NIWA
Taihoro Nukurangi

Beachlands WWTP Discharge: Assessment of microbiological effects and health risk

Prepared for Watercare

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Climate, Freshwater & Ocean Science

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Executive summary

Watercare Services Limited has a resource consent to discharge treated wastewater from Beachlands Wastewater Treatment Plant (WWTP) to the Te Puru Stream via an overland flow scheme and pond system on a tributary of the Te Puru Stream. The consent expires in 2025, and Watercare wishes to reconsent that discharge. As part of the reconsenting process, an assessment of the potential human health risks following exposure to discharged treated wastewater is required both for the current treatment plant discharge and for future discharge scenarios that consider population growth in the area with associated increases in wastewater volume.

Watercare commissioned NIWA to assess the potential health risks following exposure to treated diluted wastewater in association with primary contact recreation (e.g., swimming), consumption of uncooked watercress harvested in the Te Puru stream and consumption of raw harvested shellfish. A Quantitative Microbial Risk Assessment (QMRA) was used to assess health risks arising from viral enteric infection. Others will use these estimated health risks as inputs for a full assessment of environmental effects.

Outputs from estimated flows in the Te Puru stream from PDP and hydrodynamic modelling by DHI were used as key inputs to QMRA modelling, allowing estimates of Individual Infection Risks (IInfR) to be calculated for three freshwater sites for both swimming and watercress consumption, swimming at 10 marine sites and shellfish consumption from three sites. The estimated risks were incremental risks due to the discharge of well-treated effluent into the environment.

The estimated incremental risks were highest in the Te Puru stream, downstream from the discharge, and the risks became less as the well-treated effluent was diluted in the marine environment. However, it was clear from microbiological monitoring data that activities in the Te Puru catchment, other than the wastewater plant, were degrading water quality and resulted in additional risks to human health. High levels of faecal indicator bacteria (FIBs) were observed in the Te Puru stream at substantially higher levels than in the WWTP discharge. This makes the Te Puru stream an unsuitable source of stock drinking water and indicates that the average individual infection risk is expected to be greater than 7% per swimming event.

The WWTP risk estimates used norovirus as a reference pathogen. Risk estimates were carried out for:

- 16 exposure sites – three freshwater and 13 marine sites.
- Three exposure mechanisms – swimming, and watercress and shellfish consumption (not all exposure routes were assessed for each site).
- Seven levels of treatment or log reduction values (LRV)- 1 to 7 $\log_{10}$ reductions in virus concentrations.
- 3 discharge scenarios – Current, Interim and Stage 2.

Health risks arising from exposure to norovirus, the reference pathogen, were related tothe exposure site, exposure mechanism and the level of wastewater treatment assumed in the modelling.

- Health risks were greatest in the Te Puru stream, downstream from the discharge point for all discharge scenarios.

- Consumption of uncooked watercress harvested in the Te Puru stream resulted in the highest overall risks and was similar to primary contact/swimming risks in the stream.
- Risks in the marine environment from contact/swimming or consuming raw/lightly cooked shellfish result in risks of an order of magnitude lower than in the freshwater environment, assuming other things remain constant.
- Higher levels of treatment resulted in lower levels of risk, assuming other things remain constant.
- Increasing discharge from the plant increases the risk in the marine environment, though it had little effect on the risk estimates in the Te Puru stream.

QMRAs can help inform decisions about what level of wastewater treatment may be required by placing the health risk results in policy documents. Given that the highest risks were estimated in the freshwater environment, the National Policy Statement – Freshwater Management 2020 – Amended January 2024 (Ministry for the Environment 2024) was used as a guideline. Ensuring that the incremental risk from the dilute well- treated effluent is no greater than 1% at any exposure site for any exposure mechanism requires a log reduction value (LRV) of five, based on watercress consumption.

The watercress assessment is highly precautionary as the risks from watercress consumption are poorly quantified and understood. However, based on the assessment of the risks of swimming, an LRV greater than four would be required to keep risks below 1%.

The results reported here are the potential health risks attributable to norovirus derived from the Beachlands WWTP and are *incremental* health risks associated with a single model pathogen in the WWTP discharge. Usually, viruses are the principal pathogen of concern from well-treated wastewater. If, however, the WWTP fails to achieve these reductions, non-viral pathogens such as bacteria or protozoa may also be of concern.

1 Introduction

The Beachlands Wastewater Treatment Plant (WWTP) is operated by Watercare Services Limited. Watercare has a resource consent to discharge treated wastewater to the Te Puru Stream. As part of the process of reconsenting the existing discharge, an assessment of the potential human health risks following exposure to discharged treated wastewater is required for the current treatment plant discharge and also for future discharge scenarios that consider population growth in the area with associated increases in wastewater volume.

To address consenting requirements, Watercare Services Limited commissioned NIWA to prepare a Quantitative Microbial Risk Assessment (QMRA) and assess the potential for adverse effects on human health following recreation in, or consumption of foods such as shellfish and watercress gathered from, waters affected by the discharge of treated wastewater from the Beachlands WWTP. The QMRA relates to microbial pathogens and the incremental risks associated with the Beachlands WWTP discharge.

To assist with the assessment of health risks, NIWA also undertook an assessment of the wastewater discharge and microbial water quality of the receiving environment and at downstream locations where recreation occurs. This assessment focuses primarily on faecal indicator bacteria (FIB) and provides a broader "microbiological context" for health risks to recreational users as it incorporates other contaminant sources (e.g., diffuse, urban runoff, wildlife) in addition to the Beachlands WWTP.

The current operation at Beachlands- Maraetai (Beachlands) WWTP is an activated sludge plant with biological nutrient removal (BNR). The treatment of wastewater at the WWTP consists of initial screening followed by primary treatment in aerated lagoons (four-stage Bardenpho lagoon), settlement in clarifying basins, and disk filtration followed by UV disinfection (Figure A-3). Stormflows are buffered in lagoons before passing back through the WWTP for final treatment and discharge. Figure A-1 provides a schematic of the WWTP and treatment units.

The UV disinfected treated effluent is piped to a riparian buffer zone for land application where it is discharged via above-ground perforated distribution channels in parallel resulting in ground soakage to a large pond ("Farm Pond"). The outlet from the Farm Pond flows into a tributary of the Te Puru Stream which flows through moderately steep pastoral land down to the estuary at Te Puru Park/Kelly's Beach. The Farm Pond is located approximately 4.1 km upstream from the estuary.

The Beachlands WWTP currently serves a population of around 10,000. However, there is a need to extend this capacity to meet population growth due to housing development in the area. Watercare is planning to stage plant capacity with an interim upgrade of the plant to serve around 20,000 and a Stage 2 upgrade to serve 30,000 people (Andrew Slaney, process engineer, Stantec, pers comm). It is proposed that the plant will continue to discharge to the tributary of the Te Puru stream with increased effluent volume.

The catchment surrounding the Te Puru Stream is low relief, and mainly low intensity pastoral agriculture with areas of native forest and regenerating bush in stream gullies. The Te Puru Stream forms from a number of tributaries. The "reference" tributary joins Te Puru stream (Site E) at around 350 m downstream from the Farm Pond. The main stem of the stream (the Black Barn Tributary) joins at around 1.2 km further downstream (Site C) (Figure B-1). The Te Puru Stream drains into the estuary (Te Puru Park) just downstream from a quarry ("Quarry" site) (Figure 3-2). The estuary is around 1.1 km in length and fringed by mangroves on mudflats on the seaward side. The Te Puru Stream flows out across the beach for around one hour before and after low tide following a channel for about 150 m to the low water spring tide level.

Health risk assessment

Health risk assessment studies often use "faecal indicators" (faecal indicator bacteria, FIB) to estimate faecal contamination and human health risks. In New Zealand fresh waters, *Escherichia coli* (*E. coli*) is the preferred FIB, and enterococci are the preferred FIB for coastal waters. However, the association between indicators and pathogens, disease-causing organisms, tends to break down in wastewater treatment. In these circumstances, complying with FIB numerical limits, such as those in the "Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas" (MfE/MoH 2003) referred to here as the Guidelines, does not guarantee safety.

Risk assessments overcome the problem of a lack of a relationship between indicator organisms and pathogens by considering the actual or likely content of pathogens discharged in the treated wastewater effluent and the subsequent health risk to individuals exposed to residual pathogens.

Quantitative Microbial Risk Assessment (QMRA) quantifies the human health risks associated with wastewater treatment and disposal schemes. This procedure uses dose-response data for pathogens alongside water users' exposure to potentially contaminated water. The procedure may include health risks from consuming harvested food (including mahinga kai, such as shellfish) that may be exposed to treated, diluted wastewater (i.e., effluent). These data are used in computer simulations to estimate an individual's infection or illness risk.

QMRA is increasingly used to quantify the human health risks associated with wastewater treatment and disposal schemes (World Health Organization 2016). NIWA has developed a standardised QMRA methodology that may be customised and applied to most circumstances involving the discharge of treated wastewater to recreational waters.

1.1 Scope of report

This QMRA was undertaken using site-specific and other information. Site-specific information regarding the dilution of treated effluent in the environment was provided by DHI and PDP, the expected level of pathogens in wastewater from other New Zealand studies, and information regarding the volumes of food and water ingested as well and the infectivity of viruses (e.g., dose-response) come from the literature.

NIWA carried out a site visit but performed no fieldwork or data collection for this QMRA. Microbiological water quality data for the Beachlands WWTP and receiving environment were provided by Aquatic Environmental Sciences and Coasts and Catchment. The QMRA modelling was based on previous models of a similar nature (e.g., McBride 2017; Stott et al. 2023; Wood and Hudson 2023), which included updated parameters since the *2004 QMRA Report* on Beachlands WWTP (Stott and McBride 2004) was carried out.

Quantitative risk assessment involves a multistage process of identifying candidate pathogens, routes whereby the community may be exposed to organisms and modes of exposure. In this case, it was assumed that the candidate pathogen was norovirus and that the two key exposure routes were swimming and the consumption of foods exposed to diluted effluent, such as raw or lightly cooked shellfish and uncooked watercress[1]. These assumptions are reasonable, as other New Zealand QMRAs indicated that norovirus (in its disaggregated form) represents the greatest risk to individuals from swimming and shellfish consumption compared to other pathogens commonly considered in QMRA modelling of the Individual Infection Risk (IInfR).

The potential impacts on the quality of livestock drinking water abstracted from Te Puru Stream was considered within the microbiological context assessment.

1.2 Outline of report

The report is laid out into sections:

- Section 2 describes the microbiological context for the likely impact of the wastewater discharge observed from the perspective of discharged wastewater characteristics and background health risks indicated by the microbial water quality of the local receiving environment.
- Section 3 describes the methodology for the QMRA, the parameters used for modelling health risks, and the resulting modelled health risks.
- Section 4 summarises the potential public health impact of the Beachlands WWTP discharge for livestock drinking water, recreational water users and consumers of shellfish and watercress.

[1] Watercress and the possibility of watercress harvesting was identified upstream of the WWTP (Jason Scharvi-Coles, Process Technician, Watercare Services Limited, Pers comm 27 Oct 2023) and harvesting may occur downstream of the WWTP.

2 Microbiological context

To assist with the assessment of health risks, a microbiological assessment of the receiving environment was undertaken as a component of the QMRA. This assessment focuses primarily on faecal indicator bacteria (FIB) and provides a broader context for health risks to recreational users as it incorporates other contaminant sources (e.g., diffuse, urban runoff, wildlife) in addition to Beachlands WWTP. Data used to establish this "microbiological context" for the local receiving environment and Te Puru Stream included compliance monitoring of wastewater discharge volumes and concentrations of faecal indicator bacteria such as faecal coliforms, *E. coli* and enterococci measured in the discharge and receiving environment.

These data were used to estimate the risks from human contact with treated wastewater using criteria and guideline values from the New Zealand Recreational Water Quality Guidelines (Ministry for the Environment and Ministry of Health 2003), and the National Policy Statement for Freshwater Management (Ministry for the Environment (Manata Mo Te Taiao) and Te Kaawanatanga o Aotearoa (New Zealand Government) 2024). It is important to note that these Guidelines should not be used to assess risks from wastewater discharges, as the treatment process may alter the relationship between FIB and pathogens. This lack of a reliable relationship is one of the key reasons why the QMRA approach was chosen to estimate risk. However, analysing FIB data and comparing them with the Guidelines and other frameworks does provide another way to estimate the prevailing health risk to water users from contamination sources other than well treated wastewater, particularly during recreational or bathing seasons. Data were also used to assess spatial patterns of risk.

The potential risk to livestock consuming water sourced from the Te Puru stream containing treated wastewater was also considered and assessed using guideline values from the Australian and New Zealand Guidelines for Fresh and Marine Water quality (ANZECC and ARMCANZ 2000).

FIB concentrations can provide some indication of the effect that discharge of treated wastewater has on the receiving waters. However, this report does not attribute risk to any specific source. This is particularly relevant for discharged wastewaters as the relationship between indicator and pathogen is not assured. While wastewater treatment effectively reduces FIB concentrations, other pathogens may be less affected by treatment processes and thus persist at levels that still pose health risks to the public if exposed.

2.1 Data sources

Water quality and discharge data were provided by Aquatic Environmental Sciences Ltd (Mark James) and Coast and Catchment (Shane Kelly). NIWA collated available compliance, and other relevant monitoring data for wastewater discharge, and the receiving environment. Data were reviewed and the outcomes of an exploratory data analysis used to provide a context for the QMRA.

Datasets used for this assessment were sourced from several different monitoring programmes. As part of the WWTP monitoring plan, concentrations of faecal indicator bacteria (faecal coliforms and *E. coli)* are measured weekly from grab samples of secondary treated wastewater and tertiary treated effluent to verify the efficacy of the UV disinfection process and quality of discharged wastewater. Additionally, a short-term intensive monitoring campaign was undertaken from September 2023 to March 2024) for the WWTP. This also included raw and treated wastewater quality and a synoptic water quality survey along the Te Puru Stream to Te Puru Park as well as analysis of enterococci in addition to faecal coliforms and *E. coli.* Consequently, datasets are not of equivalent lengths and monitoring of selected variables (e.g., enterococci) was initiated during the life of the spatial survey for the Te Puru stream.

2.1.1 Wastewater

Data for WWTP flows (total daily discharge m^3/d) and faecal indicator bacteria (FIB) (faecal coliform and *E. coli*) were supplied for treated effluent pre- and post- UV treatment for 1 Jan 2018 – 14 Jan 2024.

Frequency of analysis for FIB concentrations was typically weekly and are expressed as CFU/100 mL after membrane filtration analysis. Data were used with limited modification including:

- Calculation of instantaneous load as a product of the daily average wastewater flow (discharge rate) and FIB concentration on the day the grab sample was collected.
- Removal of data due to erroneous results. This included n=18 data points for FIB results reported as < 10 CFU/100 mL in pre-UV treated wastewater samples as concentrations as low as this in secondary treated wastewater seems unlikely. For tertiary treated wastewater, three outlier values were removed for faecal coliform concentrations reported as 2 or 3 orders of magnitude higher than *E. coli*. These discrepancies seem improbable considering the majority of faecal coliforms typically comprise *E. coli.* One erroneous result for FIBs (faecal coliform, *E. coli* and enterococci) was removed from the short-term sampling campaign due to improbably high 10^3-10^4 CFU/100 mL concentrations in the discharged wastewater ("WWTP Outlet").

Current limits for the microbial quality of treated wastewater from Beachlands WWTP is a consented median of ≤ 14 faecal coliforms CFU/100 mL determined from 10 consecutive samples (ARC 2005; Watercare Services Limited 2022). There is no consent limit stipulated for *E. coli.* However, *E. coli* are a subgroup of faecal coliforms and are the main contributor particularly where animal wastes and human sewage are the primary source of faecal contamination (Horan 2003). As a conservative approach similar limits may be considered for *E. coli* concentrations in the treated wastewater.

No pathogen data is available for the WWTP.

2.1.2 Receiving environment

Treated wastewater from the WWTP discharges via surface irrigation to a riparian buffer as an overland flow scheme for the disposal of the UV-disinfected effluent. Depending on the slope and saturation of the soil horizon, wastewater will travel as overland flow or infiltrate the soil horizon and travel as subsurface flow towards a large pond (Farm Pond) located on a tributary of the Te Puru Stream.

The Te Puru stream flows down through a catchment mainly dominated by pastoral land use eventually reaching the coast and discharging into the estuarine environment at Kelly's beach. The stream is reasonably narrow (average width 1.7 m) and shallow at typically <0.5 m depth during summer low flows (Bioresearches 2022). Stream flow varies spatially with headwater tributaries experiencing lower flows, while water flows generally increase with distance downstream.

A short-term monitoring programme was established to provide spatial water quality characteristics for the Te Puru stream and selected tributary sites during spring to late summer low flow conditions. Data for this limited duration monitoring programme was available from 11 September 2023 to 6 March 2024 and was supplied by Coast and Catchment (Shane Kelly).

Information from the short-term monitoring sites was cross-referenced with the QMRA site locations.

2.2 Results

Data were examined to characterise the discharged wastewater and the nature and scale of its effects on the environment. Exploratory analysis was undertaken using TimeTrends V11 and R 4.2.2.

The locations of various sample points are indicated in Figure A-1 for WWTP sampling sites, Figure 3-2 for QMRA sites and Figure B-1 for the Te Puru Stream spatial monitoring survey.

2.2.1 Beachlands WWTP Wastewater discharge

The daily discharge limit for the Beachlands WWTP is 2,800 m^3/d (Watercare Services Limited 2022).

Time series data for wastewater discharge (m^3/d) is summarised in Figure 2-1 for total daily rates. The time series for 2021 is incomplete due to missing data. Data indicates discharge rates fluctuate throughout the year and are punctuated intermittently by short periods of considerably higher flows that exceed the daily discharge limit of 2,800 m^3/d.

