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

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	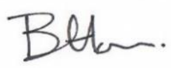	
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EXECUTIVE SUMMARY

The current QMRA considers risks to human health from the discharge of wastewater from the Kaeo WWTP into the Kaeo River and the Whangaroa Harbour. These receiving waters will also be impacted by other, mainly diffuse, sources of contamination. These other sources 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 seven locations; the point of discharge into the Kaeo River, four other locations within the riverine component of the discharge course, and two at points within the Whangaroa Harbour, including a site within a commercial oyster farm. Risks were assessed at river 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 maximal at the point at which the effluent discharges to the Kaeo River and decrease with distance from this point. Risks were greater under river mean flow conditions than under mean annual low flows. While this might appear paradoxical, it appears that low flow conditions allow greater tidal flushing in the Kaeo River, while greater river flow volumes may 'hold back' the inflow of seawater.

At 3 $\log_{10}$ viral removal (the likely approximate removal rate of the Kaeo WWTP) risks of illness due to swimming in the affected environment would equate to recreational water classification of good or excellent at all sites.

Risks associated with consumption of shellfish from the affected area were only assessed for estuarine and seawater sites, near the mouth of the Kaeo River and within the Whangaroa Harbour. At 3 $\log_{10}$ removal by the Kaeo WWTP and mean river flow conditions the risk of illness from consumption of raw shellfish harvested from the affected environment was ≥1% and frequently ≥5%. Under conditions of river mean annual low flow (MALF) risks of illness from consumption of raw shellfish harvested from the affected locations were generally mostly <1%.

Commercial oyster farms operate under a regulated control scheme, which specifies maximum microbial levels (faecal coliforms for water, *E. coli* for shellfish flesh). Modelling of concentrations of these microbial species at the oyster farm site, due to the Kaeo WWTP discharge, suggests that the discharge is unlikely to be a single cause of the microbial limits being exceeded.

Although the actual levels of WWTP viral reduction are unknown, literature information suggests that the combination of secondary treatment and tertiary UV treatment is highly likely to result in viral removal rates of at least 2 $\log_{10}$ and may feasibly be greater than 3 $\log_{10}$.

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 to water from the Kaeo wastewater treatment plant (WWTP). The existing resource consent (CON20100720501) authorising the discharge of treated wastewater to the Kaeo River expires on 31 October 2022.

The Kaeo WWTP is located approximately due west of Kaeo township and is on the opposite side of the Kaeo River to the town centre. The treatment plant is made up of an oxidation pond, a biofilter in the form of a trickling gravel bed and UV treatment. While there is a constructed wetland, it is not in good condition and is currently being by-passed. The discharge wastewater enters a covered drain that discharges into the Kaeo River about 500 m from the WWTP, downstream of Kaeo township. The discharge to the Kaeo River is typically about 140 m^3/day (about 0.0016 m^3/s), with a consented volume of 360 m^3/day (about 0.0042 m^3/s).

The Kaeo River flows into the Whangaroa Harbour approximately 3 km from the discharge point. Whangaroa Harbour is an arm of Whangaroa Bay. The Kaeo River has a strong tidal influence. Whangaroa Harbour contains two commercial oyster farms; one in Touwai Bay and one directly offshore from the mouth of the Kaeo River. Impacts on water and shellfish quality for the latter of these two farms was specifically considered in the current study. The oyster farm in Touwai Bay was considered to be sufficient distant from the Kaeo WWTP to be unaffected by the discharge.

FNDC require a technical assessment which reports on the likely risk of the discharge to public health.

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 Kaeo WWTP.
- Estimation of the risk of illness due to norovirus from primary contact recreation (swimming) and consumption of raw kaimoana (shellfish) at agreed locations within the Kaeo River and Whangaroa Harbour.

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. Risks of gastrointestinal disease due to primary contact recreation (swimming) and consumption of raw shellfish 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 event considered is a single day of water-contact recreation in wastewater-affected water.

2.2.1 Selection of assessment sites

Seven representative assessment sites were selected for the screening assessment. Sites were selected to cover the course of the discharge down the Kaeo River and into the Whangaroa Harbour. The seven sites are described in Table 1.

