objectives. The numbers representing transitions between bands were typically based on experimental studies examining the tolerance of different organisms to different stressor levels (e.g., Hickey 2013 for nitrate). The NOF contains attribute bands for nitrate nitrogen, ammoniacal nitrogen, periphyton abundance and a faecal indicator bacteria (*E. coli*—with human health recreation thresholds) (MfE 2014), which are potentially relevant to Te Waikoropupū. The NOF also has attribute bands for DO, however, the application guidance is for ‘below point sources’ of possible pollution so they are not directly applicable to the Te Waikoropupū assessment. As yet, however, no attribute states or national bottom lines are available for any spring or groundwater ecosystem, even though the NPSFM explicitly includes aquifers as one of the types of freshwater bodies that it seeks to manage for ecosystem health. Indeed, it seems that aquifer GDEs and spring basin GDEs are probably too diverse with respect to some key attributes for setting meaningful national bottom lines.

The *Instream Plant and Nutrient Guidelines* (Matheson et al. 2016) provide an understanding of the relationships between a range of instream objectives and levels of instream plants, define periphyton guidelines that will help meet these objectives, and suggest general nutrient criteria to help enable high-level compliance with the periphyton guidelines.

The *Drinking Water Standards for New Zealand* (MoH 2008) assist in the management of public and private drinking-water. The *Drinking Water Standards* do this by providing requirements for drinking-water safety by specifying the maximum amounts of substances, organisms, contaminants or residues that may be present in drinking water, among other specifications. The suitability of Te Waikoropupū water for drinking is not within the scope of this report, but we note that the spring water is hard (relatively high concentrations of calcium/magnesium carbonate) and concentrations of chloride are relatively high due to the sea water contribution to the aquifer.

The *Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas* aim to help water managers control the public health risk from microbiological contamination in recreational waters (MfE 2003). The guidelines use a combination of a qualitative risk grading of a catchment, supported by the direct measurement of appropriate faecal indicators, to assess the suitability of a site for recreation. These guidelines are relevant to all three of Te Waikoropupū's aquatic ecosystems, although contact recreation is considered culturally inappropriate in the Main Spring.

4.2. Spring basin and riverine groundwater-dependent ecosystems

This section refers to groundwater-dependent ecosystems in the Main Spring basin and the spring basins associated with the Dancing Sand spring and the Fish Creek springs. It also refers to the downstream riverine GDEs—so including the lower reaches of Fish Creek, and the Springs River.

4.2.1. Nutrients

Nitrogen and phosphorus are the primary nutrients affecting aquatic plant growth and can have detrimental effects on aquatic ecosystem health by stimulating excessive growth of algae and other aquatic plants. There are also potentially direct toxic effects of some nitrogen compounds (ammoniacal nitrogen [NH_4-N] and nitrate nitrogen [NO_3-N]) on aquatic life that need to be considered.

Te Waikoropupū's spring basin GDE mostly meets the surface water guidelines (Table 2), although nitrate nitrogen concentrations sometimes exceed the instream plant and nutrient guidelines. One sample (from Michaelis in 1970) exceeded the ammonium toxicity annual maximum value. The median nitrate nitrogen concentration (over the full record and over the last 10 years) was lower than both the ANZECC trigger level and the NPSFM nitrate toxicity level, but concentrations have increased overall since 1970, despite a small decrease recently (2013–2016). Instream plant and nutrient guidelines were occasionally exceeded for dissolved inorganic nitrogen however this does not necessarily mean that periphyton will proliferate as dissolved reactive phosphorus concentrations, and the ratio of nitrogen to phosphorus, are low and more likely to be limiting periphyton growth than nitrate levels. Nevertheless, it will be important to monitor both nitrate and phosphorus concentrations closely in the future. For further discussion on nutrients see Section 4.3.1.

Table 2. Status of nutrient attributes for Te Waikoropupū in relation to various guideline values. ND = no data. Status colours are green (meet relevant guidelines), orange (occasional exceedance), red (exceed guidelines, action required).

Attribute	**ANZECC physico-chemical trigger value – lowland rivers**[4]	**NPSFM NOF attribute states for rivers**[5]	**Instream Plant and nutrient guidelines**	**Drinking water guideline**	**Te Waikoropupū spring basin GDE value**	**Guidelines met or exceeded**
TP	0.033 mg/L		0.010–0.075 mg/L		ND	ND
TN	0.614 mg/L		0.070–0.660 mg/L		ND	ND
DRP/FRP	0.010 mg/L		0.011–0.018 mg/L		0.006 mg/L (0.001–0.080)	🟩
NH_4-N	0.021 mg/L				< 0.010 mg/L (0.001–0.069)	🟩
NH_4-N toxicity		A Band ≤ 0.030 mg/L; (Annual median) ≤ 0.050 mg/L (Annual maximum)			< 0.010 mg/L (0.001–0.069)	🟧
NO_3-N	0.444 mg/L		0.035–1.1 mg/L[6]	50 mg/L	0.39 mg/L (0.12–0.92)	🟧
NO_3-N toxicity		A Band ≤ 1.0 mg/L[7] (Annual median) ≤ 1.5 mg/L (Annual 95th percentile)			0.39 mg/L (0.12–0.92)	🟩

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[4] Note that physico-chemical trigger values do not relate to adverse effects on river ecology (see text).
[5] MfE (2014) values applicable to rivers.
[6] Total dissolved inorganic nitrogen concentration, not just nitrate nitrogen.
[7] These levels relate to sites with conservative water hardness. Site specific guidelines are much higher—see Hickey (2015).

