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Author:

OPMCSA - Intern - Rachel Teen

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Water-borne illnesses in Aotearoa New Zealand – past, present, future

Rachel Teen, OPMCSA Fellow

Executive Summary

This literature review identifies waterborne illness outbreaks that have occurred in Aotearoa New Zealand, provides a snapshot of the current situation, and identifies some ways that may assist to anticipate future waterborne illness outbreaks.

Data has been collected using a scoping review method to identify and map reporting of, and research about, waterborne illness outbreaks within Aotearoa. The literature covers the types of breaches to, and available evidence for, drinking water safety; presents what research has been conducted; and notes requirements for the future.

Prior to the Havelock North contamination event, research that was specific to New Zealand's unique, diverse, environment, has covered significant issues such as those in heavily populated urban and rural farming environments, the effects of climate change, the continuous call for multibarrier approaches, and the identification of economic issues – on the one-hand as drivers of the increase in disease and on the other as inhibitive of adequate measures to prevent outbreaks.

The Darfield and Havelock North outbreaks significantly affected the drinking water supply (DWS) environment. While the Darfield event shocked and reminded authorities of the vulnerabilities of New Zealand's drinking water distribution systems it did not result in a nationwide overhaul.

The 2016 contamination events at Havelock North did.

This, the largest reported Campylobacter outbreak in the world, finally accelerated a long-called-for, new legislative framework for New Zealand's drinking water. Numerous legislative actions and systemic changes were set in motion and consequently actioned. Subsequent studies within Aotearoa have solidified the correlation between land activities and unproportionally high rates of illness from waterborne diseases – particularly Campylobacter, Cryptosporidium, and Giardia. On-going national reporting shows no sign of immediate case reductions, particularly with rising temperatures and more extreme precipitation events predicted into the future.

However, there are approaches and tools that can assist to anticipate the levels of waterborne illness outbreaks from large and small DWS systems throughout Aotearoa. The evidence shows that recognising humans are not constantly dependable would be a significant starting point. If individuals and departments operate in isolation to simply tick off requirements to meet regulations, then DWS systems will continue to fail. The application of an integrated risk management approach that facilitates inter-departmental and inter-organisational cooperation - using reliable, integrated practices and processes – will inevitably reduce the risk of outbreaks. Investment in contemporary, online monitoring, and surveillance and maintenance tools in conjunction with predictive water modelling technologies, is fundamental.

Contents

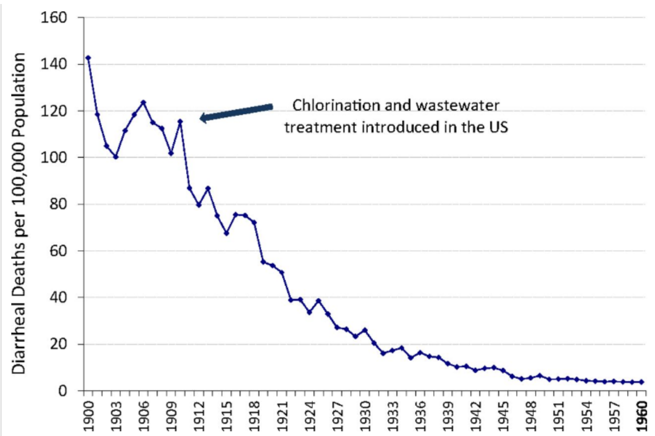
1. Introduction

This literature review endeavours to capture New Zealand's experience of waterborne illness outbreaks. It delves into New Zealand's drinking water literature regarding the occurrence of bacterial protozoan transmissions from Campylobacter, Cryptosporidium, and Giardia disease. The final section synthesises various studies regarding ways future waterborne illness outbreaks could be anticipated and prevented. Previous work and reports have been used to compile a list of New Zealand's waterborne illness outbreaks (refer to Appendix 1).

1.1 Global overview of waterborne illness outbreaks

According to the USA's Environmental Protection Authority Climate Change Adaptation Resource Centre (2024), the climate impacts on water quality, and therefore human health, primarily originate from rainfall event runoff, erosion and sedimentation, and harmful algal blooms – all of which they warn are likely to increase as global temperatures rise. It is the role of environmental protection authorities and central government agencies to alert their regional and local governments to the dangers of higher temperatures, precipitation variances, and significant runoff events that can impact reservoir water quality. To try and reduce these landscape-scale risks, such agencies recommend maintenance and improvements through water catchment management practices that minimise pollutant runoff and promote groundwater recharge and reservoir management methods (Australian Government, 2022; Environmental Protection Agency, 2021; National Institute of Environmental Health Sciences, 2022; United States Environmental Protection Agency, 2024).

Since the turn of the nineteenth century, global improvements in research and the development of urban water supply and wastewater treatment systems have been made to prevent waterborne illness outbreaks. For example, in the United States of America, diarrheal death rates from cholera and dysentery dropped significantly from 1900 to the 1940s. Refer to Figure 1 below.



Diarrheal death rates in the United States from 1900 to 1960 per 100,000 population showing the rapid drop associated with the development of urban water and wastewater treatment systems, which began to be introduced around 1909. Diarrheal death rates include both cholera and dysentery. Data from refs. 100 and 101.

Figure 1: Diarrheal death rates in the United States of America from 1900 to 1960 per 100,000 population, showing the rapid drop associated with the development of urban water and wastewater treatment systems, which began to be introduced around 1909. Diarrheal death rates include both cholera and dysentery (Gleick, 2018).

However, the presence of parasitic protozoa in water distribution systems (WDS) still present significant health risks worldwide (Efstratiou et al., 2017). WDS networks are vulnerable to deficiencies, particularly concerning routine maintenance requiring water outages, and have the potential to (re)contaminate treated water, causing an increased risk in gastrointestinal cases for consumers (Ercumen et al., 2014). Guidelines for drinking water quality, provided by the World Health Organisation state the standard value for microbiological parameters as 'zero' – bacterial parameters should be completely absent from 100 ml of water[1] and protozoa from 10 litres (World Health Organization, 2022). While global waterborne illness outbreaks continue to cause considerable direct and indirect medical costs, and productivity losses, they also create a significant loss of trust among consumers using public water supplies (Viñas et al., 2019). More robust and standardised prevention strategies for water safety have long been called for, in conjunction with regulated outbreak reporting to better understand the impacts of waterborne pathogenic protozoa on public health (Karanis et al., 2006).

In 2006, a study carried out by Karanis et al. (2006) identified over 325 reported waterborne illness outbreaks of parasitic protozoan disease since a selection of countries had begun collating such statistics. A comprehensive update across a slightly broader number of countries by Efstratiou et al. (2017) revealed at least 381 reported outbreaks between 2011 and 2016. While malaria stands out as a major killer worldwide and outbreaks are not always recorded (World Health Organisation, 2021) the review by Efstratiou et al. (2017) found Cryptosporidium as the most common etiological agent (63%) followed by Giardia spp at 37%. With such exponential increase in reported outbreaks it is crucial to devise prevention strategies for drinking water safety against the presence of protozoan parasites in aquatic ecosystems (Karanis et al., 2006). Efstratiou et al. (2017) compiled a list of waterborne Cryptosporidiosis and Giardiasis outbreaks between 2011 and 2016 and found at least 381 documented outbreaks attributable to waterborne transmission of parasitic protozoa. According to Efstratiou et al.'s analysis (2017) nearly half (49% or 188 outbreaks) occurred in New Zealand and Australia, 41% in North America, and 9% in Europe. Refer to Figure 2.

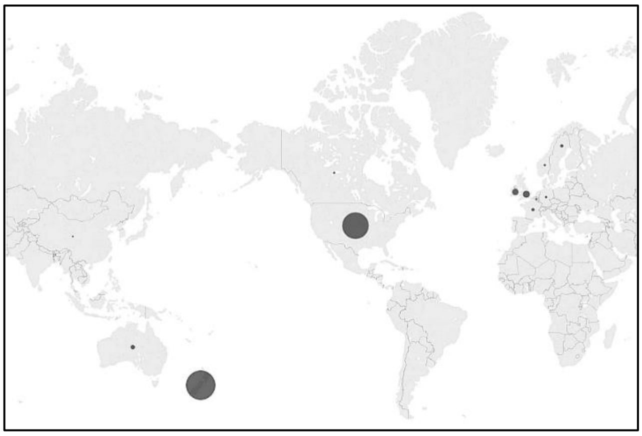


Figure 2: Global distribution of reported waterborne cryptosporidiosis and Giardiasis outbreaks summarised from a 2011-2016 literature review (Efstratiou et al., 2017).

[1] Large water supplies' bacterial parameters must not be present in 95% of samples taken over 12 months.

Their work demonstrated the importance of epidemiological records to help understand the burden of waterborne diseases globally, particularly for developing countries that lack reliable systems for information gathering (Efstratiou et al., 2017). They also raised the point that while progress in reporting and monitoring systems was advancing, the increase in reports may not necessarily equate to worsening conditions across regions. For example, the stated that the efficiencies of New Zealand's reporting systems likely underpin the high proportion of outbreak reports (Efstratiou et al., 2017).

1.2 Waterborne illnesses in New Zealand

New Zealand's landscapes are spectacularly diverse – sand dunes, active volcanoes, braided rivers, alps, and fiords – allowing for a vast range of land ecosystems to develop – 152 significant classes and 71 rare ecosystems – all with distinct plants and animals (Singers & Rogers, 2014). Before humans arrived at the Archipelago of Aotearoa New Zealand, native bush and birdlife ecosystems flourished (Ministry for the Environment & NZ, 2024). Māori arrived between 900 and 1200 A.D. and modified the environment, and by the end of the 1800s, European arrival and activities had also begun to alter original ecosystems. Native bush clearance and the establishment of agricultural pastureland have resulted in about half the total land area allocated for agriculture, forestry, and housing (Ministry for the Environment & NZ, 2024).

As populations have increased and immigrated to these shores, agricultural activities have intensified, and small settlements have become towns or cities. With this increased human activity also comes an increase in parasitic protozoan transmission (Ministry for the Environment, 2022). The effects of waterborne illness are very often painful, sometimes leading to death. The variables that align and culminate to cause such discomfort and disruption are numerous, complex, and intricate. Consequently, the water-borne illness research field is vast and varied. Across New Zealand's rural landscape, many animals are farmed within the vicinity that drinking water is sourced from rivers, lakes, and groundwater (Ministry for the Environment, 2020; Snel et al., 2009). The use of these water sources for drinking water supplies can be perceived as a good indicator of its mauri|health; however, when activities around these waterbodies are not adequately managed they become contaminated and people become ill (Taumata Arowai, 2023). Such contaminations have been particularly frequent in rural communities and for marae who rely on water from unfiltered systems such as tank water and groundwater wells in intensively farmed areas (Harmsworth et al., 2016; Hobbs et al., 2024). Increased risk of contamination is likely to occur with extreme rainfall events and higher temperatures (Harmsworth et al., 2016; Lal et al., 2013; Wilson et al., 2011).

By international standards, New Zealand has high incidence rates of potentially waterborne diseases, particularly Campylobacteriosis, Cryptosporidiosis, and Giardiasis (Weinstein et al., 2000). They are particularly prevalent in several towns and cities, thereby increasing health risks to drinking water consumers (Phiri et al., 2020). The Ministry of Health aligns to the WHO's no or low tolerance guidelines and cases of enteric diseases are recorded by public health personnel in New Zealand's national database known as EpiSurv (King et al., 2011).

While the Ministry of Health provides a comprehensive schedule of diseases that must be notified to the Medical Officer of Health[2], a specific waterborne derivative diseases factsheet from Auckland Regional Public Health (ARPH) provides a useful list for this review. Refer to Table 1.

Table 1: ARPH promotional flyer to educate the public about notifiable enteric diseases (Health New Zealand Te Whatu Ora, 2024).

Notifiable enteric diseases:	**Waterborne condition:**
Campylobacteriosis (bacteria)	Water contaminated with *E. coli*
Cholera (bacteria)	Water contaminated with *vibrio cholera*
Cryptosporidiosis (protozoa)	Water contaminated with *Crypto* parasites
Giardiasis (protozoa)	Water contaminated with *Giardia Lamblia*
Hepatitis A & E (viral)	Water contaminated with the *Hepatitis* virus
Listeriosis (bacterial)	Water contaminated with *Listeria monocytogenes*
Norovirus / rotavirus (viral)	Norovirus from food and waterborne outbreaks; Rotavirus = contaminated DW
Outbreaks of acute gastroenteritis	
Salmonellosis (bacterial)	Water contaminated with *Salmonella*
Shigellosis (bacterial)	Water contaminated with *Shigella*
Typhoid and paratyphoid (bacterial)	Water contaminated with *Salmonella typhi*
VTEC/STEC (verotoxin/Shiga toxin-producing E. coli) (bacterial)	Water contaminated with a subset of *E. coli*
Yersiniosis (bacterial)	Water contaminated with *Yersinia bacteria;* Also, poorly handled food, especially pork.

[2] Notifiable diseases | Ministry of Health NZ

1.3 New Zealand's WBI report monitoring and current regulatory framework.

This section summarises the current monitoring systems and regulatory framework for Aotearoa. Before the early 1990s, Water Information New Zealand (WINZ) managed the repository for all water-related monitoring and test results with the Institute of Environmental Science and Research (ESR) on an ad-hoc basis (Hoque et al., 2004). Over the years, drinking water information has not been gathered for supplies serving less than 101 people, self-supplies, or water carriers. Therefore, 944,000 (18.6%) people sourced drinking water outside the regulations enforced by the Health Act of 1956, i.e., self-supplies from rainwater tanks and bores.