Table 1. Assessment locations for Kaeo WWTP QMRA

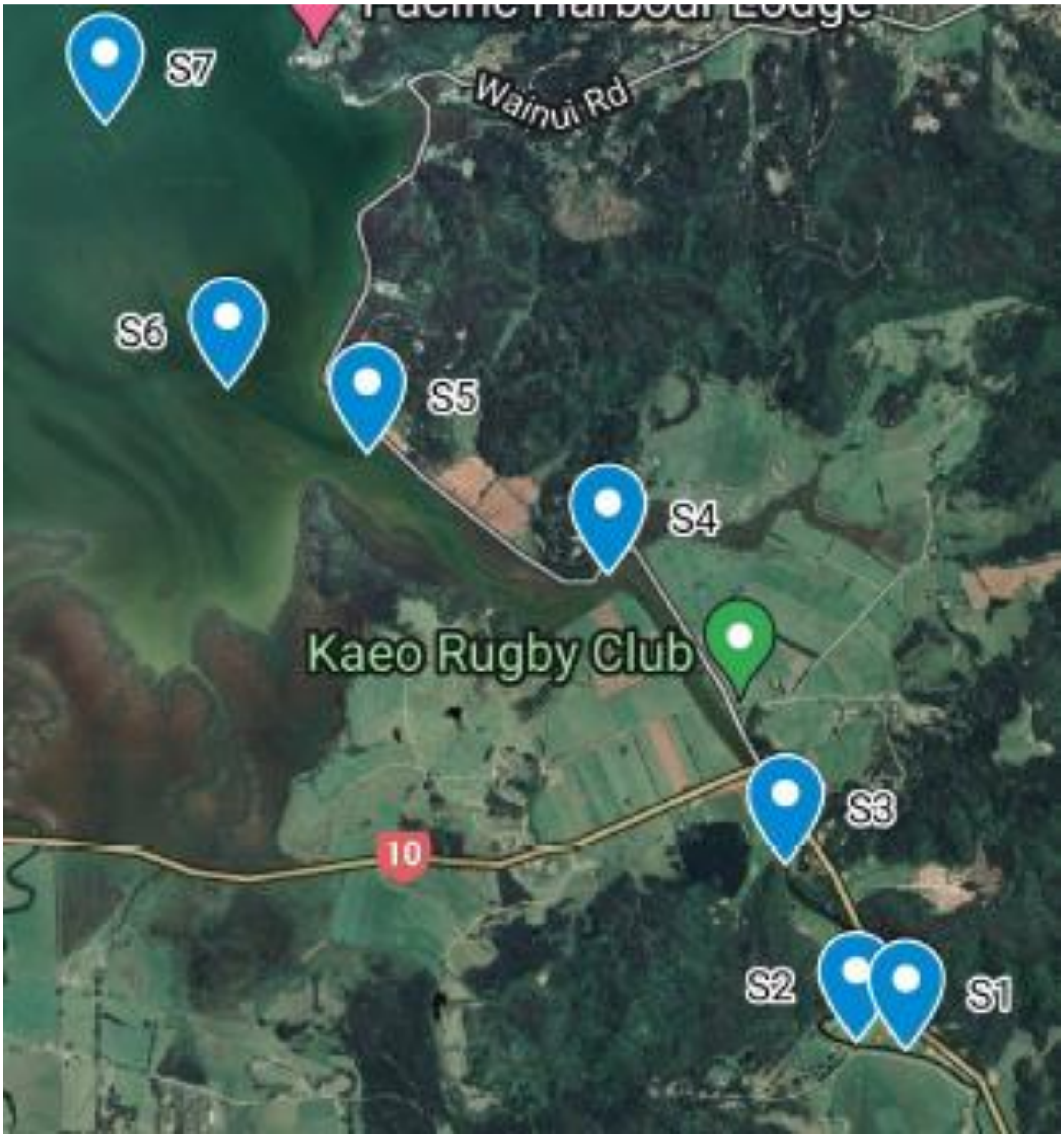
Site	Location	Longitude[a]	Latitude[a]
S1	Approximately 200 m upstream from discharge point	173.7682674	-35.09277186
S2	Discharge point to Kaeo River	173.7656787	-35.09248057
S3	Downstream, approximately 350 m before State Highway 10 crosses the Kaeo River	173.7626549	-35.08567193
S4	Downstream, adjacent to entry of stream, at major bend in Kaeo River	173.7543757	-35.07457584
S5	Mouth of Kaeo River	173.7431091	-35.06994282
S6	Whangaroa Harbour, midway between Kaeo River mouth and oyster farm	173.7365711	-35.06744006
S7	Whangaroa Harbour, within oyster farm	173.7308864	-35.05736755

[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 Kaeo WWTP wastewater discharge

