Quantitative Microbial Risk Assessment of New Plymouth Wastewater Treatment Plant

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Climate, Freshwater & Ocean Science

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Executive summary

A consent condition for the operation of the New Plymouth Wastewater Treatment Plant (NPWWTP) is that New Plymouth District Council (NPDC) will submit to the Chief Executive, Taranaki Regional Council, a Quantitative Microbial Risk Assessment (QMRA) of the discharge focusing primarily on bypass discharges. Bypass discharges occur in situations where effluent is treated but at reduced levels from normal operations. NPDC commissioned NIWA to carry out a QMRA on contact recreation (e.g., swimming) and shellfish consumption from 31 coastal water sites off New Plymouth. The results from this QMRA were compared to a 2012 study.

QMRA is a computer simulation approach that takes information from various sources to quantify microbiological risks to human health. This project used QMRA to estimate an individual's risk of becoming ill from norovirus via exposure to diluted treated effluent from NPWWTP through swimming or shellfish consumption. The risks are presented as Individual Illness Risks (IIR) which is the average per event, either a swim or shellfish feed.

The Individual Illness Risks (IIR) have been estimated at 31 coastal sites off New Plymouth. One site is directly inshore from the NPWWTP wastewater outfall, which discharges treated effluent to the Tasman Sea, approximately 480 m offshore and close to the mouth of the Waiwhakaiho River. Twelve sites are east of the outfall, and 18 sites are west. The sites are spread approximately 10 km up and down the coast from the discharge.

Risks were estimated for various scenarios, encompassing four levels of treatment, two climate conditions and two seasons. The level of treatment influences the concentration of norovirus being discharged into the Tasman Sea at the outfall. The climate and seasonal factors influence the dilution of treated effluent at each site. The four levels of treatment were normal operation (Base conditions) with bioreactors, clarifiers and chlorination; bypass conditions where effluent bypassed the bioreactors and clarifiers but is chlorinated; and two levels of UV treatment in addition to the normal operation of the plant. Climate conditions considered were La Niña and El Niño weather patterns as well as two "seasons" or time periods, summer vs a whole year.

Human health risks were shown to vary spatially along the coast, with the greatest risks at sites close to the wastewater discharge and lower risks further away. In accordance with the *2012 QMRA Report*, the IIR results are compared with the 1% (A/B) risk threshold from the Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas (MfE/MoH 2003). In the case of bypass flow (where the effluent is treated but at a reduced level from normal operations), the estimated Individual Illness Risks (IIR) for each individual exposure ranged from approximately 0.1 to 2.1% for primary contact recreation (swimming) and 2.3 to 16.0% for shellfish consumption. The risks were lower during normal operation (Base conditions), ranging from 0.02 to 0.49% for primary contact recreation (swimming) and 0.7 to 8.2% for shellfish consumption.

Scenarios showed that factors such as season and climatic variations such as La Niña and El Niño influenced the estimated risk. However, overall, these factors were less important in influencing risk than the level of treatment or site location.

The risks outlined in this report, especially those associated with bypass events, are similar but higher compared to those in the *2012 QMRA Report*. Under bypass conditions, between 11 and 13 sites had IIR greater than 1% for swimming, indicating the risks are more widely distributed along the shore than in the *2012 QMRA Report,* where only 2 out of 31 sites had risks above 1%. In both this and the *2012 QMRA Report,* all 31 sites had risks elevated above 1% for shellfish risks during bypass conditions. Under normal operations, IIR for shellfish were above 1% at 21 sites for the *2012 QMRA Report* and 29 sites for the current report. Though the estimated risks are higher than in the previous report, the increases in estimated risks are due to updated modelling parameters rather than changes in the risk itself. These updated parameters better reflect our current understanding of risks rather than fundamental changes to the actual risks from swimming or shellfish consumption.

1 Introduction

The New Plymouth Wastewater Treatment Plant (NPWWTP), also known as Waiwhakaiho Wastewater Treatment Plant, is located approximately five kilometres east of central New Plymouth and operated by the District Council. NPWWTP receives trade wastes and raw sewage from Waitara, Bell Block, Inglewood, New Plymouth City, and Ōākura and discharges treated effluent through a 480-metre ocean outfall into the Tasman Sea (NPDC 2023).

A consent condition for operating the discharge from the plant[1] is that New Plymouth District Council must provide the Chief Executive, Taranaki Regional Council, with a Quantitative Microbial Risk Assessment (QMRA) of the discharge specifically addressing bypass discharges. Bypass discharges are where the effluent is treated but at a reduced level from normal operations. New Plymouth District Council commissioned NIWA to prepare a QMRA report which estimates the potential human health risks associated with recreational activities in, or consumption of shellfish gathered from, waters affected by the discharge of well-treated effluent from the Waiwhakaiho Wastewater Treatment Plant (WWTP).

The report also compares the current estimates of illness risk with a previous QMRA carried out in 2012 (McBride 2012), referred to as the *2012 QMRA Report*. The current QMRA report, referred to as the *2023 QMRA Report*, will accompany a context report (in preparation), which places the risks arising from the wastewater discharge within a context defined by shoreline faecal indicator bacteria concentrations.

This *2023 QMRA Report* assesses health risks at 31 sites: 12 east of the outfall, 18 west of the outfall, these sites are spread approximately 10 km up and down the coast from the discharge and one site directly inshore of the outfall (Figure 1-1).

[1] Condition 13 of Consent 0882-4.1.

Figure 1-1: New Plymouth coastline and the QMRA sites. East (E1–E12) and West (W1–W18) of the outfall plus one site directly inshore (Inshore). Site coordinates are provided in Appendix A.

1.1 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. 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.

1.2 Scope

This QMRA was undertaken using information regarding the assumed efficacy of the wastewater treatment process provided by NPDC, dilution data provided by MetOcean Solutions Limited, the expected level of pathogens in wastewater from this and other New Zealand studies, in addition to information regarding the infectivity of viruses (e.g., dose-response) derived from the literature.

NIWA performed no fieldwork or data collection for this QMRA. Microbiological water quality data for the NPWWTP and receiving environment were provided by NPDC. 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 *2012 QMRA Report* on NPWWTP 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 process for the *2012 QMRA Report* was adequate, that the candidate pathogen was norovirus, and that the two key exposure routes were swimming and the consumption of raw or lightly cooked shellfish. 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 Illness Risk (IIR).

2 Quantitative Microbial Risk Assessment

To assist NPDC and the local community in understanding the health risks arising from the discharge of treated wastewater from the New Plymouth Wastewater Treatment Plant to the Tasman Sea, NIWA was commissioned to undertake a QMRA for the discharge. This assessment relates to the *incremental* risks associated with wastewater discharge, i.e., it does not consider background risks or account for risks associated with other potential sources of microbial contaminants, such as stormwater or illicit discharges from boats (Landrigan et al. 2020).

The health risk assessment process comprises multiple steps (described graphically in Figure 2-1), 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 a Monte Carlo computer simulation is used, which calls for repetitive sampling from distributions and ranges of key variables rather than just using single average values (such as median or 95th percentile values)[2]. This approach is particularly important given that the majority of the risk is caused by combinations of inputs toward the extremes of their ranges, the combined effects of which may not be detected when using averages or other single values.

Under the circumstances in which treated wastewater is discharged to the Tasman Sea, human targets' primary modes of exposure to pathogenic microorganisms are via contact recreation or consumption of raw or undercooked shellfish that may be exposed to the plume of highly diluted, treated wastewater, as noted above. Contact recreation can consist of primary and secondary contact. Primary contact includes swimming (full body immersion), and secondary may include activities such as fishing. Secondary risks are lower than primary risks (Rijal et al. 2011), so secondary risks were not considered here or in the *2012 QMRA Report*. Each of the four stages listed above is considered in turn, and all the modelling parameters, with the exception of dilution factors, can be found in Tables 2-1 and 2-2.

