A Quantitative Microbial Risk Assessment of the Opononi WWTP discharge and receiving environment

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Contents

Executive Summary

Wastewater is treated at the Opononi wastewater treatment plant (WWTP) using a combination of mechanically aerated lagoon, with one brush aerator, followed by a detention pond (for retention and sludge settling) prior to transfer of wastewater to the constructed wetland treatment system. Treated effluent discharges to the Hokianga Harbour during an outgoing tide via a submerged. Apart from the Opononi WWTP, three other upstream WWTPs (i.e. Kaikohe, Kohukohu and Rawene WWTPs) discharge into the Hokianga Harbour.

As part of the process of renewing the consent for the Opononi Wastewater Treatment Plant (WWTP) marine shoreline discharge, a Quantitative Microbial Risk Assessment (QMRA) has been prepared to assess the viral enteric illness risks related to contact recreation and consumption of harvested shellfish , as well as the acute febrile illness (respiratory) risks associated with potential inhalation of spray droplets following discharge from the outfall. The QMRA is a fundamental part of the discharge application, not only because it provides an assessment of the health risks associated with the outfall discharge, but also because it provides an indication of the WWTP virus treatment/disinfection required to alleviate those risks.

Presented in this report is information on all water-related enteric and respiratory illnesses whose causative agents have an established dose-response formulation. Consistent with previous QMRAs, for environmental waters impacted by treated wastewater, the ideal pathogens considered for this human risk assessment are the viruses: norovirus, enterovirus and adenovirus. While norovirus and enterovirus are used as QMRA pathogens to assess risks associated with ingestion of water or raw shellfish harvested from the exposure sites, adenovirus is used to assess risks associated with inhalation of water. Typical concentrations of these viruses in untreated wastewater, as have been documented in previous New Zealand QMRAs, were used to assess risks associated with ingestion of potentially polluted water and inhalation of aerosolised pathogens e.g. during water-skiing or for people accessing the shore close to the outfall being subject to wave/wind driven spray. In addition to recreational exposure, this QMRA assessed three established shellfish gathering sites for risks related to consumption of raw shellfish harvested at these sites. Pathogen concentrations arising from the discharge of treated wastewater from an outfall into the ocean near the harbour were predicted at these sites using a hydrodynamic model calibrated by MetOcean (2020).

As with previous NZ QMRAs, we sought out to determine if there will be any risks associated with the discharge, should various levels of log removals be achieved at the Opononi WWTP. Four scenarios of virus removal in the existing treatment systems at the Opononi WWTP were modelled, these being 1-log, 2-log, 3-log and 4-log reductions corresponding to 10-, 100-, 1,000- and 10,000-fold reductions in virus concentrations.

At the end of the QMRA, a comparative analysis was conducted. That is, we determined the virus log reductions assumed to be achieved at the Opononi WWTP (as informed by previously published values for similar treatment systems)[1]. We then assessed whether this level of treatment is associated with any form of health risks based on our QMRA results for that level of treatment.

In order to optimize public health protection, this QMRA applied a precautionary approach all through the entire process, for instance through the inclusion of occasional very high influent virus concentrations that occur during on-going but undetected viral illness outbreak in the community.

Hydrodynamic Modelling

A three-dimensional hydrodynamic model was calibrated by MetOcean. This included a comparison of model performance against measured water levels and currents and the mixing of the treated wastewater plume and oceanic waters near the discharge point (MetOcean 2020). Time series of virus dilutions were extracted from the year-long 2017 simulation (*el nino* and *la nina*) for 8 selected exposure sites and subsequently provided to SEL and applied in the QMRA to assess the risk of recreational illness (i.e. swimmers and people in close proximity to wave/wind driven spray) and individuals who consume raw shellfish.

QMRA Results

Results of the QMRA show that if 1-log virus (i.e. 10-fold) reduction is achieved by the WWTP, then at all the sites illness risks associated with ingestion and inhalation of water potentially containing enterovirus or norovirus from the discharge will be reduced below the "no observable adverse effect level" (NOAEL). However, under this same virus reduction level, the discharge of treated wastewater from the WWTP generally poses "low" risk of illness associated with consumption of raw shellfish (although the IIRs were only fractionally above the 1% threshold for NOAL).

Wastewater treatment that reduces virus concentrations in the WWTP discharge by 2-log (i.e. 100-fold) reduction will reduce health risks associated with the discharge (in relation to inhalation, ingestion during swimming and consumption of shellfish harvested) at all exposure sites, to levels below the NOAEL.

In published literature, a 2log virus removal is the most predominantly reported level of reduction in virus concentrations in constructed wetland treatment systems. In line with the QMRA results, if the wetland treatment system is achieving a 2log virus removal, as commonly indicated by available literature, the level of treatment currently applied at the Opononi WWTP is sufficient to reduce illness risks associated

[1] An equally robust approach to determine the virus log reductions currently being achieved at the Opononi WWTP is to make a statistical comparison of a year long monitoring exercise of virus influent and effluent virus concentrations.

with recreation or consumption of harvested raw shellfish below the “no observable adverse effect level” (NOAEL).

1. Introduction

Wastewater is treated at the Opononi wastewater treatment plant (WWTP) using a combination of mechanically aerated lagoon, with one brush aerator, followed by a detention pond (for retention and sludge settling) prior to transfer of wastewater to the constructed wetland treatment system. Treated effluent discharges to the Hokianga Harbour (approximately 2.6km from the Harbour mouth) during an outgoing tide via a submerged outfall. Apart from the Opononi WWTP, three other upstream WWTPs (i.e. Kaikohe, Kohukohu and Rawene WWTPs) discharge into the Hokianga Harbour.

As part of the process of renewing resource consents for the Opononi WWTP discharge into the Hokianga Harbour, a Quantitative Microbial Risk Assessment (QMRA) is required to address enteric illness risks related to consumption of harvested shellfish and contact recreation, as well as acute febrile illness risks associated with potential inhalation of water following the discharge and dilution in the receiving environment. The QMRA is a fundamental part of the discharge application, not only because it interfaces with the hydrodynamic studies, but because it provides some feedback loop to the WWTP treatment requirement.

To allow the Northland Regional Council (NRC) to properly assess risk to human health from the Opononi WWTP discharge, Question 2 of the S92 request for further information specifically requests that:

> *"the applicant shall identify recreational swimming and food gathering areas that are within the area between where the discharge leaves the channel and the shore. A quantitative microbiological risk assessment of the level of risk to public health shall be undertaken for these identified areas. If there is a quantifiable risk to public health in an area, then the assessment shall recommend mitigation measures to reduce this risk to an acceptable level"*

This QMRA report is designed to fulfil the requirements of the S92 request from NRC and is presented into topical sections. Section 2 presents a general summary of the hydrodynamic modelling (from MetOcean) which provides insights on the fate of the wastewater plume in the receiving environment. Section 3 captures a discussion on the approach used in the QMRA modelling, while Section 4 and 5 report and discuss the results of risks associated with ingestion and inhalation of water and consumption of shellfish at sites potentially impacted by the treated Opononi WWTP discharge water. Section 6 provides recommendations and section 7 conclusion.

2. Dilution modelling

MetOcean (2020) conducted three-dimensional hydrodynamic model simulations carried out for the assessment of the public health risk associated with the Opononi

WWTP. This allows quantitative estimations of distribution of wastewater dilutions at key sites in the receiving environment.

To ensure that a worst-case scenario is captured in the modelling:

(a) All four WWTPs discharging into the harbour were simultaneously "turned on", such that the effect modelled at exposure sites in this QMRA for Opononi WWTP also captured additional effects from WWTPs upstream of the Opononi WWTP.
(b) A conservative tracer run was adopted in the hydrodynamic modelling. That is, the 'effective' dilutions are generally reflective of physical dilution due to currents only (that is, solar inactivation was excluded). The reasons for the exclusion of solar inactivation in the hydrodynamic model are supported by published literatures (e.g. see Silverman 2013, Linden et al 2007; Jin & Flury 2002). To summarise, the effectiveness of sunlight inactivation of waterborne viruses depends on complex and variable environmental factors (e.g. the intensity and spectrum of sunlight), characteristics of the water containing the virus particles (e.g. pH, dissolved oxygen, ionic strength, source and concentration of photosensitizers), and peculiarities of the virus particles (e.g. virus structures, genome type and prevalence of sites susceptible to photo-transformation; protein capsid composition and structure). These uncertainties present a core challenge in accurately modelling virus inactivation rates. Despite the uncertainties associated with estimating the actual rates of UV inactivation that would take place in the receiving environment, it is certain that ultraviolet inactivation will occur. MetOcean's approach to exclude ultraviolet inactivation from the hydrodynamic module (as was applied in the conservative tracer model run) is thus, from a public health protection perspective, a highly precautionary approach.