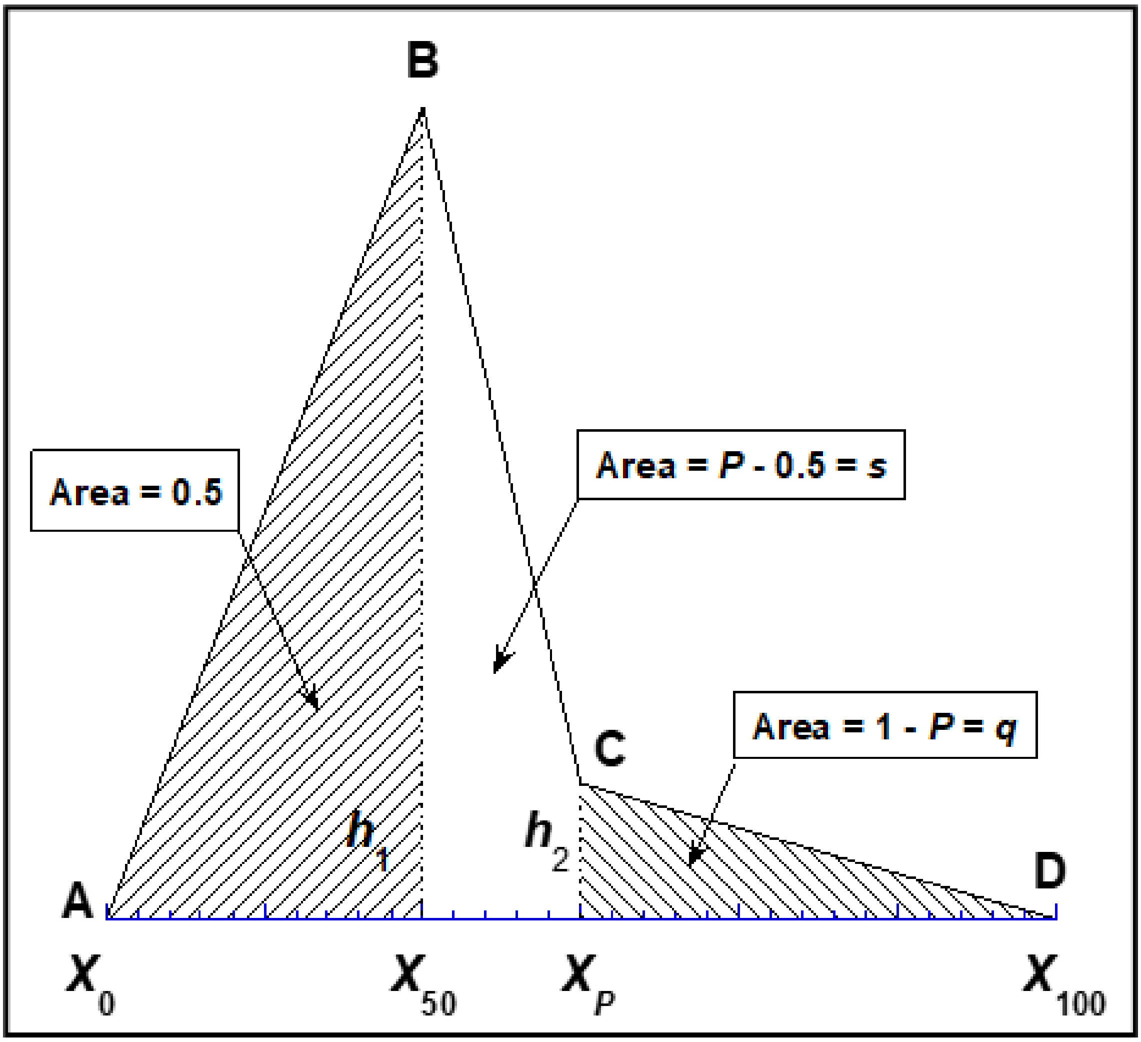


2.2.2 Viral concentrations in receiving waters

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. The general form of the hockey stick distribution is shown in Figure 2.

Figure 2. General form of the custom hockey stick distribution



In the absence of specific information on the influent to the Kaeo 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 (5.0 $\log_{10}$ genome copies/L), with a minimum and maximum of 100 and 3.0E+7 genome copies/L and a 95th percentile of 1.9E+5 genome copies/L. This distribution of norovirus concentrations is the same as used previously for QMRAs in the Far North region (Cressey, 2020; Cressey and Armstrong, 2020).

Table 2 provides summary statistics from recent New Zealand and international studies on the norovirus content of raw wastewater.

Table 2. Literature information on the norovirus content of raw wastewater

Country	Details	Norovirus content ($\log_{10}$ gc/L)	Reference
New Zealand	New Plymouth WWTP influent	GII 5.7 and 5.6 GI 3.7 and 4.1	(NPDC, 2022)
China	Raw wastewater from three WWTPs in Nanjing	GII 5.4-5.9 GI 3.9-4.1	(Liu *et al.*, 2021)
UK	Influent from five WWTPs	GII Geometric mean 4.2 Range 1.7-6.8	(Palfrey *et al.*, 2011)
Sweden	Influent from Rya WWTP in Gothenberg	GII 4.0-8.3 GI 6.5-9.3	(Wang *et al.*, 2020)

gc: genome copies

Although some very high norovirus concentrations were reported in the Swedish study summarised in Table 1, the remaining studies are largely consistent and support the currently used distribution of norovirus concentrations for raw wastewater.

<u>Viral removal at the WWTP</u>

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 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 $\log_{10}$.

