Science for Communities

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

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EXECUTIVE SUMMARY

The current QMRA considers risks to human health from the discharge of wastewater from the Kaikohe wastewater treatment plant (WWTP) into the Wairoro-Punakitere-Tāheke-Waima river system and the Hokianga 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. 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).

Risks were assessed at seven locations; the point of discharge from the Kaikohe WWTP, two within the riverine component of the discharge course, two near the outlet of the Waima river to the Hokianga Harbour and two at points within the Hokianga Harbour. Risks were assessed at mean or median dilutions and at low dilution (95th percentile or 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.

At a minimal 1 $\log_{10}$ removal of noroviruses by the Kaikohe WWTP and low dilution (95th percentile or MALF), risks associated with swimming exceed 5% at three modelled locations, equating to a poor classification with respect to recreational water quality. However at 3 $\log_{10}$ viral removal the recreational water classification would be fair to excellent at all sites.

Although the actual levels of WWTP viral reduction are unknown, literature information suggests that the combination of secondary treatment and tertiary treatment through constructed wetlands is highly likely to result in viral removal rates of 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.

Other WWTPs (Ōpononi-Ōmāpere, Rawene and Kohukohu) discharge Into the Hokianga Harbour and will contribute to risks associated with recreational water contact. However, hydrodynamic modelling suggests that the combined discharge from the four WWTPs is very similar to that for Kaikohe WWTP alone, particularly in the upper harbour.

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 Kaikohe wastewater treatment plant (WWTP). The existing resource consent authorising the discharge of treated wastewater into the Wairoro Stream expires on 30 November 2021 and an application to renew the consent will be lodged by 30 August 2021.

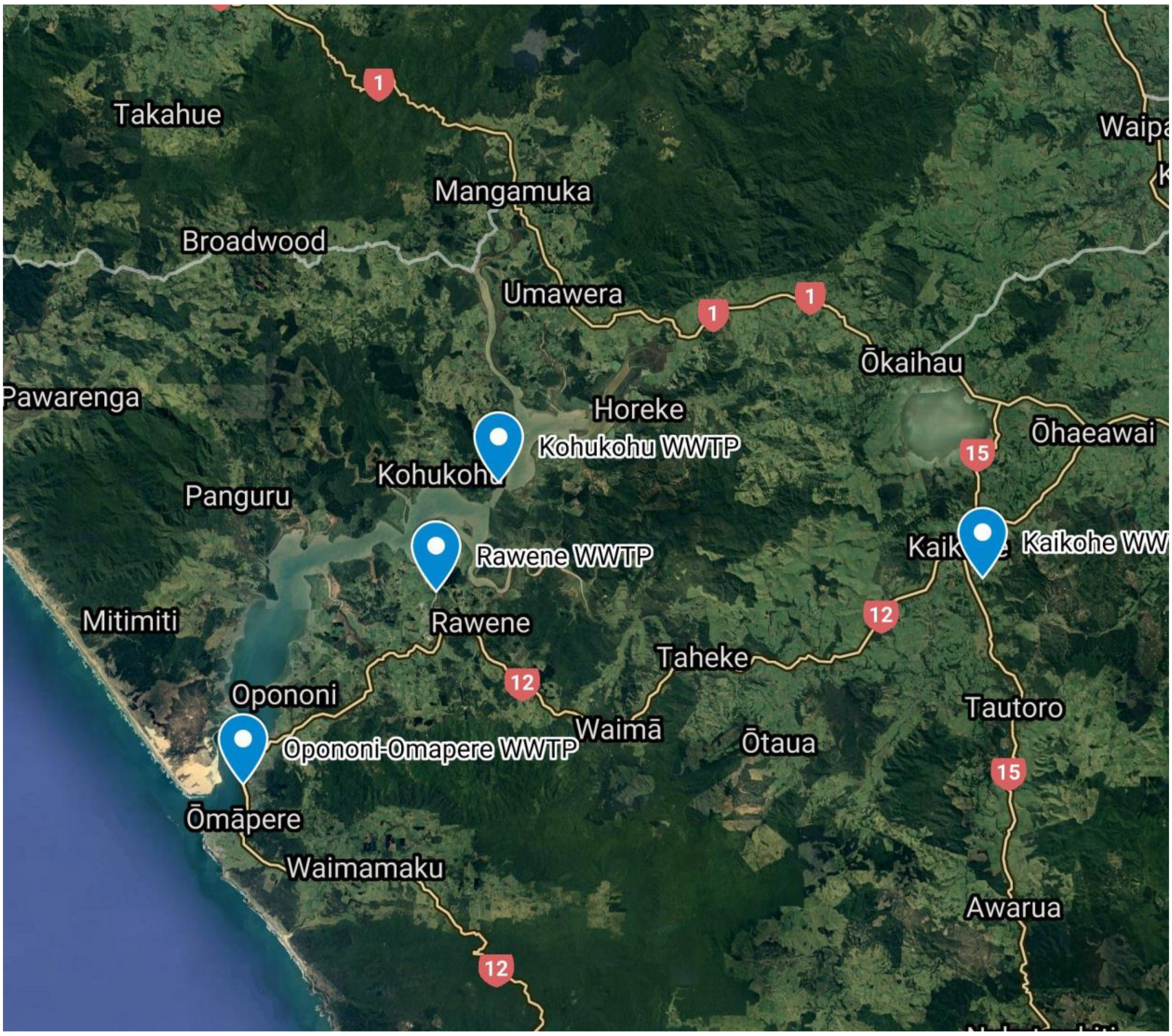
The treatment plant is located to the south of the township of Kaikohe and accessed off the end of Cumber Road. The WWTP services about 1,613 properties within the urban areas of Kaikohe and Ngawha. Average influent flows between 2017-2020 were 1,862 m^3/day while the 90th percentile flows were 2,983 m^3/day. The treatment plant is made up of an anaerobic pond followed by an oxidation pond and constructed wetland. From the constructed wetland, treated wastewater discharges into the Wairoro Stream. The plant does not have UV disinfection but this is likely to be something that will be included in an upgrade planned around 2024-2025.