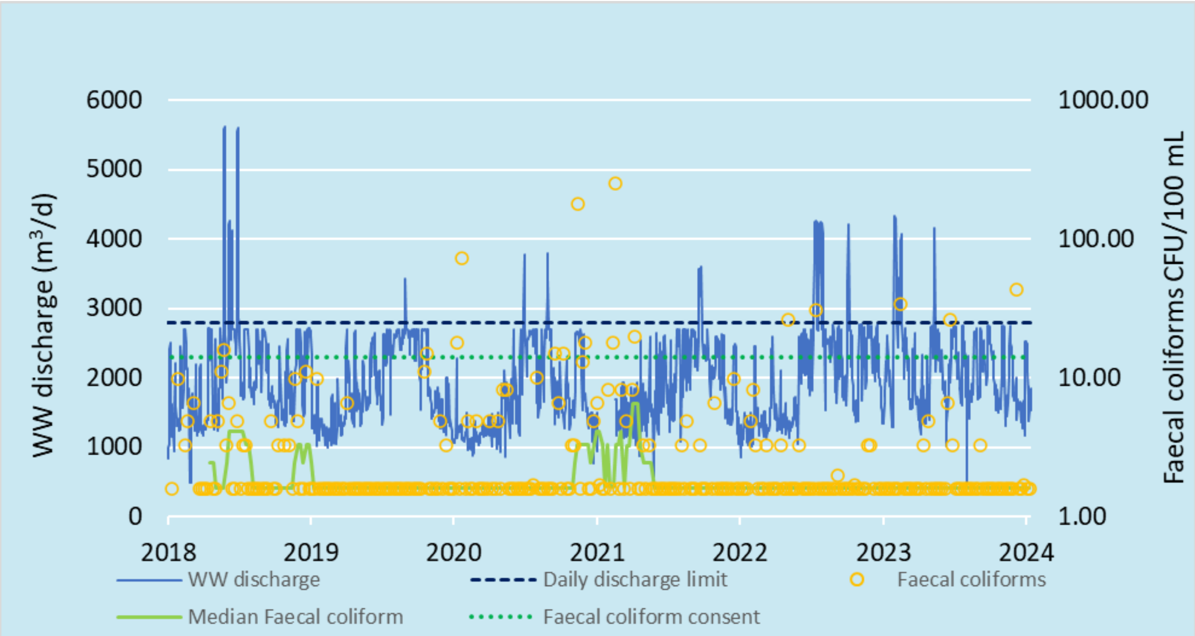

Figure 2-1: Time series of wastewater total daily flows and faecal coliform levels in wastewater discharged from Beachlands WWTP. All data shown from 1 Jan 2018 to 14 Jan 2024. Consent limits for discharge (m^3/d) and faecal coliforms (median CFU/100mL) shown. Median faecal coliforms shown as running median on 10 consecutive samples. Note $\log_{10}$ scale on y-axis for faecal coliforms. Note also that flow balancing ponds are used to prevent discharges exceeding the daily discharge consent limit where possible.

There is evidence of seasonal variation in wastewater discharge with larger median and mean discharge rates in the winter months June – September (Figure 2-2). Conversely, late summer and early spring months experience lower flows influenced by generally drier conditions.

Annual mean discharge rates range from 2041 m^3/d (2018) to 2139 m^3/d (2023) with a slight consistent upward trend in daily average flow on an annual basis since 2020 (Figure 2-3). Deseasonalised trend analysis suggests that this increase is approximately 1.6% per year.

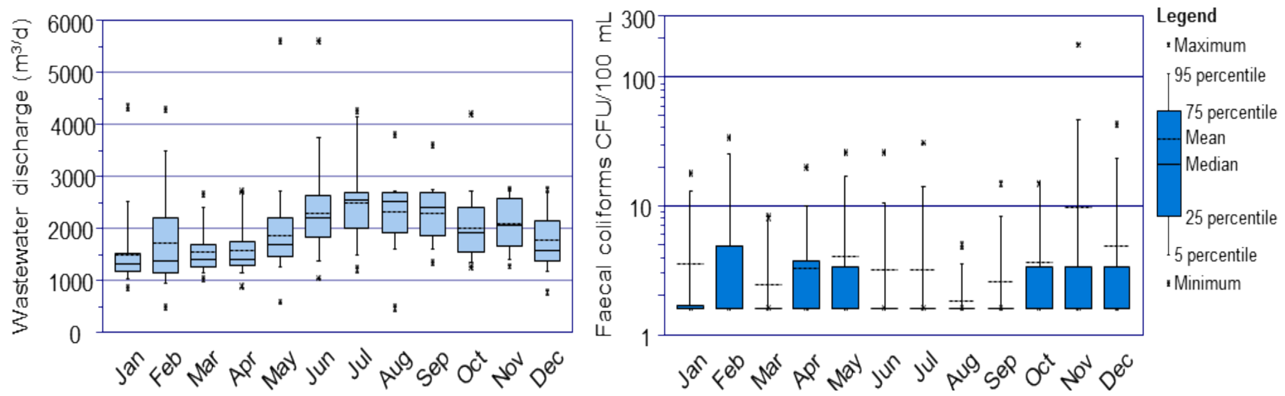

Figure 2-2: Seasonal (monthly) summary of daily wastewater discharge and faecal coliform concentration in UV treated wastewater (2018-2023 inclusive). Censored data shown for faecal coliforms. Note $\log_{10}$ scale on y-axis for faecal coliform data. Median shown as dotted line, mean as solid line.

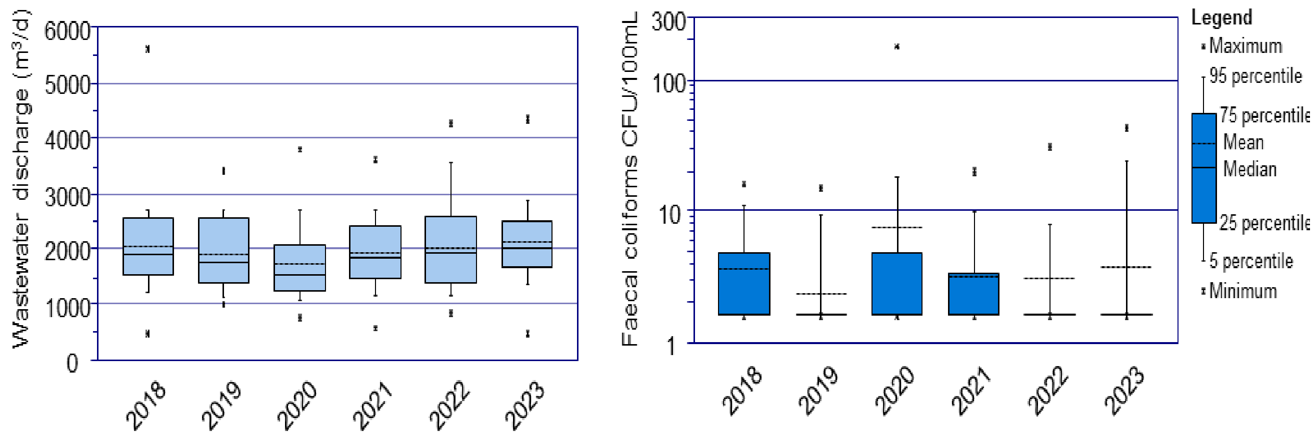

Figure 2-3: Annual (yearly) summary of daily discharge characteristics and faecal coliform concentrations in UV disinfected wastewater for 2028-2023 inclusive. Censored data shown for faecal coliforms. Note $\log_{10}$ scale on y-axis for faecal coliform data. Median shown as dotted line, mean as solid line.

Wastewater microbiological characteristics

Faecal indicator bacteria (faecal coliforms and *E. coli*) are monitored in the secondary treated wastewater after disc filter treatment and before UV treatment, and after UV treatment to confirm disinfection is achieved. Concentrations of faecal coliforms in the UV treated wastewater varies over two orders of magnitude (Figure 2-2). However, levels in the discharged wastewater are mostly below 10 CFU/100 mL. Current consent limits are for a median concentration of ≤ 14 faecal coliforms/ 100 mL (based on 10 consecutive samples) and for the majority of the time, concentrations remain below this threshold. On occasions, elevated levels of faecal coliforms are observed but these do not appear to coincide with relatively high discharge rates (Figure 2-1). High levels of FIB in UV- disinfected wastewater whether faecal coliform or E. coli do not seem to be linked to the performance of the UV process (see discussion below). However, FIB concentrations in UV-treated wastewaters show less variability at higher UV transmissivity (%) levels (Figure A-5).

The monthly median and mean faecal coliform concentrations in the treated wastewater are typically less than 5 CFU/100 mL (Figure 2-2). However, there is an observed increase in faecal coliform concentrations in discharged wastewater during the summer months. Notably, average and 95th percentile concentrations are highest between November and February, likely due to reduced dilution of the wastewater during this period. This suggests a greater potential for faecal contamination in the receiving environment during summer in relation to the microbiological faecal indicator bacteria quality associated with the discharged effluent from the Beachlands WWTP.

Faecal coliform concentrations in UV disinfected wastewaters are summarised in Table 2-1. Annual medians were consistently < 2 CFU/100 mL. Consent limits being considered for the various scenario options are likely to be median faecal coliforms <10 CFU/100 mL and a 90th and 95th percentile of 100 CFU/100 mL (Andrew Slaney, Process Engineer, Stantec). These conditions are met under current operating conditions (Table 2-1) based on annual summaries. Seasonal variations in wastewater characteristics in Figure 2-2 illustrates the importance of monitoring to detect any deviations in treated wastewater quality. In instances where elevated concentrations are identified, increasing the frequency of monitoring can help distinguish between spurious results and the need for action to rectify treatment system inefficiencies.

Table 2-1: Annual summary of faecal coliform concentrations in UV treated wastewater discharged from Beachlands WWTP. Note all data summarised.

Year	N	Mean	Median	95th percentile	Maximum
2018	44	3.7	1.6	11.0	16
2019	53	2.4	1.6	9.3	15
2020	52	8.8	1.6	18.0	180
2021	51	8.1	1.6	17.6	250
2022	52	3.0	1.6	7.9	31
2023	52	3.7	1.6	24.1	43

The removal performance of the WWTP is assessed using both the short-term monitoring dataset and the compliance monitoring dataset. These datasets allow for the assessment of removal efficacy throughout the WWTP and specifically for the UV disinfection process.

The Beachlands WWTP demonstrates relatively consistent removal performance for the UV disinfection process with average log_{10} removal ranging from 3.2 to 3.9 throughout the year (Figure 2-5). Highest removal rates are typically observed during summer months coinciding with periods of elevated FIB concentrations in secondary treated wastewater prior to UV treatment (Figure 2-4).

This observation highlights the WWTP's capacity for UV disinfection, as it effectively manages high concentrations of FIB in UV influent wastewaters without compromising disinfection efficiency. The removal efficacy of UV treatment did not seem to be affected by discharge flows or the transmissivity of the UV process (Figure A-2 and Figure A-5). However, while FIB are effectively inactivated by UV disinfection, other pathogens such as viruses exhibit different responses to UV treatment. Some viruses are reported to be particularly resilient to UV disinfection processes with their susceptibility varying depending on the specific type of virus (Malayeri et al. 2016).

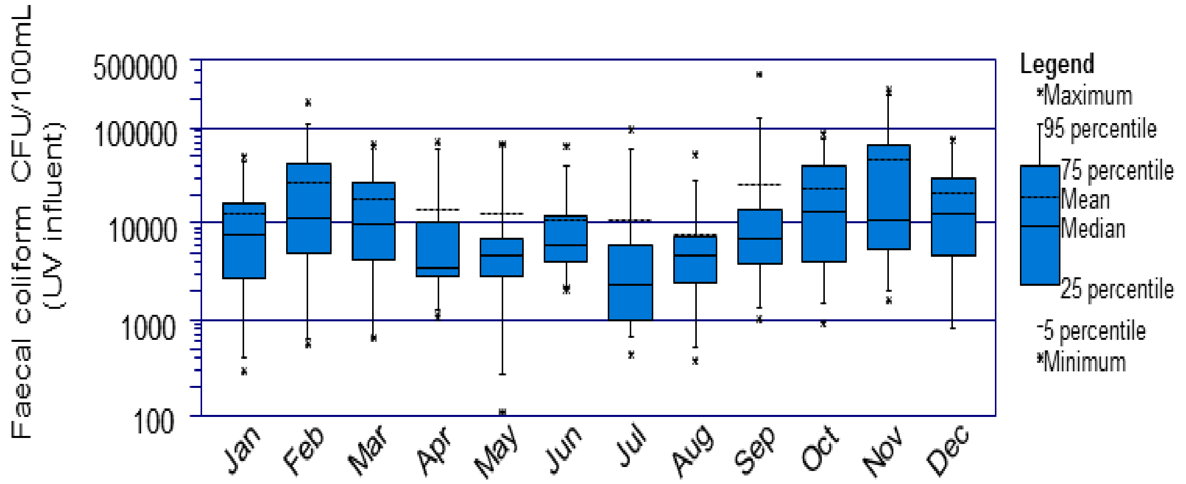

Figure 2-4: Seasonal variability in faecal coliform concentrations in wastewaters immediately upstream of the UV treatment system. Censored data. Note log_{10} scale on y-axis. Median shown as dotted line, mean as solid line.

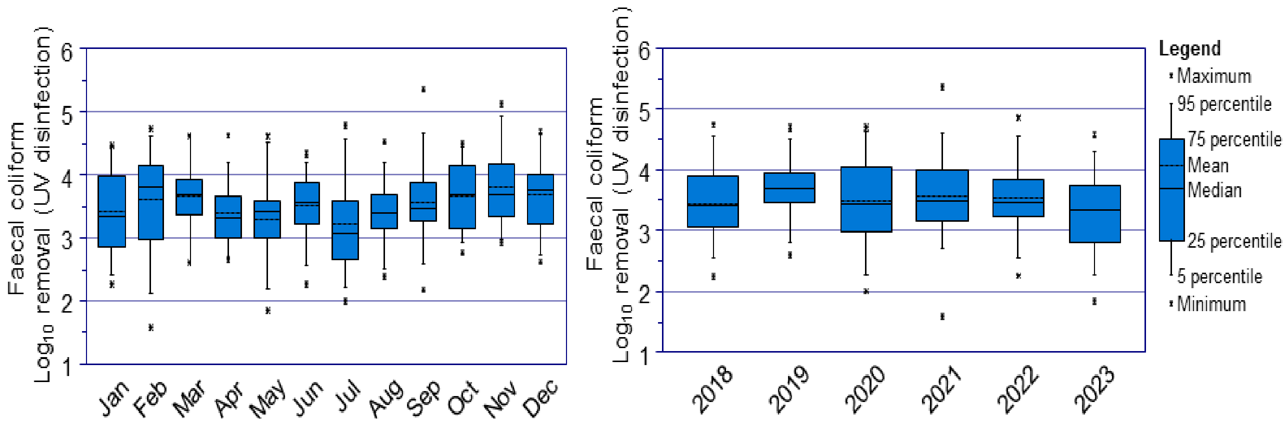

Figure 2-5: Seasonal and annual removal performance for UV disinfection of wastewater at Beachlands WWTP. Log_{10} removal shown for faecal coliforms from censored data. Median shown as dotted line, mean as solid line.

Overall, data indicate effective removal of FIB throughout the WWTP with 2-3 $\log_{10}$ removal prior to the UV treatment system, typically resulting in around 6 $\log_{10}$ overall removal for faecal coliforms, *E. coli* and enterococci (from inlet to outlet) (Table 2-2). Similar removal is observed for the different types of FIBs. Although removal remains relatively consistent during the sampling campaign, greater variability is observed during late summer, particularly in February (Figure 2-6).

Table 2-2: Removal (log10) of faecal indicator bacteria through the WWTP. Censored data from 1 October 2023 to 6 Mar 2024 inclusive. Data from short-term monitoring campaign from the WWTP inlet and WWTP outlet.

Faecal indicator bacteria	N	Min	Median	Mean	95th percentile	Max
Faecal coliform	63	4.4	6.6	6.5	7.3	7.4
E. coli	63	5.2	6.4	6.4	6.9	7.0
Enterococci	63	4.6	6.0	6.0	6.5	7.8

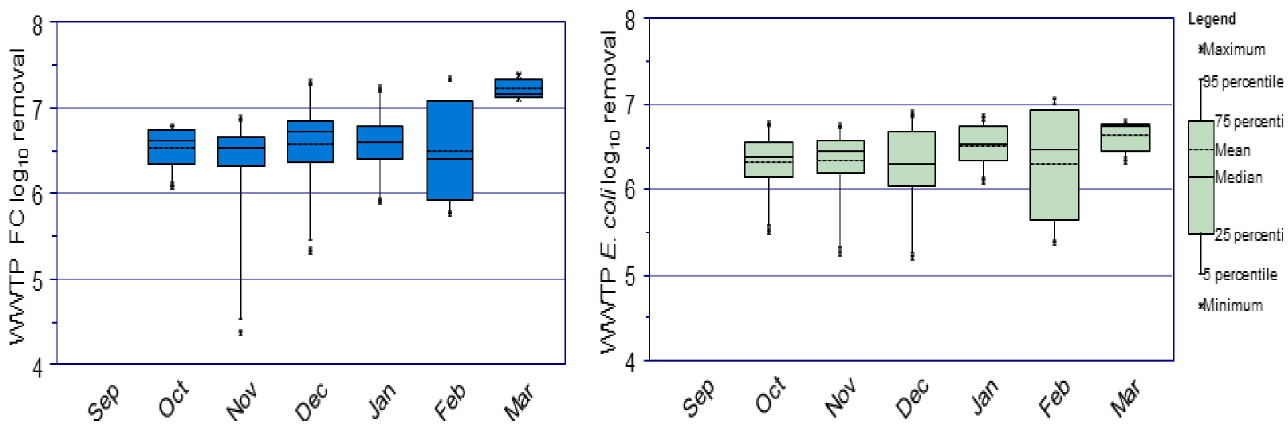

Figure 2-6: Seasonal variability in microbial removal performance of the WWTP for faecal coliforms (left) and E. coli (right) . Censored data shown. Median shown as dotted line, mean as solid line.