Health risks are usually presented as estimates of Individual Infection Risks (IInfR) or Individual Illness Risks (IIR). The level of wastewater treatment and dilution in the environment determines these risks. Risks can be estimated for adult and child receptors, for ingestion and inhalation exposure routes. However, this QMRA considered the illness risk (IIR) to ensure comparability with the *2012 QMRA Report* and the *Guidelines*. In scenarios of primary exposure to water, a precautionary approach was adopted by assuming all receptors to be children, given their typically higher water ingestion rates during swimming.

[2] Using a simple-averages approach can substantially underestimate human health risk.

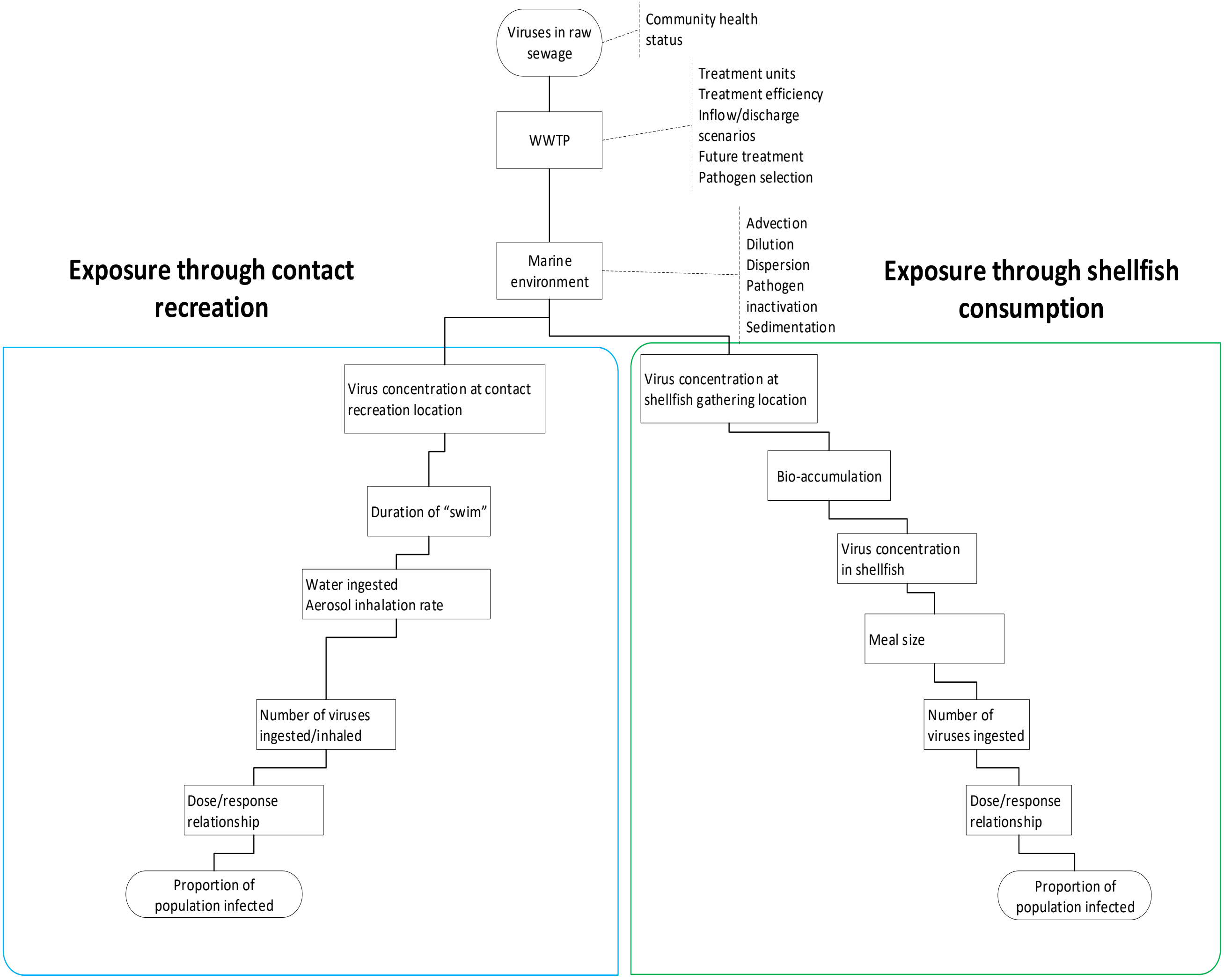

Figure 2-1: Schematic describing the QMRA process.

2.1 Hazard identification - selecting the pathogens of concern

An assessment of pathogens of concern was carried out for the *2012 QMRA Report*, and norovirus was identified as a pathogen of concern. In general terms, for sites impacted by WWTPs discharging well-treated human-derived wastewater, there is widespread agreement that human viruses are the principal aetiological agent causing gastrointestinal disease in water users and consumers of raw shellfish, e.g., Lodder and De Roda Husman (2005) and Sinclair et al. (2009). Norovirus is considered the most significant health risk from environmental water containing a small amount of treated wastewater (Soller et al. 2010; Graciaa et al. 2018). We also have New Zealand specific information about expected levels of norovirus in wastewater and knowledge of the human dose-response relationship between pathogens and infection, which makes calculations of risks using the QMRA approach possible. In addition, focusing on norovirus ensures the results are comparable with the *2012 QMRA Report*.

2.2 Assessing exposure

Assessing exposure requires a description of the pathways in which people could become exposed to pathogens from treated wastewater. The two pathways of concern considered in *this 2023 QMRA*

Report are the unintentional ingestion of surface waters while swimming (primary contact) and the ingestion of raw or lightly cooked shellfish exposed to diluted treated wastewater.

Estimating the dose of pathogens a person may ingest during an event involves considering the concentration of pathogens in diluted wastewater, the volume of water ingested, or the amount of shellfish consumed. Although these quantities are not precisely known, we can approximate their likely values, which are discussed below.

2.2.1 Pathogen concentrations

Measuring pathogen concentrations in diluted wastewater at many sites is difficult to do accurately and generally impracticable. Instead, estimates of pathogen concentrations in raw sewage (influent) combined with WWTP virus removal efficiency are used to estimate the concentration of pathogens in the effluent. Dilution modelling is then used to estimate the concentration of diluted effluent at any point in space and time.

WWTP influent concentrations

Norovirus concentration in raw sewage depends on several factors, including the incidence of disease in the population served by the WWTP and is known to vary over time. Information used or gathered in other QMRA studies (McBride 2011; McBride 2012; McBride 2016; Stott and Wood 2022; Stott et al. 2023) were compared with wastewater norovirus monitoring results provided by NPDC. The NPDC results appeared similar to measurements conducted elsewhere, prompting the adoption of a set of parameters employed in other recent QMRAs. The median virus concentration values used in the *2023 QMRA Report* have a value of 1×10^5 gc/L and is an order of magnitude higher than the median[3] value of 1×10^4 gc/L in the *2012 QMRA Report.*

A "Hockey-Stick" distribution was used to describe a skewed distribution of norovirus influent concentrations. This was defined by minimum, median, and maximum viral concentrations and a break at the 95th percentile to extend the right-hand tail of the triangular distribution (McBride 2005).