4.2.2. Clarity

The ANZECC water clarity trigger level for lowland rivers is 0.8 m. The water clarity of Te Waikoropupū is considerably better than this and, as mentioned above, within the Main Spring basin is among the clearest waters in the world. It is not relevant to compare water clarity of a groundwater-fed system like Te Waikoropupū with the lowland rivers on which ANZECC was based. Even the clearest rain-fed rivers have water clarity no higher than 20 m. Given the extreme water clarity of Te Waikoropupū it is more relevant to maintain water clarity at its presently very high state. Clarity has only been measured once directly within the Te Waikoropupū spring basin (Davies-Colley & Smith 1995) due to technical and logistical challenges, so it is impossible to know how much variability there is in clarity measurements from day to day, or if there are any trends in water clarity over a longer period. Indications of a potential decline in water clarity in the Springs River from 1997–2014 upstream of the NZ King Salmon farm discharge (Figure 7) require more investigation. Further investigations of water clarity using various techniques are being trialled to determine if there is a suitable approach for regular monitoring.

4.2.3. Dissolved oxygen

The ANZECC & ARMCANZ (2000) trigger level to initiate management action for DO in lowland rivers ranges from 98–105% saturation. This trigger level was based on a relatively small number of spot DO measurements taken during daylight hours and is not relevant to daily minimum concentrations which normally occur at dawn. The earlier ANZECC (1992) trigger level of 80% saturation is more relevant to daily minimum values and broadly equivalent to the NPSFM attribute state for minimum daily DO at sites downstream of point sources discharges (greater than 7.5–8.0 mg/L) (Band A attribute states, MfE 2014).

The wide range in values reported from the spring basin GDE since 1995 (4–7 mg/L, extremes 2–9.5 mg/L, Figure 8) reveals the naturally high variability in time and space within the highly dynamic environment. DO levels within the springs basin close to the Main Spring vent are below the guidelines (50–53% saturation), but this almost certainly reflects the groundwater-fed nature of the system. Groundwater systems, particularly deep aquifers with long residence times, often have lower DO levels (Michaelis 1976), which again suggests that it is not appropriate to compare measurements from Te Waikoropupū with the default ANZECC guidelines.

The levels of DO in Te Waikoropupū are relatively low and have probably always been at, or similar to, these levels. The depressed DO concentrations within the spring basin GDE may be an important factor contributing to its unusual biodiversity, conceivably favouring species otherwise limited physiologically or competitively. For example, we understand that these lower DO concentrations periodically impair fish health and salmon growth within NZ King Salmon Ltd's adjacent farm. However, those species naturally present within Te Waikoropupū are presumably adapted to cope with the naturally low DO levels.

4.2.4. pH

All available data on pH within Te Waikoropupū are from the spring basin GDE. There are no ANZECC or NPSFM trigger values for the pH of spring waters, however, most measured values were within the lower and upper ANZECC trigger values for rivers (7.2–7.8) indicating no cause for concern.

The small, consistent increase in pH observed since 1971 indicates a longer term change (Figure 11). Although unlikely to be ecologically significant on its own, it must be evaluated along with other observed changes to establish overall implications for the aquifer and springs ecosystems. The cause of the observed small long-term increase in pH is unknown, but could include increased growth of aquatic plants within the springs basin, changes in the pH of upwelling water, or a result of a change in the general time of day when samples are collected (because pH can vary considerably over a 24-hour period).

4.2.5. Water temperature

There are no water temperature guidelines in ANZECC or the NPSFM. However, scientific studies have shown that the most temperature-sensitive native freshwater organisms prefer water temperatures below 18 °C (Olsen et al. 2011; Quinn et al. 1994). Detailed studies on the growth requirements of brown trout indicate that growth rates are at their maximum between temperatures of 7–17 °C (Elliott 1994). Most water temperature data for Te Waikoropupū are from the spring basin GDE. Spot measurements reveal some variation (c. 11.0–13.5 °C) within the basin, probably due to solar warming, and/or measurement at slightly different locations. Data collected close to the Main Spring vent reveal groundwater's very strong influence on the spring basin GDE's water temperature with measurements consistently close to 11.7 °C over the years and therefore within the acceptable range for the freshwater macroinvertebrates and fish that are present.

4.2.6. E. coli

The faecal indicator bacterium *E. coli* is used to indicate the possible presence of harmful microbes and pathogens sourced from faecal pollution that pose a potential risk to people drinking or contacting the water. The *Drinking Water Standards for New Zealand* (MoH 2008) require drinking water supplies to have less than 1 *E. coli* per 100 mL. Guidelines for swimming and secondary contact recreation allow higher values of *E. coli*: 126 and 260 *E. coli* per 100 ml, respectively. Based on NPSFM objectives, A-band rivers should have ≤ 260 *E. coli* per 100 mL (MfE 2014).