A performance review of the Kaeo WWTP was carried out by Jacobs New Zealand Limited (Stumbles, 2021). Viral removal was assessed by monitoring of F-specific bacteriophage in grab samples from different points in the treatment train. F-specific bacteriophage, also known as F-RNA bacteriophage, is a culturable virus, commonly present at high concentrations in human effluent. The fact that it is culturable makes it much easier to measure than enteric viruses such as norovirus. Treatment performance with respect to bacteriophage removal was reported to be 3.3 $\log_{10}$.

While there is ongoing discussion as to appropriateness of F-specific bacteriophage as a surrogate for norovirus, the study of Palfrey et al. (2011) reported reasonable agreement between F-specific bacteriophage removal and norovirus removal across five WWTPs, with overall mean removal of F-specific bacteriophage of 2.1 log_{10} and overall mean removal of norovirus of 1.5 log_{10}. Good correlations between the concentrations of F-specific bacteriophage and enteric viruses have been reported in receiving freshwater environments (Havelaar *et al.*, 1993). On the basis of available information, F-specific bacteriophage should be considered a suitable surrogate for norovirus with respect to removal performance of the Kaeo WWTP.

While the degree of removal of enteric viruses by the Kaeo WWTP and UV treatment is unknown, it seems likely that this combination of treatments will result in viral removal rates greater than 2 log_{10} and probably greater than 3 log_{10}. This is consistent with the performance of the WWTP for removal of F-specific bacteriophage (Stumbles, 2021). 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 and shellfish consumption risk.

Wastewater dilution

MetOcean Solutions used the open-source model SCHISM[1] to provide high-resolution modelling of the tidal/river/stream discharge hydrodynamics for the Kaeo WWTP wastewater discharge (MetOcean Solutions, 2022). 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; Low discharge rate (48 m^3/day, 0.00055 m^3/s)
- Mean river flow; Consent discharge rate (360 m^3/day, 0.0042 m^3/s)
- Mean river flow; Peak discharge rate (927 m^3/day, 0.0107 m^3/s)
- Mean annual low flow (MALF); Low discharge rate
- MALF; Consent discharge rate
- MALF; Peak discharge rate

Mean and MALF flows for the Kaeo 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 Whangaroa Harbour and Kaeo River. The output time series of tracer concentrations at the seven agreed assessment sites (S1-S7) 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 seven selected sites and each of the six scenarios is included in Table 3.

[1] http://ccrm.vims.edu/schismweb/ Accessed 1 October 2020
[2] https://shiny.niwa.co.nz/nzrivermaps/ Accessed 10 March 2022

Table 3. Summary for dilution of a theoretical tracer (1 mg/L) at seven selected sites in the course of the Kaeo 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	Approximately 200 m upstream from discharge point	1.2E-3 (1.2E-3)/ 1.4E-3 (2.7E-3)	3.1E-3 (2.8E-3)/ 4.1E-3 (8.1E-3)	3.0E-3 (6.3E-3)/ 6.5E-3 (1.2E-2)
S2	Discharge point to Kaeo River	8.6E-3 (1.4E-2)/ 3.3E-3 (5.3E-3)	3.6E-2 (5.7E-2)/ 1.1E-2 (1.6E-2)	6.9E-2 (9.9E-2)/ 1.7E-2 (2.7E-2)
S3	Downstream, approximately 350 m before State Highway 10 crosses the Kaeo River	3.8E-3 (8.4E-3)/ 1.1E-3 (3.2E-3)	1.5E-2 (3.2E-2)/ 3.1E-3 (8.7E-3)	3.5E-2 (7.1E-2)/ 4.5E-3 (1.3E-2)
S4	Downstream, adjacent to entry of stream, at major bend in Kaeo River	2.4E-3 (5.8E-3)/ 2.5E-4 (1.2E-3)	9.5E-3 (2.2E-2)/ 6.6E-4 (3.2E-3)	2.1E-2 (5.0E-2)/ 9.2E-4 (4.5E-3)
S5	Mouth of Kaeo River	1.9E-3 (5.8E-3)/ 4.0E-5 (1.8E-4)	7.6E-3 (2.3E-2)/ 1.1E-4 (4.2E-4)	1.6E-2 (5.2E-2) 1.5E-4 (6.0E-4)
S6	Whangaroa Harbour, midway between Kaeo River mouth and oyster farm	1.3E-3 (4.5E-3)/ 1.6E-5 (4.6E-5)	5.1E-3 (1.8E-2)/ 4.3E-5 (1.2E-4)	1.0E-2 (3.8E-2)/ 5.8E-5 (1.6E-4)
S7	Whangaroa Harbour, within oyster farm	4.2E-4 (9.3E-4)/ 1.5E-6 (3.0E-6)	1.6E-3 (3.6E-3)/ 4.1E-6 (8.2E-6)	3.3E-3 (7.6E-3) 5.6E-6 (1.1E-5)

MALF: mean annual low flow

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

In this format, the dilution is expressed as a relative concentration, relative to a discharge concentration of 1 mg/L. Within the QMRA model dilutions are applied as multipliers to the discharge concentration of viruses, to give the predicted concentration of viruses at locations S1-S7.