Consequently, the reported risks from this QMRA include the worst-case scenario and may be overstated.

Far North District Council (FNDC) identified eight potential sites where recreation and raw shellfish harvesting is most likely to occur in the receiving environment. These sites were applied as key exposure sites in this QMRA (see Figure 1 and Table 1).

Time series of dilutions of virus concentrations were extracted from the year-long 2018 simulation for selected locations shown in Table 1. This time series data was later applied in the QMRA to assess the risk of illness to recreation (i.e. swimmers and inhalation) and individuals who consume raw shellfish (Section 3).

Table 1. Geographical coordinates and description of the exposure sites under consideration in this QMRA.

Site number	Site name	Latitude	Longitude	Description
1	CR1	-35.504251°	173.390411°	Upstream of the Opononi WWTP discharge, Hokianga Harbour Opononi LAWA site
2	CR2	-35.515411°	173.387529°	Upstream of the Opononi WWTP discharge
3	SF1	-35.519921°	173.371407°	Downstream of the Opononi WWTP discharge, situated west of the Opononi WWTP outfall
4	SF2	-35.523065°	173.384118°	Downstream of the Opononi WWTP discharge
5	CR3-SF3	-35.534885°	173.384695°	Downstream of the Opononi WWTP discharge, Omapere at Old Wharf Road LAWA site
6	SF4	-35.532088°	173.381731°	Downstream of the Opononi WWTP discharge
7	CR4-SF5	-35.535154°	173.371413°	Downstream of the Opononi WWTP discharge
8	CR5-SF6	-35.538855°	173.364246°	Downstream of the Opononi WWTP discharge

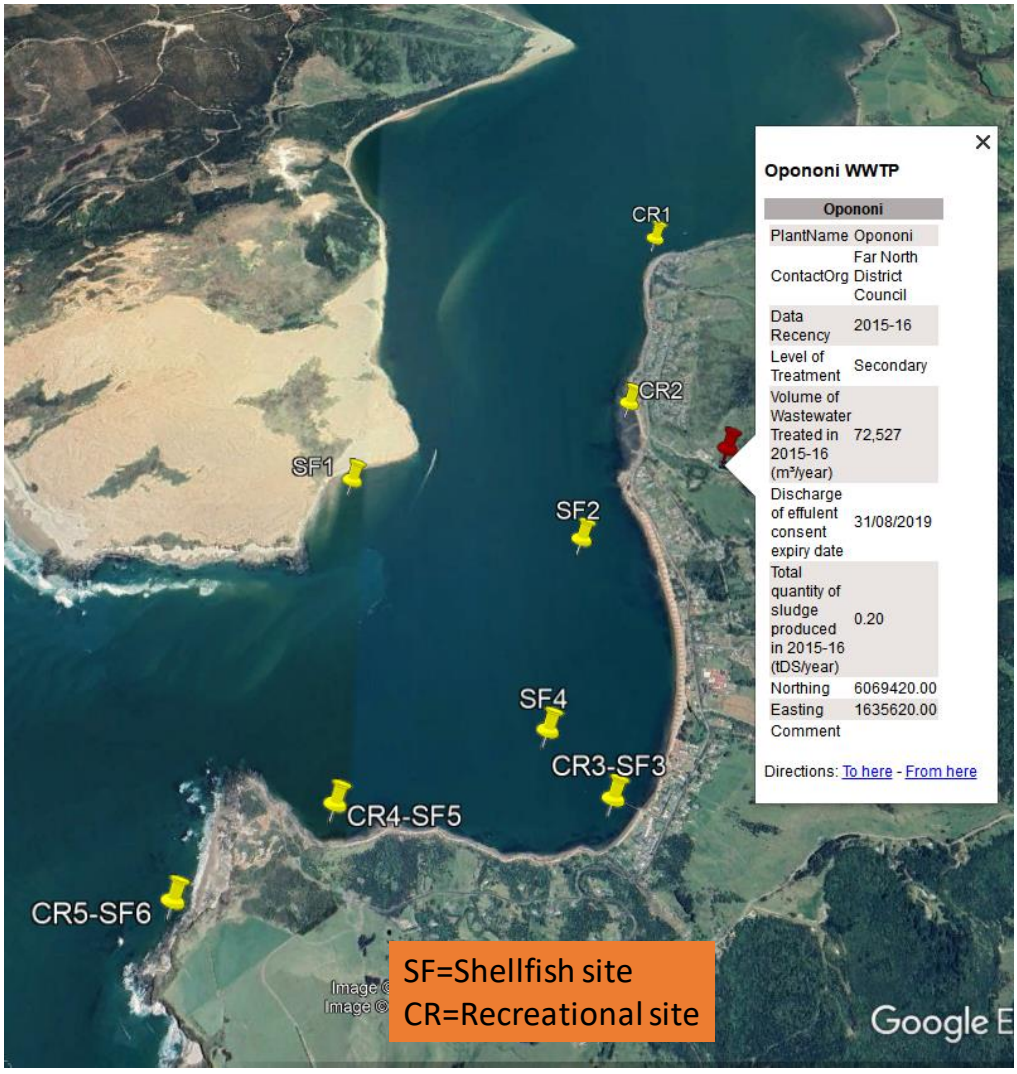

Figure 1. Location of assessment sites under consideration in this QMRA.

The 95th percentile dilutions of the virus dilutions during the conservative tracer model runs are presented in Table 2. High dilutions of up to 10^5 were observed during both *el nina*[2] and *la nina* conditions. For instance, dilutions in the receiving environment ranged from 2.03 x 10^5 at SF1 (the shoreline site situated west of the Opononi WWTP outfall) to 2.31 x 10^5 at Site CR5-SF6 (the outlet of the harbour).

Table 2. 95th percentile dilutions from the annual simulation of a conservative tracer at the QMRA sites. Source concentration is assumed to be 1 Unit.

Scenario	CR1	CR2	CR3-SF3	CR4-SF5	CR5-SF6	SF1	SF2	SF4
El nino	2.30E+05	2.31E+05	2.14E+05	2.11E+05	2.31E+05	2.03E+05	2.07E+05	2.11E+05
La nina	1.34E+05	1.36E+05	1.26E+05	1.28E+05	1.68E+05	1.26E+05	1.32E+05	1.26E+05

3. Quantitative Microbial Risk Assessment

3.1 Overview

Quantitative Microbial Risk Assessment (QMRA) is a framework that applies information and data incorporated into mathematical models to assess the potential public health risks from pathogens after discharge in a receiving environment such as water[3]. While quantitative risk assessment was initially designed to assess risks of exposure to various hazards, particularly chemicals, it has since been modified to incorporate risks related to exposure to microbial pathogens (NRC 1983). Risk is the combination of the likelihood of identified hazards causing harm in exposed populations in a specified time frame and the severity of the consequences (Hrudey, Hrudey, and Pollard 2006).

Typically, four steps are involved in a QMRA (Haas, Rose, and Gerba 1999). These are: hazard identification, exposure assessment, dose-response analysis, and risk characterization.

[2] El Niño and La Niña, the two most common climatic conditions experienced in NZ, are "opposite phases of a naturally occurring global climate cycle known as the El Niño Southern Oscillation, or ENSO for short. ENSO influences rainfall, temperature, and wind patterns" (kindly see https://niwa.co.nz/climate/information-and-resources/elnino) .

[3] It is important to note that the assessment only relates to the risk from a particular discharge, i.e. it doesn't take into account the risks associated with other discharges (for example, stormwater or non-point source discharges) that may be in the area.