While *E. coli* has only been sampled once at Te Waikoropupū, the measured levels were below these values. For example, the levels of *E. coli* recorded at the Main Spring and at the Fish Creek spring were < 1 *E. coli* per 100 ml, whereas levels were up to 23 *E. coli* per 100 ml further downstream. This suggests that water directly from the springs meets the drinking water guidelines (for *E. coli*), while further downstream the contact recreation guidelines are still met.

4.2.7. Biological measures

As mentioned above, MCI scores can be interpreted in the following way for rivers: more than 119 = excellent; 100–119 = good; 80–99 = fair; and < 80 = poor (Stark & Maxted 2007). MCI scores recorded at the sites in Springs River upstream from the salmon farm (i.e. in the riverine GDE) typically have ranged from 100–120 (Figure 16), which represents 'good' ecological health. The fact that MCI scores are not in the 'excellent' category probably reflects the natural groundwater-fed nature of Te Waikoropupū (stable flows, abundant aquatic plants and low DO concentration) rather than a sign of degraded health *per se*. There have been no surveys of aquatic invertebrates within the spring basin GDE itself since the 1970s, and caution should be applied to inferring this ecosystem's current health from measurements further downstream in the riverine GDE.

We are not aware of any periphyton biomass measurements from Te Waikoropupū or the Springs River so are unable to compare these levels with instream plant guidelines or NPSFM attributes states (e.g. < 50 mg chlorophyll-*a*/m^2 for A-band rivers). Due to the constant flow and lack of floods, aquatic plants and algae are expected to be abundant in Te Waikoropupū. Large accumulations of green algae are often seen on the rocks in unshaded patches within Fish Creek in summer (Figure 18), but this seems to be the exception rather than a common phenomenon throughout the spring basin GDE or riverine GDE.

As mentioned in Section 3.2.3, there are records of four introduced aquatic plants within Te Waikoropupū. Their presence is not ideal, but none of these plants are strongly invasive macrophytes like *Lagarosiphon major* or *Egeria densa*, which have been known to dominate and substantially alter habitat quality in other waterways in New Zealand. Efforts to avoid the introduction of the invasive diatom *Didymosphenia geminata* (often known as Didymo or 'rock snot') to Te Waikoropupū appear to have been successful so far.

Figure 18. Fish Creek at Te Waikoropupū showing algal growth beside the walkway.

4.3. Aquifer and associated groundwater-dependent ecosystem

4.3.1. Nutrients

There are no established limits or national bottom-line for any nutrients in groundwater in the NPSFM. However, the direct toxic effects of some nitrogen compounds (nitrate nitrogen [NO_3-N] and ammonia [NH_3]) on invertebrates inhabiting subsurface groundwater-dependent ecosystems are potentially important, especially in low DO environments.

Available toxicity guidelines for nitrates were developed from chronic toxicity data for 30 species covering 9 taxonomic groups: freshwater fishes (12 species), crustaceans (7 species, including two amphipods), amphibians (4 species), molluscs (3 species), insects (3 species) and microalgae (1 species) (Hickey 2016). Six of these species are native to New Zealand. The guidelines recommend a nitrate concentration of 1.1 mg NO_3-N/L for high conservation value systems, which represents 99% species protection (Hickey 2016). This guideline is similar to the annual median threshold for A-band status (1.0 mg/L) in the NPSFM (MFE 2014).

None of the species used to develop these guidelines are obligate groundwater-dwelling species (i.e. species that are only found in groundwaters). Amphipods and other crustaceans dominate in groundwaters, and amphipods are considered to be more sensitive than most other invertebrates to many contaminants (Thomas 1993; Hickey & Martin 2009). However, there are no useful data on how groundwater species of any group differ from surface water species in their vulnerabilities to nitrate. Acute toxicity data on amphipods and other crustaceans that might inhabit near-surface groundwater habitats indicate a wide variability in sensitivity to nitrate concentrations with the amphipods *Eulimnogammarus toletanus* and *Echinogammarus echinosetosus* found to be most sensitive, therefore leading to a recommended maximum level of 2.0 mg NO_3-N/L for protecting the most sensitive freshwater invertebrate species (Camargo et al. 2005).

Surface waters are high in DO relative to many spring waters and most groundwater (Scarsbrook et al. 2007; Fenwick 2016), and especially relative to concentrations likely in finer pore microhabitats that comprise much of the volume of most aquifer systems. Information on the effects of nitrates under lower DO concentrations is scarce[8], but, because nitrate (and nitrite) blocks blood pigments from carrying oxygen (e.g., Alonso & Camargo 2003), their toxic effects are likely to be greater under reduced DO availability. Increased toxicity of nitrate at lower DO concentrations was demonstrated recently for a New Zealand freshwater crustacean (pers. comm., ID Marsden, School of Biological Sciences, University of Canterbury). Similarly, survival (96 hours) of marine prawns in 1.6 NH_3-N mg/L decreased from 67% at 5.7 mg O_2/L to just 10% with a halving of DO to 2.3 mg/L (Allan et al. 1990) (although ammonia acts in a slightly different way to nitrate and nitrite).