2.2.2 Impact of wastewater discharge on receiving waters

As previously observed, there was little noticeable increase in the total daily volume of wastewater discharged between 2018 and 2023 (Figure 2-3). Additionally, concentrations of FIB in UV treated wastewater remained relatively constant over this period (Figure 2-1 and Figure 2-3). Consequently, the flux or instantaneous load of FIB has also remained stable during this time as shown in Figure 2-7. These flux or load estimates serve as indicators of the potential impact on receiving waters. For instance, the median daily flux of faecal coliforms discharged ranged from 3×10^7 /day to 4×10^7 /day for faecal coliforms during the period 2018 to 2023.

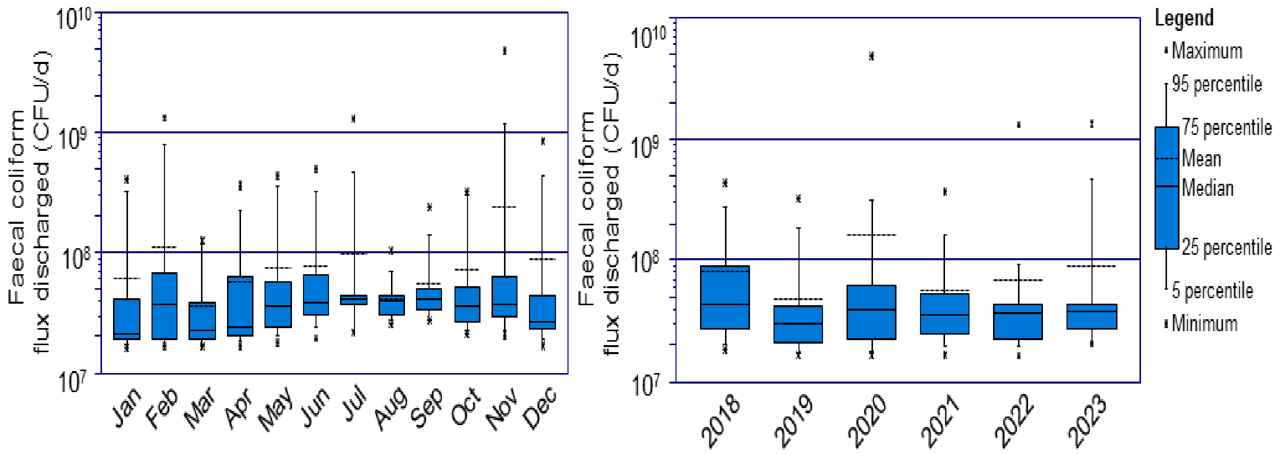

Figure 2-7: Seasonal and annual summary of calculated daily wastewater flux of faecal coliform (#/d) or instantaneous load discharged from the WWTP (2018-2023 inclusive). Censored data. Note log_{10} scale on y-axis. Median shown as dotted line, mean as solid line.

Figure 2-7 illustrates that the average flux or load of faecal coliform values peak during the summer months, suggesting a greater release of FIB during the season when recreational activities in downstream receiving waters are likely greatest. Moreover, the 95th percentile flux values remain high throughout the year at ≥ 10^8 CFU/day. Similar trends are observed for the flux of *E. coli* from the WWTP (data not shown). This indicates that extreme FIB loads are possible year-round with potential implications for similar trends in viruses.

While exposure to higher levels of FIB suggests an increased health risk, it is important to note that this observation is specific to faecal coliforms and *E. coli* which serve as indicators of the likely presence of pathogens. However, it highlights the importance of ongoing monitoring to ensure continued protection of environmental and public health.

2.2.3 Receiving environment

Relatively sparse microbiological water quality data exists for the tributary of Te Puru Stream and the main stem of the Te Puru Stream potentially influenced by the Beachlands WWTP discharge. Microbial water quality data from the short-term monitoring campaign is shown in Figure 2-9 and Figure 2-10 for FIB concentrations in discharged treated wastewater and at reference and impact sites downstream from the WWTP. Various guideline values are shown to enable comparison with results of the short-term monitoring.

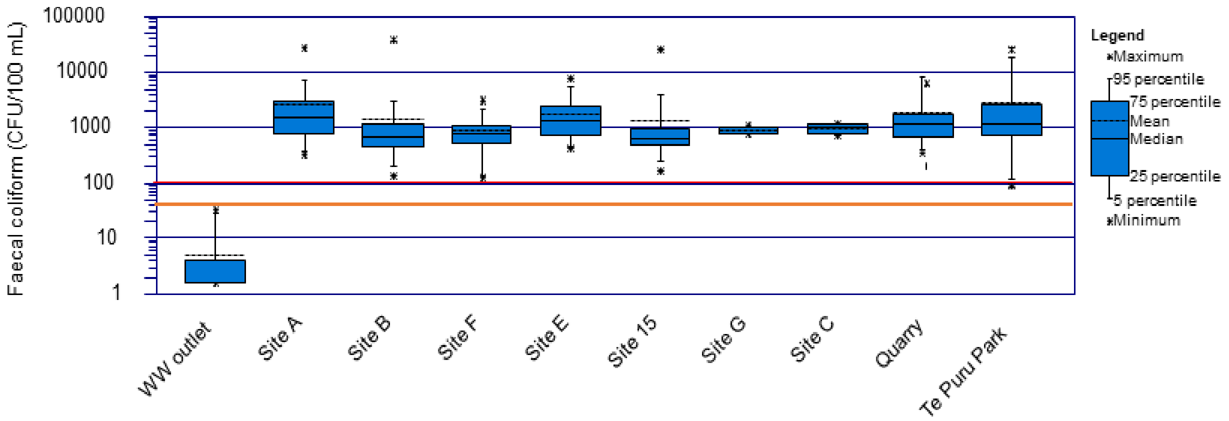

Figure 2-8: Spatial trend in faecal coliform concentrations for final treated wastewater and at various sites along the Te Puru Stream. ANZECC (2000) guideline for livestock drinking water quality shown as thick red line (median 100/100 mL) and MfE/MoH (2003) shellfish harvesting as thick orange line (median 14/100 mL).

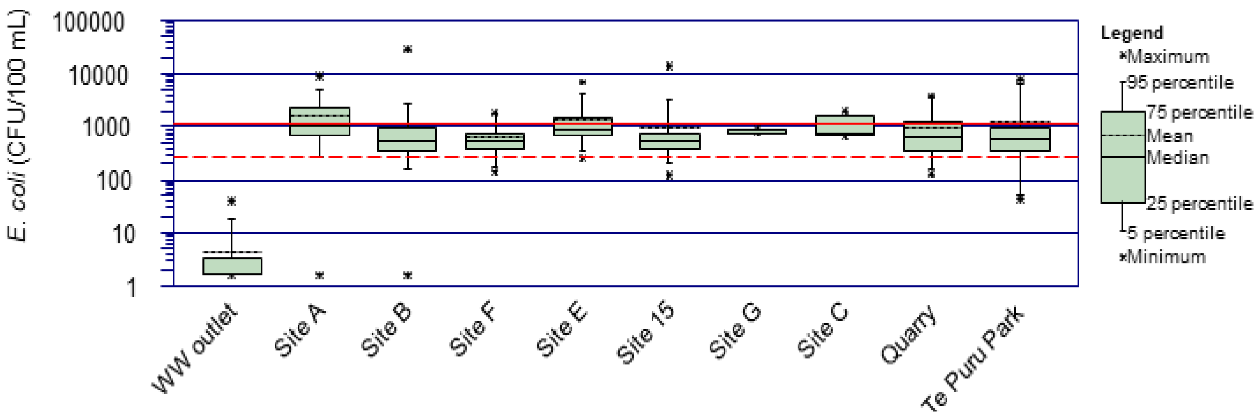

Figure 2-9: Spatial trend in *E. coli* concentrations for final treated wastewater and at various sites along the Te Puru Stream. NPS-FM median (260/100 mL) (dashed red line) and 95th percentile (1200/100 mL) (solid red line) numeric attribute values for human contact shown for Band E.

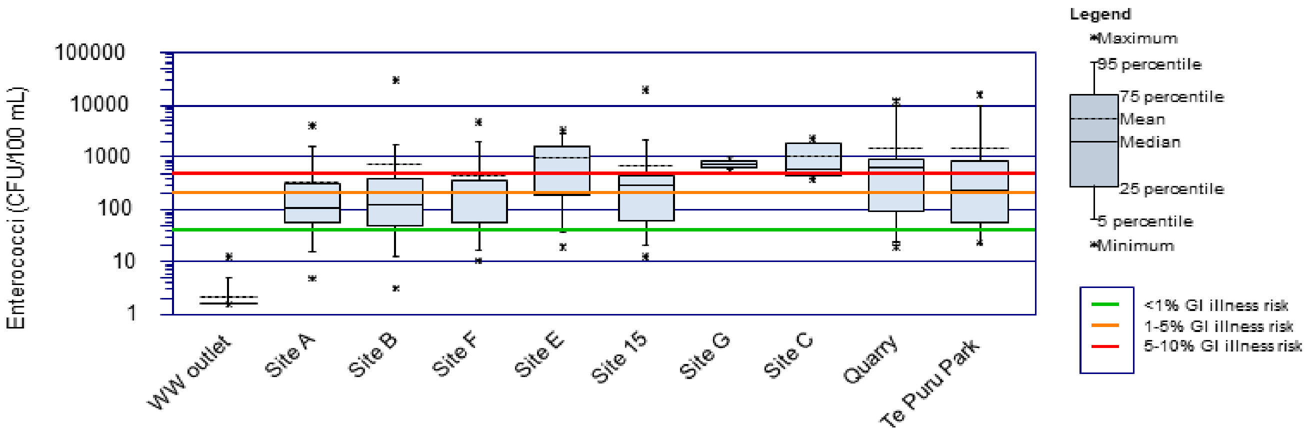

Figure 2-10: Spatial trend in enterococci concentrations for final treated wastewater and at various sites along the Te Puru Stream. MfE/MoH (2003) guidelines for recreation in marine waters shown (green = 40/100 mL; amber = 200/100 mL; red = 500/100 mL) corresponding to potential gastrointestinal illness risk categories.

The data indicate that the wastewater discharge has no discernible impact on FIB levels in the receiving environment, particularly in the Te Puru stream downstream from the WWTP. Faecal coliform, *E. coli* and enterococci show similar spatial trends with concentrations typically three orders of magnitude higher than those in treated wastewater. Of note is that Site E which serves as a reference site located upstream on a different tributary and unaffected by the WWTP discharge, consistently shows higher levels of FIB compared to Sites B and F which are directly downstream of the WWTP.

Concentrations of faecal indicators in the Black Barn tributary (north–west catchment) are typically 1.5 – 2 times higher than that at the Black Barn site (downstream from the Farm Pond) indicating that agricultural sources are probably the major contributor to contamination. Other reference tributaries also show high levels of faecal contamination.

Concentrations of FIB are also notably higher at Site A, located upstream of the Farm Pond[2]. Site A will be contributing to the poor water quality of the Farm Pond itself. The elevated levels at Site B will be influenced by high concentrations of FIB in inflowing waters from Site A. Furthermore, observations of large numbers of birds in the area suggests a contribution to the high FIB concentrations at Site B from avian sources.

Median concentrations for FIB remain high at Site 15 (the Bridge site used in the QMRA) with a slight increase observed at Site C, potentially attributable to inputs from a large tributary. FIB values are also high, though more variable at the Quarry site and at Te Puru Park. Site 15 is the closest downstream site to the WWTP, where the public can access the Te Puru stream, and the Quarry site is the lowest point on the river at which tidal effects do not influence it. These sites were chosen to represent the freshwater risks for the QMRA.

The persistently high levels of FIB along the Te Puru Stream network could be attributed to several factors. Agricultural sources are probably the major contributor to contamination, with input from ephemeral drainage ditches from adjoining pastoral land evident as well as unregulated cattle access, with opportunities for direct faecal deposition into the stream. Limited dilution in the stream due to low natural flow rates may contribute to the sustained elevation of FIB levels. There does not appear to be a significant relationship between FIB levels and distance from the discharge point, indicating that dilution from stream flow is minimal. For example, the median normalised flow at site 15 is estimated to be 3.4 L/s compared to a wastewater discharge rate of 23 L/s (data provided by PDP). Dilution modelling by PDP further supports this observation, indicating that treated wastewater comprises almost the entirety of flow in the Te Puru Stream for 50% of the time at Site 15 (the Bridge).

The Te Puru stream flows through areas of pastoral land-use where livestock access to the stream may occur despite fencing for stock exclusion. Reports of livestock observed in the stream at Site 15 highlights this challenge (Rebecca Stott, *pers comm*). The presence of livestock in the vicinity of the stream directly contributes to the microbial loading in the stream, thereby influencing FIB levels.

[2] The Farm Pond receives drainage waters from the riparian land application site.

2.2.4 Health risk implications

Concentrations of FIB in the receiving environment are often compared with various microbiological water quality guidelines to assess potential risks. However, these guidelines recommend against their application in waters with point sources of pollution. However, for the purposes of this microbiological context, they have been used to assess the potential risks from a variety of contaminating sources as a comparator for the QMRA which assesses the incremental risks attributed solely to the WWTP.

Human contact

It is unlikely that the Te Puru stream will be used for recreational activities. However, human contact with water may occur through harvesting of mahinga kai. The presence of kakahi (freshwater mussels) has been reported at Site E (upstream from the confluence with the Farm pond tributary at the Bridge site) and watercress at several sites along the Te Puru stream including Site A (above the Farm Pond), Site F, Site 15 (QMRA site "the Bridge") and further downstream at sites G and C (Bioresearches 2022) (Rebecca Stott *pers comm*).

The NPS-FM provides criteria for water suitability for human contact based on concentrations of *E. coli* (Ministry for the Environment (Manata Mo Te Taiao) and Te Kaawanatanga o Aotearoa (New Zealand Government) 2024)(Table 9). Four metrics (numeric attribute states) are proposed to assess the suitability of sites for contact. These metrics include the % exceedances over 540 *E. coli*/100 mL and 260 *E. coli* /100 mL, as well as median and 95th percentile concentrations. In Figure 2-9, data for all sites are presented together with median (> 260 *E. coli*/100 mL) and 95th percentile (>1200 *E. coli*/100 mL) values for Band E. It is evident that all sites exceed these thresholds and are consequently graded as Band E. For this attribute band, the predicted average risks of infection exceed 7% based on a random exposure on a random day.

Enterococci is the preferred indicator for assessing the potential risks associated with recreational activities in marine waters. Concentrations of enterococci from the spatial survey are compared with the marine risk thresholds in the Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas (Ministry for the Environment and Ministry of Health 2003), which include gastrointestinal illness risks.

Table H1 of the MfE/MoH (2003) guidelines provides three illness risk thresholds that are used for long-term grading of marine recreational water quality based on 95th percentiles:

Waters graded "A" are considered to have a very high recreational water quality, likely to cause fewer than 1 case of gastrointestinal illness out of 100 exposures (< 1% IIR).
Waters graded "B" are considered to have high recreational water quality, likely to cause up to 5 cases of gastrointestinal illness out of 100 exposures (≥ 1% to ≤ 5% IIR).
Waters graded "C" represents a risk of up to 10% for gastrointestinal illness (> 5% to ≤ 10% IIR).
Waters graded "D" represents a risk of more than 10% for gastrointestinal illness (>10% IIR).

Figure 2-10 presents the results for enterococci for all sites from the spatial survey alongside the corresponding risk thresholds. It is evident that all sites exceed the three thresholds. Notably, the Te

Puru Park site (an estuarine site where recreational activity is most likely to occur) is categorized as Grade D, indicating an associated potential risk of gastrointestinal illness exceeding 10%.

Shellfish consumption

Microbiological water quality guidelines for recreational shellfish harvesting are outlined in the MfE/MoH (2003) guidelines. According to these recommendations, median concentrations of faecal coliforms should not exceed 14 per 100 mL and no more than 10% of samples should exceed 43 faecal coliforms/100 mL. From the data presented in Figure 2-8 and in Table B-2, it is evident that the Te Puru Park site significantly exceeds the shellfish harvesting criteria and as such, it would not be considered suitable for shellfish harvesting. However, although several species of shellfish are present at this site, their current size makes them too small for legal harvesting (Sim-Smith 2023).

Livestock drinking water

The (ANZECC and ARMCANZ 2000) guidelines provide recommendations for the microbiological quality of livestock drinking water with a guideline value of a median concentration of 100 faecal coliforms per 100 mL. Figure 2-8 depicts faecal coliform concentrations at various sites alongside the guideline value for livestock drinking water. All sites exceed this value, making them unsuitable as a source of drinking water for livestock. Moreover, the ANZECC guidelines recommend that investigations into likely causes are warranted when 20% of results exceed four times the median trigger value. As shown in Table B-2, this criterion is met for all sites, emphasizing the need for an understanding of the sources and underlying causes of elevated concentrations of FIB in the Te Puru Stream network.

3 QMRA

This Quantitative Microbial Risk Assessment (QMRA) aims to assist Watercare and the local community in understanding the potential health risks associated with the discharge of treated wastewater from the Beachlands Wastewater Treatment Plant into the Te Puru stream,

Kelly's Beach, and Tamaki Strait. The assessment only considers risks associated with wastewater discharge, and it does not account for background risks or risks associated with other potential sources of microbial contaminants, such as agriculture (Phiri et al. 2020) , wildfowl (Moriarty et al. 2011), stormwater into the stream, or illicit dischargesfrom boats into the sea (Landrigan et al.

