Science for Communities

SCREENING QUANTITATIVE MICROBIAL RISK ASSESSMENT (QMRA): HIHI WASTEWATER TREATMENT PLANT

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EXECUTIVE SUMMARY

The current QMRA considers risks to human health from the discharge of wastewater from the Hihi wastewater treatment plant (WWTP) into the Hihi Stream and Hihi Beach area of Doubtless Bay. These receiving waters will also be impacted by other, mainly diffuse, sources of contamination. These other sources are not considered in the current QMRA. The QMRA is a screening exercise and considers only the pathogen shown to be associated with the highest levels of risk in other QMRAs (norovirus) and risks from primary contact recreation (swimming) and raw shellfish consumption.

Risks were assessed at six locations: two near the mouth of the Hihi stream onto Hihi beach and four at points within the Doubtless Bay area. Risks were assessed for three discharge rates, (low, consent, or peak discharge), at two levels of river outflow (mean flow and mean annual low flow (MALF)), and at four levels of viral removal by the WWTP (1, 2, 3 and 4 $\log_{10}$). Risks were compared to the risk levels for the attribute bands in the *National Policy Statement for Freshwater Management*. The attribute bands are not only applicable to freshwater environments, but also estuarine and coastal receiving environments. While the national policy statement is not applicable to risks associated with shellfish consumption, the risk cut-offs for the attribute bands were used generically to classify risks associated with voluntary recreational activities.

At a minimal 1 $\log_{10}$ removal of noroviruses by the Hihi WWTP risks associated with swimming may exceed 1% at one modelled location (the point at which the discharge meets Hihi Beach), equating to a fair classification with respect to recreational water quality at this location and good to excellent classification at all other assessment sites. However, at 3 $\log_{10}$ viral removal the recreational water classification would be excellent at all sites.

At the expected 3 $\log_{10}$ removal rate, the risks of illness due to raw shellfish consumption were <3% at all sites under all scenarios and <1% except to peak flow scenarios at the point the discharge meets Hihi Beach.

This assessment has taken a conservative approach at a number of points, and it is expected that risks, for the majority of the time, will be lower than those estimated in the current QMRA.

1. INTRODUCTION

1.1 BACKGROUND

The Far North District Council (FNDC) is preparing technical documents to support the resource consent application to renew the discharge of wastewater from the Hihi Wastewater Treatment Plant (WWTP) operation. The existing resource consent authorises the discharge of treated wastewater into the Hihi Stream, which then flows into Hihi Beach at Doubtless Bay. The current resource consent expires on 30 November 2022.

The Hihi WWTP is made up of an activated sludge reactor, clarifier, sand filters and UV treatment. The treated wastewater then passes through a constructed wetland, which flows into the Hihi stream. The discharge to the Hihi Stream is typically about 20-40 m^3/day (about 0.00023-0.00046 m^3/s), with a consented volume of up to 250 m^3/day (about 0.0028 m^3/s). At the discharge point, the mean annual flow in the Hihi Stream is 0.0082 m^3/s, with a mean annual low flow (MALF) of 0.0016 m^3/s. Based on these flows the expected dilution of wastewater in the Hihi Stream will be no more than 50-fold.

The approximate river distance from the WWTP discharge point to the stream mouth is 670 m. Hydrodynamic modelling work completed by MetOcean Solutions indicates that further dilution is considerable once the discharge enters Doubtless Bay (MetOcean Solutions, 2021).

FNDC require a technical assessment which reports on the likely risk of the discharge to public health, considering the risks from primary contact recreation (swimming) and the consumption of raw shellfish.

1.2 CURRENT ASSESSMENT

The screening QMRA presented in the current report adopted the same general approach to that carried out in QMRA conducted elsewhere in New Zealand but abbreviated to fit the screening nature of the exercise.

Based on other recent New Zealand QMRAs, including one completed for FNDC in relation to the East Coast (Taipa) WWTP (Cressey and Armstrong, 2020), the technical assessment will consider the risks associated with norovirus in discharged wastewater. Norovirus has consistently been the pathogen representing the greatest human health risks in recent QMRAs. The assessment includes two components:

- Review of available information on norovirus removal by the processes in place at the Hihi WWTP.
- Estimation of the risk of illness due to norovirus from primary contact recreation (swimming) at agreed locations within Doubtless Bay and risks from consumption of raw kaimoana (shellfish) harvested at or near the same locations. The agreed locations are shown in Figure 1.

2. METHODS

Quantitative Microbial Risk Assessment (QMRA) consists of four basic steps:

1. Hazard identification. Selection of the hazard(s). For microbial risk assessments the hazard(s) will be bacterial, viral or protozoan human pathogens
2. Exposure assessment. Estimation of exposure to the pathogen(s) at selected sites through selected human activities
3. Hazard characterisation. Characterisation of the dose-response relationship for the pathogen(s)
4. Risk characterisation. Characterisation and communication of the health risks.

QMRA uses statistical distributions (parametric or non-parametric) for the inputs to the assessment and combines these distributions using Monte Carlo simulation modelling. Modelling involves repeated sampling from the distributions and means that any plausible 'what-if' scenario will be included within the analysis. This approach is particularly useful, as the majority of the risk is caused by combinations of inputs toward the upper extremes of the input distributions, the combined effects of which are unlikely to be detected when using averages.

2.1 HAZARD IDENTIFICATION

Based on previous New Zealand wastewater discharge QMRAs, the current study only considered risks associated with norovirus, as the likely 'worst case' microbial pathogen.

