Water-Related Health Risks Analysis

for the proposed Akaroa wastewater scheme

Prepared for CH2M Beca Ltd

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Authors/Contributors:
Graham McBride

For any information regarding this report please contact:

Graham McBride
Principal Scientist
Aquatic Pollution
+64-7-856 1725
graham.mcbride@niwa.co.nz

National Institute of Water & Atmospheric Research Ltd
Gate 10, Silverdale Road
Hillcrest, Hamilton 3216
PO Box 11115, Hillcrest
Hamilton 3251
New Zealand

Phone +64-7-856 7026
Fax +64-7-856 0151

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Reviewed by

Dr C Palliser

Approved for release by

Dr R Craggs

Formatting checked by

Executive summary

A new wastewater treatment and disposal scheme is proposed for Akaroa, intended to improve the quality of the Harbour's waters. In particular, its promotion has been based on the expectation that the new treatment plant will produce high quality wastewater, by including membrane disinfection. A key benefit of this is the further reduction in the risk of illness among water users. In particular, its promotion has been based on the expectation that the augmented treatment processes, which include membrane disinfection, will reduce the risk of illness among water users. This mainly concerns swimmers, especially children, who tend to ingest more water during their "exposure" to the Harbour waters. It also concerns consumers of raw shellfish harvested from Harbour sites. The proposed scheme also includes a longer outfall (2.5 km), as opposed to the existing 100 m outfall which will further decrease any contamination at recreational sites.

The proposed wastewater discharge has been subjected to a quantitative microbial risk assessment (QMRA), using Norovirus as the modelled pathogen. This work is based on recent findings about the pathogenic importance of Noroviruses in human sewage and good information about the Norovirus dose-response information, enabling this quantitative analysis to be performed.

We have used results from mathematical modelling of mixing and inactivation processes in Harbour waters affected by the virus concentration profiles for conditions expected to prevail in the future (i.e., up to the year 2041). These have been used in a "Monte Carlo" statistical model to predict likely illness risks for swimmers at each of fourteen Harbour sites, most of which are located on the shoreline, with one located near the site of the proposed outfall diffuser.

The modelling found that in general, water contact risks are low, and would not cause a breach of the "A" Microbiological Assessment Category of the New Zealand "Microbiological water quality guidelines for marine and freshwater recreational areas" (MfE and MoH, 2003). Shellfish consumption risks are somewhat higher, such that temporary signage may be required for winter wet-weather wastewater flow conditions where some of the influent bypasses the main treatment process and receives receives fine screening (primary treatment) and UV disinfection.

1 Introduction

A new wastewater treatment scheme has been proposed for Akaroa, replacing the present WWTP to the south of the town at the end of Beach Road (Figure 1-1). The current outfall discharges treated wastewater (the treatment process consists of a fine screen, Imhoff tanks, a trickling filter, a secondary clarifier and UV disinfection) through a 100 m long outfall, at depth of 5.9 m, off Redhouse Bay under Consent CRC071865. As part of a long-term strategic plan on water and wastewater management in the Akaroa area, Christchurch City Council (CCC) commissioned the Akaroa Wastewater Project in late 2013 to modify and upgrade the wastewater reticulation system, and construct a new treatment plant and harbour outfall. Council has committed to a 'best quality wastewater' approach in upgrading the system. This includes a biological nitrogen removal (BNR) process using Modified Ludzak-Ettinger (MLE) reactors with membrane disinfection (MBR).[i] All flows will be discharged via a 2.5 km outfall into the main channel of the Harbour (as shown in Figure 1-1). Occasional high wastewater flows will bypass the main treatment units, but will be subjected to screening and UV disinfection before discharge via the harbour outfall.

Figure 1-1: Location of present and proposed outfall sites: "x-WWTP" denotes existing WWTP and short 100 m outfall; "n-WWTP" denotes proposed WWTP site and 2.5 km long outfall. [*Background image*: TerraMetrics, Digital Globe, Google Earth].

CH2M Beca Ltd has been engaged by Christchurch City Council (CCC) to undertake investigations, obtain appropriate consents, and design and monitor the construction and commissioning of a new wastewater treatment plant (WWTP) to the north of Akaroa township, including upgrades of the trunk wastewater pipeline and the new outfall.

The CH2M Beca project team includes Cawthron Institute (Harbour water quality and ecology), OCEL Consultants NZ Ltd (Harbour outfall design and construction) and NIWA (Harbour contaminant modelling and public-health risk).

This report covers the public health risk component. It uses QMRA (Quantitative Microbial Risk Assessment) which focusses on a pathogen (or pathogens) understood to be the principal cause of any wastewater-associated health effects on recreational water users, particularly swimmers and consumers of raw shellfish harvested from Harbour sites.

The QMRA is informed by recently-developed information on a particularly important human pathogen: Norovirus. It is also informed by data obtained from the contaminant model, which predicts Norovirus concentrations at each of 14 contact recreation sites in the Harbour (see Figure 1-2 and Table 1-1), for a constant effluent Norovirus concentration of 1,000 genome copies per cubic metre (= 1 virion per litre). Those results (Bell et al. 2014) are then scaled in the QMRA by the predicted virus concentrations in the effluent discharged from the outfall.

