A review of river microbial water quality data in the Northland region

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March 2023

Report for the Northland Regional Council

Client Report Number: RE450/2023/029

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1. Executive Summary

Northland Regional Council (NRC) asked AgResearch to conduct a review of their microbial water quality data to: (1) understand the current state of microbial water quality (as indicated by *Escherichia coli* or *E. coli*) across the Northland region, (2) identify any key drivers affecting microbial water quality and (3) provide advice on mitigation options that could be adopted in Northland. Water quality monitoring data was provided by NRC and the analysis was conducted by a summer intern based at AgResearch. The data was inspected at each of the sites with sufficient data to calculate the appropriate water quality metrics selected for analysis. Site gradings were calculated for the river water quality monitoring and swimming sites using the guidelines from the National Policy Statement for Freshwater Management 2020 (NPS-FM 2020).

Analyses were conducted separately for the river water quality monitoring network sites and the river swimming water quality program sites due to different sampling protocols required for the respective assessments of the *E. coli* gradings. The long-term gradings from the river water quality monitoring sites showed the challenge Northland has in achieving a C grade or higher as expected in the microbial water quality guidelines. As per the NPS-FM 2020, the microbial water quality guidelines require calculating 4 different metrics based on the *E. coli* concentrations; the overall grading is then based on the worst grading of the four metrics. The four individual metrics are based on the median, proportions of samples >260 and >540 MPN 100 mL^{-1}, and the 95th percentile. Overall, there was only one site that achieved a long-term A grade; three sites received a B grade; one C grade; 21 D grades; and 38 E grades. The swimming water quality grading is based only on the 95th percentile value and the criteria are more stringent than for the river water quality monitoring. Consequently, based on the long-term assessment, all 19 swimming sites were graded as D (poor). However, all swimming sites would classify as swimmable for 19 to 82% of the time.

E. coli data on the discharges from sewage wastewater treatment plant discharges and related up and downstream monitoring of the river was provided. Of the nine sites able to be assessed it appears that two sites had obvious impacts and two sites showed small impacts. There was no obvious *E. coli* impact on river water quality for the five remaining sites. However, this does not mean that the sewage discharges are not having an impact in the local receiving environment at these five sites. Sewerage discharges should be managed at the local scale, taking into consideration other contaminants and social and cultural impacts, which is beyond the scope of this report.

Long-term trend analysis was conducted at all river water quality monitoring sites. Eleven sites had statistically significant trends. Six sites showed a statistically significant decreasing *E. coli* trend (improving water quality) and five sites showed a statistically significant increasing *E. coli* trend (decreasing water quality). This data is provided to the Northland Regional Council to support further local investigations.

Investigation of the potential drivers of the *E. coli* in the rivers was conducted by correlation analysis between other water quality parameters and land use in each catchment. For each monitoring site the upstream catchment and corresponding land-use information was determined from the Land Cover Database version five (LCDBv5). A correlation analysis

was conducted on the *E. coli* concentrations and other water quality parameters from both the river water quality monitoring network. The *E. coli* concentrations in the Northland River network did not show any consistent relationships with other water quality parameters, rainfall, river flow or stream morphology. The patterns of contaminant concentrations predominantly indicated diffuse pollution sources of *E. coli*. There was a consistent relationship between *E. coli* concentrations and land-use which is also observed across NZ. That is, higher concentrations are associated with intensive land use (high producing exotic grasslands) and lower concentrations associated with native forest and other forested land-use. As expected, the correlation with animal agricultural land use was higher than for non-animal land use. This is due to potential animal access to streams, animal defecation on pasture and farm dairy effluent (FDE) management. Mapping of FDE across Northland appeared to show a relationship between the density of FDE discharges and median stream *E. coli* concentrations. Note that FDE management discharges to the river network is likely to be sporadic and spatially distributed in Northland and will, therefore, impact on water quality data as a diffuse source rather than a point source.

Since 2011 the Northland Regional Council has sent 236 samples for faecal source tracking analysis. The faecal source tracking results found no evidence of **fresh** human sources but still frequently (87%) identified low levels of (presumably aged) human sources with no apparent relationship with site, *E. coli* concentrations, rainfall or river flows. Avian faecal source markers were frequently (92%) detected in low levels with no apparent relationship with site, *E. coli* concentrations, rainfall or river flows. Ruminant faecal markers were detected in 80% of the samples and there appeared to be a relationship between high proportion of ruminant markers and high *E. coli* in the samples, rainfall and some other diffuse contaminants/indicators (specifically, turbidity, suspended solids and black disc visibility).

Previous research in Northland had identified the low-level presence of naturalized *E. coli* in Northland rivers. Naturalized *E. coli* is a term used to describe non-faecal strains of *Escherichia* that will be "counted" in routine *E. coli* testing methods but are not related to recent faecal contamination. However, more recent work conducted nationally has shown that naturalized *E. coli* are more likely to be identified in more pristine waters and the *E. coli* counts in contaminated waters are dominated by *E. coli* strains from faecal sources. There is no scientific justification for "discounting" *E. coli* concentrations measured in water samples using new techniques that can identify the presence of naturalized *E. coli*.

The investigation of the potential drivers of *E. coli* concentrations in Northland rivers presents a relatively clear picture, that point discharges from sewage systems are not having a major impact on microbial water quality at the regional scale. Intensive land-use appears to have the largest impact on microbial water quality data in the region. The lack of relationship between *E. coli* concentrations and other water quality parameters, such as rainfall, flow and stream morphology, all point to diffuse inputs as the most likely source of *E. coli* in Northland rivers. That is, multiple small sources distributed across the landscape adding up to a large effect.

Recommended mitigation options for agricultural land are: stream fencing to exclude stock, riparian buffer strips and FDE management. It is recommended to include sheep farming in any stream fencing and/or riparian planting policy due to the high concentrations of *E. coli* shed by sheep relative to cows. Forested land has less impact on microbial water quality but could potentially benefit from reducing the number of pests (possums, deer and pigs) for this land-use which could also have a co-benefit of increasing carbon sequestration. Non-livestock land uses can sometimes use organic fertilizers which can contain faecal material and hence *E. coli*. As these organic fertilizers are typically broadcast applied to the land surface, they are a high risk of *E. coli* losses in runoff events. Policy on appropriate use of this fertilizer to minimise the impact on surface waters maybe needed. Wetlands may also provide some buffering of water flows and *E. coli* concentrations that will benefit water quality.

The key message from this analysis is that the Northland region has high levels of *E. coli* in the river networks across the region that appear to be generated from diffuse pollution sources from intensive land uses. The challenge with these diffuse sources will be implementing multiple actions to mitigate these multiple sources of *E. coli*.

2. Background

All regional councils must respond to the National Policy Statement for Freshwater Management (NPS-FM 2020) by setting water quality limits and developing plans to meet the new limits. To aid in this process Northland Regional Council (NRC) approached AgResearch to conduct a review of their microbial water quality data and provide advice for future policy direction. NRC provided AgResearch with the *E. coli* and related water quality data collected between January 2000 and December 2021 for the analysis. A summer internship role was created at AgResearch to conduct the data analysis for the project with AgResearch providing the reporting and advice. The aim of the data analysis was to: (1) understand the current state of microbial water quality across the Northland region, (2) identify any key drivers affecting microbial water quality and (3) provide advice on mitigation options that could be adopted in Northland.

It is important to note that the authors of this report have not lived in the Northland region and, therefore, do not have the detailed knowledge of the Northland landscapes and rivers systems that local inhabitants have. To help with this knowledge gap we have provided as much of the raw data from the analysis as possible in appendices and raw data via email so that local NRC staff with local knowledge can investigate the raw data from of specific sites. The interpretation of this analysis is based on what the monitoring data is showing.

It is also important to note that this work is based on the routine water quality monitoring data. The routine water quality monitoring methodology is used to develop an understanding of the state of the water quality in a river. As such, this sampling method is not designed to understand or quantify where sources of contaminants are coming from or how to mitigate these losses to water. Determining the sources of contaminants, their pathways, and mitigation options, all use different research methodologies. Routine water quality monitoring data can only be used to identify generic sources of water quality contamination. Therefore, the advice provided in Section 6 of this report is based on the high-level results from this analysis and the authors extensive knowledge of microbial contamination of surface waters and other published research on sources, pathways and mitigation options.

3. Methods

3.1 Site Selection

The Northland Regional Council (NRC) monitors water quality on a regional scale through a River Water Quality Monitoring Network (RWQMN). Similarly, the National Institute of Water and Air (NIWA) also run a national network of similar sites (NWQMN). These networks aim to provide NRC with important local water quality information and identify long term water quality trends.

Data from 70 sites were provided as part of the RWQMN and NWQMN programmes covering the period from 2000 to 2021. These included measurements of water temperature, conductivity, dissolved oxygen, pH, clarity, nutrient concentrations (various forms of nitrogen and phosphorus), suspended solids, turbidity, and bacterial sample data. From these sites, six were removed due to insufficient data to allow for calculation of long term gradings and assessment of water quality state according to NPS-FM guidelines and classifications. The NPS-FM states that "*Attribute state should be determined by using a minimum of 60 samples over a maximum of 5 years, collected on a regular basis regardless of weather and flow conditions. However, where a sample has been missed due to adverse weather or error, attribute state may be determined using samples over a longer timeframe*". The six sites not used to calculate a water quality metric were: Kerikeri Basin Reserve, Manaia SH10, Puwera, Raumanga Te Mai Rd, Aurere Pekerau Rd and Aurere Pekerau Rd Old.

Northland Regional Council also monitor summer seasonal water quality at a selection of 22 popular swimming sites (marine and freshwater) throughout the region in the Recreational Swimming Water Quality Programme (RSWQP). These sites are monitored on a weekly basis solely for *E. coli* across a four-month summer period (i.e., from December until March). A selection of 19 enclosed freshwater sites have been included in this report. From these sites, three sites (Hokianga Harbour, Tauranga Stream at Tauranga Bay and Otiria Stream) strictly had insufficient data (<50 data points) to calculate a long term grading according to the NPS-FM 2020 guidelines. However, we have calculated the data for these three sites and present here the results for the reader's information.

3.2 Water Quality Metrics and Parameters

3.2.1 RWQMN water quality metrics and parameters

Water quality metrics and parameters are used to assess the long-term grading to reflect the risk associated with bacterial infection and overall water quality state. The long-term grading is assigned as the worst of the four *E. coli* most probable number (MPN) metrics, specifically, the median, 95th percentile (95%ile) and percent of samples exceeding 260 and 540 *E. coli* MPN 100 mL^{-1}. These metrics were calculated from samples taken over 5 years with a minimum of 60 samples using the most recent data i.e. up to 2021. For some sites, the 60-sample minimum could not be reached over this 5-year period. In these cases, an additional year of samples was added until the minimum of 60 samples was reached. The whole extra year's data was used to avoid any potential seasonal effect of only selecting part of a year.

From these samples the 95%ile was calculated using the Hazen method (MfE 2023), along with the median and percentages exceeding 260 and 540 *E. coli* MPN 100 mL^{-1}. Using the guidelines outlined by NPS-FM 2020, a state was attributed to each water quality metric and then overall water quality assessed according to the worst metric score (Table 1).

Table 1. The *E. coli* swimming categories (attribute states) based on Table 9 in the NPS-FM 2020. All values are *E. coli* MPN 100 mL^{-1}.

Category	Percentage of samples above 540	Percentage of samples above 260	Median	95th percentile
A (Blue)	<5%	<20%	≤130	≤540
B (Green)	5-10%	20-30%	≤130	≤1000
C (Yellow)	10-20%	30-34%	≤130	≤1200
D (Orange)	20-30%	>34%	>130	>1200
E (Red)	>30%	>50%	>260	>1200

These parameters were also used to investigate if there was a difference between hard-bottomed and soft-bottomed stream habitat types within the RWQMN dataset. The RWQMN sites were categorised into their respective stream habitat types and plotted against one another.

3.2.2 Bathing water quality metrics and parameters

The long-term grade is a guide to general microbial water quality at a site and is characterised overall as one of four gradings over the recreational swimming period. The gradings for swimming sites are based on the Hazen 95th percentile value of *E. coli* 100 mL^{-1}. The 95th percentile value for a long-term grading should be calculated using at least 50 samples over the last five bathing seasons as part of the RSWQP. If sites had fewer than 50 samples in this period, an additional bathing season was included to calculate the 95th percentile value. Similar to the RWQMN water quality metrics, the Hazen method was used to calculate the 95th percentile value. Following the grading threshold values outlined by NPS-FM 2020, each selected site was provided with a long-term grading ranging from excellent to poor (Table 2).

Table 2. Long-term swimming grading categories based on Table 22 in the NPS-FM 2020. Based on a minimum of 50 samples collected during the bathing season. All values are *E. coli* MPN 100 mL^{-1}.

Long-term Grading	95th percentile
A – Excellent	≤130
B – Good	≤260
C – Fair	≤540
D - Poor	>540

Using the Recreational Swimming Quality Report produced annually by the NRC as a guide, long term suitability for swimming was assessed at each RSWQP site. Based on the number of times each state occurred, a proportion of the total time was attributed to each suitability state.

