

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

JULY 2025

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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 considers 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 (2, 3, 4 and 5 log₁₀). For sites closest to the point of discharge, the impact of estimated future increases in the volume of wastewater discharged was also considered. 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 2 log₁₀ removal of noroviruses by the Kaikohe WWTP and low dilution (95th percentile or MALF), risks associated with swimming only exceed 5% (indicative of poor water quality) at the point of discharge into the Wairoro Stream. However, at levels of viral removal expected by the proposed treatment process (4+ log₁₀ viral removal) the recreational water classification would be excellent at all sites under all conditions. This includes scenarios of increased future treated wastewater discharge volumes.

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.

1. INTRODUCTION

1.1 BACKGROUND

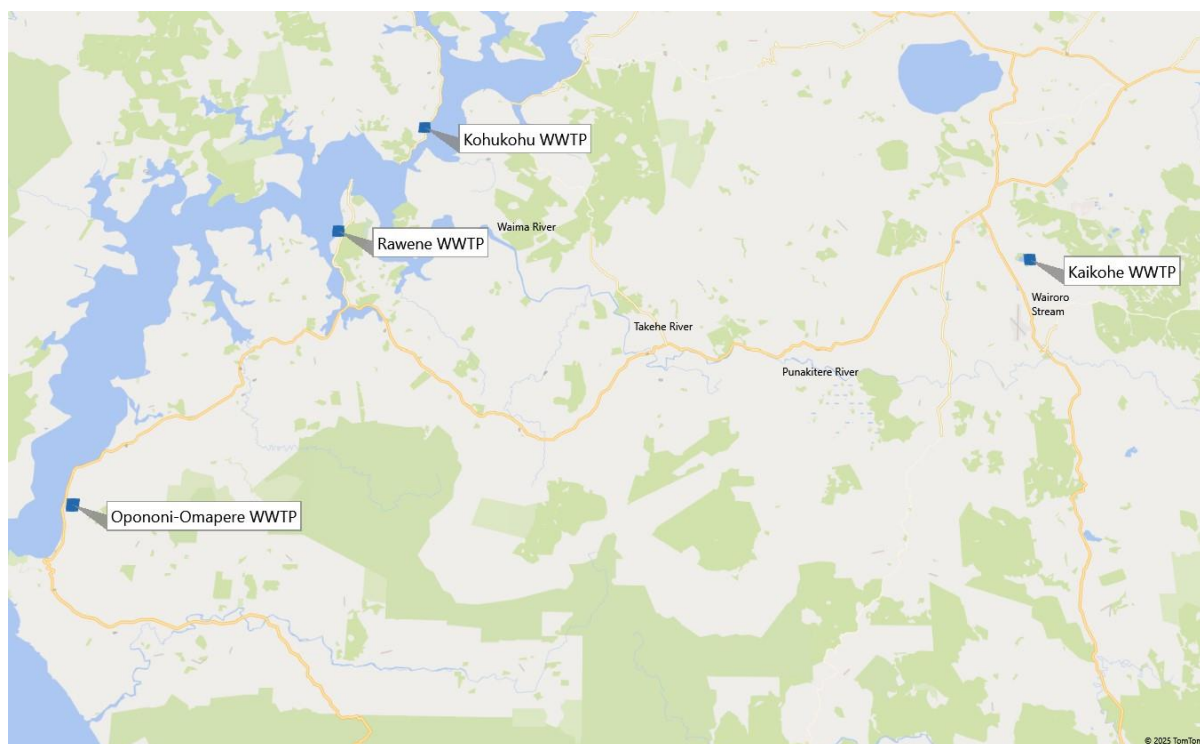
The Far North District Council (FNDC) previously prepared technical documents to support the resource consent application to renew the discharge of wastewater to water from the Kaikohe wastewater treatment plant (WWTP). The existing resource consent authorising the discharge of treated wastewater into the Wairoro Stream expired on 30 November 2021 and an application to renew the consent was lodged in August 2021. A quantitative microbial risk assessment (QMRA) was prepared at that time, to support the resource consent application (Cressey, 2021)

The application was placed on hold by Northland Regional Council to allow a working group to be established to determine the future options for the Kaikohe WWTP. Since that time Beca has been engaged by FNDC to assess treatment upgrade options and work with hapu. Beca have lodged a revised consent application and have subsequently received a request under section 92 (s92) of the Resource Management Act 1991 for an updated QMRA.