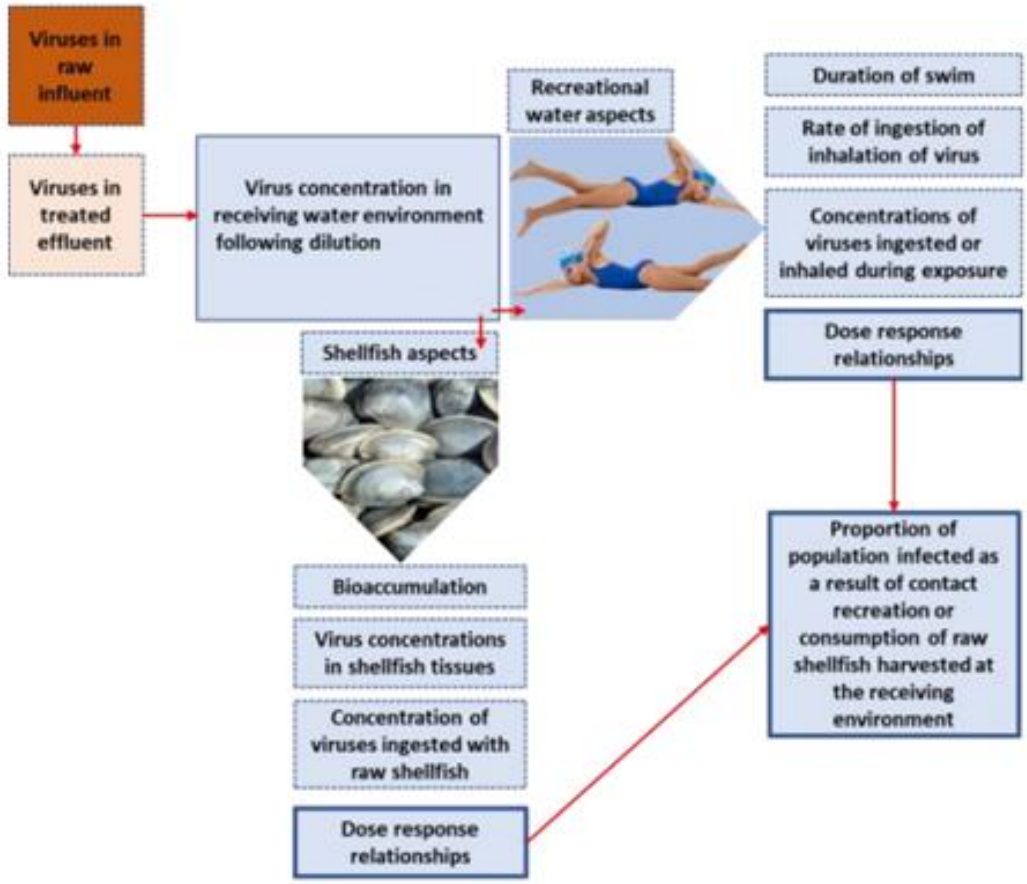

Figure 2. Typical stages in a QMRA.

3.2 Hazard analysis

Wastewater can contain several pathogenic species (Jacangelo et al. 2003; McBride 2007). The majority of pathogens in wastewater are enteric, that is, they affect the digestive system, and may present a serious health risk if ingested (Hai et al. 2014). These include: protozoans, which can cause life-threatening diseases including giardiasis, cryptosporidiosis, helminthiasis, dysentery and amoebic meningoencephalitis (Bitton 2010); viruses, which can cause paralysis, meningitis, respiratory disease, encephalitis, congenital heart anomalies and acute febrile respiratory illnesses (AFRI) and gastrointestinal illnesses (GI) (Melnick, Gerba, and Wallis 1978; Toze 1997; Okoh, Sibanda, and Gusha 2010); and bacteria, consisting of the enteropathogenic and opportunistic bacteria which cause gastrointestinal diseases such as cholera, dysentery, salmonellosis, typhoid and paratyphoid fever (Toze 1997; Cabral 2010).

Because the tests for pathogens are time-consuming and expensive, it is not practical to implement such testing on a routine basis. Instead, regulatory bodies support testing for faecal indicator bacteria (FIB) (e.g. enterococci and faecal coliforms) as a cost-effective means to assessing the presence of faecal contamination and the

quality of treated effluent. These generally non-pathogenic bacteria are contained in the gut of warm-blooded animals, including humans, in large concentrations. Research shows that most pathogens die at the same rate as FIB, and hence the numbers of FIB in the treated effluent can be used to indicate the presence of pathogens.

While focus has been placed on enterococci concentrations for regulatory purposes, limitations associated with the use of conventional FIB as an indicator for viruses is well documented (Wade et al. 2008, Wade et al. 2010, USEPA 2015). Furthermore, as most standard wastewater treatment and disinfection processes vary in their efficiency in eliminating viruses, treated effluent may still contain concentrations of enteric viruses that present a significant public health risk (Lodder et al. 2010; Okoh, Sibanda, and Gusha 2010). Several enteric viruses have been described in published literature as associated with outbreaks due to exposure to polluted recreational water (Jiang et al., 2007; Sinclair et al., 2009, USEPA 2015). These include noroviruses, adenoviruses, hepatitis A viruses, echoviruses and Coxsackie viruses (Hauri et al. 2005; Lodder et al. 2010). Literature has also suggested that the greatest public health risk linked with the discharge of treated wastewater relates mainly to viruses (Courault et al. 2017; Prevost et al. 2015). A unique characteristic of viral infections is that a high proportion of the exposed populations could be potentially affected, often leading to very high incidences of gastroenteritis that can then be spread by person-to-person contact to other individuals who were not directly exposed to the polluted waters (Patel et al. 2008; Widdowson, Monroe, and Glass 2005). For instance, a single vomiting incident from an individual infected with norovirus could expel up to 30 million virus particles (Tung-Thompson et al. 2015). In community settings, this could result in contamination of surfaces with large numbers of viruses, effectively promoting the further spread of the pathogens.

For environmental waters impacted by treated wastewater, the ideal reference pathogens considered for human risk assessment are the viruses: norovirus, enterovirus and adenovirus (McBride 2016a,b). These viruses have been used as representative viruses for previous studies in New Zealand (McBride 2011, 2012, 2016a,b). While norovirus and enterovirus are significant contributors to enteric infections, adenovirus (Type 4) can cause respiratory illnesses via inhalation of aerosols from contaminated water during swimming, water-skiing or people accessing the shore close to the outfall being subject to wave/wind driven spray. Hence, in this study, norovirus and enterovirus were used as reference QMRA pathogens for primary contact recreation and shellfish consumption. For secondary contact recreation, which includes activities such as shoreline walking, jogging, paddling, wading, boating and fishing, in which there may be some direct contact but the chance of swallowing water is unlikely, only adenovirus (Type 4) was used as reference pathogen for assessing risks associated with inhalation of potentially polluted water (e.g. from wind or wave-induced spray) containing aerosolised pathogens. Other technical reasons that warranted the choice of these reference pathogens are detailed in Appendix 1. Typical concentrations of these reference viruses in untreated wastewater are presented in Table 3 and are in line with values

have been documented in several previous New Zealand QMRAs (e.g. Dada 2018a; 2018b; McBride 2011, 2016a, b).

3.3 Exposure Assessment

Exposure assessment involves identification of populations that could be affected by pathogens. The main individuals at risk of exposure to pathogens in the receiving environment of the Opononi WWTP are those that engage in any sort of contact recreation or those who consume raw shellfish collected from any site potentially impacted by the discharge. In order to assess the potential level of exposure, the following were considered:

- proximity of the QMRA site[4] to the discharge outlet;
- the possible exposure pathways that allow the pathogen to reach people and cause infection (through the air, through ingesting polluted water, consuming shellfish etc.);
- range (minimum, maximum and median) of pathogen concentrations in treated effluent;
- discharge volumes of the treated wastewater;
- the environmental fate of the microbial contaminants in the receiving environment: dilution of viral pathogens in the receiving marine environment;
- how much water a child[5] will ingest or inhale over a period of time during a particular recreational activity;
- how much raw shellfish harvested from the impact sites that an individual will consume at one sitting; and
- estimation of the amount, frequency, length of time of exposure, and doses for an exposure.

3.3.1 Opononi WWTP influent and effluent virus concentrations

There are no available data on the influent and effluent virus concentrations in the Opononi WWTP discharge. Notwithstanding, a range of influent virus concentrations have already been reported in long term studies in New Zealand, and these have been used as representative influent virus concentrations in previous New Zealand QMRAs (e.g. Dada 2018a; 2018b; McBride 2016a,b). Influent virus concentrations (minimum, maximum and median) applied in this QMRA were therefore based on these previous documented ranges (see Table 3).

[4] FNDC was responsible for identifying potential exposure sites for the QMRA.
[5] A child is considered the worst-case risk because studies show that ingestion rates for children are twice as much as for adults (e.g. Dufour et al.2006) as reported in McBride (2017) QMRA for Bell Island WWTP outfall.

A range of possible log_{10} reductions[6] in virus concentrations are possible following WWTP treatment processes. For instance, this could range from 1-log reduction to as high as 4-log reductions. In this QRMA, we assessed health risks that would be associated with the discharge, assuming any of these levels of influent virus reductions is achieved at the Opononi WWTP before the treated wastewater is discharged into the receiving environment.