3.3 Land Cover

3.3.1 Land cover using LCDB and watersheds

Watersheds were created for each site within the RWQMN and RSWQP. These were created using a local 15 m DEM and the River Environment Classification version 2 (REC2), forming a re-classified stream network for the region. These watersheds were used in conjunction with the Land Cover Database (v5.0) or LCDB5 to calculate the proportion of different landcover types associated with each site.

3.3.2 Dairy cow numbers and discharge consents

The 2017 Dairy Cow numbers as reported by StatsNZ for the Northland region were investigated (https://www.stats.govt.nz/indicators/livestock-numbers). Discharge consents for Farm Dairy Effluent (FDE) and wastewater treatment plants (WWTP) from the NRC database were also mapped in conjunction with *E. coli* median values.

3.4 Correlation Analysis

Correlation analysis was used to determine the significance, strength and direction of linear relationships between *E. coli* concentrations and a range of environmental parameters. The strength of the Pearson correlations were categorised as weak if $r < 0.5$, moderate if $r > 0.5$ and < 0.7, and strong if $r \geq 0.7$.

3.4.1 Correlation between *E. coli* and environmental parameters at RWQMN sites

Correlation analyses between *E. coli* concentration and pH, temperature, dissolved oxygen, dissolved reactive phosphorus, total phosphorus, ammoniacal nitrogen, total nitrogen, total suspended solids, black disc and turbidity were undertaken. These were plotted using a linear model and the relationships were assessed using the above thresholds to assign relationship strength and significance.

3.4.2 Correlation between *E. coli*, rainfall and flow at RSWQP (swimming) sites

Because swimming water quality samples were only being analysed for *E. coli* concentration, correlations could only be explored between *E. coli* and 24 hour rainfall, 48 hour rainfall, 72 hour rainfall and river flow. These were also plotted using a linear model and the relationships were assessed using the above thresholds for relationship strength and significance.

3.4.3 Correlation between *E. coli* and landcover at RWQMN and RSWQP sites

For the RWQMN sites, a correlation analysis was run between the four *E. coli* metrics and the proportion of each different 2018 land cover category for each site from the LCDB5. For the Swimming water quality sites, a correlation was run between the 95%ile and the proportion of each different 2018 land cover category for each site from the LCDB5. The r correlation between each land cover type was plotted as a bar chart to visualise the influence of land use on microbial water quality. The reliability of these correlations was assessed using the proportion of each land cover in the individual catchments and the number of catchments that contained each land cover type. The strength of the relationship with land cover was graded as reliable, neutral or unreliable if there were >10, 6 to 10 or ≤5 sites/catchments containing that specific land cover classification, respectively.

3.5 Sewage - Wastewater Treatment Plants (WWTP)

The concentrations of *E. coli* in the wastewater discharged by the sewage treatment systems were identified along with monitoring concentrations in the river/stream up and down stream of the discharge point. This data was plotted as boxplots to identify the relative impact of the discharge on the receiving river/stream.

3.6 Long-term Trend Analysis

Long term trend analysis was run across all sites that had sufficient data in the RWQMN. To remove seasonality within the complete *E. coli* dataset at each site, a linear model was fitted. This was used to predict the *E. coli* at each month for each year. These predictions were averaged across the whole year and then the average *E. coli* value for each sample year through time was plotted to show the long-term *E. coli* trend at each site. The long-term trend was considered significant if the p-value was ≤ 0.05. Other national studies have conducted long-term trend analyses that have been assessed over different fixed time periods (e.g. Larned et al. 2016). For this analysis we chose to plot the trend over the longest dataset available at each site.

4. Results and Discussion

4.1 Microbial Water Quality State

From the data provided we were able to assemble datasets from 64 different sites across Northland with sufficient data points (>60) that allowed calculation of microbial water quality statistics (Figure 1). Overall, there was only one site that achieved an A grade, three sites achieved B grades, one site achieved C grade, 21 sites achieved D grades and 38 sites achieved E grades (Table 3). These data show the challenges that Northland has with achieving the national microbial water quality standards. Previous analyses by MfE have shown that Northland has more challenges than other regions in NZ (MfE 2017). The overall grading is recorded as the worst grade of the four different *E. coli* metrics; this is complicated as the median metric effectively has only three grades (A, D and E) and the 95th percentile has no E grade (Tables 1 & 3). Therefore, to investigate the relative impact of the four different *E. coli* metrics in this report, we summed the number of A, B and C grades into an “acceptable” category and grades D and E into “unacceptable”. Using this approach, the number of acceptable grades for the Median, >260, >540 and 95%ile metrics were 11, 14, 20 and 7 sites, respectively. This indicates that using the 95%ile and the median metrics resulted in more sites failing to achieve a C grade or better in Northland. Note that the terms acceptable and unacceptable and their definition are just used for this analysis only. We acknowledge that the NRC definitions of what is locally considered an acceptable or unacceptable grade for microbial water quality in Northland will be based on the local communities’ values in accordance with the principles of Te Mana o te Wai.

For further details of the water quality data used to create the metrics in Table 3 we have generated box plots of the data, with the plots aligned from highest to lowest median values (Figure 2). The Peria site at Honeymoon Valley Road is the only site that achieved an A grade and this is plotted as the 7th box from the right with the lowest 95%ile value (Figure 2). The other sites that achieved B or C grades (Punaruku, Tapapa, Wairau and Mangakino Lane) also had low 95%ile values. The site with the lowest median, Waipoua at SH12, was graded D due to its high 95%ile value. Reading the box plots from right to left, by the time you get to the Victoria site the median value is >130 and the sites to the left will all default to at least a D grade. By the time you get to the Ngunguru site, the median is >260 and all sites to the left will default to an E grade (Figure 2). For many of the sites the 95%ile value far exceeds the maximum acceptable value of 1200 (Figure 2). These results indicate that it is the high variability of the *E. coli* concentrations that result in difficulties achieving good microbial water quality gradings. Reducing the higher concentrations of the 95%ile should make a difference by bringing down all the other metrics.

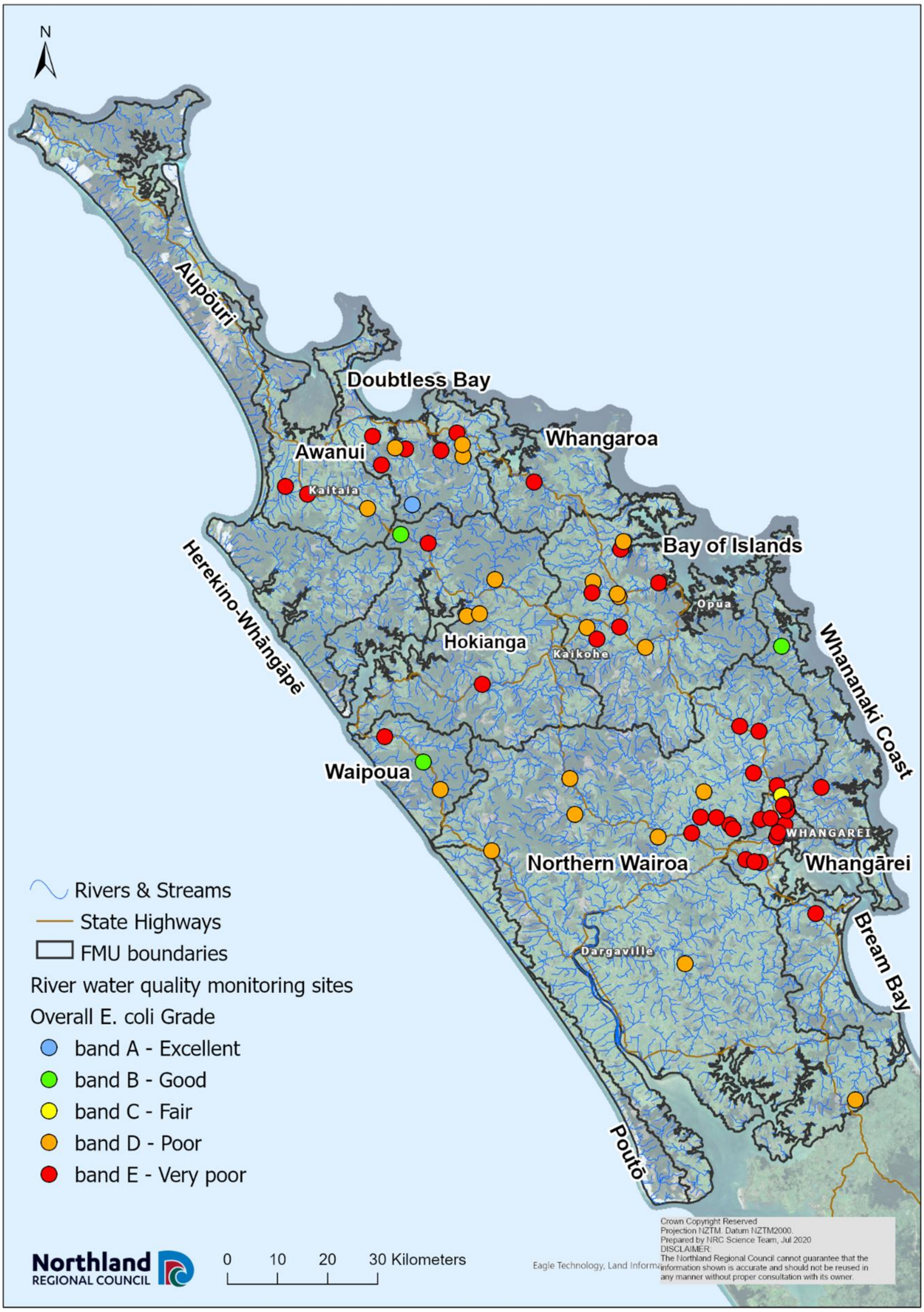

Figure 1. River water quality monitoring network (RWQMN) sites across Northland. The points are colour coded based on the overall microbial water quality grading from Table 3.

Table 3. NPS-FM assessment of the microbial water quality grades for all river water quality monitoring network (RWQMN) sites and associated Freshwater Management Units. The number of sampling years is the number of years included to 2021, required to have at least 60 samples to calculate the metrics. The cells contain the calculated metric and are colour coded according to the grading with A = blue, B = green, C = yellow, D = orange and E = red. The Overall grade is the worst grading of the 4 individual metrics.

Site Name	**Freshwater Management Unit (FMU)**	**Number of sampling years**	**Median *E. coli* (MPN/100 mL)**	**% exceed >260 *E. coli* (MPN/100 mL)**	**% exceed >540 *E. coli* (MPN/100 mL)**	**95th percentile *E. coli* (MPN/100 mL)**	**Overall Grade**
Awanui at FNDC	Awanui	6	330	55%	27%	12609	E
Awanui at Waihue Channel	Awanui	6	309.5	53%	32%	15665	E
Hakaru at Topuni	Northern Wairoa	6	122	26%	19%	17000	D
Hatea at Mair Park	Whangārei	4	425	76%	39%	12800	E
Hatea at Whangarei Falls	Whangārei	6	547.5	86%	51%	3700	E
Kaeo at Dip Road	Whangaroa	6	341	55%	33%	8255	E
Kaihu at Gorge	Northern Wairoa	6	185	30%	16%	4352	D
Kenana at Kenana Road	Doubtless Bay	6	354	68%	28%	1189	E
Kerikeri at Stone Store	Bay of Islands	6	285.5	53%	34%	25000	E
Mangahahuru at Apotu Road	Northern Wairoa	6	303.5	57%	18%	10149	E
Mangahahuru at Main Road	Northern Wairoa	6	467	70%	42%	3700	E
Mangakahia at Titoki	Northern Wairoa	5	201	42%	22%	5087	D
Mangakahia at Twin Bridges	Northern Wairoa	6	120	31%	16%	5725	D
Mangakino at Mangakino Lane	Whangārei	6	120	18%	8%	1034	C
Mangakino US Waitaua Confluence	Whangārei	7	553	89%	53%	2000	E
Mangamuka at Iwitaua Road	Hokianga	6	340	67%	36%	2824	E
Manganui at Mititai Road	Northern Wairoa	7	104.5	29%	22%	3876	D
Mangere at Kara Road	Northern Wairoa	6	610	85%	54%	2704	E