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 m³/day while the 90th percentile flows were 2,983 m³/day. The treatment process currently includes an anaerobic pond followed by an oxidation pond and constructed wetland. From the constructed wetland, treated wastewater discharges into the Wairoro Stream. A preferred option for treatment upgrade has been proposed, including secondary treatment by membrane bioreactor (MBR) and tertiary treatment by UV. It should be noted that the upgrade will involve replacement of the existing treatment processes, rather than addition to the existing processes.

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 45 km. 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).

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 m³/day, respectively, compared to 1710 m³/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 QMRA presented in the current report adopted the same general approach to that carried out in QMRA conducted elsewhere in New Zealand.

Based on other recent New Zealand QMRAs, the technical assessment will consider the risks associated with norovirus in discharged wastewater. Norovirus has consistently been the pathogen representing the greatest human health risk in recent QMRAs, due to its frequent occurrence in human wastewater, its relative resistance to conventional wastewater treatment and its high infectivity. The assessment includes two components:

- Review of available information on norovirus removal by the processes proposed for 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 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:

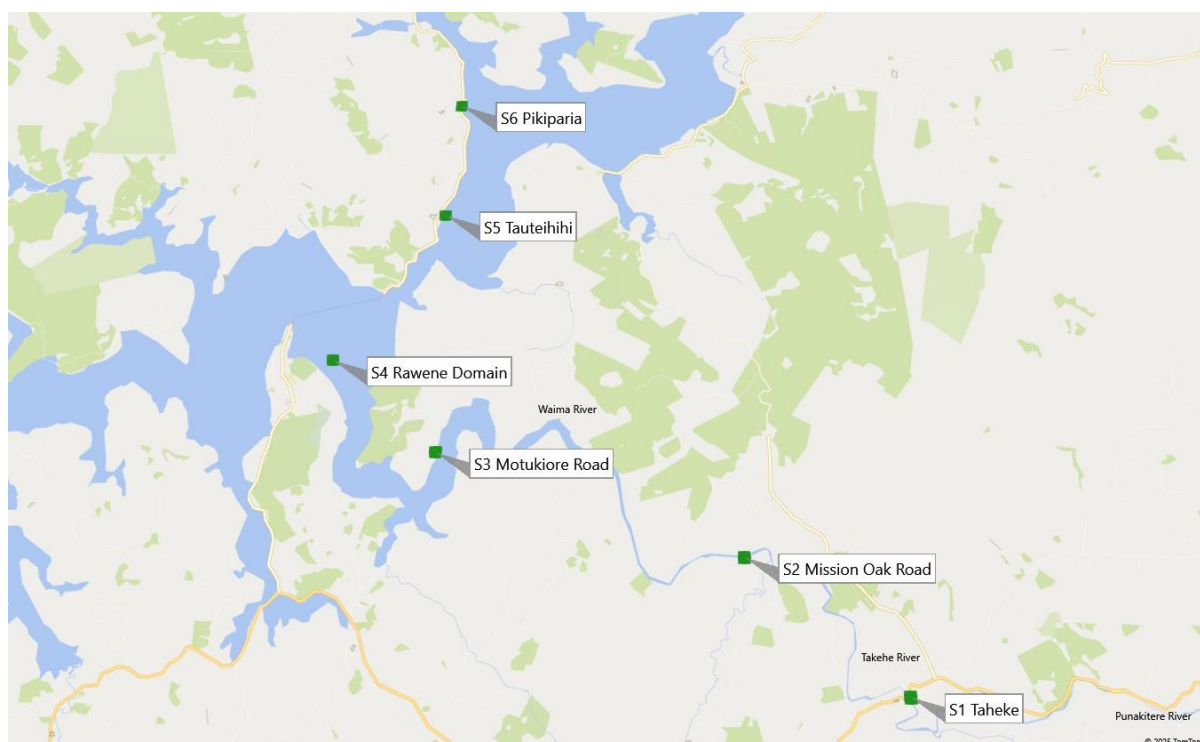
- S1 Tāheke (Tāheke marae)
- S2 Mission Oak Road (Moehau marae)
- S3 Motukiore Road
- S4 Rawene domain
- S5 Tauteihihi (Tauteihihi marae)
- S6 Pikipāria (Pikipāria marae)

