MATAURA QUANTITATIVE MICROBIAL RISK ASSESSMENT (QMRA)

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PREPARED BY:

Peter Cressey, Risk and Response Group

Roger Hodson, Environment Southland

Nick Ward, Environment Southland

Bronwyn Humphries, Food, Water and Biowaste Group

PREPARED FOR:	**Environment Southland**
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REVIEWED BY:	**Dr Beverley Horn, Risk and Response Group**
	Dr Rob Lake, Risk and Response Group

Peer reviewer	Peer reviewer	Author
Dr Beverley Horn	**Dr Rob Lake**	**Peter Cressey**
Senior Scientist, Risk and Response group	Manager, Risk and Response Group	Senior Scientist, Risk and Response group

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DISCLAIMER

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EXECUTIVE SUMMARY

The Mataura River rises in the Eyre Mountains south of Lake Wakatipu and passes through the towns of Gore and Mataura before discharging into Toetoes Bay, east of Invercargill. Two major point discharges to the Mataura River occur from the Gore Wastewater Treatment Plant (WWTP), at Gore, and the Alliance Mataura meat processing plant, at Mataura.

Water sampled from the Mataura River, below the discharge from the Alliance Mataura meat processing plant often does not meet the *Escherichia coli* guideline levels for recreational water. However, given the mixture of effluent sources discharging to the Mataura River, there was speculation that accepted relationships between indicator bacteria (*E. coli*) and pathogenic bacteria (*Campylobacter* spp.) may differ from those that the national recreational freshwater guidelines are based on.

Available information has been used to estimate the risk of *Campylobacter* infection associated with children swimming in the Mataura River in the environs of Mataura township using quantitative microbial risk assessment (QMRA). Three scenarios were used to estimate the level of *Campylobacter* contamination of the river:

- Actual measurements of *Campylobacter* in the river (May 2017)
- Dilution of Gore WWTP and Alliance Mataura effluent *Campylobacter* in the river (May 2017)
- Estimation of *Campylobacter* from a previously determined regression against river flow rate.

The first two scenarios are based on data collected during a single day of sampling and it is uncertain how representative the results from this sampling are of the ‘normal’ contamination levels in the Mataura River. The third scenario uses a wider range of data to predict *Campylobacter* concentrations from river flow rates.

The first two scenarios result in very low mean estimates of the *Campylobacter* infection risk (<0.1%), while the third scenario results in mean estimates of 2.8 and 1.7%, depending on whether high river flows are excluded from the estimate, as representing ‘unswimmable’ conditions.

Based on the single day of sampling, the QMRA suggests that effluent discharged from the Gore WWTP and Alliance Mataura contribute a relatively small proportion of the overall *Campylobacter* risk. This is consistent with other work that indicated that *Campylobacter* contamination in this region of the Mataura River was predominantly of wild fowl origin.

The first two QMRA scenarios would result in this region of the Mataura River being classified in the highest water quality category for microbiological quality under either the old or updated categorisation schemes. The third scenario would result in a lower water quality categorisation.

It should be noted that the current QMRA only considers risks of *Campylobacter* infection and other pathogenic microorganisms will potentially be present in the Mataura River. In particular, it is likely that discharge effluent from the Gore WWTP will contain human enteric viruses, such as norovirus.

Defining risks in terms of children swimming is a conservative (risk maximising) approach, as other population groups and types of contact recreation will result in ingestion of lower amounts of water and represent lower risks of *Campylobacter* infection. However, conservatism in risk assessment is appropriate, as decisions based on QMRA should be protective of those at highest risk.

1. INTRODUCTION

The Mataura River rises in the Eyre Mountains south of Lake Wakatipu and passes through the towns of Gore and Mataura before discharging into Toetoes Bay, east of Invercargill. Two major point discharges to the Mataura River occur from the Gore Wastewater Treatment Plant (WWTP), at Gore, and the Alliance Mataura meat processing plant, at Mataura.[1]

Water sampled from the Mataura River, below the discharge from the Alliance Mataura meat processing plant often does not meet the *Escherichia coli* guideline levels for recreational water. However, given the mixture of effluent sources discharging to the Mataura River, there was speculation that accepted relationships between indictor bacteria (*E. coli*) and pathogenic bacteria (*Campylobacter* spp.) may differ from those that the national recreational freshwater guidelines are based on. The freshwater guidelines are based on a moderate correlation between concentrations of *E. coli* and *Campylobacter*, with the original data set having a mean *E. coli* concentration of 93 CFU/100 mL and a mean *Campylobacter* concentration of 0.9 MPN/100 mL (McBride *et al.*, 2002).

1.1 QUANTITATIVE MICROBIAL RISK ASSESSMENT (QMRA)

QMRA uses information on the concentrations of pathogen microorganisms in environmental media and contact rates of humans with those environmental media to estimate human exposure doses. These dose estimates are then combined with information on the dose-response relationship for the pathogen to derive estimates of the probability of infection due to contact with the environmental media.

In the current instance the QMRA considers the risk of *Campylobacter* infection from people swimming in the Mataura River at a point immediately below the discharge from the Alliance Mataura meat processing plant; the furthest downstream of the two major point discharges. Figure 1 shows a map of the Gore district, in the region of Gore and Mataura.

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[1] http://www.alliance.co.nz/contact-us/plant-locations/ Accessed 13 June 2017

Figure 1. Gore district in the region of Gore and Mataura

Reproduced from http://www.goredc.govt.nz/assets/documents/maps/gore-district-general-map.pdf

2. MATAURA RIVER AND EFFLUENT DISCHARGES

2.1 MATAURA RIVER

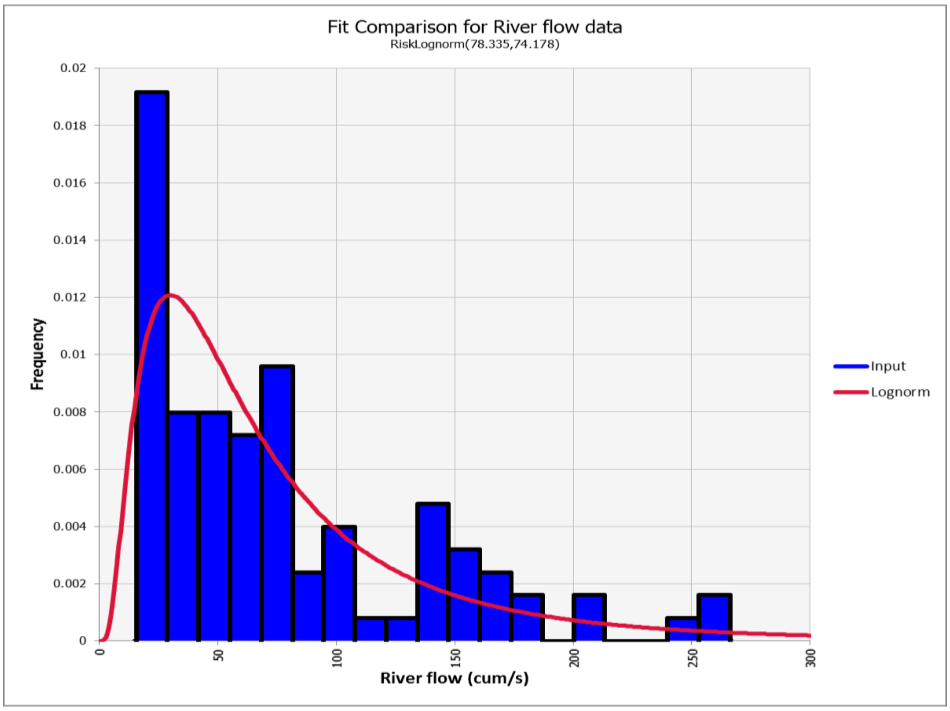
There are four flow monitoring stations on the main stem of the Mataura River, and a number of others on its various tributaries (Paine, 2012). Figure 1 summarises the flow characteristics at the Gore and Tuturau monitoring stations from a range of sources.

Table 1. Summary statistics in m^3/s for the Mataura River

Monitoring station	Period covered	Min	Max	Mean	Median	Std Dev	Reference
Gore	1977-2012	8.00	2297.00	64.77	48.90	65.18	(Paine, 2012)
Gore	NS	7.0	2288	49.28	35.14		(Hughes *et al.*, 2011)
Gore	NS	7.0	2297	65.14	49.28		ES
Tuturau	NS	6.2	2407	71.90	55.75		(Hughes *et al.*, 2011)
Tuturau	2014-2017	15.6	266	77.07	59.46	60.16	Alliance Mataura
Tuturau	NS	6.2	2407	71.9	55.75		ES

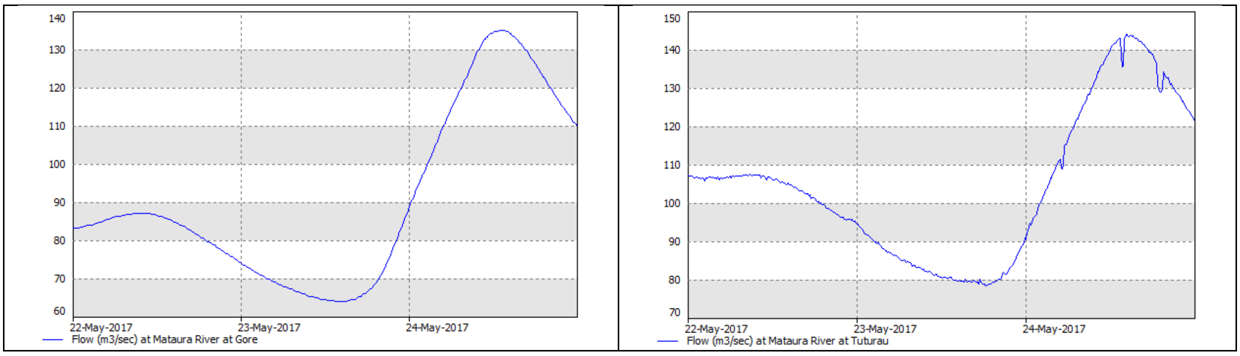
The daily river flow data provided by Alliance Mataura were used to examine the distribution of river flows at the Tuturau monitoring site. Figure 1 shows the distribution of river flows as a histogram. The BestFit function of the Excel add-in @Risk was used to examine statistical distributions that could be used to describe these data. Figure 2 shows the best fitting lognormal distribution, with a mean of 78.33 m^3/s and a standard deviation of 74.18 m^3/s.