2020). Therefore, the estimated risk will be the incremental risks from wastewater rather than the total risks.

The health risk assessment process comprises multiple steps (described graphically in Figure 3-1), including:

1. Select the hazard(s), i.e., the pathogen(s) of concern—exposure to which can give rise to illness.
2. Assess exposures to the pathogens at key sites.
3. Characterise the pathogens' dose response.
4. Risk characterisation.

The "Quantitative" aspect of QMRA relates particularly to item 4—risk characterisation—in which Monte Carlo computer simulation is used. These simulations use repetitive sampling where possible, to take into account variability and uncertainty in model inputs, so does not restrict the analysis to using single point estimates, which may misrepresent the risk. This approach is particularly important given that higher risks may be caused by combinations of inputs toward the extremes of their ranges, the combined effects of which may not be detected when using single values.

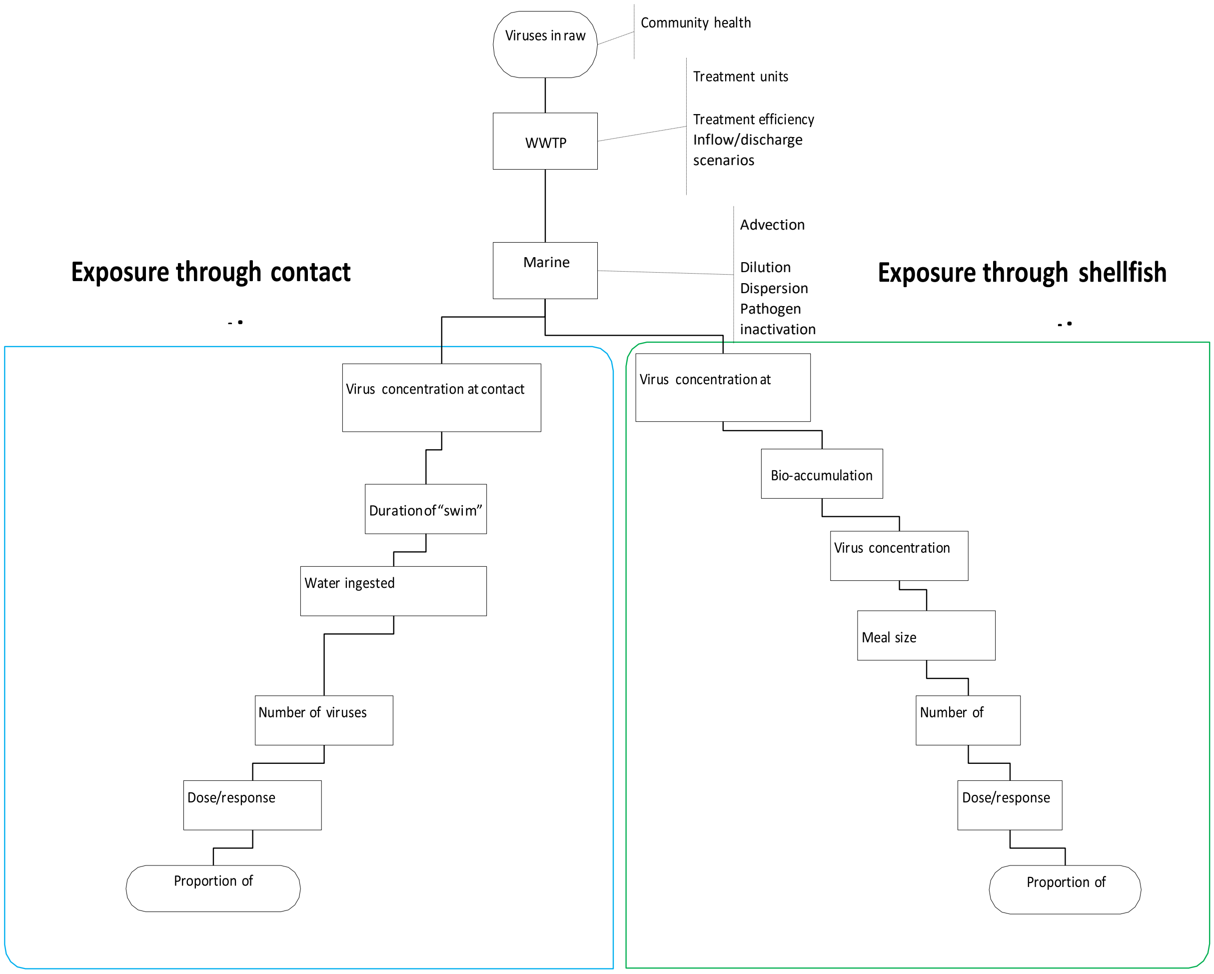

Figure 3-1: Schematic describing the QMRA process for the marine environment.

3.1 Select Hazard

Human-derived wastewater potentially contains a wide range of pathogenic organisms, which can harm human health if they enter into the environment. Assessing the risk from every potential pathogen found in treated wastewater is impracticable. Instead, in this analysis, norovirus is chosen as a reference pathogen (World Health Organization 2016). Reference pathogen(s) represent the risk of a broader group of pathogens that may be found in the expected exposure pathways. The exposure pathway is the route people outside the boundary of Beachlands wastewater treatment plant could come into contact with a pathogen from the effluent.

The most likely exposure pathway involves a hazardous event where pathogens are not removed/inactivated by the treatment system and are discharged into the Te Puru stream, which flows into the sea at Kelly's Beach and moves east or west along the coast. People could come into contact and ingest dilute well-treated effluent at various points in the Te Puru stream and the sea via activities such as primary contact (swimming) or through the consumption of food such as shellfish in the marine environment or, in the case of Te Puru stream, consumption of watercress. Other exposure pathways, such as secondary contact (boating, fishing, etc.,) will also be present but are not considered as these represent lower risks per event than primary contact or food consumption.

3.1.1 Why norovirus?

For people exposed to treated effluent from human sources, epidemiological evidence (Sinclair et al. 2009; Landrigan et al. 2020) and evidence from previous QMRAs (Soller et al. 2010; Stott and Wood 2022) point towards norovirus causing a significant burden of enteric illness. Viruses, such as norovirus, show a tendency to be more resistant to disinfection than bacterial pathogens such as *Campylobacter* or protozoal pathogens such as *Giardia* or helminths that are rare in New Zealand water (McBride 2017), so pathogens other than viruses were not considered.

The choice of pathogenic virus considers the burden of illness and the ability to quantify the risk. In a previous QMRA of the Beachlands WWTP, carried out in 2004 (Stott and McBride 2004), norovirus was not considered; there was no published dose-response model at the time. Instead, Adenovirus and Rotavirus were chosen as reference pathogens for respiratory and oral ingestion routes, respectively.

In this current study, the respiratory route was not considered, as previous studies (Stott and Wood 2022; Wood and Hudson 2023) indicate that illness rates are generally lower than those of the oral route. Rotavirus, though highly infectious and potentially very serious, particularly for children, has limited evidence of waterborne infection in NZ (McBride 2017), and there is now a vaccination programme (Health New Zealand 2024). So, norovirus was chosen as the reference pathogen.

3.2 Assess exposure routes

Assessing exposure requires identifying and quantifying the routes whereby people could be exposed to pathogens from wastewater. This includes assessing the source of the pathogen(s), barriers to preventing people from being exposed to pathogens and mechanisms of exposure (World Health Organization 2016). This assessment includes choices of what to include and exclude from the QMRA. In the first part of this section, we provide a qualitative description of the exposure routes before quantifying them.

3.3 Qualitative description of exposure and site assessment

In this assessment, wastewater is the source of pathogens. The most likely route a person outside the Beachlands WWTP comes into contact with a pathogen from wastewater is through the well- treated wastewater discharged into the Te Puru stream, which flows down into Kelly's Beach and, ultimately, Tamaki Strait.

There are three barriers to exposure: firstly, the wastewater treatment system that removes and or inactivates pathogens; secondly, dilution in the environment that reduces the concentration of pathogens in water; and thirdly, the removal of pathogens from the environment by various mechanisms, including inactivation. Only the first two barriers are considered. Pathogens, such as norovirus, persist in the environment for some time (Rexin et al. 2024), so removing pathogens from the environment is not considered.

For norovirus, there are two modes of exposure from diluted treated wastewater. They are accidental ingestion whilst swimming or splashing in the water and the consumption of food exposed to well-treated wastewater.

The combination of barriers, modes of exposure and the environment downstream of the WWTP, as it moves from a freshwater to a marine environment, has implications for modes of exposure, particularly for the consumption of food exposed to dilute wastewater. Watercress was identified downstream of the WWTP (Bioresearches 2024 Draft), and recreational and commercial shellfish harvesting was identified.

Dr Shane Kelly (Coast and Catchment Environmental Consultants) provided the locations of marine exposure sites, and Dr Mark James (Aquatic Environmental Sciences) provided freshwater sites. The marine sites included safeswim sites[3] augmented by other sites where swimming may occur, such as Kelly's Beach. Shellfish exposure was assessed at three sites. Shellfish risks were not assessed for Kelly's Beach as they are too small to harvest (Sim-Smith 2023). The approximate site locations are shown in Figure 3-2 and coordinates are given in Table 3-1.

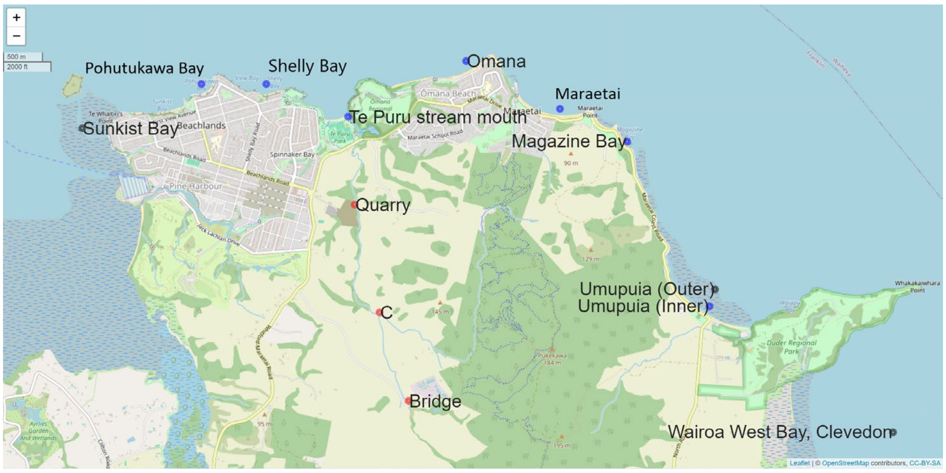

Figure 3-2: Location of QMRA assessment sites. Red = River sites, Blue = Marine (swim), Black = Marine (shellfish).

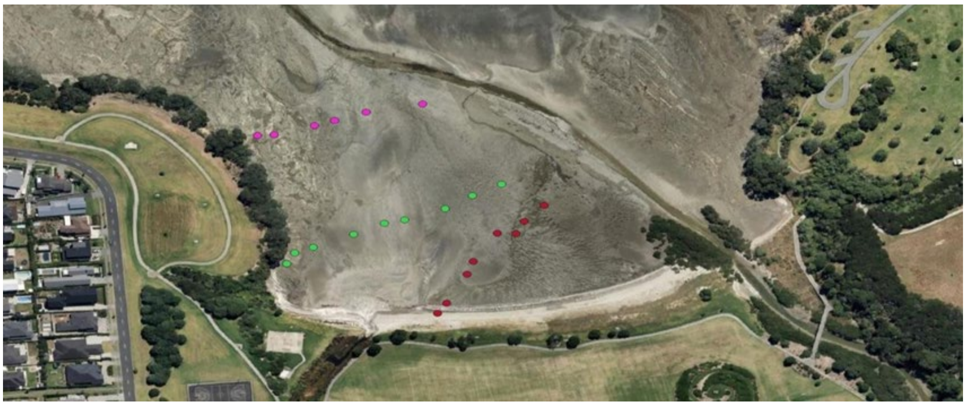

Figure 3-3: Location of QMRA assessment sites on Kelly's Beach. The beach is covered with water part of the day, so dilution at three transects following the water's edge were chosen to represent the mid-Kellys beach site. Pink - Northern, green – Mid, dark red - Eastern transect (image provided by John Oldman, DHI).

[3] Safeswim combines real-time monitoring of the wastewater and stormwater networks with predictive models, to provide forecasts of water quality at swimming sites.

Table 3-1: Coordinates of sites assessed for health risks. Excluding coordinates of three transects.

Site	Longitude	Latitude	Type
Wairoa West Bay, Clevedon	175.0952	-36.9172	Shellfish
Umupuia (Outer)	175.0700	-36.901	Shellfish
Sunkist Bay	174.9803	-36.8827	Shellfish
Magazine Bay	175.0575	-36.8842	Marine
Shelly Bay	175.0064	-36.8777	Marine
Pohutukawa Bay	174.9972	-36.8777	Marine
Omana	175.0347	-36.8751	Marine
Umupuia (Inner)	175.0692	-36.9029	Marine
Maraetai	175.0480	-36.8805	Marine
Te Puru stream mouth175.0179-36.8814MarineBridge	175.0265	-36.9136	River
C	175.0224	-36.9036	River
Quarry	175.0189	-36.8914	River

The health risks to norovirus exposure are assessed based on infection due to exposure to dilute treated wastewater. Norovirus is also highly infectious and is easily transmitted from a person infected through wastewater to another person. However, only primary transmission from wastewater is included in this analysis, excluding secondary person-to-person transmission. This is in line with the approach adopted by National Policy Statement for Freshwater Management NPS-FM (Ministry for the Environment 2023) and Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas (MfE and MoH 2003).

3.4 Quantifying exposure routes

The goal of quantifying exposure routes is to estimate the norovirus dose an individual may receive during an exposure event. The quantification involves estimating the concentration of norovirus in raw (influent) wastewater, removal of norovirus through treatment systems, dilution of wastewater in the environment, and ingesting food and water. The modelling parameters are discussed below and, with the exception of the dilution parameters, are summarised in Table 3-3.

3.4.1 The concentration of norovirus in raw wastewater

Information on the concentration of norovirus in influent (raw) wastewater is not available for Beachlands WWTP. So, along with many of the more recent New Zealand QMRAs (Cressey 2021; Dada 2021; Stott et al. 2023; Wood and Hudson 2023), this QMRA uses standard factors for norovirus and assumes the hockey stick function (McBride 2005) adequately describes the distribution. The hockey stick function is described by minimum, median, and maximum values of $1x10^3$, $1x10^5$, and $1x10^7$ genome copies/L, respectively, and a breakpoint at the 95th percentile.

Hamadieh et al. (2021) reported maximum concentrations of ~$1x10^{8.5}$ genome copies/L which are greater than those used in New Zealand QMRAs. Eftim et al. (2017) noted in their systematic literature review that the concentration of norovirus was lower in New Zealand than in Europe or

Africa. Given the observation that New Zealand studies suggest lower norovirus concentrations than elsewhere in the world, it is reasonable to stick with the standard factors used in previous New Zealand QMRAs.

3.4.2 Removal of norovirus by the treatment process

One of the principal roles of a wastewater treatment plant is to remove pathogenic microorganisms before the effluent discharges to the environment. Estimates of the efficacy of pathogen removal under current, interim and Stage 2 flow conditions equate to 23, 42 and 71 L/s discharge rates, respectively, were unavailable when preparing the QMRA. Instead, simulations of 10-fold, 100-fold, 1,000-fold and 10,000-fold, 100,000-fold, 1,000,000-fold and 10,000,000-fold are carrier out. These levels of treatments are referred to as 1, 2, 3, 4, 5, 6, and 7 log reduction values (LRV). Based on the estimated virus influent and effluent concentration data in the previous QMRA (Stott and McBride 2004), the LRVs for the plant were inferred to be in the range of 4.3-6.0 based on time of year, for two viruses, adenovirus and rotavirus[4].

3.4.3 Dilution

Treated effluent enters the Te Puru steam and flows down to Kelly's Beach and into Tamaki Strait. The plume of highly diluted treated wastewater moves along the coast rather than crossing the Tamaki Strait (*pers com* John Oldman, DHI), so sites on Waiheke Island were not considered.

Three discharge scenarios were considered: current (23 L/s), interim (42 L/s) and Stage 2 (71 L/s) flow conditions. Dilution in the Te Puru stream was estimated from flow duration curves provided by PDP. DHI provided estimates of dilution in the marine environment.

PDP estimated naturalised flow duration curves for the Bridge site and used scaling factors of 1.84 and 2.24 to develop flow records at site C and Quarry, respectively. It was believed that these estimates would underestimate the naturalised flow, and any resulting estimates of dilution would be conservative[5]. Dilution estimates using the three scenarios assumed constant outflow from the WWTP. As the median naturalised flow at the Bridge was estimated to be 3.4 L/s, treated effluent, 23 L/s under current conditions, makes up a substantial proportion of the flow.

DHI provided two sets of dilution figures covering a period from 2 January 2020 to 20 December 2020. One set of figures estimated the dilution at the surface, and the other was close to the seabed for the sites identified by Dr Shane Kelly (Coast and Catchment Environmental Consultants).

Inspection of the dilution figures noted that dilution estimates were particularly high, or absent, probably as an artefact of the modelling process, during the start of January and a decision was made only to use data from 17 January onwards.

The dilution figures are presented in Figure 3-4. Dilutions were the lowest at the Bridge site, the closest sited below the plant and increased as the water flowed downstream. Below the quarry site, there is a tidal influence in the stream. The dilution at the Te Puru stream mouth (median dilution is

[4] Assumes estimated virus concentration in influent and effluent is perfectly positively correlated.