At the end of the QMRA, a validation exercise was then conducted. That is, we determined the virus log reductions currently being achieved at the Opononi WWTP (as informed by previously published values for similar treatment systems)[7]. We then assessed whether this level of treatment is associated with any form of health risks based on our QMRA results for that level of treatment.

3.3.2 Predicting exposure doses

The dose of the pathogen that an individual ingests, inhales or comes in contact with is an important component of the dose-response models used to predict the probability of infection or illness. In order to convert pathogen concentrations into doses, reference was made to the influent virus concentrations, the ingestion or inhalation rates for the water users (adults and children, in the case of swimming or other contact recreation), as well as shellfish bioaccumulation factors (in the case of shellfish harvesters). Details of these dose response models are presented in Appendices 1 to 3.

For risks due to swimming, water ingestion rates applied in the QMRA (Table 3) were based on previous studies that have applied biochemical procedures to trace a decomposition product of chlorine-stabilizing chloroisocyanurate which passes through the surveyed swimmers' bodies unmetabolized (Dufouer et al 2006, McBride 2016).

Table 3 Distributions and inputs for the QMRA (Adapted from McBride 2016a,b).

Parameter	QMRA Statistics applied	Comments
Influent concentration, Adenovirus	Minimum = 2,000 Median = 5,000 Maximum = 30,000,000	Hockey stick distribution, as previously described (McBride 2007, 2011; 2012; 2016 a,b). Norovirus harmonization factor of 18.5 was included, in line with McBride 2011 and 2017)
Influent concentration, Norovirus	Minimum = 100 Median = 10,000 Maximum = 10,000,000	
Influent concentration, Enterovirus	Minimum = 500 Median = 4,000 Maximum = 50,000,000	

[6] Also called log removal value (LRV). It is a measure of the ability of a treatment processes to remove the viruses in question. An LRV of 1 (i.e. 1log removal) is equivalent to 90% removal of a target pathogen, an LRV of 2 (i.e. 2log removal) is equivalent to 99% removal, an LRV of 3 is equivalent to 99.9% removal, and 4 log reduction = 99.99% reduction etc.

[7] An equally robust approach to determine the virus log reductions currently being achieved at the Opononi WWTP is to make a statistical comparison of a year-long monitoring exercise of virus influent and effluent virus concentrations.

Parameter	QMRA Statistics applied	Comments
Duration of swim (hours)	Minimum = 0.1 Median = 0.25 Maximum = 2	For child or adult (McBride 2007, 2011; 2012; 2016 a,b)
Swimmers water ingestion rate, mL per hour	Minimum = 20 Median =50 Maximum = 100	PERT distribution for a child rate. Typically, adult rate is half the child rate (Dufour et al, 2006)
Water inhalation rate, mL per hour	Minimum = 10 Median =25 Maximum = 50	PERT distribution for an adult, assumed as half of child rate (McBride 2007, 2011; 2012; 2016 a,b)
Dose response parameters	Enterovirus (beta-binomial model, α = 1.3, β =75) Prob(illness/infection)=1	Dada 2018a; 2018b; McBride 2007, 2011; 2012; 2016; Stewart et al. 2017, Soller et al. 2010a,b
	Adenovirus Type 4 (simple binomial model, r = 0.4142). Only 3-10% of adenoviruses cause respiratory illnesses. Prob(illness/infection)=0.5	Dada 2018a; 2018b; McBride 2007, 2011; 2012; 2016; Stewart et al. 2017, Soller et al. 2010 a,b, Kundu et al. 2013
	Norovirus (beta-binomial model, α = 0.04, β =0.055) Prob(illness/infection)=0.6	Dada 2018a; 2018b; McBride 2007, 2011; 2012; 2016; Stewart et al.2017, Soller et al. 2010 a,b
Shellfish size	α = 2.2046 β = 75.072 γ = -0.903	Loglogistic distribution between 5g and 800g, based on estimates of daily intake of consumers of raw shellfish (see McBride 2005, McBride 2007, 2011; 2012; 2016, Russel et al.1999)
Pathogen bioaccumulation factor (PBAF)	Mean = 49.9 Standard deviation = 20.93	Normal distributions around mean. Pathogen dose upon consumption of 100 grams of shellfish is a product of the PBAF and the number of pathogens in an equivalent volume of water (see Burkhardt & Calci 2000, McBride 2007, 2011; 2012; 2016)

In order to assess risks due to consumption of raw harvested shellfish, ingestion rates used were in line with estimates of daily intake of 98 consumers of mussels, oysters, scallops, pipi and tuatua in the 1997 National Nutrition Survey, as reported in previous New Zealand QMRAs (e.g. Dada 2018a,b, Stewart et al.2017, McBride 2005, 2016a,b).

It is important to note that previous QMRA reports (e.g. McBride 2016 a, b) have assessed risks due to ingestion of raw shellfish tissue using bivalve molluscs as the vector. This is because bivalve molluscs are very common and accessible in New Zealand waters, are very frequently consumed raw; and because they are known to 'bioaccumulate' pathogens, hence the additional multiplier effect called the pathogen

bioaccumulative factor (PBAF, see Table 3) applied in our model (Bellou, Kokkinos, and Vantarakis 2013; Hanley 2015; Hassard et al. 2017).

3.3.3 Dose-response models

Dose-response models estimate the risk of a response (for example, infection or illness) given a known dose of a pathogen. Dose-response models are mathematical functions which describe the dose-response relationship for specific pathogens, transmission routes and hosts. Additional dose-response details are presented in the Appendix 2 and 3.

3.3.4 Risk characterization

Information from the previous steps were incorporated into Monte Carlo simulations to determine the likelihood of illness from exposure to pathogens. The Monte Carlo simulation is a randomization method that applies multiple random sampling from distributions assigned to key input variables in a model, in a way that incorporates the uncertainty profiles of each key input variable into the uncertainty profile of the output.

Typically, in a Monte Carlo model run, 100 individuals who do not have prior knowledge of existing contamination in the water are 'exposed' to potentially infectious water on a given day and this exposure is repeated 1,000 times. Therefore, the total number of exposures is 100,000. The result of the analysis is a full range of possible risks, including average and worst-case scenarios, associated with exposure to pathogens during the identified recreational activities or following consumption of raw shellfish. Monte Carlo simulations were undertaken using @Risk software (Palisade, NY). QMRA results are reported in terms of both infection and illness. It is noted however, that not all individuals that become infected eventually become ill. Although pathogen-dose response models in literature were determined based on infection endpoint, illness endpoint can be estimated simply using a uniform probability for illness as was done in several previous QMRAs (e.g. McBride 2011, 2017). Infection/illness ratios of 0.6 and 0.5 were applied for noroviruses and adenoviruses (McBride 2016), respectively. Due to the relative unavailability of dose-response and morbidity data for enterovirus, a precautionary approach was used in this study, that is, it was assumed that every individual who contracted enterovirus infections also became ill, hence a conservative infection/illness ratio of 1 was applied. This is in line with methods applied in previous New Zealand QMRAs (e.g. McBride 2011, 2016).

The predicted risk is reported as the IIR (individual illness risk), calculated as the total number of infection cases divided by the total number of exposures, expressed as a percentage. The IIR is then compared with thresholds defined in the New Zealand "*Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas*" (MfE/MoH 2003). Depending on the risk being examined, the applicable NZ thresholds differ.

In the case of risk due to gastrointestinal illnesses (GI) as a result of ingestion of polluted water while swimming or consumption of raw shellfish harvested from the impacted sites, the following thresholds apply:

- high illness risk (>10% GI illness);
- moderate illness risk (5-10% GI illness);
- low illness risk (1-5% GI illness);
- NOAEL (<1%); the 1% IIR threshold, also referred to as the 'no observable adverse effects level (NOAEL), is the widely-accepted threshold when assessing the effect of wastewater discharge on recreational health risk (Dada 2018a; 2018b; McBride 2016a,b, 2017; Stewart et al.2017).

In the case of acute febrile respiratory illness (AFRI) risks due to inhalation of pathogens in spray water, near or at the impacted sites, comparatively lower thresholds apply:

- high illness risk (>3.9% AFRI illness);
- moderate illness risk (1.9-3.9% AFRI illness);
- low illness risk (0.3-<1.9% AFRI illness);
- NOAEL (<0.3%).

With respect to the MfE/MoH (2003) guidelines for marine waters[8]:

- High risks relate to 95th percentile enterococci concentrations greater than 500 enterococci/100mL.
- Moderate risks relate to 95th percentile enterococci concentrations between 201 and 500 enterococci/100mL.
- Low risks generally relate to 95th percentile enterococci concentrations between 41 and 200 enterococci/100mL.
- NOAEL relate to 95th percentile concentrations ≤40 enterococci/100mL.