Risks associated with wastewater-contaminated water include two types of infection and illness:

- Gastrointestinal disease, due to:
  - ingestion of water during recreational water-contact, and
  - consumption of raw shellfish, gastropod or finfish flesh.
- Respiratory ailments, due to inhalation of aerosols formed during contact recreation, such as water skiing, surfing or by nearby breaking waves.

Noroviruses have only been associated with gastrointestinal disease. Due to the screening nature of the current exercise, only risks of gastrointestinal disease due to primary contact recreation (swimming) and consumption of raw shellfish harvested from the affected environment were considered.

2.2 EXPOSURE ASSESSMENT

Exposure refers to the dose of some agent that is ingested, absorbed, or inhaled during a specified period. For microbial pathogens, adverse health effects usually occur in an acute time frame and are generally considered to be due to a single exposure event. In the current QMRA, the exposure events considered are a single day of water-contact recreation in wastewater-affected water or a single meal of raw shellfish harvested from the affected environment.

2.2.1 Selection of assessment sites

Six representative assessment sites were selected for the screening assessment. Sites were selected encompass accessible locations in Doubtless Bay on or adjacent to the Hihi Beach area. The six sites are described in Table 1.

Table 1. Assessment locations for Hihi WWTP QMRA

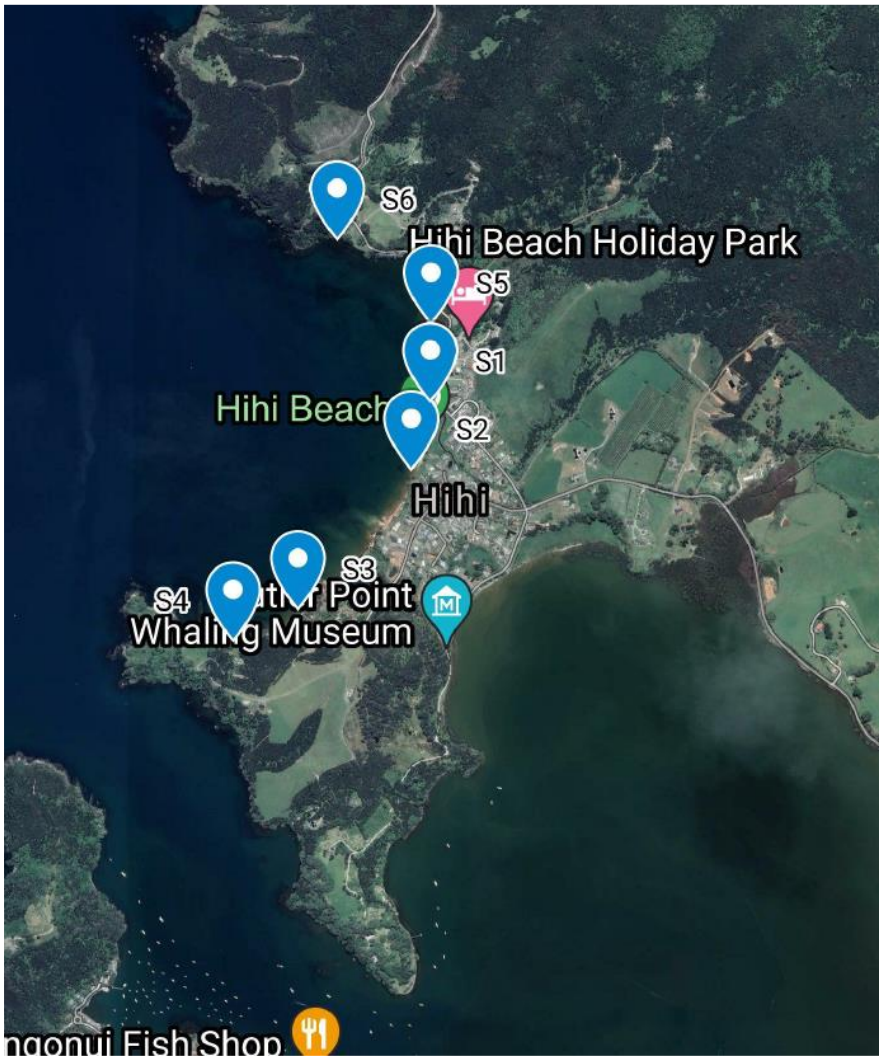
Site	Location	Longitude[a]	Latitude[a]
S1	Mouth of Hihi Stream	173.5382862	-34.97068628
S2	150m South of Hihi stream mouth	173.5373411	-34.97252694
S3	Hihi beach 750m south of mouth beyond headland	173.5332178	-34.97639849
S4	Hihi beach 920m south of mouth beyond 2 headlands	173.5316477	-34.97680286
S5	Hihi beach 300m north of mouth	173.5380502	-34.96860513
S6	Hihi beach 600m north of mouth, 400m east of S5	173.5350678	-34.96668535

[a] Based on World Geodetic System WGS84

Figure 1 shows the location of the assessment sites.

The viral concentrations at the sites of interest are a function of the viral concentration of discharged wastewater, dilution between the point of discharge and the site of interest and viral inactivation during the period between discharge and reaching the site of interest. The viral concentration of discharge wastewater is a function of the viral concentration of WWTP influent and the reductions in viral concentrations achieved by the WWTP.