During the mid-2000s, the New Zealand government faced mounting evidence and increasing incidences of notified cases of waterborne illness. They commissioned ESR to provide a preliminary report on the relationship between New Zealand's drinking water quality and waterborne gastrointestinal disease (GID) and whether the Drinking Water Standards for New Zealand (DWSNZ) were optimal (Ball, 2007). The report, a significant milestone in New Zealand's understanding of waterborne outbreaks, revealed that an average of 16.8 such incidents occurred annually, affecting 145 people. This data underscores the importance of the ongoing efforts to provide safe water for the entire population.

The Ministry for the Environment proposed National Environmental Standards for sources of human drinking water (Ministry for the Environment, 2007) and the Ministry of Health (2007) produced a guide to pathogens for small drinking water supplies and a guide to the new drinking water standards that had come into force (Nokes, 2008). By 2009, the Ministry of Health had contracted ESR to produce a summarised resource, complete with worksheets, for health professionals, planners and small water suppliers who sought information about the linkages between water supplies and health and the impacts of climate change (Lange & Gregor, 2009). A review of the WINZ and ESR process was undertaken by Wood (2011). By 2017, significant improvements had been made to New Zealand's monitoring systems. All 835,000 data results from the WINZ database were merged into a new system, Water On-Line. This online tool not only streamlined updates but also improved access to and the integration of drinking water information, marking a significant step forward in our efforts to ensure water safety (Eurofins, 2021).

ESR annually compiles statistics from health professionals who, under the Health Act 1956, are required to inform their local medical officer of health any suspected or diagnosis of notifiable disease. Since 1997, all notified data has been entered into the EpiSurv database via a secure web-based portal, and the definitions for notification of conditions and diseases are available in the frequently updated *Communicable Disease Control Manual* available online from the Ministry of Health. From December 2007, all laboratories are required to report any illness cases from the MoH's schedule of diseases to medical officers, and these notifications form the basis for surveillance and control of such diseases throughout New Zealand (ESR, 2021). The Epidemiology Team and Health Group staff at ESR generate regular and ad hoc reports from the EpiSurv data and publish the results on www.surv.esr.cri.nz. There are various critical components and communication channels involved in reporting notifiable diseases. Refer to Figure 3.

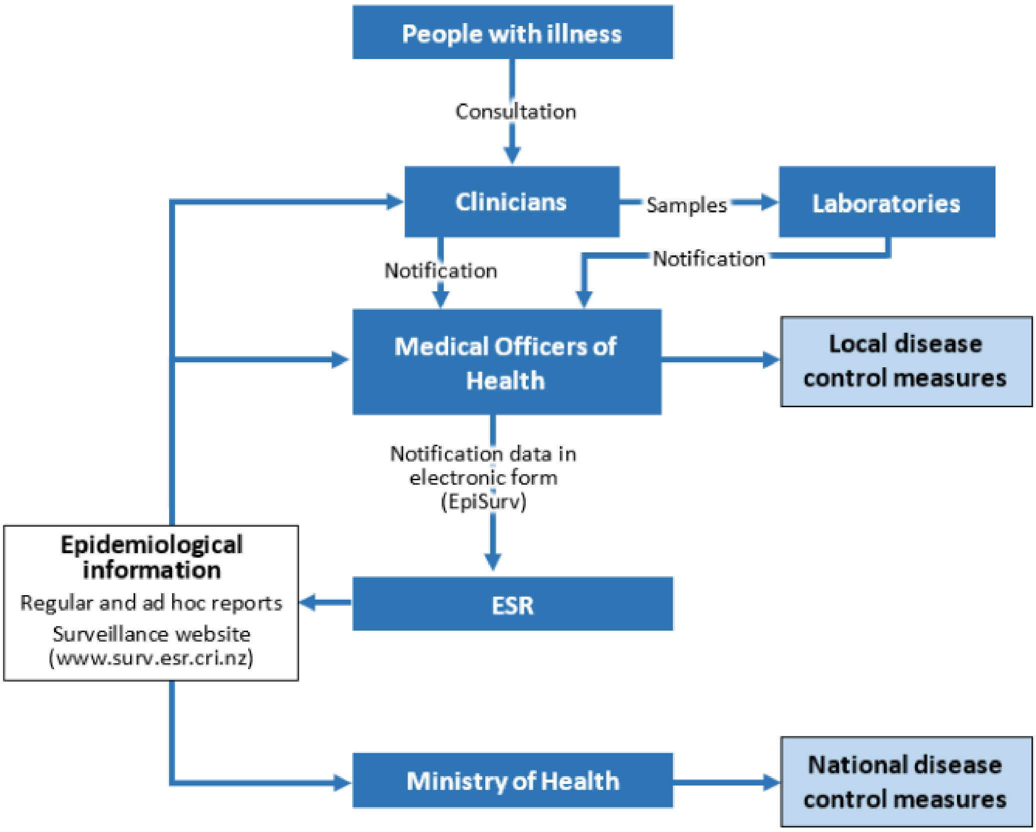


Figure 3: Key components and information flow surveillant notifiable disease across New Zealand.

New Zealand's Water Service Act commenced on 15 November 2021 to establish new drinking water standards and regulate all individuals and organisations supplying drinking water. Taumata Arowai was also established earlier that year as an independent Crown entity for water services and regulations, thereby taking over responsibilities for water regulation from the Ministry of Health[3]. Taumata Arowai works collaboratively with other central government agencies and organisations across New Zealand, including with whānau, hapū, and iwi Māori, Crown entities (Ministry for the Environment, Ministry of Health, and Department of Internal Affairs), public health units (PHUs) alongside regional, city and district councils, drinking water suppliers, and water management companies.

As the regulator, Taumata Arowai works to influence the water services sector toward best practices and continuously improve public health outcomes (through access to safe drinking water), the environment (land, rivers, and coasts) and drinking water, wastewater, and stormwater services. Any individual or organisation supplying water to the public must be formally registered with Taumata Arowai and compliant. Various government agencies have different roles and responsibilities to all work to maintain water management standards; refer to Figure 4.

[3] Excluding domestic self-suppliers.

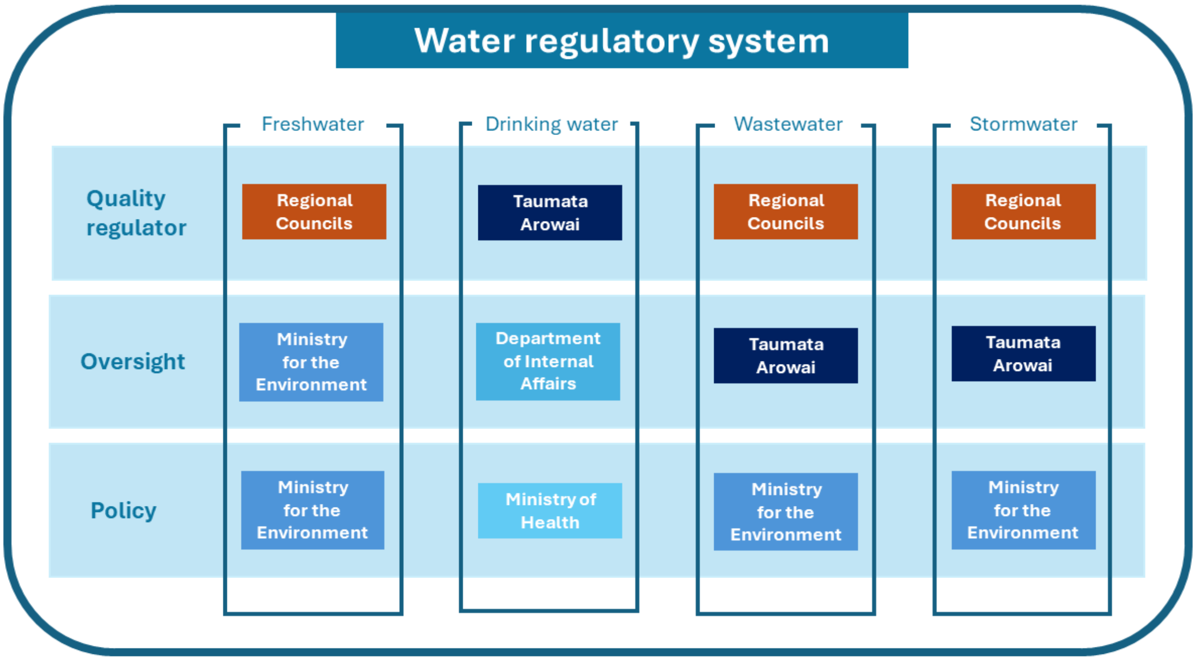


Figure 4: New Zealand's current drinking water, wastewater, and stormwater regulatory framework Source: Taumata Arowai (NZ Government, 2024).

In general, water quality compliance across Aotearoa is highest for larger suppliers and decreases through the supply sizes to medium, minor, and small population supply size categories (MoH, 2021). Table 2 shows the number of people who are receiving drinking water that is compliant with the Health Act 1956 and the *Drinking-water Standards for New Zealand 2005 (revised 2018)*.

Table 2: Population of consumers under compliant drinking water systems (MoH, 2021)

Compliance category	Number of people	Percentage under compliance	Percentage change
Bacteriological	3,945,000	95.2	-0.1
Protozoal	3,313,000	80.0	+1.3
Chemical	4,104,000	99.1	+1.6

Table 3 below provides spatial context for the number of people residing within each of New Zealand's District Health Board regions and under their responsibility. It lists a breakdown of the population for each district as of 2021.

Table 3: District Health Board populations 2021.

District Health Board (DHB)	Population
Northland	197,900
Waitemata	639,400
Auckland	499,100
Counties Manukau	601,300
Waikato	445,200
Lakes	118,400
Bay of Plenty	269,800
Tairawhiti	51,500
Taranaki	126,600
Hawke's Bay	181,400
Whanganui	69,100
Mid-Central	189,100
Hutt Valley	160,300
Capital & Coast	326,800
Wairarapa	49,900
Nelson Marlborough	164,100
West Coast	32,700
Canterbury	586,400
South Canterbury	62,200
Southern	351,400
TOTAL	5,122,600

2. Methodology

A scoping review has been carried out to identify and map the research and evidence of waterborne illness outbreaks specific to New Zealand. The review identified the types of available evidence in this field, clarified the essential definitions and concepts within the literature, examined how research has been conducted in the field, identified significant characteristics and gaps, and, if required in the future, could go on to be used as a precursor to a systematic review engaging a group of researchers (Munn et al., 2018; Peters et al., 2015).

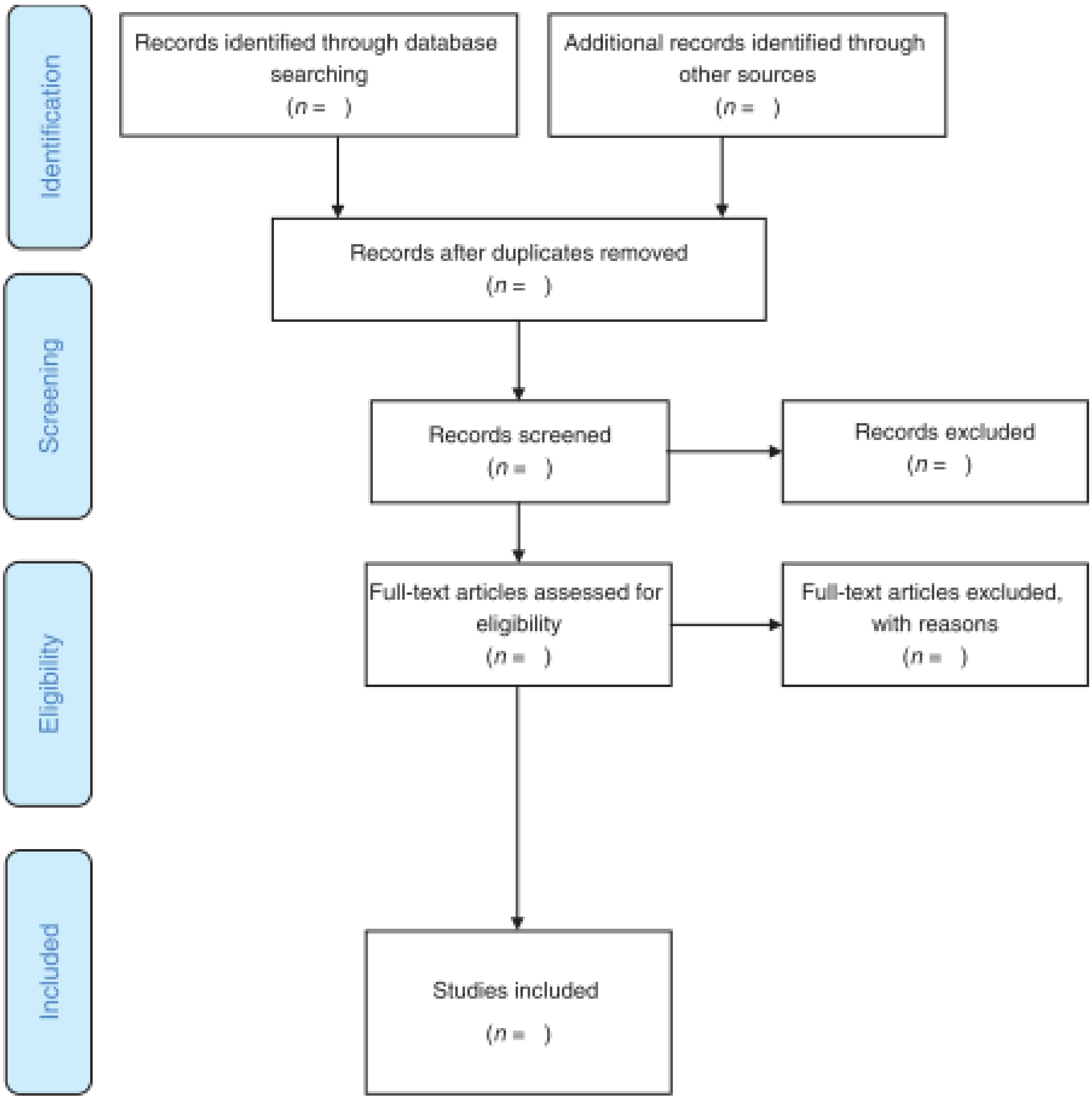


Figure 5: Flow diagram for the scoping review process (Peters et al., 2015).