WWTP virus removal efficacy

A fundamental purpose of a WWTP is to remove pathogens from influent wastewater. The effect of treatment efficacy on estimated human health risks was assessed assuming four levels of treatment (virus removal) efficacy, ranging from one $\log_{10}$ to four $\log_{10}$ reductions (reflecting 10-fold to 10,000-fold reduction) of virus concentrations from raw sewage at the WWTP inlet to treated sewage discharged from the plant. The four levels of treatment and assumed efficacy were:

- Normal operation with the screening of influent, which passes through bioreactors and clarifiers, then chlorination before discharge to the Tasman Sea, was assumed to result in 2-$\log_{10}$ reduction (100-fold decrease) in norovirus.
- Bypass conditions were assumed to result in 1-$\log_{10}$ reduction (10-fold decrease) in norovirus, where effluent is chlorinated but not fully treated. Bypass operations involve chlorination before discharge, but the effluent does not pass through the bioreactors or clarifiers.

[3] The *2012 QMRA Report* referred to the median as the mode. In practice, median and mode are the same for a Hockey-Stick distribution as defined by McBride (2005).

- Installation of artificial UV disinfection could result in 3 or 4 $\log_{10}$ reductions (1000 to 10,000-fold decrease in norovirus). UV disinfection would be in addition to the normal treatment process.

These levels of treatment and assumed virus reductions are the same as in the *2012 QMRA Report*.

Dilution

When treated effluent is discharged into the aquatic environment e.g., via an outfall, it becomes diluted. Factors like effluent volume, tides, weather conditions and distance from the outfall influence the degree of dilution. Consequently, at any point, dilution levels fluctuate over time. Pathogens may also become inactivated over time, ceasing to pose a risk to human health. However, there is limited information on the inactivation of norovirus, and the existing information ranges from no inactivation to rapid inactivation (Kennedy et al. 2023). So, a precautionary decision was made not to include norovirus inactivation in this QMRA. The *2012 QMRA Report* included a viricidal effect of sunlight inactivating norovirus in the Tasman Sea.

MetOcean estimated the dilution of treated effluent at 31 sites under two climatic conditions, La Niña and El Niño. These estimates allowed for varying effluent outflows. The dilution estimates used the “hybrid approach” to process the dilution modelling results, which has the advantage of conserving high concentration peaks (A. Berthot, MetOcean, pers. comm.), which are often high-risk events. The hybrid approach is discussed in more detail in the section comparing the *2023 QMRA Report* with the *2012 QMRA Report* results.

2.2.2 Volume of water

The volume of water ingested during a swimming event was estimated from ingestion rates (Dorevitch et al. 2011; ESR 2016; Dufour et al. 2017; ESR 2021) and swim duration for children (Schets et al. 2011). Children behave differently from adults around water, often staying in the water longer, submerging their heads more often and swallowing more water than adults (Schets et al. 2011; Dufour et al. 2017). Therefore, the selection of children as the receptor for the QMRA calculations is a precautionary approach. The *2012 QMRA Report* assumed a lower ingestion rate, and there was no difference between adult and child ingestion rates.

2.2.3 Meal size

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.

2.3 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.

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)[4] 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 harmonisation factor 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 are modelled in both aggregated and disaggregated forms. However, previous QMRA modelling e.g., McBride (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 have taken the more conservative approach) – this is consistent with previous QMRA practice (e.g., McBride 2017).

2.4 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 Illness Risk (IIR) per exposure event: a swim or a shellfish feed rather than an individual's cumulative illness risk over a period of time.

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 Tables 2-1 and 2-2. 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.

[4] 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.

Table 2-1: Distributions and inputs for the QMRA – swimming.

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)) aligns with the influent monitoring provided by NPDC to this project.
	Median	$1x10^5$	
	Maximum	$1x10^7$	
Hockey stick, norovirus, Xp unitless		0.95	
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 et al. 2013). Current PCR methods more effectively detect virions, so clinical trial data divided by harmonisation factor.
Wastewater treatment efficacy, Log_{10} virus reduction (LRV)	Unitless	1 - 4	LRVs represent assumed treatment efficacy for scenarios of: Bypass flow, Base conditions, Base conditions and UV (3-log), and Base conditions and UV (4-log).
Exposure parameters - swimming			
Duration of swim (hours)	Minimum	0.2	Program Evaluation and Review Technique (PERT) distribution for a child after Schets et al. (2011).
	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	75	
	Maximum	250	
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).

[5] The dose response for norovirus often used in QMRAs is for NoV GI. Both genotypes NoV GI and NoV GII are found in wastewater. Teunis et al. 2020 also compared NoV genotype challenge studies and outbreaks reporting that the infectivity of NoV GI is higher than NoV GII. We have considered that all noroviruses have similar infectivity as NoV GI as a conservative assumption.

Component	Statistic/parameter	Distributions/comments
The conditional probability of illness given infection NoV(norovirus)[6], unitless	0.6	Pr (ill|Inf) NoV: (Soller et al. 2010), Table 1.

Table 2-2: Distributions and inputs for the QMRA – Shellfish ingestion models.

Component	Statistic/parameter		Distributions/comments
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	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.
	Std. dev.	20.93	

[6] Teunis et al. 2008 predict substantial illness probabilities (among the infected) only at very high doses. As a precautionary measure, this QMRA assumes that the conditional probability of illness given infection is independent of dose, and constant at 0.6 and that the pathogenicity for NoV GI and NoV GII is approximately equal at a given dose (Teunis et al. 2020).

3 Scenarios modelled

Eight scenarios were modelled for recreational primary water contact (Table 3-1) and five for shellfish consumption (Table 3-2). The scenarios covered various levels of wastewater treatment, seasons and climate. There were four levels of wastewater treatment performance for NPWWTP operations:

- Normal levels of treatment, achieving 2 orders of reduction in norovirus.
- A bypass condition, with reduced viral removal achieving 1 order of reduction in norovirus.
- UV treatment, in addition to the normal treatment level, resulted in 3 and 4 orders of reductions in norovirus.

Two climate conditions, La Niña and El Niño, plus two "seasons", summer and a whole year, were considered; summer was assumed to include the months of December, January and February. Rather than model a combined total of 32 potential scenarios, only a subset of potential scenarios were modelled, focusing on El Niño, which was expected to exacerbate onshore winds and drive conditions where the effluent plume may impinge the foreshore.

The scenarios were broadly similar to those in the *2012 QMRA Report*, though the naming of the scenarios modelled has changed for this *2023 QMRA Report*. Case names between the shellfish and swimming scenarios have been harmonised to have the same meaning for both exposure routes.

Table 3-1: Scenarios for primary recreational contact.

Case	Climate	Season*	Treatment
Base 1	La Niña	Summer	Normal
Base 2	La Niña	All Year	Normal
Base 3	El Niño	Summer	Normal
Base 4	El Niño	All Year	Normal
Bypass - summer	El Niño	Summer	Bypass
Bypass	El Niño	All Year	Bypass
UV3	El Niño	All Year	UV
UV4	El Niño	All Year	UV

*Summer was assumed to include the months of December, January and February.

Table 3-2: Scenarios for raw shellfish consumption.

Case	Climate	Season*	Treatment
Base 3	El Niño	Summer	Normal
Base 4**	El Niño	All Year	Normal
Bypass -summer	El Niño	Summer	Bypass
Bypass	El Niño	All Year	Bypass
UV3	El Niño	All Year	UV
UV4	El Niño	All Year	UV

* Summer was assumed to include the months of December, January and February.
** Was called Base 1 in the 2012 QMRA.