[5] Note attached to flow duration curves by Phil Hook (PDP) 31 January 2024

13,700 fold under current conditions), is substantially higher than in the freshwater environment upstream (median dilution 1.1 at the Bridge under current conditions).

When the initial dilution analysis was carried out, it was noted that some of the sites in Kelly's Beach would only occasionally be covered by water. Given this observation, three transects were made in Kelly's Beach (Northern, Mid and Eastern Transect) to estimate the dilution at the water's edge rather than a fixed point on the beach. See DHI report for details.

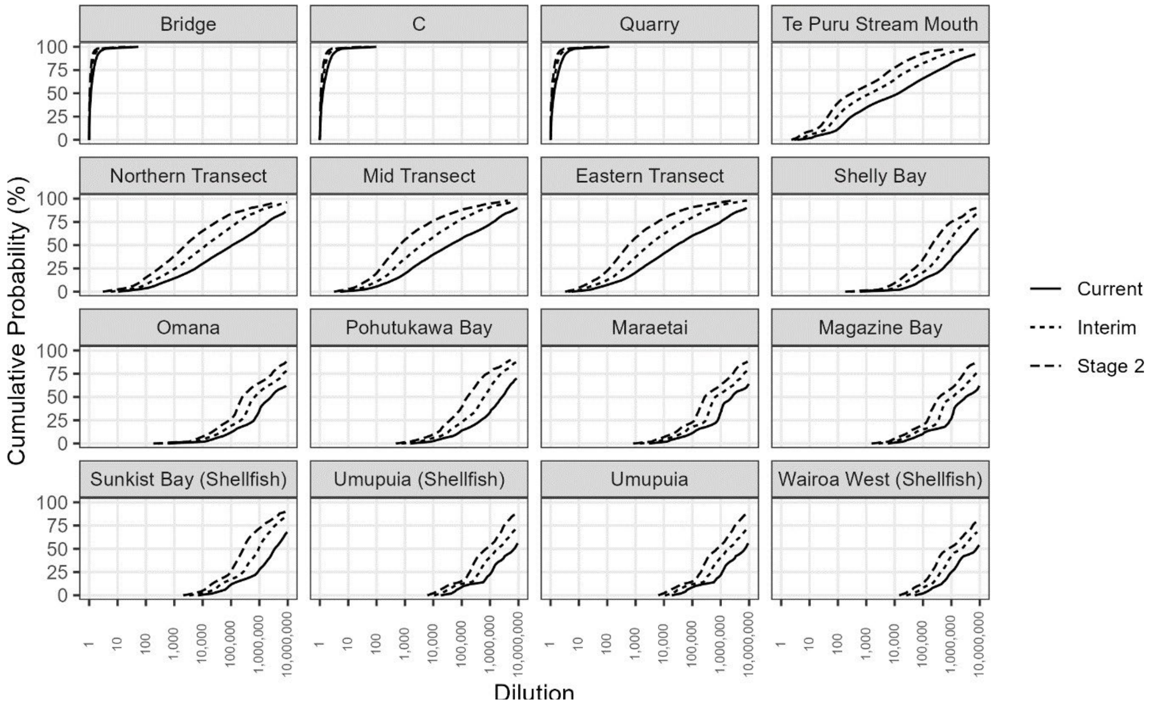

Figure 3-4: Cumulative distribution curves for dilution at 16 sites and three discharge scenarios. . The sites are in order from lowest dilution (top left) to highest dilution (bottom right). Note the logarithmic scale for the dilution axis and values of over 10,000,000 have not been plotted. The lowest dilutions are in the Te Puru stream. Once the flow enters Kelly's Beach the dilutions increase rapidly.

3.4.4 Ingestion of food and water

Viruses in water can be ingested directly through water consumption or indirectly through the ingestion of animals or plants that have been exposed to viruses in water. In the case of direct ingestion, the question is how much water people consume, and for foods, the question is how much food is consumed and what the virus content of the foods is.

3.4.5 Direct ingestion of water

Water-related activities can result in the unintentional ingestion of water. Swimming, known as primary contact, tends to result in greater volumes of water being ingested than secondary contact activities such as boating or fishing, etc., (Dorevitch et al. 2011). Evidence suggests that children ingest water at a higher rate and spend more time in the water swimming than adults (Dufour et al. 2017). So, children swimming in water were chosen as a susceptible part of the population.

New Zealand specific data is not available. However, the World Health Organization (2016) guidance on QMRAs quotes a range of figures for the volume of water accidentally ingested during swimming, ranging from 20-100 mL per event. Though the World Health Organization (2021) Guidelines on recreational water quality quote higher per event figures of 140-250 mL for children.

The volume of water accidentally ingested is likely to vary from persons to persons. Schets et al. (2011) published information on duration of swimming with average durations ranging from 8-240 minutes and 12-270 minutes for children in seawater and freshwater, respectively. Dufour et al. (2017) estimated ingestion rate in the range from 0-280 mL/h with an arithmetic mean of 32 mL/h.

In this work we assumed a log normal distribution with minimum, mean, standard deviation and maximum ingestion rates of 5, 53, 75 and 250 mL/h. The duration of events was modelled with a PERT distribution with a minimum value of 12 minutes, mode of 1 hour and maximum of 4 hours. These figures have been used in previous QMRAs (Stott and Wood 2022; Wood and Stott 2023) and result in a mean ingestion volume of approximately 64 ml per event with 5^{th} and 95^{th} percentile ranging from 6.6 to 216 mL per event. The mean values are in the range given by the World Health Organization (2016) guidance on QMRAs, and though the parameters are different from those used by Cressey (2021), the overall results are similar.

3.4.6 Ingestion of watercress

Watercress, also called wātakirihi or kōwhitiwhiti is a valued mahinga kai for tanagata whenua and may be consumed in raw or cooked form (Eason et al. 2020). Microbial contamination, *Escherichia coli*, a faecal indicator organism, and *Campylobacter*, a pathogen, have been detected on watercress (Edmonds and Hawke 2004; Donnison et al. 2009). As well as the possibility of pathogens attaching to the surface of plants, there is evidence that pathogens, such as norovirus, can be internalised by plants such as lettuce, and in addition, hydroponically grown produce internalise more pathogens than soil-grown pathogens (King et al. 2020).

To calculate the amount of norovirus that may be ingested when eating watercress, we need to estimate the amount of watercress consumed and the concentration of pathogens in the watercress.

There is little specific evidence (i.e., published data) for watercress around norovirus contamination; instead, we used lettuce as a model. DiCaprio et al. (2012) demonstrated that hydroponically grown lettuce could efficiently internalise norovirus. However, Urbanucci et al. (2009) did not find norovirus to become internalised in their experimental setup, and the conclusion of a study by Wei et al. (2011) was somewhere in between.

Therefore, considerable uncertainty exists about how efficiently pathogens can be internalised or attached to lettuce from water. QMRAs of norovirus in lettuce have considered internalisation and surface attachment (Sales-Ortells et al. 2015) and internalisation only (Chandrasekaran and Jiang 2018). Chandrasekaran and Jiang (2018) modelled virus transport efficiency from water to the root (74%) and root to leaf (48%) but with wide bands of uncertainty.

Where there is minimal data or wide bands of uncertainty, the appropriate course of action is to assume the worst-case scenario (National Research Council 2009). In this case, it would be to assume that the norovirus concentration in the plant is the same as the water it is growing in, and that norovirus is present on the surface of the leaves either in the form of water or attached to the leaves. In this case, it would appear reasonable only to consider the mass of the leaves and any attached water and ignore the additional contamination solely due to the surface, which would be a minor component of the overall microbial load. For this exercise, we assume that 1 gram of plant matter equals 1 millilitre of water and ignore any virus inactivation in the plant.

Various workers have estimated the quantity of watercress consumed during a single meal. These New Zealand estimates vary from 40-230 g per meal (40 (Eason et al. 2020), 155 (Phillips et al. 2011) and 230 g (Turner et al. 2005)). So, for the worst-case scenario, it was assumed that the mean size was 250 g/meal, but a best-case scenario 40 g/meal was also simulated to test how sensitive the risk model would be. Unlike shellfish or primary contact risk assessments, the consumption amount used is a fixed point estimate and can be described as a screening assessment (World Health Organization 2016)

3.4.7 Shellfish

Shellfish can bioaccumulate pathogens in their flesh, so consuming 1 g of shellfish is equivalent to ingesting more than 1 mL of water. Burkhardt and Calci (2000) estimated Bioaccumulation Factors (BAF) for shellfish and noted that BAF varied by season. Following the precautionary approach, we used the maximum BAF value (Burkhardt and Calci 2000). By combining McBride's (2012) estimates of shellfish consumption using survey data from Parnell et al. (2001) along with BAF and the concentration of pathogens in the water, it is possible to estimate the pathogen dose associated with the consumption of raw or lightly cooked shellfish. McBride (2012) estimates that the mean meal size of 100 g is similar to the average shellfish meal size estimated by Guy et al. (2021), which is 106 g.

3.5 Dose-response

The risks from norovirus depend on the dose individuals receive i.e., the number of viruses ingested. Teunis et al. (2008) developed a dose-response model for norovirus, which suggests that higher doses lead to a higher chance of infection. Information from the Teunis et al. (2008) was used to estimate what proportion of the population was susceptible to norovirus and what proportion of those who are inflected become ill.

Noroviruses are a diverse group of single-stranded RNA viruses that currently consist of 10 genogroups (Chhabra et al. 2019). Teunis et al. (2008) only report dose-response models for norovirus genogroup 1 (GI), whereas concentrations of norovirus genogroup 2 (GII) are typically greater in raw sewage in New Zealand than those of GI. Due to the lack of a specific dose-response model for genogroup 2 (GII)[6] we assume that GI and GII have the same dose-response relationship.

Since Teunis et al. (2008) developed the dose-response, analytical techniques have also improved. We therefore include a dose-response method harmonisation factor (MHF) to account for these differences (Kundu et al. 2013).

Norovirus may exist in aggregated (clumped) and disaggregated forms, and Deere and Ryan (2022) recommend that norovirus QMRAs modelled in both aggregated and disaggregated forms. However, previous QMRA modelling e.g., McBride, Graham B (2014), indicated that disaggregated norovirus creates a consistently greater illness risk than the aggregated form. In response, we have limited our consideration and discussion to illness risks arising from the disaggregated norovirus form (i.e., we

[6] A model has recently been proposed for NoV GII by Teunis et al. (2020) but the application of this dose-response model is less certain.

have taken the more conservative approach) – this is consistent with previous QMRA practice (e.g., McBride (2017)).

3.6 Risk characterisation

Risk characterisation brings together information on dose response and the probability of illness given exposure over a specified time period. This QMRA estimated health risks in terms of Individual Infection Risks (IInfR) per exposure event: a swim, a feed of raw or lightly cooked shellfish or watercress.

Monte Carlo statistical modelling allows for a range of likely conditions to be included in health risk estimates, including relatively infrequent but highly influential elevated virus concentrations (McBride 2005; Haas et al. 2014). A "Monte Carlo" approach allows for repeated sampling from various parameter distributions to build a *risk profile*. Variability, such as the concentration of pathogens in shellfish meal size, is taken into account by taking many random samples from defined statistical distributions. The parameters of variables used within the QMRA modelling are shown in Table 3-3. The Monte Carlo simulations were conducted in Excel using the @Risk add-in (Palisade 2020).

Health risks are estimated following exposure of a hypothetical population (a group of 100 "individuals") to an individual "dose" on any particular day. The total number of individuals becoming ill from 100 people exposed is determined as the risk outcome for that iteration. This procedure is repeated for a total of 10,000 iterations drawn at random from the distributions of key input variables. For instance, the consumption of one million shellfish meals is simulated to capture the variability and uncertainty in the model's inputs.

3.7 Scenarios modelled

The population served by the Beachlands WWTP currently serves a population of 10,000 people and is predicted to grow. Three scenarios serving different populations and volumes of effluent discharge were considered, are listed in Table 3-2.

Table 3-2: Modelled scenarios -population served, effluent flow and scenario name.

Scenario name	Population served (people)	Volume of treated effluent discharged to the Te Puru stream (L/s)
Current	10,000	23
Interim	18,000	42
Stage 2	30,000	71

3.8 Results

The results of the QMRA are presented in tabular and graphical forms. It is possible to compare the results against either the related Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas (MfE and MoH 2003) or the National Policy Statement for Freshwater

Management, the NPS-FM (Ministry for the Environment 2023) for swimming. There are no guidelines for the consumption of shellfish or watercress. The values for freshwater are based on infection risk from *Campylobacter* and the risk of gastrointestinal illness (from a range of pathogens) in marine environments.

The same metric, infection risks, is used for marine and freshwater environments to facilitate easier comparisons. In addition, shellfish and watercress risk are also compared against the same infection metric. The graphical results are presented against the five attribute bands from Table 9 of the NPS-FM (see Table 3-4). There are national targets for 80% of rivers to be suitable for swimming (blue, green and yellow category) by 2030 (Ministry for the Environment 2023).

Table 3-3: Summary of QMRA modelling input parameters.

Component	Statistic/parameter		Distributions/comments
Influent virus concentration			Bounded "hockey stick" distribution (McBride 2005), strongly right-skewed.
Influent norovirus concentration, genome copies per litre (gc/L)	Minimum	$1x10^3$	Typical range found for New Zealand cities (e.g., Napier, New Plymouth— (McBride 2011; McBride 2012; McBride 2017)).
	Median	$1x10^5$	
	Maximum	$1x10^7$	
Hockey stick, norovirus, Xp	Unitless	0.95	
Treatment efficacy			
Wastewater treatment efficacy, Log10 virus reduction (LRV)	Unitless	1 - 7	LRVs represent a range of treatment efficacies
Exposure parameters - swimming			
Duration of swim (hours)	Minimum	0.2	Distribution for a child after Schets et al. (2011) based on distribution using Program Evaluation and Review Technique (PERT) .
	Mode	1	
	Maximum	4	
Swimmers water ingestion rate (mL per hour)	Minimum	5	Truncated lognormal distribution (ESR 2016), (Table 19); (Dufour et al. 2017) for children (<16 yr). The minimum value was set at 5 mL/h, an ingestion rate equivalent to one tablespoon of seawater per hour. This estimation of the minimum value took into account information from ESR (2021), which evaluated the raw data from Dufour et al. (2017) and the observation that ingestion rates appear to be greater than inhalation rates, so the minimum value was set to be greater than the minimum inhalation rate of Dorevitch et al. (2011).
	Mean	53	
	Std. Dev	75	
	Maximum	250	
Exposure parameters - watercress			
Meal size (g)	Minimum	40	Point estimates used in calculations figures after Eason et al. (2020), and 230 g Turner et al. (2005)).
	Maximum	250	
Exposure parameters - shellfish			
Shellfish meal size (g)	α	2.2046	A log logistic distribution was used, truncated below at 5 g and above at 800 g, from bivalve mollusc consumption data from Parnell et al. (2001) and McBride (2012).
	β	75.072	
	γ	–0.903	
Bioaccumulation factor, ratio	Mean	49.9	

Component	Statistic/parameter		Distributions/comments
	Std. Dev.	20.93	Using normal distributions, truncated at 1 and 100. The pathogen dose ingested on eating 100 grams of shellfish is BAF x the number of pathogens in the equivalent volume of water (Burkhardt and Calci 2000). The chosen factors are for F+ coliphage in winter. The use of a normal distribution for BAFs allows half of these factors to be below 50 yet retain a precautionary approach.
Dose Response			
Probability infection norovirus GI_5 per exposure event (disaggregated)	α	0.04	Beta-binomial (for individual doses, i) is described by two parameters α and β (Teunis et al. 2008), Table III, 8fII1+8fIIb, no aggregation. ID_{50} infection =26.
	β	0.055	
Fraction of secretor-positive individuals (susceptible to norovirus infection)	Unitless	0.74	Proportion susceptible, P (Teunis et al. 2008).
The conditional probability of illness given infection NoV (norovirus)	Unitless	0.68	Pr (ill|Inf) NoV: estimated from Soller et al. (2008)
Method harmonisation factor for norovirus,	Unitless	18.5	The dose-response equation and current monitoring methods use RT-qPCR methodology but on different genetic target sequences with differences in critical threshold standard curves (McBride, Graham B. et al. 2013). Current PCR methods more effectively detect virions, norovirus concentration data divided by harmonisation factor.

Table 3-4: Summary of average infection risks from the NPS-FM.

Attribute Band	(Infection) Risk (%)
A - blue	1
B - green	2
C - yellow	3
D - orange	>3 and <7
E - red	>7

3.8.1 Swimming risks

The mean Individual Infection Risk (IInfR)% is highest at low Log Reduction Values (LRV); as LRV increases, the risks decrease. The sites with the highest risks were the Bridge, site C and Quarry (see Figure 3-5 and Figure 3-6). The risk falls as we move into the marine environment, Te Puru stream mouth, Kelly's Beach, and into sites along the coast. The numerical results for each scenario are presented in Table 3-5 to Table 3-7.