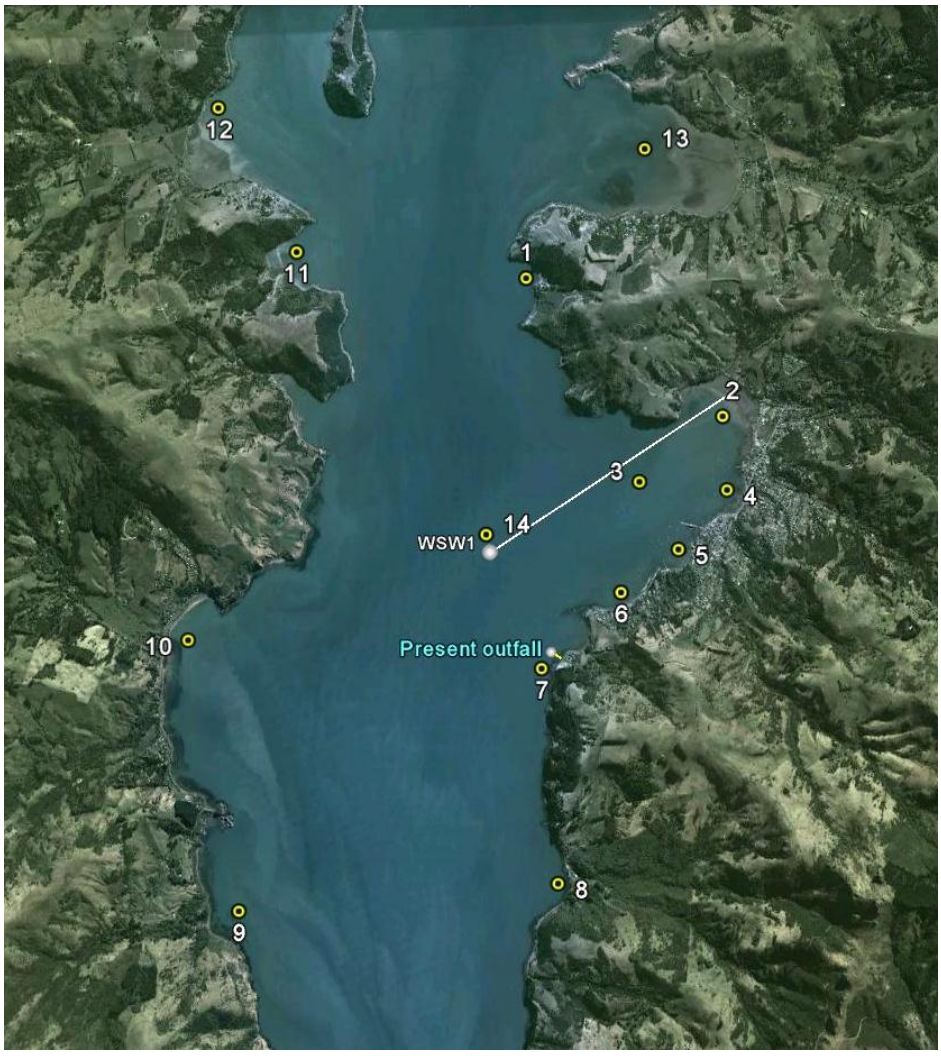

Figure 1-2: Locations of the fourteen contact recreation sites. North point is upward (see Table 1-1 for site names and codes). All sites except No. 14 are near the coastline; Site 14 is 150 m north of the diffuser.

Table 1-1: Recreational water sites: numbers, descriptions, codes. Sites 7–10 have also been used to assess health risks from harvested shellfish, eaten raw

Number	Site	Code
1	Lushington Bay	LuB
2	Childrens Bay	ChB
3	Offshore Childrens Bay	OCB
4	French Bay - CBD	FBC
5	French Bay - Wharf	FBW
6	Glen Bay	GnB
7[a]	Existing outfall/WWTP	ExW
8	The Kaik	ThK
9	Ohinepaka Bay	OhB
10	Wainui	Wai
11	Petit Carenage Bay	PCB
12	French Farm Bay	FFB
13	Takamatua Bay	TaB
14	Mid Harbour, 150 m north of diffuser	MHb

[a] Site ExW is 150 m southwest of the existing outfall

1.1 Structure of this report

Section 2 gives the rationale for the QMRA process, based on Norovirus. Results are given in tabular form in section 3 and discussed in Section 4. Conclusions drawn are listed in section 5. A glossary of key terms is give in section 7.

A number of detailed technical issues are elaborated in the Endnotes on 31 and 32.

2 Quantitative Microbial Risk Assessment

This Quantitative Microbial Risk Assessment (QMRA) is based on the risk of Norovirus illness, using the infection dose-response findings reported by Teunis et al. (2008) and its associated conditional probability of illness (given that infection has occurred), as employed by Schoen and Ashbolt (2010) and Soller et al. (2010). It should be noted that QMRA differs from the approach that has often been adopted that uses a relationship established between Faecal Indicator Bacteria (FIB, e.g., enterococci) and water-contact-related human health risk (e.g., as reported by Bolton-Ritchie 2013). That is because the epidemiological studies, upon which that relationship is based, were conducted on waters much further removed from point sources than is the case for the Akaroa discharge. For such near-proximity cases the current New Zealand water quality microbiological guidelines for recreational areas encourage a direct assessment of issues associated with illness-causing pathogens and health effects (MfE/MoH 2003, at pages 3 and 4). Current understanding of the pathogens associated with a receiving water containing some amount of treated wastewater has it that Norovirus generally poses the greatest health risk (Sinclair et al. 2009, Soller et al. 2010). [ii]

2.1 QMRA and the Monte Carlo technique

This QMRA uses a "Monte Carlo" quantitative statistical iterative modelling approach to handle variability and uncertainty in its components. Therefore, many of the input variables are assigned statistical distributions of their likely values, from which random samples are drawn in a 10,000-fold iterative process. On each of these 10,000 "exposure days", and for each site, one hundred healthy people (swimmers, surfers, etc.) are exposed to the water and another 100 consume raw shellfish. Each of these exposures may contain some viruses and so, on each iteration and for each individual, the probability of illness is computed. The end results of this iterative statistical sampling are "risk profiles", averaged over the 10,000 days. That wealth of information is summarised for each site by computing the "Individual's Illness Risk" ("IIR"), calculated as the number of cases of illness (over all 100 people on each of the 10,000 days) divided by the total number of occasions when exposure to the virus may occur (that is, 1,000,000 exposures).

All calculations have been conducted using the @RISK software (Palisade Corp. 2013) embedded in MS Excel 2010®. That software provides numerous statistical distributions that are not available in Excel. It also provides an attractive Monte Carlo simulation environment that is easily understood by any person with only moderate proficiency in spreadsheets.

The generic calculation sequence is shown on Figure 2-1.