It is also important to consider the aquifers as a whole. Concentrations of nitrate nitrogen (and other dissolved substances) in water emerging from these springs are averages of concentrations for the entire catchment system comprising the three (or more) aquifers comprising Te Waikoropupū. Monitoring data show that nitrate nitrogen concentrations in excess of 2.0 mg/L are common in some alluvial parts of the system, with concentrations occasionally exceeding 8.0 mg NO_3-N/L in parts of the limestone aquifer in the lower Takaka valley (Stevens 2010). Such elevated concentrations indicate the potential for biodiversity and ecosystem functioning to be affected in those areas. Consequently, conservative limits for nutrients generally, and nitrate nitrogen in particular, seem advisable.

The combination of likely differences in the physiological effects of nitrate between the dominant invertebrates inhabiting surface water and groundwater, the reduced DO concentrations in groundwaters, and the apparent non-linear interactive effect of reduced DO on nitrate toxicity indicates the need for conservative limits for nitrate in groundwaters generally, and for Te Waikoropupū specifically. Pre-2000 data indicate that water emerging into the Main Spring basin from Main and Dancing Sands springs generally contained 0.30-0.40 mg NO_3-N/L (Figure 5). Concentrations have increased since the 1970s (and then decreased from 2013-2017) therefore conservative limits

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[8] Most toxicity investigations ignore the potential for any dissolved oxygen-toxicant synergistic effects, because manipulating dissolved oxygen is likely to alter the experiment's redox state and resulting equilibrium concentrations of nitrate, nitrite, ammonia and ammonium (e.g., Alonso & Camargo 2003, 2015).

are appropriate. For these reasons, we recommend a trigger for further management action in the range between 0.40-0.50 mg NO_3-N /L for Te Waikoropupū, in the absence of further evidence. All values in this range are very conservative and less than half of the value (1.0 mg NO_3-N/L) representing the transition point between A-band and B-band waterbodies for nitrate toxicity in the NPSFM. These concentrations are not critical levels where effects are likely or imminent, but rather levels representing a healthy ecosystem.

4.3.2. Clarity

Water clarity within the aquifer GDE is not monitored and is assumed to average that emerging from the springs. We note that natural land cover, especially forest in high rainfall catchments, may contribute coloured dissolved organic matter to surface water and groundwater, and that natural physical and biological processes usually remove this visible colour. Disrupting these processes and/or overloading them with excess dissolved organic matter, notably from intensive land use activities, has the potential to alter water clarity within the aquifer and water discharging from the springs. For this reason, future monitoring of groundwater quality at selected locations within the aquifer and catchment seems warranted.

4.3.3. Dissolved oxygen

Groundwater usually contains less DO than surface waters because there is no photosynthesis to produce oxygen, and only minimal contact with air to replace oxygen consumed by natural ecosystem processes while underground (Michaelis 1976). Thus, DO usually decreases with time underground in alluvial aquifers, although there may be oxygenation of groundwater in some karst systems if the water has access to the atmosphere (i.e. via underground aerated caverns). Water moves through aquifers at different speeds, so considerable spatial heterogeneity in DO content within and between aquifers is expected. For these reasons, it appears impractical to establish meaningful DO limits for more than specific points within individual aquifers; nor are there ANZECC or NPSFM DO trigger levels for groundwaters.

Concentrations measured recently near the Main Spring vent were lower than those measured by divers at the vent in the early 1970s, although the difference (about 10% or 1 mg/L) is only slightly greater than typical DO measurement uncertainty. Further reductions in DO in the aquifer may trigger release of phosphorus adsorbed to minerals present in the groundwater aquifer. This release occurs at higher DO concentrations for manganese (Mn)-bound phosphorus (starting at about 5 mg/L) and at lower DO concentrations for iron (Fe)-bound phosphorus (starting at about 2 mg/L) (Gibbs & Hickey 2012; Stumm & Morgan 1995). This phenomenon is well known for lakes and results in large releases of phosphorus to the bottom waters of lakes during anoxic periods. However, being a karst aquifer the risk of this occurring within Te Waikoropupū is low because phosphorus released will be adsorbed onto carbonate surfaces and/or effectively precipitated out as calcium phosphate (apatite) (e.g. Cable et al. 2002). It is important that phosphorus release is avoided as any increase could overcome the current apparent phosphorus limitation on plant growth, potentially triggering blooms of periphyton and macrophytes within the spring basin GDE and the downstream riverine GDE, changing their visual appearance and water quality.

It is important to maintain DO concentrations in Te Waikoropupū's aquifer GDE and spring basin GDE at no less than their current state because lower levels are likely to cause harmful physiological effects on some invertebrates in all three ecosystems. Lower DO levels would also alter water quality, algae and plant dynamics in surface water ecosystems, and ecosystem processes overall.

Because natural aquifer GDE biogeochemical processes deplete DO during groundwater's passage through an aquifer, natural aquifer flow regimes are essential to maintaining natural DO concentrations (assuming no confounding factors (e.g., no increase in organic carbon loads from anthropogenic sources)). Groundwater flow is driven principally by hydraulic gradient (or hydraulic head) and this reduces as water levels decline. Thus, water level is one of the key determinants of DO concentrations in subsurface GDEs.