Site Name	Freshwater Management Unit (FMU)	Number of sampling years	Median *E. coli* (MPN/100 mL)	% exceed >260 *E. coli* (MPN/100 mL)	% exceed >540 *E. coli* (MPN/100 mL)	95th percentile *E. coli* (MPN/100 mL)	Overall Grade
Mangere at Knight Road	Northern Wairoa	5	757	94%	80%	22100	E
Mangere at Kokopu Road	Northern Wairoa	6	637.5	90%	68%	4066	E
Mangere at Wood Road	Northern Wairoa	6	420	75%	38%	2630	E
Ngunguru at Coalhill Lane	Whananaki Coast	6	256.5	50%	25%	8475	E
Opouteke at Suspension Bridge	Northern Wairoa	6	142	30%	15%	2350	D
Oruaiti at Sawyer Road	Doubtless Bay	7	189.5	36%	19%	3076	D
Oruaiti at Windust Road	Doubtless Bay	7	300	60%	24%	5000	E
Oruru at Oruru Road	Doubtless Bay	5	379	72%	34%	5750	E
Otaika at Cemetery Road	Whangārei	6	845	79%	59%	3873	E
Otaika at Otaika Valley Road	Whangārei	5	762	94%	69%	5260	E
Otakaranga at Otaika Valley Road	Whangārei	7	460	72%	46%	3585	E
Paranui at Paranui Road	Doubtless Bay	6	199	34%	11%	1442	D
Parapara at Taumata Road	Doubtless Bay	6	330	66%	25%	3350	E
Parapara at Parapara Toatoa Road	Doubtless Bay	6	311	61%	18%	1663	E
Pekepeka at Ohaeawai	Bay of Islands	6	234	42%	12%	1723	D
Peria at Honeymoon Valley US Dutton Rd	Doubtless Bay	6	119.5	16%	4%	520	A
Pukenui at Kanehiana Drive	Whangārei	6	342.5	62%	28%	3757	E
Punakitere at Taheke	Hokianga	7	380	66%	37%	5103	E
Punaruku at Russell Road	Whananaki Coast	6	86	18%	7%	874	B
Raumanga at Bernard Street	Whangārei	6	703	95%	62%	4495	E

Site Name	Freshwater Management Unit (FMU)	Number of sampling years	Median *E. coli* (MPN/100 mL)	% exceed >260 *E. coli* (MPN/100 mL)	% exceed >540 *E. coli* (MPN/100 mL)	95th percentile *E. coli* (MPN/100 mL)	Overall Grade
Ruakaka at Flyger Road	Bream Bay	6	495.5	80%	47%	8164	E
Stony Creek at Sawyer Road	Doubtless Bay	7	150	27%	13%	1785	D
Tapapa at SH1	Hokianga	6	120	21%	7%	604	B
Utakura at Horeke Rd	Hokianga	6	221	45%	15%	3908	D
Utakura at Okaka Road	Hokianga	6	235	42%	23%	5720	D
Victoria at Victoria Valley Road	Awanui	6	160	26%	11%	1040	D
Waiarohia at Second Avenue	Whangārei	5	543	74%	50%	13398	E
Waiarohia at Whau Valley	Whangārei	5	340	67%	28%	1460	E
Waiaruhe D/S Mangamutu Confluence	Bay of Islands	7	285	57%	24%	4474	E
Waiaruhe at Puketona	Bay of Islands	7	258	47%	21%	1900	D
Waiharakeke at Stringers Road	Bay of Islands	9	251.5	47%	22%	13250	D
Waimamaku at SH12	Waipoua	6	286.5	53%	25%	5243	E
Waiotu at SH1	Northern Wairoa	6	357.5	62%	27%	13085	E
Waipao at Draffin Road	Northern Wairoa	6	663	88%	61%	7044	E
Waipapa at Forest Ranger	Hokianga	6	95.65	20%	13%	1308	D
Waipapa at Waipapa Landing	Bay of Islands	6	195	35%	18%	4214	D
Waipapa at Waimate North Road	Bay of Islands	7	243	46%	23%	4101	D
Waipoua at SH12	Waipoua	6	72	15%	12%	1860	D
Wairau at SH12	Waipoua	6	96.5	26%	6%	756	B
Wairua at Purua	Northern Wairoa	6	110	35%	25%	22476	D
Waitangi at SH10	Bay of Islands	7	259	48%	23%	4759	D

Site Name	Freshwater Management Unit (FMU)	Number of sampling years	Median *E. coli* (MPN/100 mL)	% exceed >260 *E. coli* (MPN/100 mL)	% exceed >540 *E. coli* (MPN/100 mL)	95th percentile *E. coli* (MPN/100 mL)	Overall Grade
Waitangi at Waimate North Road	Bay of Islands	5	445	69%	38%	8689	E
Waitangi at Wakelins	Bay of Islands	5	225.2	44%	33%	4235	E
Waitaua at Vinegar Hill Road	Whangārei	6	610	93%	57%	2000	E
Watercress at SH1	Bay of Islands	6	367	72%	40%	5356	E
Whakapara at Cableway	Northern Wairoa	6	300	56%	23%	18469	E

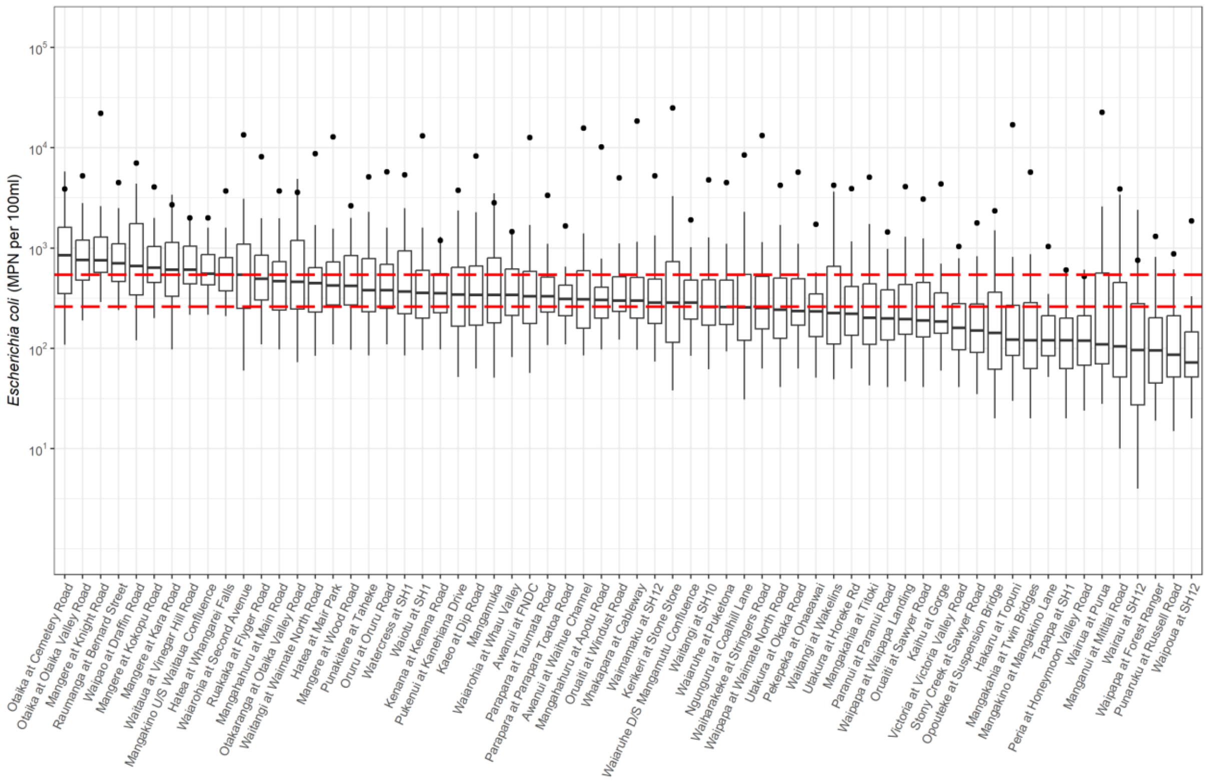

Figure 2. Box plots of the *E. coli* concentrations for each site in the river water quality monitoring network. The horizontal line is the median, the boxes are the interquartile range, the whiskers are 1.5 times the interquartile range and the points show the 95th percentile values. To help with interpretation of the Log_{10} scale on the Y axis there are red dotted lines at 260 and 540 *E. coli* 100 mL^{-1}. The sites are plotted from the highest median on the left to the lowest median on the right.

4.2 Swimming Water Quality State

From the data provided we were able to calculate a water quality grading for 19 swimming sites across Northland (Figure 3). The swimming water quality standards are based only on the 95%ile metric only and are much more stringent than for the NPS-FM water quality monitoring metrics. Therefore, based on the long-term standards, all 19 sites were graded as poor (Figure 3 and Table 4). Despite poor grading for all swimming sites based on long-term *E. coli* data, 19-82% of the time during the bathing season these sites were suitable for swimming (Table 4). The distributions of the data at each site are summarised as box plots which clearly show the high 95%ile values at all sites (Figure 4). The long-term swimming grading is poor if the 95%ile is >540 and only 2 sites had 95%iles less than 1000 *E. coli* 100 mL^{-1}. This long-term grading indicates the challenges for Northland have in achieving swimming water quality standards.

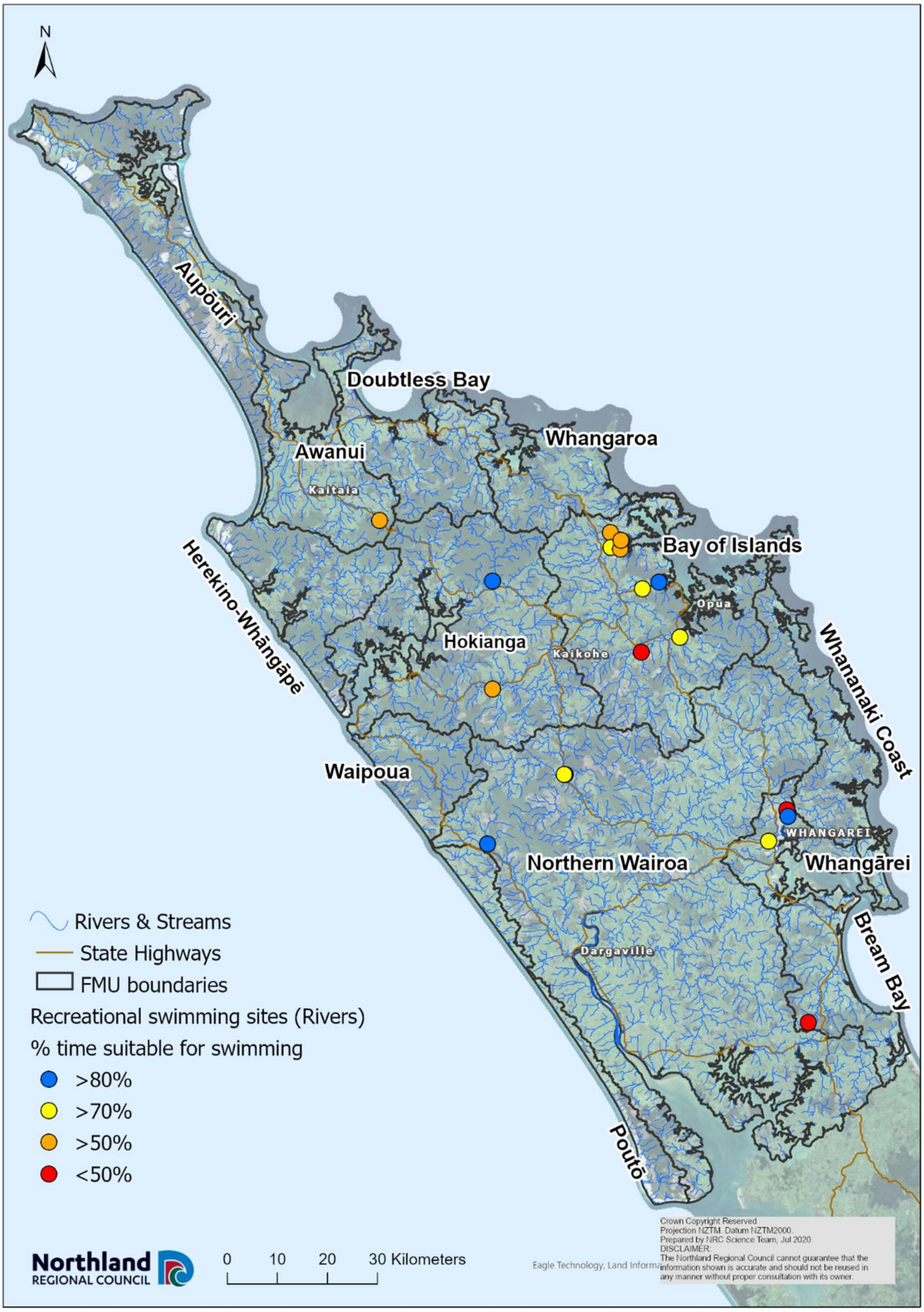

Figure 3. Monitored swimming water quality locations and suitability assessments for Northland sites.

Table 4. Summary of the water quality grading at the swimming sites, including the number of samples and number of years used to calculate the metrics. Note the four sites highlighted in grey all have less than the recommended 50 samples required to assign a long-term grade (NPS-FM 2020) but are included for comparison.