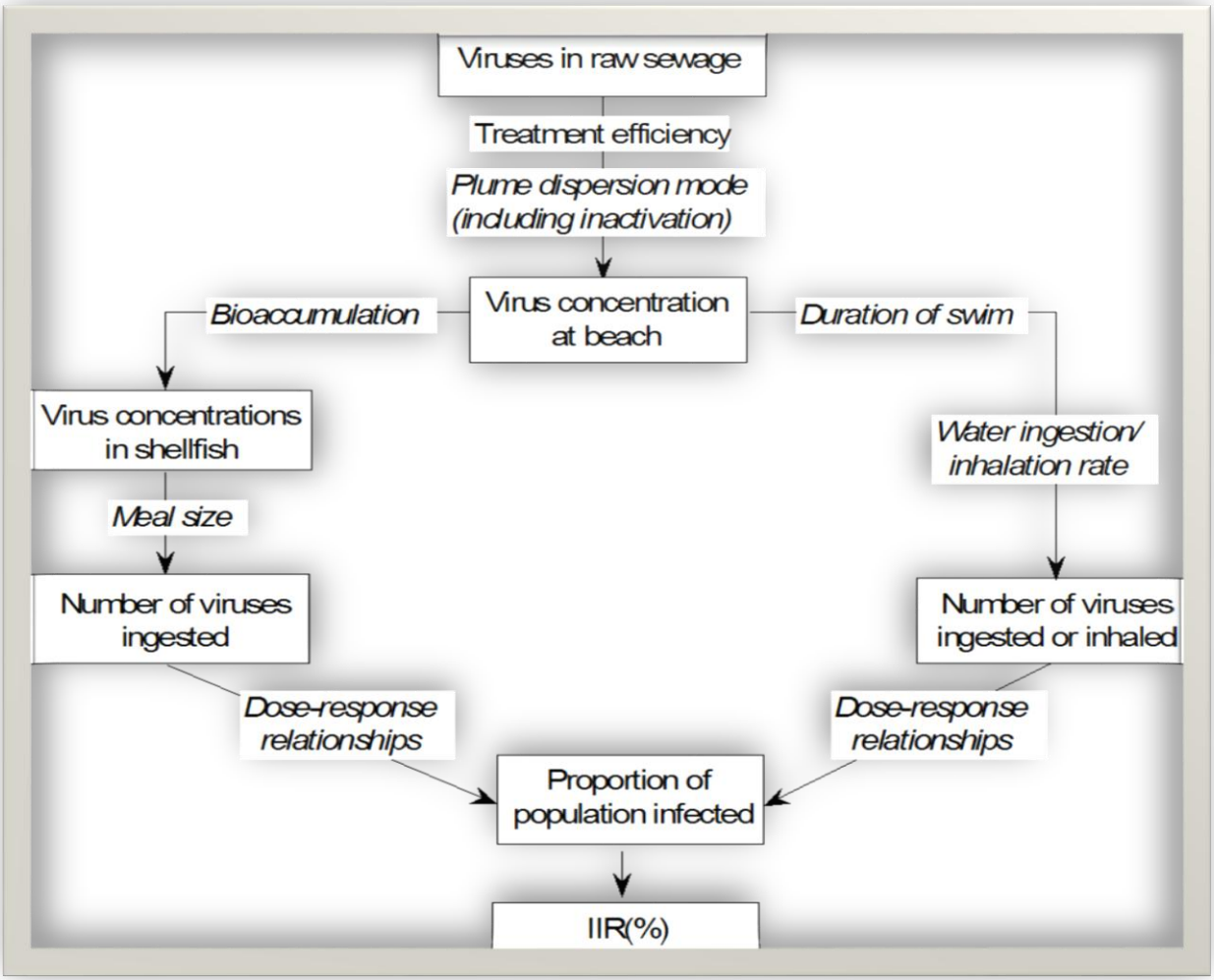

Figure 2-1: QMRA calculation sequence for recreational water-contact and for consumers of raw shellfish (italicised items are assigned statistical distributions from which random samples are drawn at each iteration).

2.2 Input variables

The input variables include: the duration of an individual's swimming events, their water ingestion rates, the influent Norovirus concentration and virus removal efficacy throughout the treatment train. Those concentrations are transformed to empirical concentration distributions at each exposure site using the results of computational hydrodynamic modelling prepared by Bell et al. (2014). These calculations have included the viricidal effects of sunlight-UV which varies with time-of-day, season, cloudiness, and plume turbidity. They refer to conditions expected to prevail at Akaroa up to the year 2041.

2.2.1 Why Norovirus?

Noroviruses are a principal cause of viral gastroenteritis. They all are single-stranded RNA viruses that have been classified into 5 genogroups (GI to GV). Strains I, II and IV can infect humans (particularly strain II, see Matthews et al. 2012), while GIII infects bovine species and GV has recently been identified in mice. The GI viruses are highly infectious for a proportion of the population (Teunis et al. 2008)[iii] and spread easily by direct person-to-

person or person-surface-person contact. By analogy, the GII genogroup exhibits the same behaviour. They also can be associated with waterborne gastroenteritis (Parshionikar et al. 2003) or shellfish-associated gastroenteritis (Lees et al. 1995, Thebault et al. 2013) and are therefore a hazard to recreational water users (Gray et al. 1997). They have been detected in both raw and treated wastewaters (Nordgren et al. 2009), with strains of GI and GII predominating in human sewage that are typically very similar to human strains circulating in the population (van den Berg et al. 2005). Therefore the public may be at appreciable risk whenever there is exposure to human wastes (animal viruses are generally thought to be not infectious to humans, and so other animal pathogens—bacteria and protozoa—come into play). For the purposes of the QMRA, Noroviruses therefore represent the primary potential risk of infection from human wastewaters via ingestion for primary contact users, such as swimmers, surfers and bodyboarders.

Respiratory viruses, particularly some Adenoviruses, may also need to be considered within a QMRA. Respiratory symptoms (via inhalation of contaminated water) are sometimes associated with contact with sewage-impacted coastal waters (WHO, 2003), including New Zealand (McBride et al. 1998). Respiratory-associated viruses are probably the commonest causes of acute respiratory infections, reportedly causing around 70% of acute sore throats for example (Mims et al. 2004). They can be particularly resistant to disinfection (Gerba et al. 2003, Thompson et al. 2003). However, while Adenoviruses are commonly found in water (Horwitz 2001), including wastewater, many strains give rise to gastrointestinal illness (e.g., the 40/41 strain complex) and a rather smaller proportion of them are associated with respiratory symptoms. In particular we have clinical trial information available only for the respiratory-illness-causing Adenovirus 4 (Couch et al. 1965, 1966a&b) for which a dose-response model has been developed (Haas et al. 1999). Given that Fong et al. (2010) found only 3% of wastewater Adenoviruses were Type 4, and that other QMRA studies in New Zealand have predicted that illness via ingestion among recreational water users near marine outfalls to be rather higher than illness-via-inhalation (Stott & McBride 2011), this study has not included this infection route.[iv] A recent study of wet weather bypass flows at Moa Point, Wellington, has included consideration of respiratory effects. The coastal waters near Moa Point are of course much more energetic than in Akaroa Harbour, so the potential for the generation and subsequent inhalation of aerosols is that much greater.

2.2.2 Influent and effluent Norovirus distributions

These are key variables driving the risk assessment and so deserve some detailed explanation.