The 2023 QMRA modelling only considers current wastewater flows, whereas the *2012 QMRA Report* also considered future flows. Additionally, the current *2023 QMRA Report* discusses climate. However, the *2012 QMRA Report* used a different terminology referring to El Niño climatic conditions as 2002/03 and La Niña climatic conditions as 1998/99.

4 Results

Results for the estimated IIR values for recreational primary contact (swimming) are given in Table 4-1 and Figure 5-1, and those for shellfish consumption are presented in Table 4-2 and Figure 5-2. There are several things to note:

- Shellfish risks are higher than swimming risks for any given location and scenario.
- Bypass conditions result in higher risk than normal (Base) operating conditions.
- Risks vary spatially, tending to be higher in the proximity of the outfall and reducing with distance away from the outfall.

The estimated risks have been compared with the risk thresholds in the Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas (MfE/MoH 2003), which include gastrointestinal illness risks. There are no guideline values for the risks from shellfish harvesting, so the marine recreational water quality guidelines have been used as a comparator. 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:

- 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).

In accordance with the *2012 QMRA Report*, we compare our IIR results with the 1% (A/B) risk threshold. However, this *2023 QMRA Report* does not make statements as to what levels of risk are or should be considered tolerable.

It should be noted that The National Policy Statement for Freshwater Management (NPS-FM) 2020 – Amended 2023 (Ministry for the Environment 2020) has national targets for river and lake suitability for primary contact in the form of swimming. The NPS-FM swimmabity targets are set around average infection risks of 3% or less[7]. The MfE/MoH (2003) freshwater and marine guidelines (*the Guidelines*) differ from the NPS-FM (2020), principally in terms of their health outcomes.

The NPS-FM is based on infection risk from a specific pathogen, *Campylobacter*. In contrast, *the Guidelines* use gastroenteritis illness, caused by any waterborne pathogen, as the health end member. Infection is when pathogens enter the body and multiply, but gastroenteritis illness is a further stage when a body shows symptoms such as diarrhoea, vomiting etc (Drexler 2010). So, the numerical values in *the Guidelines* are not directly comparable with the NPS-FM swimmablity targets. Freshwater targets are not discussed further.

[7] Refer to Table 9 in the NPS-FM (2020).

Table 4-1: IIR(%) results for recreational contact -swimming. The results are arranged from West to East of the outfall.

Site	Bypass	Bypass - summer	Base 1	Base 2	Base 3	Base 4	UV (3-log)	UV (4-log)
W18	0.111	0.123	0.036	0.024	0.016	0.014	0.001	<0.001
W17	0.122	0.114	0.035	0.028	0.016	0.016	0.002	<0.001
W16	0.880	0.535	0.391	0.308	0.083	0.155	0.020	0.002
W15	0.618	0.526	0.180	0.147	0.091	0.109	0.014	0.002
W14	0.426	0.385	0.101	0.077	0.056	0.063	0.008	0.001
W13	0.494	0.457	0.113	0.095	0.076	0.078	0.011	0.001
W12	0.736	0.669	0.194	0.148	0.111	0.118	0.015	0.001
W11	0.641	0.636	0.151	0.117	0.110	0.109	0.016	0.002
W10	0.808	0.773	0.203	0.163	0.120	0.125	0.014	0.001
W9	0.575	0.554	0.136	0.102	0.087	0.090	0.010	0.001
W8	0.575	0.619	0.129	0.089	0.100	0.088	0.012	0.001
W7	0.596	0.648	0.126	0.088	0.098	0.088	0.011	0.001
W6	0.677	0.734	0.140	0.100	0.119	0.105	0.010	0.001
W5	0.743	0.817	0.146	0.110	0.132	0.118	0.015	0.002
W4	0.768	0.856	0.145	0.110	0.138	0.121	0.015	0.001
W3	1.048	1.166	0.237	0.185	0.202	0.179	0.020	0.002
W2	1.836	2.046	0.454	0.383	0.364	0.323	0.047	0.005
W1	1.926	2.021	0.494	0.429	0.369	0.353	0.046	0.006
Inshore	1.663	1.958	0.394	0.312	0.356	0.300	0.043	0.005
E1	1.108	1.176	0.268	0.217	0.205	0.193	0.024	0.003
E2	1.209	1.411	0.241	0.210	0.246	0.210	0.027	0.002
E3	1.740	2.095	0.321	0.282	0.370	0.302	0.041	0.004
E4	1.492	1.684	0.232	0.216	0.290	0.255	0.031	0.003
E5	0.968	1.052	0.141	0.126	0.179	0.161	0.017	0.002
E6	1.164	1.366	0.145	0.141	0.215	0.181	0.020	0.002
E7	1.021	1.179	0.140	0.135	0.192	0.164	0.019	0.001
E8	1.176	1.443	0.141	0.141	0.230	0.186	0.023	0.003
E9	0.656	0.785	0.069	0.074	0.121	0.101	0.012	0.001
E10	0.919	1.046	0.084	0.097	0.167	0.142	0.017	0.001
E11	0.581	0.681	0.048	0.056	0.100	0.084	0.010	0.001
E12	0.198	0.182	0.012	0.016	0.026	0.027	0.003	<0.001

Table 4-2: IIR(%) results for raw shellfish consumption. The results are arranged from West to East of the outfall.

Site	Bypass	Bypass – summer	Base 3	Base 4	UV (3-log)	UV (4-log)
W18	2.316	2.270	0.724	0.697	0.128	0.019
W17	2.247	2.163	0.623	0.581	0.104	0.011
W16	9.624	7.62	2.695	3.818	0.840	0.151
W15	8.318	7.075	2.685	3.332	0.752	0.131
W14	7.413	6.383	2.322	2.778	0.595	0.096
W13	7.781	6.771	2.618	3.073	0.685	0.104
W12	8.442	7.381	2.993	3.466	0.780	0.121
W11	8.087	7.198	2.918	3.257	0.741	0.116
W10	8.835	8.074	3.479	3.799	0.803	0.130
W9	8.433	7.702	3.204	3.494	0.793	0.129
W8	7.609	7.102	2.975	3.021	0.670	0.108
W7	8.340	8.081	3.645	3.544	0.828	0.132
W6	8.772	8.563	3.885	3.750	0.866	0.146
W5	8.688	8.679	3.849	3.650	0.821	0.129
W4	8.669	8.961	3.792	3.521	0.776	0.131
W3	12.495	13.385	6.295	5.786	1.347	0.235
W2	13.311	14.417	7.482	6.770	1.754	0.308
W1	12.862	13.12	6.785	6.516	1.536	0.260
Inshore	13.142	14.869	8.283	7.138	2.200	0.420
E1	12.135	13.651	6.665	5.999	1.546	0.266
E2	13.200	14.786	7.439	6.500	1.629	0.292
E3	12.642	14.404	6.858	5.803	1.295	0.210
E4	14.827	16.034	8.228	7.526	1.761	0.315
E5	13.249	13.995	6.497	6.141	1.366	0.219
E6	11.970	13.027	5.447	4.812	0.975	0.147
E7	11.112	11.895	5.162	4.654	1.005	0.168
E8	11.804	13.123	5.379	4.555	0.906	0.136
E9	11.079	11.999	5.21	4.584	0.972	0.159
E10	10.811	11.597	4.829	4.352	0.870	0.127
E11	7.099	7.693	2.799	2.371	0.448	0.069
E12	4.960	4.481	1.407	1.538	0.291	0.042

5 Discussion and comparison with 2012 QMRA results

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 NPWWTP or faecal contaminants derived from other sources that could be conveyed to the Tasman Sea off the coast of New Plymouth. The results reported here are the potential health risks attributable to norovirus derived from the NPWWTP and are *incremental* health risks associated with a single model pathogen in the NPWWTP discharge. Usually, viruses are the principal pathogen of concern from well-treated wastewater. If, however, the WWTP fails to achieve these reductions, particularly during the Bypass scenarios, non-viral pathogens such as bacteria or protozoa may also be of concern.