Figure 1. Location of assessment sites for Hihi WWTP wastewater discharge



2.2.2 Viral concentrations in receiving waters

Viral influent concentrations used in the current QMRA

Recent QMRAs carried out in New Zealand have used 'standardised' viral concentrations for influent (Cressey and Armstrong, 2020; McBride, 2016; McBride and Hudson, 2016; Oldman and Dada, 2020). This approach models the viral concentrations as a custom 'hockey-stick' distribution, defined by minimum, median and maximum viral concentration. The term hockey-stick comes from the fact that the custom distribution has a break at the 95th percentile and an extended triangular right-hand tail.

In the absence of specific information on the influent to the Hihi WWTP, this approach was used for the current QMRA. The rationale for this approach is that, in any community the average proportion of people with viral infections will be similar, over time. While the distribution of viral concentrations in influent from a small community are likely to be more variable day-to-day than for a large community, over time the distribution will be similar

Both norovirus GI and GII are infectious to humans. However, results from analyses of New Zealand wastewaters suggest that GI concentrations are typically at least one order of magnitude less than GII concentrations (Cressey and Armstrong, 2020).

Based on the complete body of New Zealand data and the review of Eftim *et al.* (2017), the concentration of norovirus GII was modelled with a median of 1.0E+5 genome copies/L, with a minimum and maximum of 100 and 3.0E+7 genome copies/L. This distribution of norovirus concentrations is the same as used previous for a QMRA in the Far North region (Cressey and Armstrong, 2020).

Viral removal at the WWTP

Little specific information is available on the removal of viruses by wastewater treatment processes in New Zealand. While some sources report on the viral content of influent and effluent from the same plant (McBride, 2016; Norquay, 2017; TDC, 2020), no attempt has been made to account for the time it takes the wastewater to progress through the plant and comparisons are not strictly comparing the same wastewater.

A limited number of studies in the scientific literature have considered viral removal during wastewater treatment processes. Studies on removal of norovirus through secondary wastewater treatment have reported log reductions in the range from no significant removal to removal of greater than 3 $\log_{10}$ (Campos *et al.*, 2016; El-Senousy and Abou-Elela, 2017; Ito *et al.*, 2016; Lee *et al.*, 2019; Montazeri *et al.*, 2015; Prado *et al.*, 2019; Qiu *et al.*, 2015; Simhon *et al.*, 2019; Symonds *et al.*, 2014; van den Berg *et al.*, 2005). The mean reduction across these studies is about 1.5 $\log_{10}$. UV treatment has generally been reported to result in modest further reductions in norovirus concentrations, in the range 0.2-0.8 $\log_{10}$ (Barrett *et al.*, 2016; Campos *et al.*, 2016; Qiu *et al.*, 2015), while constructed wetlands have been reported to remove greater than 2 $\log_{10}$ norovirus (Rachmadi *et al.*, 2016).

While the degree of removal of enteric viruses by the Hihi WWTP is unknown, it seems likely that the combination of treatments will result in viral removal rates greater than 2 $\log_{10}$ and probably greater than 3 $\log_{10}$. Due to uncertainty in this aspect of the QMRA, the model was run for four viral reduction levels (1, 2, 3 or 4 $\log_{10}$), to determine what level of viral reduction is required to achieve an acceptable level of swimming or seafood consumption risk.

Wastewater dilution

MetOcean Solutions used the open-source model SCHISM[1] to provide high-resolution modelling of the tidal/ stream discharge hydrodynamics for the Hihi WWTP wastewater discharge (MetOcean Solutions, 2021). Contaminant dilution was modelled using the Eulerian tracer technique. The tracers are assumed to be neutrally buoyant and not decay.

Dilution data are presented as concentrations of a putative contaminant, constantly discharged at a concentration of 1 mg/L. MetOcean Solutions generated dilution data as a time series (20-minute intervals) over one full month (neap-spring tide cycle).

Dilution were modelled for six scenarios:

- Mean river flow (0.0082 m^3/s); Low discharge rate (40 m^3/day, 0.0005 m^3/s)
- Mean river flow; Consent discharge rate (250 m^3/day, 0.0028 m^3/s)
- Mean river flow; Peak discharge rate (1600 m^3/day, 0.0185 m^3/s)
- Mean annual low flow (MALF, 0.0016 m^3/s); Low discharge rate
- MALF; Consent discharge rate
- MALF; Peak discharge rate

Mean and MALF flows for the Hihi River were taken from the National Institute of Water and Atmospheric Research's (NIWA) *NZ River Maps*.[2]

The simulations of tracer dilutions were run over a full month (two spring-neap tidal cycles) to describe the tidal flow variation effect on the plume within the Hihi Beach and Doubtless Bay area. The output time series of tracer concentrations at the six agreed assessment sites (S1-S6) were provided to ESR and were used in the QMRA model as an empirical distribution. That is, the QMRA model sampled (with replacement) tracer concentrations at random from the full set of tracer concentrations. Summary statistics for the tracer concentration (dilution) for the six selected sites and each of the six scenarios is included in Table 2.