Name	Number of Samples	Sample Years	95th Percentile Hazen	Overall Grade	Suitable #	Suitable %	Alert #	Alert %	Action #	Action %
Ahuroa Piroa Falls	87	5	2400	D - Poor	19	22%	27	31%	41	47%
Hatea Whangarei Falls	72	5	6097	D - Poor	21	29%	32	44%	19	26%
Hatea Whareora Rd	29	2	2640	D - Poor	22	76%	2	7%	5	17%
Kaihu Swimming Hole	67	5	2401	D - Poor	51	76%	5	8%	11	16%
Kapiro Purerua Rd	67	5	2481	D - Poor	26	37%	25	36%	19	27%
Kerikeri Rainbow Falls	79	5	2830	D - Poor	47	60%	16	20%	16	20%
Kerikeri Stone Store	89	5	7014	D - Poor	34	38%	17	19%	38	43%
Mangakahia Twin Bridge	63	5	10742	D - Poor	42	67%	7	11%	14	22%
Mangakahia Swimming Hole	31	2	1590	D - Poor	21	68%	2	6%	8	26%
Otaua Stream at Otaua Road	61	5	4591	D - Poor	25	41%	19	31%	17	28%
RaumangaValley Park	90	5	1497	D - Poor	46	51%	28	31%	16	18%
Tirohanga	80	5	1477	D - Poor	43	54%	17	21%	20	25%
Victoria DOC Reserve	88	5	1460	D - Poor	39	44%	28	32%	21	24%
Waiharakeke Lucas Rd	31	2	4537	D - Poor	6	19%	9	29%	16	52%
Waipapa Charlies Rock	39	3	2265	D - Poor	18	46%	15	38%	6	15%
Waipapa Waihou Valley	71	5	971	D - Poor	57	80%	6	9%	8	11%
Waipoua at Swimming Hole	78	5	874	D - Poor	64	82%	8	10%	6	8%
Waitangi at Lily Pond	64	5	3383	D - Poor	38	59%	17	27%	9	14%
Waitangi at Wakelins	80	5	1094	D - Poor	59	74%	12	15%	9	11%

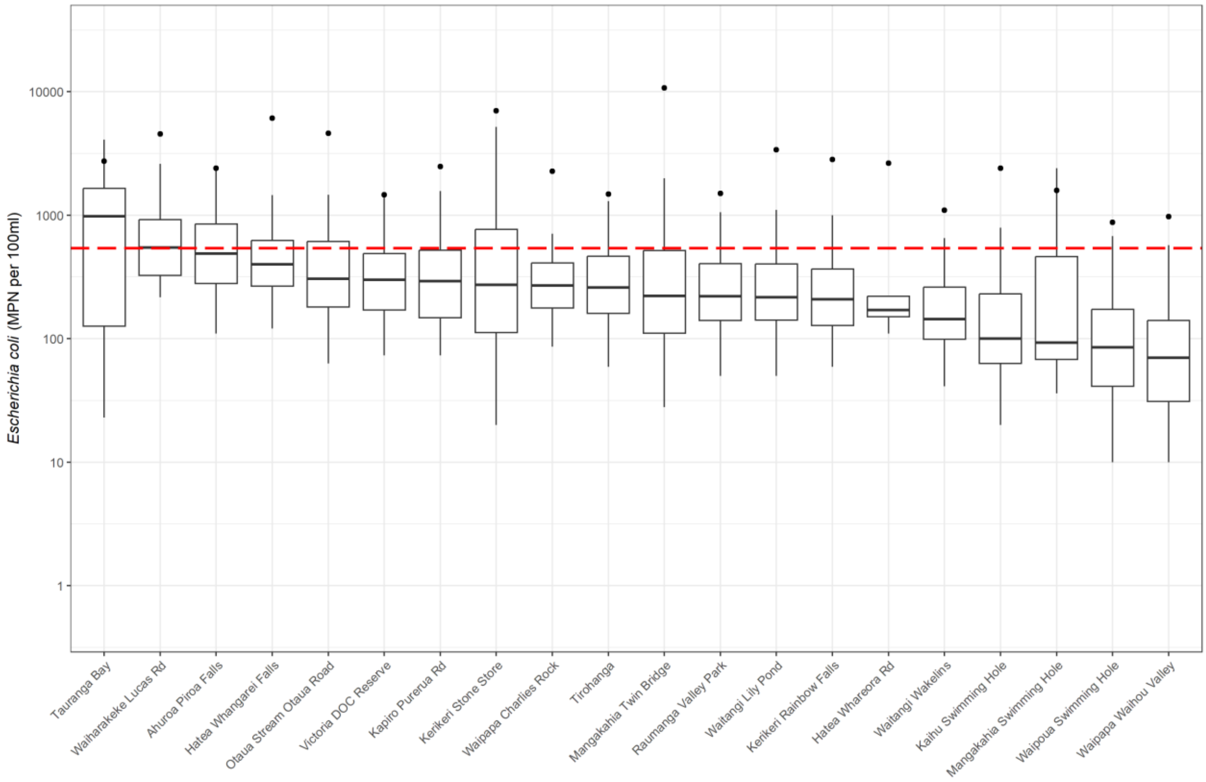

Figure 4. Box plots of the *E. coli* concentrations for each swimming water quality monitoring site. The horizontal line is the median, the boxes are the interquartile range, the whiskers are 1.5 times the interquartile range and the points are the 95th percentile values. Note that the y axis is plotted on a Log_{10} scale. The sites are plotted from the highest median on the left to the lowest median on the right. The dashed red line is at 540 MPN 100 mL^{-1}.

4.3 Sewage – Wastewater Treatment Plant Discharges

From the data provided, it appears that not all sewage discharges in Northland are into freshwater systems, with only 9 sites being identified as discharging into rivers (Figure 5). There were obvious impacts on downstream concentrations at the Hihi and Ngunguru sites, small impacts at Kawakawa and Kaikohe and no obvious *E. coli* impacts at Kaitaia, Kaeo, Maungaturoto, Hikurangi, Kaikohoe and Opononi (Figure 5). It should be noted that although the downstream *E. coli* concentration may not be increased by the sewage discharge, this does not mean that the sewage discharge is not having an impact on the environment. There could be other cultural impacts or impacts on other water quality contaminant levels and stream values. The management of point source discharges from sewage systems is best managed at a local detailed scale, which is beyond the scope of the microbial (*E. coli*) water quality analysis in this report.

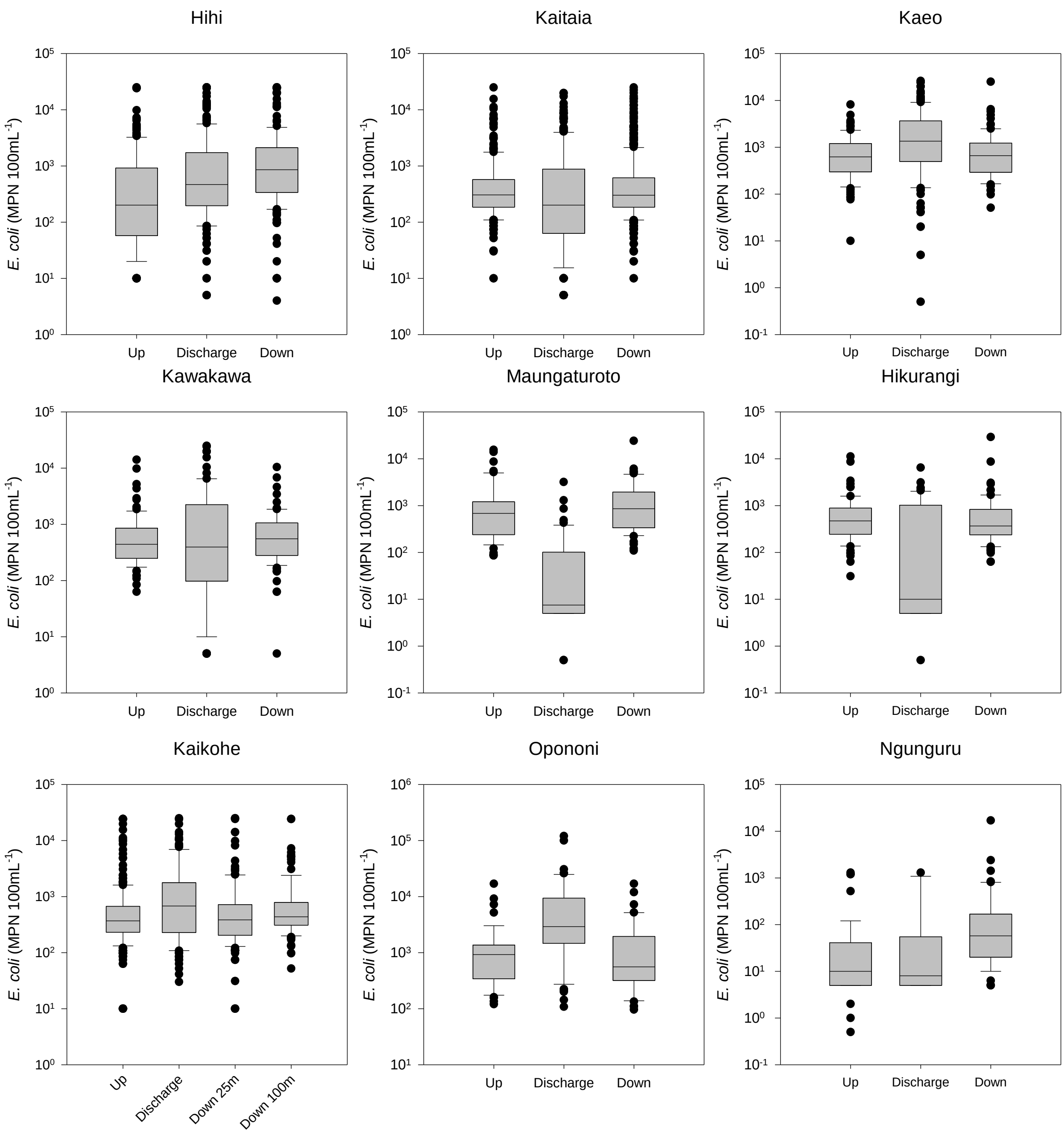

Figure 5. *E. coli* concentrations in discharge from sewage plants and associated concentrations in receiving waters up- and down-stream of the discharge point.

4.4 Long-term Trends in Microbial Water Quality Data

Temporal trend analysis was not a focus of this project as the authors did not have the local knowledge or access to any trends in drivers to analyse the results. However, we have provided data and trends in Appendix 1 so that NRC staff can investigate if desired. The trend analysis showed that most results were not statistically significant, but some sites appeared to increase, some appeared to decrease, and many sites showed little change. There were six sites with a statistically significant ($p < 0.05$) decreasing *E. coli* trend (increasing water quality): Hakaru at Topuni, Kaeo at Dip Road, Mangahahuru at Apotu Road, Peria at Honemoon Valley Road, Punaruku at Russell Road and Utakura at Horeke

Road. There were five sites with a statistically significant ($p < 0.05$) increasing *E. coli* trend (decreasing water quality): Kaihu at Gorge, Kenana at Kenana Road, Mangahahuru at Main Road, Mangamuka at Iwitaua Road and Whakapara at Cableway. Interestingly, the two sites monitored on the Mangahahuru river had statistically significant but contrasting trend directions. Many trend analyses will try to focus on a set time period to answer a specific question on relative change (Larned et al. 2016). However, for this report the trend analysis for the full length of data available at each site has been plotted.

5. Investigation of Potential Drivers of *E. coli* Water Quality

5.1 Other Water Quality Parameters

Relationships between *E. coli* concentrations and other water quality parameters were investigated using correlation analysis. The specific parameters selected were pH, temperature, dissolved oxygen, dissolved reactive phosphorus, total phosphorus, ammoniacal nitrogen, total nitrogen, total suspended solids, black disc and turbidity. The raw results for these analyses are presented in Appendix 2 and can be provided to NRC in a spreadsheet. Correlations were conducted on the analyses from individual samples. With a combined total of 71 sites from both the river water quality monitoring network and swimming sites and 10 different parameters, over 700 tests were conducted.

Firstly, a word of caution for interpreting the results of a large number of statistical tests: when conducting a correlation test the significance threshold for a p-value is usually set to 0.05. This means that if the p-value is <0.05 then we are 95% confident that the correlation we see in the data is real. For a single correlation test this is a good approach. However, there is still a 5% chance that the correlation we see in the data is not real i.e. a false positive result. When the number of tests you do on a large dataset is increased, the chance of making a false positive result is also increased. In this analysis we have conducted more than 700 tests and, therefore, we could expect to make approximately 35 false positive conclusions. Just because the test shows a positive result for the relationship between *E. coli* and another water quality parameter at one site does not mean that the apparent relationship is important. Overall importance is best determined by identifying patterns such as the relationship occurring at multiple sites or multiple water quality parameters showing a relationship at the same site.

Overall, there were very few strong relationships detected between *E. coli* and other measured water quality parameters. As cautioned above, there is also the possibility that most of these strong relationships are false positive results (Appendix 2). For the pH and dissolved oxygen parameters, the lack of a relationship with *E. coli* suggests an absence of major point source discharges into Northland rivers (near the monitored sites) as pH and dissolved oxygen are typically not affected by diffuse pollution sources. There were no strong relationships between *E. coli* and water temperature at any of the sites, indicating a lack of seasonal effect. Additionally, there were no strong relationships between *E. coli* and dissolved reactive phosphorus, ammoniacal nitrogen or total nitrogen. There were a small number of strong relationships between total phosphorus, total suspended solids, turbidity and black disc. These last four parameters are all often related to soil particles in water and could indicate a common transport process with *E. coli* sources in these catchments. However, for these last four contaminants/indicators, only three sites had a strong relationship for all four parameters at the same site (Hakaru, Mania SH10 and Oruaiti Sawyer Rd) and even then the Mania SH10 site was based on approximately 15 data points (Appendix 2). The absence of relationships between *E. coli* and other water quality parameters is likely a reflection of the naturally high variability of *E. coli* concentrations in rivers and the high variability in diffuse *E. coli* sources to surface waters in Northland (Muirhead & Meenken, 2018; Muirhead et al. 2011).