<u>Viral inactivation after discharge</u>

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.

The recent QMRA of Pouillot *et al*. (2021) did include consideration of viral attenuation during the period between discharge and uptake by oysters. However, the magnitude of the concentration reductions modelled was not reported and the inclusion of this factor does not seem to have been a major determinant in their risk assessment.

For the course of the Kaeo 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 Kaeo 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 4.

Table 4. Water ingestion parameters from the swimming pool survey of Dufour et al. (2017)

Age group	Water intake description		Mean duration (minutes)
	Geometric mean (95%CI) (mL/hr)	Maximum (mL/hr)	
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 riverine and estuarine 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 freshwater swimming, the parameterised distributions are normal ($\mu = 4.1, \sigma = 0.8$) for children, normal ($\mu = 3.5, \sigma = 0.94$) for adult females and normal ($\mu = 3.6, \sigma = 0.85$) for adult males. The units for these parameters are the natural log of minutes. For example, the mean of the distribution for children is $e^{4.1} = 60.3$ 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 Kaeo River-Whangaroa Harbour system. 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 $\mu = 4.1$ and $\sigma = 0.8$. 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

Commercial oyster farming operations are present in the Whangaroa Harbour, approximately 700 m from the mouth of the Kaeo River. No information was available on recreational shellfish gathering locations. The assessment of risks associated with shellfish gathering and consumption was restricted to assessment sites S4-S7.

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, 2016; McBride and Hudson, 2016; McBride, 2014; 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.

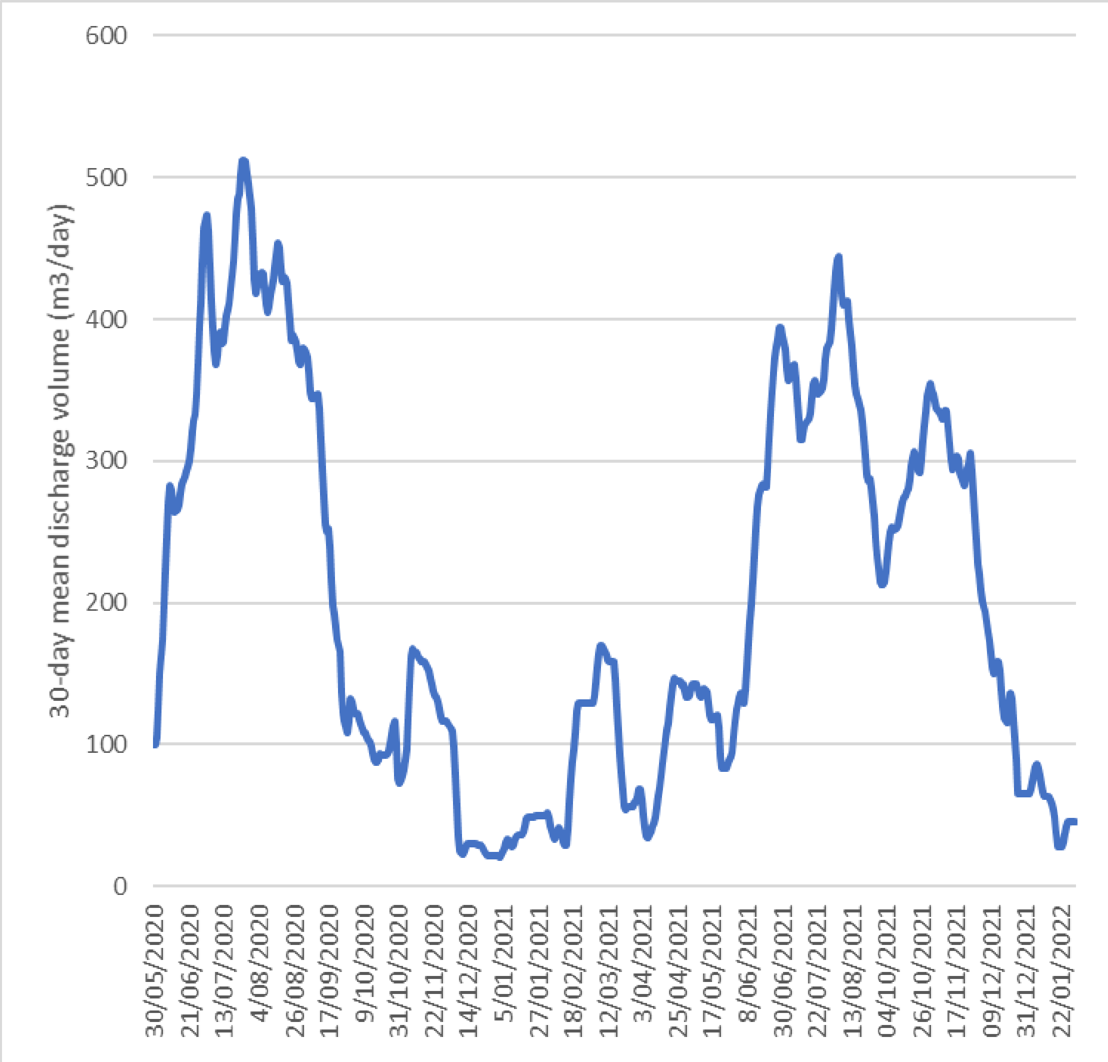
It should be noted that other studies on virus accumulation by bivalve shellfish have shown much lower rates of bioaccumulation. Amoroso *et al*. (2020) carried out accumulation studies for rotavirus in mussels (*Mytilus galloprovincialis*). Mussels accumulated rotavirus to approximately the same concentration 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 depuration. 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 over the full simulated time series and the BAF discussed above.