The Wairoro Stream, along with the Punakitere and Tāheke Rivers, forms part of the upper catchment of the Waima River, which flows into the Hokianga Harbour. The approximate river distance from the discharge point to the harbour is 45km. Hydrodynamic modelling work completed by MetOcean Solutions indicates that dilution is fairly limited within the receiving catchment up to the point at which the flows from the Waima River/estuary reach the main harbour channel (MetOcean Solutions, 2020).

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

Other WWTPs (Ōpononi-Ōmāpere, Rawene and Kohukohu) discharge Into the Hokianga Harbour and will contribute to risks associated with recreational water contact. However, hydrodynamic modelling suggests that the combined discharge from the four WWTPs Is very similar to that for Kaikohe WWTP alone, particularly in the upper harbour (MetOcean Solutions, 2020). The other WWTP discharge directly to the harbour and discharge much lower volumes than the Kaikohe WWTP, with 30-day average discharge limits of 450, 254 and 40 m^3/day, respectively, compared to 1710 m^3/day for Kaikohe WWTP. Figure 1 shows the locations of the four WWTPs.

Figure 1. Location of WWTPs discharging to the Hokianga Harbour



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 Kaikohe WWTP.
- Estimation of the risk of illness due to norovirus from primary contact recreation (swimming) at agreed locations within the Wairoro-Punakitere-Tāheke-Waima-Hokianga catchment.

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) were considered. This decision was made as swimming is plausible at any location with sufficient water flows, while kaimoana collection will only occur at specific locations. Information on such specific locations was not available at this time.