5.2 Rainfall and River Flows

There is a general belief that *E. coli* concentrations in rivers increase during storm-runoff events and, therefore, there is an expectation that *E. coli* concentrations will be related to river flows or rainfall (Muirhead et al. 2004; Davies-Colley et al. 2008; Ballantine & Davies-Colley 2013). However, this expectation is not always supported by river monitoring data and this appears to be the case for the Northland data. Details of these results are presented in Appendix 3. There were only 3 sites that exhibited a strong relationship between *E. coli* and flow: Hakaru, Kerikeri Basin Reserve and Manaia SH10 (Figure 6). The Kerikeri Basin Reserve site showed a strong relationship with rainfall in the previous 48 and 72 hours. The Manaia SH10 site also showed a strong relationship with rainfall in the previous 24, 48 and 72 hours, however, as noted above, there were only 15 data points from this site so the result is not convincing.

Plots of contaminant concentration versus flow rate can also be used to investigate the relative importance of point source discharges versus diffuse sources of contaminant inputs. A hypothetical example of these point/diffuse source discharges is shown in Figure 7. If you have a constant point source discharge into a river of clean water, then the downstream concentrations relative to flow would look like the red line in Figure 7 as the constant contaminant load is effectively diluted into a larger volume of water as the flow rate increases. In contrast, for a diffuse pollution source you would expect concentrations to slowly increase with river flow rates as per the blue line in Figure 7. If you have a combination of both point and diffuse sources in the same river, then you would expect the green line that has the characteristic hockey stick curving up at low flow rates (Figure 7). The Northland data shows none of these hockey stick curves, indicating that the *E. coli* sources are dominated by diffuse sources throughout the catchments (Figure 6). Even though most of the relationships are not statistically significant, most show positive relationship consistant with a diffuse pollution source (Figure 6).

Farm dairy effluent discharges in Northland will most likely impact on water quality data as a diffuse source of *E. coli*. From conversations with NRC staff it appears that even when a FDE pond discharge directly to water is consented, the ponds will not always discharge to the stream. If raw effluent is generated every day from the milking shed, but no FDE is being discharged to the stream, then this indicates two potential processes are occuring. Firstly, effluent could be leaking through the pond liner into ground water and entering the stream via that pathway. Any leakage from pond system can be detected by using a pond drop test (IPENZ, 2017). Secondly, evaporation rates could exceed the volume of liquid entering the ponds from the milking shed. In this second situation, discharges to the stream will occur sporadicaly depending on water use in the milking shed and evaporation rates. The effect of either leakage or evaporation will result in FDE discharges appearing in water quality monitroing data (collected at the catchment scale) as a diffuse source. Peak numbers of *E. coli* discharged by FDE systems, either from ponds or irrigation systems, will occur when rainfall coincides with the milking season when FDE is being generated (Muirhead and Stephens, 2018).

One of the effects of high flowrates during storm events is the increase in contaminant loads transported in the steam network. This has a greater effect on *E. coli* loads than for other contaminants (Davies-Colley et al. 2008; Ballantine & Davies-Colley 2013). This means there is a much greater load of *E. coli* transported in the river during storm runoff events. The total load of *E. coli* in a river has an impact on the waterbody (lake, estuary or ocean) that the river discharges into as this large pulse of storm water has to be diluted and dispersed over time. However, the river microbial water quality metrics are based on concentrations, not loads. Because a river spends more days per year in a base-flow state than storm-flow state, *E. coli* concentrations during base-flow conditions have a large impact on the river water quality metrics – particularly the median concentration. Note that many sites in Northland are graded D or worse due to the high median *E. coli* concentration. Regardless of the relative size of the annual load of *E. coli* deposited into a river, sources that occur during base-flow conditions will have a disproportionately large impact on the microbial river water quality metrics. These base-flow impacting sources are likely to be animal access to streams, FDE management and irrigation systems (Muirhead et al. 2011; Muirhead 2015). This base-flow impact can be seen in Figure 6, where for many sites, high *E. coli* concentrations occur at a wide range of flows.

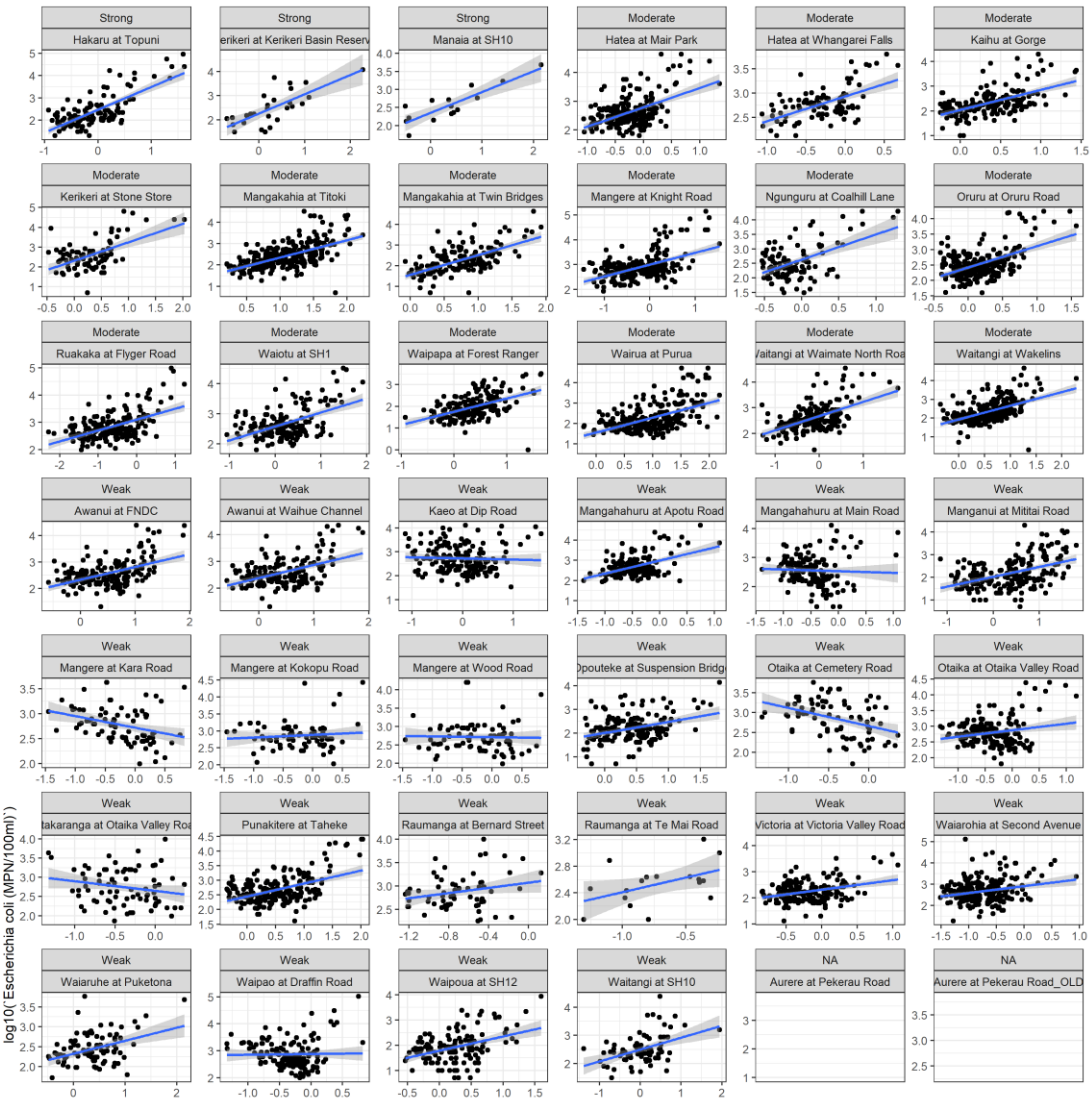

Figure 6. Relationship between Log *E. coli* concentrations (y axis) and Log flow (x axis) for the sites where there were suitable flow data. The blue line is the correlation and the grey areas the 95 % confidence interval on the correlation. At the top of each individual graph is an indication of the strength of the correlation.

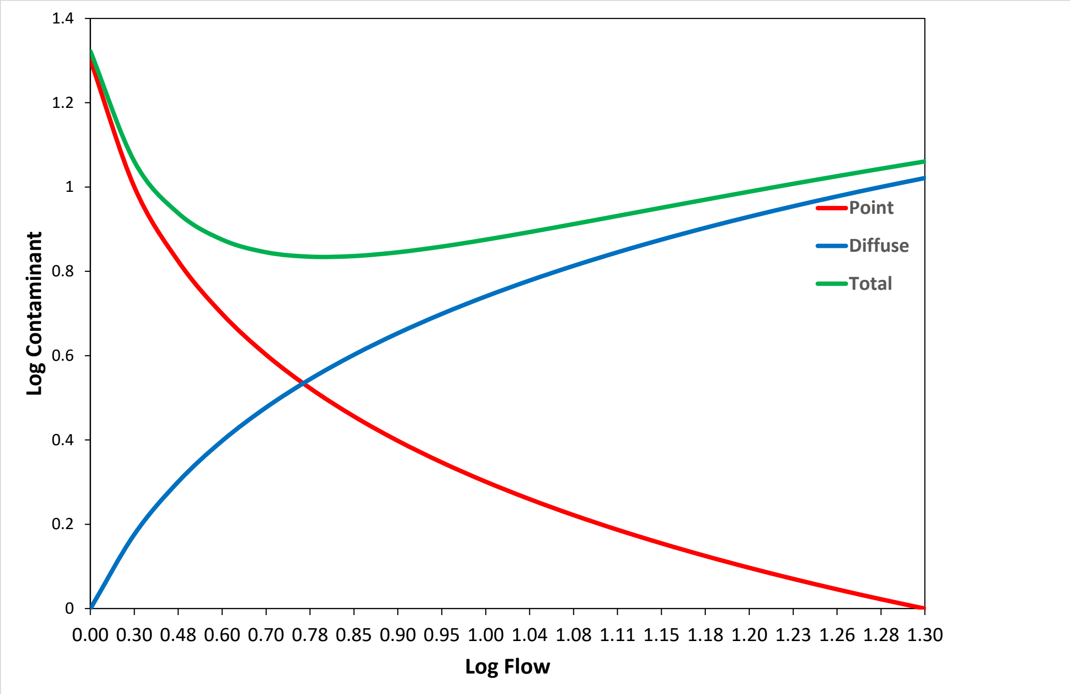

Figure 7. Illustration of the hypothetical relationship between Log contaminant concentration and Log flowrate showing the relative effect of point and diffuse pollution sources.

5.3 Stream Morphology

It is known that a reservoir of *E. coli* can form in the sediments of a river network (Muirhead et al. 2004; Wilkinson et al. 2011). Soft bottom streams naturally have a larger sediment store leading to a hypothesis that a soft bottom stream will store more *E. coli* than a hard bottom stream, leading to higher *E. coli* concentrations in the waters of streams with a soft bottom morphology. This was investigated by comparing the four microbial water quality metrics for hard bottom and soft bottom rivers in Northland (Figure 8). The results showed that the median values and ranges for the four microbial water quality metrics were similar between the hard and soft bottomed rivers. However, the interquartile ranges were "off set" indicating that the distribution for the hard bottom streams was skewed lower and the soft bottom streams skewed higher. Overall, there appears to be no major difference between the hard and soft bottomed streams. Furthermore, other factors, such as land-use, may correlate with the hard bottom/soft bottom morphology of streams, thus confounding the relationships. Further investigation is required to understand how *E. coli* in stream sediments affects microbial water quality metrics (Cho et al. 2016).