In order to assess the plausibility of the three selected discharge volume scenarios for assessing the risks associated with shellfish consumption, daily information on discharge volumes from the Kaeo WWTP (Mandy Wilson, Far North District Council, personal communication) were calculated as 30-day running means (Figure 3)

Figure 3. Running mean (30-day) discharge volumes from the Kaeo WWTP



The information in Figure 3 indicates that the 30-day running mean discharge volume does not approach the peak discharge volume 927 m^3/day at any stage and only occasionally exceeds the consented discharge volume of 360 m^3/day. The peak discharge scenario is not appropriate for the assessment of risks associated with shellfish consumption and for this component of the QMRA only consent and low discharge rate were modelled.

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 5. Simulations were performed using the Excel plug-in @RISK (Palisade Corporation). The models were run for 100,000 iterations for each site, with each iteration representing a potential swimming or shellfish consumption 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 or a single meal of raw shellfish.

Table 5. 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[a] 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 Upstream of discharge point		Empirical distribution
S2 Discharge point		Empirical distribution
S3 Upstream of SH10 bridge		Empirical distribution
S4 Kaeo River bend near mouth		Empirical distribution
S5 Kaeo River mouth		Empirical distribution
S6 Whangaroa Harbour near Kaeo River mouth		Empirical distribution
S7 Whangaroa Harbour at oyster farm		Empirical distribution
Exposure factors		
Duration of swimming event (minutes)[b]	μ = 4.1, σ = 0.8	Normal. The result is the natural log of the duration
Water ingestion rate (mL/hr)[b]	Minimum = 0.6 Most likely = 23.9 Maximum = 153.3	Beta pert
Shellfish serving size (g)	μ = 82.7, σ = 73.4, truncated at 0 and 375	Lognormal
Shellfish bioaccumulation factor (BAF)	μ = 49.4, σ = 7.4, truncated at 1 and 100	Normal
Dose-response relationship		
Norovirus	α = 0.04, β = 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 the IIR estimates in the current study. Table 6 summarises the relevant aspects of the attribute bands from the national policy statement.

Table 6. Attribute bands for primary human contact with freshwater and coastal 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 Kaeo WWTP discharge are summarised in Table 7.

Table 7. Individual Illness Risk (%) at seven sites in the environs of the Kaeo WWTP discharge for gastrointestinal illness associated with norovirus from swimming

Location	Log$_{10}$ norovirus removal by Kaeo WWTP[a]			
	1	2	3	4
Mean river flows – Consent discharge				
S1	2.5	0.62	0.09	0.009
S2	11.6	3.0	0.71	0.11
S3	6.8	1.5	0.36	0.048
S4	5.1	1.2	0.27	0.044
S5	4.4	1.1	0.24	0.021
S6	3.3	0.80	0.14	0.018
S7	1.7	0.42	0.05	0.007
Mean river flows – Low discharge				
S1	1.5	0.34	0.043	0.003
S2	5.2	1.2	0.25	0.031
S3	2.8	0.66	0.12	0.009
S4	2.1	0.53	0.09	0.004
S5	1.8	0.46	0.07	0.005
S6	1.4	0.33	0.04	0.006
S7	0.74	0.14	0.01	<0.001
Mean river flows – Peak discharge				
S1	2.3	0.53	0.084	0.009
S2	14.7	4.5	1.0	0.21
S3	10.2	2.6	0.61	0.12
S4	7.9	1.9	0.48	0.084
S5	6.6	1.6	0.39	0.058
S6	5.0	1.2	0.27	0.030
S7	2.6	0.62	0.12	0.009
MALF – Consent discharge				
S1	3.0	0.74	0.14	0.013
S2	5.9	1.3	0.31	0.037
S3	2.1	0.48	0.094	0.007
S4	0.73	0.17	0.030	0.001
S5	0.23	0.036	0.002	<0.001
S6	0.092	0.012	0.003	<0.001
S7	0.014	<0.001	<0.001	<0.001
MALF – Low discharge				
S1	1.6	0.36	0.048	0.004
S2	2.7	0.66	0.10	0.008
S3	1.0	0.25	0.034	0.002
S4	0.40	0.076	0.013	<0.001
S5	0.11	0.007	<0.001	<0.001
S6	0.042	0.008	0.001	<0.001
S7	0.007	<0.001	<0.001	<0.001
MALF – Peak discharge				
S1	4.1	0.99	0.19	0.025
S2	7.8	1.7	0.43	0.054
S3	2.8	0.59	0.13	0.016
S4	0.89	0.21	0.034	0.002
S5	0.29	0.049	0.003	<0.001
S6	0.11	0.018	0.003	0.001
S7	0.016	<0.001	<0.001	<0.001