Figure 2. Summary of Mataura River daily flow rates (Tuturau monitoring site), October 2014-February 2017



Sampling of effluent and river water to support the current QMRA occurred across 22-24 May 2017. Figure 3 shows the flow measurements for the Mataura River, at the Gore and Tuturau monitoring sites during this period.

Figure 3. Mataura River flows (m^3/s) during 22-24 May 2017, as measured at the Gore and Tuturau monitoring sites



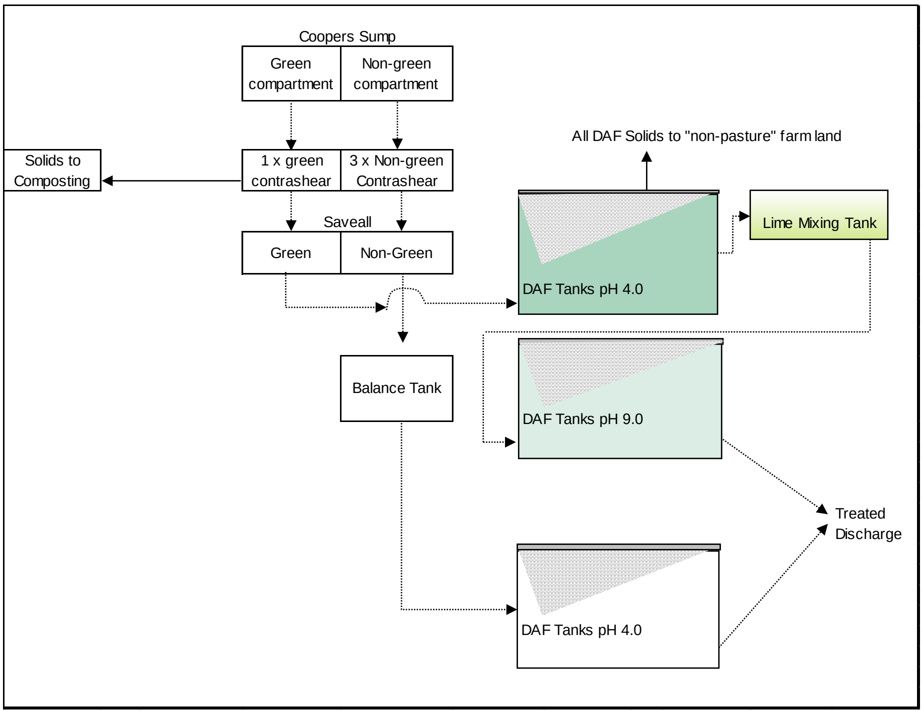
Source: http://envdata.es.govt.nz/index.aspx?c=flow

Sampling was completed at all sites by 10:45 am 24 May 2017. While a more detailed analysis is not possible, it appears that Mataura River flows at Gore and Tuturau were slightly above average during 22-23 May 2017, with a rapid increase in flows during the first half of 24 May 2017.

2.2 ALLIANCE MATAURA

Alliance Mataura treat their meat processing plant effluent in two streams, green and non-green (Richardson, 2016). Figure 4 shows a schematic of the wastewater treatment process at Alliance Mataura. The green stream undergoes a two-stage pH adjustment, followed by dissolved air flotation (DAF), with recovery of the precipitated solids. The extra treatment of the green stream is intended to decrease the phosphorus loading in this stream.

Figure 4. Schematic of the wastewater treatment process at Allaince Mataura

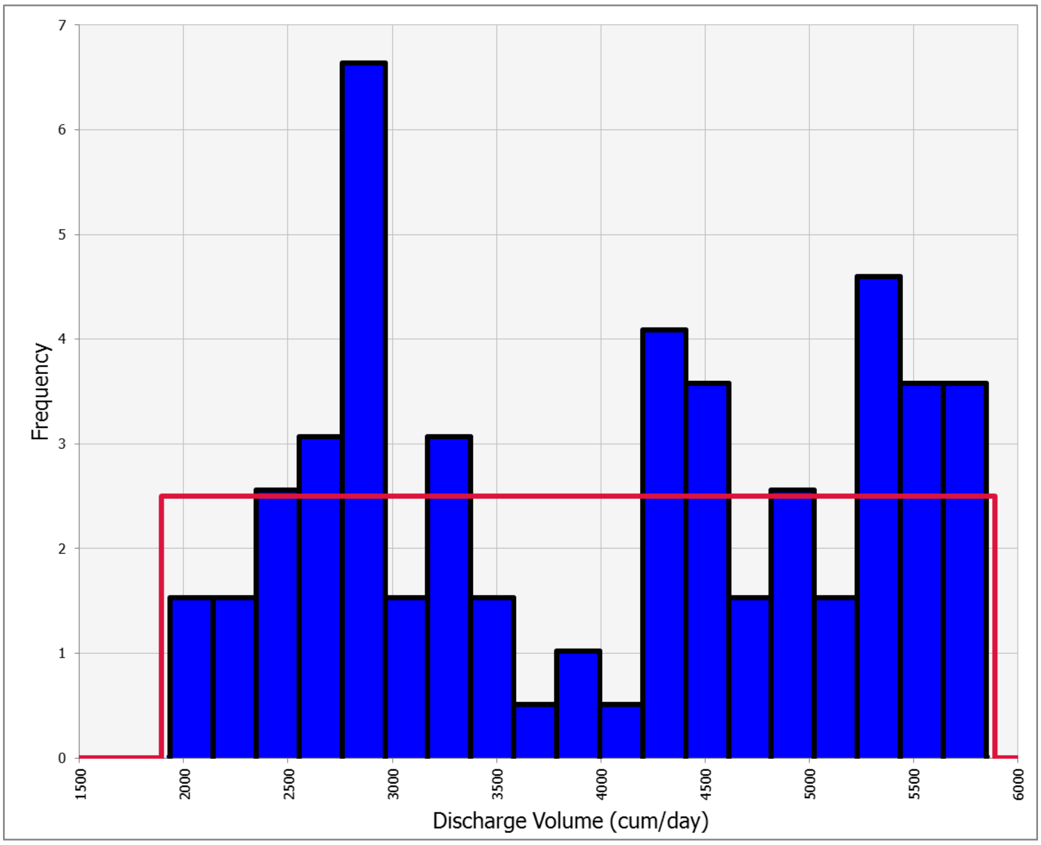


The two effluent streams (green and non-green) at combined at the point of discharge.

During the period 1 October 2015 to 5 July 2016, the mean daily effluent discharge to the Mataura River was 4078 m^3/day (range 2285-5575 m^3/day) (Richardson, 2016). Data provided directly by Alliance Mataura, for the period October 2014 to February 2017, gave a mean discharge volume of 4004 m^3/day (range 1935-5850 m^3/day) (Jessica McKee, Alliance Mataura, personal communication). Figure 5 shows a histogram of daily effluent discharge volumes from Alliance Mataura. There is no obvious pattern to the discharge volumes and, using the BestFit function of the Excel add-in @Risk, the distribution of daily effluent discharge volumes would be best represented by a uniform distribution, between 1935 and 5850 m^3/day.

Daily discharge volumes were assessed against mean daily river flow rates at the Tuturau monitoring site for the period October 2014 until February 2017, to determine if there was any adjustment of effluent discharge to river flow conditions, such as increased discharge under conditions of high river flows. No association was found between discharge volume and river flow (R^2 = 0.01). This suggests that discharge volume and river flow can be treated as independent variables. River flow volumes were in the range 260-8800 (mean = 1900) times the associated effluent discharge volume, indicating that the effluent discharge would have a very minor impact on the volume of water in the river.

Figure 5. Distribution of Alliance Mataura effluent discharge volumes, October 2014-February 2017



During the sampling period for the current study, flows for the green and non-green streams were in the range 126-147 m^3/hour and 126-141 m^3/hour. Assuming 24-hour discharge, these flows equate to discharge volumes in the range 3024-3528 m^3/day and 3024-3384 m^3/day for green and non-green streams, respectively (Jessica McKee, Alliance Mataura, personal communication). However, it appears that effluent was not continually discharged and daily total discharge volumes are likely to be within the range identified above.

It is worth noting that the volumes of the two effluent streams appear to be approximately the same and for the current model they have been assumed to be the same, on average.

2.3 GORE WWTP

It has been reported that, during dry weather, 1,000-7,000 m^3/day of treated wastewater is discharged from the Gore WWTP oxidation ponds to the river. However, because stormwater in some parts of Gore also flows into the oxidation ponds, the amount of treated wastewater discharged to the river can rise to over 20,000 m^3/day during periods of wet weather (Environment Southland, 2011).