5.1 Recreational water contact

The results for recreational water contact show that the risk under normal Base operating conditions is lower than 1% IIR but is greatest close to the outfall (Figure 5-1). Under La Niña conditions, the risks are elevated above El Niño conditions to the west of the Outfall and reduced to the east, but these differences due to climatic influences are less significant than either the levels of treatment or differences between the closest and further sites from the outfall.

In situations of bypass flow, where treatment efficacy is reduced, the risk is elevated above 1% IIR between sites W3 and E10, but less than 5%. The other sites remain at less than 1% IIR. This assessment assumes that bypass flows achieve a 10-fold reduction in pathogen concentration; if this reduction is not achieved, the risks will be higher.

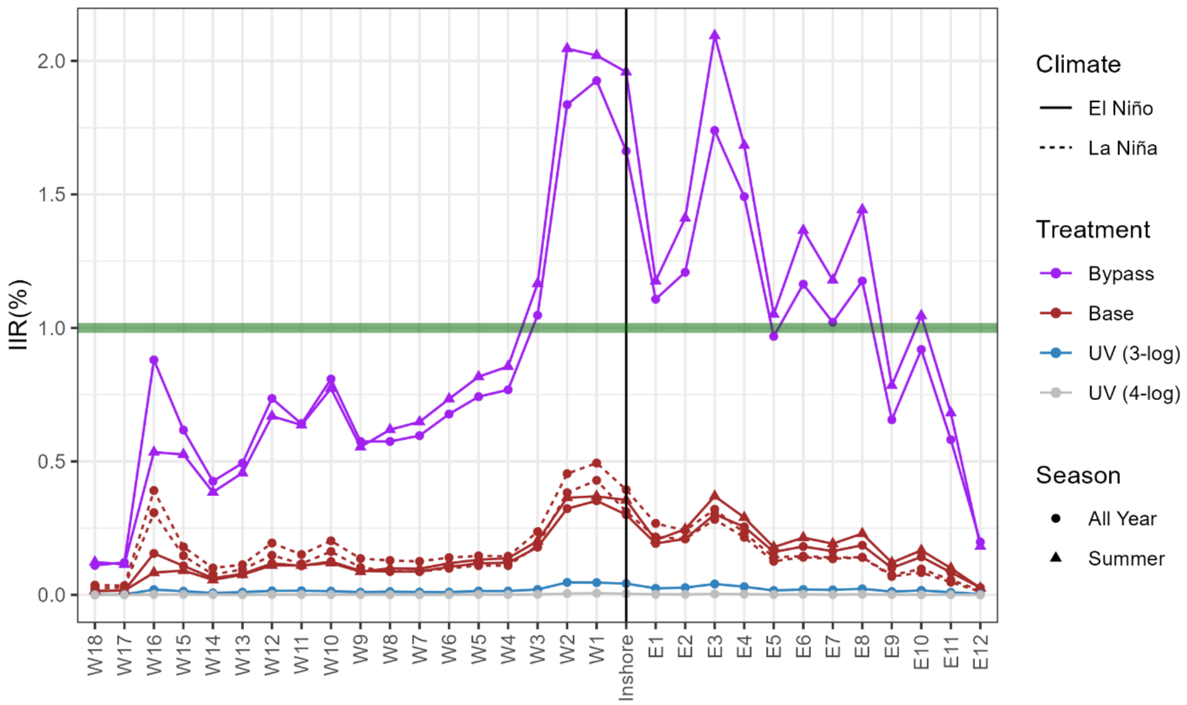

Figure 5-1: IIR(%) results for recreational contact- swimming. The green horizontal line represents an illness risk of 1%.

It is important to note that the risks presented in Table 4-1 and Figure 5-1 are average risks. The process of averaging smooths out both high and low-risk events so that the risk may be higher or lower than the estimated average for any specific event, as shown in Table 5-1, for Bypass conditions. For 50% of the time, the QMRA estimated zero out of 100 people became ill, and 90% of the time, five or fewer people became ill out of 100 people. The risk profile indicates that although occasionally relatively high numbers of people may become ill, these infrequent events elevate the overall average risks.

Table 5-1: Number of cases of illness out of 100 similarly-exposed people for water-contact recreation.

	Scenario for Inshore site for All year and El Niño conditions			
Percentile	Bypass	Base 4	UV (3-log)	UV (4-log)
50%	0	0	0	0
60%	1	0	0	0
70%	1	0	0	0
80%	2	0	0	0
90%	5	1	0	0
95%	9	1	0	0
98%	12	3	1	0
99%	18	6	1	0
100%*	33	24	15	3
Mean – IIR(%)	**1.663**	**0.300**	**0.043**	**0.005**

*Maximum value

In general, it is difficult to predict when there will be an increased risk, such as a disease outbreak in a community, when higher pathogen loads will enter the WWTP. If we could predict these risks, proactive measures could be implemented to mitigate them and diminish the overall risk. Unfortunately, anticipating these high-risk situations before people are exposed to them is typically unfeasible. Consequently, the average risks presented in this *2023 QMRA Report* are the most appropriate estimates of human health risks.

5.2 Consumption of raw and lightly cooked shellfish

The results for the shellfish assessment show that the IIR risk under normal Base operating conditions ranges from slightly greater than 8% at the Inshore and E4 locations to less than 1% at sites W17 and W18. Risks were elevated above 5% between sites W3 and E9, though risks were slightly lower than the 5% threshold for the All Year scenario for sites E6 to E9.

Under Bypass flow conditions, risks were elevated above 5% at all sites except the most distant sites to the East (E12) and the West (W18 and W17). For sites closer to the outfall (W3 to E10) the risks were higher than 10%.

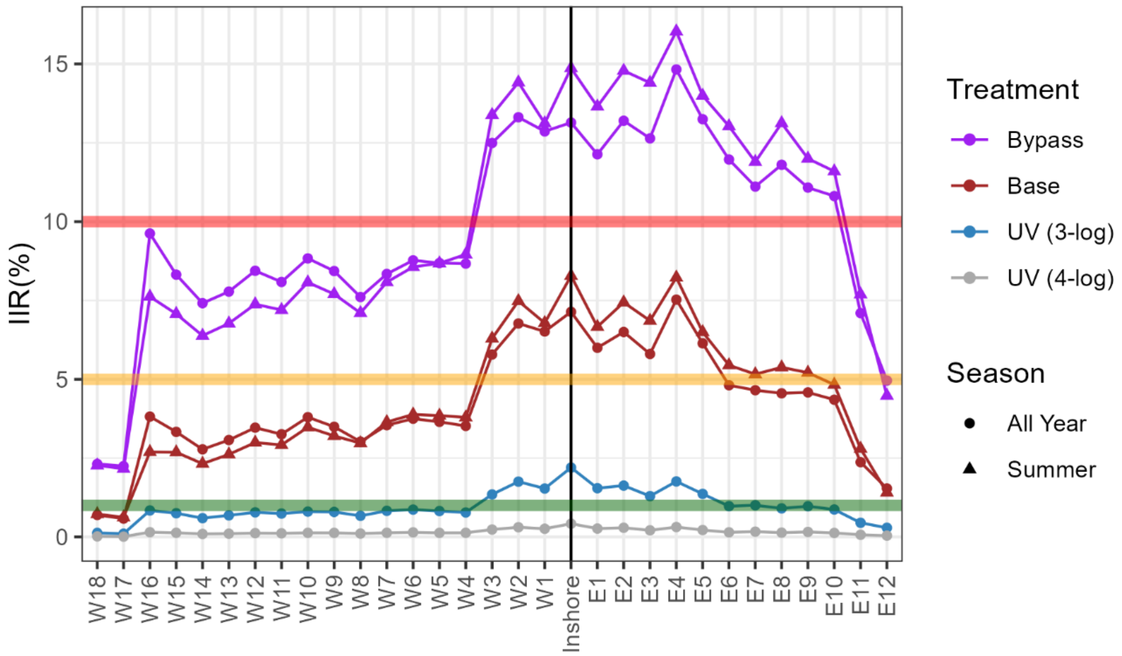

Figure 5-2: IIR (%) results for raw and lightly cooked shellfish consumption. The red, orange and green horizontal lines represent 10, 5, and 1% risk, respectively.