The first consideration is the efficacy of the treatment system to remove pathogens. In discussion with Beca staff we have used a uniform distribution of the "Log_{10}" virus reduction factor, ranging from 3 to 4. In other words, between three and four orders-of-magnitude reduction in the influent concentration of viruses. For the possible (but rare) bypass events, these reduction factors have been halved (because a sizeable part of that flow will receive full treatment while the rest, up to about half the total flow, will receive fine screening (primary treatment) and UV disinfection. But account is also taken of the increased dilution of influent concentrations during wet weather. By simple flow calculations the "bypass dilution factor" has been taken as 7.[v]

Quantitative methods for Norovirus enumeration have only become available recently (ESR now offers an excellent service, using “qPCR”—a quantitative Polymerase Chain Reaction biochemical technique). Accordingly, information on its distributions in raw and treated wastewater is much less available than the traditional faecal indicator bacteria. Some data are available internationally (e.g., Lodder and de Husman, 2005, van den Berg et al. 2005, da Silva et al. 2007, Katayama et al. 2008), showing that Norovirus can exhibit extreme variability (da Silva et al. report from non-detection up to 10^9 genome copies per litre). However, some New Zealand data are available. Hewitt et al. (2011) have published a review of influent and effluent Noroviruses (and other viruses) in raw and treated (prior to any disinfection] for ten New Zealand wastewater treatment plants on three occasions over a summer. From all these results, along with the monitoring CCC undertook of the Akaroa influent wastewater in December 2013 and January 2014, we can infer the following:

- Standard wastewater treatment systems (excluding disinfection) are relatively ineffective in reducing Norovirus concentrations.
- Some results, e.g., for Napier influent (and effluent) in November 2010 appear rather high compared to those reported by Hewitt et al. (2011), which may well have had to do with a Napier Norovirus illness pattern that was not detected.[vi]
- Results for Akaroa Treatment Pant influent monitoring in December 2013 and January 2014 (Table 2-1) are more in accordance with the results report by Hewitt et al. (2011), i.e., median concentrations about 10^4 genome copies per litre, maximum (Genogroup II) a little over 10^6 per L.
- If concentrations as high as 10^9 per litre occur (as reported for France by da Silva et al. 2007) one would expect there to have been a substantial outbreak in the community which of itself should cause public advisories against swimming or shellfish harvesting to be posted.[vii]

Table 2-1: Akaroa wastewater treatment plant influent concentrations.

Date	Norovirus, genome copies per litre	
	Genogroup I	Genogroup II
11-Dec-13	2.60×10^3	1.10×10^4
18-Dec-13	6.40×10^3	1.90×10^4
27-Dec-13	1.60×10^3	9.20×10^4
31-Dec-13	1.40×10^4	4.20×10^3
8-Jan-14	1.20×10^4	4.40×10^4
16-Jan-14	3.00×10^4	1.40×10^4
22-Jan-14	1.00×10^4	4.60×10^4
30-Jan-14	1.50×10^3	3.40×10^6

Accordingly, we have used minimum, mode and maximum Akaroa influent values of 10^2, 10^4 and 10^7 genome copies per litre, as has also been done for a recent QMRA study for New Plymouth (McBride 2012) and Hawera (Palliser et al. 2013). These have been used as input to a right-skewed “Hockey-stick” distribution (McBride 2005) for the random sampling.

2.2.3 Amount of water ingested

Few “exposure studies” are available on swimmers' ingestion rates. Dufour et al. (2006) used chloroisocyanurates tracers in a freshwater swimming pool study and found that the average amount of water swallowed by children and adults during swimming was 37 mL and 16 mL per event, respectively, where each event lasted at least 45 minutes.[viii] This was subsequently modified in their full study (Evans et al. 2006) that reported children and adult swallowed rates of 47 mL and 24 mL per event respectively. One quarter of the swimmers swallowed 85 mL or more, and some swallowed up to 280 mL.

Dorevitch et al. (2011) used survey methods and similar chemical testing to define three modes of contact: low (rowing, boating, fishing, wading, non-capsizing kayaking and canoeing); middle (canoeing and kayaking with occasional capsizing); high (swimmers). Average ingestions for these three categories were 3.8, 5.8 and 10 mL per event, respectively. The duration of each event was generally less than one hour and separate ingestion rates between children and adults were not identified.

In pooling the results of these exposure studies, we have assumed the following:

- Minimum, mode and maximum durations for a contact-recreation event are 0.1, 0.5 and 2 hours.
- Minimum, mode and maximum ingestion rates during contact-recreation (swimming, surfing, kite surfing, wind surfing, bodyboarding, kayaking and surf life-saving) are 10, 30 and 100 mL per hour. These results apply to children. Adults' ingestion rate is taken as one half of these values.

2.2.4 Dose-response

The uncertainty inherent in the Norovirus infection dose-response curve is handled by surrounding the curve by an uncertainty distribution, from which random samples are also drawn.[ix] The conditional probability of illness (given that infection has occurred) has been based on the approach of Schoen & Ashbolt (2010) and Soller et al. (2010).[x,xi] Note that this probability is always less than unity, reflecting the common observation (in clinical trials) that some people may become infected but fail to become ill (i.e., display no illness symptoms).

2.2.5 Summary of distributions and related parameters

These are described in full in Table 2-2.

Table 2-2: Distributions and statistics used in the QMRA model.

Component	Statistics	Distributions and comments
Influent Norovirus concentration (per litre)	Minimum Mode Maximum 0 10^4 10^7	See discussion in Section 2.2.2.
Duration of an exposure event (h)	Minimum Mode Maximum 0.1 0.5 2	Duration and ingestion rate are each described by a PERT distribution.[a] The volume ingested on each iteration (mL) is then simply the product of these two numbers. See the discussion in Section 2.2.3 explaining the choice of parameter values.
Ingestion rate by a child during a water-contact event (mL/h) (adult rate taken as one half the child rate)	Minimum Mode Maximum 10 30 100	
Shellfish meal size (g)	α β γ 2.2046 75.072 −0.903	Using the Loglogistic distribution, truncated below at 5 g and above at 800 g, obtained by fitting distributions to estimates of daily intake of 98 consumers of mussels, oysters, scallops, Pipi and Tuatua in the 1997 National Nutrition Survey (Russell et al. 1999).
Bioaccumulation factor (*BAF*)[b]	Mean Standard deviation 49.9 20.93	Using a normal distribution, truncated below at 1 and above at 100. The pathogen dose ingested on eating *M* grams of shellfish is *BAF* x the number of pathogens in the equivalent volume of seawater.
Norovirus dose-response harmonisation factor	18.5	Accounts for the difference between: (i) the PCR method used in the clinical trial data used by Teunis et al. (2008) (i.e., Liu et al. 2010) to establish a dose-response relationship and (ii) the methods used by ESR to assay Noroviruses (Wolf et al. 2010 for GI, Kageyama et al. 2003 for GII). To achieve harmony, the ESR result is divided by the factor (McBride et al. 2013). This gives the appropriate "dose" to enter into the dose-response relationship identified by Teunis et al. (2008).

[a] *PERT distributions are based on the standard beta distribution, they are bounded at the minimum and maximum values*.
[b] *Source*: Burkhardt & Calci (2000), using October – January (USA) data or FRNA phage in eastern oysters.

2.3 Scenarios modelled

Five water contact scenarios have been modelled as shown in Table 2-3.

Table 2-3: Scenarios modelled for recreational water contact.