Table 2. Summary for dilution of a theoretical tracer (1 mg/L) at six selected sites in the course of the Hihi WWTP discharge

Site code	Site	Concentration of tracer, mean (95th percentile)[a] (mg/L), Mean river flow/MALF river flow		
		Low Discharge	Consent Discharge	Peak Discharge
S1	Mouth of Hihi Stream	2.2E-4 (6.0E-4)/ 2.4E-4(5.5E-4)	1.3E-03(3.1E-3)/ 8.3E-4(1.6E-3)	5.6E-3(1.3E-2)/ 5.0E-3(9.9E-3)
S2	150m South of Hihi stream mouth	1.6E-6 (7.2E-6)/ 1.5E-5(2.4E-5)	2.5E-5(9.4E-5)/ 9.4E-5(1.6E-4)	4.5E-4(1.0E-3)/ 8.4E-4(1.2E-3)
S3	Hihi beach 750m south of mouth beyond headland	3.8E-8(4.9E-8)/ 6.9E-7(1.5E-6)	2.3E-7(2.9E-7)/ 4.1E-6(8.5E-6)	1.2E-6(1.9E-6)/ 4.6E-5(8.0E-5)
S4	Hihi beach 920m south of mouth beyond 2 headlands	3.8E-8(4.9E-8)/ 5.0E-7(1.2E-6)	2.3E-7(2.9E-7)/ 3.0E-6(6.7E-6)	1.2E-6(1.5E-6)/ 3.3E-5(6.5E-5)
S5	Hihi beach 300m north of mouth	2.2E-5(4.2E-5)/ 1.1E-5(1.5E-5)	1.3E-4(2.2E-4)/ 6.7E-5(8.4E-5)	6.5E-4(9.9E-4)/ 5.9E-4(6.9E-4)
S6	Hihi beach 600m north of mouth, 400m east of S5	6.4E-6(1.4E-5)/ 2.2E-6(3.1E-6)	3.6E-5(7.1E-5)/ 1.4E-5(1.9E-5)	1.8E-4(3.5E-4)/ 1.4E-4(1.6E-4)

MALF: mean annual low flow

[a] Concentrations are in scientific notation; 1.0E-5 = 1.0 x 10^{-5} = 0.00001

[1] http://ccrm.vims.edu/schismweb/ Accessed 1 October 2020

[2] https://shiny.niwa.co.nz/nzrivermaps/ Accessed 10 March 2022

Viral inactivation after discharge

A proportion of viruses released into the environment will be inactivated (attenuated) between the point of release and the point of contact with humans. Exposure to sunlight and the salinity of the estuarine water or seawater will be contributing factors (Liang *et al.*, 2017).

Survival of viruses (human adenovirus and murine norovirus) in river water was shown to be temperature dependent (longer survival at lower temperatures) (Ibrahim *et al.*, 2019). Inactivation was minimal up to seven days, irrespective of temperature.

Pinon and Vialette (2018) reported similar findings, the time for a 1 $\log_{10}$ reduction in viral concentrations of 5.25 days for MS2 bacteriophage in river water at 15°C.

Liang *et al*. (2017) examined attenuation of human adenovirus, as influenced by salinity and light intensity. Attenuation was expressed as the time in hours for a 1 $\log_{10}$ reduction in viral concentration, as measured by target DNA. It should be noted that actual attenuation could be greater, as DNA may still be present even though viruses are no longer infective. At the maximum salinity (27.2 ppt) and sunlight intensity (0.65 kW/m^2) examined, time for a 1 $\log_{10}$ reduction for adenovirus was 3.3 hours. Experiments were carried out at a water temperature of 26°C.

Considerably longer 1 $\log_{10}$ reduction times (9.4 days) for human adenovirus were reported from experiments in seawater microcosms, maintained at 14-18°C and exposed to natural sunlight in a diurnal cycle (Ahmed *et al.*, 2014). Similarly, virtually no decrease in adenovirus concentrations was observed in seawater maintained in the dark at 20°C for 24 hours (Carratalà *et al.*, 2013).

Recombinant adenovirus and murine norovirus were agitated in seawater tanks (16°C, salinity and light intensity not reported) for 24 hours (Garcia *et al.*, 2015). Only minor decreases in adenovirus concentrations (0.37 $\log_{10}$) were reported. Greater decreases in murine norovirus concentrations (1.12 $\log_{10}$) were reported.

Norovirus GI and GII were exposed to simulated summer (17°C, 20 MJ/m^2 per day irradiance) and winter (10°C, 5 MJ/m^2 per day) conditions in seawater (Flannery *et al.*, 2013). Times for 1 $\log_{10}$ reduction for GI/GII were 21.5/20.5 hours under summer conditions and 89.3/83.9 hours under winter conditions.

Hihi WWTP discharge information is available on flow rates and river width. However, no information on linear flow velocities was found. Given that viral attenuation appears to be minimal over the course of several hours, it is likely that limited viral attenuation in Hihi WWTP wastewater will occur between discharge and human exposure. It was conservatively assumed that no attenuation would occur.

2.2.3 Exposure factors

For all exposure routes considered, the exposure dose is the simple product of the concentration of viruses in the exposure media (water or shellfish) and the ingested amount of the exposure media. Parameters defining the amount of water ingested are termed exposure factors. Relevant exposure factors are discussed and defined in the following sections.

Primary contact recreation (swimming)

Rate of water ingestion

The current QMRA considered risks associated with primary contact recreation downstream from the wastewater discharge point. In this context, the most likely form of primary contact recreation will be swimming.

No information is available on water ingestion during swimming in New Zealand. The most commonly used water ingestion information for environmental QMRAs was derived from a pilot swimming pool study in the USA (Dufour *et al.*, 2006). The volume of water ingested was estimated by measuring the concentration of the chlorine-stabilising chemical cyanuric acid in the urine of swimmers and in the pool water. Cyanuric acid passes through the human body without undergoing metabolic changes. The full study by the same research group has subsequently been published (Dufour *et al.*, 2017). Summary data from this study are included in Table 3.