4. QMRA Results

The results of the QMRA analysis for individuals exposed to a range of reference pathogens under the various proposed discharge scenarios are presented in Table 4 to Table 8.

[8] in Hudson and McBride (2017)

4.1 Risks associated with ingestion of water

Table 4. Child's Enteric Illness Risk (%) at eight identified sites potentially impacted by enterovirus during different Opononi WWTP discharge scenarios.

Virus Log Reduction	Exposure site	El nino		La nina	
		Summer	Annual	Summer	Annual
1 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1
2 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1
3 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1
4 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1

IIR> 10%	High enteric illness risk
IIR (5.0-10%)	Moderate enteric illness risk
IIR (1.0-4.99%)	Low enteric illness risk
IIR <1%	NOAEL

Table 5. Child's Enteric Illness Risk (%) at eight identified sites potentially impacted by norovirus during different Opononi WWTP discharge scenarios.

Virus Log Reduction	Exposure site	El nino		La nina	
		Summer	Annual	Summer	Annual
1 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1
2 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1
3 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1
4 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1

IIR> 10%	High enteric illness risk
IIR (5.0-10%)	Moderate enteric illness risk
IIR (1.0-4.99%)	Low enteric illness risk
IIR <1%	NOAEL

4.2 Risks associated with inhalation of water

Table 6. Child's Acute Febrile Illness Risk (%) at eight identified sites potentially impacted by adenoviruses during different Opononi WWTP discharge scenarios.

Virus Log Reduction	Exposure site	El nino		La nina	
		Summer	Annual	Summer	Annual
1 Log Reduction	CR1	<0.1	0.12	<0.1	0.14
	CR2	<0.1	<0.1	<0.1	0.21
	CR3-SF3	<0.1	0.15	<0.1	0.23
	CR4-SF5	<0.1	0.11	<0.1	0.21
	CR5-SF6	<0.1	0.11	<0.1	0.15
	SF1	<0.1	0.17	<0.1	0.21
	SF2	<0.1	<0.1	<0.1	0.25
	SF4	<0.1	0.15	<0.1	0.26
2 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1
3 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1
4 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1

IIR> 3.9%	High AFR illness risk
IIR (1.9 - 3.9%)	Moderate AFR illness risk
IIR (0.3 - <1.9%)	Low AFR illness risk
IIR <0.3%	NOAEL

*AFR =Acute Febrile Respiratory

4.3 Risks associated with shellfish harvesting and consumption

Table 7. Individual's Illness Risk (%) associated with consumption of raw shellfish collected at exposure sites that are potentially impacted with enteroviruses as a result of Opononi WWTP discharge.

Virus Log Reduction	Exposure site	El nino		La nina	
		Summer	Annual	Summer	Annual
1 Log Reduction	CR1	0.67	1.13	0.70	0.89
	CR2	0.60	0.89	0.60	1.13
	CR3-SF3	0.73	0.94	0.64	1.40
	CR4-SF5	0.71	0.96	0.72	1.10
	CR5-SF6	0.67	0.94	0.62	1.32
	SF1	0.70	0.76	0.76	1.28
	SF2	0.73	1.19	0.69	1.03
	SF4	0.65	1.10	0.85	0.98
2 Log Reduction	CR1	<0.1	0.21	0.11	0.17
	CR2	<0.1	0.14	<0.1	0.25
	CR3-SF3	0.12	0.17	<0.1	0.28
	CR4-SF5	<0.1	0.17	0.13	0.20
	CR5-SF6	<0.1	0.17	0.10	0.24
	SF1	0.10	0.12	0.11	0.25
	SF2	<0.1	0.18	0.11	0.22
	SF4	0.13	0.19	0.14	0.21
3 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1
4 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1

IIR> 10%	High enteric illness risk
IIR (5.0-10%)	Moderate enteric illness risk
IIR (1.0-4.99%)	Low enteric illness risk
IIR <1%	NOAEL

Table 8. Individual's Illness Risk (%) associated with consumption of raw shellfish collected at exposure sites that are potentially contaminated with noroviruses as a result of Opononi WWTP discharge.

Virus LogReduction	Exposure site	El nino		La nina	
		Summer	Annual	Summer	Annual
1 Log Reduction	CR1	0.96	1.15	0.95	1.03
	CR2	0.95	0.99	0.91	0.98
	CR3-SF3	0.92	1.00	0.96	1.03
	CR4-SF5	0.91	1.10	0.95	1.17
	CR5-SF6	0.92	1.07	0.90	1.07
	SF1	0.90	1.04	0.91	1.05
	SF2	0.89	1.03	0.91	1.01
	SF4	0.90	0.99	0.94	1.01
2 Log Reduction	CR1	0.28	0.37	0.26	0.31
	CR2	0.22	0.34	0.25	0.36
	CR3-SF3	0.30	0.37	0.25	0.50
	CR4-SF5	0.27	0.32	0.27	0.39
	CR5-SF6	0.24	0.42	0.25	0.29
	SF1	0.23	0.32	0.24	0.30
	SF2	0.27	0.35	0.24	0.35
	SF4	<0.1	<0.1	<0.1	<0.1
3 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1
4 Log Reduction	CR1	<0.1	<0.1	<0.1	<0.1
	CR2	<0.1	<0.1	<0.1	<0.1
	CR3-SF3	<0.1	<0.1	<0.1	<0.1
	CR4-SF5	<0.1	<0.1	<0.1	<0.1
	CR5-SF6	<0.1	<0.1	<0.1	<0.1
	SF1	<0.1	<0.1	<0.1	<0.1
	SF2	<0.1	<0.1	<0.1	<0.1
	SF4	<0.1	<0.1	<0.1	<0.1

IIR> 10%	High enteric illness risk
IIR (5.0-10%)	Moderate enteric illness risk
IIR (1.0-4.99%)	Low enteric illness risk
IIR <1%	NOAEL

5. Discussion

5.1 Overview

In order to optimize public health protection, a precautionary approach to this QMRA has been applied through the entire process. For instance, using a hockey-stick distribution fitting, the QMRA included considerations for very high influent virus concentrations that occasionally occur during illness outbreaks in the community. While these high concentrations are rare, they have a high potential impact on the estimated risks. Another precautionary approach in this QMRA is to report the children's illness risk as opposed to the generally lower adults' risk[9], particularly considering that the . This is consistent with previous QMRAs e.g. the Bell Island QMRA (McBride 2017). This QMRA also included a dilution-only scenario which does not include solar ultraviolet-based inactivation of viruses, to capture risks posed to early-morning recreational water users. Therefore, the reported risks from this QMRA include the worst-case scenario and may be overstated.

5.2 QMRA results for recreation – ingestion of water

The QMRA results for children (Table 4 to Table 5) show that if a 1-log virus reduction for enterovirus or norovirus is achieved by the Opononi WWTP, then at all eight assessment sites, illness risks associated with ingestion of water potentially polluted by enterovirus or norovirus are reduced below the "no observable adverse effect level" (NOAEL).

5.3 QMRA results for recreation – inhalation of water

The QMRA results for children (Table 6) generally indicate that individual illness risks (IIR) were slightly higher during *la nina* than *el nino* conditions. This is understandable as the hydrodynamic modelling showed comparatively lower dilutions during *la nina* conditions. For instance, 95th percentile dilutions at the CR3-SF3 site, downstream of the Opononi WWTP discharge (Omapere at Old Wharf Road LAWA site) under *el nino* conditions was 2.14 x 10^{5}, nearly double the 95th percentile dilution achieved during *la nina* conditions at the same site (see Table 2).

The QMRA modelling found that if a 1-log virus reduction for adenovirus is achieved by the Opononi WWTP, then at all eight assessment sites, illness risks associated with inhalation of water potentially polluted by adenovirus are reduced below the "no observable adverse effect level" (NOAEL).

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[9] The 1997 National Nutrition Survey, as reported in previous New Zealand QMRAs (e.g. Dada 2018a,b, Stewart et al.2017, McBride 2005, 2016a,b) was based on adults' consumption rate for raw harvested shellfish. This study consistent with previous New Zealand QMRAs (e.g. Dada 2018a,b, Stewart et al.2017, McBride 2005, 2016a,b) used children's consumption rate that is double the published adults' rate. Hence, the risks herein reported are conservative.