2.1 The literature search

As a well-regarded bibliometric database, Scopus was used for its extensive range and interdisciplinary coverage of peer-reviewed material (Huddleston et al., 2022). While widely used for social science research, Scopus has been reported as having a bias toward the natural sciences and engineering (38%) (Huddleston et al., 2022). The Scopus search did not include 'AND New Zealand', so peer-reviewed literature could provide a global context and understanding of waterborne illness research and trends. A search was also conducted on the PubMed database using 'waterborne illness outbreaks' specific to New Zealand. Many results for this search had previously been found from SCOPUS. The third database to be searched was Google Scholar to explore a broader range of data (Gerlak et al., 2018), and "New Zealand" was added to geographically target these searches. Finally, a review of the University of Auckland library database using "waterborne illness outbreaks New Zealand" was undertaken to cross-check findings from Scopus, PubMed, and Google Scholar and increase the capture of New Zealand-specific literature.

Search 1 SCOPUS: TITLE-ABS-KEY (waterborne illness outbreak)

Search 2 PubMed: TITLE-ABS-KEY (waterborne illness outbreak AND New Zealand)

Search 3 GOOGLE SCHOLAR: TITLE-ABS-KEY (waterborne illness outbreak AND New Zealand AND *Giardia* AND *Campylobacter* AND *Cryptosporidium* AND *E. Coli*)

Search 4 University of Auckland: (waterborne illness outbreaks AND New Zealand)

Instead of developing an all-inclusive search thread, individual queries were also run to target more relevant results. These search queries used waterborne, water treatment, outbreak, *E. Coli/ Escherichia coli*, *Cryptosporid**, *Campylobact**, *Giardi**, *norovirus*, and *rotavirus*. Article titles and abstracts were screened for eligibility, and if the article appeared relevant, the full text was reviewed and catalogued. The bibliographies of all relevant articles published after 2016 were reviewed to identify additional cited references. Many of these cited references provided direction to the grey literature of government reports, conferences, and some websites.

In summary, published academic (peer-reviewed) literature (n=102), reports and documents, and materials produced by the local, regional, and central government, research institutes, and some non-governmental organisations (n=73) regarding 'water-borne illness outbreak in New Zealand' up to the year 2024 were reviewed. A small amount of international literature (n=12) was catalogued from the Scopus search to inform the global context of waterborne illness outbreaks. The total resources reviewed was 187. Of the 187 resources, only 46 focused on outbreak situations and 18 detailed specific outbreaks, while 55 provided broader or related and relevant information.

In total, 119 reviewed articles were found to be eligible according to the criteria: (i) drinking water outbreak confined geographically to New Zealand; (ii) surveillance of potential factors of interest to the drinking water parasitic protozoa transmission. Table 4 summarises the inclusion and exclusion criteria for the literature that was found.

Table: 4. Inclusion and exclusion criteria for screening abstracts and full-text literature.

Inclusion	Exclusion[4]
Peer-reviewed articles (journal articles and reviews)	Non-peer-reviewed articles
Articles available online from Scopus	Articles and reports not available from Scopus, Google Scholar, or Auckland University Library
Articles from Google Scholar	The focus is on elements that are incidental to waterborne illness outbreaks (e.g. foodborne sickness)
Articles and reports accessible through Auckland University Library	The abstract does not mention waterborne illness
Articles and reports written about waterborne illness in New Zealand	The article focus is on global trends in waterborne illness
Abstract/executive summary refers to waterborne illnesses/s	Articles focused on chemical water pollutants such as Nitrogen or Phosphorous

2.2 EpiSurv information

Appendix 1 of this review combined waterborne illness outbreak information from ESR's *Notifiable Diseases in New Zealand annual reports* as informed by the EpiSurv database where all notifiable illnesses, specific to waterborne diseases, are reported. Other academic and grey literature have also provided outbreak information from the search methods described in section 2.1.

2.3 Anticipation of future waterborne illness outbreaks.

PubMed and Scopus searches for: "future waterborne illness", "waterborne illness future", "waterborne illness increase", "waterborne illness" AND "future" did not return relevant literature for this review. Therefore, information regarding anticipated waterborne illness outbreak factors from within the already 'approved' sources were used.

[4] For the section on the anticipation of future waterborne illness outbreaks articles referring to detection methods or advances in detection were sought from the international articles generated by Scopus, Google Scholar, and Auckland University library.

3. NZ's waterborne illness context, concerns, and outbreaks

New Zealand's waterways are under significant pressure from human impacts that are forecast to increase with a changing climate (Prickett & Joy, 2024). While waterborne illness outbreaks in Aotearoa are the focus of this scoping review, the outbreaks themselves are not the only indicator of increasing protozoic and parasitic presence in drinking water. The whakatauki|proverb 'ka mua, ka muri', meaning 'look to the past to inform the future', has been engaged to emphasise past waterborne illness trajectories while simultaneously attempting to anticipate future frequency and likelihood of outbreaks in New Zealand. A significant amount of research literature at the time of and 'surrounding' the outbreaks has accumulated to provide context and improve knowledge. A combination of research and reports on outbreaks, prior concerns, and post-event analyses are included to help convey the broader context in which waterborne illness outbreaks have occurred.

3.1 Waterborne illness contexts and research concerns, pre-2016.

In 1984, the largest reported waterborne outbreak occurred in Queenstown, affecting 3,500 people using town water supply (Ball, 2007), and other outbreaks followed (refer to Appendix 1). From the culmination of these incidents and the subsequent developments of the 1990s drinking water testing regime, several New Zealand studies began to be published. With a nationwide population of ~3.6 million Weinstein et al. (2000) was one of the first to characterise New Zealand's drinking water in an ecological and environmental sense. They suggested a link between high incidence rates of gastroenteritis and increases in pathogenic contamination of drinking water due to high rainfall events.

A focus on the emerging threat of waterborne illness conditions and outcomes became prevalent. While Savill et al. (2001) proved that water is likely to transmit Campylobacteriosis, Duncanson et al. (2000) examined and found a relationship between high rates of Cryptosporidiosis and local communities using ungraded drinking water supply systems.

Environmental and social factors were recognised as affected by seasonal and geographic infection patterns (Hoque et al., 2004). Giardiasis was the most notified waterborne disease in Aotearoa then[5], and the risk of *Giardia* outbreaks was of concern. Hoque et al. (2002) assessed and identified vulnerable groups in Auckland's adult population. Hoque et al. (2003) also identified a reduction in the number of incidences of *Giardia* for consumers using Auckland's metropolitan mains water supply. From an economic perspective, Hales et al. (2003) also highlighted that deprived communities in New Zealand probably experienced disproportionate adverse health effects due to

[5] Nearly 2,000 cases of *Giardia* infection were notified each year, an incidence rate of 41.9 per 100,000 population. Hoque et al., (2002).

poor water quality in urban areas where the odds of high-risk water supplies were 3.76 times greater than those in the least deprived deciles.

Rural and farming issues

As farming intensified on the Canterbury Plains, concerns were raised regarding land pollutants running off into waterways. The relationship between water quality and land use is complex due to agricultural intensification and legacy nutrients (Julian et al., 2017), and various studies have highlighted the potential for microbial contamination of water sources by agricultural activities. McLeod et al. (2008) observed that soils with drainage impediments or well-developed structures are more likely to experience microbial bypass flow, while those with porous structures are less susceptible. This is particularly relevant in rural areas where zoonotic (originating from farm animals to humans) transmission of Cryptosporidium occurs (Snel et al., 2009a) and where high dairy cattle densities is correlated with an increase the incidence of Cryptosporidiosis illness for children under five years old (Lal et al., 2016).

Larned et al. (2004) warned of the risks to river water quality due to intensive land-use changes in low-lying catchments while Collins and Rutherford (2004) developed a model to also assess the effects of those changes on local streams. The latter introduced the then novel idea of riparian buffer strip plantings and fencing to improve water quality by trapping bacteria with vegetation and preventing stock excretion directly into or near streams and seepage zones. Miller et al. (2008) and Collins et al. (2007) also identified beneficial farm management practices, such as vegetated buffer strips and straw mulch applications, as effective in reducing Cryptosporidium loading in runoff and faecal contamination of water bodies. However, the impact of these practices were found to be variable depending on the specific farm factors and management practices (Miller et al., 2008). For instance, fencing off high-order streams from stock misses 77 per cent of the national contamination load from small-order streams (McDowell et al., 2017).

A study by Close et al. (2010) looked at the transport of Escherichia coli, faecal coliforms, and Campylobacter spp. through the soil and vadose zone to groundwater and found minimal impact on the microbial quality of groundwater due to spray irrigation using centre pivot irrigators at rates of 18 mm every three to four days or spray irrigators at rates of approximately 55 mm every two weeks. However, for Chique et al. (2020) the presence of Cryptosporidiosis in groundwater supplies intended for human consumption was of significant concern, and the potential for contamination from cattle crossing streams was well-documented (Collins et al., 2007; Davies-Colley et al., 2004). The effectiveness of riparian zone protection from cattle in improving water quality has since been demonstrated, and the movement of bacteria and bacteriophages in irrigated effluent into and through alluvial gravel aquifers was investigated (Stutter et al., 2012). Stutter et al. (2012) stressed the importance of creating ecologically diverse buffer strips to provide multiple benefits to both water and the adjacent land.

Climate Change

With such a comparatively higher reported incidence rate of Giardiasis (Snel et al., 2009b) and Cryptosporidium (Snel et al., 2009a) waterborne illnesses in Aotearoa, scholars have investigated projections under climate change conditions. The extreme weather events climate change presents will impact drinking water supplies (McBride et al., 2014) through drought periods with rising water temperatures and low flow periods (reducing dilution) and during deluge periods with increased water volumes and contaminant mobility.

Studies have shown that communities without reticulated water supplies are more vulnerable to protozoan diseases (Wilson et al., 2011) and that severe weather conditions can contribute to the development of cryptosporidiosis clusters (Grout et al., 2024) or children to be exposed to higher risks of Campylobacteriosis during the summer swimming season (McBride et al., 2014). An investigation into the association between regional climate variability and enteric disease incidence in New Zealand further revealed that droughts or extended dry periods increase concentrations of effluent pathogens which are subsequently flushed into water sources during rainfall events (Lal et al., 2015). Such sporadic events can overwhelm water supply distribution systems and lead to waterborne illness outbreaks (Lal et al., 2015).

The Institute for Environmental Science Research (ESR) has produced publications on climate change, *Environmental health indicators: Development tool to assess and monitor the impacts of climate change on human health* (Hambling, 2012) for health boards and local authorities; the *Water supply climate change vulnerability assessment tool handbook* (Nokes, 2012) for small communities to assess the vulnerability of their drinking-water supplies; and *Climate Change, water supplies and health* (Lange & Gregor, 2009) for water suppliers, health professionals, environmental practitioners, and planners to plan for the impacts of climate change.

Multibarrier approach

Studies specific to new management and treatments for drinking water improvement also emerged. The presence of human pathogenic viruses in drinking water sources has been a growing concern, with studies finding high levels of enteric viruses in New Zealand's surface waters (Williamson et al., 2011). However, the implementation of consistent multibarrier approaches to prevent waterborne illnesses has been inconsistent due to competing interests and financial constraints (Bartholomew et al., 2014). Such inconsistencies have been instrumental in outbreaks across the country, such as a central South Island ski resort (Hewitt et al., 2007); a hotel in the same region (Jack et al., 2013; Nicholas & Weaver, 2016); the Darfield, Canterbury, outbreak (Blakemore & Washington, 2012; Callander et al., 2014; Canterbury District Health Board, 2013; Sheerin et al., 2014), the Havelock North, Hawke's Bay Campylobacter outbreak (Department of Internal Affairs, 2017a, 2017b; Gilpin et al., 2020; Hrudey & Hrudey, 2019; Pourzand & Hales, 2023) and likely many others – refer to Appendix 1.

Taking a multi-barrier approach, which considers the whole water ecosystem and various interventions, could be more effective at preventing waterborne illness outbreaks (Weinstein et al., 2000). A multi-barrier approach to drinking water, as suggested by Hrudey et al. (2006b), could potentially address these challenges by incorporating a range of protective measures (Chambers et al., 2022; Department of Internal Affairs, 2017b; Prickett & Joy, 2024).