Detailed wastewater discharge data were provided by the Gore District Council (Donique Weatherburn, Gore District Council, personal communication). The Gore WWTP plant includes an Actiflo plant.[2] The Actiflo plant has particular advantages with respect to phosphorus removal. The Actiflo plant operates when the Mataura River flow is <60 m^3/s and discharges to the river, the oxidation ponds discharge to the river when the river flow is >60 m^3/s. Prior to April 2015, both Actiflo and oxidation ponds would often discharge to the

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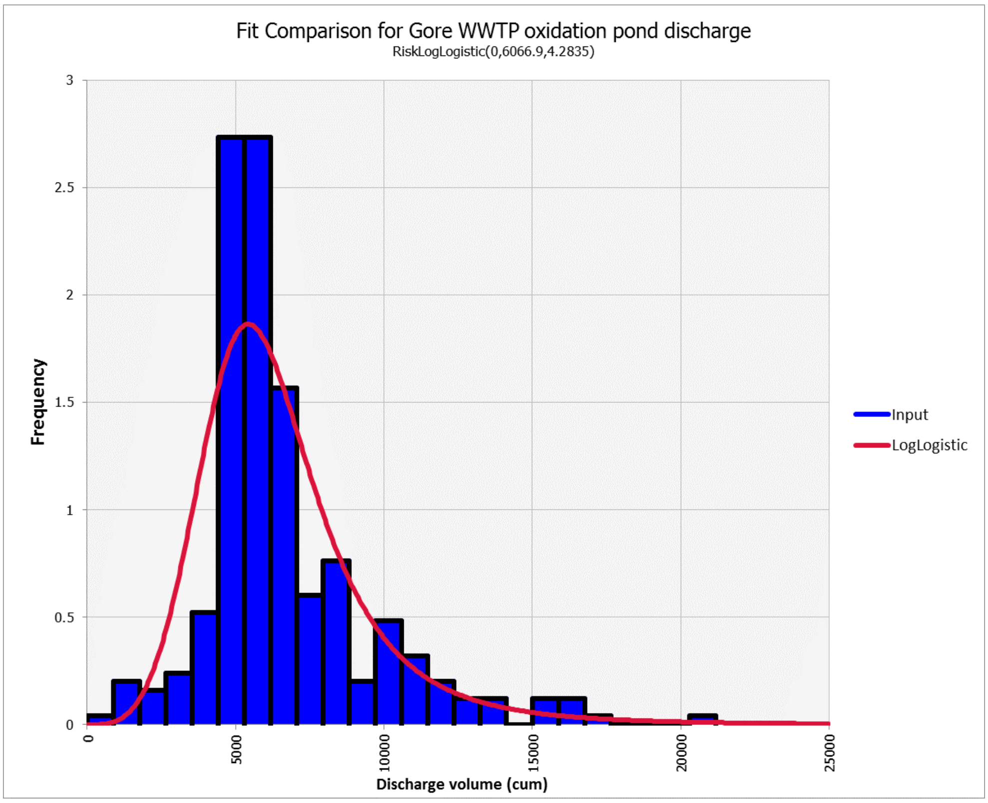
[2] http://technomaps.veoliawatertechnologies.com/actiflo/en/ Accessed 19 June 2017

river on the same day. However, since that time the two discharge options have been largely complementary. On the sampling dates for the current project, river flows were >60 m^3/s.

For days when only the oxidation ponds were discharging to the Mataura River, the mean discharge volume was 6605 m^3/s (range 2-21169 m^3/s). Figure 5 shows a graphical representation of the distribution of discharge volumes from the oxidation pond only and the best-fitting statistical distribution, which in this case is a loglogistic distribution.

Figure 6. Distribution of Gore WWTP (oxidation pond only) effluent discharge volumes, January 2012-June 2017



3. MICROBIOLOGICAL MONITORING

Effluent discharges from the Gore WWTP and Alliance Mataura (green and non-green) and Mataura River water (immediately downstream from the Alliance Mataura discharge) were sampled and analysed for *Escherichia coli* and *Campylobacter* spp on 23-24 May 2017. In addition, a larger body of data is available on *E.coli* testing of these media. Historical data were used, where relevant, to determine whether effluent and water sampled for the current project were typical of the microbiological quality seen at these sites.

3.1 MATAURA RIVER

3.1.1 May 2017

Table 2 summarises the results of microbiological analyses of Mataura River water sampled on 23-24 May 2017.

Table 2. Microbiological quality of Mataura River water, sampled 23-24 May 2017

Date/time	River flow (m^3/s)	*E. coli* (CFU/100 mL)	*Campylobacter* spp. (MPN/100 mL)
23/05/2017 13:45	79.93	600	<0.3
23/05/2017 15:45	79.66	400	<0.3
23/05/2017 17:45	79.02	300	<0.3
23/05/2017 19:45	79.82	1100	0.4
23/05/2017 21:45	83.19	900	0.4
23/05/2017 23:45	90.40	600	<0.3
24/05/2017 1:45	99.06	1100	0.4
24/05/2017 3:45	107.18	900	<0.3
Mean	**87.30**	**738**	

Sampling point: 200 m downstream of Mataura bridge (1280862 Easting, 4875568 Northing)

It is worth noting that *Campylobacter* spp. concentrations above the limit of detection (LOD; 0.3 MPN/100 mL) were associated with the highest observed *E.coli* concentrations, with *Campylobacter* spp. present at approximately 0.04% of the *E. coli* concentration. The national recreational freshwater guidelines were derived from a data set in which the mean *Campylobacter* concentration was approximately 1% of the mean *E. coli* concentration (McBride *et al.*, 2002).

Two earlier water samples had been taken at the same monitoring site as that used in the current study (March and August 2015) (Dr Elaine Moriarty, ESR, personal communication). These sample were also analysed for *E. coli* and *Campylobacter*, as well as markers of faecal sources. Details of the findings were:

- Sample one did not contain detectable *E.coli* (<1 CFU/100 mL), but contained *Campylobacter* spp. at a concentration of 4.3 MPN/100 mL, identified as *C. jejuni*. Contamination profiling (faecal source tracking) was consistent with wildfowl.
- Sample two contained 210 CFU/100 mL *E. coli* and 2.3 MPN/100 mL *Campylobacter* spp., identified as *C. jejuni*. Contamination profiling (faecal source tracking) was consistent with a mixture of human, ruminant and wildfowl.

3.1.2 Autumn and Spring 2015

The samples taken of the Mataura River during a single 24-hour period in May 2017 represent a fairly narrow range of microbial quality and less variance than is likely to be encountered during a typical contact recreation season. During 2015, a number of river locations in Southland were sampled and analysed for both *E.coli* and *Campylobacter* spp. (Dr Elaine Moriarty, ESR, personal communication). Samples were taken at three sites of relevance to the current study; Gore, Mataura Bridge and Tuturau. Some of the samples were collected after significant rainfall events and a wider range of microbiological quality was found. Results are summarised in Table 3. River flow rates have also been included. As daily average flow rates are not available, these have been calculated as the mean of the day start, day finish and mid-day flow rates.[3]

Table 3. Microbiological quality and flow rates for Mataura River, 2015

Site	Sampling date	*E.coli* (CFU/100 mL)	*Campylobacter* spp (MPN/100 mL)	Mean river flow (m^3/s)
Gore	15/04/2015	4800	460	84
Gore	13/05/2015	3000	24	187
Gore	14/10/2015	400	3	75
Gore	18/11/2015	130	<0.3	38
Mataura Bridge	15/04/2015	3000	43	93
Mataura Bridge	13/05/2015	6000	93	181
Mataura Bridge	14/10/2015	500	9.3	75
Mataura Bridge	18/11/2015	400	2.3	42
200 m downstream of Mataura Bridge	11/03/2015	<1	4.3	33
200 m downstream of Mataura Bridge	12/08/2015	210	2.3	91

Flow rates for the Mataura Bridge and 200 m downstream of the Mataura Bridge were taken from the Tuturau monitoring site

The data in Table 3 were examined for the relationships between the microbial quality measures and river flow rate. Log-log plots produced the best correlations. This would be expected, as the underlying distributions of both concentration and flow data are likely to be right-skewed. The relationship between *E. coli* and *Campylobacter* concentrations was quite strong ($R^2 = 0.87$, excluding the 11/03/2015 data point). Relationships between river flow and either *E. coli* or *Campylobacter* concentrations were less strong ($R^2 = 0.56$ and 0.44, respectively). Figure 7 shows the log-log plot for river flow rate against *Campylobacter* concentration.

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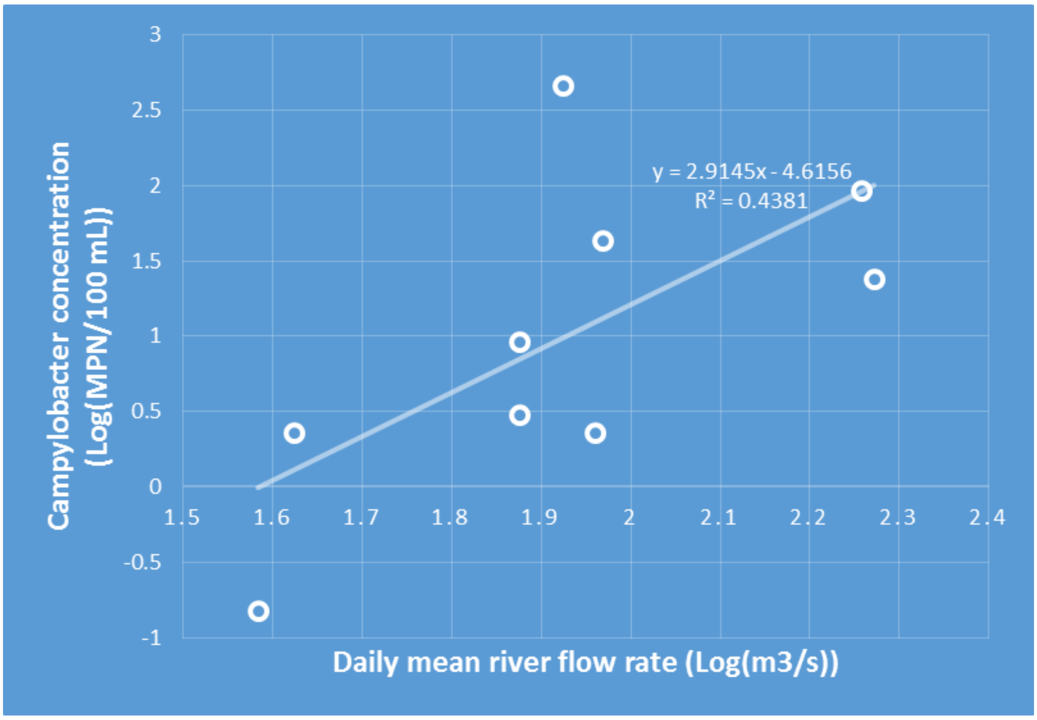
[3] http://envdata.es.govt.nz/index.aspx?c=flow Accessed 10 August 2017

Figure 7. Relationship between Matura River flow rate and *Campylobacter* concentration, 2015



3.2 ALLIANCE MATAURA EFFLUENT

Table 4 summarises the results of microbiological analyses of Alliance Mataura effluent (green and non-green) sampled on 22-23 May 2017.