5.4 QMRA results for shellfish harvesting and consumption

The QMRA modelling results for shellfish harvesting and consumption (Table 7 and Table 8) show that if a 1-log virus reduction for norovirus and enterovirus is achieved by the Opononi WWTP, then at all sites, low illness risks are associated with consumption of raw shellfish. It is important to note that the generally "low" risk of illness associated with consumption of raw shellfish harvested at these sites may be as a result of the exclusion of inactivation occurring as a result of solar radiation in the receiving environment[10]. We note also that the IIRs associated with consumption of raw shellfish are only fractionally above the 1% threshold for NOAL.

Risks associated with shellfish consumption were generally higher than for ingestion of water while swimming because of the conservative approach used for the modelling of enteric illness risks associated with shellfish risk consumption. We applied the bioaccumulation factor to assess risk associated with ingestion of raw shellfish tissue. Also, we assumed that consumption of shellfish is instantaneous (i.e. without depuration). While depuration of shellfish after harvesting and adequate refrigeration before consumption are key steps that commercial harvesters take to reduce health risks, these steps are not routinely taken by consumers of recreational shellfish. Hence consideration of depuration was not included in this QMRA. As noted in McBride (2017), this explains why risks from raw shellfish consumption are always calculated to be rather higher than risks associated with swimming in or near to the shellfish-harvesting waters.

Additionally, all four WWTPs discharging into the harbour were simultaneously "turned on", i.e. discharging wastewater, such that the effect modelled at exposure sites in this QMRA for Opononi WWTP also captured additional effects from WWTPs upstream of the Opononi WWTP. Given these considerations, we are following conservative principles and hence, reporting a worst-case scenario.

If a 2-log reduction in enterovirus and norovirus concentrations is achieved at the WWTP before discharge, enteric illness risks among individuals who consume raw shellfish collected at the shellfish harvesting sites are reduced to below the NOAEL at all the exposure sites.

5.5 Comparison of QMRA results with existing virus removals at the Opononi WWTP

The QMRA shows that if a 2-log (i.e. 100-fold) reduction in enterovirus, norovirus and adenovirus concentrations is achieved at the Opononi WWTP before discharge, enteric and acute respiratory febrile illness risks among individuals who engage in recreation or consume raw shellfish collected at the shellfish harvesting sites are reduced below the NOAEL at all sites assessed. Furthermore, the results show that if a 1-log (i.e. 10-fold) reduction in enterovirus, norovirus and adenovirus

[10] Since conservative tracer dilutions were used for the QMRA herein reported.

concentrations is achieved at the Opononi WWTP before discharge, enteric illness risks are only fractionally above the no observable effect threshold.

Further to the results obtained in this QMRA, it was necessary to assess if the current treatment system at the Opononi WWTP achieves this level of virus reduction. There are no monitoring data on the range of actual reduction in influent virus concentration at Opononi WWTP. However, literature reveal that the performance of constructed wetland systems used for wastewater treatment will vary depending on the presence and type of plants, filter depth and sand type, operational parameters, temperature effects and retention time (Quiñónez-Dìaz et al 2001). Notwithstanding, a summary of virus removals reported in available literature (Table 9) suggest that 2log virus removals is the most predominantly reported level of reduction in virus concentrations in wetlands. Therefore, and in the absence of any monitoring data, this information suggests that the level of treatment currently applied at the Opononi WWTP (if its virus reduction performance is consistent with the literature, i.e. an average 2log virus removal) is sufficient to reduce illness risks associated with recreation or consumption of harvested raw shellfish below the "no observable adverse effect level" (NOAEL).

Another indication that the required 2-log virus removal is currently being achieved at the Opononi WWTP is reflected in the faecal indicator bacteria concentration of the receiving environment water samples. Available water quality data[11] for the CR3-SF3 site (i.e. Omapere at Old Wharf Road, downstream of the Opononi WWTP discharge) and Hokianga Harbour Opononi LAWA (upstream of the Opononi WWTP discharge) sites indicates that only low health risk exists at these sites if used for recreational bathing. For instance, the 5-year 95th percentile enterococci concentration for Omapere at Old Wharf Road and Hokianga Harbour Opononi are 52 enterococci/100 mL and 70 enterococci/100 mL, respectively[12]. These concentrations are marginally above the threshold for sites classified as A in terms of the Microbiological Assessment Category (MAC) guidelines (MfE/MoH 2003), hence are classified as B. While there is no data on a recent Sanitary Inspection Category (SIC) for these sites, other potential contaminant sources (such as urban runoff, streams draining catchments etc.) may impair water quality during storm events. This was reflected in the enterococci data routinely collected by the NRC at CR3-SF3 site. For instance, enterococci concentrations at CR3-SF3 site generally did not exceed the acceptable[13] single sample threshold of 140 enterococci/100 mL (Green mode, see

[11] The Northland Regional Council has routinely monitored bathing sites, including coastal sites that are upstream and downstream of the Opononi WWTP (i.e. Hokianga Harbour Opononi and Omapere at Old Wharf Road, respectively). While data at the Omapere at Old Wharf Road site has only been collected since 2018 till date, enterococci data has since 2009 been collected at the Hokianga Harbour Opononi site. In terms of the Microbiological Assessment Category (MAC) guidelines (MfE/MoH 2003), enterococci <40 cells/mL =Band A, >40 and <200 cells/mL =Band B, >200 and <500 cells/mL =Band C and >500 cells/mL = Band D.

[12] 2014/15-2019/20 bathing seasons, although Omapere at Old Wharf Road site has only been collected since 2018 till date

[13] The most recent data (5 year long, 2014-2019) are herein analysed in relation to the guidelines stipulated in the Ministry for Environment/Ministry of Health (MfE/MoH) 2003 Microbiological water quality guidelines for marine and freshwater recreational areas. The MoH guidelines propose a three-tier management framework based on enterococci indicator values, i.e. surveillance (green), alert (amber) and action (red) modes. For the Microbiological Assessment Category (MAC) marked as "acceptable/green", no single sample should present with enterococci greater than 140 enterococci/100 mL. The alert mode requires investigation of the causes of the elevated levels and increased sampling to enable the risks to bathers to be more accurately assessed. The action mode requires the local authority and health authorities to warn the public that the beach is considered unsuitable for recreation.

upper image in Figure 3), except in one instance on the 3rd of December 2018 *when a lot of storm water was released onto the beach*[14] (observed concentration on storm event day = 680 enterococci/100 mL).

Table 9 Commonly reported virus removals in wetland treatment systems.

Type of wetland	Virus/Indicators studied	Virus removals (in %)	Virus log removals	Reference
Subsurface-flow wetland	Bacteriophages	98.80%	~2 log	Vidales et al (2003)
Surface flow wetlands	Enteric viruses (norovirus, adenovirus and enterovirus)	90-99.9%	1 to 3 log	Rachmadi, et al (2016)
Surface flow wetlands	MS-2 bacteriophages	99%	2 log	Gersberg RM et al (1989)
Surface flow wetlands	Enteric viruses	95-99%	~2 log	Gerba CP et al (2013)
Free water surface plus horizontal subsurface flow wetland	Adenovirus	99%	2 log	Kaliakatsos et al (2019)
Free water surface plus horizontal subsurface flow wetland	Enterovirus	99.9%	3 log	Kaliakatsos et al (2020)
Laboratory-simulated wetland	MS2, PRD1, and indigenous bacteriophages	99%	2 log	Vinluan (1996)
Aerated constructed wetland	Bacteriophages	99%	2 log	Stefanakis et al (2019)
Aerated constructed wetland	Enteric viruses	98 %	~2 log	Quiñónez-Dìaz et al (2001)
Subsurface flow wetland	Enteric viruses	98 %	~2 log	Karpiscak et al. (1996)

[14] Comments attached to Enterococci data recorded by Northland Regional Council