Economics

Economic factors of waterborne illness outbreaks also warrant consideration. Economic activity has been determined as a driver of the outbreaks (from the intensification of farming) (Foote et al., 2015; Ministry for the Environment, 2021) and as having economic implications on communities due to illness outbreaks (Moore et al., 2017; Sheerin et al., 2014). There have been calls to increase the amount of preventative efforts against enteric disease to address disparities across social determinants such as access to health care, housing conditions, and income levels (Baker et al., 2012). Protecting freshwater ecosystems will assist in reducing social and ethnic inequalities (Baker et al., 2012), and provide economic benefits for and from tourism, energy generation, recreation, natural and cultural heritage (Leathwick et al., 2010).

3.2 The pivotal outbreaks: 2014-2016.

Aotearoa has experienced numerous notifications of waterborne illness outbreaks and cases that description and analysis are not possible in the confines of this work. However, a synopsis of the largest outbreaks and mention of others is provided here.

3.2.1 Darfield

In August 2012, Darfield, Canterbury, experienced a significant heavy rain event after a dry period. The Darfield water supply was situated below a paddock grazed by sheep (Sheerin et al., 2014) with an unfenced well-head (Bartholomew et al., 2014), the failure of the new deep bore forcing the use of the decommission shallow bore (Blakemore & Washington, 2012), the groundwater's susceptibility to microbial contamination (Burbery, 2014) and the DWS's manual chlorination applications before and during the heavy rain event (Canterbury District Health Board, 2013). A descriptive outbreak investigation was performed after the Darfield Campylobacteriosis outbreak following an *Escherichia coli* transgression on 16 August 2012 (Bartholomew et al., 2014). Heavy rains, contamination of water with animal effluent from nearby paddocks, and failures in the treatment of drinking water distributed pathogens through the town's water supply.

Alongside a significant amount of media attention, several reports and publications were generated from the Darfield outbreak. Selwyn District Council (SDC) worked with Opus Consulting to report on 'lessons learned' (Blakemore & Washington, 2012) particularly the importance of staff diligence, clarity of responsibilities and structured reporting, compliance testing, activity management plans, and public health risk management plans; the Canterbury District Health Board (2013) reassured the local community it was supporting SDC to adopt a multi-barrier approach; Bartholomew et al. (2014) called for the government to enforce standards and legislation, ESR (2015) reported extensively on a selection of areas not achieving the Drinking Water Standards, and Sheerin et al. (2014) estimated significant costs and economic impacts on the local community.

Within two weeks, on 27 August 2012, 11 people from a group of 15 diners at a central Otago hotel had become ill with gastroenteritis between 24 and 48 hours after dining. The group reported drinking table water, and over the next fortnight, three other groups around the locale reported similar symptoms. Investigations found there had been an airlock in the chlorine pump, and re-establishment of chlorination dosing had been ineffective against the neighbouring septic disposal field run-off that potentially seeped into the groundwater used for drinking (Jack et al., 2013). The drinking water was found to be contaminated with norovirus (NoV), and highlighted the risk of small community water supplies being unregulated but available for public use (Jack et al., 2013).

3.2.2 Havelock North

On 12 August 2016, the small North Island town of Havelock North was hit by an unprecedented drinking water contamination event and public health emergency. Gilpin et al. (2020) estimated that between 6260 and 8320 cases of illness, including up to 2230 who lived outside the reticulation area, 42 hospitalisations, and illness factors contributing to at least four deaths were linked to the contaminated water supply. An untreated reticulated water supply was contaminated following a heavy rainfall event that caused sheep faeces to drain into a shallow aquifer. Early water testing for pathogens identified *Campylobacter jejuni* genotyping, which helped define the outbreak's source and confirm outbreak periods and cases.

The risk assessment team that completed the water safety plan (WSP) underestimated the risks of contamination events that could affect human health and overestimated the groundwater supply's and bore heads' security (Graham et al., 2023). Historical *Escherichia coli* transgressions had been dismissed as likely due to testing errors and not recognised as significant warning signals. A series of multibarrier approach failures – legal failures from Hawke's Bay Regional Council, standards of care from Hastings District council, inaccurate assessment of supply risks from consultants, and failure of regulatory responsibilities by the District Health Board and Ministry of Health (Department of Internal Affairs, 2017b). Graham et al. (2023) identified the overarching issue as narrow focused compliance with the specifics of the Health Act (1956) rather than using the WSP as a proactive tool to understand and manage the overall risk to public health. The emergency tested the response capacity of local and national authorities (Teen et al., 2020) and became the largest-ever recorded Campylobacteriosis outbreak (Gilpin et al., 2020).

This outbreak resulted in unprecedented inquiries (Department of Internal Affairs, 2017a, 2017b), reports (Moore et al., 2017), and academic papers (Gilpin et al., 2020; Hrudey & Hrudey, 2019). The government inquiry found widespread institutional issues and failures that needed to be urgently addressed (Graham, 2020). Consequently, the incident became a significant turning point for New Zealand's water reform (Chambers et al., 2022; Jessamine et al., 2018) and there began work and focus toward a new regulatory framework (Chambers et al., 2022) to be comprised of the national drinking water regulator (Prickett et al., 2023) and the Water Act (2021).

Although details of all New Zealand outbreaks have not resulted in publications, most are included in this review. Refer to Appendix 1 for a compilation of waterborne outbreaks in New Zealand that have been officially reported and documented since the 1980s.

3.3 Waterborne illness outbreak prevention research

As stages 1 and 2 of the Havelock North Inquiry were undertaken (Department of Internal Affairs, 2017a, 2017b) more nuanced research on avian pollutants and stream water began to emerge. Research published by Snelder et al. (2018) and Julian et al. (2017) was timely, having begun before the Havelock North incident. Although both works did not have a microbiological focus, both reinforced the connectivity between land activities, agricultural intensification, water bodies, and drinking water.

Lai. et al. (2020) found that hospitalisation risks increased two days after heavy rainfall and that the risk was modified for locations with time-weighted long-term exposure to rainfall. Lambing and calving seasons (September-November) were identified as a peak time for human Cryptosporidiosis case illness notifications, with elevations also present in Autumn (Garcia et al., 2020). Aotearoa has a high diversity of species and subtypes, some of which are rarely detected in other countries (Garcia et al., 2020).

As institutional changes began to evolve, the link to public health risks associated with Campylobacter strains in river water was identified (French et al., 2022; Ministry for the Environment, 2021; Phiri et al., 2021; Phiri et al., 2020; Shrestha et al., 2019). Wilson et al. (2021) underscored the severe health consequences of a Campylobacteriosis outbreak on vulnerable populations, and the need for improved water management through public health reforms and economic inefficiencies was emphasised (Chambers et al., 2022).

Post-Water Act (2021)

The Water Services Act 2021 has undoubtedly influenced research topics and directions and the frequency and messaging of waterborne illness factors to New Zealand's wider public. Regardless, ESR's latest Annual Report (ESR, 2021) and website dashboard information (ESR, 2024) confirms that microbial pathogens in New Zealand's freshwater sources still pose significant health risks. Twenty years on from the highest Giardiasis illness incident report, Cryptosporidium as one of the most frequently reported waterborne illness in Aotearoa (Farmers Weekly, 2024; Hayman et al., 2023). Still, scientists and the health sector continue to have to work hard to convince New Zealanders that both human and animal sources of Cryptosporidium can contaminate drinking water, particularly in the months of September and October (Baker et al., 2023).

Hobbs et al. (2024) have highlighted the structural inequities in geospatial data quality regarding population, area-level deprivation, ethnicity, and urban/rural classification, which can hinder efforts to address health disparities. Pourzand (2023) and French et al. (2022) have both explored the impact of human activities on water quality and the potential for disease outbreaks.

Graham et al. (2023) have called for a focus on the ability of water supply organisations to manage risk and for more conversations with water suppliers about integrated risk management rather than solely on preparing and meeting WSP requirements. By integrating risk management activities across another part of water operations so that the whole organisation understands how to manage the risks then, more people will understand the "changing nature of risk and the need to regularly revise and update their risk tools, including their WSP" (Graham et al., 2023, p. 1569).

ESR continues to record monthly waterborne disease notification data for monthly reports and collates it for the annual reporting of information on how New Zealanders' health is affected by three potentially waterborne diseases: Campylobacteriosis, Giardiasis, and Cryptosporidiosis. The most recent report, February 2024, provides data up to 2021. Additionally, monthly reporting is carried out and published on the ESR website (ESR, 2024).

Environmental Health Intelligence New Zealand (EIHNZ) works with ESR to provide information and intelligence about how our natural environment affects the health of our population[6]. Information can be found for both drinking water and recreational water use. The February 2024 report provides notification rates for Campylobacteriosis, Cryptosporidiosis, and Giardiasis from 2001 to 2021. While most cases of these illnesses occur from food-borne contaminations, only a fraction occur through waterborne transmission (Health New Zealand Te Whatu Ora, 2024; King et al., 2011). In 2009, the Campylobacteriosis notification rate was ~160 per 100,000 people, slowly trending downwards to 108.8 per 100,000 people (5,720 notifications) by 2021 (EHINZ, 2024). Refer to Figure 6.

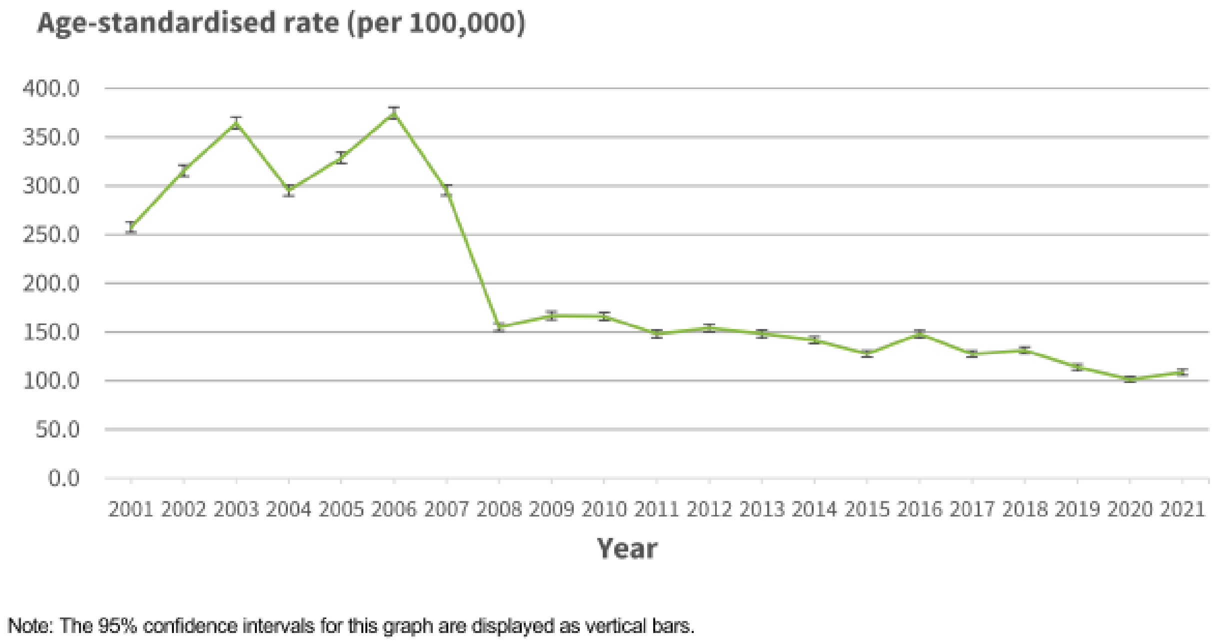


Figure 6: Age-standardised rate (per 100,000) of notified cases of Campylobacteriosis 2001-2021. Source: EHINZ (2024).

[6] EHINZ

EIHNZ noted 2008's large decrease in the Campylobacteriosis rate as in line with the new food safety regulations introduced for poultry production the previous year. This reduction in food-related cases exposes the pattern of cases attributable to contact with contaminated water (EHINZ, 2024).

The notification rate for cryptosporidiosis was volatile from 2014 to 2018, with a subsequent decline between 2018 and 2021. Refer to Figure 7.

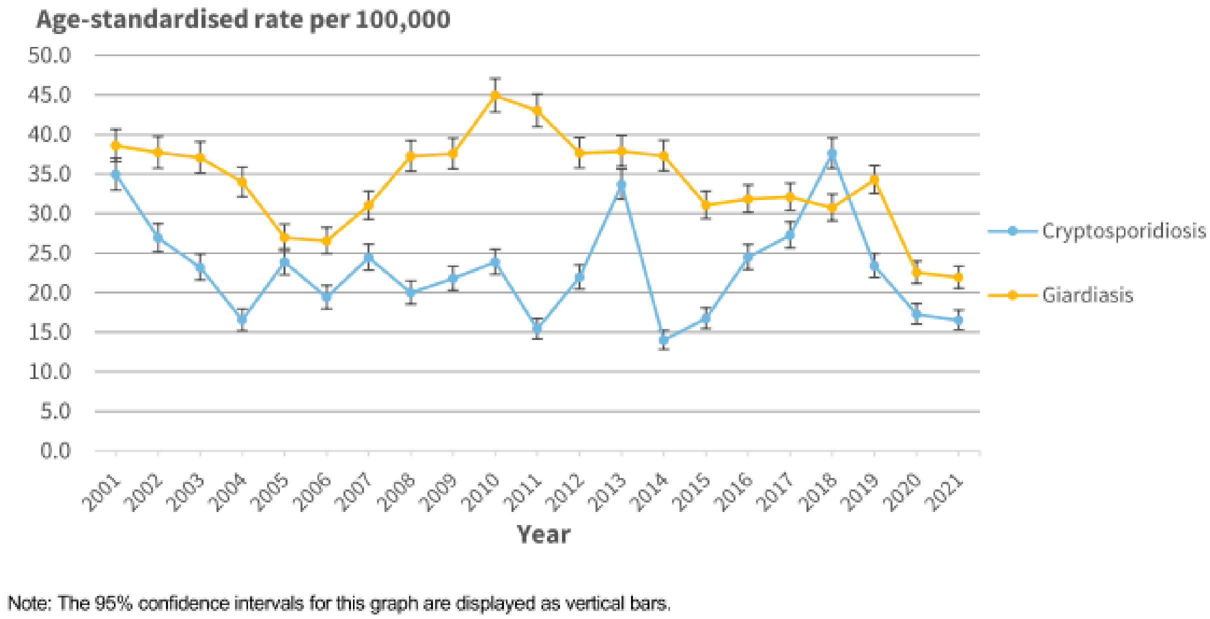


Figure 7: Age-standardised rate (per 100,000) of notified cases of cryptosporidiosis and Giardiasis 2001-2021. Source: EHINZ (2024).