Scenario	Group exposed	Season[a]	WWTP operation
1	Children	Summer	Normal
2	Children	"Winter"	Normal
3	Adults	Summer	Normal
4	Adults	"Winter"	Normal
5	Children	"Winter"	Partial bypass

[a] "Winter" denotes all months outside the bathing season (April – October inclusive)

Note that the calculation procedures for these scenarios presume that the mode of discharge remains relatively unchanged for a number of tidal cycles—the "lag times" for discharged wastewater to reach the shoreline are substantial. To make predictions for shorter-term conditions (i.e., bypass events) we effectively have to assume these conditions prevail for a longer time, so our approach for those conditions is precautionary.

For shellfish consumption we calculate risks for sites 7 – 10 for summer conditions, for normal "winter" conditions and for bypass "winter" conditions. Bypass conditions do not arise for summer conditions because storms generally occur in winter and ground conditions mean that summer storms have little impact on flows (pers. comm. Reuben Bouman, CH2M Beca, 7 April 2014). The nature of the exposure data for shellfish consumption does not allow us to separate between children and adults.

3 Results

3.1 Recreational water contact

The calculated risk profiles and associated IIR values for all sites and for each of the five scenarios are given in Table 3-1 – Table 3-5. As noted in Section 2.1, these detailed results can be summarised using a single number, defined as the proportion of all potential exposures that gave rise to cases of illness.

Table 3-1: Risk profiles and IIR(%) for recreational water contact for Scenario 1. Child, summer, normal conditions (no bypass)

Percentile	Number of illness cases per 100 swimmers (children) on any summer's day at each site													
	1: LuB	2: ChB	3: OCB	4: FBC	5: FBW	6: GnB	7: ExW	8: ThK	9: OhB	10:Wai	11: PCB	12: FFB	13: TaB	14: MHb
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98%ile	0	0	0	0	0	0	1	0	0	0	0	0	0	1
99%ile	0	0	0	0	0	0	1	0	0	0	0	0	0	2
99.5%ile	0	0	1	0	0	0	2	1	0	0	0	0	0	4
99.9%ile	1	1	1	1	2	1	6	1	1	1	0	0	0	10
Maximum	3	3	4	2	5	3	11	3	2	2	1	0	1	15
IIR(%)	0.0035	0.0047	0.0064	0.0051	0.0059	0.0055	0.0437	0.0074	0.0036	0.0027	0.0001	0	0.0001	0.0771

"IIR" is the Individual's Illness Risk. The other numbers in this table are the number of predicted illness cases among 100 child swimmers on any random summer day. So, for example, at site ExW (150 m southwest of the existing outfall) for 98% of the time there would be no more than 1 illness case (out of 100 child swimmers).

Table 3-2: Risk profiles and IIR(%) for recreational water contact for Scenario 2. Child, "Winter", normal conditions (no bypass)

Percentile	Number of illness cases per 100 swimmers (children) on any non-summer day at each site													
	1: LuB	2: ChB	3: OCB	4: FBC	5: FBW	6: GnB	7: ExW	8: ThK	9: OhB	10:Wai	11: PCB	12: FFB	13: TaB	14: MHb
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	1
98%ile	0	0	0	0	0	0	1	0	0	0	0	0	0	1
99%ile	0	1	1	1	1	1	2	1	0	1	0	0	0	3
99.5%ile	1	2	1	1	2	1	3	1	1	1	1	0	0	5
99.9%ile	3	4	4	3	5	3	7	3	2	2	2	1	1	9
Maximum	6	18	17	17	13	16	17	14	10	12	5	2	3	13
IIR(%)	0.0146	0.0273	0.0264	0.0273	0.0298	0.0227	0.0558	0.024	0.0150	0.0159	0.0076	0.0015	0.0019	0.0807

"IIR" is the Individual's Illness Risk. The other numbers in this table are the number of predicted illness cases among 100 child swimmers on any random day outside of the bathing season. So, for example, at site ExW (150 m southwest of the existing outfall) for 98% of the time there would be no more than 1 illness case (out of 100 child swimmers).

Table 3-3: Risk profiles and IIR(%) for recreational water contact for Scenario 3. Adult, summer, normal conditions (no bypass)

Percentile	Number of illness cases per 100 swimmers (adults) on any summer's day at each site													
	1: LuB	2: ChB	3: OCB	4: FBC	5: FBW	6: GnB	7: ExW	8: ThK	9: OhB	10:Wai	11: PCB	12: FFB	13: TaB	14: MHb
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	1
99%ile	0	0	0	0	0	0	1	0	0	0	0	0	0	1
99.5%ile	0	0	0	0	0	0	1	0	0	0	0	0	0	3
99.9%ile	1	1	1	1	1	1	3	1	1	1	0	0	0	6
Maximum	1	2	2	2	2	2	9	3	2	1	1	0	1	8
IIR(%)	0.0014	0.0031	0.0029	0.0027	0.0027	0.0026	0.0225	0.0033	0.0016	0.0016	0.0001	0	0.0001	0.0411

"IIR" is the Individual's Illness Risk. The other numbers in this table are the number of predicted illness cases among 100 adult swimmers on any random summer day. So, for example, at site ExW (150 m southwest of the existing outfall) for 99% of the time there would be no more than 1 illness case (out of 100 adult swimmers).

Table 3-4: Risk profiles and IIR(%) for recreational water contact for Scenario 4. Adult, "Winter", normal conditions (no bypass)

Percentile	Number of illness cases per 100 swimmers (adults) on any non-summer's day at each site													
	1: LuB	2: ChB	3: OCB	4: FBC	5: FBW	6: GnB	7: ExW	8: ThK	9: OhB	10:Wai	11: PCB	12: FFB	13: TaB	14: MHb
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
96%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	1
99%ile	0	0	0	0	0	0	1	0	0	0	0	0	0	1
99.5%ile	1	1	1	1	1	1	2	1	0	1	0	0	0	2
99.9%ile	2	3	3	2	3	2	5	2	1	1	1	0	0	5
Maximum	3	12	16	14	7	10	17	9	4	8	4	2	2	10
IIR(%)	0.0083	0.0148	0.0141	0.0149	0.0147	0.0115	0.0297	0.0121	0.0057	0.0078	0.0037	0.0008	0.0008	0.0410

"IIR" is the Individual's Illness Risk. The other numbers in this table are the number of predicted illness cases among 100 adult swimmers on any random day outside of the bathing season. So, for example, at site ExW (150 m southwest of the existing outfall) for 99% of the time there would be no more than 1 illness case (out of 100 adult swimmers).