4.3.4. pH

The only pH data directly relevant to the aquifer GDE appear to be Michaelis's (1976) records for samples taken by divers directly from the vent of Main Spring and Dancing Sands Spring. These records best represent the pH of pre-emergent groundwater. These averaged 7.5 (range 7.4–7.7, n = 7) and establish a baseline for this parameter in the absence of any guideline or trigger values for aquifer water pH.

Subsequent data on Te Waikoropupū water pH are more representative of spring basin GDE water, and the dynamic nature of processes within that basin probably explains much of the variability in these data. However, the trend of gradually increasing pH in spring basin GDE water since the early 1970s indicates a possible change in aquifer GDE water. Although this change may be inconsequential ecologically, its occurrence in tandem with increased nitrate nitrogen concentrations and decreased DO concentrations, adds to concern regarding an overall change in quality of water emerging from the aquifer GDE.

4.3.5. Water temperature

Water temperature within Te Waikoropupū's aquifer GDE appears to be constant at 11.7 °C. It is important that this does not change because many groundwater species appear adapted to life within narrow temperature ranges. Higher temperatures are likely to have greater effects because oxygen demands will be increased and oxygen solubility in water reduced. However, as the aquifer GDE is such a large underground system, temperatures are strongly buffered and unlikely to change.

4.3.6. *E. coli*

Aquifer GDE water emerging directly from both Main and Fish Creek springs met drinking water guidelines (for *E. coli*), based on single samples of water from both these locations (see Section 4.2.6).

4.3.7. Biological measures

There are no biological data for any direct assessment of the aquifer GDE's health, nor are there any standards or relevant data for comparison. Consequently, it is impossible to directly assess the health of this important ecosystem.

4.4. Potential risks to the aquifer and springs

The potential risks facing the ecosystem health of Te Waikoropupū include:

- *Water abstraction*—increases in consumptive abstraction directly from the aquifer or from the waterways contributing to the aquifer could reduce flows within the aquifer and from the springs, although there is not a 1:1 relationship between rates of abstraction and flow from the aquifer. Increased abstraction may also prolong periods of drying in the upper sections of Fish Creek and reduce flow velocities within parts of the aquifer with possible subsequent effects on DO concentrations. To avoid effects of water abstraction on ecosystem health, flow management options are currently being considered by the Takaka FLAG.
- *Increased sediment load*—because of its size and volume, the aquifer currently acts as an effective trap/filter for sediment from the surrounding catchment, part of the reason for the extremely high water clarity within Te Waikoropupū. It is important to avoid increases in sediment supply to the aquifers associated with land disturbance and erosion in the catchment generally. Controls on sediment supply are especially important in areas closer to the springs where shorter residence durations and surface and subsurface flow paths increase the risk of these materials being carried into the spring basin.
- *Increased nutrient loads*—concentrations of nitrogen and phosphorus need to be maintained within levels that will help avoid excessive growth of aquatic plants and algae. The ratio of nitrogen to phosphorus in water from Te Waikoropupū (around 40:1) suggests that phosphorus concentrations, rather than nitrogen concentrations are more likely to be limiting plant growth. It is also important to avoid concentrations of nitrate nitrogen reaching levels that could be toxic for sensitive aquatic organisms. Monitoring of phosphorus concentrations needs to reliably detect low phosphorus concentrations present in Te Waikoropupū spring waters.
- *More pathogens*–levels of microbial contaminants in Te Waikoropupū are currently very low. It is important to maintain the ability of the aquifer to trap/disinfect any

bacterial contamination getting into the aquifer and to avoid stock access to surface waters in the vicinity of Te Waikoropupū.

- *Increased organic matter loads*—dissolved and particulate organic matter such as leaves, wood, and humic acids (sourced from vegetation growing in the surrounding catchment) is washed into the aquifer and is effectively trapped and broken down by the microorganisms and other groundwater fauna living there. This process is responsible for the extremely low concentration of dissolved organic matter and thus the high water clarity of Te Waikoropupū. DO is used in the process of breaking down organic matter, and being deep underground, DO levels cannot be replenished through exchange with the atmosphere. This explains the relatively low DO concentrations of water from Te Waikoropupū (and other groundwater-dependent ecosystems). If there was an increase in the load of organic matter to the aquifer there is a risk that more oxygen would be used up in the breakdown of this material. Reductions in DO levels within the aquifer could alter the microbial community in the aquifer and the effectiveness of breakdown processes and thus water clarity. It could also lead to change in geochemical processes resulting in release of contaminants such as iron and manganese—together with any phosphorus bound to those minerals. Therefore it is important to avoid any increases in inputs of organic matter to the aquifer, particularly of organic wastes from anthropogenic sources that could break down and consume large amounts of oxygen. The best way to monitor this risk is to examine DO and coloured dissolved organic matter concentrations in Te Waikoropupū Springs and in waters feeding the aquifer. Baseline monitoring of dissolved and total manganese and iron concentrations should also be continued as key indicators of aquifer geochemistry processes.
- *Hydrology*—is complex in Te Waikoropupū with the salinity (as measured by electrical conductivity, EC) varying markedly with flow through the springs. The salinity of the spring increases at higher flows—caused by a postulated ‘venturi’ mechanism which entrains greater amounts of seawater from deep areas of the aquifer as the groundwater flow velocities increase. This process results in a variable combination of old marine water and freshwater depending on the flow at the springs—a process which may confound the interpretation of long-term water quality monitoring programmes using relatively infrequent sampling. Routine monitoring of conductivity (and possibly chloride) should be included with all water quality monitoring to assist in interpretation of this process.
- *Climate change* is expected to cause a rise in average temperatures and more extreme fluctuations in weather and flows in the upper South Island. Water temperatures within the aquifer are effectively equilibrated with the temperature of the marble stratum and strongly buffered from changes in surface temperatures. Therefore, the effects on average temperatures are expected to be minor.