5.3 Comparison of risks between the 2023 and 2012 QMRA Report results

Similar scenarios were run for this (2023) QMRA as the *2012 QMRA Report*. The current *2023 QMRA Report* uses the best available information and updated estimates of:

- Dilution.
- Influent virus concentration.
- Exposure parameters – swimming.
- Dose-response.

Therefore, the current estimates are expected to differ from those in the *2012 QMRA Report*. The shellfish parameters of meal size and bioaccumulation factors remained the same as those used in the *2012 QMRA Report*, as did estimates of treatment efficiency.

Risks for recreational contact for swimming during bypass conditions were higher for the current modelling exercise than the previous 2012 estimates. In the *2012 QMRA Report* 2 sites out of 31 exceed IIR of 1% whereas 11(all year) and 13 (summer) sites exceeded this value in the 2023 report, indicating the risks are more widely distributed along the shore than in the *2012 QMRA Report.*

The risks under base conditions remained under 1% for both *2012* and *2023 QMRA Report* estimates. In some cases, the *2012 QMRA Report* estimates were higher than the *2023 QMRA* estimates, but generally, the overall results under base conditions were similar.

The variation in recreation risks between adjacent sites, particularly during bypass conditions, was more noticeable in the 2023 QMRA than in the *2012 QMRA Report.* Sites E1 and E2 have lower IIR than their adjacent sites, and W16 has elevated risks.

The *2012 QMRA Report* pointed out that while the average risk is less than 1%, there may be times of elevated risk, which may be early to mid-morning after sustained onshore breezes. We have no information from this current analysis to either support or refute this claim.

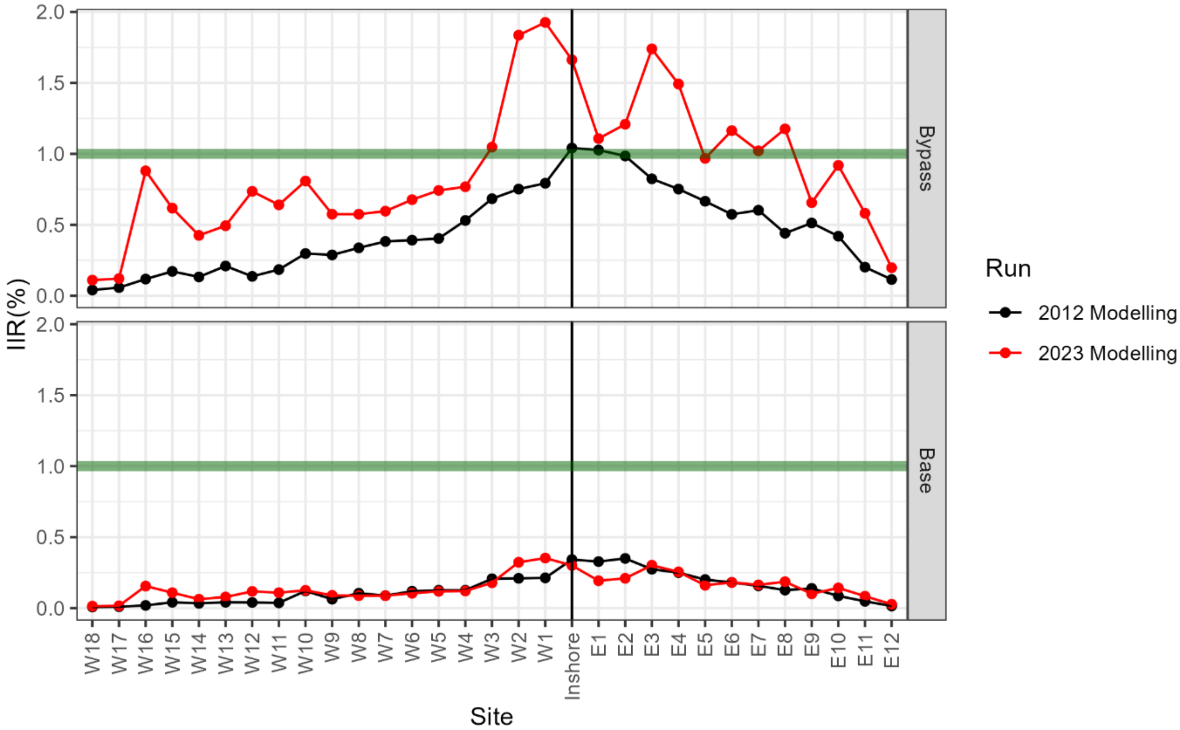

Figure 5-3: Comparison of 2012 and current (2023) QMRA estimated of IIR(%) for Base and Bypass Swimming IIR. For All year and El Niño conditions. The green line represents 1% IIR.

Estimated risks for shellfish consumption were higher in the *2023 QMRA Report* than in the *2012 QMRA Report* for both the base/normal operation (Figure 5-4) and bypass (Figure 5-5) conditions. The exception was site E1 during Bypass conditions, where the 2012 estimate was higher.

The risks in both QMRA modelling runs are elevated at sites close to the outfall. However, the 2012 QMRA shows a constant decrease away from the highest estimated risk at site E1, whereas in this *2023 QMRA Report* the estimates have a less smooth reduction in risk and also appear to plateau between sites W16 and W4.

In both this and the *2012 QMRA Report,* all 31 sites had risks elevated above 1% for shellfish risks during bypass. Under normal operations, IIR for shellfish were above 1% at 21 sites for the *2012 QMRA Report* and 29 sites for the current report.