Table 3-5: Risk profiles and IIR(%) for recreational water contact for Scenario 5. Child, "winter" (Partial bypass at the WWTP)

Percentile	Number of illness cases per 100 swimmers (children) on any non-summer's day at each site													
	1: LuB	2: ChB	3: OCB	4: FBC	5: FBW	6: GnB	7: ExW	8: ThK	9: OhB	10:Wai	11: PCB	12: FFB	13: TaB	14: MHb
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90%ile	0	0	0	0	0	0	0	0	0	0	0	0	0	0
95%ile	0	0	0	0	0	0	1	0	0	0	0	0	0	1
96%ile	0	1	1	1	1	0	1	1	0	0	0	0	0	2
97%ile	1	1	1	1	1	1	3	1	1	1	0	0	0	4
98%ile	1	2	2	2	2	2	5	2	1	1	0	0	0	7
99%ile	3	5	4	4	5	4	9	5	3	3	1	0	0	12
99.5%ile	5	8	7	8	8	7	13	8	5	5	3	1	1	16
99.9%ile	11	15	14	15	14	13	18	14	10	10	9	2	2	20
Maximum	16	26	21	27	23	25	24	27	21	24	17	6	7	25
IIR(%)	0.0959	0.1483	0.1354	0.1476	0.1459	0.1276	0.2883	0.1543	0.0984	0.095	0.0487	0.0112	0.0127	0.379

"IIR" is the Individual's Illness Risk. The other numbers in this table are the number of predicted illness cases among 100 child swimmers on any random day outside of the bathing season for a prolonged bypass event at the WWTP. So, for example, at site ExW (150 m southwest of the existing outfall) for 95% of the time there would be no more than 1 illness case (out of 100 child swimmers). Note that the high percentile results in this table are of very low probability, because bypasses are uncommon and of short duration. Accordingly, the IIR percentages are the most appropriate indicator of health risk.

Table 3-6: IIR(%) recreational water-contact results for all sites and scenarios.

	IIR(%) for Scenario:				
Site	**1**	**2**	**3**	**4**	**5**
1: LuB	0.004	0.015	0.001	0.008	0.096
2: ChB	0.005	0.027	0.003	0.015	0.148
3: OCB	0.006	0.026	0.003	0.014	0.135
4: FBC	0.005	0.027	0.003	0.015	0.148
5: FBW	0.006	0.030	0.003	0.015	0.146
6: GnB	0.006	0.023	0.003	0.012	0.128
7: ExW	0.044	0.056	0.023	0.030	0.288
8: ThK	0.007	0.024	0.003	0.012	0.154
9: OhB	0.004	0.015	0.002	0.006	0.098
10: Wai	0.003	0.016	0.002	0.008	0.095
11: PCB	0.000	0.008	0.000	0.004	0.049
12: FFB	0.000	0.002	0.000	0.001	0.011
13: TaB	0.000	0.002	0.000	0.001	0.013
14: MHb	0.077	0.081	0.041	0.041	0.379

3.2 Raw shellfish consumption

Risk profiles and associated IIR(%) values have also been calculated for consumption of raw shellfish harvested from sites 7 – 10. These results are given in Table 3-7 for summer or winter. They apply to any person (child or adult).

Table 3-7: Calculated risk profiles and IIR(%) for raw shellfish consumption.

Percentile	Summer results (no bypass) at Site:				"Winter" results (no bypass) at Site:				"Winter" results (with bypass) at Site:			
	7: ExW	8: ThK	9: OhB	10: Wai	7: ExW	8: ThK	9: OhB	10: Wai	7: ExW	8: ThK	9: OhB	10: Wai
Minimum	0	0	0	0	0	0	0	0	0	0	0	0
10%ile	0	0	0	0	0	0	0	0	0	0	0	0
20%ile	0	0	0	0	0	0	0	0	1	0	0	0
30%ile	0	0	0	0	0	0	0	0	1	0	0	0
40%ile	0	0	0	0	0	0	0	0	2	1	0	0
50%il	0	0	0	0	0	0	0	0	3	1	1	0
60%ile	0	0	0	0	0	0	0	0	3	1	1	1
70%ile	1	0	0	0	1	0	0	0	5	2	1	1
75%ile	1	0	0	0	1	0	0	0	5	3	2	2
80%ile	1	0	0	0	1	1	0	0	7	3	2	2
85%ile	1	0	0	0	2	1	1	1	8	4	3	3
90%ile	2	1	0	0	3	1	1	1	11	6	4	4
95%ile	6	2	1	1	8	5	3	2	17	14	11	10
96%ile	12	4	2	1	12	8	5	4	19	16	15	14
97%ile	15	8	4	3	15	12	10	9	20	18	17	17
98%ile	18	12	9	6	18	15	14	14	22	20	19	19
99%ile	21	16	13	11	21	19	18	18	24	23	22	22
99.5%ile	23	19	16	14	23	22	20	20	26	25	24	24
99.9%ile	27	24	21	20	27	26	24	25	31	28	28	28
Maximum	33	26	25	26	33	31	27	29	35	34	31	33
IIR(%)	1.266	0.587	0.410	0.319	1.41	0.938	0.752	0.707	4.323	2.558	1.974	1.822

"IIR" is the Individual's Illness Risk. The other numbers in this table are the number of predicted illness cases among 100 consumers of raw shellfish any random day in the indicated season and WWTP status (no bypass, bypass). So, for example, at site ExW in summer for 95% of the time there would be no more than 6 illness cases (out of 100 child swimmers).

4 Discussion

In all cases predicted risks are contingent on the assumed inactivation efficacy of the activated sludge and membrane filtration process at the WWTP during normal flows and screening and UV disinfection for bypass flows. We have assumed (after discussion with CH2M Beca staff, particularly Reuben Bouman) that the plant would operate at between 3 and 4 "$\log_{10}$", i.e., between 3 and 4 orders of magnitude reduction of the concentration of viable Noroviruses, from influent to effluent. Were it to be sustained at 4 $\log_{10}$ (or higher), predicted risks to swimmers and shellfish consumers would reduce.

4.1 Recreational water contact

The results for recreational water-contact (summarised in Table 3-6) indicate that swimmers' risks attributable to the outfall are low in all cases. They are higher for children than for adults (compare scenarios 1 and 3; scenarios 2 and 4) and for all shoreline sites are highest at site 7 (of the thirteen nearshore sites its lag time is the shortest). As expected, the risks at site 14, in mid-Harbour close by the proposed diffuser, are the highest. That is because that site's short lag time minimises the time for natural in-Harbour virus inactivation processes (e.g. solar irradiation, predation) to occur. Bypass events (scenario 5) do cause some elevation of the risk, but even at the mid-Harbour site 14 these are less than 0.5%—reaping the benefits of WWTP disinfection processes and large initial dilutions of the wastewater discharged from a diffuser near the sea-bed, mixing with ambient Harbour water as the plume rises to the water surface, under buoyancy.

These risks are generally low when compared to “tolerable” risks inherent in the New Zealand water quality guidelines for recreational areas (MfE/MoH 2003), as discussed below. As noted in part above, that is a consequence of the efficacy of the treatment and disinfection processes at the WWTP and the degree of dilution and inactivation of viruses in the Harbour waters. The main water flow is along the axis of the Harbour, and so it exhibits rather long lag times before reaching exposure sites, during which time there is opportunity for removal of viruses from Harbour water. That removal is effected by the joint actions of natural UV irradiation and grazing by higher-order microbes.