Giardiasis' notification rates present a notable drop from 2019 to 2020 after no prior significant change. Refer to Figure 7. EHINZ (2024) suggest this could be partially attributable to reduced access to healthcare and incident reporting, particularly during COVID-19 restrictions at that time.

Gaps in waterborne disease illness knowledge

A range of studies have highlighted the ongoing need to improve monitoring, evaluating, and managing drinking water and the connected environment to prevent future waterborne illness outbreaks (Graham, 2020; Graham et al., 2023; Hrudey, 2021; Jenkins, 2018; Wilson et al., 2011). However, the current approach to monitoring and management of waterborne diseases and failure to learn from past mistakes has been highlighted at the operator level (Wu et al., 2009), governance level (Hjorth & Madani, 2023), and at the ministry level (Department of Internal Affairs, 2017a, 2017b). Further studies have been recommended into levels of adaptive water management (Hjorth & Madani, 2023), acceptance of integrated risk management plans (Hrudey & Hrudey, 2019), and national standardisation of drinking water monitoring, recording, and record-keeping (Chambers et al., 2022).

4. Anticipation of future waterborne outbreaks

This section of the review draws predominantly from information on ways to investigate whether waterborne illness outbreaks can be anticipated and, if so, how. Three key areas can assist with forecasting: improvements in human reliability, infallibility, and collaboration; investing in water modelling technologies and data collection; and monitoring, surveying, and maintaining high standards of drinking water quality.

4.1 Human reliability, infallibility, and collaboration

While improvements in human reliability will not directly anticipate future waterborne outbreaks, advancing institutional knowledge and implementing systematic reporting will improve water institutions' skills and ability to better predict and prevent such events. Given the comparatively high levels of economic and intellectual resources available in New Zealand (and other 'developing' countries) Hrudey and Hrudey (2019) point to recurring themes of complacency, naiveté, ignorance, failure to learn from experience, and chemophobia as crucial factors in waterborne illness outbreaks. Similarly, Hrudey et al. (2006a), Rizak and Hrudey (2008), and Wu et al. (2009), have identified prevention as the most logical, cost-effective, and safest way to counteract levels of sickness and fatalities, and they highlight risk management as the most effective approach.

A strategic framework of collaboration has been proposed to address some of these issues by using resilience-based tools and mechanisms to reduce human error across consumer, drinking water retailers and policy regulator groups (Tang et al., 2013). Local and central governments are eager to include local Indigenous Māori groups in water management planning processes through meaningful engagement and collaboration (Harmsworth et al., 2016). Such engagement inherently focuses on the mauri of water, the concept of *te mana o te wai*, and sustainability principles that would assist significantly in reducing the incidents of waterborne illnesses.

In line with Graham et al.'s (2023) work, the creation of learning networks (operators, supervisors, consumers, local physicians, and policy-makers), inter-organisational cooperation, and an efficient information and communication technology (ICT) platform for such a network (Tang et al., 2013) can simplify reporting processes and improve emergency response times.

At the nationwide level, Chambers et al. (2022) have called out drinking water management in New Zealand and the urgent need for 1) the protection of public health and promotion of health equity; and 2) drinking water management to become more economically efficient. They identify four main areas that will achieve this – standardisation of drinking water monitoring, reporting, and record keeping; better access to or expansion of technical expertise for all water suppliers; an increase in the availability of capital for expenditure that improves system efficiencies; and technical expertise present on executive boards to bolster best-practice decision-making and minimise political influences.

Looking toward global networking solutions to help prevent waterborne illness outbreaks, Efstratiou et al.'s, (2017) work has called for an international effort that would collaborate to form a standardised reporting system. The authors suggested a surveillance system, under a title such as 'National Working Network for Waterborne Parasites', be established as a first step toward combating parasitic protozoa, particularly as a warming climate will likely continue to increase the threat of significant waterborne illness outbreaks (Efstratiou et al., 2017). However, no such organisation appears to have eventuated.

Enhancing institutional knowledge and implementing systematic, nationwide reporting will improve water institutions' ability to predict and prevent future waterborne outbreaks.

4.2 Waterborne disease modelling technology

Modelling has emerged as an approach to help treat and contain general illness outbreaks (ESR, 2023; Hyllestad et al., 2021; Prickett et al., 2024). Creating abstract representations of real-world systems, process, or data helps gain insights, make predictions, or design solutions and assists scientists and researchers to more accurately map how waterborne illness outbreaks may unfold in the short- and sometimes long-term. Such models can be created using epidemiological, environmental, risk assessment, and case study approaches. While Recknagel et al.'s (2017) study of early warning *in situ* sensors can predict drinking water reservoirs' cyanotoxin concentrations, Viñas et al. (2019) provide a comprehensive global overview of epidemiological investigations and the use of quantitative microbial risk assessment (QMRA) tools to manage drinking water supply risks and assist with decision making.

Adnan et al.'s (2020) New Zealand example gathered retrospective data from the Havelock North 2016 *Campylobacter* outbreak and found that alternative data sources can provide earlier indications of a large waterborne illness outbreak than medically reported cases. Using Local Moran's 1 (ArcGIS) autoregressive modelling with spatiotemporal clustering and online software, such as Twitter and Google Trends, provided good quality outbreak indication data three to four days before medical case notifications. The modelling correlated spatiotemporal clusters of spikes in school absenteeism and consumer helpline inquiries. Adnan et al. (2020) retrospectively confirmed that had council authorities in Havelock North and Hastings been aware of and used such modelling, they would have identified clusters and outbreaks earlier than routine methods for public health notifications.

More recently, work from Hussain et al. (2023) states that previous waterborne disease research has focused on predicting water quality indexes and forecasting water quality parameters. Such work has used statistical methods that are only sometimes easy to apply across populations or interpret. They suggest that machine learning, an artificial intelligence concept, could be used to develop models incorporating existing datasets to help forecast future events. Their study, focused on malaria and typhoid, repeats how important modelling work is but was undertaken in highly populated areas that could predict levels of illness outbreak. However, this AI approach is novel and developing, and their work has recognised how crucial age, patient history, and water quality test results are in being able to model and predict cases of water-borne illness.

4.3 Monitoring, surveillance, and maintenance

Improved management of drinking water supplies is urgently needed to protect public health, promote health equity and improve economic efficiencies (Chambers et al., 2022). Online technologies to monitor drinking water quality have significantly evolved in accuracy and accessibility but cannot be used in isolation (Brester et al., 2020). To detect harmful microbial growth in water distribution systems, periodic observations representing different water quality variables can be carried out (Brester et al., 2020). Current laboratory-based methods are used but are considered expensive, time-consuming and require highly trained personnel to sample and test. Issues with laboratory testing are not only about the inability to test for all factors and combinations of scenarios but also restricted to the microbial numbers present at the time samples were taken – not the number of microorganisms that could occur in the future (Frick et al., 2008). To forecast bacterial abundance Brester et al. (2020) have suggested the concentration of disinfectants and physiochemical water characteristics as relevant, reliable, and practical parameters to use for pathogen-related predictive modelling. Predictive modelling, based on advanced learning algorithms and risk assessment systems, can offer reasonable week-long predictions to help manage contamination risks in drinking water (Brester et al., 2020).

In the United States of America, the Centres for Disease Control and Prevention (CDC) has developed methods to estimate illnesses for waterborne pathogens (U.S. Department of Health and Human Services, 2024). Based on data from waterborne disease outbreak surveillance systems reporting, they divide the data into three key categories – surveillance data (information data from public health officials, laboratories, hospitals), scientific literature (evidenced-based resources that estimate cases for a variety of pathogens not entered in the official surveillance system), and administrative data around hospitalisations, emergency departments, ambulance information systems. To determine illnesses for each pathogen they multiply the adjusted number by the proportion of illnesses in acquired across the US (not including international travel) and the proportion transmitted by water to yield an estimated number of illnesses that are domestically contracted and waterborne. CDC add those estimates for each pathogen to provide a total and apply an uncertainty model to generate a point estimate and 95% credible interval. Refer to Figure 8.

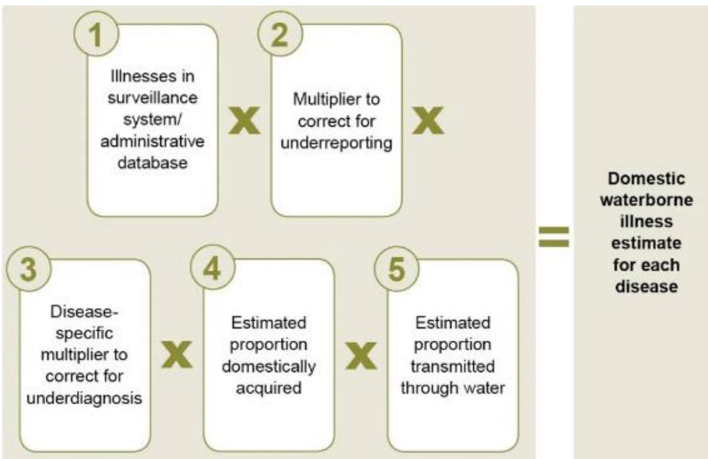


Figure 8: Illness burden estimate. Source: U.S. Department of Health and Human Services (2024)

CDC also provides the formula they apply to estimate the visit burden on emergency departments, hospitalisations, and deaths. Additionally, CDC presents the estimated total direct healthcare cost using the total number of out-of-pocket and insurer payments for emergency department visits and hospitalisations due to waterborne disease transmission. Such formulas might be applied using a nuanced-to-New Zealand approach to estimate the potential waterborne illness burden in Aotearoa using the national EpiSurv database.

A 2021 review by Hyllestad et al., investigated whether Syndromic surveillance (SyS) can pinpoint a threshold number of early symptomatic waterborne illness cases and recognise an outbreak days ahead of traditional methods. There are theoretical advantages to using SyS, but “false alarms” can occur due to high values of specificity and sensitivity in the surveillance technology and the timeliness around detection and reporting (European Center for Disease Control, 2014). Until Hyllestad et al. (2021) can prove SyS as more reliable, the focus should remain on illness prevention measures and combined health and environmental research data that have enough resources to facilitate surveillance systems. Further investigations into variations of reliable data sources, such as spatial and temporal data, are needed (Hyllestad et al., 2021).

In Aotearoa, instead of monitoring degrading impacts on drinking water reservoirs, a freshwater monitoring programme has been developed by AgResearch (Our Land & Water, 2021) to monitor any collective, positive effects of water protection activities, such as stream fencing and riparian plantings, wetland restoration and changes in farming practices. Data from such monitoring could potentially provide information and frameworks to develop, calibrate, and validate catchment models more nuanced to our New Zealand water environments.

A seemingly more promising, microbial risk assessment tool (MRA) has been developed by a science team (GW modellers, hydrologists, and microbiologists) at ESR. Where water supply wells are situated close to areas of high levels or potentially risky activities the MRA tool can provide a transparent and objective basis from which to make decisions around land use activities. These activities are typically on-site and community wastewater management systems, pastoral farming, stormwater system, animal effluent (including application), and wildfowl. The tool is being used to assist local councils to make informed consent decisions by more effectively assessing potential risks from different land use activities undertaken near protected drinking water zones (ESR, 2023). A user interface is currently being developed to facilitate the easy access and adoption of the MRA by planners and decision makers in Aotearoa and possibly overseas (ESR, 2023).

5. Conclusion

To date, New Zealand's approach to waterborne illness outbreaks can be characterised as reactionary. As isolated or multiple events have occurred the obligatory investigations have been carried out and duly reported. With the passing of the Water Services Act (2021) comes the opportunity to proactively manage drinking water and regulate drinking water individuals and organisations. But successful containment of predicted increases, let alone risk reduction, in waterborne illness outbreaks will not occur if individuals and organisations operate in isolation.

Large and small water suppliers now have the opportunity to implement an integrated risk management system across their whole, respective, organisation and community, not just the water distribution department. All drinking water suppliers must embrace new approaches and relevant tools that help to anticipate waterborne illness. This review recommends the allocation of responsibilities and information using an integrated risk management approach to reduce outbreak instances and more likely prevent them.