Table 4. Microbiological quality of Alliance Mataura effluent (green and non-green), sampled 22-23 May 2017

Date/time	**Green**		**Non-green**	
	E. coli **(000 CFU/100 mL)**	***Campylobacter*** **spp. (MPN/100 mL)**	***E. coli*** **(000 CFU/100 mL)**	***Campylobacter*** **spp. (MPN/100 mL)**
22/05/2017 10:15			160	0.61
22/05/2017 12:15			240	1.5
22/05/2017 14:15			280	1.5
22/05/2017 16:15			330	15
22/05/2017 18:15			280	46
22/05/2017 20:15			64	9.3
22/05/2017 22:15			370	46
23/05/2017 0:15			220	0.9
23/05/2017 2:15			200	2.3
23/05/2017 4:15			150	2.3
23/05/2017 6:15			320	0.4
23/05/2017 8:15			110	4.3
22/05/2017 10:45	160	24		
22/05/2017 12:45	77	24		
22/05/2017 14:45	20	15		
22/05/2017 16:45	11	1.5		
22/05/2017 18:45	4	24		
22/05/2017 20:45	9	15		
22/05/2017 22:45	10	46		
23/05/2017 0:45	12	24		
23/05/2017 2:45	17	46		
23/05/2017 4:45	54	24		
23/05/2017 6:45	74	46		
23/05/2017 8:45	110	24		
Mean	**46.5**	**26.1**	**227**	**10.8**

For the two waste streams, the mean *Campylobacter* concentration was 0.06 and 0.005% of the mean *E. coli* concentration, respectively for the green and non-green streams. The national recreational freshwater guidelines were derived from a data set in which the mean *Campylobacter* concentration was approximately 1% of the mean *E. coli* concentration (McBride *et al.*, 2002).

Alliance Mataura have also provided *E. coli* concentration data for these two wastewater streams, covering three monitoring years (Jessica McKee, Alliance Mataura, personal communication). The results of this monitoring are summarised in Table 5.

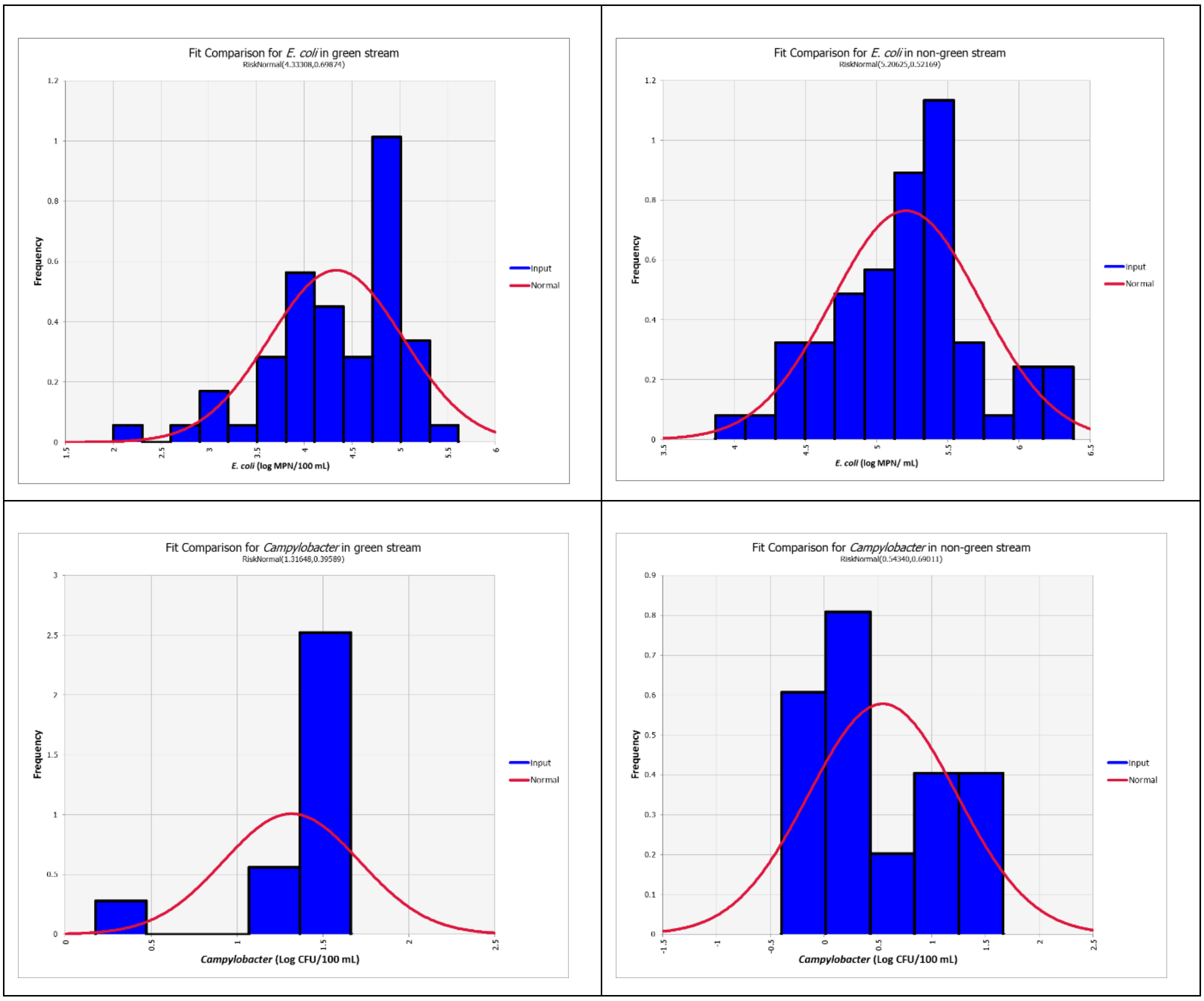
Table 5. Summary statistics for *E.coli* monitoring of Alliance Mataura effluent (green and non-green), 2014-2017

	2014-2015		**2015-2016**		**2016-2017**	
	Green	Non-green	Green	Non-green	Green	Non-green
Number of measurements	48	48	42	42	5	5
Mean (000 MPN/100 mL)	191	1520	51.7	355	53.8	333
Median (000 MPN/100 mL)	72.5	395	23.5	155	61	210
Minimum (000 MPN/100 mL)	0.2	13	0.1	7.4	5.8	55
Maximum (000 MPN/100 mL)	1400	8800	410	2400	100	920
Standard deviation (000 MPN/100 mL)	316	2492	74.3	587	35.9	341

The data in Table 5 suggest that *E.coli* concentrations in the green effluent are generally an order of magnitude lower than those in the non-green stream. The data also suggest that there was a significant decrease in the *E. coli* content of both effluent streams between the 2014-2015 and subsequent years. The mean *E. coli* concentrations for both streams were very similar for the 2015-2016 and 2016-2017 years, although relatively few measurements are available for the 2016-2017 year. The mean *E. coli* concentrations for the latter two years are also very similar to the mean *E.coli* concentrations found during sampling carried out in May 2017. This suggests that the microbiological results from effluent sampled on 22-23 May 2017 are likely to be representative of Alliance Mataura's 'normal' effluent.

Figure 8 shows an assessment of the distributional form of the *E. coli* and *Campylobacter* data from Alliance Mataura's green and non-green streams. For *E.coli*, data were consolidated across 2015-2016, 2016-2017 and the May 2017 sampling. *Campylobacter* data are solely from the May 2017 sampling. The distribution of microbial counts is generally considered to conform to a lognormal distribution (Commeau *et al.*, 2012; Engel *et al.*, 2001; Peleg *et al.*, 2012). That is, if a series of microbial counts are converted to log form, the statistical distribution of the logs will be approximately normal. All concentration data were converted to $\log_{10}$ and assessed by distributional form using the BestFit function of @Risk. In all cases, the log-transformed data could be satisfactorily represented by a normal distribution, as judged by the Anderson-Darling goodness-of-fit parameter.

Figure 8. Histograms and best-fit normal distributions for *E. coli* and *Campylobacter* concentration from Alliance Mataura green and non-green effluent discharges



In further examining the May 2017 data, no significant correlation was found between *E. coli* concentrations in green and non-green effluent, across the sampling period (R^2 = 0.12) or between *E. coli* and *Campylobacter* concentrations for either the green (R^2 = 0.005) or non-green (R^2 = 0.23) effluent streams.