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

River low flow (MALF) conditions are generally associated with lowers risks of norovirus illness from swimming than mean flows. While this might appear paradoxical, it appears that low flow conditions allow greater tidal flushing in the Kaeo River, while greater river flow volumes may 'hold back' the inflow of seawater.

At 3 $\log_{10}$ viral removal by the Kaeo WWTP, the risks of norovirus illness from discharge of effluent to the Kaeo River would equate to a good or excellent recreational water quality classification under all circumstance, except at the discharge point under conditions of peak discharge and mean river flows. The available evidence from the Jacobs performance assessment of the Kaeo WWTP (Stumbles, 2021) and the scientific literature suggests that norovirus removal will be of this order.

At 2 $\log_{10}$ viral removal by the Kaeo WWTP, the risks of norovirus illness from discharge of effluent to the Kaeo River would equate to at least a fair recreational water quality classification under all circumstance.

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 Kaeo WWTP discharge are summarised in Table 8.

Table 8. Individual Illness Risk (%) at four sites in the environs of the Kaeo WWTP discharge for gastrointestinal illness associated with noroviruses from raw shellfish consumption

Location	$\log_{10}$ norovirus removal by Kaeo WWTP[a]			
	1	2	3	4
River mean flow – Consent discharge				
S4	23.4	21.2	14.9	2.3
S5	23.2	21.1	13.4	1.8
S6	22.9	20.6	10.4	1.3
S7	21.6	17.5	3.8	0.35
River mean flow – Low discharge				
S4	22.2	19.1	5.7	0.15
S5	22.1	18.4	4.4	0.11
S6	21.6	16.7	3.0	0.08
S7	20.2	8.9	1.0	0.02
MALF – Consent discharge				
S4	20.9	12.6	1.7	0.16
S5	15.9	2.6	0.26	0.034
S6	9.4	1.1	0.11	0.009
S7	0.94	0.091	0.009	0.004
MALF – Low discharge				
S4	19.3	6.1	0.63	0.069
S5	8.7	0.94	0.092	0.011
S6	3.9	0.39	0.047	0.004
S7	0.34	0.031	0.007	0.002

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 4 $\log_{10}$ viral removal by the Kaeo WWTP, the risks of norovirus illness from discharge of effluent to the Kaeo River would equate to risk levels in the fair to excellent range. However, even at 3 $\log_{10}$ reduction in viral concentrations risk levels will be greater than 10% under some circumstances, particularly at mean river flows.

3.3 IMPACT OF KAEO WWTP DISCHARGE ON MICROBIAL INDICATORS AT COMMERCIAL OYSTER FARM

While the current QMRA is primarily concerned with impacts of the Kaeo WWTP discharge on human health, the proximity of oyster farms in Whangaroa Harbour means there is potential for both human health and financial impacts. Commercial shellfish farming operations in New Zealand operate under a regulated control scheme (MPI, 2021). The regulated control scheme species acceptable microbial contamination levels for seawater and shellfish:

- faecal coliform (FC) median MPN of the seawater samples does not exceed 14 per 100 mL, and not more than 10% of the samples exceed an MPN of 43 per 100 ml; and
- *Escherichia coli* median MPN of the BMS (bivalve molluscan shellfish) samples does not exceed 230 per 100 grams and not more than 10% of the samples exceed an MPN of 700 per 100 grams.

Based on influent FC and *E. coli* concentrations of 10^6 CFU/100 mL (Stumbles, 2021), the QMRA model was run to examine the likely contribution of the Kaeo WWTP discharge to FC and *E.coli* concentrations at the oyster farm (S7, Table 9). This approach assumes that *E. coli* will bioaccumulate in oysters in a similar manner to viruses.