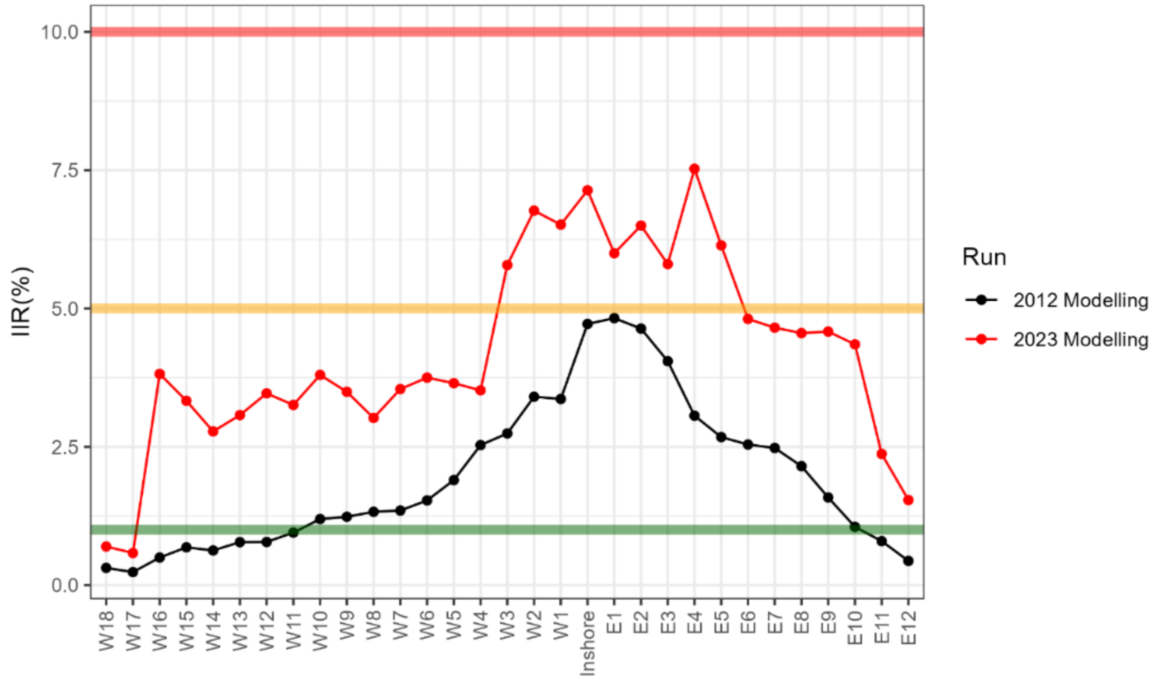

Figure 5-4: Comparison of 2012 and current (2023) QMRA estimated of IIR for shellfish consumption under Base conditions. For All year, under El Niño conditions. Green, orange and red line represent 1, 5 and 10% risks.

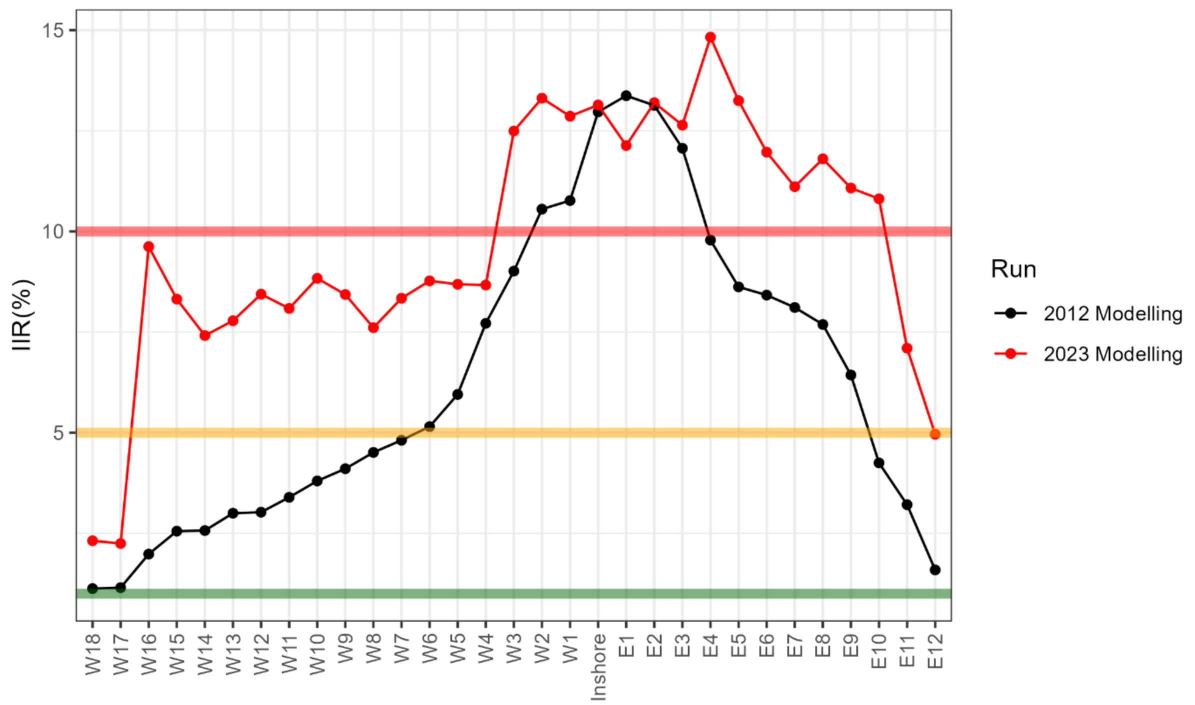

Figure 5-5: Comparison of 2012 and current (2023) QMRA estimated of IIR for shellfish consumption under Bypass conditions. For All year, under El Niño conditions. The green, orange and red lines represent 1, 5 and 10% risks.

As stated earlier, the results were expected to differ between the 2012 and 2023 QMRAs because several factors were updated between the two QMRA exercises. Updating influent virus concentrations from a median value of 1×10^4 to 1×10^5 gc/L between the 2012 and 2023 estimates was expected to increase estimated risks, and an increase in upper limits for volumes and duration of swimming for the 2023 QMRA was expected to do the same. These changes, plus changes to dose-response relationships[8], are likely to result in an overall shift, potentially upward, in the estimated risk. However, these adjustments do not explain changes in the spatial distribution of risks.

The dilution factor is the only factor that exhibits spatial variation in the QMRA. Our understanding of the dilution modelling is based on discussions with MetOcean, including e-mail correspondence with Alexis Berthot of MetOcean. The results of the particle cloud modelling approach used by MetOcean can be processed in two ways to estimate the dilution at any given point. One is a kernel density approach, which smooths out the estimated values. The other is a 2D box-counting approach, which helps retain the variability in the estimates but is not particularly effective for estimating high dilutions (low concentrations). The *2012 QMRA Report* used the kernel density approach, whereas the current work used a hybrid approach that retains the low dilutions estimated by the 2D box-counting approach but can also estimate high dilutions from the kernel density approach. In addition, the dilution modelling for the *2012 QMRA Report* assumed a constant wastewater outflow, whilst the dilution modelling for the *2023 QMRA Report* took into account variable wastewater discharge at the outfall[9].

Dilution estimates provided by MetOcean for each site are presented in Figure 5-6. The estimates are normalised against a nominal concentration of particles at the outfall ($C_{Site}/C_{Outfall}$), with higher ratio values indicating lower dilution. As dilution varies over time due to wind and tide, for example, the 95th percentile values are shown to represent situations when dilutions are low, and the associated risks tend to be higher. In both the 2012 and 2023 dilution modelling, the least dilute values are close to the outfall, and dilution increases to the east and west away from the outfall. For the 2012 dilution modelling, there is a steady increase in dilution to the west, whereas the 2023 modelling shows a slightly different pattern. The 2023 pattern is less smooth than the *2012 QMRA Report*, with the 2023 dilutions plateauing between sites W16 and W4. The variability in dilution explains why the risks at E1 and E2 are lower than the neighbouring sites for swimming risks under bypass conditions.

Overall, the 2023 modelling approach for estimating the dilution of treated wastewater is more precautionary than the 2012 approach and results in lower levels of dilutions than were estimated for the *2012 QMRA Report*. In addition, the spatial patterns of risk for the current *2023* and *2012 QMRA Reports* show distinct similarities with their respective dilutions shown in Figure 5.6, with a plateauing (levelling off) of the risks between sites W16 and W4 in the current report, but risks falling steadily with distance in the *2012 QMRA Report*.