Note that the summary risks (see "IIR" results in Table 3-6) are averaged over substantial periods of time. As noted in Section 2.1, in computing these averages the QMRA model first calculates risk profiles (reported in Table 3-1 – Table 3-5) and the averaging process, by its very nature, smoothes out the peak risks predicted. For example, consider site ExW for scenario 1 (children, summer conditions, see Table 3-1). For over 97% of the time, the risk to recreational water-users attributable to the outfall is absent, principally because the plume from the outfall is either absent or very low in concentration. However, for the time that it is present there is a small risk. This is a rather similar outcome to that predicted for other coastal outfalls of disinfected wastewater (e.g., Napier—McBride 2011).

4.1.1 Tolerable risks for recreational water-contact

New Zealand microbiological water quality guidelines (MfE/MoH 2003) follow recommendations from the World Health Organisation (WHO 2003). In particular, subject to the results of sanitary surveys of the catchment draining into a recreational area, they set contact-recreation-associated illness bathing-season risk thresholds for beaches maintaining

a “very good” Suitability for Recreation Grade (SFRG) as posing <1% risk of gastrointestinal illness (and <0.3%–1.9% risk for Acute Febrile Respiratory Illness); "good" grading as posing 1%–5% risk of gastrointestinal illness (and 0.3%–1.9% risk for Acute Febrile Respiratory Illness). For beaches in a “fair” or “poor” state, these risks are 5%–10% and 1.9%–3.9%, respectively.

As noted in section 2.2.1, respiratory agents such as Adenoviruses are less important in the rather quiescent Akaroa Harbour waters compared with an open coast (e.g., Wellington coastline), and so we expect respiratory effects to be less important than gastrointestinal.

Even though this study’s average predicted gastrointestinal risks attributable to the outfall are less than 1% (even for Bypass events), the beach SFRG results derived by the Regional Council (Bolton-Ritchie 2013) do not explicitly reflect that. This is entirely appropriate because: (i) other local sources (stormwater, leakage, wastewater inflow) can and do contribute to microbial contamination, and (ii) sanitary survey information used by the guidelines can obviate the possibility of reaching a higher grade.

However, it is evident from Environment Canterbury's monitoring (Bolton-Ritchie 2013, Figure 5-3 and Appendix 13) that there have been ongoing improvements in the microbial condition of some Harbour water sites. This is in terms of the lower surveillance limit given on page D6 of New Zealand Guidelines (MfE/MoH 2003), i.e., 40 enterococci per 100 mL and, more particularly in terms of the assigned SFRG. For example, Akaroa main beach (site 4)[xii] has improved from "Poor" (2002–2003 to "Fair" (2003–2006) and "Good" (2006–2010). The improvements being made to Akaroa’s wastewater system in this project will continue this progress.

4.2 Consumption of raw shellfish

The IIR results for shellfish consumption for sites 7 – 10 (Table 3-7) indicate risks higher than those faced by swimmers at these sites—in keeping with findings of other studies such as New Plymouth (McBride 2012). In normal operation of the treatment plant, these IIR values can be as high as 1.5% (for "Winter" conditions at site 7). They are more elevated during bypass conditions, reflecting the lower efficacy of artificial UV disinfection for bypass flows.

Note that, because shellfish retain microbes for some time, the risk profiles (from which IIR values are calculated) are more gently-rising than those found for contact recreation, meaning that risks are more often present.

4.2.1 Tolerable risks for raw shellfish consumption

Existing specifications for bivalve molluscan shellfish harvesting[xiii] do not present explicit tolerable risk levels. Their requirement for water samples is based on faecal coliforms (median MPN not to exceed 14 per 100 mL and no more than 10% of the samples to exceed 43 MPN per 100 mL), a practice also followed by Environment Canterbury (Bolton-Ritchie 2013). These were derived from calculations by advisers to the US Public Health Service after a shellfish-related typhoid outbreak in the early parts of last century. In particular, it was believed that typhoid could be avoided if not more than 50% of the 1 mL portions examined were positive for total coliforms. This was used to calculate a limit of 70 total coliforms per 100 mL which was later adjusted (by a factor of five) to derive a limit of 14 faecal coliforms per 100 mL (McBride 1990).

Nevertheless, if we assume that " good" conditions prevail if the predicted shellfish-associated illness risk is between 1% and 5% (as for the SFRG, as discussed above), then the results shown in Table 3-7 indicate that sites 9 and 10 would be better than “good”, as would site 8 in summer (and would be almost-so in winter). Site 7's risks are a little higher than the 1% threshold and so would only qualify as “good”. For bypass flows, risks can reach nearly 5% and the erection of temporary signage warning against shellfish-gathering would seem appropriate.

Note however, that the (rather brief) “Shellfish-Gathering Waters” section of the New Zealand guidelines (MfE/MoH 2003, Section F) states that “The guidelines apply to waters in a catchment where a prior sanitary survey has shown that there are no point sources of public health concern”. This issue may be best considered further in consultation with the competent public health authorities.

5 Conclusions

Illness risks to swimmers attributable to the proposed wastewater treatment and disposal upgrades, up to 2041, can be expected to be below 1% over any bathing season (summer or "winter". This holds true even for occasional bypass treatment events in winter (because the bypass flow will receive some disinfection before discharge to the Harbour). For a small proportion of winter there may be higher risks, which would particularly occur when and if there is an outbreak of Norovirus illness in the contributing population.

Risks from consumption of raw shellfish harvested from Harbour sites indicates a low but somewhat higher risks than for contact recreation. Again, these arise when the sewered community is contributing unusually large concentrations of Norovirus.

Overall, the scheme can be expected to contribute to an ongoing improvement in Harbour water quality and a significant reduction in human health risk.