6. References

Adnan, M., Gao, X., Bai, X., Newbern, E., Sherwood, J., Jones, N., Baker, M., Wood, T., & Gao, W. (2020, Sep 17). Potential early identification of a large campylobacter outbreak using alternative surveillance data sources: Autoregressive modelling and spatiotemporal clustering. *JMIR Public Health Surveill, 6*(3), e18281. https://doi.org/10.2196/18281

Australian Government. (2022). *Australian Drinking Water Guidelines*. https://www.nhmrc.gov.au/about-us/publications/australian-drinking-water-guidelines#block-views-block-file-attachments-content-block-1

Baker, M., Barnard, L., Kvalsvig, A., Verrall, A., Zhang, J., Keall, M., Wilson, N., Wall, T., & Howden-Chapman, P. (2012). Increasing incidence of serious infectious diseases and inequalities in New Zealand: A national epidemiological study. *The Lancet (British edition), 379*(9821), 1112-1119. https://doi.org/10.1016/S0140-6736(11)61780-7

Baker, M., Prickett, M., Pourzand, F., Kerr, J., & Hales, S. (2023). *Queenstown outbreak highlights future challenges for clean drinking water* [Press release]

Ball, A. (2007). *Estimation of the burden of water-borne disease in New Zealand: Preliminary report.* Environmental Science and Reesarch Limited. https://ndhadeliver.natlib.govt.nz/delivery/DeliveryManagerServlet?dps_pid=IE970327

Bartholomew, N., Brunton, C., Mitchell, P., Williamson, J., & Gilpin, B. (2014). A waterborne outbreak of campylobacteriosis in the South Island of New Zealand due to a failure to implement a multi-barrier approach. [Open access]. *Journal of Water and Health, 12*(3), 555-563. https://doi.org/10.2166/wh.2014.155

Blakemore, R., & Washington, M. (2012). Darfield water supply contamination event: Lessons learned [Report for Selwyn District Council]. *Water New Zealand*, 11.

Brester, C., Ryzhikov, I., Siponen, S., Jayaprakashb, B., Ikonen, J., Pitkänen, T., Miettinenb, I., Torvinen, E., & Kolehmainen, M. (2020). Potential and limitations of a pilot-scale drinking water distribution system for bacterial community predictive modelling. *Science of The Total Environment, 71*(7). https://doi.org/10.1016/j.scitotenv.2020.137249

Burbery, L. (2014). *The potential hazard on-site wastewater treatment systems in Darfield and Kirwee present to local groundwater quality and critique of current assessment methods.* (14004). Ministry of Health.

Callander, P., Steffens, C., Thomas, N., Donaldson, S., England, M., Pattle Delamore Partners Ltd, Marlborough District Council, & Council., S. D. (2014). *E. Coli* contamination in "secure" groundwater sourced drinking water supplies. *Department of Internal Affairs*, 13. https://www.dia.govt.nz/diawebsite.nsf/Files/Havelock-North-Drinking-Water/$file/Ref-p_callander.pdf

Canterbury District Health Board. (2013). *Community and public health report to the Darfield community: An outbreak of waterborne gastroenteritis in Darfield, Canterbury July - August 2012.* https://www.cph.co.nz/wp-content/uploads/darfieldoutbreakcommunityreport.pdf

Chambers, T., Wilson, N., Hales, S., Prickett, M., Ellison, E., & Baker, M. (2022). Beyond muddy waters: Three Waters reforms required to future-proof water service delivery and protect public health in Aotearoa New Zealand. *The New Zealand medical journal, 135 1566*, 87-95. https://doi.org/https://pubmed.ncbi.nlm.nih.gov/36455181/

Chique, C., Hynds, P., Andrade, L., Burke, L., Morris, D., Ryan, M., & O'Dwyer, J. (2020). Cryptosporidium spp. in groundwater supplies intended for human consumption: A descriptive review of global prevalence, risk factors & knowledge gaps. *Water Research, 176*.

Close, M., Noonan, M., Hector, R., & Bright, J. (2010). Microbial transport from dairying under two spray-irrigation systems in Canterbury, New Zealand. *Journal of Environmental Quality, 39*(3), 824-833. https://doi.org/10.2134/jeq2009.0208

Collins, R., McLeod, M., Hedley, M., Donnison, A., Close, M., Hanly, J., Horne, D., Ross, C., Davies-Colley, R., Bagshaw, C., & Matthews, L. (2007). Best management practices to mitigate faecal contamination by livestock of New Zealand waters. *New Zealand Journal of Agricultural Research, 50*(2), 267-278. https://doi.org/10.1080/00288230709510294

Collins, R., & Rutherford, K. (2004). Modelling bacterial water quality in streams draining pastoral land. *Water Research, 38*(3), 700-712. https://doi.org/10.1016/j.watres.2003.10.045

Davies-Colley, R., Nagels, J., Smith, R., Young, R., & Phillips, C. (2004). Water quality impact of a dairy cow herd crossing a stream. *New Zealand Journal of Marine and Freshwater Research, 38*(4), 569-576. https://doi.org/10.1080/00288330.2004.9517262

Department of Internal Affairs. (2017a). *Government Inquiry into Havelock North Drinking Water: Stage 1*. New Zealand Government. https://www.dia.govt.nz/vwluResources/Report-Havelock-North-Water-Inquiry-Stage-1/$file/Report-Havelock-North-Water-Inquiry-Stage-1.pdf

Department of Internal Affairs. (2017b). *Government Inquiry into Havelock North Drinking Water: Stage 2*. New Zealand Government. https://www.dia.govt.nz/diawebsite.nsf/Files/Report-Havelock-North-Water-Inquiry-Stage-2/$file/Report-Havelock-North-Water-Inquiry-Stage-2.pdf

Duncanson, M., Russell, N., Weinstein, P., Baker, M., Skelly, C., Hearnden, M., & Woodward, A. (2000). Rates of notified cryptosporidiosis and quality of drinking water supplies in Aotearoa, New Zealand. *Water research (Oxford), 34*(15), 3804-3812. https://doi.org/10.1016/S0043-1354(00)00125-1

Efstratiou, A., Ongerth, J., & Karanis, P. (2017). Waterborne transmission of protozoan parasites: Review of worldwide outbreaks - an update 2011–2016. *Water Research, 114*, 14-22. https://doi.org/https://doi.org/10.1016/j.watres.2017.01.036

EHINZ. (2024). *Notifications of potentially waterborne diseases.* Environmental Health Intelligence New Zealand (EHINZ). https://www.ehinz.ac.nz/assets/Factsheets/Released_2024/Notifications-of-potentially-waterborne-diseases.pdf

Environmental Protection Agency, I. (2021). *Drinking water quality in public supplies*. https://www.epa.ie/publications/compliance--enforcement/drinking-water/annual-drinking-water-reports/drinking-water-quality-in-public-supplies-2021.php

Ercumen, A., Gruber, J., & Colford, J. (2014). Water distribution system deficiencies and gastrointestinal Illness: A systematic review and meta-analysis. *Environmental Health Perspectives, 122*(7), 651-660. https://doi.org/10.1289/ehp.1306912

ESR. (2007). *Annual summary of outbreaks in New Zealand 2006* (FW 0741). Institute of Environmental Science Research. file://file/Usersr$/rmt105/Home/Downloads/2006Outbreakreport.pdf

ESR. (2020). *Notifiable diseases in New Zealand: Annual report 2020*. Institute of Environmental Science and Research Limited. https://testsite3.esr.cri.nz/assets/1Reports/Public-Health-Surveillance-/Annual-notifiable-disease-report-and-data/esr-notifiable-diseases-annual-surveillance-summary-2020.pdf

ESR. (2021). *Notifiable diseases in New Zealand: Annual report 2021*. Institute of Environmental Science and Research Limited. https://www.esr.cri.nz/digital-library/notifiable-diseases-annual-surveillance-summary-2021/

ESR. (2023). *Groundwater Research Impact Report | Pūrongo Pānga Rangahau Wainuku 2023*. Environmental Science Research Institute.

ESR. (2024). *Surveillance and Intelligence*. https://www.esr.cri.nz/expertise/public-health#SurveillanceandIntelligence

Eurofins. (2021). *New National drinking-water database to replace WINZ*. Eurofins Scientific 2021. https://www.eurofins.co.nz/water-testing/news/new-national-drinking-water-database-to-replace-winz/

European Center for Disease Control. (2014). *Data quality monitoring and surveillance system evaluation: A handbook of methods and evaluation.* European Centre for Disease Prevention and Control (EDC). https://www.ecdc.europa.eu/ https://doi.org/10.2900/35329

Farmers Weekly. (2024, May, 2024). Climate extremes increase risk of cryptosporidium outbreaks. *Farmers Weekly*, (May, 2024). https://www.farmersweekly.co.nz/

Foote, K., Joy, M., & Death, R. (2015). New Zealand dairy farming: Milking our environment for all its worth. *Environmental Management, 56*(3), 709-720. https://doi.org/10.1007/s00267-015-0517-x

French, R., Charon, J., le Lay, C., Muller, C., & Holmes, E. (2022). Human land use impacts viral diversity and abundance in a New Zealand river. *Virus Evolution, 8*(1). https://doi.org/10.1093/ve/veac032

Frick, W., Ge, Z., & Zepp, R. (2008). Nowcasting and forecasting concentrations of biological contaminants at beaches: A feasibility and case study. *Environmental Science & Technology, 42*(13), 4818-4824. https://doi.org/10.1021/es703185p

Garcia, R., Pita, A., Velathanthiri, N., French, N., & Hayman, D. (2020, 2020/07/01). Species and genotypes causing human cryptosporidiosis in New Zealand. *Parasitology Research, 119*(7), 2317-2326. https://doi.org/10.1007/s00436-020-06729-w

Gerlak, A. K., House-Peters, L., Varady, R. G., Albrecht, T., Zúñiga-Terán, A., de Grenade, R. R., Cook, C., & Scott, C. A. (2018, 2018/04/01/). Water security: A review of place-based research. *Environmental Science & Policy, 82*, 79-89. https://doi.org/https://doi.org/10.1016/j.envsci.2018.01.009

Gilpin, B., Walker, T., Paine, S., Sherwood, J., Mackereth, G., Wood, T., Hambling, T., Hewison, C., Brounts, A., Wilson, M., Scholes, P., Robson, B., Lin, S., Cornelius, A., Rivas, L., Hayman, D., French, N., Zhang, J., Wilkinson, D., Midwinter, A., Biggs, P., Jagroop, A., Eyre, R., Baker, M., & Jones, N. (2020). A large scale waterborne *Campylobacteriosis* outbreak, Havelock North, New Zealand. *Journal of Infection, 81*(3), 390-395. https://doi.org/10.1016/j.jinf.2020.06.065

Gleick, P. (2018). Transitions to freshwater sustainability. *PNAS, 115*(36). https://doi.org/10.1073/pnas.1808893115

Graham, J. (2020). Waterborne illness sparks major water reform in New Zealand. [Note]. *Journal - American Water Works Association, 112*(3), 30-36. https://doi.org/10.1002/awwa.1461

Graham, J., Russell, K., & Gilpin, B. (2023). When the implementation of water safety plans fail: Rethinking the approach to water safety planning following a serious waterborne outbreak and implications for subsequent water sector reforms. *Journal of Water and Health, 21*(10), 1562-1571. https://doi.org/10.2166/wh.2023.188

Grout, L., Hales, S., Baker, M., French, N., & Wilson, N. (2024). Severe weather events and cryptosporidiosis in Aotearoa New Zealand: A case series of space–time clusters. *Epidemiology and Infection, 152*, e64, Article e64. https://doi.org/10.1017/S095026882400058X

Hales, S., Black, W., Skelly, C., Salmond, C., & Weinstein, P. (2003). Social deprivation and the public health risks of community drinking water supplies in New Zealand. *Journal of epidemiology and community health (1979), 57*(8), 581-583. https://doi.org/10.1136/jech.57.8.581

Hambling, T. (2012). *Environmental Health Indicators: Development of a tool to assess and monitor the impacts of climate change on human health.* (Health analysis & information for action (HAIFA), Issue. Environmental Science and Research Limited.

Harmsworth, G., Awatere, S., & Robb, M. (2016, 12/01). Indigenous Māori values and perspectives to inform freshwater management in Aotearoa-New Zealand. *Ecology and Society, 21*. https://doi.org/10.5751/ES-08804-210409

Hayman, D., Garcia-Ramirez, J., Pita, A., Velathanthiri, N., Knox, M., Ogbuigwe, P., Baker, M., Rostami, K., Deroles-Main, J., & Gilpin, B. (2023). PREPRINT: Diagnosis of protozoa diarrhoea in Campylobacter patients increases markedly with molecular techniques. *MedRxiv, unsure*, unsure. https://doi.org/10.1101/2023.01.05.23284190

Health New Zealand Te Whatu Ora. (2024). *Clearance criteria for enteric diseases in the Auckland region*. New Zealand Government. https://www.arphs.health.nz/assets/Uploads/Resources/Disease-and-illness/Clearance-Criteria-for-Enteric-Diseases_20240326_NPHS_JH.pdf

Hewitt, J., Bell, D., Simmons, G., Rivera-Aban, M., Wolf, S., & Greening, G. (2007). Gastroenteritis outbreak caused by waterborne norovirus at a New Zealand ski resort. *Applied and Environmental Microbiology, 73*(24), 7853-7857. https://doi.org/10.1128/aem.00718-07

Hjorth, P., & Madani, K. (2023, 2023/05/01). Adaptive water management: On the need for using the post-WWII science in water governance. *Water resources management, 37*(6), 2247-2270. https://doi.org/10.1007/s11269-022-03373-0

Hobbs, M., Puente-Sierra, M., Marek, L., Broadbent, J., & Chambers, T. (2024). Examining the structural inequities in the quality of nationwide drinking water data in Aotearoa New Zealand: A geospatial cross-sectional study. *Applied Spatial Analysis and Policy*. https://doi.org/10.1007/s12061-024-09571-0

Hoque, E., Hope, V., & Shrestha, R. (2004). A descriptive epidemiology of giardiasis in NZ and gaps in surveillance data. *New Zealand Medical Journal, 117*(1205), 14.