Table 3. Water ingestion parameters from the swimming pool survey of Dufour et al. (2017)

	Water intake description		
Age group	**Geometric mean (95%CI) (mL/hr)**	**Maximum (mL/hr)**	**Mean duration (minutes)**
Children	23.9 (17-33)	153	95.9
Teenagers	23.7 (19-30)	287	55.8
Adults	12.4 (11-14)	333	50.3

While not included in the scientific paper, ESR have obtained the raw data from this study and, for all age groups, the minimum ingested volumes are about 1 mL or 0.6-1.2 mL/hr (Dr Alfred Dufour, USEPA, personal communication).

A search of the scientific literature did not identify any studies subsequent to the Dufour study on the amount of water ingested during primary contact recreation. The information from the Dufour study continues to be the best available.

The Dufour *et al*. (2017) study was carried out in swimming pools, while the current QMRA considers a largely marine recreational environment. Schets *et al.* (2011) compared self-reported volumes of water ingested during swimming in a swimming pool, in freshwater and in seawater. For children (<15 years), the highest amount of water was ingested during swimming in a pool (mean = 51 mL/event), compared to freshwater (37 mL/event) and seawater (31 mL/event). This suggests that the Dufour data may be conservative for water ingestion during riverine/estuarine swimming, which is appropriate for risk assessment.

Duration of contact recreation events

In the absence of New Zealand specific data, the study of Schets *et al.* (2011) provides the most applicable data for the current QMRA – actual measurements of the duration of swimming in freshwater or seawater. The current QMRA includes freshwater, estuarine and seawater locations, a conservative decision was made to base the duration of swimming on the longer freshwater durations from the Schets *et al.* study. This study also provides details of normal distributions fitted to the natural log of the distribution of swimming duration times. For seawater swimming, the parameterised distributions are normal ($\mu = 3.8$, $\sigma = 0.8$) for children, normal ($\mu = 3.5$, $\sigma = 0.85$) for adult females and normal ($\mu = 3.2$, $\sigma = 0.94$) for adult males. The units for these parameters are the natural log of minutes. For example, the mean of the distribution for children is $e^{3.8} = 44.7$ minutes.

While it could be argued that swimming habits may differ in New Zealand compared with the USA and the Netherlands, there is no evidence to support this argument.

Water ingestion – summary

Children spend more time in the water during contact recreation and ingest water at a higher mean rate than adults. Therefore, the current QMRA conservatively based risk estimates on children swimming at specified points within the Doubtless Bay. Water ingested was determined as the product of the ingestion rate and the recreation duration, with the ingestion rate represented by a beta pert distribution with minimum = 0.6 mL/hr, mean = 23.9 mL/hr and maximum = 153.3 mL/hr. The duration of exposure was represented by a distribution whose natural log was normally distributed with μ = 3.8 and σ = 0.8. The exponential of this distribution is the duration of recreation in minutes.

As the normal distribution used for the duration of swimming events has no maximum (or minimum) value, there is potential for the combination of the distributions for water ingestion rate and swimming duration to produce an unrealistically high estimate of the amount of water ingested during swimming. Ingestion of up to 800 mL of water has been reported for competitive swimmers (Allen *et al.*, 1982) and this value was used as an upper limit on the amount of water ingested during any swimming event.

Shellfish consumption

Accumulation of viruses by shellfish

Bivalve molluscan shellfish feed by filtering large volumes of seawater. This means that they may bioaccumulate contaminants, including viral pathogens. QMRA involving shellfish consumption usually try to account for bioaccumulation of pathogen particles by the shellfish (McBride and Hudson, 2016). Limited information is available on the rate of virus accumulation by shellfish. Previous New Zealand viral QMRAs have used bioaccumulation factors (BAFs) derived by Burkhardt and Calci (2000) for the enteric virus surrogate, F+ coliphage in oysters (*Crassostrea virginica*). The bioaccumulation factor is the concentration of the organism in shellfish flesh, divided by the concentration in the surrounding water. The study of Burkhardt and Calci (2000) demonstrated that viral BAFs were highest during the autumn-winter (mean 49.9, standard deviation 7.4) and relatively modest in spring-summer (mean 2.9, standard deviation 0.5). Previous New Zealand QMRAs used the autumn-winter bioaccumulation figures as a conservative estimate of bioaccumulation by all shellfish of all viruses (McBride *et al.*, 2005; McBride, 2014; McBride, 2016; McBride and Hudson, 2016; URS New Zealand, 2013).

In the study of Burkhardt and Calci (2000) the period of high viral bioaccumulation occurred at seawater temperatures of approximately 15-20°C, with low viral bioaccumulation occurring at seawater temperatures >20°C. Average seawater temperatures in Northland vary between approximately 16 and 20°C (NIWA, 2013). On this basis, the approach used in previous New Zealand QMRAs of using cold season BAFs appears appropriate.

It should be noted that other studies on virus accumulation by bivalve shellfish have shown much lower rates of bioaccumulation. Amoroso *et al.* (2020) carried out accumulation studies for rotavirus in mussels (*Mytilus galloprovincialis*). Mussels accumulated rotavirus to approximately the same concentration as the surrounding water, but not to any greater concentration.

No specific information was found to enable estimation of BAFs for norovirus in shellfish.

Previous QMRAs have based the estimated viral content of shellfish on the instantaneous viral concentration of the water and application of the BAF discussed above. However, the viral content of shellfish is the product of processes of accumulation, retention, and degradation.

The available evidence suggests that viral levels in shellfish may reach a steady state, reflecting their mean exposure to the virus, rather than their instantaneous exposure (Dr Joanne Hewitt, ESR, personal communication). There is evidence that retention of norovirus in shellfish is mediated through binding to type-A like receptors in the shellfish gut (Tian *et al.*, 2007). This mechanism is likely to be cumulative, but saturable. To accommodate this approach to viral accumulation, the virus content of shellfish at the identified sites was estimated from the mean water virus concentration at that site and the BAF discussed above.