3.3 GORE WWTP

Table 6 summarises the results of microbiological analyses of Gore WWTP effluent sampled on 23-24 May 2017.

Table 6. Microbiological quality of Gore WWTP effluent, sampled 23-24 May 2017

Date/time	*E. coli* (CFU/100 mL)	*Campylobacter* spp. (MPN/100 mL)
23/05/2017 12:45	3	<0.3
23/05/2017 14:45	<1	<0.3
23/05/2017 16:45	<1	<0.3
23/05/2017 18:45	1	0.4
23/05/2017 20:45	3	0.4
23/05/2017 22:45	<1	<0.3
24/05/2017 0:45	2	0.4
24/05/2017 2:45	1	<0.3
24/05/2017 4:45	<1	<0.3
24/05/2017 6:45	2	0.4
24/05/2017 8:45	1	<0.3
24/05/2017 10:45	<1	<0.3

Sampling location: Gore District Council Gore WWTP pond

Levels of microbial contamination in Gore WWTP effluent are very low, compared to concentrations in meat processing effluent.

The Gore District Council also provided information on *E.coli* concentrations in effluent discharged from their oxidation ponds, for the period 2012-2017. These data and corresponding data for the Mataura River, immediately upstream and immediately downstream of the discharge point are summarised in Table 7.

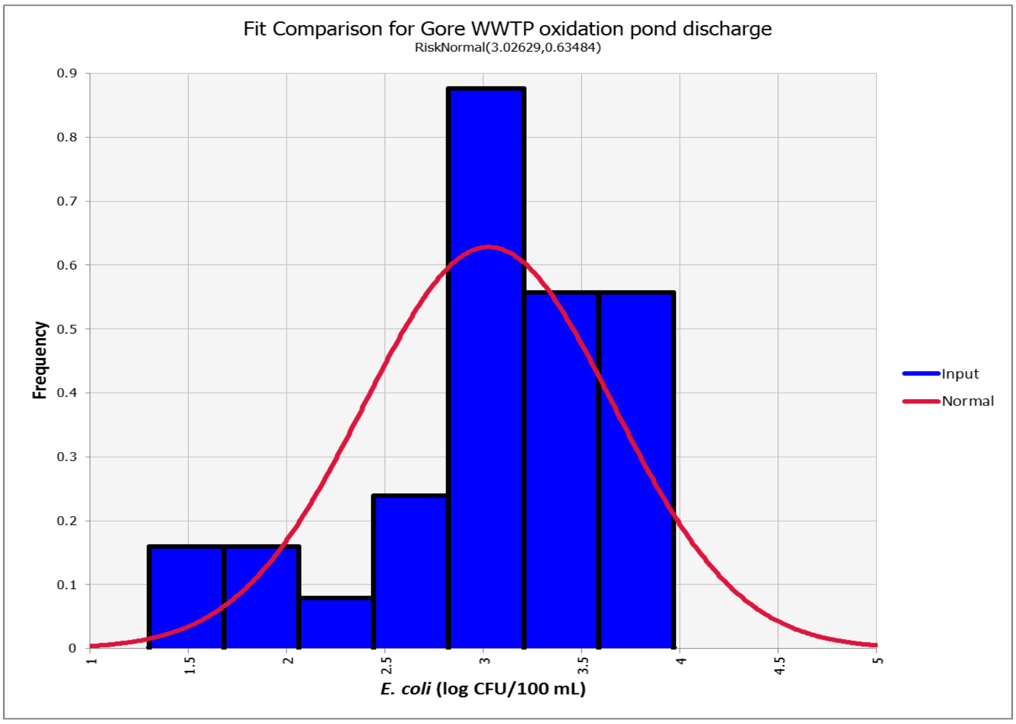
Table 7. Summary of *E. coli* concentrations in Gore WWTP oxidation pond discharge and in the Mataura River up- and down-stream of the discharge point, 2012-2017

Sample site	*E. coli* (CFU/100 mL)		
	Mean	Median	Range
Oxidation pond discharge	2068	1263	<10 - 9210
Mataura River, upstream	438	329	20 - 1700
Mataura River, downstream	370	336	41 - 1400

The data in Table 7 indicate little or no impact of the Gore WWTP discharge on *E.coli* concentrations in Mataura River.

Figure 9 shows the distribution of *E.coli* concentrations in Gore WWTP effluent and the best-fitting normal distribution (log transformed data).

Figure 9. Distribution of *E. coli* concentrations in Gore WWTP oxidation pond discharge effluent (2012-2017) and the best associated normal distribution



4. QUANTITATIVE MICROBIAL RISK ASSESSMENT (QMRA) - INPUTS

Microbial risks associated with recreational water use are usually expressed in terms of the individual infection risk (IIR) (McBride, 2011; McBride *et al.*, 2013; McBride, 2014; Soller *et al.*, 2006; Soller *et al.*, 2010a; Soller *et al.*, 2010b; Soller *et al.*, 2014). IIR is the probability of an individual becoming infected, but not necessarily ill, due to a defined recreational water activity. This approach is also the basis for the current New Zealand freshwater recreational water quality guidelines (MfE, 2003). The current QMRA will assess the IIR due to *Campylobacter* spp. from swimming in the Mataura River at a point below the Alliance Mataura discharge.

Three approaches will be taken to determining the concentration of *Campylobacter* spp. in the Mataura River:

- The actual concentration of *Campylobacter* spp. measured at a point 200 m downstream of the Mataura Bridge on 23-24 May; or
- The concentration of *Campylobacter* spp. at a point 200 m downstream of the Mataura Bridge, estimated from information on *Campylobacter* spp. in Gore WWTP and Alliance Mataura discharge effluent, daily discharge volumes and river flow rates.
- The concentration of *Campylobacter* spp. at a point 200 m downstream of the Mataura Bridge, estimated from the relationship between river flow and *Campylobacter* concentration, based on data from a 2015 study.

The second approach requires application of several assumptions:

- That the *Campylobacter* spp. concentration measure on 22-24 May 2017 are typical of the wastewaters analysed;
- That the effluents from Gore WWTP and Alliance Mataura are discharged at a uniform rate over a 24-hour period;
- That the discharge effluent undergoes complete and uniform dilution in the river flow volume and that *Campylobacter* spp. are not subsequently absorbed into river sediments or other environmental media and do not undergo growth or die-off.

4.1 *CAMPYLOBACTER* SPP. CONCENTRATION IN THE MATAURA RIVER

4.1.1 Scenario 1: Measured concentration

The direct measurements of *Campylobacter* spp. in the Mataura River include a mixture of quantified and left-censored data. In this context, left-censored refers to analytical results reported as less than the limit of detection (Helsel, 2005). If the underlying form of the data distribution is known, then techniques are available to estimate the parameters of that distribution, even though only part of the distribution is 'visible'.

The microbiological distributions summarised in Section 3 of this report can all be satisfactorily represented by a normal distribution, following log-transformation. That is, the underlying distribution can be assumed to be lognormal. Assuming that the distribution of *Campylobacter* spp. concentrations in the Mataura River was also lognormal, a range of statistical techniques can be used to estimate the mean and standard deviation of the underlying lognormal distribution (Huybrechts *et al.*, 2002; Kuttatharmmakul *et al.*, 2000; Kuttatharmmakul *et al.*, 2001).

A range of variants on the maximum likelihood estimation (MLE) method gave similar estimates of the mean and standard deviation. Based on experience the estimates based on bias corrected-MLE were selected ($\mu = 0.343$, $\sigma = 0.146$).

4.1.2 Scenario 2. Simulated concentration

No information on *Campylobacter* spp. concentrations in waste discharges to the Mataura River or background concentrations in the river were available other than these generated from the current project.

Distributions of *Campylobacter* spp. concentrations in discharge effluent and discharge volumes were used to calculate the average loading of *Campylobacter* spp. entering the river per second. As discharges were assumed to occur uniformly, loadings were adding and combined with flow volumes at the Tuturau monitoring point to determine a putative *Campylobacter* spp. concentration at that point.

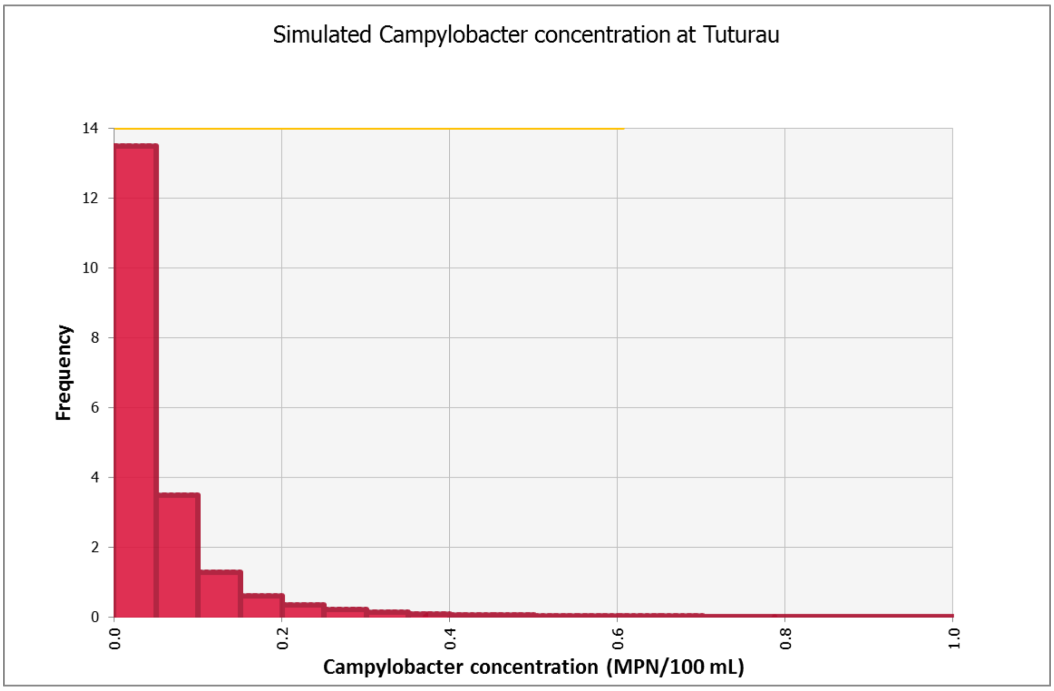
Campylobacter concentrations in discharges from the Gore WWTP are similar to concentrations in the river, being a mixture of values below the LOD and values just above the LOD. Using the bias-corrected MLE method, estimates of the mean and standard deviation of the association lognormal distribution can be derived, with $\mu = 0.329$ and $\sigma = 0.176$.