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 2 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

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.

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.

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.

The specific treatment processes proposed for the Kaikohe WWTP upgrade are secondary MBR and tertiary UV disinfection. Studies have considered removal of viruses, including noroviruses, by secondary MBR treatment. Summaries of log removal values for noroviruses are summarised in Table 1.

Table 1: Summary of log removal values (LRV) for membrane bioreactor (MBR) treatment of wastewater

Norovirus genotype	LRV, mean (range)	Reference
NV GI	3.1	Canh <i>et al.</i> (2025)
NV GII	3.4	
NV GII	(>0.2 - >3.4) ^a	Miura <i>et al.</i> (2015)
NV GII	3.9 (3.5-4.8)	Simmons <i>et al.</i> (2011)
NV GI	3.0 (>1.5-3.3) ^{a,b}	Francy <i>et al.</i> (2012)
NV GI/GII	2.3	Purnell <i>et al.</i> (2016)
NV GI	1.8 (>0.7->2.7) ^a	Gurung <i>et al.</i> (2017)
NV GII	3.0 (>2.1->3.6)	
NV GII		Tang <i>et al.</i> (2024)
- Plant A	2.8	
- Plant B	2.8	

NV: norovirus, LRV: log removal value

^a LRVs expressed as 'greater than' represent situations where viruses were not detected in the effluent

^b Measure of central tendency is the median, rather than the mean

The studies summarised in Table 1 demonstrate a good level of consistency and it is likely that a MBR will contribute a LRV of about 3.

The additional LRVs due to UV disinfection will depend on the specifications of the UV unit installed. The viricidal ability of a UV treatment system is dependent on the UV fluence or dose and LRVs of 4 or greater have been demonstrated for a wide range of enteric viruses if a sufficiently high UV fluence is applied (Augsburger *et al.*, 2021). It has been suggested that murine norovirus (MNV) and Tulane virus (TV) may act as conservative surrogates for human norovirus in determining LRVs due to UV treatment (Mariita *et al.*, 2022). Mean UV doses to achieve a LRV of 4 for these viruses have been reported as 26 and 69 mJ/cm² for MNV and TV, respectively (Augsburger *et al.*, 2021).

While the degree of removal of enteric viruses by the proposed Kaikohe WWTP upgrade is unknown, it seems likely that this combination of treatments will result in viral removal rates greater than 4 log₁₀. This is consistent with an assessment conducted by Beca, which estimated a 1.5 log₁₀ viral LRV for the current Kaikohe WWTP and a 5 log₁₀ LRV for the Kaikohe WWTP upgrade (Hayden Porter, Beca, personal communication). Due to uncertainty in this aspect of the QMRA, the model was run for four levels of viral reduction

(2, 3, 4 or 5 log₁₀), 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 SCHISM² 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 data³ for the discharge point (0.768 m³/s) and Duddy Road (14.1 m³/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. During El Niño conditions, New Zealand typically experiences stronger or more frequent westerly winds during summer, leading to a greater risk of drier-than-normal conditions in east coast areas and more rain than normal in the west. In winter, colder southerly winds tend to prevail, while in spring and autumn, south-westerlies tend to be stronger or more frequent, bringing a mix of the summer and winter effects. During La Niña conditions, more north-easterly winds occur, which tend to bring moist, rainy conditions to the north-east of the North Island, and reduced rainfall to the south and south-west of the South Island (MetOcean Solutions, 2020). 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 m³/day (0.02 m³/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 2.