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

Six representative assessment sites were selected for the screening assessment. Sites were selected for proximity to marae along the course of the wastewater discharge using the resource Māori Maps.[1] The six sites are:

- S1 Tāheke (Tāheke marae)
- S2 Mission Oak Road (Moehau marae)
- S3 Motukiore Road
- S4 Rawene domain
- S5 Tauteihihi (Tauteihihi marae)
- S6 Pikipāria (Pikipāria marae)

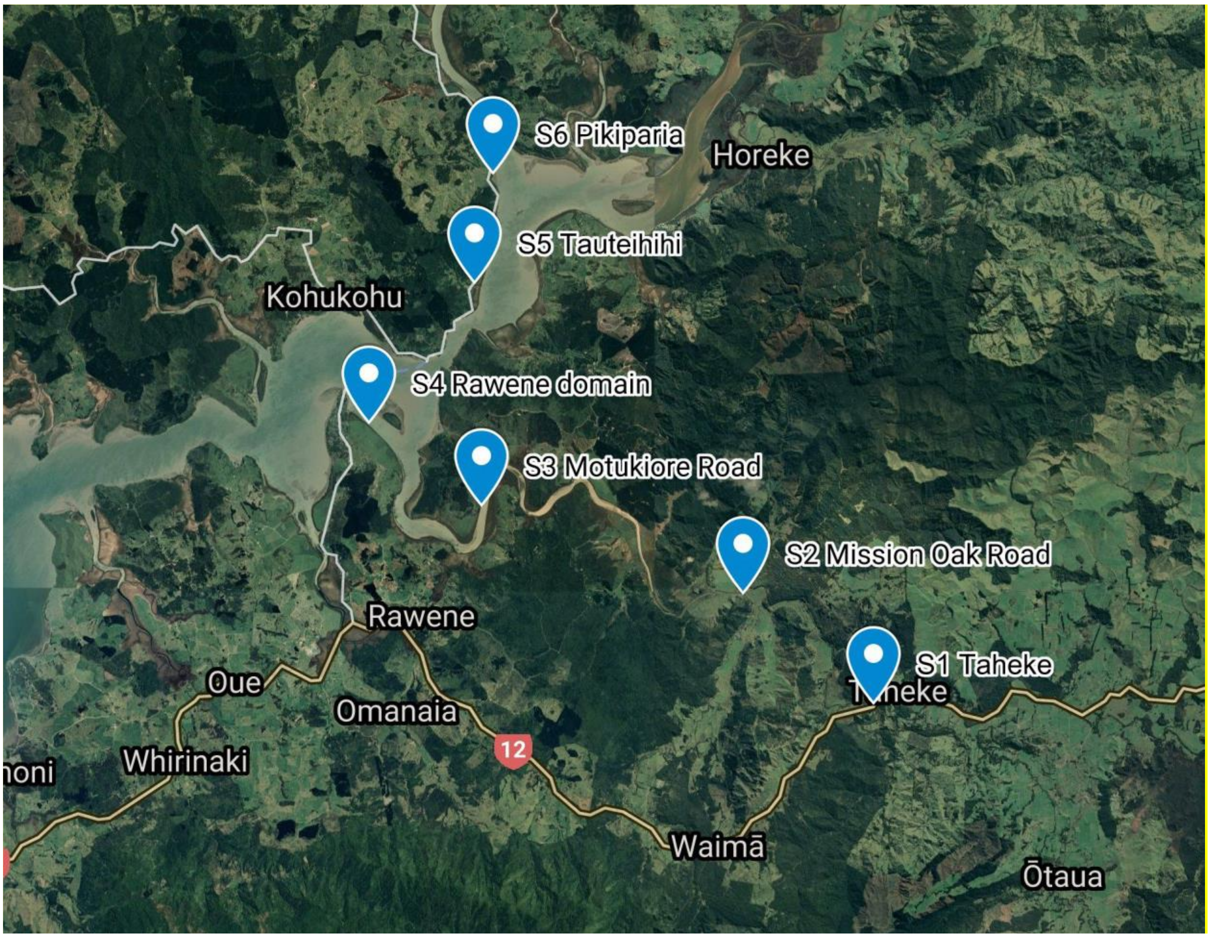
In addition, risks were assessed at the point of discharge from the Kaikohe WWTP into the Wairoro Stream (S0). This assessment site represents a worst-case scenario swimming site for the risks associated with the Kaikohe WWTP discharge.