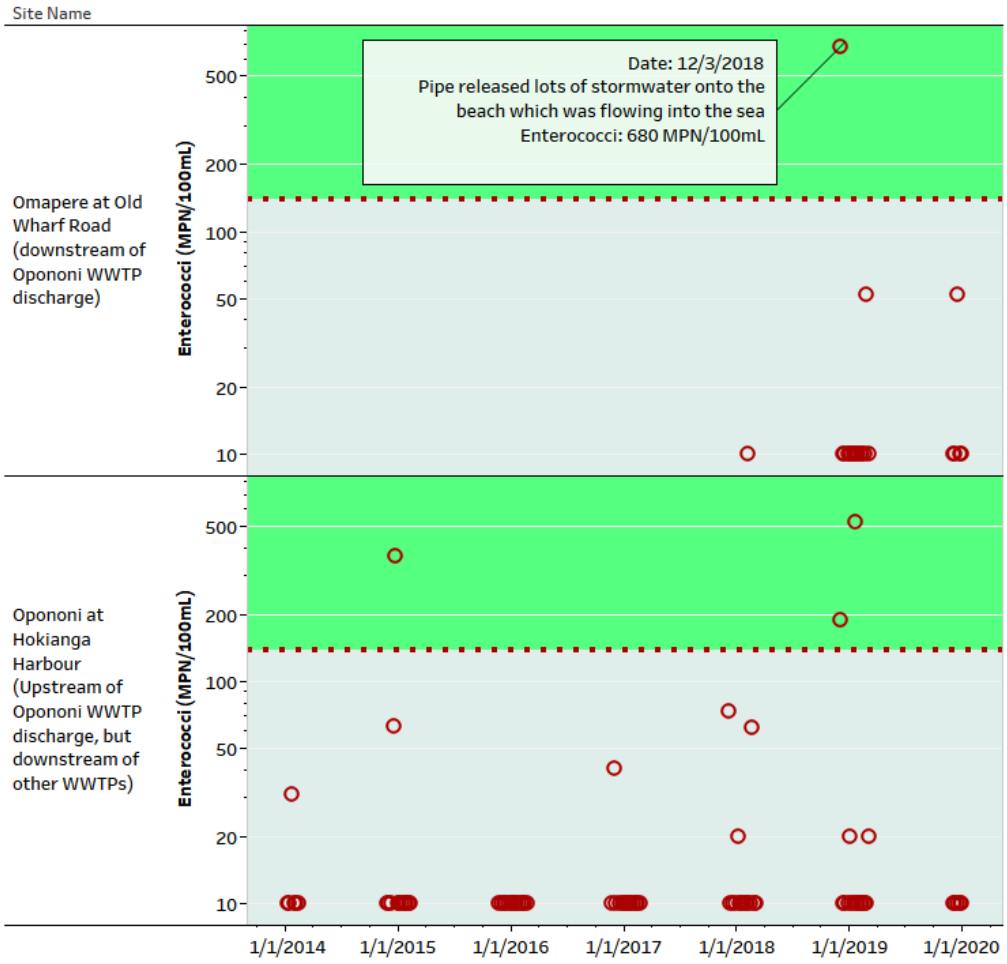

Figure 3. Enterococci concentrations of water samples collected at the Omapere at Old Wharf Road (upper image) and Hokianga Harbour Opononi (lower image) sites. Samples with enterococci concentrations below the acceptable enterococci concentrations of 140 enterococci/100 mL (Green mode) for marine waters are shaded in light blue, otherwise green[15].

The MetOcean hydrodynamic model, which included considerations for tidal movement, has shown that during conditions of backflushing of tidal waves back into the Harbour, the dilution in the receiving environment is very high (for example 95th percentile dilution at Site CR1 is 230,000 and 134,000 during *el nino* and *la nina* conditions) , given the small amount of the discharge and the large amount of water available for mixing in the Hokianga Harbour. It was thus not surprising that this QMRA predicted that health risks associated with swimming at Site CR1 (Upstream of the Opononi WWTP discharge and closest to the Hokianga Harbour Opononi LAWA

[15] While enterococci data at the Omapere at Old Wharf Road site has only been collected since 2018 till date, enterococci data has since 2009 been collected at the Hokianga Harbour Opononi site. Also, there is no data on sanitary inspection categories of the assessment site. Hence, it was impossible to analyse the enterococci data based on MoH/MfE (2003) criteria using Microbiological Assessment and Sanitary Inspection Categories (MAC-SIC). Hence, the MoH/MfE (2003) criteria based on surveillance, alert and action levels for marine waters was adopted.

site where NRC conducts routine microbiological monitoring of recreational water quality) was below the no observable adverse effects level. In agreement with our QMRA results, at Hokianga Harbour Opononi site, only two samples out of the last 67 monthly water samples collected between 2015 and 2019 exceeded acceptable enterococci concentrations of 140 enterococci/100 mL (Green mode, see lower image in Figure 3). This indicates that in terms of recreation, the water at Hokianga Harbour Opononi site was generally of acceptable quality and was not being impacted by the Opononi WWTP.

One important conservative, yet representative approach in this QMRA is the use of dilution factors that would be obtained should Opononi WWTP discharge wastewater into the Hokianga Harbour already receiving treated wastewater input from all three upstream WWTPs (i.e. Kaikohe, Kohukohu and Rawene WWTPs). This explains why all four WWTPs discharging into the harbour were simultaneously turned on, such that the effect modelled at exposure sites in this QMRA for Opononi WWTP also captured additional effects from WWTPs upstream of the Opononi WWTP.

It is important to note that the QMRA results herein presented are for attributable risk, i.e., the increment in risk associated with the Opononi WWTP. Hence, it does not include risks associated with overflows or stormwater runoff from catchment sources.

6. Conclusions

The QMRA shows that if 1-log virus reduction (i.e. 10-fold) is achieved by the Opononi WWTP, then at all sites assessed, illness risks associated with ingestion of water potentially containing enterovirus or norovirus from the discharge will be reduced below the "no observable adverse effect level" (NOAEL). However, under this same virus reduction level, the discharge of treated wastewater from the WWTP generally poses "low" risk of illness associated with consumption of raw shellfish (although the IIRs were only fractionally above the 1% threshold for NOAL).

Wastewater treatment that reduces virus concentrations in the Opononi WWTP discharge by 2-log reduction (i.e. 100-fold) will reduce health risks associated with the discharge (in relation to inhalation, ingestion during swimming and consumption of shellfish harvested) at all exposure sites, to levels below the NOAEL.

In published literature, a 2log virus removal is the most predominantly reported level of reduction in virus concentrations in constructed wetland treatment systems. In line with the QMRA results, if the Opononi wetland treatment system is achieving a 2log virus removal as commonly indicated by available literature, the level of treatment currently applied at the Opononi WWTP is sufficient to reduce illness risks associated with recreation or consumption of harvested raw shellfish below the "no observable adverse effect level" (NOAEL).

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Appendices

Appendix 1 Additional notes on choice of QMRA reference pathogens

We selected noroviruses as the first representative viral pathogen for this QMRA because:

1. Noroviruses are host-specific, present mostly in human waste. This makes them ideal candidates for tracking primary sources of human-related faecal contamination in the environment (Ahmed et al., 2010; Mara and Sleigh, 2010).
2. Human noroviruses are now the most common cause of gastroenteritis outbreaks in children in developed countries worldwide, implicated in >90% of nonbacterial and ≈50% of all-cause epidemic gastroenteritis worldwide (Lopman et al. 2016; Lofranco 2017). They are unquestionably the most common viral cause of gastroenteritis[16] for which dose-response data are available (Mara and Sleigh, 2010; Teunis et al., 2008, CDC 2015, Farkas et al.2017).
3. As with other enteric viruses, they are often symptomatic or pauci-symptomatic[17]; they can even present a high risk of morbidity and mortality in vulnerable (high-risk) populations such as young children, elderly individuals and immunocompromised patients (Prevost et al., 2015).
4. Noroviruses often present higher illness risks than other viruses ((Vergara, Rose, and Gin 2016). Also, noroviruses have a much lower ID_{50} (the minimum dose of norovirus pathogens that can cause infection in 50% of exposed and susceptible subjects) than other viruses. Dose-response relationships suggest that a single norovirus particle can cause infections in more than 40% of susceptible individuals, a rate much higher than other viruses (McBride, 2011).
5. Norovirus outbreaks can occur throughout the year, but have been reported to occur more frequently during the colder winter seasons in temperate climates (Lofranco 2017; CDC 2014; Maunula, Miettinen, and Von Bonsdorff 2005; Ahmed, Lopman, and Levy 2013). A similar observation was made in the scoping and surrogate study on virus concentration at Mangere WWTP influent, New Zealand (Simpson et al.2003).

We selected enterovirus as a second representative viral pathogen for this QMRA because:

1. Enterovirus, one of the largest genera of viruses classified within the Picornaviridae family, represents a significant burden to public health globally (Lofranco 2017).
2. Enteroviruses target either intestinal or upper respiratory tract cells resulting in an upper respiratory tract infection or gastrointestinal illness. Enterovirus

[16] norovirus mainly affects children under the age of three
[17] i.e. presenting few symptoms.

types can cause a wide spectrum of diseases within humans and present a broad range of symptoms.
3. Enteroviruses are also transmissible via sewage contaminated waters (Lofranco 2017; Health Canada 2012).
4. Although human enterovirus outbreaks can occur throughout the year depending on the strain, in temperate climates, enterovirus infections are most prevalent during summer months (Sedmak, Bina, and MacDonald 2003; Costan-Longares et al. 2008; PHAC 2015).