No evidence was found to suggest that recreational shellfish collection in New Zealand is other than a year-round activity.

Consumption of shellfish – serving size

The 2008/2009 New Zealand Adult Nutrition Survey collected detailed information on foods consumed by adult New Zealander (n = 4,721) during a 24-hour period (University of Otago and Ministry of Health, 2011). Analysis has been carried out of the reported serving sizes for specific foods, including bivalve shellfish (Cressey, 2013). The mean serving size for bivalve shellfish was 79.3 g, with a median of 65.5 g and a 95th percentile of 164 g. The distribution of serving sizes could be satisfactorily represented by a lognormal distribution with mean 82.7 g and standard deviation 73.4 g. The distribution of serving sizes was truncated at the highest reported shellfish serving size (375 g).

Viruses are inactivated by cooking. The QMRA is related to consumption of raw shellfish. It has been assumed that the distribution of serving sizes for raw shellfish is not substantially different to the distribution of all shellfish serving sizes.

2.3 DOSE-RESPONSE

The dose-response relationship is a mathematical description of the probability of infection (or illness) for a given exposure dose. Dose-response relationships are derived from clinical trials, in which volunteers receive known amounts of pathogen, or from the analysis of outbreaks of illness associated with a defined exposure to the pathogen. Dose-response relationships can be highly uncertain, as they are influenced not only by uncertainty in the source data, but also the choice of mathematical model. For comparability, the dose-response models used in the current QMRA are those most frequently used in New Zealand QMRAs.

Norovirus is associated with uncomplicated acute gastroenteritis.

More effort has gone into characterising the dose-response relationship for norovirus than other viruses potentially transmitted through the environment. Based on human challenge experiments with the Norwalk strain, beta-binomial parameters were estimated, $\alpha = 0.040$ and $\beta = 0.055$ (Teunis *et al.*, 2008).

Viruses suspended in water can cluster into aggregates of varying sizes, depending on the ionic strength, pH, and properties of the viral protein coat or envelope. The study of Teunis *et al*. (2008) noted this phenomenon in their norovirus stock solutions and calculated a mean aggregate size of approximately 400 virus particles. Aggregation will tend to decrease the infectivity of viral solutions by effectively reducing the concentration of virus infectious units. For the current QMRA, it was assumed that noroviruses would be present in a disaggregated form.

The strength of the norovirus inoculum was determined by PCR but using a different approach to that currently used in New Zealand for norovirus quantification. A dose harmonisation factor (18.5) has been derived to provide equivalence between the methods (McBride *et al.*, 2013).

The probability of illness, given infection, has been represented as a fixed proportion (0.6) (McBride *et al.*, 2013; Soller *et al.*, 2010). The reference study for the dose-response

relationship indicated that the probability of illness, given infection, was a function of exposure dose (Teunis *et al.*, 2008). However, the association was quite weak and the fixed proportion used in QMRA was the mean probability across doses.

Teunis *et al*. (2008) identified that there was a proportion of the volunteer cohort who appeared to be resistant to infection, even at very high norovirus doses. It has been suggested that this resistance may be due to acquired immunity or genetic factors. This factor has been included in previous New Zealand QMRAs, assuming that the proportion of the New Zealand population susceptible to norovirus infection is the same as the proportion susceptible in the original volunteer study (74%) and this approach is used in the current QMRA.

2.4 RISK CHARACTERISATION: CONDUCTING THE QMRA

In order to adequately reflect limits to knowledge on key features of the risk assessment and inherent variability in the exposure events, Monte Carlo simulation modelling is used (Vose, 2008). In simpler models key input variables may be represented by a single number. However, input variables, such as viral concentrations, are known to be variable and, in most cases, uncertain. Simulation models 'sample' at random from input distributions, effectively addressing the complete range of possible 'what-if' scenarios. A summary of the input distributions used in the current study is shown in Table 4. Simulations were performed using R statistical software (R Core Team, 2018). Truncated distributions were modelled using the mc2d package (Pouillot and Delignette-Muller, 2010). The models were run for 100,000 iterations for each site, with each iteration representing a potential swimming event. Results are presented as the Individual Illness Risk (IIR); the probability of an individual becoming ill from exposure to the specified virus from a single swimming event.

Table 4. Input variable and associated parameters used in the current QMRA

Input variable	Parameters	Distribution
Influent viral concentrations		
Norovirus (genome copies/L)	Minimum = 100 Median = 1E+5 95th percentile = 1.9E+5 Maximum = 3E+7	Custom hockey stick
Viral removal by WWTP	1, 2, 3 or 4 log_{10}	
Viral inactivation during transit to specified sites	Considered to be negligible	
Effluent dilution factors at specified sites		
S1		Empirical distribution
S2		Empirical distribution
S3		Empirical distribution
S4		Empirical distribution
S5		Empirical distribution
S6		Empirical distribution
Exposure factors		
Duration of saltwater swimming event (minutes)	$\mu = 3.8$, $\sigma = 0.8$	Normal. The result is the natural log of the duration
Water ingestion rate (mL/hr)	Minimum = 0.6 Most likely = 23.9 Maximum = 153.3	Beta pert
Shellfish serving size (g)	$\mu = 82.7$, $\sigma = 73.4$, truncated at 0 and 375	Lognormal
Shellfish bioaccumulation factor (BAF)	$\mu = 49.4$, $\sigma = 7.4$, truncated at 1 and 100	Normal
Dose-response relationship		
Norovirus	$\alpha = 0.04$, $\beta = 0.055$, P (ill | infection) = 0.6, P(susceptible) = 0.74 Dose harmonisation factor = 18.5	Beta binomial