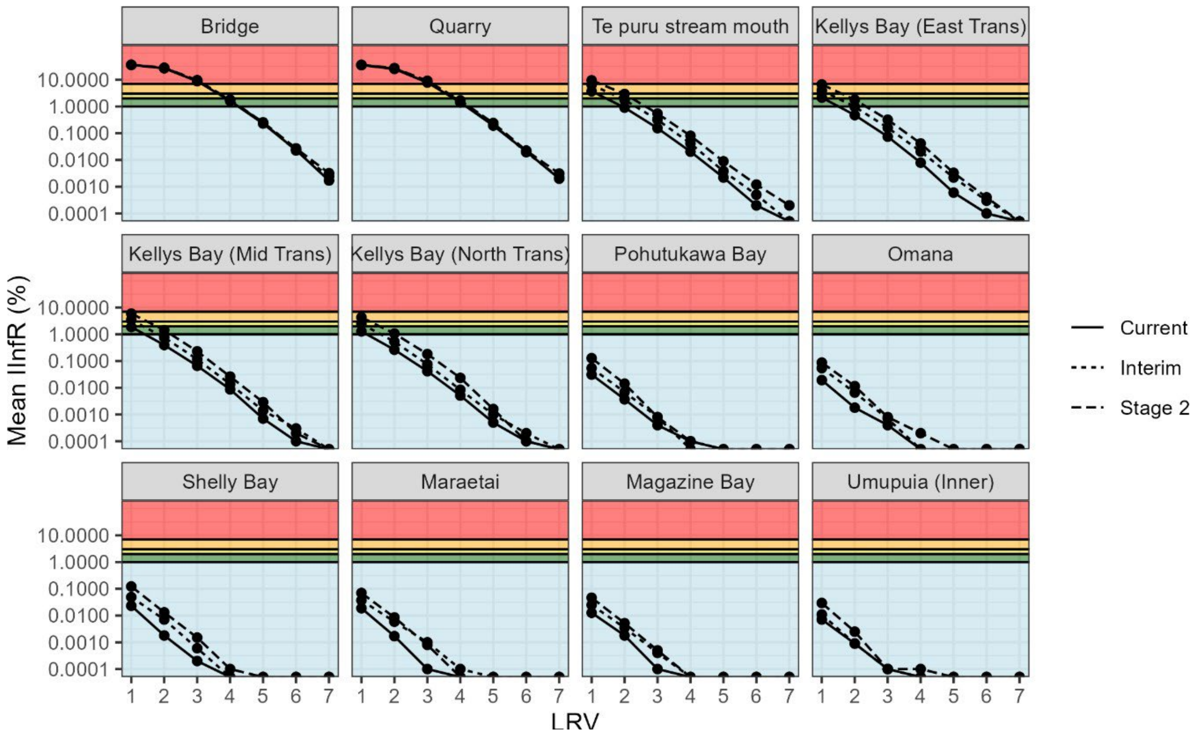

Figure 3-5: Mean infection risk (IInfR) from swimming at 12 sites (3 river and 9 marine). The colours relate to the NPS-FM categories: blue IInfR < 1% per event, green 1 -2%, yellow 2-3%, orange 3-7% and red>7%

Due to the low level of dilution in the Te Puru stream, the increase in discharge volume makes minimal difference in the overall risks (Figure 3-6). Though the flow may increase, the concentration of treated effluent remains the same. At sites with higher dilution, in the marine environment, increase in flow makes a more noticeable increase in risk (Figure 3-5).

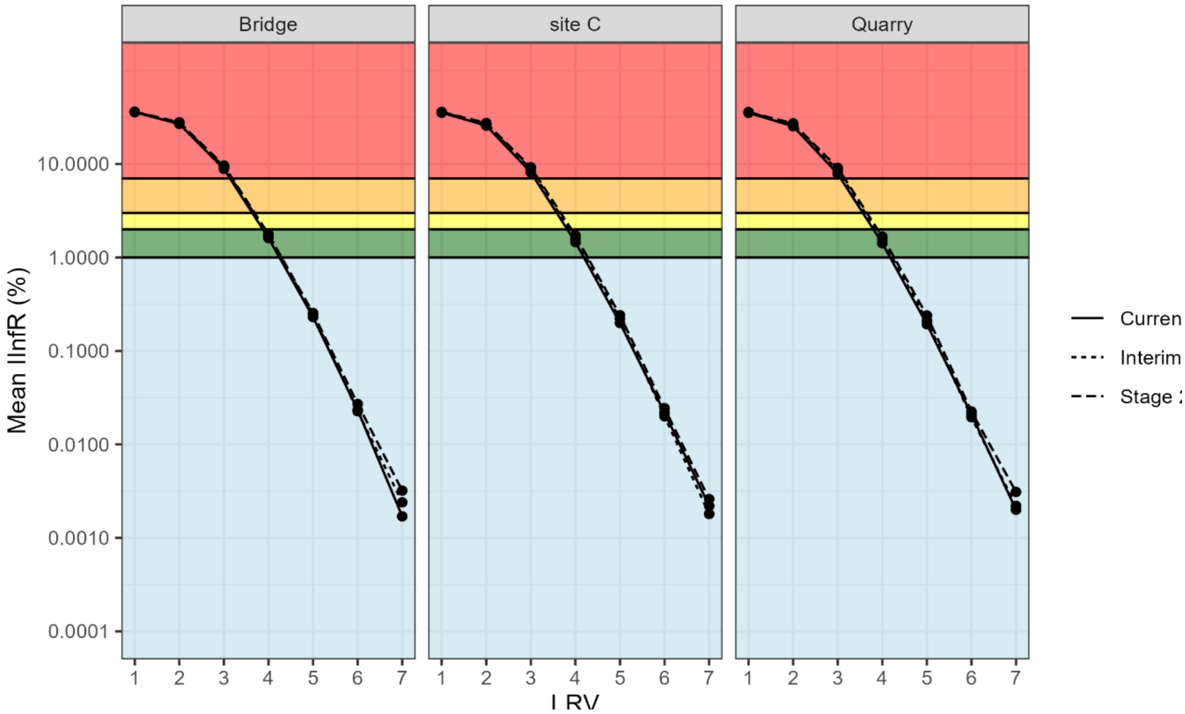

Figure 3-6: Mean infection risk (IInfR) from primary contact recreation at three sites in the Te Puru stream. The colours relate to the NPS-FM categories: blue IInfR < 1% per event, green 1 -2%, yellow 2-3%, orange 3-7% and red >7%. Higher levels of treatment result in lower risks.

Table 3-5: Estimated Individual Infection Risks (IInfR) % for swimming at various sites and levels of treatment for the current situation. Site C not shown, values between results from Bridge and Quarry sites.

		Log Reduction Values						
Site	**Type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Bridge	River	35.8568	26.8367	8.8485	1.6142	0.2302	0.0233	0.0017
Quarry	River	35.3138	25.3612	7.8621	1.4218	0.1931	0.0209	0.002
Te Puru stream mouth	Marine	3.7073	0.9078	0.1539	0.0205	0.0022	0.0002	<0.0001
Kelly's Beach (East Trans)	Marine	2.1469	0.4768	0.0745	0.0079	0.0006	0.0001	<0.0001
Kelly's Beach (Mid Trans)	Marine	1.8781	0.3969	0.066	0.0087	0.0007	0.0001	<0.0001
Kelly's Beach (North Trans)	Marine	1.2841	0.2644	0.0417	0.0051	0.0005	0.0001	<0.0001
Pohutukawa Bay	Marine	0.0310	0.0037	0.0004	0.0001	<0.0001	<0.0001	<0.0001
Omana	Marine	0.0193	0.0018	0.0004	<0.0001	<0.0001	<0.0001	<0.0001
Shelly Bay	Marine	0.0232	0.0018	0.0002	<0.0001	<0.0001	<0.0001	<0.0001
Maraetai	Marine	0.0188	0.0017	0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Magazine Bay	Marine	0.0127	0.0018	0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Umupuia (Inner)	Marine	0.0071	0.0009	0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table 3-6: Estimated Individual Infection Risks (IInfR) % for swimming at various sites and levels of treatment for the interim scenario.

		Log Reduction Values						
Site	**Type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Bridge	River	36.0961	27.5595	9.3046	1.7083	0.2459	0.0226	0.0024
Quarry	River	35.7183	26.5196	8.5621	1.5684	0.2111	0.0195	0.0022
Te Puru stream mouth	Marine	6.4807	1.7647	0.3161	0.0416	0.0038	0.0005	<0.0001
Kelly's Beach (East Trans)	Marine	3.9705	0.9701	0.1609	0.0207	0.0022	0.0003	<0.0001
Kelly's Beach (Mid Trans)	Marine	3.4452	0.7585	0.1162	0.0137	0.0014	0.0003	<0.0001
Kelly's Beach (North Trans)	Marine	2.4431	0.5287	0.0753	0.0084	0.001	0.0002	<0.0001
Pohutukawa Bay	Marine	0.0543	0.0069	0.0008	<0.0001	<0.0001	<0.0001	<0.0001
Omana	Marine	0.0542	0.0066	0.0007	<0.0001	<0.0001	<0.0001	<0.0001
Shelly Bay	Marine	0.049	0.0071	0.0006	<0.0001	<0.0001	<0.0001	<0.0001
Maraetai	Marine	0.0373	0.0059	0.001	0.0001	<0.0001	<0.0001	<0.0001
Magazine Bay	Marine	0.0249	0.0035	0.0004	<0.0001	<0.0001	<0.0001	<0.0001
Umupuia (Inner)	Marine	0.0110	0.0009	0.0001	<0.0001	<0.0001	<0.0001	<0.0001

Table 3-7: Estimated Individual Infection Risks (IInfR) % for swimming at various sites and levels of treatment for the Stage 2 scenario.

		Log Reduction Values						
Site	**Type**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Bridge	River	36.2398	27.9538	9.6281	1.7742	0.2546	0.0271	0.0032
Quarry	River	35.9687	27.2249	9.1028	1.6747	0.2398	0.0225	0.0031
Te Puru stream mouth	Marine	9.5143	2.9343	0.5416	0.0803	0.0089	0.0012	0.0002
Kelly's Beach (East Trans)	Marine	6.6750	1.7806	0.3204	0.0414	0.0033	0.0004	<0.0001
Kelly's Beach (Mid Trans)	Marine	5.9304	1.4411	0.2306	0.0262	0.0029	0.0002	<0.0001
Kelly's Beach (North Trans)	Marine	4.2925	1.0641	0.1818	0.0234	0.0016	0.0001	<0.0001
Pohutukawa Bay	Marine	0.1278	0.0142	0.0008	0.0001	<0.0001	<0.0001	<0.0001
Omana	Marine	0.0874	0.0115	0.0008	0.0002	<0.0001	<0.0001	<0.0001
Shelly Bay	Marine	0.1226	0.0132	0.0015	0.0001	<0.0001	<0.0001	<0.0001
Maraetai	Marine	0.0701	0.0085	0.0008	<0.0001	<0.0001	<0.0001	<0.0001
Magazine Bay	Marine	0.0465	0.0052	0.0005	<0.0001	<0.0001	<0.0001	<0.0001
Umupuia (Inner)	Marine	0.0295	0.0025	0.0001	0.0001	<0.0001	<0.0001	<0.0001

3.8.2 Risks from watercress consumption.

Risks from watercress are only assessed in the freshwater environment and relate to watercress consumed in its raw form and uncooked. Our understanding of the ability of watercress to internalise norovirus is limited, so the assumptions made in the QMRA are precautionary, including using a meal size at the upper end of the estimated average meal sizes. The results are shown in Figure 3-7.

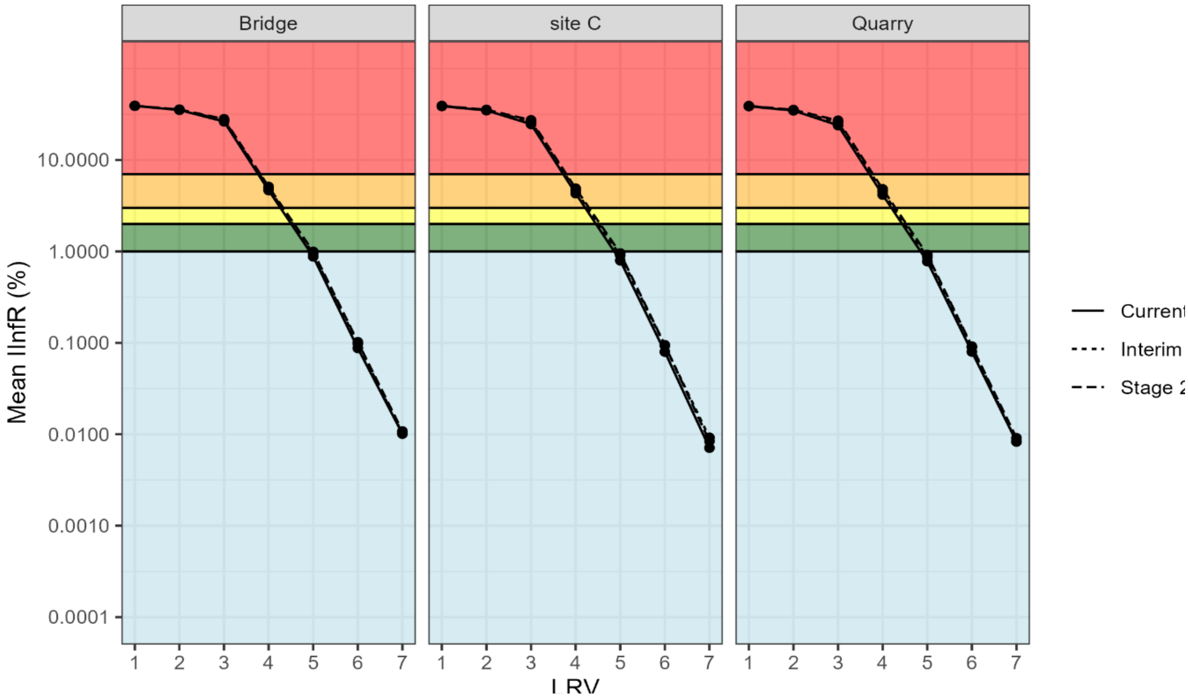

Figure 3-7: Mean infection risk (IInfR) from consumption of watercress harvested at three sites in the Te Puru stream assuming a meal size of 250 g. The colours relate to the NPS-FM categories: blue IInfR < 1% per event, green 1 -2%, yellow 2-3%, orange 3-7% and red >7%.

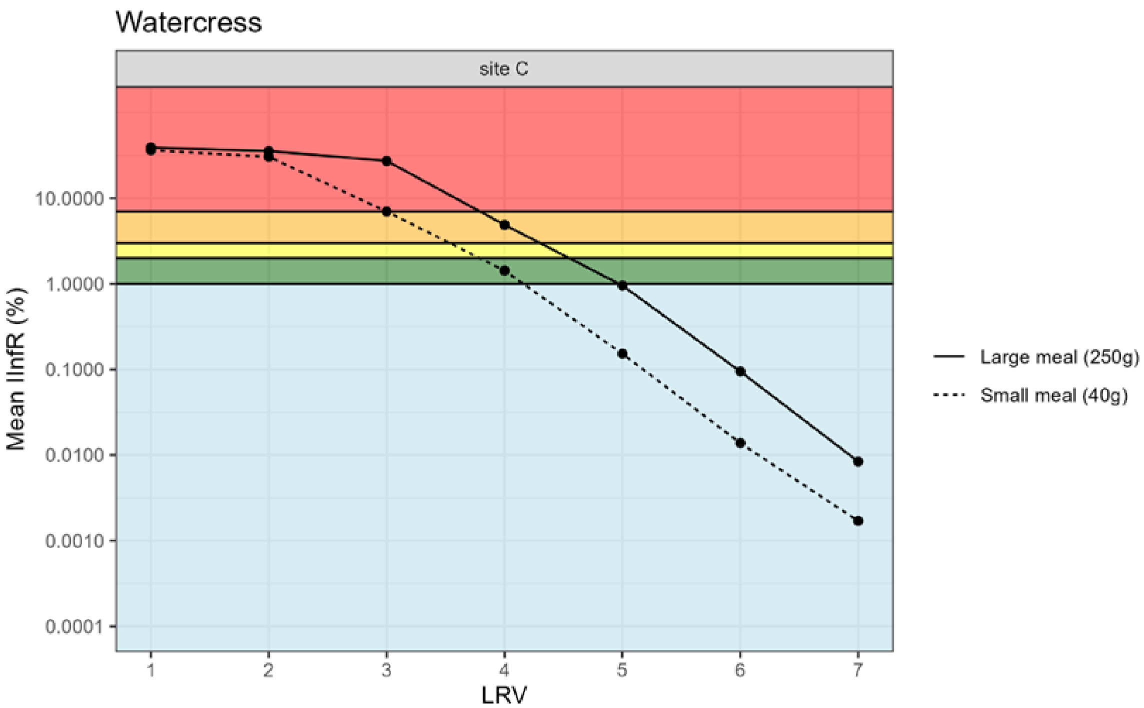

Figure 3-8: Mean infection risk (IInfR) from consumption of large and small watercress meal size harvested from site C. The colours relate to the NPS-FM categories: blue IInfR < 1% per event, green 1 -2%, yellow 2-3%, orange 3-7% and red >7%.

Though using the larger meal size is appropriate for assessing risk, it is instructive to see how sensitive the model is to the quality of watercress ingested. The larger meal size is approximately six times larger than the small mean size. The risk from the smaller mean size is lower than the large meal size (Figure 3-8). However, the difference in risk, at size C for a LRV of 4 is only a factor of approximately 3.5. So, halving the meal size does not result in halving the estimated risk. A full list of risk estimates are presented in Table 3-8.

Table 3-8: Estimated Individual Infection Risks (IInfR) % for consuming watercress harvested at three sites on the Te Puru stream.