Figure 1 shows the location of the assessment sites, except for S0.

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.

[1] https://maorimaps.com/ Accessed 18 June 2021

Figure 2. Location of assessment sites for Kaikohe 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 Kaikohe 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. Due to the very long right-hand ‘tail’ on this distribution, the custom hockey stick distribution was used (McBride, 2016). 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 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 $\log_{10}$.

The constructed wetlands used as tertiary treatment of Kaikohe WWTP will further reduce viral loadings. It has been reported that a horizontal subsurface flow wetland was able to reduce concentrations of adenovirus and norovirus by 2.0 and 2.5 $\log_{10}$, respectively (Rachmadi *et al.*, 2016). A further study reported reductions in the range 0.9-3.2 $\log_{10}$ for indicator viruses (somatic coliphage and MS2 coliphage) during passage through a constructed wetland (Amarasiri *et al.*, 2017).

While the degree of removal of enteric viruses by the Kaikohe WWTP and constructed wetlands 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 $\log_{10}$. Due to uncertainty in this aspect of the QMRA, the model was run for four decade 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 risk.

Wastewater dilution

MetOcean Solutions used the open-source model SCHISM[2] to provide high-resolution modelling of the tidal/river/stream discharge hydrodynamics for the Kaikohe WWTP wastewater discharge (MetOcean Solutions, 2020). Contaminant dilution was modelled using the Eulerian tracer technique. The tracers are assumed to be neutrally buoyant and not decay. Due to the long distance between the discharge point at Kaikohe and the Hokianga harbour and the lack of time series data for the upper reaches of the discharge course, MetOcean modelled a discharge point closer to the harbour. The modelled discharge point was in the vicinity of Duddy Road, downstream of assessment sites S1 and S2. MetOcean used mean flow data[3] for the discharge point (0.768 m^3/s) and Duddy Road (14.1 m^3/s) to define an additional dilution factor, prior to the modelled discharge point.

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 (hourly intervals) over one full month (neap-spring tide cycle) for El Niño and La Niña years. Data were presented for 50th (median) and 95th percentile dilutions.

Discharge from the Kaikohe WWTP was assumed to be continuous and at the 30-day average discharge limit of 1710 m^3/day (0.02 m^3/s). For sites upstream of the modelled discharge point mean dilutions were calculated as the ratio between the mean discharge and the mean flow at the assessment site. For sites downstream of the modelled discharge point approximate median and 95th percentile dilutions were taken from figures in the MetOcean report.

A summary for the tracer concentration (dilution) for the six selected sites and each of the two scenarios is included in Table 1.

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

Site code	Site	Data source	Concentration of tracer, mean/median (95th percentile)[a] (mg/L)	
			El Niño	La Niña
S0	Kaikohe WWTP (discharge point)	Ratio of mean flows: Discharge = 0.02 m^3/s River at Kaikohe: Mean = 0.781 m^3/s MALF = 0.135 m^3/s	Mean = 2.6E-2 MALF = 1.5E-1	
S1	Tāheke	Ratio of mean flows: Discharge = 0.02 m^3/s River at Tāheke: Mean = 11.01 m^3/s MALF = 1.51 m^3/s	Mean = 1.8E-3 MALF = 1.3E-2	
S2	Mission Oak Road	Ratio of mean flows: Discharge = 0.02 m^3/s River at Mission Oak Road: Mean = 13.08 m^3/s MALF = 2.22 m^3/s	Mean = 1.5E-3 MALF = 9.0E-3	
S3	Motukiore Road	MetOcean report	1.0E-3 (2.5E-2)	2.5E-3 (2.5E-2)
S4	Rawene domain	MetOcean report	5.0E-4 (1.0E-2)	1.0E-3 (1.0E-2)
S5	Tauteihihi	MetOcean report	2.5E-4 (1E-3)	1.0E-3 (2.5E-3)
S6	Pikipāria	MetOcean report	2.5E-4 (1E-3)	1.0E-3 (2.5E-3)

MALF: mean annual low flow

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

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

[3] https://shiny.niwa.co.nz/nzrivermaps/ Accessed 18 June 2021

In this format, the dilution is expressed as a relative concentration, relative to a discharge concentration of 1 mg/L. Within the QMRA model these dilutions are applied as multipliers to the discharge concentration of viruses, to give the predicted concentration of viruses at locations S0-S6.