[a] The 95th percentile break point for the custom hockey stick distribution was calculated according to the method of McBride et al. (2013)
[b] The distribution for the combination of the water ingestion rate and the duration of swimming was truncated at 800 mL for a single swimming event

The simulation analysis is reported as IIRs. The *National Policy Statement for Freshwater Management* (New Zealand Government, 2020) similarly reports lake and river attribute bands in terms of the probability of infection with *Campylobacter*. This National Policy Statement applies to all freshwater (including groundwater) and, to the extent they are affected by freshwater, to receiving environments (which may include estuaries and the wider coastal marine area). The same bands were used to classify IIR estimates in the current study. Table 5 summarises the relevant aspects of the attribute bands from the national policy statement.

Table 5. Attribute bands for primary human contact with freshwater and costal receiving waters

Attribute band	Description
Excellent	<0.1% infection risk 95% of the time
Good	0.1 - 1% infection risk 95% of the time
Fair	1 - 5% infection risk 95% of the time
Poor	>5% infection risk at least 5% of the time

The descriptions of the attribute bands are expressed as both a probability of infection and a proportion of the time when the risk will be in that range. This structuring does not align with the approach to determining IIRs. However, the risk breakpoints from the national policy statement were used to classify the IIRs determined through the QMRA.

No similar classification framework is available classifying the risks due to consumption of raw shellfish. However, as swimming and shellfish consumption are both voluntary recreational activities, the risk break points included in the national policy statement were also applied to risks from raw shellfish consumption.

3. RESULTS AND DISCUSSION

3.1 PRIMARY CONTACT RECREATION

Outputs of QMRA modelling of norovirus illness risks associated with swimming at specified sites relevant to the Hihi WWTP discharge are summarised in Table 6.

Table 6. Individual Illness Risk (%) at six sites in the environs of the Hihi WWTP discharge for gastrointestinal illness associated with norovirus from swimming

Location	Log_{10} norovirus removal by Hihi WWTP[a]			
	1	2	3	4
Mean river flows – Consent discharge				
S1	0.7	0.18	0.004	<0.001
S2	0.021	<0.001	<0.001	<0.001
S3	<0.001	<0.001	<0.001	<0.001
S4	<0.001	<0.001	<0.001	<0.001
S5	0.13	0.001	<0.001	<0.001
S6	0.024	<0.001	<0.001	<0.001
Mean river flows – Low discharge				
S1	0.26	0.012	<0.001	<0.001
S2	<0.001	<0.001	<0.001	<0.001
S3	<0.001	<0.001	<0.001	<0.001
S4	<0.001	<0.001	<0.001	<0.001
S5	0.011	<0.001	<0.001	<0.001
S6	<0.001	<0.001	<0.001	<0.001
Mean river flows – Peak discharge				
S1	1.7	0.47	0.043	0.001
S2	0.37	0.039	0.001	<0.001
S3	<0.001	<0.001	<0.001	<0.001
S4	<0.001	<0.001	<0.001	<0.001
S5	0.52	0.047	0.001	<0.001
S6	0.22	0.004	<0.001	<0.001
MALF – Consent discharge				
S1	0.57	0.093	0.001	<0.001
S2	0.1	<0.001	<0.001	<0.001
S3	<0.001	<0.001	<0.001	<0.001
S4	<0.001	<0.001	<0.001	<0.001
S5	0.056	<0.001	<0.001	<0.001
S6	0.005	<0.001	<0.001	<0.001
MALF – Low discharge				
S1	0.29	0.011	<0.001	<0.001
S2	0.002	<0.001	<0.001	<0.001
S3	<0.001	<0.001	<0.001	<0.001
S4	<0.001	<0.001	<0.001	<0.001
S5	0.001	<0.001	<0.001	<0.001
S6	<0.001	<0.001	<0.001	<0.001
MALF – Peak discharge				
S1	1.6	0.47	0.054	<0.001
S2	0.3	0.089	<0.001	<0.001
S3	0.029	<0.001	<0.001	<0.001
S4	0.12	<0.001	<0.001	<0.001
S5	0.48	0.045	0.001	<0.001
S6	0.15	0.002	<0.001	<0.001

[a] Shading indicates attribute classes under the national policy statement, blue = excellent, green = good, yellow = fair and red = poor

MALF: mean annual low flow (river).

Norovirus removal by the WWTP of 1 log_{10} (90% reduction) would result in predicted risks (IIRs) associated with ingestion of water while swimming near the Hihi Stream mouth (site 1)

greater than 1% (1 illness for every 100 swimming events) only during peak discharge from WWTP. At a 2 $\log_{10}$ removal risks would be below 0.5% under all scenarios considered for all sites. At 2 $\log_{10}$ removal risks would equate to recreational water quality ranging from good (S1) to excellent (S2 – S6).

The current QMRA indicates that at 3 $\log_{10}$ viral removal by the Hihi WWTP, the risks of norovirus illness would equate to excellent recreational water quality at all sites.

While no specific information is available on the viral removal capacity of the Hihi WWTP, it is likely that the complete process will achieve removals in excess of 2 $\log_{10}$ (see section 2.2.3 for a discussion of likely viral removal rates) and likely greater than 3 $\log_{10}$. At 3 $\log_{10}$ virus removal, the estimated illness risk due to swimming would be ≤0.05% (1 in 2000) at all sites.