						Log Reduction Values			
Site	**Scenario**	**Meal Size**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Bridge	Current	Large meal (250 g)	39.0324	35.2912	26.362	4.6653	0.8777	0.0875	0.0101
Bridge	Interim	Large meal (250 g)	39.1709	35.5648	27.4721	4.9172	0.9421	0.0977	0.0102
Bridge	Stage 2	Large meal (250 g)	39.2486	35.7409	28.0846	5.1056	0.9953	0.1022	0.0108
Bridge	Current	Small meal (40 g)	36.1463	29.9434	6.6303	1.3316	0.1407	0.0148	0.0023
Bridge	Interim	Small meal (40 g)	36.3984	30.6445	7.0047	1.4333	0.1575	0.0159	0.0013
Bridge	Stage 2	Small meal (40 g)	36.5403	30.9935	7.2642	1.4874	0.1645	0.0168	0.0022
site C	Current	Large meal (250 g)	38.8059	34.9014	24.6775	4.3173	0.7961	0.0798	0.0071
site C	Interim	Large meal (250 g)	39.0286	35.2796	26.3075	4.6341	0.9039	0.0934	0.0092
site C	Stage 2	Large meal (250 g)	39.1516	35.5276	27.3287	4.8918	0.9553	0.0947	0.0084
site C	Current	Small meal (40 g)	35.769	28.7529	6.1099	1.2145	0.1269	0.012	0.0015
site C	Interim	Small meal (40 g)	36.1301	29.9029	6.5843	1.3561	0.1456	0.0149	0.0015
site C	Stage 2	Small meal (40 g)	36.3693	30.5261	6.9821	1.4287	0.1525	0.0138	0.0017
Quarry	Current	Large meal (250 g)	38.7089	34.7436	23.9775	4.1658	0.7783	0.0799	0.0083
Quarry	Interim	Large meal (250 g)	38.9625	35.1728	25.8166	4.5324	0.8661	0.0896	0.0083
Quarry	Stage 2	Large meal (250 g)	39.091	35.4188	27.0622	4.806	0.9203	0.0916	0.0091
Quarry	Current	Small meal (40 g)	35.6414	28.2111	5.8852	1.1953	0.1238	0.0121	0.0015
Quarry	Interim	Small meal (40 g)	36.0297	29.5997	6.4362	1.3058	0.1415	0.0152	0.0014
Quarry	Stage 2	Small meal (40 g)	36.2762	30.3638	6.8191	1.3852	0.1462	0.0154	0.0015

3.8.3 Risks from shellfish consumption

No shellfish harvesting sites have been identified close to the Te Puru steam mouth. The estimated risks under all discharge scenarios and levels of treatment (LRV) are less than 1% IInfR.

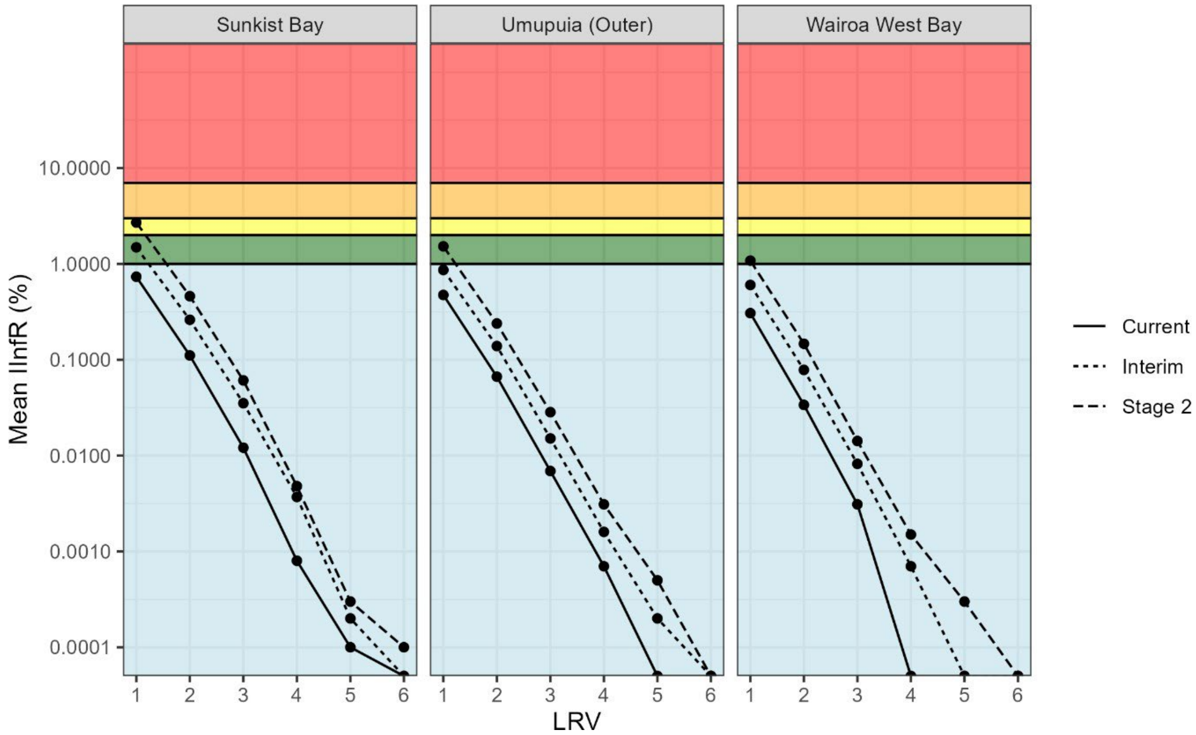

Figure 3-9: Mean infection risk (IInfR) from shellfish consumption from three sites. The colours relate to the NPS-FM categories: blue IInfR < 1% per event, green 1 -2%, yellow 2-3%, orange 3-7% and red>7%.

Table 3-9: Estimated Individual Infection Risks (IInfR) % for consuming shellfish harvested at three marine sites.

		Log Reduction Values					
site	**scenario**	**1**	**2**	**3**	**4**	**5**	**6**
Sunkist Bay	Current	0.7352	0.1109	0.0121	0.0008	0.0001	<0.0001
Sunkist Bay	Interim	1.4901	0.2614	0.0352	0.0037	0.0002	<0.0001
Sunkist Bay	Stage 2	2.7046	0.4606	0.0609	0.0048	0.0003	0.0001
Umupuia (Outer)	Current	0.4743	0.0666	0.0069	0.0007	<0.0001	<0.0001
Umupuia (Outer)	Interim	0.8650	0.1389	0.0151	0.0016	0.0002	<0.0001
Umupuia (Outer)	Stage 2	1.5271	0.2390	0.0284	0.0031	0.0005	<0.0001
Wairoa West Bay	Current	0.3064	0.0338	0.0031	<0.0001	<0.0001	<0.0001
Wairoa West Bay	Interim	0.6033	0.0784	0.0082	0.0007	<0.0001	<0.0001
Wairoa West Bay	Stage 2	1.0817	0.1469	0.0142	0.0015	0.0003	<0.0001

4 Discussion and Conclusions

From the results in Sections 2 and 3, the following inferences can be made:

4.1.1 Microbial quality of the WWTP discharge

Wastewater monitoring indicates a consistent microbiological quality of disinfected treated effluent with median levels below 2 counts/100 mL, well within the current consent limit of median ≤ 14 faecal coliforms/100 mL.

Concentrations of faecal indicator bacteria levels in discharged wastewaters are predominantly below 10 CFU/100 mL with 95th percentiles remaining under 25 CFU/100 mL. This suggests that the current treatment measures are in line with proposed consent conditions accommodating interim and future population growth scenarios. These proposed conditions include median concentrations of < 10 faecal coliforms /100 mL and 90th and 95th percentiles of 100 faecal coliforms/100 mL. Furthermore, there is no present evidence indicating a deterioration in treated wastewater quality with higher flows as shown in Figure 2-3 and Figure A-4.

There is evidence of a weak seasonality effect with slightly higher levels of faecal coliforms in treated effluent in the summer months (Figure 2-2) suggesting greater potential for impact from wastewater discharge on the receiving environment during summer.

Overall, current data highlight the efficacy of current treatment processes in maintaining wastewater quality within acceptable limits, despite varying flow rates. However, ongoing assessment of wastewater quality will be essential to ensure that treatment facilities remain effective in managing potential changes in wastewater characteristics associated with increased population and flow rates projected to increase from 23 L/s currently to 71 L/s for future population growth scenarios.

4.1.2 Efficacy of removing FIB

There was no evidence of deterioration of disinfection efficacy by the UV plant in response to discharge flows (Figure 2-1 and Figure A-4). Highest removal rates were typically seen during the summer months coinciding with elevated FIB concentrations in UV influent wastewaters (Figure 2-4 and Figure 2-5).

Removal of FIB by the WWTP ranged from 4.4 log_{10} to 7.8 log_{10} with median log_{10} reductions of 6.6, 6.5 and 6.0 for faecal coliforms, *E. coli* and enterococci respectively (Table 2-2 and Figure 2-6).

While the removal of FIB serves as a useful indicator of overall treatment efficacy, it does not guarantee complete removal of all viral pathogens and may overestimate the reduction of viable viruses. FIB are larger in size compared to viruses, making them easier to remove through conventional wastewater treatment processes such as sedimentation and filtration. FIB are also more susceptible to inactivation and die-off due to tertiary disinfection such as UV treatment.

However, the removal of FIB during wastewater treatment serves as an upper limit of the log reduction value (LRV) for virus removal in the Beachlands WWTP as viruses may exhibit greater resistance to treatment processes particularly disinfection treatment and are not as effectively removed.

Opportunities for removal of microbes, including viruses, exist after UV treatment during surface irrigation and land application of treated wastewater to the riparian buffer zone. Processes such as solar disinfection, infiltration into the soil horizon, attenuation in the soil matrix through filtration and attachment to soil particles and microbial degradation can attenuate and reduce viral transport to the Farm Pond, enhancing the overall removal efficiency further (Schijven et al. 2017).

4.2 The receiving environment

There was no evidence of an annual increase in daily average FIB load discharged from the WWTP (Figure 2-7), but a seasonal trend was apparent, with average FIB instantaneous load peaking in summer months, indicating a potential for higher environmental loading from the WWTP during that time.

The discharge from the WWTP, however, does not account for elevated FIB levels in the receiving environment and Te Puru stream; sites in these locations had median concentrations up to three or more orders of magnitude higher than the treated effluent. These higher levels implicate additional sources of faecal contamination within the Te Puru stream catchment. Potential sources of contamination contributing to the poor water quality of the stream include the presence and density of birds such as those residing at the Farm Pond, runoff and drainage from low intensity agriculture, and direct deposition by cattle. These factors can collectively contribute to FIB contamination beyond what is solely attributable to the WWTP discharge.

The additional faecal inputs from various sources, including livestock, will significantly affect the microbial quality of the stream water posing associated risks. Depending on the contributing source, these risks may not differ substantially from waters affected by human sources (Soller et al. 2010).

4.2.1 Potential health risks

The disparity between the “high” level of FIB in the Te Puru Stream and the “low” level of FIB discharged in the WWTP treated effluent implies the presence of other sources of contamination beyond the WWTP. In this microbiological context, risks associated with human contact and shellfish consumption at freshwater or estuarine sites are based on FIB levels and reflect the impact of faecal contaminants from all sources other than just the wastewater treatment plant.

Human contact

Comparing FIB water quality with risk thresholds for human contact activities, FIB levels at all sites in the Te Puru stream and local receiving environment correspond to Band E (red) categories. Predicted infection risks exceed 7% on average for these freshwater environments. Downstream estuarine sites are anticipated to have a risk of illness greater than 10% according to the MfE/MoH (2003) grading criteria.

Shellfish consumption

FIB water quality conditions at all sites exceed criteria for recreational shellfish harvesting, making them unsuitable for shellfish gathering. However, the shellfish observed in the estuary at Te Puru Park are considered too small for harvesting, further reinforcing the unsuitability of these sites for shellfish collection and consumption at the present time.

Livestock drinking water

Levels of faecal indicator bacteria in Te Puru stream resulting from the WWTP discharge are considered to be negligible. However, the presence of high faecal contamination in the stream which may be abstracted for cattle drinking water, exceeds median values of 600 faecal coliforms/100 mL.

This is well above the recommended median value of 100 faecal coliforms /100mL for livestock drinking water and is therefore not considered suitable for this purpose at any site along the Te Puru Stream network.

4.3 Wastewater risk assessment (QMRA)

The low level of FIB in the treated effluent is not a guarantee of safety as there is the potential for the relationship between indicator organisms and pathogens to be altered by the treatment process (MfE/MoH 2003). In this case, a Quantitative Microbial Risk Assessment (QMRA) was chosen as an alternative approach to assess human health risks. The QMRA can help estimate the risks associated with the WWTP (wastewater treatment plant), which is particularly useful when there are multiple sources of microbial hazards in the environment.

The overall QMRA findings showed that the efficacy of treatment, as indicated by the Log Reduction Values (LRV), was a significant factor in modifying the risk to human health together with other factors such as dilution and the mechanism of exposure (swimming, consumption of watercress or shellfish). The higher the levels of treatment efficacy, the lower the risk, while greater levels of dilution of treated effluent also lower the risk.

The level of dilution varied according to the exposure site and discharge scenario. Marine sites further away from the wastewater discharge tended to have higher dilution levels and lower risk. Within the Te Puru stream, there is little opportunity for the treated effluent to become diluted downstream of the plant until it reaches the marine environment. So, the estimated risks did not vary significantly in the stream downstream from the plant.

Increasing discharge from the plant from the Current to Interim and Stage 2 resulted in increased risks in the marine environment but very little increase in risks in the Te Puru stream. An assumption within the QMRA model is that the concentration of pathogens in effluent does not change with the scenarios, though the volume increases. Therefore, as long as the level of treatment remains constant, we do not expect the risks to change in the stream as we move from the Current to Stage 2 discharge flows.

The mechanism by which an individual could become exposed to dilute treated effluent also influences risk. While there are multiple exposure routes for an exposure site, such as swimming or consumption of uncooked watercress, watercress has the highest estimated risk.

4.3.1 Stream environment

The highest risks in the QMRA were estimated at the Bridge site, immediately below the discharge of the WWTP under the Stage 2 scenario for watercress consumption. The risks under Stage 2 scenario at the Bridge for LRV = 5, the IInfR were 0.995% for watercress consumption and 0.255% for swimming. Moving downstream, the watercress risks fell to 0.920% at the Quarry, an absolute difference of 0.075 percentage points between the Bridge and the Quarry site. Likewise, the swimming risks fell to 0.240%, a difference of 0.015 percentage points. The difference between the current and Stage 2 scenarios was 0.118 and 0.024 percentage points for watercress and swimming, respectively. The difference between the A and B attributes bands from the NPS-FM is a difference of one percentage point.

4.3.2 Marine environment

For the sites assessed, the highest risks were from swimming at the Te Puru stream mouth under the Stage 2 scenario, followed by the three other assessment sites along the shoreline in Kelly's Beach. The risks in Kellys Beach were an order of magnitude higher than swimming at sites outside the Kelly's Beach bay area.

Shellfish have the ability to bioaccumulate viruses. So for a similar site at Umupuia, the shellfish risks are approximately 50 greater than that for swimming. Using an LRV = 1, for illustrative purposes, the swimming risks are 0.0295% and the shellfish risks are 1.5271% under Stage 2 scenario.

4.3.3 Level of treatment required

The actual risks to health in the Te Puru stream, Kelly's Beach and along the coastlines from contact with water depends on a number of factors and the wastewater discharge is only one of these factors. However to manage the incremental risks from the WWTP and keep the Individual Infection Risk (IInfR) below 1% would require treatment to achieve 5 LRV for sites in the Te Puru stream and this would ensure health risks at all the other sites for swimming and shellfish consumption would be kept below 1%. This assessment is based on a watercress analysis which is highly precautionary, nevertheless the assessment of swimming risks calls for an LRV of over 4.

4.4 Health Risk

In considering the predicted health risks from this QMRA, it should be noted that risk modelling did not consider the potential impact on health from other types of human pathogens that could be discharged from the Beachlands WWTP or faecal contaminants derived from other sources that could be conveyed to the Te Puru Stream and downstream coastal environment.

The results reported here are the potential health risks attributable to norovirus derived from the Beachlands WWTP and are *incremental* health risks associated with a single model pathogen in the WWTP discharge. Usually, viruses are the principal pathogen of concern from well-treated wastewater. If, however, the WWTP fails to achieve these reductions, non-viral pathogens such as bacteria or protozoa may also be of concern.

5 Acknowledgements

We thank Jason Scharvi-Coles (Watercare Services Limited) for providing a tour of the Beachlands WWTP and the land application discharge area, Mark James (Aquatic Environmental Services) for facilitating the supply of WWTP data, Shane Kelly (Coasts and Catchment) for supplying collated results from the short-term monitoring campaign, Phil Hook and Joseph Gibson of PDP for discussions and data regarding dilution of wastewater in the Te Puru Stream and John Oldman (DHI) for discussions and dilution modelling data for the stream, shoreline and coastal waters.

6 Glossary of abbreviations and terms

E. coli	*Escherichia coli*. The preferred faecal indicator bacteria for freshwater microbiological water quality assessment in New Zealand.
exposure pathway	Describes the source of the pathogen, transport route, barriers to exposure and the mechanism of exposure.
FIB	Faecal indicator bacteria. Excreted bacteria whose presence indicates faecal contamination and the potential presence of other excreted microorganisms such as pathogens.
hazardous event	An event which introduces a hazard (pathogen) into the water or fails to remove the hazard from the water.
hydroponically grown	Grown in water as opposed to soil.
PERT distribution	The Program Evaluation and Review Technique or PERT distribution is a continuous statistical distribution defined by minimum, mode and maximum values. It is used to model values obtained from expert opinion.
QMRA	Quantitative Microbial Risk Assessment.
Uncertainty	Lack of knowledge about the true value.
Variability	Observed differences are due to the true heterogeneity of a quantity (World Health Organization 2016), such as the variability of children's height in a class.
WWTP	Wastewater Treatment Plant.

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Appendix A Beachlands Wastewater Treatment Plant

A site visit to Beachlands Wastewater Treatment Plant was undertaken on 27/10/2023 to provide familiarisation with the WWTP site and the discharge receiving environment (Figure A-3).

The existing treatment configuration of Beachlands WWTP is shown as a schematic in Figure A-1.