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.

For the course of the Kaikohe 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 Kaikohe 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.

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 2.

Table 2. 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).

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 previous section, water ingestion was expressed as a rate (mL/hr). In order for a total volume of ingested water to be calculated, these rates must be combined with a duration of the contact recreation (swimming) event. Table 3 summarises values used in previous New Zealand QMRAs and values from the scientific literature.

Table 3. Estimates of the duration of contract recreation used in New Zealand QMRAs and overseas estimates (USA and Netherlands)

Age group	Duration of swimming (hours)	Reference
Children or adults	0.10, 0.25, 2.0 (minimum, mode, maximum)	(McBride and Hudson, 2016)
Children or adults	0.25, 0.50, 2.0 (minimum, mode, maximum)	(McBride *et al.*, 2013)
Children or adults	0.10, 0.50, 2.0 (minimum, mode, maximum)	(McBride, 2014)
	Geometric mean (95%CI for mean)	(Dufour *et al.*, 2017)
Children	1.60 (1.47-1.73)	
Teenagers	0.93 (0.87-0.98)	
Adults		
- All	0.84 (0.82-0.87)	
- Female	0.85 (0.82-0.90)	
- Male	0.83 (0.78-0.87)	
	Mean (95%CI for duration)	(Schets *et al.*, 2011)
Children (<15 years)		
- Swimming pool	1.35 (0.40-3.30)	
- Freshwater	1.32 (0.20-4.50)	
- Seawater	1.08 (0.13-4.00)	
Female (≥15 years)		
- Swimming pool	1.12 (0.32-2.83)	
- Freshwater	0.90 (0.10-3.67)	
- Seawater	0.68 (0.07-3.00)	
Male (≥15 years)		
- Swimming pool	1.13 (0.32-3.00)	
- Freshwater	0.90 (0.12-3.33)	
- Seawater	0.75 (0.10-2.67)	

The data summarised in Table 3 suggest that estimates of swimming duration used in previous New Zealand QMRAs may be low. 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.

The study design 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. Given that the current QMRA includes both 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.

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 Wairoro-Waima-Hokianga 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.

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 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 event. Results are presented as the Individual Illness Risk (IIR); the probability of a susceptible 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[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		
S0 Kaikohe WWTP (discharge point)	Mean = 0.025 MALF = 0.15	Point values
S1 Tāheke	Mean = 0.0018 MALF = 0.013	Point values
S2 Mission Oak Road	Mean = 0.0015 MALF = 0.009	Point values
S3 Motukiore Road	El Niño Median = 0.001, 95th percentile = 0.025 La Niña Median = 0.0025, 95th percentile = 0.025	Point values
S4 Rawene domain	El Niño Median = 0.0005, 95th percentile = 0.01 La Niña Median = 0.001, 95th percentile = 0.01	Point values
S5 Tauteihihi	El Niño Median = 0.00025, 95th percentile = 0.001 La Niña Median = 0.001, 95th percentile = 0.0025	Point values
S6 Pikipāria	El Niño Median = 0.00025, 95th percentile = 0.001 La Niña Median = 0.001, 95th percentile = 0.0025	Point values
Exposure factors		
Duration of swimming event (minutes)	$\mu = 4.1$, $\sigma = 0.8$	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
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)

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). For the current exercise, it was assumed that the probability of infection with *Campylobacter* could be equated to the probability of illness due to norovirus.

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. As an approximation the risk at the mean annual low flow (MALF – freshwater site) and the risk at the 95th percentile dilution were taken to be the maximum risks prevailing 95% of the time.