  However, more severe and prolonged droughts interspersed with more severe floods could influence conditions within the aquifer and Te Waikoropupū. More severe flooding could lead to increases in sediment and organic matter loads, while prolonged droughts may result in lower flows from Te Waikoropupū and more prolonged drying in the upper sections of Fish Creek. Another possible effect of climate change on the spring would be modification of the water fluxes in the aquifer, which may impact on the confinement status of the aquifer and the contribution of sea water. Continuous monitoring for conductivity is one of the parameters that would contribute to understanding climate-related changes to Te Waikoropupū water quality.

- *Invasive species*—the introduction of invasive aquatic plants, such as *Lagarosiphon* or *Didymosphenia*, would result in substantial change to the biodiversity and habitat quality within Te Waikoropupū's spring basin ecosystems. Similarly, introduction of pest fish, like koi carp and *Gambusia*, would have a marked effect on natural biodiversity and ecological values within the spring basin GDE by altering the habitat quality and preying on other species.
- *Cobb Power Scheme operation*—the storage of water in the Cobb Dam during high flow periods and subsequent release of water during lower flow periods has resulted in increased average flows from Te Waikoropupū (Weir & Fenemor 2015). Changes in flow in the upper Takaka River resulting from short-term changes in generation at the Cobb powerhouse lead to a delayed response in spring flow at Te Waikoropupū (Figure 19). Due to the long water residence time within the aquifer, these short-term flow responses are the result of changes in pressure (hydraulic head) within the aquifer rather than a direct flow connection. Dramatic changes in the operating regime for the Cobb Power Scheme (e.g. higher peak flows; generation to meet spot electricity prices) might have substantial changes on flows at Te Waikoropupū, however, the operating regime of the scheme is controlled by their resource consent conditions.
- *Arthur Marble Aquifer management outside the Takaka catchment*—due to the nature of the mixed system at the Main Spring (shallow young water mixed with older water recharged from the karstic uplands) all of the aforementioned risks could apply to a limited extent outside the Takaka catchment in areas with marble and yet impact water quality at the spring, albeit through a delayed response. Therefore consideration should be given, when drafting the relevant management plans to impacts at the springs.

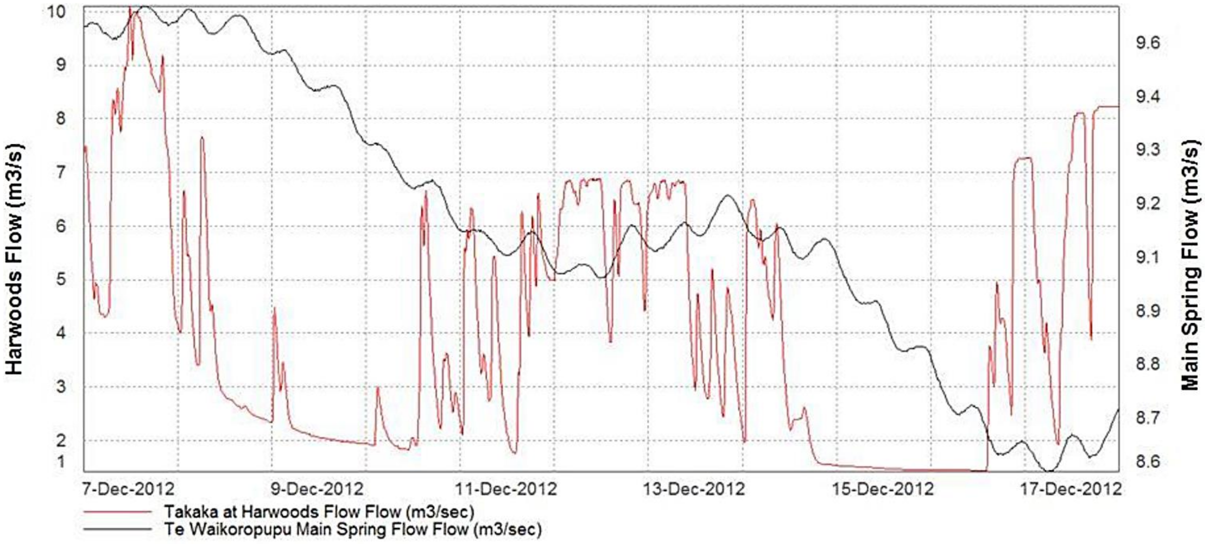

Figure 19. Graph showing the relationship between flows in the upper Takaka River (at Harwoods) and flows in the Main Spring. Tidal fluctuations in flow at the Main Spring are also shown.