The risks associated with exposure to noroviruses during swimming are likely to be overestimated to some extent, as it was assumed that no viral aggregation would occur. It was also assumed that viral attenuation would be negligible.

3.2 SHELLFISH CONSUMPTION

Outputs of QMRA modelling of norovirus illness risks associated with raw shellfish consumption of shellfish harvested from specified sites relevant to the Hihi WWTP discharge are summarised in Table 7.

Table 7. Individual Illness Risk (%) at six sites in the environs of the Hihi WWTP discharge for gastrointestinal illness associated with noroviruses from raw shellfish consumption

Location	Log_{10} norovirus removal by Hihi WWTP[a]			
	1	2	3	4
Mean river flows – Consent discharge				
S1	15	5.3	0.68	0.081
S2	1.3	0.15	0.023	0.004
S3	0.017	0.002	<0.001	<0.001
S4	0.011	0.003	<0.001	<0.001
S5	5	0.67	0.059	0.005
S6	0.18	0.2	0.016	0.001
Mean river flows – Low discharge				
S1	7.3	1.1	0.12	0.019
S2	0.099	0.015	0.004	<0.001
S3	0.002	<0.001	<0.001	<0.001
S4	0.003	<0.001	<0.001	<0.001
S5	1.2	0.12	0.008	<0.001
S6	0.35	0.034	0.002	<0.001
Mean river flows – Peak discharge				
S1	18	12	2.7	0.29
S2	11	2.3	0.25	0.036
S3	0.065	0.008	0.001	<0.001
S4	0.063	0.004	<0.001	<0.001
S5	12	3	0.36	0.032
S6	6.7	0.98	0.11	0.005
MALF – Consent discharge				
S1	13	3.7	0.42	0.054
S2	4.2	0.51	0.063	0.009
S3	0.2	0.026	0.002	<0.001
S4	0.17	0.018	0.003	<0.001
S5	3.1	0.37	0.033	0.003
S6	0.78	0.08	0.003	<0.001
MALF – Low discharge				
S1	7.7	1.2	0.14	0.019
S2	0.87	0.097	0.015	0.004
S3	0.04	0.005	<0.001	<0.001
S4	0.025	0.003	<0.001	<0.001
S5	0.59	0.05	0.005	<0.001
S6	0.14	0.005	<0.001	<0.001
MALF – Peak discharge				
S1	18	11	2.4	0.25
S2	14	3.8	0.47	0.059
S3	2.2	0.23	0.028	0.003
S4	1.7	0.19	0.019	0.003
S5	12	2.8	0.34	0.029
S6	5.5	0.76	0.076	0.003

[a] Shading indicates attribute classes under the national policy statement, blue = excellent, green = good, yellow = fair and red = poor
MALF: mean annual low flow (river).

Due to the bioaccumulation of viruses by bivalve molluscan shellfish, the risks associated with this activity are higher than those associated with swimming at the same locations. At 3 log_{10} viral removal by the Hihi WWTP, the risks of norovirus illness from discharge of effluent to the

Hihi River would equate to risk levels in the fair to excellent range. However, at 2 $\log_{10}$ reduction in viral concentrations risk levels will be greater than 5% under some scenarios at the point that the discharge reaches Hihi beach. It is unknown whether shellfish harvesting occurs at this location.

4. CONCLUSIONS

The current QMRA considers risks to human health from the discharge of wastewater from the Hihi WWTP into the Hihi stream and then into Doubtless Bay at Hihi beach. Other sources of microbial contamination are not considered in the current QMRA.

Risk were considered for primary contact recreation (swimming) and consumption of raw shellfish harvested within the affected area. Risks were assessed at six locations; the point of discharge of the Hihi stream onto Hihi Beach and at five other points within the Hihi Beach/Doubtless Bay area. Risks were assessed at stream mean flows or mean annual low flow (MALF), at low, peak or consented discharge rates and at four levels of viral removal by the WWTP (1, 2, 3 and 4 $\log_{10}$). Risks were compared to the risk levels for the attribute bands in the National Policy Statement for Freshwater Management. The attribute bands are not only applicable to freshwater environments, but also estuarine and coastal receiving environments. While the national policy statement is not applicable to risks associated with shellfish consumption, the risk cut-offs for the attribute bands were used generically to classify risks associated with voluntary recreational activities.

As would be expected, risks were highest at the Hihi Stream mouth and decrease with distance from the mouth. Risks were similar under river mean annual low flows and mean flow conditions. This would be expected, as dilution of the discharged wastewater in the Hihi Stream will be minor compared to dilution in Doubtless Bay.

At a minimal 1 $\log_{10}$ removal of noroviruses by the Hihi WWTP, risks associated with swimming exceed 1% but not >5% at one of the modelled locations (the point at which the discharge meets Hihi Beach), equating to a fair classification with respect to recreational water quality (New Zealand Government, 2020). However, at 3 $\log_{10}$ viral removal the recreational water classification would be excellent at all sites.

For shellfish collected from the environments under investigation then consumed raw; at 3 $\log_{10}$ viral removal by the Hihi WWTP, the risks of norovirus illness would equate to risk levels in the fair to excellent range. The processes included in the Hihi WWTP treatment train are likely to result in greater than 3 $\log_{10}$ viral removal.

This assessment has taken a conservative approach at a number of points, and it is expected that risks, for the majority of the time, will be lower than those estimated in the current QMRA.

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