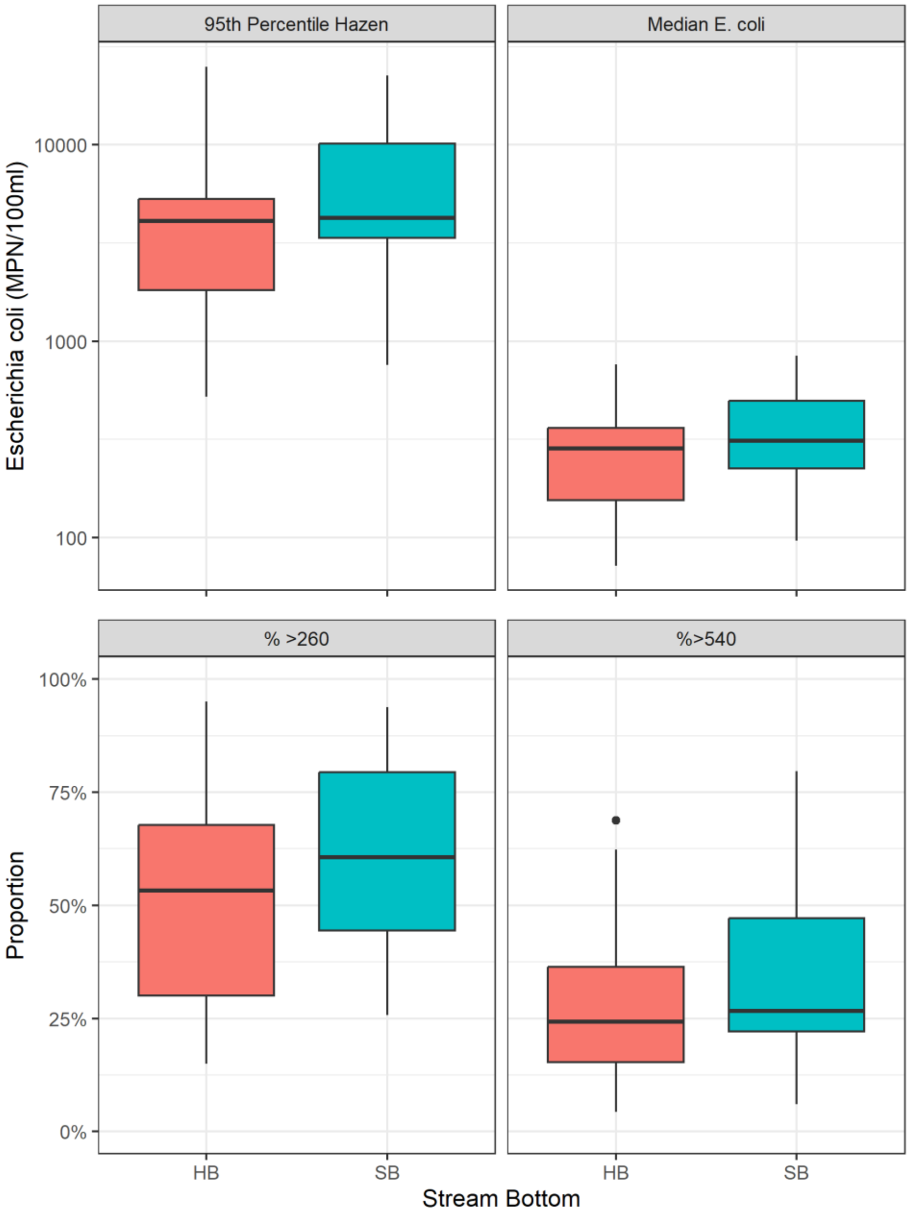

Figure 8. Box plots of the four *E. coli* water quality metrics separated into hard bottom (HB) and soft bottom (SB) stream morphologies. The horizontal line is the median, boxes are the interquartile range, whiskers are 1.5 times the interquartile range and points are outliers.

5.4 Land-use

For the river water quality monitoring network sites, we conducted correlations between the four *E. coli* metrics and the land cover in the respective catchments (Figure 9). For the swimming water quality sites, correlations were conducted between the 95%ile metric and the land cover in the respective catchments (Figure 10). Full details of the land cover correlations are provided in Appendix 4. The relationship with land cover was consistent across the four *E. coli* metrics for the landcovers classified as reliable (Figure 9). Land cover was consistently significantly related to the 95%ile metrics for both the river water quality monitoring network sites and the swimming sites. For the RWQMN sites the largest positive and negative correlations were with the high producing exotic grass land and indigenous forest, respectively (Figure 9). All grass land covers were combined as productive livestock land use based on the assumption that the land would have animals depositing *E. coli* onto the pasture and all these areas showed a positive correlation i.e. increasing areas of land used for productive livestock in the catchment were associated with increasing *E. coli* concentrations in water. These productive livestock lands also had a positive correlation at the swimming sites (Figure 10). An attempt was made to align dairy cow stocking density with the river water quality monitoring sites. However, due to difficulties reconciling differences between the large-scale cattle numbers data and the small-scale water quality catchments, this approach was rejected as it would be inaccurate at the local catchment scale. The FDE discharge data is more accurate at the small scale and shows the relationship with median *E. coli* concentrations (Figure 11). Northland Regional Council monitoring of FDE discharges indicates an impact of discharges on microbial contaminants immediately downstream of the discharge point (Muirhead & Stephens, 2018). FDE pond systems are not very effective at removing *E. coli* from the effluent. Multiple studies conducted in the Waikato region demonstrate that *E. coli* concentrations in pond discharges are typically greater than 10^4 MPN 100 mL^{-1} and can be as high as 10^6 MPN 100 mL^{-1} (Craggs et al. 2004; Donnison et al. 2011). An FDE modelling study in Northland also indicated that FDE pond discharges to streams will have an impact on the microbial water quality metrics in streams and that converting to a best practice deferred irrigation strategy could significantly reduce the impacts of current FDE managements (Muirhead & Stephens, 2018).

Non-animal productive land, such as orchards and crops, also had a positive but smaller effect on *E. coli* although this land cover was less frequent in catchments hence the relationship is less reliable. This land is assumed to have no or few animals present so is likely to have less *E. coli* although some of this land may use organic fertilizers that will contain *E. coli*. Urban areas also showed a positive correlation with stream *E. coli* concentrations (Figures 9 & 10). Urban areas usually have significant areas of impermeable surfaces (roofs, roads, footpaths, industrial land etc) and stormwater collection infrastructure that convey runoff directly to surface waters. Urban areas are a small proportion of land use in most catchments, however (Appendix 4). Of the forested areas, indigenous forest and Manuka/Kanuka were always negatively correlated with *E. coli,* whereas exotic forest or harvested forest areas showed a small negative correlation at RWQMN sites and a large positive correlation at the swimming sites (Figures 9 & 10). It is important to note that forests are not without *E. coli* sources such as birds, possums, deer, pigs etc. Unfortunately, there is little data available to help understand the impacts of these sources or how to mitigate them. However, their impact is certainly less than agricultural land: the 4 RWQMN sites that achieved A or B grades were all in catchments with forested land cover and the one site that achieved C grade contained only 5% areas as productive livestock land.

The relationships between landcover and *E. coli* metrics in Northland is consistent with other modelling studies conducted in Northland and wider NZ (Elliott et al., 2016; Larned et al., 2016; Pearson et al., 2020; Snelder et al., 2016). These studies all indicate that intensive agriculture is a key source of *E. coli* inputs to surface waters and that microbial water quality is generally higher in rivers and streams draining forested areas.

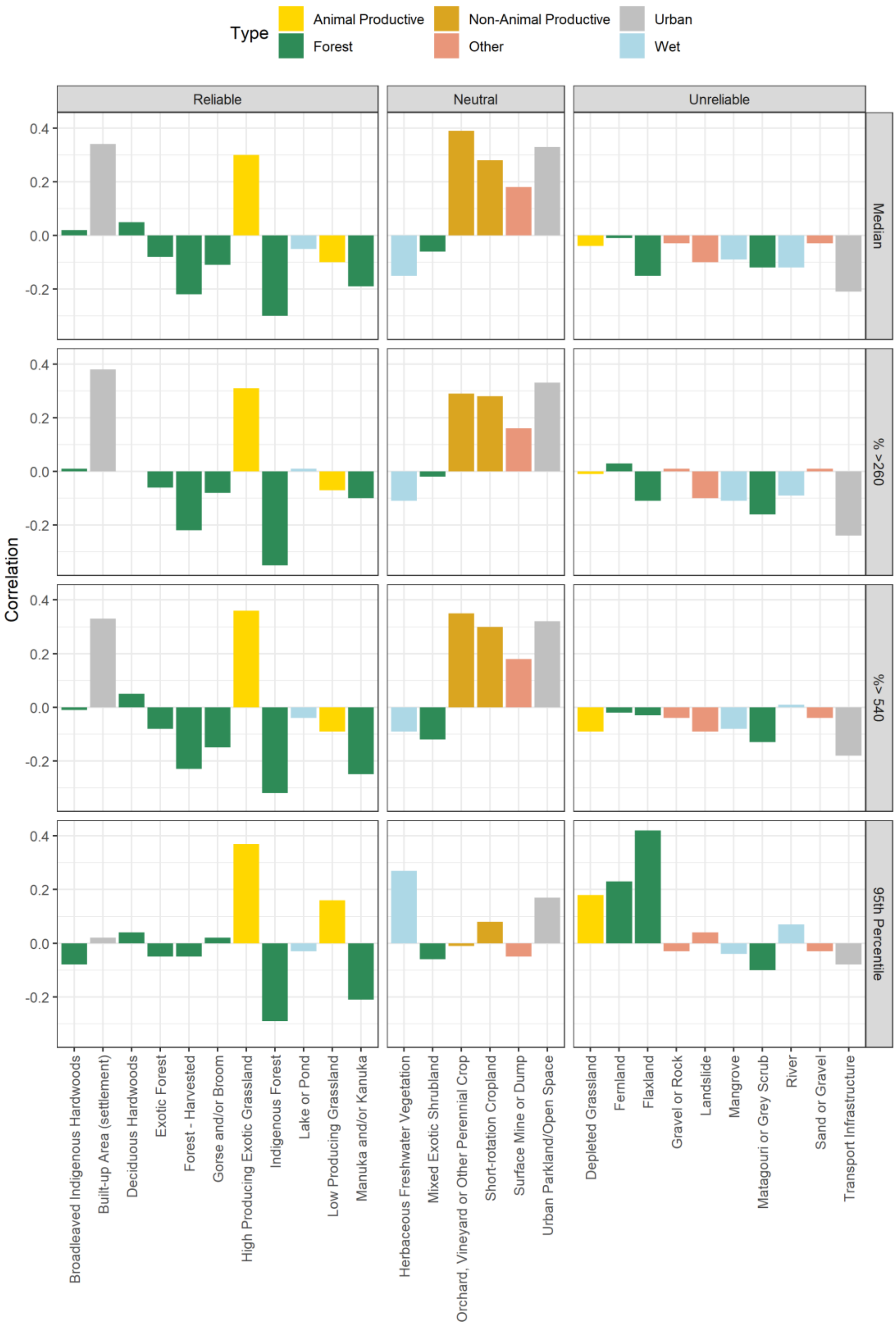

Figure 9. Pearson correlation coefficients between land cover types and the four microbial water quality metrics derived from the RWQMN dataset. Data are designated reliable, neutral or unreliable based on the number of catchments containing those land covers. The LCDB5 land cover categories are colour coded into broader land use groupings.

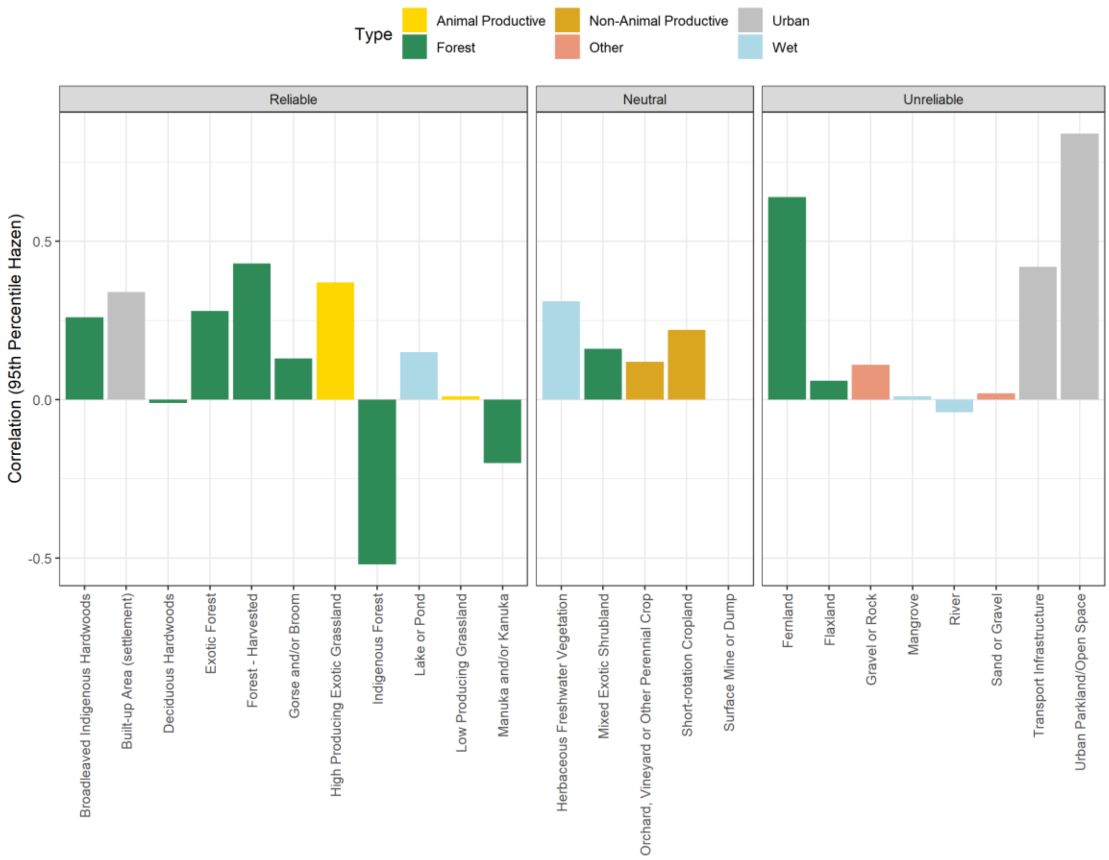

Figure 10. Correlation (r) values between landcover and the 95%ile derived for the swimming water quality program sites. Data are designated reliable, neutral or unreliable based on the number of catchments with those landcovers present. The LCDB5 land cover categories are colour coded into broader land use groupings.