The concentration of *Campylobacter* spp. in the Mataura River at Tuturau was determined as:

$$C_{Campy,Tut} = \frac{C_{Campy,Gore\,WWTP} \times V_{Discharge,Gore\,WWTP} + C_{Campy,Alliance} \times V_{Discharge,Alliance}}{34560 \times F_{Mataura,Tuturau}}$$

Where C is concentration, V is volume and F is flow. The factor of 34560 converts flows in m^3/s to daily volumes. Each of the variables in the equation are represented by distribution, as shown in the previous sections. The simulated output distribution is shown in Figure 10.

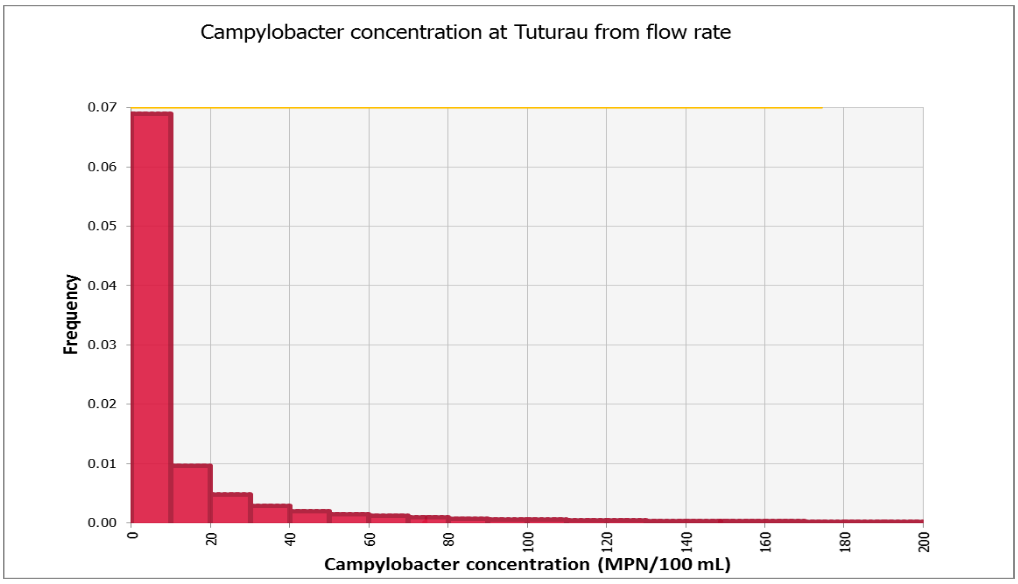
Figure 10. Simulated concentration of *Campylobacter* spp. in the Mataura River, based on discharges from Alliance Mataura and the Gore WWTP



4.1.3 Scenario 3: Concentration based on regression against flow rate

As discussed in section 3.1.2, data from a 2015 survey allows definition of a regression equation between river flow rate and the concentration of *Campylobacter* spp. for the Mataura River in the environs of Gore/Mataura. The resultant distribution of *Campylobacter* spp. concentrations is shown in Figure 11.

Figure 11. Simulated concentration of *Campylobacter* spp. in the Mataura River, based on regression against river flow rate



It should be noted that this scenario estimates substantially higher *Campylobacter* spp. concentrations than the other two scenarios. However, this wider range of concentrations is consistent with the findings of the 2015 survey, in which *Campylobacter* concentrations up to 460 MPN/100 mL were observed.

4.1.4 River flow rates unsuitable for swimming

The current QMRA considers risks associated with swimming in the Mataura River, as swimming is the contract recreation activity in which water ingestion and infection risk will be greatest. Scenarios 2 and 3 above include consideration of the complete range of river flow rates, as represented by a lognormal distribution. However, swimming is highly unlikely at very high river flow rates. To test the sensitivity of the QMRA model to inclusion of very high river flows, models were re-run with the distribution of river flow rates truncated at the 95th percentile (212 m^3/s).

4.2 WATER INGESTION DURING CONTACT RECREATION

4.2.1 Rate of water ingestion

The current QMRA is based on risks associated with primary contact recreation at the Tuturau monitoring site. In this context, the most likely form of primary contact recreation will be swimming.

No information is available on water ingestion during swimming in New Zealand. The most commonly used water ingestion information used in environmental QMRAs was derived from a swimming pool study in the USA (Dufour *et al.*, 2006). The volume of water ingested was estimated by measuring the concentration of the chlorine-stabilising chemical cyanuric acid in the urine of swimmers and in the pool water. Cyanuric acid passes through the human body without undergoing metabolic changes. A larger study by the same research group has recently been published (Dufour *et al.*, 2017). Table 8 summarises water ingestion parameters used in previous New Zealand QMRAs and compares them to the results of this recent swimming pool study.

Table 8. Comparison of water ingestion parameters used in New Zealand QMRA and swimming pool survey parameters from Dufour et al. (2017)

Age group	Water intake description	Reference
	Minimum, mode, maximum (mL/hr)	(McBride and Hudson, 2016)
Children	20, 50, 100	
Adults	10, 25, 50	
	Minimum, mode, maximum (mL/hr)	(McBride *et al.*, 2013)
Children	15, 75, 150	
Adults	10, 50, 100	
	Minimum, mode, maximum (mL/hr)	(McBride, 2014)
Children	10, 30, 100	
Adults	5, 15, 50	
	Geometric mean (95%CI) (mL/hr)	(Dufour *et al.*, 2017)
Children	23.9 (17-33)	
Teenagers	23.7 (19-30)	
Adults		
- All	12.4 (11-14)	
- Female	9.4 (8-11)	
- Male	26.4 (13-20)	

The data in Table 8 show an inconsistent approach to the modelling of water ingestion in New Zealand QMRAs. The New Zealand models for water ingestion while swimming also appear to overestimate rates in comparison to Dufour *et al*. (2017). It is interesting to note that the mode values used in McBride (2014) are close to the upper 95th percentile confidence limits for the geometric means in Dufour *et al*. (2017) (children = 33 mL/hr, adults = 14 mL/hr).

Dufour *et al*. (2017) also provided maximum volumes of water ingested by children, teenagers and adults of 245, 267 and 279 mL, respectively. The mean durations of the swimming events were 95.9, 55.8 and 50.3 minutes, respectively, for the same age groups. Using the maximum volumes of water ingested and the mean duration of the swimming event gives maximum ingestion rates of 153.3, 287 and 333 mL/hr, respectively, for children, teenagers and adults.

While not included in the scientific paper, ESR have obtained the raw data from this study and, for all age groups, the minimum ingested volumes are about 1 mL or 0.6-1.2 mL/hr (Dr Alfred Dufour, USEPA, personal communication).

The Dufour *et al*. (2017) study was carried out in swimming pools, while the current QMRA considers a freshwater recreational environment. Schets *et al.* (2011) compared self-reported volumes of water ingested during swimming in a swimming pool, in freshwater and in seawater. For children (<15 years), the highest amount of water was ingested during swimming in a pool (mean = 51 mL/event), compared to freshwater (37 mL/event) and seawater (31 mL/event).

4.2.2 Duration of contact recreation events

In the previous section, water ingestion was expressed as a rate (mL/hr). In order for a total volume of ingested water to be calculated, these rates must be combined with a duration of the contract recreation (swimming) event. Table 9 summarises values used in previous New Zealand QMRAs and values from the scientific literature.

Table 9. Estimates of the duration of contract recreation used in New Zealand QMRAs and overseas estimates