Table 9. Estimated faecal coliform and *Escherichia coli* concentrations at oyster farm (site S7) due to Kaeo WWTP discharge

Scenario	FC, median (90th percentile), CFU/100 mL	*E. coli*, median (90th percentile), CFU/100 mL
Regulated control scheme limits	**14 (43)**	**230 (700)**
Mean river flow – consent discharge		
- 1 log_{10} reduction	140 (330)	6700 (16,000)
- 2 log_{10} reduction	14 (33)	670 (1600)
- 3 log_{10} reduction	1.4 (3.3)	67 (160)
- 4 log_{10} reduction	0.14 (0.33)	6.7 (16)
Mean river flow – low discharge		
- 1 log_{10} reduction	35 (85)	1700 (4200)
- 2 log_{10} reduction	3.5 (8.5)	170 (420)
- 3 log_{10} reduction	0.35 (0.85)	17 (42)
- 4 log_{10} reduction	0.04 (0.09)	1.7 (4.2)
Mean river flow – peak discharge		
- 1 log_{10} reduction	270 (650)	13,000 (33,000)
- 2 log_{10} reduction	27 (65)	1300 (3300)
- 3 log_{10} reduction	2.7 (6.5)	130 (330)
- 4 log_{10} reduction	0.27 (0.65)	13 (33)
MALF river flow – consent discharge		
- 1 log_{10} reduction	0.36 (0.75)	18 (38)
- 2 log_{10} reduction	0.04 (0.08)	1.8 (3.8)
- 3 log_{10} reduction	0.004 (0.008)	0.18 (0.38)
- 4 log_{10} reduction	<0.001 (<0.001)	0.02 (0.04)
MALF river flow – low discharge		
- 1 log_{10} reduction	0.13 (0.28)	6.6 (14)
- 2 log_{10} reduction	0.01 (0.03)	0.66 (1.4)
- 3 log_{10} reduction	0.001 (0.003)	0.07 (0.14)
- 4 log_{10} reduction	<0.001 (<0.001)	0.007 (0.014)
MALF river flow – peak discharge		
- 1 log_{10} reduction	0.40 (1.0)	24 (52)
- 2 log_{10} reduction	0.04 (0.10)	2.4 (5.2)
- 3 log_{10} reduction	0.004 (0.01)	0.24 (0.52)
- 4 log_{10} reduction	<0.001 (0.001)	0.02 (0.05)

FC: faecal coliforms, CFU: colony-forming units, MALF: mean annual low flow

Performance testing of the Kaeo WWTP concluded that overall reductions of FC and *E. coli* were 3.24 and 3.21 log_{10}, respectively. At worst, at 3 log_{10} reduction the effluent discharge from the Kaeo WWTP will contribute 24% and 70% of the regulatory limits for FC in seawater and *E. coli* in shellfish flesh, respectively. On the basis of the figures in Table 9 and the known performance of the Kaeo WWTP it is highly unlikely that the discharge from the WWTP alone would result in the oyster farm not complying with the requirements of the regulated control scheme. However, there are likely to be other point and diffuse sources that contribute to the microbiological quality of the Whangaroa Harbour

4. CONCLUSIONS

The current QMRA considers risks to human health from the discharge of wastewater from the Kaeo WWTP into the Kaeo River and the Whangaroa Harbour. These receiving waters will also be impacted by other, mainly diffuse, sources of contamination. These other sources 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 seven locations; the point of discharge into the Kaeo River, four other locations within the riverine component of the discharge course, and two at points within the Whangaroa Harbour. Risks were assessed at river 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 maximal at the point at which the effluent discharges to the Kaeo River and decrease with distance from this point. Risks were greater under river mean flow conditions than under mean annual low flows. While this might appear paradoxical, it appears that low flow conditions allow greater tidal flushing in the Kaeo River, while greater river flow volumes may 'hold back' the inflow of seawater.

At a minimal 1 $\log_{10}$ removal of noroviruses by the Kaeo WWTP, risks associated with swimming exceed 5% at the discharge point under five of the six scenarios considered, equating to a poor classification with respect to recreational water quality (New Zealand Government, 2020). For the scenario of mean river flows and peak discharge volumes risks greater than 5% would be expected at all assessment sites, except an upstream site and the site furthest into the Whangaroa Harbour. However, at 3 $\log_{10}$ viral removal (the likely approximate removal rate of the Kaeo WWTP) risks would equate to recreational water classification of good or excellent at all sites.

Risks associated with consumption of shellfish from the affected area were only assessed for estuarine and seawater sites, near the mouth of the Kaeo River and within the Whangaroa Harbour. At 3 $\log_{10}$ removal by the Kaeo WWTP and mean river flow conditions the risk of illness from consumption of raw shellfish harvested from the affected environment was ≥1% and frequently ≥5%. Under conditions of river mean annual low flow (MALF) risks of illness from consumption of raw shellfish harvested from the affected locations were generally mostly <1%.

Commercial oyster farms operate under a regulated control scheme, which specifies maximum microbial levels (FC for water, *E. coli* for shellfish flesh). Modelling of concentrations of these microbial species at the oyster farm site, due to the Kaeo WWTP discharge, suggests that the discharge alone is unlikely to be a cause of the microbial limits being exceeded.

Although the actual levels of WWTP viral reduction are unknown, literature information suggests that the combination of secondary treatment and tertiary UV treatment is highly likely to result in viral removal rates of at least 2 $\log_{10}$ and may feasibly be greater than 3 $\log_{10}$.

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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