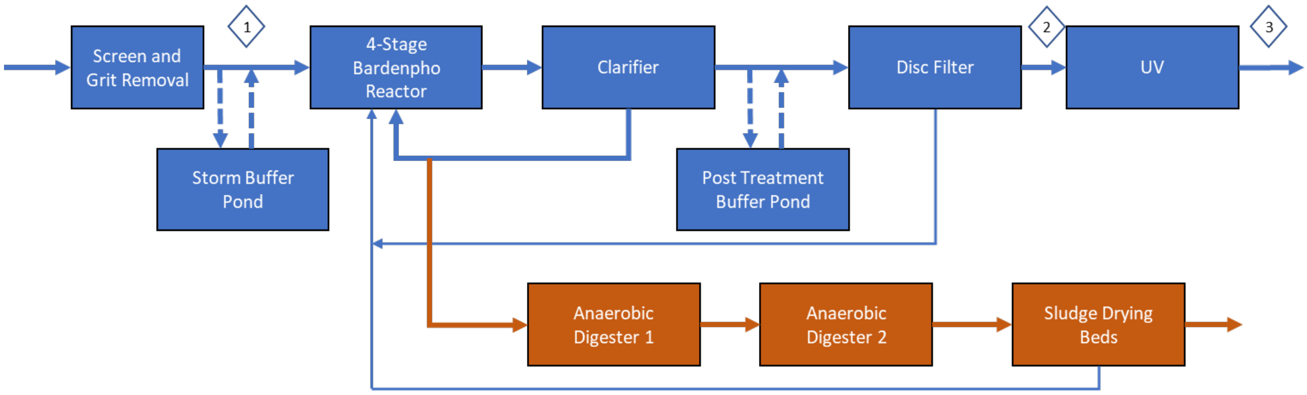

Figure A-1: Schematic of the wastewater treatment processes at Beachlands-Maraetai (Beachlands) Wastewater treatment plant. Wastewater sampling sites for microbiological water quality assessment shown. 1: raw wastewater after screening (WW inlet); 2: Pre-UV; 3: Post-UV (WW outlet).

Figure A-2: Location of Beachlands WWTP, Farm Pond and Te Puru Stream and estuary in the Beachlands catchment area.

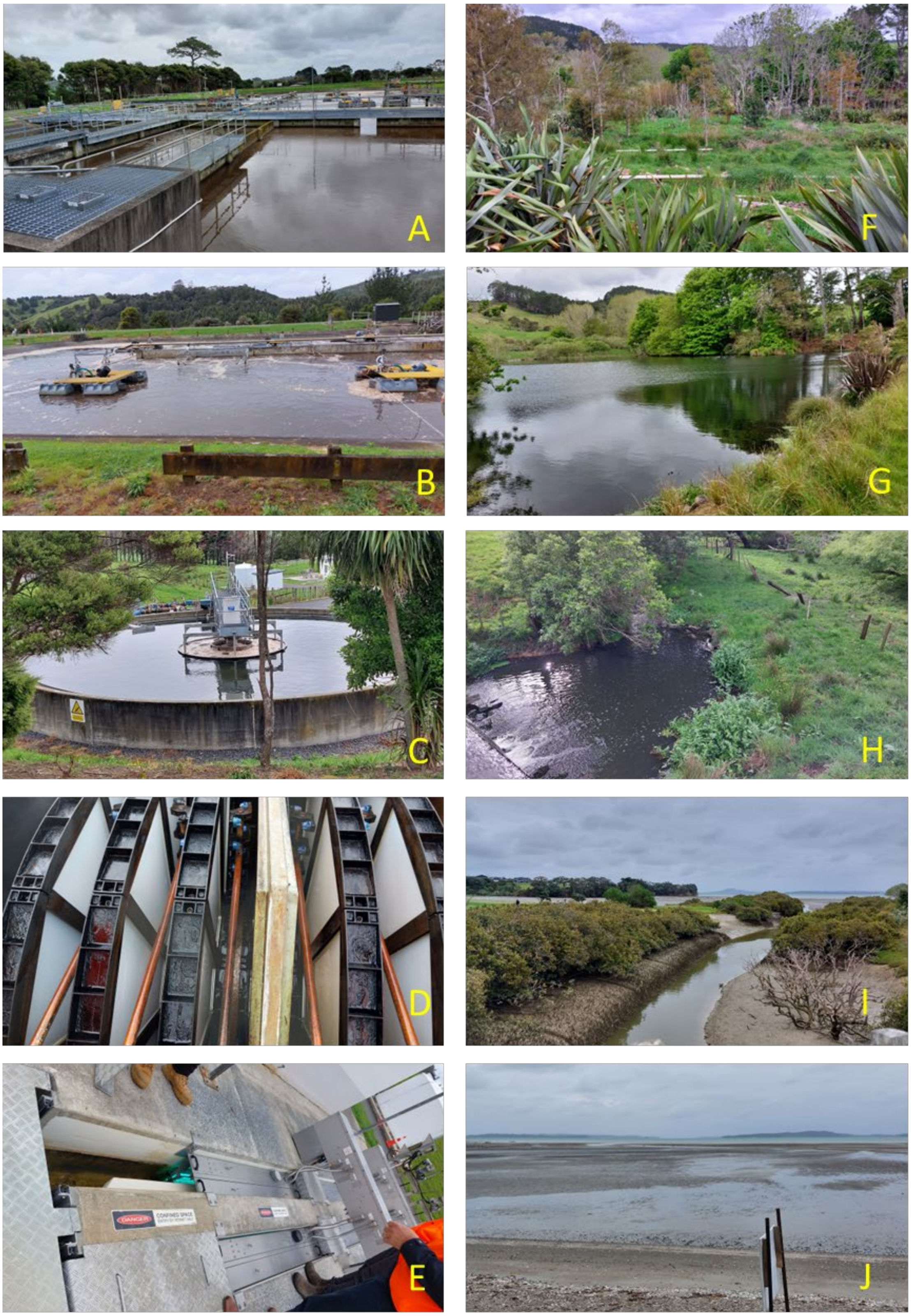

Figure A-3: Beachlands WWTP and receiving environment. WWTP (A-E); receiving environment (riparian land application F, Farm Pond G); Te Puru Stream (Bridge site H, Te Puru Park I); Estuary (J). Site visit 27 October 2023, R. Stott.

Wastewater discharge characteristics

Preliminary analysis of data for the WWTP is shown below (data supplied by Aquatic Services and Coast and Catchment) for the 2018-2024 data.

Exploration of effluent monitoring data for faecal coliform concentrations for the period Jan 2018 to Jan 2024 for which discharge data is available, does not reveal any evidence of a relationship between faecal coliform concentration in the treated wastewater and wastewater total daily discharge rates or UV transmissivity (%) (Figure A-4 and Figure A-5).

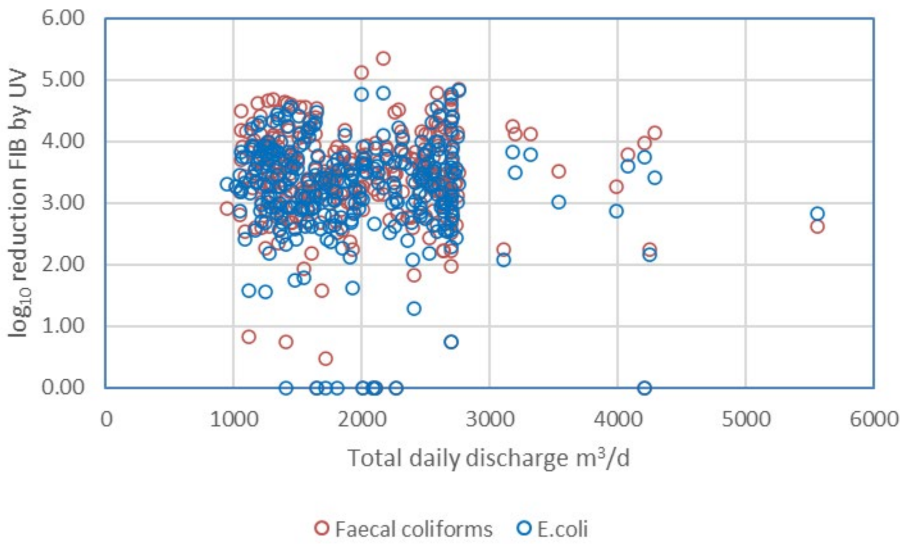

Figure A-4: Relationship between log_{10} removal of faecal coliforms by UV disinfection and total daily flow of discharged wastewater from the WWTP. Note: use of the flow balancing pond allows discharges to remain below the 2800 m^3/d in most instances.

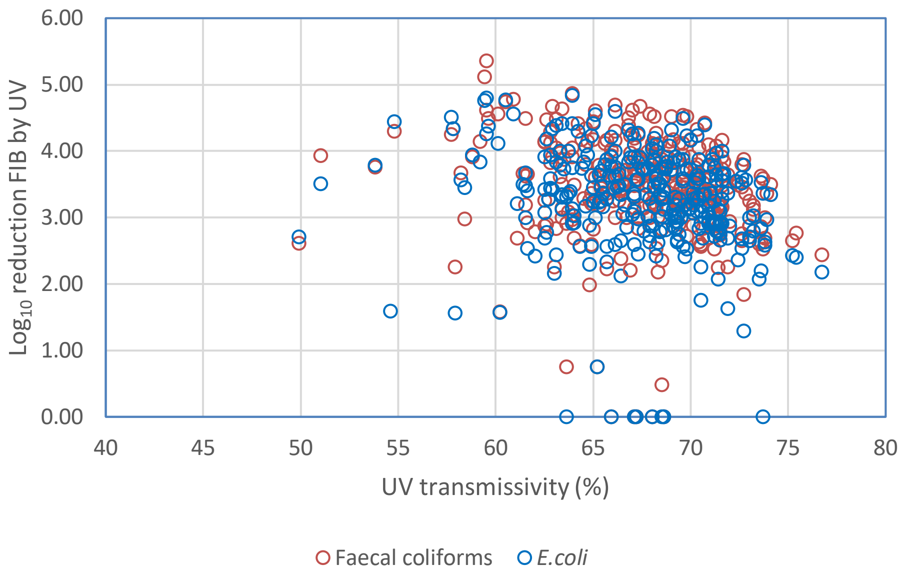

Figure A-5: Relationship between log_{10} removal of faecal coliforms by UV disinfection and UV transmissivity (%).

Appendix B Receiving environment

Short-term environmental monitoring

Sites used for the short-term monitoring campaign (September 2023 – March 2024) are shown in Figure B-1. Additional sites “Quarry” and “Te Puru Park” are shown in Figure 3-2. A description of the sites is shown in Table B-1.

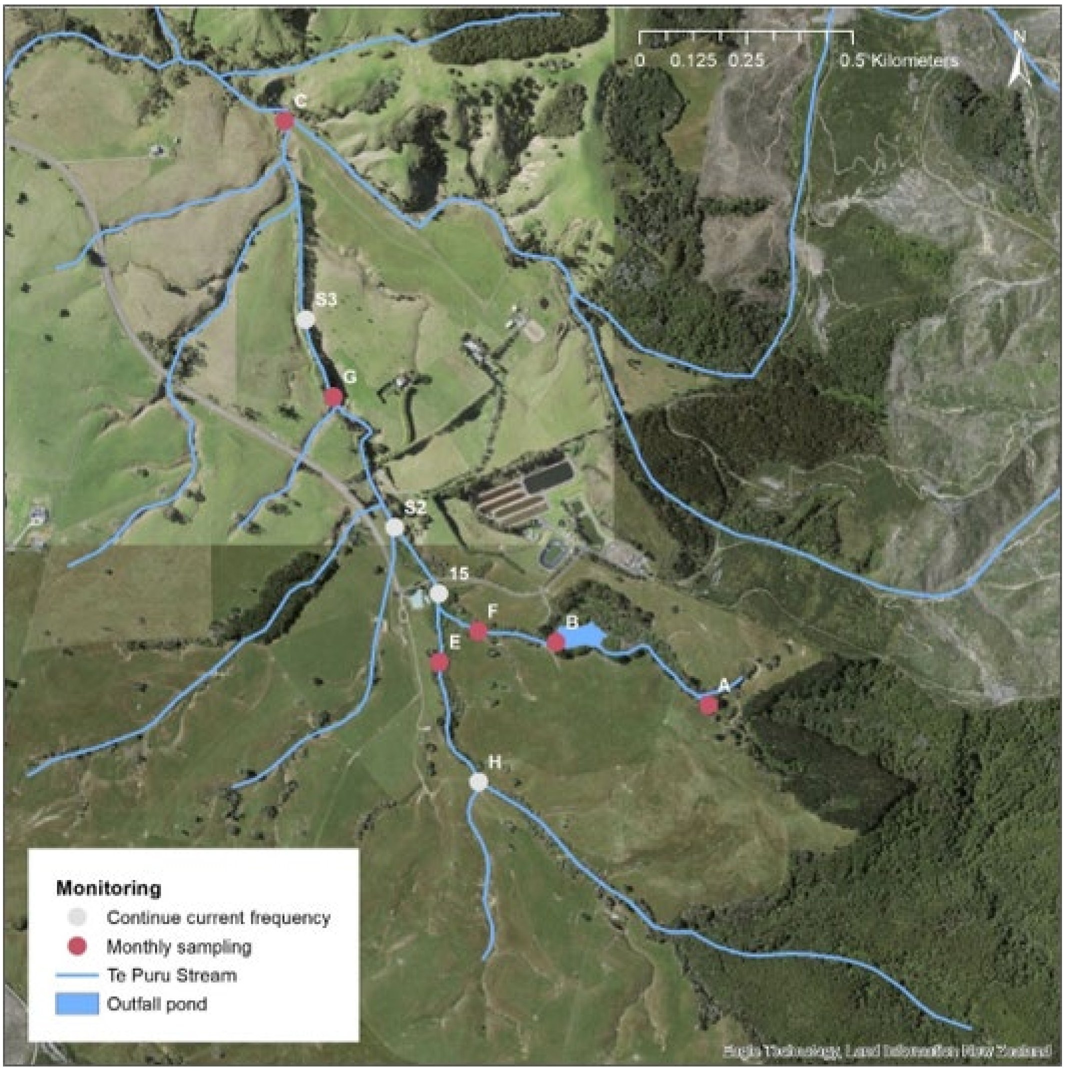

Figure B-1: Location of sites sampled for the short-term spatial survey (Sept 2023 - Mar 2024). Figure supplied by Coast and Catchment (Shane Kelly).

Table B-1: Site description and locations used in the short-term environmental monitoring campaign and cross referenced to QMRA sites. Site descriptions from Bioresearches, 2022 report.

Waterway	Site description	Site
WWTP	Raw wastewater	Wastewater influent
WWTP	Final treated (UV disinfected) wastewater	Wastewater outlet
Farm Pond Tributary	Reference site upstream of Farm Pond	Site A
Farm Pond Tributary	Effect site immediately downstream of Farm Pond discharge	Site B
Reference Tributary	Effect site approx.. 200 m downstream of Farm Pond and immediately upstream of the Te Puru Stream tributary confluence	Site F
Reference Tributary	Reference site just upstream of the confluence with the Farm Pond tributary and Te Puru Stream tributary	Site E
Te Puru Stream Tributary	Effect site immediately downstream of the confluence of the Farm Pond tributary and the Reference Tributary	Site 15 (QMRA = The Bridge)
Te Puru Stream Tributary	Effect site approx.. 600 m downstream of the Farm Pond Tributary and Reference Tributary confluence	Site G
Te Puru Stream	Effect site approx. 100 m upstream of the confluence with the main stem of the Te Puru Stream	Site C (QMRA = C)
Te Puru Stream	Quarry site	Quarry (QMRA = Quarry)
Te Puru Stream	Discharge of Te Puru Stream into Kelly's Beach estuarine environment	Te Puru Park (QMRA = Te Puru Stream mouth)

Microbiological water quality: spatial survey

A summary of microbiological water quality for treated wastewater and Te Puru Stream sites are shown in Table B-2, Table B-3 and Table B-4.

Table B-2: Summary of faecal coliform concentrations in treated wastewater and at various sites along the Te Puru Stream. Data from short-term monitoring campaign 11/9/2023 - 6/3/2024.

Site	N	Median	95th percentile	% of samples > 43 FC/100 mL
WW outlet (UV disinfected)	64	1.6	27.9	
Site A	73	1500	7340	100
Site B	73	680	3010	100
Site F	24	805	2120	100
Site E	24	1300	5430	100
Site 15 (the Bridge)	73	660	4040	100
Site G	3	780	-	100
Site C	3	1000	-	100
Quarry	15	700	5125	100
Te Puru Park	24	690	11100	100

Table B-3: Summary of *E. coli* concentrations in treated wastewater and at various sites along the Te Puru Stream. Data from short-term monitoring campaign 11/9/2023 - 6/3/2024.

Site	N	% > 540	% > 260	Median	95th percentile
WW outlet (UV disinfected)	64	0	0	1.6	18.9
Site A	73	81	95	1000	4770
Site B	73	48	82	540	2740
Site F	24	50	83	555	1800
Site E	24	83	96	880	4540
Site 15 (the Bridge)	73	49	92	520	3250
Site G	3	100	100	810	-
Site C	3	100	100	800	-
Quarry	15	60	87	640	3650
Te Puru Park	24	50	83	575	6760

Table B-4: Summary of enterococci concentrations in treated wastewater and at various sites along the Te Puru Stream. Data from short-term monitoring campaign 11/9/2023 - 6/3/2024.

Site	N	Median	95th percentile
WW outlet (UV disinfected)	64	1.6	5.25
Site A	73	110	1555
Site B	73	130	1780
Site F	24	225	2080
Site E	24	535	3020
Site 15 (the Bridge)	73	290	2170
Site G	3	750	-
Site C	3	600	-
Quarry	15	660	10040
Te Puru Park	24	245	9700