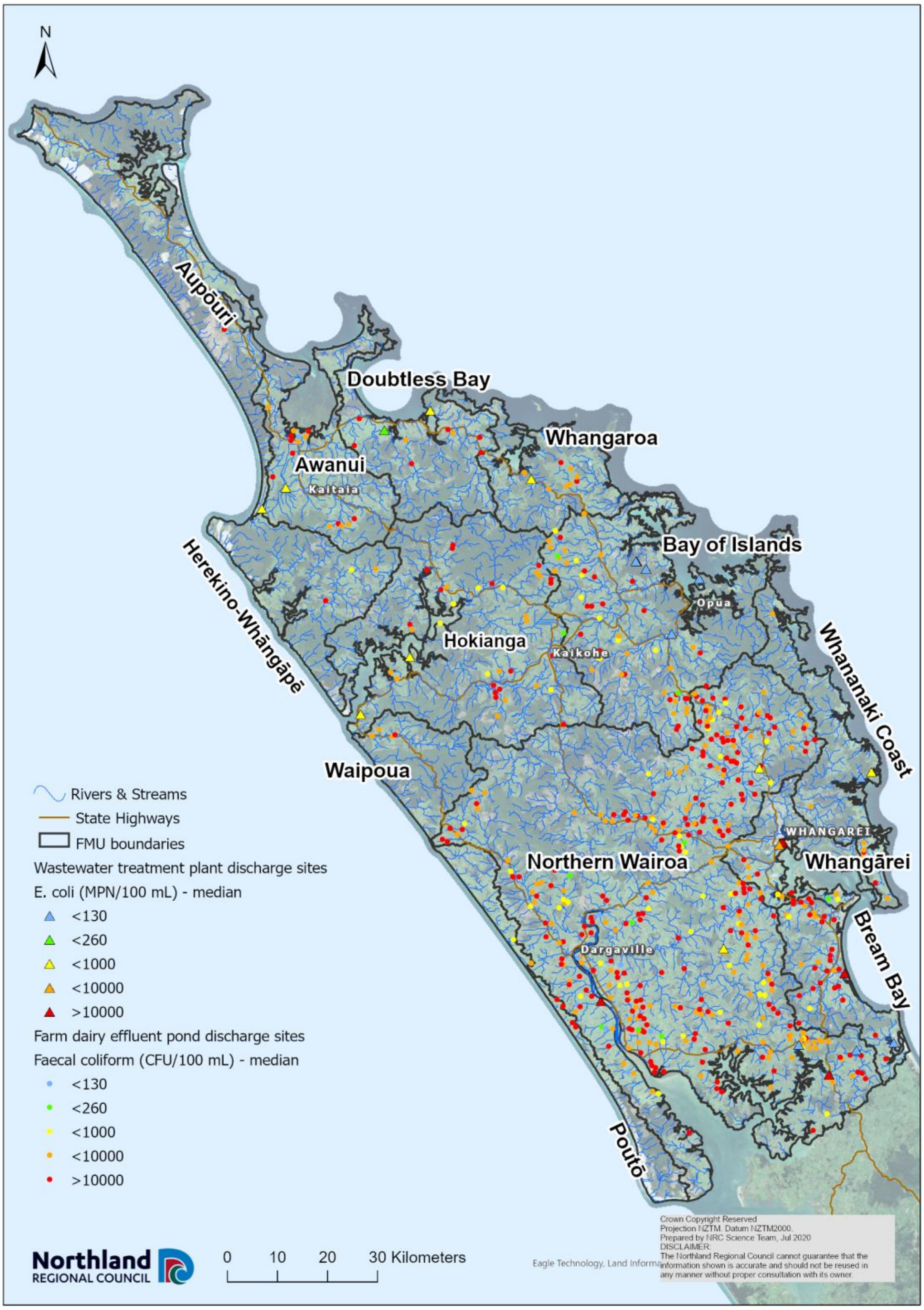

Figure 11. Map of Northland showing the locations of the FDE and WWTP discharges and the *E. coli* concentration in the discharges in relation to the river network.

5.5 Faecal Source Tracking (FST)

A number of previous studies have been conducted in Northland using faecal source tracking methods as a method for identifying key faecal sources in a number of catchments (Devane 2017; Devane 2019). Between 2011 and 2021 NRC sent 236 samples for FST analysis. The analyses included four different human FST markers: Bacteroidales, BiADO, M2 and M3. The M2 and M3 markers were only identified in five of the samples and always at less than quantifiable levels, indicating no recent human contamination. The Bacteroidales and BiADO markers were detected more frequently but these markers are less specific to human sources and, therefore, both need to be detected to have confidence that there is a human source in the water sample. A three-level classification based on the Bacteroidales and BiADO results was developed to help understand the data. The sample was classified as no human signal (0) if there was no Bacteroidales and/or no BiADO detected. Samples were deemed to have a low human signal (1) if one or both Bacteroidales and BiADO were detected at less than quantifiable levels. Sample were deemed to have a confirmed human signal (2) if both Bacteroidales and BiADO were detected at quantifiable levels. Using this classification system, 13% of the samples had no human signal, 62% had a low human signal and 25% had a confirmed human signal. There appeared to be no clear pattern of human FST markers related to sites, *E. coli* levels or rainfall (data not shown).

There are bird FST markers tested for that are a Duck specific marker and a general Avian marker. The Duck results were sporadic but the Avian marker was frequently detected. A classification system was developed based on the avian signal (0) if no Avian marker was detected. A low bird signal (1) was assigned if the Avian marker was detected at less than quantifiable levels, and a confirmed bird signal (2) if the Avian marker was quantified. Using this classification system, only 8% of the samples had no bird FST marker; 67% of the samples had low bird FST markers and 25% had confirmed bird markers. There appeared to be no clear pattern of avian FST markers related to sites, *E. coli* levels or rainfall (data not shown).

The dog-specific marker was very prevalent at low numbers in the samples. There was no Dog PCR marker identified in only two of the 236 samples tested. But a quantifiable level was only detected in eight (3%) of the samples. This means that very low levels of Dog faeces were detected in most water samples across Northland. This indicates that the dog FST marker is highly sensitive.

There are three ruminant FST markers tested for: the general Ruminant marker and a specific sheep and specific cow marker. The specific sheep and cow markers must be very low sensitivity as there was only one of each marker detected in all of the samples, despite the general ruminant marker being detected in 80% of all samples. The FST analysis lab provides a PCR Proportion Ruminant classification with five levels of: not detected (<1%), 1-10%, 10-50% and 50-100%. The number of samples in each of the ruminant classifications were 20% not detected, 3% with <1% Ruminant, 9% with 1-10% Ruminant, 28% with 10-50% Ruminant and 40% with 50-100% Ruminant. This result indicates high levels of ruminant faecal sources in Northland's water data record. There were some patterns observed with the ruminant FST sources and other water quality parameters. There appeared to be no pattern associated with the sampling site. But the samples classified as having high levels of ruminant sources appeared to correspond to higher *E. coli* concentrations in the water sample (Figure 12), higher levels of rainfall prior to sample collection (Figure 13) and the parameters of turbidity, suspended solids and black disc visibility (Figure 14). This indicates that higher levels of ruminant FST markers are associated with drivers of diffuse pollution and other diffuse pollution contaminants.

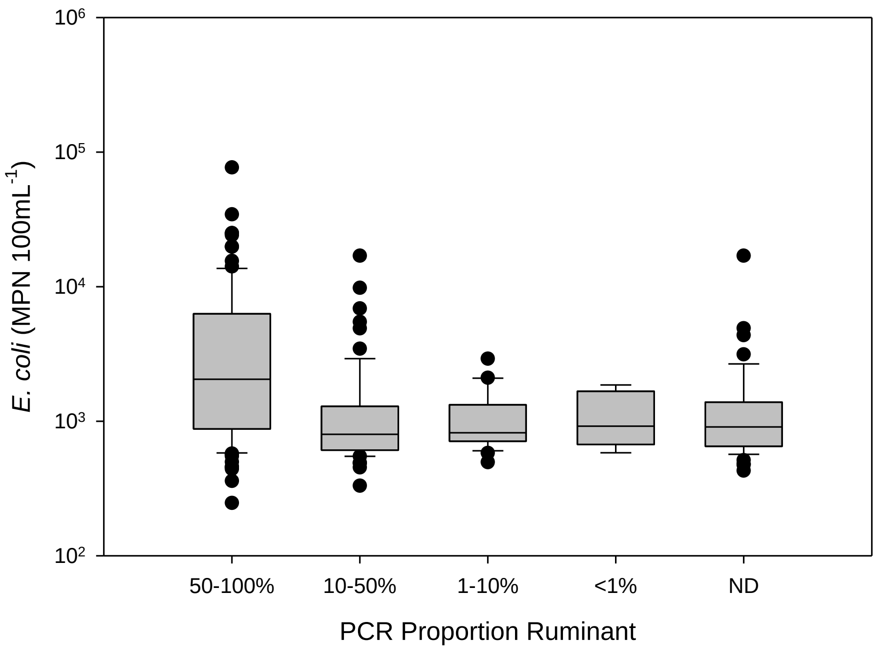

Figure 12. Relationship between the *E. coli* concentration in a sample and proportion of Ruminant FST marker. The horizontal line is the median, the boxes the interquartile range, the whiskers the 10th and 90th percentiles, and the points outliers.

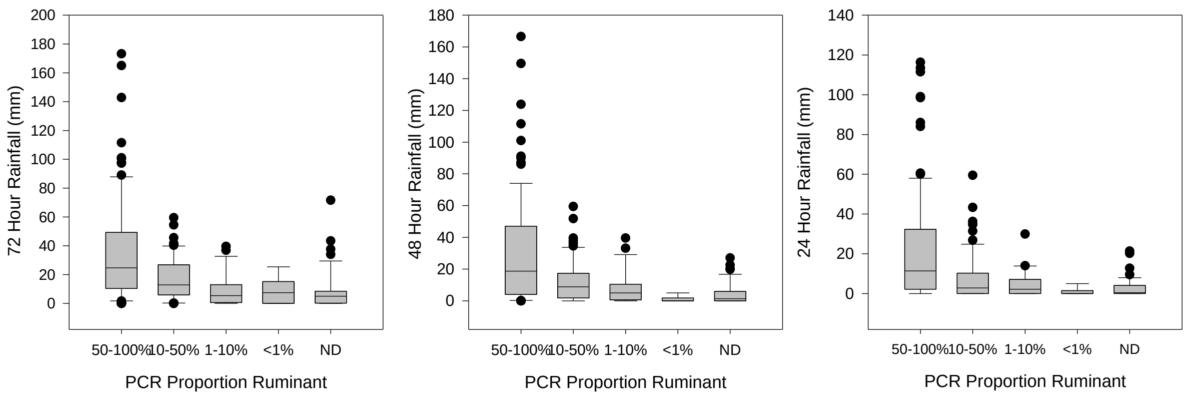

Figure 13. Relationships between the proportions of Ruminant FST marker in a sample and the amounts of rainfall falling in the 24, 48 and 72 hours prior to sample collection. The horizontal line is the median, the boxes the interquartile range, the whiskers the 10th and 90th percentiles, and the points outliers.

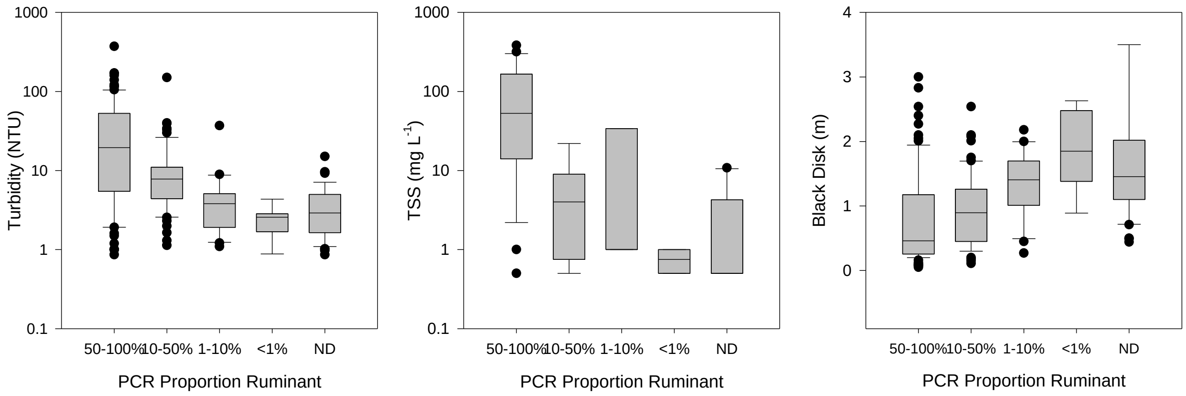

Figure 14. Relationships between the proportions of Ruminant FST marker in a sample and the turbidity, suspended solids and black disc visibility in the sample. The horizontal line is the median, the boxes the interquartile range, the whiskers the 10th and 90th percentiles, and the points outliers.