We selected adenovirus as the third representative viral pathogen for this QMRA because:

1. Adenovirus, a double-stranded DNA virus, is often detected in these same environments as noroviruses and enteroviruses (Choi and Jiang 2005; Sassoubre, Nelson, and Boehm 2012). However, compared to other viruses, it has been reported to have prolonged survival time and increased resistance to disinfection e.g. UV treatments (Albinana-Gimenez et al. 2009; Wyer et al. 2012; Kundu, McBride, and Wuertz 2013; Hewitt et al. 2013).
2. This pathogenic virus has a low infectious dose and is thus of great importance in public health (Donzelli et al. 2015). Human adenoviruses (HAdVs) cause numerous symptomatic and asymptomatic infections affecting the respiratory tract, the eyes, and the gastrointestinal tract (Carducci et al. 2016). They can be excreted in the faeces, urine, and respiratory secretions and transmitted via contact with the eyes, the faecal-oral route, or inhalation (Bambic et al. 2015)..
3. HAdVs have a number of features that justify their use as index pathogens for air in occupational settings possibly contaminated by faecally-excreted pathogens (Donzelli et al. 2015).

Appendix 2 Additional notes on dose-response characterization

A rich discussion on dose-response functions already exists in published literature (e.g. See McBride 2011, 2016a, Vergara et al.2016, USEPA 2010, WHO 2016). Dose-infection curves for the viral pathogens used have been established from clinical test results of subsets of volunteers challenged with laboratory-prepared aliquots of viral suspensions at varying serial dilutions of known mean[18] doses of viruses (Haas et al.1999). These were based primarily on two assumptions. This first assumption is the 'single-hit' hypothesis, which is that a single viral pathogen would evade the host defense mechanisms and reach its potential infection site, establish itself and then cause infection. The second assumption is based on a Poisson distribution of the viral pathogens in the laboratory-prepared viral aliquot, which better reflects a random, well-mixed population. These assumptions can be described with probability distributions.

When the probability of ingesting a dose of pathogens is Poisson-distributed and all of the ingested pathogens have an equal probability of initiating infection, the exponential dose-response model is appropriate:

$$P_{inf(d;r)} = 1 - e^{-rd} \quad \text{....eqn(1)}$$

where P_{inf} is the probability of infection, d is dose (number of pathogens), e represents the standard exponential constant, 2.7183, and r is a parameter of the distribution equal to the probability that an individual pathogen initiates infection.

When the probability of ingesting pathogens is Poisson-distributed and the probability that individual pathogens initiate infection is beta-distributed, the beta-Poisson model is appropriate:

$$P_{inf(d;\alpha,\beta)} = 1 - {}_1Fe_1(\alpha, \alpha + \beta, -d) \quad \text{....eqn(2)}$$

where α and β are parameters of the Beta distribution and ${}_1F_1$ denotes a confluent hypergeometric function. A commonly used approximation to the beta-Poisson may be used when $\beta >> 1$ and $\beta >> \alpha$, which is usually so in most cases. This approximation is:

$$P_{inf(d;\alpha,\beta)} = 1 - (1 + \frac{d}{\beta})^{-\alpha} \quad \text{....eqn(3)}$$

where P_{inf} is the probability of infection, d = mean dose, α and β are 'nonnegative shape' and location parameters, respectively. This approximation however is inadequate for noroviruses because the fitted α and β parameters (*i.e* $\beta = 0.055$, $\alpha = 0.04$) do not comply with the condition $\beta >> 1$ and $\beta >> \alpha$, hence the push for the use

[18] Doses in individuals' challenges are not measured, instead the average dose given to each member of a group is known.

of the much-more-difficult-to-evaluate hypergeometric equation (2) (as argued in McBride 2011).

One approach to QMRA is to use individual exposure per exposure occasion to represent a group visiting a polluted beach. This approach often produces unrealistic risk profiles. A very robust QMRA approach is to expose multiple people on each exposure occasion. In this case, it is possible to assign individual doses, thus eliminating the need for the Poisson averaging. Hence, for the constant r, the simple one-parameter exponential model is easily replaced by the simple bionomial model:

$$P_{inf} = 1 - (1 - r)^{i} \quad \text{....eqn(4)}$$

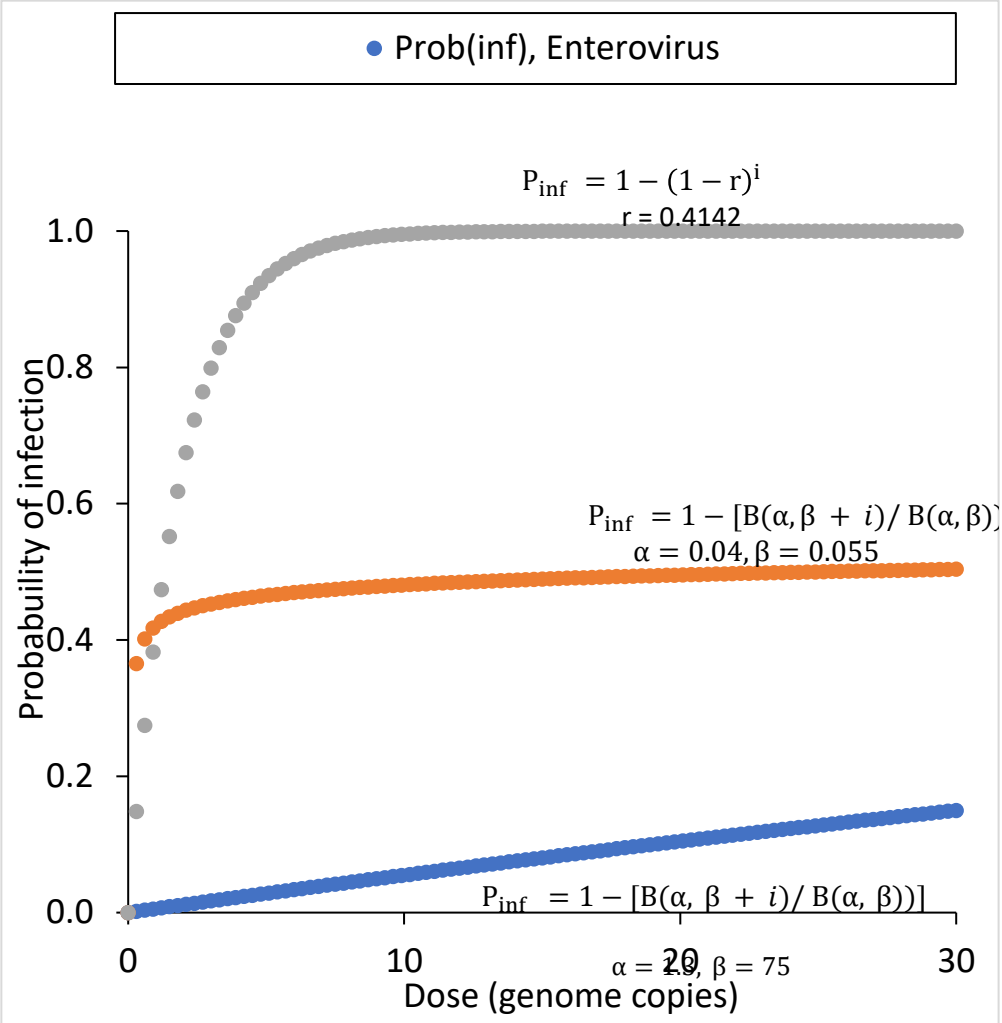
where *i* is the individual dose. Similarly, the two-parameter beta-Poisson model (eqn 2) becomes replaced with the beta-bionomial model, below, which is easily executed using the natural logarithm of the gamma function in Excel[19]:

$$P_{inf} = 1 - [B(\alpha, \beta + i) / B(\alpha, \beta))] \quad \text{....eqn(5)}$$

where P(i) is probability of infection, β is a standard beta function (Abramowitz and Stegun, 1964; Teunis et al., 2008), α and β are shape and location parameters and *i* represents a dose received by an individual.

[19] Prob of infectin = $1 - EXP\{GAMMALN(\beta + i) + GAMMALN(\alpha + \beta) - [GAMMALN(\alpha + \beta + i) + GAMMALN(\beta)]\}$ (as in McBride 2011)

Appendix 3 Dose-response curves applied in this QMRA



Plots of individual dose response curve for adenovirus type 4, enterovirus and norovirus used in this QMRA