3. RESULTS AND DISCUSSION

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

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

Location	Log_{10} norovirus removal by Kaikohe WWTP[a]			
	1	2	3	4
Freshwater sites				
Mean flows				
S0[b]	8.78	1.84	0.51	0.069
S1[b]	1.49	0.37	0.04	<0.01
S2[b]	1.35	0.32	0.03	<0.01
Mean annual low flows				
S0[b]	17.0	6.22	1.37	0.32
S1[b]	5.76	1.29	0.30	0.03
S2[b]	4.36	1.06	0.23	0.03
Estuarine/marine sites				
El Niño –median dilution				
S3	1.06	0.22	0.03	<0.01
S4	0.73	0.11	0.02	<0.01
S5	0.49	0.06	<0.01	<0.01
S6	0.47	0.05	<0.01	<0.01
El Niño – 95th percentile dilution				
S3	8.70	1.84	0.50	0.06
S4	4.68	1.08	0.22	0.03
S5	1.11	0.23	0.02	<0.01
S6	1.08	0.25	0.04	<0.01
La Niña – median dilution				
S3	1.79	0.47	0.06	0.01
S4	1.11	0.25	0.02	<0.01
S5	1.08	0.24	0.02	<0.01
S6	1.07	0.22	0.02	<0.01
La Niña – 95th percentile dilution				
S3	8.59	1.88	0.45	0.06
S4	4.61	1.11	0.24	0.02
S5	1.87	0.49	0.07	<0.01
S6	1.88	0.45	0.08	<0.01

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

[b] For sites S0, S1 and S2 dilutions were assumed to not differ with the prevailing weather pattern

Norovirus removal by the WWTP of 1 log_{10} (90% reduction) would result in predicted risks (IIRs) associated with ingestion of water while swimming at the specified sites greater than 1% (1 illness for every 100 swimming events) in most cases (exception S4-S6 at median dilution under El Niño conditions) and greater than 5% under some circumstances. At a 2 log_{10} removal risks would be below 1% for all sites under median/mean dilution conditions, except at the discharge point (S0). At 2 log_{10} removal and 95th percentile dilution or MALF conditions risks would equate to recreational water quality ranging from poor (S0) to good (S5 and S6).

The current QMRA indicates that at 3 log_{10} viral removal by the Kaikohe WWTP, the risks of norovirus illness would equate to good or excellent recreational water quality at all sites except S0, where the water quality would be classified as fair under MALF, but good under mean flows.

While no specific information is available on the viral removal capacity of the Kaikohe 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 maximum illness risk due to swimming would be ≤0.5% at all sites except the discharge point (S0).

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.

4. CONCLUSIONS

The current QMRA considers risks to human health from the discharge of wastewater from the Kaikohe WWTP into the Wairoro-Punakitere-Tāheke-Waima river system and the Hokianga 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.

Risks were assessed at seven locations; the point of discharge into the Wairoro Stream, two within the riverine component of the discharge course, two near the outlet of the Waima river to the Hokianga Harbour and two at points within the Hokianga Harbour. Risks were assessed at mean or median dilutions and at low dilution (95^{th} percentile) or 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.

At a minimal 1 $\log_{10}$ removal of noroviruses by the Kaikohe WWTP and low dilution (95^{th} percentile or MALF), risks associated with swimming exceed 5% at three modelled locations, equating to a poor classification with respect to recreational water quality (New Zealand Government, 2020). However at 3 $\log_{10}$ viral removal the recreational water classification would be fair to excellent at all sites.

Although the actual levels of WWTP viral reduction are unknown, literature information suggests that the combination of secondary treatment and tertiary treatment through constructed wetlands is highly likely to result in viral removal rates of 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.

Other WWTPs (Ōpononi-Ōmāpere, Rawene and Kohukohu) discharge Into the Hokianga Harbour (MetOcean Solutions, 2020) and will contribute to risks associated with recreational water contact. However, hydrodynamic modelling suggests that the combined discharge from the four WWTPs is very similar to that for Kaikohe WWTP alone, particularly in the upper harbour.

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