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7 Glossary of abbreviations and terms

Conditional probability of illness	The probability that an individual, already infected with Norovirus will proceed to exhibit symptoms of illness.
ID_{50}	The dose required to cause infection (or illness, as appropriate) in half of an exposed group (assuming the underlying dose-response model to be true and applicable to that group).
IIR	Individual's Illness Risk (note that this term is sometimes used to denote Individual's *Infection* Risk).
Illness	Evidence of infection by a particular pathogen accompanied by disease symptoms (vomiting, fever,…)
Infection	Host shedding of the pathogen in question. Infected individuals may or may not proceed to exhibit illness. If they do not they are in the "asymptomatic infection" state.
Genome copies	Genome fragment for the pathogen captured by the qPCR methodology.
Hypergeometric function	The mathematical function in a Norovirus dose-response relationship. Not to be confused with the hypergeometric statistical *distribution.*
Norovirus	A member of the Calicivirus group, containing five genogroups, of which groups 1, 2 (and occasionally 4) can infect humans.
Norwalk virus	A particular Calicivirus in genogroup 1.1. A norovirus outbreak at school in Norwalk Ohio in 1968 was the first recorded outbreak related to these viruses—undoubtedly preceded by numerous unrecorded cases (endemic or outbreak). The outbreak's viral agent was only identified (by electron microscopy on stored stool samples) in 1972 (http://en.wikipedia.org/wiki/Norovirus).
Percentile	The value below which a given percentage of data falls. For example, if the 95%ile is 8, then only 5% of the data are greater than 8.
Probability of illness	An individual's probability of infection (given a known dose) multiplied by the (conditional) probability of illness given that infection has already occurred.
qPCR	Virus enumeration using a laboratory quantitative Polymerase Chain Reaction.
QMRA	Quantitative Microbial Risk Assessment.

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[i] CCC has also recommended that through the consenting process the following BNR processes should remain as viable treatment alternatives for the design build contractor: Sequence Batch Reactors (SBR); Oxidation Ditch; Mixed Bed Biofilm Reactor (MBBR); Integrated Fixed Film Activated Sludge (IFAS).

[ii] These interpretations are inherently based on an assumption that the Noroviruses in question are not aggregated. That is expected to be a valid, given the vigour of the proposed treatment processes.

[iii] "Norovirus" subsumes the term "Norwalk virus". The clinical trial reported and analysed by Teunis et al. (2008) was for the original Norwalk virus (genotype group GI.1)—it had been stored in a laboratory at Emory University (Atlanta) for some years. Since the time of the first identified Norovirus outbreak (in Norwalk, Ohio, 1968) a number of other similar Caliciviruses have been identified, in genogroups I–V. Current practice is to regard the infectivity of GI.1 Norovirus as equivalent to all Noroviruses that affect humans (particularly GI and GII).

[iv] Nevertheless this issue of water-contact-related respiratory illness is an area worthy of further research, particularly in the light of the respiratory illness rates reported in the one New Zealand epidemiological study on this matter—McBride et al. (1998). In that study (at seven New Zealand beaches) those rates were generally more prominent than gastrointestinal rates, a phenomenon that has not been fully understood.

[v] Reuben Bouman (Beca) advises that the maximum winter dry-weather flow to full treatment (for 2041) is 3.3 L/s, and that the predicted Peak Storm gives rise to a volume of 5,900 m^3 receiving bypass treatment over 84 hours, which is 19.5 L/s. So to account for dilution of the influent by stormwater during bypass flow episodes, a "bypass dilution factor" of 7 was adopted [≈ (19.5 + 3.3)/3.3].

[vi] In April-May 1999 regular (weekly) monitoring of three viruses (Reoviruses, Adenoviruses, Enteroviruses) in the influent to the Mangere Wastewater Treatment plant exhibited elevated concentrations, reaching nearly three orders-of-magnitude above concentrations routinely obtained both before and after this period. It was *later* speculated that this may have been caused by a "Samoa virus" [pers. comm. Dr Francesca (community health specialist) to Graham McBride, NIWA, circa 2001]. That situation refers to a realisation in the medical community that there *had been* an unusually large number of gastrointestinal cases among south Auckland Polynesian communities. That is, the outbreak took some time to detect (in general, gastrointestinal disease is not notifiable). This event indicates that relatively confined outbreaks in large communities, giving rise to substantial elevations in virus concentrations in wastewater, may go undetected for some time. Indeed it may not be detected at all.

[vii] Some thought would have to be given to advising departed tourists.

[viii] Chloroisocyanurates are commonly added to outdoor swimming pools to stabilize chlorine disinfectants. The chloroisocyanurates decompose slowly to release chlorine and cyanuric acid. Studies have shown that ingested cyanuric acid passed through the body unmetabolised. This finding was used to determine the amount of water swallowed during swimming activity. Cyanuric acid was measured in pool water and the swimmers were asked to collect their urine for the next 24 hours and these samples were also analysed. Calculations of swimming-associated ingestion (of freshwater) were made using these data.

[ix] The dose-response curve for individual doses takes the two-parameter "beta-binomial" form (Eq. 9.23 in McBride 2005). That is, Prob(infection, given an individual dose i) = $1 - B(\alpha, \beta + i)/B(\alpha, \beta)$, where α (= 0.04) and β (= 0.055) are shape and scale parameters and B() is the standard beta function (see also McBride 2008). This differs from the equation derived for mean doses by Teunis et al. (2008), which is Prob(Infection, given a mean dose d) = $1 - {}_1F_1(\alpha, \alpha + \beta, -d)$, where ${}_1F_1()$ is the Kummer hypergeometric function. The former (beta-binomial) is not only the appropriate mathematical function (cf. the Kummer function), it is also much easier to compute (using Excel's GAMMALN function).

[x] That is, Prob(illness, given that infection has occurred) = 0.6x0.74 = 0.44 (where 60% of the infected clinical trial participants exhibited illness but 26% of the trial participants exhibited complete immunity).

[xi] Note that Teunis et al. (2008) report that the conditional probability of *illness* inferred from their clinical trial predicts remarkably low probability values unless the dose is very high, while also reporting that the probability of *infection* is very high at low doses. In Dr Teunis's communication to the

author about that (email to Graham McBride, NIWA, 6 October 2011) he said: "The interesting consequence is that low dose exposure may cause infections with few symptomatic cases, whereas high doses cause clusters of symptomatic cases". Others (e.g., Schoen and Ashbolt 2010) have used much higher values of conditional illness probabilities—derived from the trial data but regardless of dose. So, if a risk analysis uses illness (cf. infection) as its endpoint, as we do here, the difference between these two strands is extreme. Precaution says: Follow the Schoen & Ashbolt example. Some support for that stance comes from the observation that it does seem odd that people could be infected with many Noroviruses (with “infection” assessed by “fecal excretion of virus and seroconversion”) yet so few of them would become ill. Also a parallel risk model using Rotavirus (instead of Norovirus) indicates that Rotavirus illness would be the more prevalent if the Teunis et al. conditional Norovirus illness probability were to be used, and that is not expected to be the case. Most importantly, a recent analysis of Norovirus outbreaks from consumption of contaminated oysters in southern France has indicated that Norovirus illness does arise from very low doses. That is in contradiction to an even more recent study (Atmar et al. 2013), but this analysis did not take account of aggregation of the viruses in their clinical trial preparations, which may have compromised the results (McBride 2014).

[xii] See page 75 of http://ecan.govt.nz/publications/General/combine-rwq-2012-2013.pdf.

[xiii] www.foodsafety.govt.nz/elibrary/industry/Animal_Products-Applies_Anyone.pdf