Table 2: 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 (95 th 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:		

² <http://ccrm.vims.edu/schismweb/> Accessed 1 October 2020

³ <https://shiny.niwa.co.nz/nzrivermaps/> Accessed 18 June 2021

Site code	Site	Data source	Concentration of tracer, mean/median (95 th percentile) ^a (mg/L)	
			El Niño	La Niña
		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 (1.0E-3)	1.0E-3 (2.5E-3)
S6	Pikipāria	MetOcean report	2.5E-4 (1.0E-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

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.

Future discharge scenarios

It has been estimated that by 2060 the treated wastewater discharges from the Kaikohe WWTP will increase to a mean daily flow of 2,317 m³/day (0.027 m³/s), equating to an approximate 35% increase compared to current discharges (Garrett Hall, Beca, personal communication). While it is not possible to recalculate dilutions at sites S3-S6, based on these higher discharge volumes, it is possible to consider the impact of this increase on dilutions at sites S0-S2, using the same flow ratio approach as outlined above.

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 log₁₀ 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 log₁₀ 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/m²) examined, time for a 1 log₁₀ reduction for adenovirus was 3.3 hours. Experiments were carried out at a water temperature of 26°C.

Considerably longer 1 log₁₀ 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 log₁₀) were reported. Greater decreases in murine norovirus concentrations (1.12 log₁₀) were reported.

Norovirus GI and GII were exposed to simulated summer (17°C, 20 MJ/m² per day irradiance) and winter (10°C, 5 MJ/m² per day) conditions in seawater (Flannery *et al.*, 2013). Times for 1 log₁₀ 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 3.

Table 3: 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, PHF Science has 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. A study in the Netherlands by 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 $e^{3.8} = 44.7$ minutes.

While it could be argued that swimming habits may differ in New Zealand compared with the USA and the Netherlands, there are no New Zealand data to assess 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 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 in the study by Teunis was determined by PCR, but using a different approach to that currently used in New Zealand for norovirus quantification and that used in the analysis of Eftim *et al.* (2017). 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 95 th percentile = 1.9E+5 ^a	Custom hockey stick