5. RECOMMENDATIONS FOR OBJECTIVE SETTING

5.1. Critical monitoring parameters

After considering available data and potential threats to the health of Te Waikoropupū, the science panel considered that water clarity, DO, and the concentrations of nitrate nitrogen and dissolved reactive phosphorus were critical parameters for ongoing monitoring and management of Te Waikoropupū. Measurements should be made within the spring basin GDE, the aquifer GDE, waters feeding the aquifer and, as a lower priority, the riverine GDE.

The extremely high clarity of water within Te Waikoropupū is arguably the aquifer and spring system's most significant feature. Thus, this clarity must be maintained. Monitoring clarity and the processes underlying it is essential. The science panel recognised the significant logistical and technical challenges of frequently monitoring the extremely high water clarity in Te Waikoropupū, but considered that the very high and internationally significant natural values justify such investment. Trials of different approaches for measuring water clarity are currently underway to determine if regular monitoring is feasible.

Dissolved oxygen levels within Te Waikoropupū are naturally low due to the long residence time for water within the aquifer and the breakdown of organic matter that occurs naturally within the aquifer, a process that consumes oxygen. Measurements of DO at the Te Waikoropupū Springs provides an indication of the health of the aquifer GDE and any reduction could be related to changes in flow and organic matter loads to the aquifers, while measurements in waterbodies feeding the aquifers will help identify any issues prior to them being evident at the springs. Technological improvements in DO measurement over the last few decades make continuous monitoring feasible.

Concentrations of nitrate nitrogen and dissolved reactive phosphorus may affect the growth of aquatic plants and algae within Te Waikoropupū. At relatively high concentrations nitrate nitrogen can have toxic effects on sensitive aquatic species, therefore avoiding these effects is important. The Friends of Golden Bay have been monitoring these parameters weekly in the Main Spring and Fish Creek Spring since late 2015 and demonstrated that concentrations of these parameters are highly consistent from week to week. Ongoing monthly measurements (with a suitably low analytical detection limit) of nitrate nitrogen and dissolved reactive phosphorus in upwelling spring water will be sufficient to monitor any long-term changes in these parameters in the future. It is also important to maintain consistency in the analytical laboratory used, since changes in laboratory and analysis method have the potential to introduce additional variability to the data record.

Other parameters that should be monitored include:

-Invertebrates
-Manganese
-Temperature
-pH
-Chloride
-Macrophyte cover
-Dissolved organic carbon
-Ammoniacal nitrogen
-Conductivity
-Iron

Continuous measurement of temperature and conductivity (along with DO) is advised.

5.2. Triggers for further action

In keeping with the philosophy of the NPSFM (2014) to maintain and improve the overall quality of freshwaters, the FLAG is considering a wide range of quantity and quality management provisions that will apply straight away to help maintain the values identified for Te Waikoropupū. The science panel has recommended triggers for further management action relating to the four key parameters mentioned above.

The goal behind these recommended triggers is to maintain Te Waikoropupū in its current state, rather than derive the triggers from various national default guidelines which, as mentioned above, were based on a small number of rain-fed rivers and are not necessarily applicable for the groundwater-dependent ecosystems comprising Te Waikoropupū.

The panel had to balance the importance of identifying any issues of concern promptly, so actions can be implemented quickly, versus the risk of triggering occasional one-off breaches that only reflect natural variability or measurement error associated with a parameter, and thus do not justify implementation of significant management actions. This was a significant challenge given that water clarity, for example, has only been measured once in Te Waikoropupū and that there are significant logistical and technical difficulties associated with measuring such high water clarity on a regular basis.

After considering these issues the following recommendations on triggers for further action were agreed:

- water clarity[9] — 50 m
- dissolved oxygen — 45–50% saturation
- nitrate nitrogen — 0.40–0.50 mg/L
- dissolved reactive phosphorus — 0.006–0.010 mg/L.

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[9] This should be considered as an interim limit to potentially be revised if regular clarity monitoring is possible, since short-term variability in clarity, although expected to be low, is currently unknown.

Ranges, rather than single numbers, have been provided here for DO, nitrate nitrogen and dissolved reactive phosphorus to allow the FLAG to choose limits/triggers from within these ranges based on the level of risk that they are comfortable with and how they interpret the maintain and improve requirements of the NPSFM.

The annual median is considered as a suitable measurement statistic to compare with these triggers (assuming monthly data collection and recognising that natural variability will occur), although for water clarity it will depend on what monitoring options are practical. A longer review period is appropriate for parameters that are measured less frequently.

An important point to consider in relation to these recommended triggers for further action is the kind of actions that should take place if these triggers are exceeded. Further monitoring to try to identify mechanisms and potential solutions for the trigger breach will be part of the likely actions required, but the science panel emphasises that this is not the only action that should be implemented. Depending on the parameter, potential actions could include:

- controls on stock access to waterways, karst sink holes and other areas where recharge of the aquifer is occurring (both within and outside the Takaka surface water catchment)
- reviews and improvements to waste water system management (both within and outside the Takaka surface water catchment)
- analysis and implementation of additional riparian restoration efforts
- further controls on the operation of the Cobb Power Scheme
- further controls on water abstraction
- education and/or regulation relating to the need for further investment in best management practices on farms within the aquifer recharge area and in the immediate vicinity of Te Waikoropupū.