[8] The 2012 QMRA report used an approach to model the inherent uncertainty in the Norovirus dose-repose model. Modelling uncertainty in the dose-response model has not been done in recent QMRA, such as McBride (2017), which uses the approach laid out by the World Health Organisation (2016) and followed in this project.

[9] *2012 QMRA Report* assumes a mean daily discharge of 22,000 m^3/day, the median flow for the 2023 work 31,300 m^3/day peaking at 80,000 m^3/day (Alexis Berthot, pers. comm.).

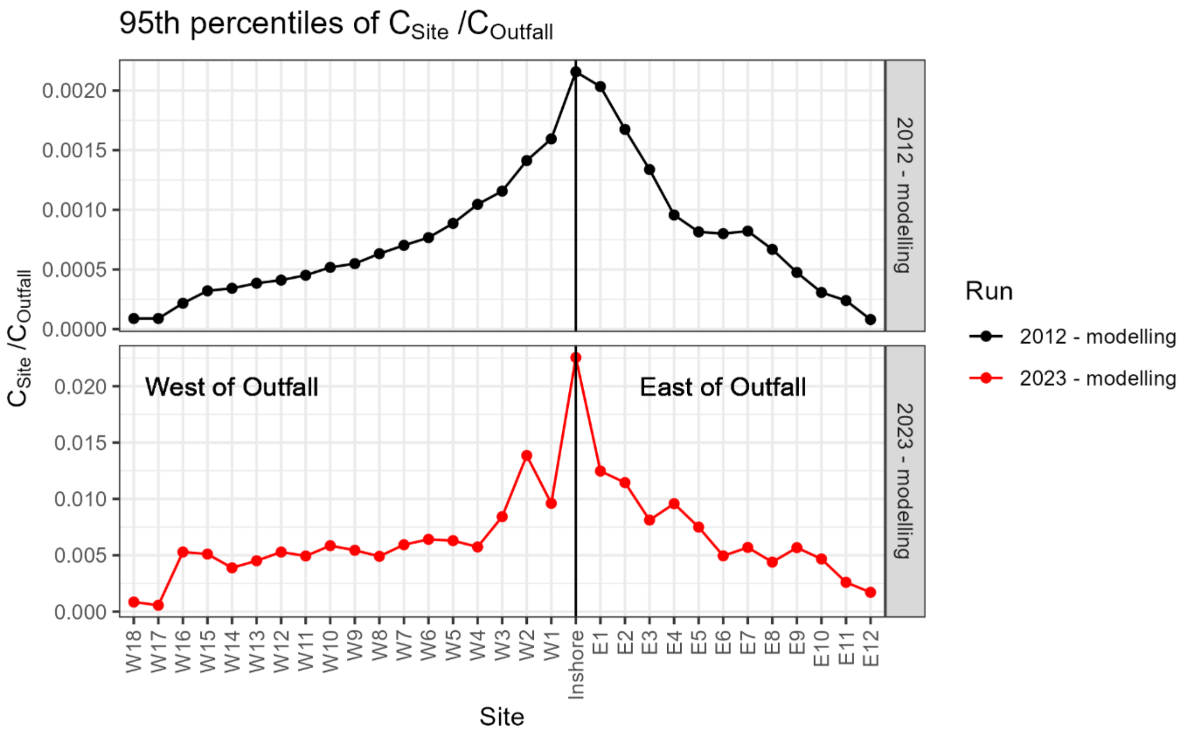

Figure 5-6: Relative dilutions under El Niño conditions for 2023 and 2012 modelling runs. The key issues are that the 2012 modelling displays a smooth reduction in dilution, whereas the 2023 estimates are "noisier" and level off to the west of the outflow. Note the difference in the scales for the y-axis, which suggests the treated wastewater in the marine receiving environment and along the coastline is less dilute than the 2012 estimates.

6 Summary

Quantitative Microbial Risk Assessment modelling has provided estimates of the potential risk of gastrointestinal illness to individuals following swimming in, or the consumption of raw or undercooked shellfish harvested from, the New Plymouth shoreline. The predicted risks are attributable to residual noroviruses in wastewater discharged from the NPWWTP only and do not include the potential risks associated with pathogens arising from other sources.

Human health risks were shown to vary spatially, with the greatest risks at sites close to the outfall discharge site and lower risks further away. In the case of bypass flow, the estimated IIR ranged from approximately 0.1 to 2.1% for primary contact recreation (swimming) and 2.3 to 16.0% for shellfish consumption. The risks were lower during normal operation (Base conditions), ranging from 0.02 to 0.49% for primary contact recreation (swimming) and 0.7 to 8.2% for shellfish consumption. Risks were further reduced when UV treatment was considered, ranging from 0.003 to 0.047 for swimming and 0.128 to 2.200% for shellfish consumption for 3 log reductions. In the case of 4 log reductions, the risks ranged from <0.001 to 0.005% for swimming and 0.019 to 0.420% for shellfish consumption.

The modelled scenarios revealed that factors such as the summer season compared to the entire year and climatic variations such as La Niña and El Niño influenced the estimated risk. However, these factors were less important in influencing risk compared to the level of treatment or site location.

The risks outlined in this *2023 QMRA Report* are higher compared to those in the *2012 QMRA Report*, especially those associated with bypass events. Moreover, the elevated risks are more widely distributed along the shore. The increase in estimated risks is primarily due to updated modelling parameters that better reflect our current understanding of risks, rather than fundamental changes to the actual risks from swimming or shellfish consumption.

7 Glossary of abbreviations and terms

BAF	Bioaccumulation Factor
Conditional probability of illness	The probability that an individual, already infected with norovirus will proceed to exhibit symptoms of illness.
gc	genome copy - Genome fragment for the pathogen captured by the qPCR methodology.
ID50	The dose required to cause infection (or illness, as appropriate) in half of an exposed group (assuming the underlying dose-response model to be true and applicable to that group).
IIR	Individual Illness Risk.
Illness	Evidence of infection by a particular pathogen accompanied by disease symptoms (vomiting, fever,…)
Infection	Host shedding of the pathogen in question. Infected individuals may or may not proceed to exhibit illness if they do not they are in the “asymptomatic infection” state.
QMRA	Quantitative Microbial Risk Assessment.
PERT distribution	The Program Evaluation and Review Technique or PERT distribution is a continuous statistical distribution is defined by minimum, mode and maximum values. It is used to model values obtained from expert opinion.

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Appendix A Site names and location details

Table A-1: Site names and location details for 31 risk assessment sites.

Site	Longitude	Latitude
Inshore	174.1134	-39.0322
E1	174.1194	-39.0313
E2	174.1226	-39.0281
E3	174.1271	-39.0254
E4	174.1326	-39.0193
E5	174.1374	-39.0156
E6	174.1411	-39.0166
E7	174.1457	-39.0142
E8	174.1471	-39.0184
E9	174.1585	-39.0133
E10	174.1742	-38.9969
E11	174.1858	-38.992
E12	174.1981	-38.9874
W1	174.1046	-39.0338
W2	174.1060	-39.0347
W3	174.1028	-39.0374
W4	174.1010	-39.0394
W5	174.0982	-39.0427
W6	174.0960	-39.0448
W7	174.0946	-39.046
W8	174.0921	-39.0475
W9	174.0849	-39.049
W10	174.0782	-39.0493
W11	174.0752	-39.0544
W12	174.0695	-39.0547
W13	174.0623	-39.053
W14	174.0580	-39.0549
W15	174.0536	-39.056
W16	174.0406	-39.0588
W17	174.0198	-39.061
W18	174.0180	-39.0673