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

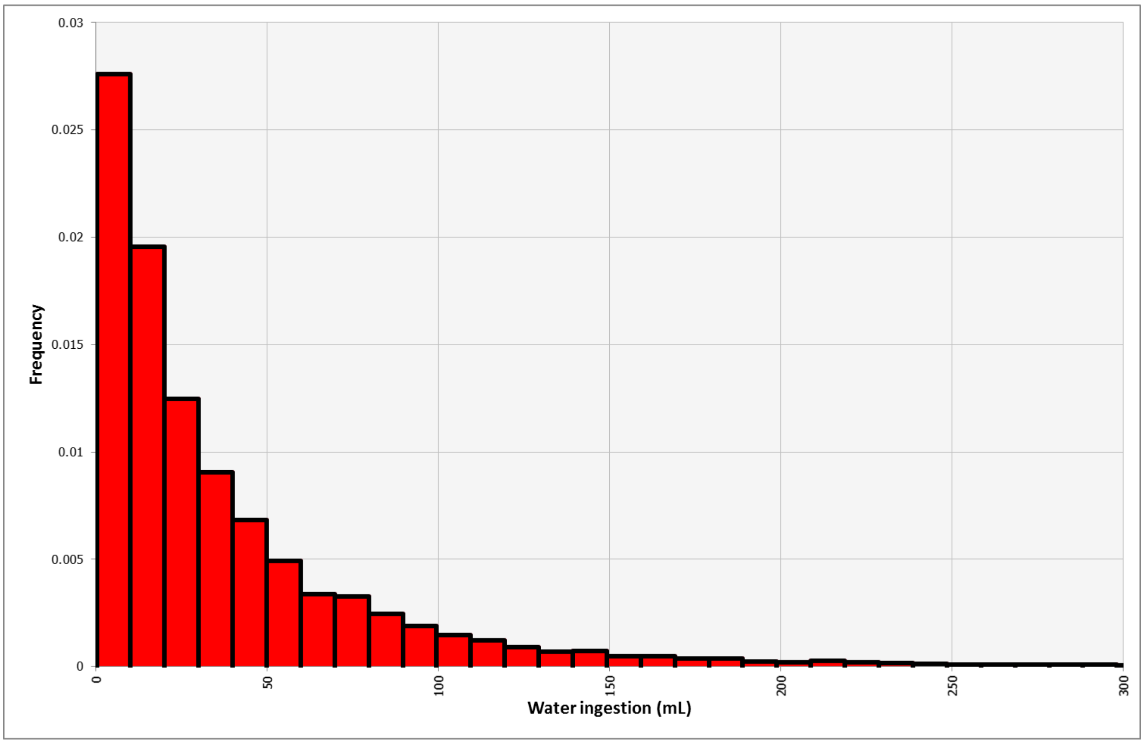
The data summarised in Table 9 suggest that estimates of swimming duration used in previous New Zealand QMRAs may be low. While it could be argued that swimming habits may differ in New Zealand to the USA and the Netherlands, this does not appear likely.

The study of Schets *et al.* (2011) provides the most applicable data for the current QMRA – actual measurements of the duration of swimming in freshwater. This study also provides details of normal distributions fitted to the natural log of the distribution of swimming duration times. For freshwater swimming, the parametised distributions are normal(4.1,0.8) for children, normal(3.5,0.94) for adult females and normal(3.6,0.85) for adult males.

4.2.3 Water ingestion – summary

Children spend longer periods of time in the water during contact recreation and ingest water at a higher mean rate. Therefore, the current QMRA based risk estimates on a children bathing in the Mataura River, 200 m downstream of the Mataura bridge. Water ingested was determined as the product of the ingestion rate and the recreation duration, with the ingestion rate represented by a beta pert distribution with minimum = 0.6 mL/hr, mean = 23.9 mL/hr and maximum = 153 mL/hr. The duration of exposure was represented by a distribution whose natural log was normally distributed with μ = 4.1 and σ = 0.8. The exponential of this distribution is the duration of recreation in minutes. Figure 12 shows the resulting distribution of water ingested during a contact recreation event by a child (<15 years).

Figure 12. Distribution of water ingestion for a child (<15 years) undertaking primary contact recreation in a freshwater environment



4.3 DOSE-RESPONSE RELATIONSHIP FOR *CAMPYLOBACTER* SPP.

The previous section outline the derivation of variables that allow the dose of *Campylobacter* spp. for a child swimming in the Mataura River to be estimated. A dose-response relationship describes the probability of an individual becoming infected with *Campylobacter* at any particular dose levels.

The dose-response relationship for *Campylobacter* spp. is usually represented by a Beta-Poisson equation. The approximate form of this equation is:

$$P_{inf} = 1-(1+(Dose/\beta))^{-\alpha} \qquad [1]$$

Where P_{inf} is the probability of infection and α and β are shape parameters. The parameters have been calculated from a human feeding trial (Black *et al.*, 1988) using an exact form of the Beta-Poisson equation (Teunis and Havelaar, 2000), with parameters $\alpha = 0.145$ and $\beta = 8.007$.

The study of Black *et al*. (1988) used two strains of *C. jejuni*: A3249 and 81-176. For 81-176, 100% infection rates were seen at each of the three doses used and no dose-response relationship can be derived. The parameters given above were derived from the data for A3249. However, an expert consultation convened by FAO and WHO argued that no distinction is made between different strains of *C. jejuni* in QMRA (FAO/WHO, 2009). The consultation combined the data for strains A3249 and 81-176 from the study of Black *et al.* (1988) and derived a satisfactory fit to the beta-Poisson dose-response model with parameters $\alpha = 0.21$ and $\beta = 59.95$. These parameters also conform better to the requirements for the simpler approximate form of the beta-Poisson equation (equation (1)), as $\beta >> \alpha$ and $\beta >> 1$.

The Beta-Poisson model, in the form expressed in Equation (1), estimates the average risk to a population following the ingestion of an average dose. In order to estimate the probability of infection for an individual consuming a meal with a specific dose, the Beta-Poisson model needs to be expressed in a format that will allow it to be simulated in a similar manner to the exposure assessment. Equation (2) reflects the same assumptions as the original Beta-Poisson model, but variability for the probability of infection from a particular dose is incorporated within the simulations so that the model estimates the risk of infection for an individual consuming a specific dose.

The simulated beta-Poisson model samples the beta distribution, using the parameters generated (α = 0.21, and β = 59.95), to estimate the probability of infection from one organism. The dose ingested is estimated using a Poisson sample, which assumes the organisms in the water with some mean concentration are randomly distributed. Finally, the probability of infection from the dose ingested is estimated assuming a binomial process with the number of trials equal to the dose ingested and the probability of 'success' at each trial equal to the value returned from the beta distribution.

$$P_{inf} = 1-(1- P_{inf}(1))^{D} \qquad [2]$$

Where:

P_{INF} is the probability of infection from the dose
$P_{INF}(1)$ is the probability of infection from one organism (Beta Distribution)
D is the number of organisms estimated to be ingested during a swimming event (Dose).

The simulated Beta-Poisson model can be interpreted as estimating, during a simulation, the probability of infection for different individuals at every iteration. Equation (2) was used to estimate the risk of *Campylobacter* infection in the current study.

5. QUANTITATIVE MICROBIAL RISK ASSESSMENT (QMRA) - OUTPUTS

Table 10 summarises the outputs from the QMRA model for children swimming in the Mataura River, 200 m downstream from the Mataura bridge. The outputs are mean estimates of individual infection risk (IIR) for three *Campylobacter* concentration scenarios and two 'swimmable' river flow scenarios. The IIR is a probability of infection. Probabilities have been converted to percentages.

Each simulation was run for 100,000 iterations, analogous to 100,000 individual swimming events. As the model delivers a point estimate of IIR, the model was re-run for 50 simulations to determine the uncertainty in the IIR estimates.

Table 10. Individual infection risk (IIR, %) associated with *Campylobacter* for children swimming in the Mataura River

Concentration scenario	Full river flow distribution, mean (95th percentile credible interval) (%)	Truncated river flow distribution, mean (95th percentile credible interval) (%)
Scenario 1 (actual)	0.070 (0.056-0.086)	-[a]
Scenario 2 (sum of discharges)	0.012 (0.007-0.019)	0.013 (0.007-0.020)
Scenario 3 (from river flow regression)	2.8 (2.7-2.9)	1.7 (1.7-1.8)

[a] Scenario 1 is not dependent on the river flow rate

Truncation of the river flow rate distribution, to discount swimming in the river under conditions of very high flows, very slightly increases the risks associated with the sum of the discharges from the Gore WWTP and Alliance Mataura. This would be expected as the high river flow events would be associated with greater dilution of the discharge effluents.

For the scenario based on river flow regression, truncation of the river flow distribution results in an approximate 40% decrease in the average IIR for *Campylobacter* infection, as this scenario would result in the highest *Campylobacter* concentrations and the highest associated *Campylobacter* dose under conditions of high river flow.

Based on the available data, the two major effluent discharges to the Mataura River in the environs of Gore/Mataura contribute a minor proportion of the *Campylobacter*-associated infection risk, with an IIR of 0.012%, compared to 0.07% (*Campylobacter* measurements in river) or 2.8% (*Campylobacter* in river predicted from river flow rate). However, it should be noted that this conclusion is based on risks estimated from a single day of effluent and river water sampling. Earlier analysis of two river waters from this region for faecal source markers suggested that *Campylobacter* were mainly of wild fowl origin, while general faecal contamination was dominated by ruminant sources (Dr Elaine Moriarty, ESR, personal communication). The faecal source analysis results and the QMRA results are consistent in indicating that the majority of *Campylobacter* contamination in this region of the Mataura River does not originate from the two main point discharge sources.

The Microbiological Assessment Categories (MACs) for freshwater included in the *Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas* (MfE, 2003) have cut-off values equating to *Campylobacter* IIRs of 0.1, 1.0 and 5.0%. Scenarios 1 and 2 in the current QMRA represent risk levels below the 0.1% level and would result in the river in this region receiving an A grading. However, scenario 3, under which the

Campylobacter concentration of the river water is a function of river flow rate, would equate to a C grading for this region of the Mataura River (between 1 and 5% IIR).

In 2017, changes were made to the *National Policy Statement for Freshwater Management,*[4] which included changes to the water quality for swimming categories.[5] These changes defined five water quality categories, with average *Campylobacter* infection risks ranging from 1% to greater than 7%. The attributes for the various categories are expressed in terms of the percentage of samples that exceed 540 *E. coli* per 100 mL (5% *Campylobacter* risk) and the percentage of samples that exceed 260 *E. coli* per 100 mL (1% *Campylobacter* risk). Table 11 gives the parameters for the new water quality categories and the corresponding parameters for the three QMRA scenarios. Parameters here are for the QMRA with restrictions on high flow rates.