Hoque, M., Hope, V., Kjellström, T., Scragg, R., & Lay-Yee, R. (2002). Risk of giardiasis in Aucklanders: A case-control study. *Int J Infect Dis, 6*(3), 191-197. https://doi.org/10.1016/s1201-9712(02)90110-4

Hoque, M., Hope, V., Scragg, R., & Kjellström, T. (2003). Children at risk of giardiasis in Auckland: A case-control analysis. [Article]. *Epidemiology and Infection, 131*(1), 655-662. https://doi.org/10.1017/s0950268803008598

Hrudey, S. (2021). *Understanding and improving the provision of safe drinking water.* https://www.scientia.global/dr-steve-e-hrudey-understanding-and-improving-the-provision-of-safe-drinking-water/

Hrudey, S., & Hrudey, E. (2019). Common themes contributing to recent drinking water disease outbreaks in affluent nations. [Article]. *Water Science and Technology: Water Supply, 19*(6), 1767-1777. https://doi.org/10.2166/ws.2019.051

Hrudey, S. E., Hrudey, E. J., & Pollard, S. J. (2006a). Risk management for assuring safe drinking water. *Environ Int, 32*(8), 948-957. https://doi.org/10.1016/j.envint.2006.06.004

Hrudey, S. E., Hrudey, E. J., & Pollard, S. J. (2006b, Dec). Risk management for assuring safe drinking water. *Environ Int, 32*(8), 948-957. https://doi.org/10.1016/j.envint.2006.06.004

Huddleston, P., Smith, T., White, I., & Elrick-Barr, C. (2022, 2022/09/01/). Adapting critical infrastructure to climate change: A scoping review. *Environmental Science & Policy, 135*, 67-76. https://doi.org/https://doi.org/10.1016/j.envsci.2022.04.015

Hussain, M., Cifci, M., Sehar, T., Nabi, S., Cheikhrouhou, O., Maqsood, H., Ibrahim, M., & Mohammad, F. (2023). Machine learning based efficient prediction of positive cases of waterborne diseases. *BMC medical informatics and decision making, 23*(1), 11-11. https://doi.org/10.1186/s12911-022-02092-1

Hyllestad, S., Amato, E., Nygard, K., Vold, L., & Aavitsland, P. (2021). The effectiveness of syndromic surveillance for the early detection of waterborne outbreaks: A systematic review. *BMC Infectious Diseases*(21). https://doi.org/10.1186/s12879-021-06387-y

Jack, S., Bell, D., & Hewitt, J. (2013). Norovirus contamination of a drinking water supply at a hotel resort. *NZ Med J, 126*(1387), 98-107.

Jenkins, B. (2018). Management of waterborne disease. In *Water management in New Zealand's Canterbury region: A sustainability framework* (pp. 277-310). Springer Netherlands. https://doi.org/10.1007/978-94-024-1213-0_9 https://doi.org/10.1007/978-94-024-1213-0_9

Jessamine, K., Watson, A., & Ogilvie, D. (2018). *Reassessment of the risks of protozoa in NZ natural waters.* New Zealand.

file:///C:/Users/rmt105/AppData/Local/Temp/MicrosoftEdgeDownloads/abed8180-ffa8-4ff7-a100-95d2824fad3b/Attachment.pdf

Julian, J., de Beurs, K., Owsley, B., Davies-Colley, R., & Ausseil, A. (2017). River water quality changes in New Zealand over 26 years: Response to land use intensity. *Hydrol. Earth Syst. Sci., 21*, 1149–1171. https://doi.org/10.5194/hess-21-1149-2017

Karanis, P., Kourenti, C., & Smith, H. (2006). Waterborne transmission of protozoan parasites: A worldwide review of outbreaks and lessons learnt. *Journal of Water and Health, 5*(1), 1-38. https://doi.org/10.2166/wh.2006.002

King, N., Lake, R., & Campbell, D. (2011). Source attribution of non-typhoid salmonellosis in New Zealand using outbreak surveillance data. *Journal of food protection, 74*(3), 438-445. https://doi.org/10.4315/0362-028X.JFP-10-323

Lai., H., Hales, S., Woodward, A., Walker, C., Marks, E., Pillai, A., Chen, R., & Morton, S. (2020). Effects of heavy rainfall on waterborne disease hospitalizations among young children in wet and dry areas of New Zealand. *Environment International, 1*(45), 106136. https://doi.org/10.1016/j.envint.2020.106136

Lal, A., Dobbins, T., Bagheri, N., Baker, M., French, N., & Hales, S. (2016, 2016/12/01). Cryptosporidiosis risk in New Zealand children under 5 years old is greatest in areas with high dairy cattle densities. *EcoHealth, 13*(4), 652-660. https://doi.org/10.1007/s10393-016-1187-8

Lal, A., Ikeda, T., French, N., Baker, M., & Hales, S. (2013). Climate variability, weather and enteric disease incidence in New Zealand: Time series analysis [Research article]. *PLOS One, 8*(12), Article e83484. https://doi.org/10.1371/journal.pone.0083484

Lal, A., Lill, A., McIntyre, M., Hales, S., Baker, M., & French, N. (2015). Environmental change and enteric zoonoses in New Zealand: A systematic review of the evidence. *Australian and New Zealand Journal of Public Health, 39*(1), 63-68. https://doi.org/https://doi.org/10.1111/1753-6405.12274

Lange, M., & Gregor, J. (2009). *Climate change, water supplies and health: A resource for health professionals, planners, and small water suppliers.* ESR.

Larned, S., Scarsbrook, M., Snelder, T., Norton, N., & Biggs, B. (2004, 2004/06/01). Water quality in low-elevation streams and rivers of New Zealand: Recent state and trends in contrasting land-cover classes. *New Zealand Journal of Marine and Freshwater Research, 38*(2), 347-366. https://doi.org/10.1080/00288330.2004.9517243

Leathwick, J., West, D., Chadderton, L., Gerbeaux, P., Kelly, D., Robertson, H., & Brown, D. (2010). *Freshwater Ecosystems of New Zealand (FENZ) Geodatabase: User guide.* http://tools.envirolink.govt.nz/assets/Uploads/FENZ-Leathwick-et-al-2010-FENZ-User-Guide-Version-One.pdf

Ma, J., Li, M., Qi, Z., Fu, M., Sun, T., Elsheikha, H., & Cong, W. (2022, Feb 1). Waterborne protozoan outbreaks: An update on the global, regional, and national prevalence from 2017 to 2020 and sources of contamination. *Sci Total Environ, 806*(Pt 2), 150562. https://doi.org/10.1016/j.scitotenv.2021.150562

Mattingley, B., Wood, D., & Nokes, C. (2015). *Non-achievement of the drinking-water standards for New Zealand*. ESR. https://www.esr.cri.nz/digital-library/non-achievement-of-the-drinking-water-standards-for-new-zealand/

McBride, G., Tait, A., & Slaney, D. (2014). Projected changes in reported campylobacteriosis and cryptosporidiosis rates as a function of climate change: A New Zealand study. *Stochastic environmental research and risk assessment, 28*(8), 2133-2147. https://doi.org/10.1007/s00477-014-0920-5

McDowell, R., Cox, N., & Snelder, T. (2017). Assessing the yield and load of contaminants with stream order: Would policy requiring livestock to be fenced out of high-order streams decrease catchment contaminant loads? *Journal of Environmental Quality, 46*(5), 1038-1047. https://doi.org/10.2134/jeq2017.05.0212

McLeod, M., Aislabie, J., Ryburn, J., & McGill, A. (2008). Regionalizing potential for microbial bypass flow through New Zealand soils. *Journal of Environmental Quality, 37*(5), 1959-1967. https://doi.org/10.2134/jeq2007.0572

Miller, W., Lewis, D., Pereira, M., Lennox, M., Conrad, P., Tate, K., & Atwill, E. (2008). Farm factors associated with reducing Cryptosporidium loading in storm runoff from dairies. *Journal of Environmental Quality, 37*(5), 1875-1882. https://doi.org/10.2134/jeq2007.0413

Ministry for the Environment. (2007). *Proposed National Environmental Standard for sources of human drinking-water: Analysis of the costs and benefits.* (798).

Ministry for the Environment. (2021). *Our land 2021: New Zealand's environmental reporting series*. NZ Government.

Ministry for the Environment. (2022). *Environment Aotearoa 2022*. NZ Government. https://environment.govt.nz/assets/publications/Environmental-Reporting/environment-aotearoa-2022.pdf

Ministry for the Environment, & NZ, S. (2024). *New Zealand's Environmental Reporting Series: Our land 2024.* (ME 1822). environment.govt.nz and www.stats.govt.nz

Ministry of Health. (2007). *Pathogens and pathways, and small drinking water supplies: Resources for the drinking-water assistance programme.*

Moore, D., Drew, R., Davies, P., & Rippon, R. (2017). *The economic costs of the Havelock North August 2016 waterborne disease outbreak.* (Prepared for the Ministry of Health, Issue. https://www.health.govt.nz/system/files/documents/publications/havelock_north_outbreak_costing_final_report_-_august_2017.pdf

Munn, Z., Peters, M., Stern, C., Tufanaru, C., McArthur, A., & Aromataris, E. (2018, Nov 19). Systematic review or scoping review? Guidance for authors when choosing between a systematic or scoping review approach. *BMC Medical Research Methodology, 18*(1), 143. https://doi.org/10.1186/s12874-018-0611-x

National Institute of Environmental Health Sciences. (2022). *Water-related illnesses: Climate change and human health.* https://www.niehs.nih.gov/research/programs/climatechange/health_impacts/waterborne_diseases#

Nicholas, G., & Weaver, L. (2016). *Effective public health practice: Insights from Cardrona 2012*. ESR for MoH.

Nokes, C. (2008). *A guide to the Ministry of Health drinking-water standards for New Zealand.* ESR. https://environment.govt.nz/assets/Publications/Files/guide-moh-drinking-water-standards-nz-jun08.pdf

Nokes, C. (2012). *Water supply climate change vulnerability assessment tool handbook.* (Health analysis & information for action (HAIFA), Issue. Environmental Science and Research Limited. https://haifa.esr.cri.nz/assets/Uploads/Docs/Water-Supply-Vulnerability-Assessment-Tool.pdf

NZ Government. (2024). *Taumata Arowai*. https://www.taumataarowai.govt.nz/

Our Land & Water. (2021). *Guidance designing freshwater monitoring programmes to detect early improvement*. AgResearch.

Peters, M., Godfrey, C., Khalil, H., McInerney, P., Parker, D., & Soares, C. (2015). Guidance for conducting systematic scoping reviews. *JBI Evidence Implementation, 13*(3), 141-146. https://doi.org/10.1097/xeb.0000000000000050

Phiri, B., French, N., Biggs, P., Stevenson, M., Reynolds, A., Garcia-R, J., & Hayman, D. (2021). Microbial contamination in drinking water at public outdoor recreation facilities in New Zealand. *Journal of Applied Microbiology, 130*(1), 302-312. https://doi.org/10.1111/jam.14772

Phiri, B., Pita, A., Hayman, D., Biggs, P., Davis, M., Fayaz, A., Canning, A., French, N., & Death, R. (2020). Does land use affect pathogen presence in New Zealand drinking water supplies? *Water Research, 185*, Article 116229. https://doi.org/10.1016/j.watres.2020.116229

Pourzand, F., & Hales, S. (2023, 2023). Impacts of extreme weather events on enteric infectious disease outbreaks: Evidence from New Zealand. *Population Medicine, 5*(Supplement). https://doi.org/10.18332/popmed/165758

Prickett, M., Chambers, T., & Hales, S. (2024). When the first barrier fails: Public health and policy implications of nitrate contamination of a municipal drinking water source in Aotearoa New Zealand. *Australasian journal of water resources, 28*(1), 64-73. https://doi.org/10.1080/13241583.2023.2272324

Prickett, M., Chambers, T., Kerr, J., Baker, M., & Hales, S. (2023). When the first barrier fails: Strengthening protection for drinking water sources. *Australasian journal of water resources*. https://www.phcc.org.nz/node/1279/printable/pdf https://doi.org/10.1080/13241583.2023.2272324

Prickett, M., & Joy, M. (2024). Aotearoa New Zealand's new Government proposal to remove hard-won protection for waterways will worsen the country's freshwater crisis. *Inland Waters*, 1-20. https://doi.org/10.1080/20442041.2024.2335738

Recknagel, F., Orr, P., Bartkow, M., Swanepoel, A., & Cao, H. (2017). Early warning of limit-exceeding concentrations of cyanobacteria and cyanotoxins in drinking water reservoirs by inferential modelling. *Harmful Algae, 69*, 18-27. https://doi.org/https://doi.org/10.1016/j.hal.2017.09.003

Rizak, S., & Hrudey, S. (2008). Drinking-water safety: Challenges for community-managed systems. *Journal of Water and Health, 6*(S1), 33-41. https://doi.org/10.2166/wh.2008.033

Savill, M., Hudson, J., Ball, A., Klena, J., Scholes, P., Whyte, R., McCormick, R., & Jankovic, D. (2001, Jul). Enumeration of Campylobacter in New Zealand recreational and drinking waters. *J Applied Microbiology, 91*(1), 38-46. https://doi.org/10.1046/j.1365-2672.2001.01337.x

Sheerin, I., Bartholomew, N., & Brunton, C. (2014). Estimated community costs of an outbreak of campylobacteriosis resulting from contamination of a public water supply in Darfield, New Zealand. *New Zealand Medical Journal, 127*(1391), 13-24.