5.3. Monitoring sites

Te Waikoropupū is more than just the springs, but part of a connected system representing the waters feeding the aquifer, the aquifer GDE, the spring basin GDE and the downstream riverine GDE. To reflect this, monitoring is ideally required in all parts of the system.

We support the ongoing monitoring close to the Main Spring vent, which provides an averaged assessment of the water quality within the aquifer GDE. However, it is important to note that there are variations in the chemical composition of the different spring vents, reflecting different water sources and heterogeneity within the aquifer. It is therefore essential to ensure consistency in the sampling location to continue long-term monitoring. Samples should continue to be collected from the viewing platform as close as possible to the Main Spring vent.

There may be delays before a response is evident at the springs considering the large volume of the aquifer and the long average residence time of water moving through the aquifer. Therefore, we also support the proposed addition of a new monitoring site on the Takaka River at Lindsays Bridge, which is just upstream of the area where large losses of river flow to the aquifer occur, losses that are representative of a considerable proportion of the water that recharges the aquifer. We also support the ongoing monitoring of a network of groundwater wells throughout the Takaka River valley to identify any concerns within groundwaters along the flow paths to the springs.

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7. APPENDICES

Appendix 1. Agenda for Ecosystem Health of Waikoropupū Springs Workshop—31 March 2016.

Objectives:

1. Summarise existing physicochemical and biological data time series for Te Waikoropupū Springs and connected water bodies to improve understanding of the current state of the springs and changes over the last 10-20 years
2. Based on results of 1., and expert knowledge, describe ecosystem health of the springs and highlight the major anthropogenic risks to spring health
3. Provide recommendations on relevant attributes (and bands) that can be used in objective-setting processes

Agenda

10:00-10:30 COFFEE
10:30-10:35 Welcome (Roger)
10:35-10:55 Objectives of the workshop and relationship with Takaka FLAG (Justin Kitto, Joseph Thomas/Lisa McGlinchey TBC)
10:55-11:15 Summary of water resources in the Takaka Catchment (Joseph Thomas)
11:15-11:35 Trends in nitrate-N, DRP and macroinvertebrates in Te Waikoropupū Springs (John Stark)
11:35-11:55 Summary of other water quality data from Te Waikoropupū Springs and factors potentially contributing to observed trends in water quality (Magali Moreau)
11:55-12:15 Sustainability of Te Waikoropupū Springs Aquifer ecosystem (Graham Fenwick)
12:15-12:35 N modelling for Te Waikoropupū Springs and land use scenarios + Don Mead water quality trend analyses (Andrew Fenemor)

12:35-1:30 LUNCH

1:30-1:50 Developments in trend analysis – and potential fish hooks to be avoided (Graham McBride)
1:50-2:10 Nitrate toxicity and water hardness (Chris Hickey)
2:10-2:40 Discussion on current state of the Springs and changes over the last 20 years
2:40-3:00 Discussion on the major anthropogenic risks to Spring health

3:00-3:15 AFTERNOON TEA

3:15-3:45 Discussion on relevant attributes relating to Spring health
3:45-4:15 Discussion on bands and limits that might be recommended to the FLAG to achieve their objectives
4:15-4:30 Next steps

Appendix 2. Physicochemical data collected at Te Waikoropupū. A green √ indicates that data were collected during the monitoring occasion, or at any stage during the monitoring period. Data were not necessarily collected on all monitoring occasions during a monitoring period.

Sampled by	**pH field**	**DO**	**Temp °C**	**Total solids[4]**	**pH lab**	**NH_4-N**	**As**	**HCO_3**	**Br**	**Ca**	**CO_3**	**Cl**	**F**	**Fe**	**Mg**	**Mn**	**NO_3-N**	**NO_2-N**	**P**	**K**	**SiO_2**	**Na**	**SO_4**	**Total solids[5]**
Michaelis (1970, 1971)[1,3]		√	√	√	√	√				√		√		√	√		√	√	√	√	√	√	√	√
Stewart & Downes (1979)[1,2]						√		√		√		√	√	√	√	√	√			√	√	√	√	
Mueller (1992)[1,2]										√					√		√			√		√	√	
Cawthron (1999)[1,3]	√		√	√		√		√		√		√		√	√	√	√			√		√	√	√
TDC (1986-2008)[1]	√		√	√	√			√	√	√		√	√	√	√		√		√	√	√	√	√	
TDC (2014-2016)[2]	√	√	√	√	√				√	√		√			√		√	√	√	√	√	√	√	
GNS (1990-2016)[1]	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Friends of Golden Bay (2015-2017)[1,2]			√	√								√					√		√					

Notes

1. measurements taken at Main Spring
2. measurements taken at Fish Creek
3. measurements taken at Dancing Sands
4. (electrical conductivity) µS/cm at 25 degrees, field
5. (electrical conductivity) µS/cm at 25 degrees, lab