Table 11. New water quality category parameters and associated parameters from the QMRA model

Category	Percentage >5% *Campylobacter* risk[a]				Percentage >1% *Campylobacter* risk[a]			
	Attribute	Scenario1	Scenario2	Scenario3	Attribute	Scenario1	Scenario2	Scenario3
A (Blue)	<5%	0.05	<0.01		<20%	1.1	0.1	16.6
B (Green)	5-10%			6.9	20-30%			
C (Yellow)	10-20%				20-34%			
D (Orange)	20-30%				>34%			
E (Red)	>30%				>50%			

[a] The water quality categories are defined in terms of *E. coli* concentrations, but have been represented here as the equivalent *Campylobacter* infection risk break points

Removing the truncation criteria for the river flow rate changes some of these values, but does not change the categories they fall into. On the basis of the figures in Table 11, under scenarios 1 and 2 Mataura River water would meet the category requirements for Category A, while under scenario 3 the river water would meet category B requirements.

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[4] http://www.mfe.govt.nz/fresh-water/national-policy-statement-freshwater-management/2017-changes Accessed 15 August 2017

[5] http://www.mfe.govt.nz/fresh-water/national-targets-swimming-water-quality/water-quality-swimming-categories-attribute Accessed 15 August 2017

6. CONCLUSIONS

Available information has been used to estimate the risk of *Campylobacter* infection associated with children swimming in the Mataura River in the environs of Mataura township. Three scenarios were used to estimate the level of *Campylobacter* contamination of the river:

- Actual measurements of *Campylobacter* in the river (determined 23-24 May 2017)
- Dilution of Gore WWTP and Alliance Mataura effluent *Campylobacter* (determined 23-24 May 2017) in the river
- Estimation of *Campylobacter* in river from a previously determined regression against river flow rate.

The first two scenarios result in very low mean estimates of the *Campylobacter* infection risk (<0.1%), while the third scenario results in mean estimates of 2.8 and 1.7%, depending on whether high river flows are excluded from the estimate, as representing ‘unswimmable’ conditions. It should be stressed that the first two scenarios are dependent on *Campylobacter* measurements made over a single 24-hour period.

The QMRA suggests that effluent discharged from the Gore WWTP and Alliance Mataura contribute a relatively small proportion of the overall *Campylobacter* risk. This is consistent with other work that indicated that *Campylobacter* contamination in this region of the Mataura River was predominantly of wild fowl origin.

The first two QMRA scenario would result in this region of the Mataura River being classified in the highest water quality category for microbiological quality under either the old or updated categorisation schemes. The third scenario would result in a lower water quality categorisation.

It should be noted that the current QMRA only considers risks of *Campylobacter* infection, and other pathogenic microorganisms will potentially be present in the Mataura River. In particular, it is likely that discharge effluent from the Gore WWTP will contain human enteric viruses, such as norovirus.

Defining risks in terms of children swimming is a conservative (risk maximising) approach, as other population groups and types of contact recreation will result in ingestion of lower amounts of water and represent lower risks of *Campylobacter* infection. However, conservatism in risk assessment is appropriate, as decisions based on QMRA should be protective of those at highest risk.

REFERENCES

Black RE, Levine MM, Clements ML, Hughes TP, Blaser MJ. (1988) Experimental *Campylobacter jejuni* infection in humans. Journal of Infectious Diseases; 157(3): 472-479.

Commeau N, Parent E, Delignette-Muller ML, Cornu M. (2012) Fitting a lognormal distribution to enumeration and absence/presence data. International Journal of Food Microbiology; 155(3): 146-152.

Dufour AP, Evans O, Behymer TD, Cantu R. (2006) Water ingestion during swimming activities in a pool: a pilot study. Journal of Water and Health; 4(4): 425-430.

Dufour AP, Behymer TD, Cantu R, Magnuson M, Wymer LJ. (2017) Ingestion of swimming pool water by recreational swimmers. Journal of Water and Health; 15(3): 429-437.

Engel R, Normand M, Horowitz J, Peleg M. (2001) A model of microbial contamination of a water reservoir. Bulletin of Mathematical Biology; 63(6): 1005-1023.

Environment Southland. (2011) Environmental Compliance Monitoring Report 2010/11. Accessed at: http://www.es.govt.nz/Document%20Library/Research%20and%20reports/Compliance%20monitoring%20reports/2010-11_compliance_monitoring_report.pdf. Accessed: 16 June 2017.

FAO/WHO. (2009) Risk assessment of *Campylobacter* spp. in broiler chickens. Technical Report. Microbiological Risk Assessment Series No. 12. Geneva. Food and Agriculture Organisation/World Health Organisation
Helsel DR. (2005) Nondetects and data analysis: Statistics for censored environmental data. New Jersey: John Wiley & Sons.

Hughes B, Harris S, Brown P. (2011) Mataura Catchment Strategic Water Study. Accessed at: http://www.es.govt.nz/Document%20Library/Plans,%20policies%20and%20strategies/Strategies/Mataura%20Catchment%20Strategic%20Water%20Study/mataura_catchment_strategic_water_study2.pdf. Accessed: 13 June 2017.

Huybrechts T, Thas O, Dewulf J, Van Langenhove H. (2002) How to estimate moments and quantiles of environmental data sets with non-detected observations? A case study on volatile organic compounds in marine water samples. Journal of Chromatography A; 975(1): 123-133.

Kuttatharmmakul S, Smeyers-Verbeke J, Massart DL, Coomans D, Noack S. (2000) The mean and standard deviation of data, some of which are below the detection limit: an introduction to maximum likelihood estimation. TrAC Trends in Analytical Chemistry; 19(4): 215-222.

Kuttatharmmakul S, Massart DL, Coomans D, Smeyers-Verbeke J. (2001) Comparison of methods for the estimation of statistical parameters of censored data. Analytica Chimica Acta; 441(2): 215-229.

McBride GB, Till D, Ryan T, Ball A, Lewis G, Palmer S, Weinstein P. (2002) Freshwater Microbiology Research Programme. Pathogen Occurrence and Human Health Risk Assessment Analysis. Wellington: Ministry for teh Environment.

McBride GB. (2011) Prediction of human health effects associated with wet weather flows in Whangarei. Effects on primary and secondary water contact and consumers of raw shellfish. NIWA Client Report HAM2011-069. Hamilton: NIWA.

McBride GB, Stott R, Miller W, Bambic D, Wuertz S. (2013) Discharge-based QMRA for estimation of public health risks from exposure to stormwater-borne pathogens in recreational waters in the United States. Water Research; 47(14): 5282-5297.

McBride GB. (2014) Water-related health risks analysis for the proposed Akaroa wastewater scheme. NIWA Client Report HAM2014-030. Hamilton: NIWA.

McBride GB, Hudson N. (2016) Quantitative Microbial Risk Assessment for the discharge of treated wastewater: Snells Beach wastewater treatment plant. HAM2016-038. Hamilton: NIWA.

MfE. (2003) Microbiological Water Quality Guidelines for Marine and Freshwater Recreational Areas. Wellington: Ministry for the Environment,.

Paine S. (2012) Hydrology of the Mataura River: A constraint on water abstraction at Gore. Wellington: Opus International Consultants Ltd.

Peleg M, Normand MD, Corradini MG. (2012) A Study of the Randomly Fluctuating Microbial Counts in Foods and Water Using the Expanded Fermi Solution as a Model. Journal of Food Science; 77(1): R63-R71.

Richardson D. (2016) Alliance Group Limited Mataura. Consent No. 202327 Permit to Discharge Treated Meatworks Wastewater to Water, 2016. Annual Monitoring and Review Report. Mataura: Alliance Group Ltd.

Schets FM, Schijven JF, de Roda Husman AM. (2011) Exposure assessment for swimmers in bathing waters and swimming pools. Water Research; 45(7): 2392-2400.

Soller JA, Eisenberg JN, DeGeorge JF, Cooper RC, Tchobanoglous G, Olivieri AW. (2006) A public health evaluation of recreational water impairment. Journal of Water and Health; 4(1): 1-19.

Soller JA, Bartrand T, Ashbolt NJ, Ravenscroft J, Wade TJ. (2010a) Estimating the primary etiologic agents in recreational freshwaters impacted by human sources of faecal contamination. Water Research; 44(16): 4736-4747.

Soller JA, Schoen ME, Bartrand T, Ravenscroft JE, Ashbolt NJ. (2010b) Estimated human health risks from exposure to recreational waters impacted by human and non-human sources of faecal contamination. Water Research; 44(16): 4674-4691.

Soller JA, Schoen ME, Varghese A, Ichida AM, Boehm AB, Eftim S, Ashbolt NJ, Ravenscroft JE. (2014) Human health risk implications of multiple sources of faecal indicator bacteria in a recreational waterbody. Water Research; 66: 254-264.

Teunis PFM, Havelaar AH. (2000) The Beta Poisson dose-response model is not a single-hit model. Risk Analysis; 20(4): 513-520.

INSTITUTE OF ENVIRONMENTAL
SCIENCE AND RESEARCH LIMITED

Kenepuru Science Centre
34 Kenepuru Drive, Kenepuru, Porirua 5022
PO Box 50348, Porirua 5240
New Zealand
T: +64 4 914 0700 **F:** +64 4 914 0770

Mt Albert Science Centre
120 Mt Albert Road, Sandringham, Auckland 1025
Private Bag 92021, Auckland 1142
New Zealand
T: +64 9 815 3670 **F:** +64 9 849 6046

NCBID – Wallaceville
66 Ward Street, Wallaceville, Upper Hutt 5018
PO Box 40158, Upper Hutt 5140
New Zealand
T: +64 4 529 0600 **F:** +64 4 529 0601

Christchurch Science Centre
27 Creyke Road, Ilam, Christchurch 8041
PO Box 29181, Christchurch 8540
New Zealand
T: +64 3 351 6019 **F:** +64 3 351 0010

www.esr.cri.nz