Input variable	Parameters	Distribution
	Maximum = $3E+7$	
<i>Viral removal by WWTP</i>	2, 3, 4 or 5 \log_{10}	
<i>Viral inactivation during transit to specified sites</i>	Considered to be negligible	
Effluent dilution factors at specified sites		
S0 Kaikohe WWTP (discharge point)	Mean (current) = 0.025 Mean (2060) = 0.034 MALF (current) = 0.15 MALF (2060) = 0.20	Point values
S1 Tāheke	Mean (current) = 0.0018 Mean (2060) = 0.0024 MALF (current) = 0.013 MALF (2060) = 0.018	Point values
S2 Mission Oak Road	Mean (current) = 0.0015 Mean (2060) = 0.0020 MALF (current) = 0.009 MALF (2060) = 0.012	Point values
S3 Motukiore Road	El Niño Median = 0.001, 95 th percentile = 0.025 La Niña Median = 0.0025, 95 th percentile = 0.025	Point values
S4 Rawene domain	El Niño Median = 0.0005, 95 th percentile = 0.01 La Niña Median = 0.001, 95 th percentile = 0.01	Point values
S5 Tauteihihi	El Niño Median = 0.00025, 95 th percentile = 0.001 La Niña Median = 0.001, 95 th percentile = 0.0025	Point values
S6 Pikipāria	El Niño Median = 0.00025, 95 th percentile = 0.001 La Niña Median = 0.001, 95 th 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	$\alpha = 0.04, \beta = 0.055, P(\text{ill} \text{infection}) = 0.6, P(\text{susceptible}) = 0.74$ 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 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. 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			
	2	3	4	5
Freshwater sites – current discharge flow scenario				
Mean flows				
S0 ^b	2.30	0.57	0.09	<0.01
S1 ^b	0.50	0.06	<0.01	<0.01
S2 ^b	0.38	0.05	<0.01	<0.01
Mean annual low flows				
S0 ^b	7.51	1.63	0.39	0.05
S1 ^b	1.51	0.41	0.04	<0.01
S2 ^b	1.20	0.26	0.03	<0.01
Freshwater sites – future (2060) discharge flow scenario				
Mean flows				
S0 ^b	2.81	0.70	0.11	0.01
S1 ^b	0.60	0.09	0.01	<0.01
S2 ^b	0.49	0.07	<0.01	<0.01
Mean annual low flows				
S0 ^b	8.90	1.99	0.48	0.07
S1 ^b	1.79	0.50	0.06	<0.01
S2 ^b	1.42	0.30	0.04	<0.01
Estuarine/marine sites				
El Niño – median dilution				
S3	0.28	0.03	<0.01	<0.01
S4	0.17	0.02	<0.01	<0.01
S5	0.09	0.01	<0.01	<0.01
S6	0.07	<0.01	<0.01	<0.01
El Niño – 95th percentile dilution				
S3	2.29	0.56	0.07	<0.01
S4	1.32	0.30	0.04	<0.01
S5	0.34	0.04	<0.01	<0.01
S6	0.27	0.03	<0.01	<0.01
La Niña – median dilution				
S3	0.56	0.07	<0.01	<0.01
S4	0.30	0.04	<0.01	<0.01
S5	0.34	0.04	<0.01	<0.01
S6	0.27	0.03	<0.01	<0.01
La Niña – 95th percentile dilution				
S3	2.29	0.56	0.07	<0.01
S4	1.32	0.30	0.04	<0.01
S5	0.58	0.09	0.01	<0.01
S6	0.57	0.07	<0.01	<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 2 log₁₀ (99% 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 some cases but only greater than 5% (indicative of poor water quality) at the discharge site during low river flow conditions. At a more realistic 4 log₁₀ removal risks would be below 1% for all sites under all conditions, and less than 0.1% except at the discharge point (S0) under low river flow conditions and marginally at mean flows under the 2060 discharge scenario. At 5 log₁₀ removal risks at all sites under all conditions would be consistent with excellent water quality. The categorisation of risks associated with swimming at sites S0-S2 is unaffected by the higher discharge volumes estimated for the future (2060), except for a minor change at site S0 under the mean flow, 4-log₁₀ reduction scenario.

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 between discharge and exposure points 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 locations within the riverine component of the discharge course, two locations near the outlet of the Waima river to the Hokianga Harbour and two locations at points within the Hokianga Harbour. Risks were assessed at mean or median dilutions and at low dilution (95th percentile) or river mean annual low flow (MALF) and at four levels of viral removal by the WWTP (2, 3, 4 and 5 log₁₀). For sites closest to the point of discharge, the impact of estimated future increases in the volume of wastewater discharged was also considered. 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 2 log₁₀ removal of noroviruses by the Kaikohe WWTP and low dilution (95th percentile or MALF), risks associated with swimming only exceed 5% (indicative of poor water quality) at the point of discharge into the Wairoro Stream (New Zealand Government, 2020). However, at levels of viral removal expected by the proposed treatment process (4+ log₁₀ viral removal) the recreational water classification would be excellent at all sites under all conditions. This includes scenarios of increased future treated wastewater discharge volumes.

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. Therefore, the improvements resulting from the upgrade of the Kaikohe WWTP should have more widespread impacts on water quality in the Hokianga Harbour.

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