Shrestha, R., Midwinter, A., Marshall, J., Collins-Emerson, J., Pleydell, E., & French, N. (2019, Dec 15). Campylobacter jejuni strains associated with wild birds and those causing human disease in six high-use recreational waterways in New Zealand. *Appl Environ Microbiol, 85*(24). https://doi.org/10.1128/aem.01228-19

Singers, N., & Rogers, G. (2014). *A classification of New Zealand's terrestrial ecosystems*. Publishing Team, Department of Conservation.

Snel, S., Baker, M., & Venugopal, K. (2009a). The epidemiology of cryptosporidiosis in New Zealand, 1997-2006 [Article]. *New Zealand Medical Journal, 122*(1290), 47-61.

Snel, S., Baker, M., & Venugopal, K. (2009b). The epidemiology of giardiasis in New Zealand, 1997-2006 [Article]. *New Zealand Medical Journal, 122*(1290), 62-75.

Snelder, T., Larned, S., & McDowell, R. (2018, 2018/07/03). Anthropogenic increases of catchment nitrogen and phosphorus loads in New Zealand. *New Zealand Journal of Marine and Freshwater Research, 52*(3), 336-361. https://doi.org/10.1080/00288330.2017.1393758

Stutter, M., Chardon, W., & Kronvang, B. (2012). Riparian buffer strips as a multifunctional management tool in agricultural landscapes: Introduction. *Journal of Environmental Quality, 41*(2), 297-303. https://doi.org/10.2134/jeq2011.0439

Tang, Y., Wu, S., Miao, X., Pollard, S., & Hrudey, S. (2013, 2013/10/15/). Resilience to evolving drinking water contamination risks: A human error prevention perspective. *Journal of Cleaner Production, 57*, 228-237. https://doi.org/https://doi.org/10.1016/j.jclepro.2013.06.018

Taumata Arowai. (2023). *Drinking Water Regulation Report 2022*. Drinking Water Regulator.

Teen, R., Roberts, L., & Challies, E. (2020). Disruption as opportunity for transformation? Insights from water supply contamination in Havelock North, New Zealand. *Local Environment, 25*(10), 810-827. https://doi.org/10.1080/13549839.2020.1839030

Thornley, C., Harte, D., Weir, R., Allen, L., Knightbridge, K., & Wood, P. (2017). Legionella longbeachae detected in an industrial cooling tower linked to a legionellosis outbreak, New Zealand, 2015: Possible waterborne transmission? [Short Report Article]. *Epidemiology and Infection, 145*(11), 2382-2389. https://doi.org/10.1017/S0950268817001170

U.S. Department of Health and Human Services. (2024). *United States Centre for Disease Control and Prevention,*.June 2024, from https://www.cdc.gov/healthywater/emergency/waterborne-disease-outbreak-investigation-toolkit/about.html

United States Environmental Protection Agency. (2024). *Climate impacts on water quality*. https://www.epa.gov/arc-x/climate-impacts-water-quality#harmful

Viñas, V., Malm, A., & Pettersson, T. (2019). Overview of microbial risks in water distribution networks and their health consequences: Quantification, modelling, trends, and future implications. *Canadian Journal of Civil Engineering, 46*(3), 149-159. https://doi.org/10.1139/cjce-2018-0216

Weinstein, P., Russell, N., & Woodward, A. (2000). Drinking water, ecology, and gastroenteritis in New Zealand. *IAHS-AISH Publication, 260*, 41-47. (International Association of Hydrological Sciences)

Williamson, W., Ball, A., Wolf, S., Hewitt, J., Lin, S., Scholes, P., Ambrose, V., Robson, B., & Greening, G. (2011). Enteric viruses in New Zealand drinking-water sources. *Water Science and Technology, 63*(8), 1744-1751. https://doi.org/doi: 10.2166/wst.2011.117.

Wilson, B., Jones, N., Wood, T., Jagroop-Dearing, A., Kubovy, J., & Baker, M. (2021). Clinical outcomes of campylobacteriosis: A case series analysis of hospitalisations associated with the Havelock North *Campylobacter* outbreak. *New Zealand Medical Journal, 134*(1547), 71-84.

Wilson, N., Slaney, D., Baker, M., Hales, S., & Britton, E. (2011). Climate change and infectious diseases in New Zealand: A brief review and tentative research agenda. *Reviews on Environmental Health, 26*(2), 93-99. https://doi.org/10.1515/reveh.2011.013

Wood, D. (2011). *Review of the quality of drinking-water data held in WINZ: A discussion document.* Ministry of Health.

World Health Organisation. (2021). *A global overview of national regulations and standards for drinking-water quality.* https://iris.who.int/bitstream/handle/10665/350981/9789240023642-eng.pdf?sequence=1

World Health Organization. (2022). *Guidelines for drinking-water quality: fourth edition incorporating the first and second addenda.*

Wu, S., Hrudey, S., French, S., Bedford, T., Soane, E., & Pollard, S. (2009). A role for human reliability analysis (HRA) in preventing drinking water incidents and securing safe drinking water. *Water Research, 43*(13), 3227-3238. https://doi.org/https://doi.org/10.1016/j.watres.2009.04.040

Appendix 1

The following table summarises waterborne outbreaks in New Zealand that have been officially reported and documented since the 1980s. Details of all outbreaks have not resulted in publications, but most, if not all, have been included in this review.

Table: 5. Waterborne outbreaks in New Zealand have been reported and or documented.

Year	Notified disease	No. of confirmed outbreaks/ cases	Location	Notes and source (where possible)
1984	Raw sewage	3,500 probable	Queenstown, Central Otago	People were affected with gastroenteritis.
1986	Campylobacteriosis	19 cases confirmed	Ashburton	Heavy rain event, no chlorination in 3-60m bore supply (Ball, 2007)
1991	Campylobacteriosis	12 cases confirmed	Havelock North	Possible back siphoning at the drinking water source (Ball, 2007)
1991	Giardiasis	50 cases	Dunedin, Otago	(Ball, 2007)
1992	Campylobacteriosis	97 cases	Hawke's Bay youth camp	Untreated bore water (Ball, 2007)
1993	Campylobacteriosis	42 cases confirmed	Canterbury campsite	Consumption of un-boiled water (Ball, 2007)
1993	Giardiasis	34 cases confirmed	Auckland	(ESR, 2007; Hoque et al., 2004; Hoque et al., 2002; Hoque et al., 2003)
1994	Campylobacteriosis	6 cases confirmed	Fairlie	Heavy rain events increased the turbidity of the Opihi River (Ball, 2007)
1995	Gastroenteritis	100 people reported	Hutt Valley camp	30 faecal coliforms/100mL were detected in drinking water (Ball, 2007)
1996	Giardiasis		Denniston, Buller	Unregistered, untreated, unprotected water consumption (Ball, 2007)
1996	Gastroenteritis	58 cases reported	Mt Hutt ski field	No UV cartridge filters were replaced on the water supply
1996	Campylobacteriosis	33 cases confirmed	Ashburton, South Canterbury	(ESR, 2007)
1997	Campylobacteriosis	67 cases suspected	Wainui camp, Akaroa	(Ball, 2007)
1997	Cryptosporidiosis	170 cases confirmed	Waikato	Turbidity in drinking water (Ball, 2007)
1997	Salmonella typhimurium	4 cases	Auckland	Drinking untreated roof water (Ball, 2007)
2001	Campylobacteriosis	137 cases confirmed	Te Aute College, Hawke's Bay	UV treatment system malfunction (Ball, 2007)

2005	Campylobacteriosis	3 cases confirmed (10 probable)	Bridge Valley School Camp, Nelson	Gilpin, B., Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2005	Campylobacteriosis	6 confirmed (34 probable)	Hawke's Bay school camp	Gilpin, B., Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2005	Campylobacteriosis	13 confirmed (21 probable)	Canterbury medical students camp	Gilpin, B., Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2005*	n/a	nil	Sherry River, Motueka	Identified as a 'hot spot' of faecal microbial pollution. Not an illness outbreak but a relevant study of dairy-herd crossings.
2006	Norovirus	218 confirmed	Cardrona Skifield, Otago	(Hewitt et al., 2007) and Gilpin slide 9 Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2006	Campylobacteriosis	2 confirmed (20 probable)	Te Kuiti school camp	Gilpin slide 9 Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2007	Gastroenteritis – unknown cause	96 confirmed	Wellington school camp	Gilpin slide 9 Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2007	Gastroenteritis – viral unknown cause	17 confirmed	Northland school	Gilpin slide 9 Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2007	Gastroenteritis – unknown cause	96 confirmed	Gastro: cause unknown	Gilpin slide 9 Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2008*	E. Coli detection drinking water system	Nil due to early council detection	Middle Renwick Rd, Blenheim (drinking water distribution system)	3 bores screened from around 20 – 25 m deep in alluvial gravel strata. Unconfined permeable strata to surface at inland section west of MRR bore field so rainfall/liquid contaminants can drain into aquifer. UV disinfection was installed (Callander et al., 2014).
2008	Campylobacteriosis	5 confirmed (39 probable)	Springston, Selwyn, Canterbury	Gilpin, B., Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2008	Campylobacteriosis	2 confirmed (13 probable)	South Canterbury youth camp	Gilpin, B., Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2010	Norovirus	-	Golden Bay Holiday Park	Gilpin, B., Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH

2010	Campylobacteriosis	1 confirmed (15 probable)	Waiouru Commanders' course, Manawatu	Gilpin, B., Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2011	Campylobacteriosis	4 confirmed	Runanga (drinking water supply)	Gilpin, B., Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2012	Campylobacteriosis	28 confirmed	Hawke's Bay camping ground (drinking water)	Gilpin, B., Ministry of Health (2019) Guidelines for DW Quality Mgmt for NZ (2nd edn). Wellington: MoH
2012	Norovirus	48 confirmed (5 probable)	Cardrona Hotel, Otago	The water supply was contaminated due to inadequate chlorination and surface flooding (Jack et al., 2013; Nicholas & Weaver, 2016).
2012	Campylobacteriosis + detection of Escherichia coli	138 suspected	Darfield, Canterbury	Weekly microbial testing revealed *coliforms* and *E. coli* due to manual chlorination failure, heavy rainfall, increased turbidity in the water supply, and the low-lying well-head located in a sheep paddock (Blakemore & Washington, 2012; Callander et al., 2014; Canterbury District Health Board, 2013; Sheerin et al., 2014)
2013	Gastroenteritis – unknown cause	(13 probable)	Nelson Lakes (scout camp)	Gilpin slide 9 Ministry of Health (2019) Dridelines for DW Quality Mgmt for NZ (2nd edn. Wellington: MoH)
2015	Cryptosporidiosis	2 outbreaks/ 5 cases		(Ma et al., 2022)
2015	Protozoa (Dientamoeba fragilis)	3 outbreaks/ 16 cases		(Ma et al., 2022)
2015	Giardiasis	8 outbreaks/ 50 cases		One case was from travelling to Nepal (Ma et al., 2022)
2015	Legionella	3 confirmed cases	Dairy processing plant, central North Island	L. longbeachae detection in cooling towers has not been previously reported in association with legionellosis outbreaks. A dairy processing plant had been extensively redeveloped to increase production capacity, which required substantial earthworks for new cooling towers (Thornley et al., 2017).
2016	Campylobacteriosis	967 confirmed (5,500 probable)	Havelock North, Hawke's Bay outbreak	953 cases were physician-reported, 42 were hospitalised, three developed Guillain-Barré syndrome, and Campylobacter infection contributed to at least four deaths. (Department of Internal Affairs, 2017a, 2017b; Gilpin et al., 2020;

				Hrudey & Hrudey, 2019; Pourzand & Hales, 2023)
2016	Giardiasis	5 outbreaks/ 16 cases		(Ma et al., 2022)
2016	Cryptosporidiosis	3 outbreaks/ 9 cases		(Ma et al., 2022)
2017	Giardiasis	3 outbreaks/ 9 cases		(Ma et al., 2022)
2017	Cryptosporidiosis	2 outbreaks/ 6 cases		(Ma et al., 2022)
2021*	Lead concentrations		Waikouaiti, Karitane, Hawksbury Otago	Although not classified as a waterborne illness, lead can have serious health implications.
2021	Legionella	5 cases	Not stated	L. pneumophila (associated with warm water systems) (ESR, 2020)
2021	Cryptosporidiosis	6 cases	Southern District Health Board, Southland	Human infection, not water-borne: Student farm visit. (ESR, 2020)
2022	Campylobacteriosis	1 outbreaks/ 3 cases	Southland	ESR Annual Report 2021 (in draft)
2022	Campylobacteriosis	1 outbreaks/ 5 cases	Counties Manukau	ESR Annual Report 2021 (in draft)
2022	Giardiasis	1 outbreaks/ 3 cases	Northland	ESR Annual Report (in draft)
2023	Cryptosporidiosis	60 cases	Queenstown, Central Otago	Still undetermined. (Baker et al., 2023)
2024	Cryptosporidiosis	9 cases	Various (ESR)	Recreational water (ESR monthly reports January-March 2024).

*= not a direct 'outbreak' but useful for overall context.

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