Key messages from these FST results are, firstly, there appear to be very low levels of human and dog faecal sources. The remaining results identify birds and ruminant sources or are inconclusive. Results at individual sites are variable from sample to sample. The ruminant sources appear to be the dominant source of faecal contamination in any of the rivers investigated in Northland and is associated with diffuse pollution signals.

5.6 Naturalized *E. coli*

Until relatively recently, *E. coli* was considered a reliable indicator of faecal contamination as it is a relatively common component of the gut microbiome from humans and animals (including avian species) (Devane et al., 2020). However, recent sub-typing of *E. coli* has revealed that there are some *E. coli*-like *Escherichia* species that are genetically distinct from faecal *E. coli*, that are stably maintained in the environment and are unlikely to be significant human pathogens (Cookson et al., 2022). Although these cryptic or 'naturalized' *E. coli*-like *Escherichia* species are genetically different, current culture-based methods for monitoring water quality are unable to distinguish them from faecal *E. coli* types. Similarly, some faecal *E. coli* sub-types may also persist in the environment and represent naturalized *E. coli* associated with non-recent faecal contamination events (Devane et al., 2020). Preliminary evidence suggests that the presence of these naturalized faecal *E. coli* is correlated with other persistent freshwater pathogens such as cryptosporidia who, in their resistant oocyst form, are able to persist in freshwater long after any faecal contamination event (Moinet et al. 2021).

Studies undertaken to sub-type the faecal indicator bacteria isolated from freshwater sites of contrasting observed land uses, including native forest and sheep and beef, and dairy farms, have indicated the presence of *E. coli* and *E. coli*-like *Escherichia* species that may not be associated with recent faecal contamination events (Cookson et al., 2022). Previous work by ESR colleagues investigated four freshwater swimming sites (Waitangi at Wakelin's, Victoria at DOC Reserve, Waipoua, and Hatea at Whangarei Falls) (Devane 2017). Samples collected from all sites, other than Hatea at Whangarei Falls, indicated the presence of 'naturalized' *Escherichia* at concentrations ranging from 9 to 20% of the total *E.*

coli population (Devane 2017). These data indicate that at certain freshwater sampling sites the 'naturalized' *Escherichia* may confound current water quality assessments leading to an apparent over-estimation of human health risk. However, due to the limited number of samples analysed, no definitive conclusions can be drawn about the occurrence of 'naturalized' *E. coli* or *E. coli*-like *Escherichia* species in Northland.

It is important to note that the quantitative microbial risk analysis (QMRA) method used to derive the microbial water quality guidelines in NZ includes the potential for some naturalized *E. coli* to be present in the samples (Till et al., 2008) i.e. the risk to human health was related to the generic *E. coli* concentration in the water. Therefore, if naturalized *E. coli* were naturally present in low numbers in the original water samples, then this is already accounted for in the risk assessment. No assessment of the potential presence of naturalized *E. coli* was conducted on the original samples used to derive the microbial water quality guidelines. As a result, there is no scientific justification for "discounting" *E. coli* concentrations measured in water samples using new techniques that can identify the presence of naturalized *E. coli*.

5.7 General Summary of Potential Drivers

The investigation of the potential drivers of *E. coli* concentrations in Northland rivers presents a relatively clear picture. The lack of the "hockey stick" curve in the concentration vs flow graphs, backed up by the data from sewage treatment plant discharges and low levels of human faecal source tracking markers, indicates that point discharges from sewage systems are not having a major impact on microbial water quality at the regional scale. At a locale scale, immediately downstream from a sewage discharge there will be an impact on microbial water quality and other water quality and cultural values. But at the larger regional scale the data does not indicate point sources of sewage discharge. The lack of relationship between *E. coli* concentrations and other water quality parameters, rainfall, flows and stream morphology, all point to a classic situation of diffuse sources of *E. coli* in Northland's rivers. The ruminant faecal source tracking markers and their relationship with *E. coli* concentrations and rainfall point to pastoral agriculture as a key source of diffuse pollution. Diffuse pollution is multiple small sources distributed across the landscape adding up to a large effect. This is further supported by the wide range of *E. coli* concentrations measured at most sites across Northland (Figures 2 & 4).

The key factor that could be related to the microbial water quality metrics is land use, with poorer water quality associated with intensive land use and better water quality associated with native forest. This relationship with intensive land use is consistent across the country and has been shown in previous work for Northland (Rissmann & Pearson, 2020). Because intensive land use is managed, there is the possibility to change management to reduce microbial impacts on water. A challenge with diffuse pollution is that it is generated from multiple sources and hence will require multiple actions to mitigate these sources.

6. Recommendations

6.1 Agricultural Land

6.1.1 Stream fencing

Stream fencing is aimed at keeping animals out of streams to prevent direct deposition of faecal material into the stream. The reported effectiveness of stream fencing is highly variable, ranging from zero to 96% effective (Muirhead 2019). But we can have confidence that this mitigation will improve microbial water quality when widely implemented (Muirhead 2015). Because animals can be in a stream any day of the year, this mitigation will reduce stream concentrations during base-flow conditions. This will reduce 95th percentile values at the farm-scale and should reduce 95%ile and median values at the catchment-scale (Muirhead et al. 2011; Muirhead 2015). Part of keeping animals out of streams will require the use of bridges or culverts for stream crossings. There is scientific and modelling data to support bridges or culverts as an *E. coli* mitigation option (Davies-Colley et al. 2004; Muirhead et al. 2011; Ballantine & Davies-Colley 2013; Muirhead 2015; Muirhead & Doole 2017).

Current New Zealand regulations only require the fencing of cattle, deer and pigs out of streams on flat landscapes. Given the size of the challenge of achieving the microbial water quality guidelines in Northland, implementing just the national regulations is unlikely to be enough. Fencing regulations could be considered for some sheep farmland as well. Sheep excrete high concentrations of *E. coli* in their faeces and thus even small amounts deposited into streams will have an impact (Moriarty et al. 2015: Muirhead & Doole 2017; Muirhead 2023). In some catchments it may also be appropriate to extend fencing to higher slopes.

Fencing animals out of streams will have other environmental benefits such as stream bank stabilisation reducing sediment inputs and protecting stream habitats.

6.1.2 Riparian buffer strips

Riparian buffer strips involve placing a fence a distance away from the stream bank and planting riparian plants in the space between the fence and the stream. This riparian buffer zone has two potential benefits: firstly, this prevents the deposition of animal faeces in the riparian zone that will generate a lot of runoff and, secondly, removing animal hoof pressure from the soils in this zone should increase soil infiltration rates providing the opportunity for some of the runoff from the pasture areas to be absorbed before it reaches the stream. It is important to note that, while the benefit of stream fencing occurs during base-flow conditions, the additional effect of a riparian buffer strip is through reducing runoff from the land during storm events.

While it is clear that riparian buffer strips should improve microbial water quality, the science on the effectiveness has not been quantitatively confirmed. This is due to two factors: (1) the amount of *E. coli* “removed by” the buffer zone is poorly defined, and (2) how this affects stream *E. coli* concentrations is also poorly understood. The amount of *E. coli* “removed by” the buffer zone is a combination of two factors: (1a) less *E. coli* deposited in the riparian zone means that the runoff generated in the riparian zone should have a lower concentration and (1b) infiltration of runoff generated outside the riparian zone could reduce both the volume of runoff that reaches the stream and the concentration of *E. coli* in that runoff. It is clear that antecedent soil wetness in the catchment before a rainfall event and the amount and intensity of the rainfall in an individual event will all affect how the riparian zone functions and hence the overall amount of *E. coli* "removed by" the riparian zone. Thus, the amount of *E. coli* "removed by" a riparian buffer will vary considerably from event to event.

Returning to point (2) above, we do not yet have a good understanding of the extent to which *E. coli* that enter a stream during storm flows impact on the water quality guideline metrics. i.e. do all the *E. coli* that enter a stream during runoff flow all the way to the river mouth and therefore only impact on storm flows? Or do some of the runoff *E. coli* get trapped in the stream sediments and subsequently bleed out during base-flow conditions contributing to stream median concentrations? (Wilkinson et al. 2011; Davies-Colley et al. 2008; Drummond et al. 2022; Pachepsky et al. 2017). Thus, if a riparian buffer did reduce the *E. coli* numbers in the runoff by 25%, this would not necessarily result in a 25% reduction in the microbial water quality metrics. Furthermore, if the effect of a riparian buffer only occurs during a runoff event then this mitigation option may only reduce the 95%ile values and not the median. Until these questions can be answered we cannot provide estimates on the potential effectiveness of riparian buffer strips but can only conclude that they should provide some additional benefit to reducing in-stream *E. coli* concentrations.

Riparian buffers can also provide other environmental benefits of protecting stream habitats and attenuating other nutrients (Zhang et al. 2010). There are a number of websites providing information on planting and maintaining riparian buffers and farm environment award winning farms that have demonstrated the action i.e. https://www.dairynz.co.nz/environment/on-farm-actions/waterways/;
https://niwa.co.nz/sites/niwa.co.nz/files/Riparian%20Guidelines%20WEB.pdf;
https://landcare.org.nz/wp-content/uploads/2022/05/Planting-and-Water-Systems.pdf.
https://nzfeawards.org.nz/.

6.1.3 Farm dairy effluent (FDE) management

Best practice management of FDE in New Zealand is to capture and apply FDE to land (https://www.dairynz.co.nz/publications/environment/farm-dairy-effluent-design-standards-and-code-of-practice/). This includes the use of FDE storage systems to minimise the loss of FDE from the irrigated land. Northland Regional Council should consider adopting these standards as one action that will contribute to improved microbial water quality in the region.

FDE also contains nutrients which, if discharged to streams, will add to the nutrient load in the stream. Furthermore, any nutrients discharged to a stream represents a net loss of nutrients from the farm system that will need to be replaced with purchased fertilizer.

6.2 Forested Land

Forested land typically has low *E. coli* losses and the highest microbial water quality across the country. This is also true for Northland but it should be noted from section 4.1 that not all fully forested catchments will automatically achieve "A" grade water quality. This is potentially due to wild animals, such as deer, pigs and birds in these forests. Where intensive pest management occurs to reduce pest numbers, freshwater quality is often improved (Cookson et al. 2022). Recent work by the He Waka Eke Noa process has also identified a potential carbon sequestering benefit of reducing pest pressure in forests (HWEN 2022; Davis & Meurk 2001). There could be a co-benefit for reducing *E. coli* contamination of water as a result of controlling pest numbers in forested areas.

6.3 Horticulture and Arable Land

Horticultural and arable land should have lower *E. coli* losses due to the limited amount of faeces being deposited on the land compared to that expected under livestock agriculture. It should be noted that there will still be some *E. coli* losses due to the small numbers of animals and birds that could be on this land. One potential risk for this land use is the use of organic fertilizers. Organic fertilizers often contain manures with high concentrations of *E. coli* and, coupled with the fact that that these fertilizers are often broadcast applied across large areas of land, means that there is a high risk of *E. coli* losses during runoff events (Cho et al. 2016). This also applies to the spreading of manures and solid wastes from FDE management systems or woolsheds.

Mitigation options for organic fertilizers would be understanding the *E. coli* numbers in the material, applying at times to minimise the risk of runoff events and providing a buffer of land between the application area and surface water.

6.4 Wetlands

Wetlands can be installed in the landscape to intercept drainage from any land use. There is minimal published data on the effectiveness of wetlands for mitigating *E. coli* in drainage from land, but some studies have shown *E. coli* concentrations generally decreasing through a wetland. However, outlet concentrations can remain relatively consistent indicating some microbial persistence (Hathaway et al. 2011). Wetlands can provide some buffering of both flows and contaminant concentrations; wetlands may therefore help to attenuate high concentrations of *E. coli* in runoff from the land which may help to reduce 95%ile concentrations in streams (Mulling et al. 2013). Wetlands will also provide other water quality and biodiversity benefits (Tanner & Sukias 2011; Asare et al. 2022).

6.5 Land-use Change

There is little scientific data on the transition period of landuse change on microbial water quality indicators i.e. we don't know how long it will take for changes in land use to be seen in water quality records. However, in the long-term it is probably safe to say that the effect will be equivalent to the differences seen between these land uses now (see section 5.4). There is evidence that retiring land from pastoral agriculture to forestry can reduce *E. coli* concentrations in streams (Donnison et al. 2004). It is also logical that landuse change away from intensive livestock agriculture will be more effective than applying mitigations to intensive land-use.

6.6 Sewage – Wastewater Treatment Plants

Wastewater treatment plants that treat sewage from urban areas can discharge the treated wastewater to surface waters and there are a number of these systems in Northland. The data from the RWQMN sites do not indicate that these discharges are having an impact at the broad regional scale. However, these discharges can have an impact at the local scale and it is recommended that NRC identify and respond to these impacts at the local scale as appropriate.

7. Acknowledgements

Thanks to Northland Regional Council for providing the data used in this analysis. Thanks to NRC staff of Jean-Charles Perquin for initial discussions and setting up this project and to Manas Chakraborty and Richard Griffith for feedback and comments to help put this work into the context of Northland. Thanks to Manas Chakraborty for producing the maps. Thanks to Timothy Bilton for help with the R coding and statistical analysis and Karren O'Neill for help with ArcGIS and spatial analysis.

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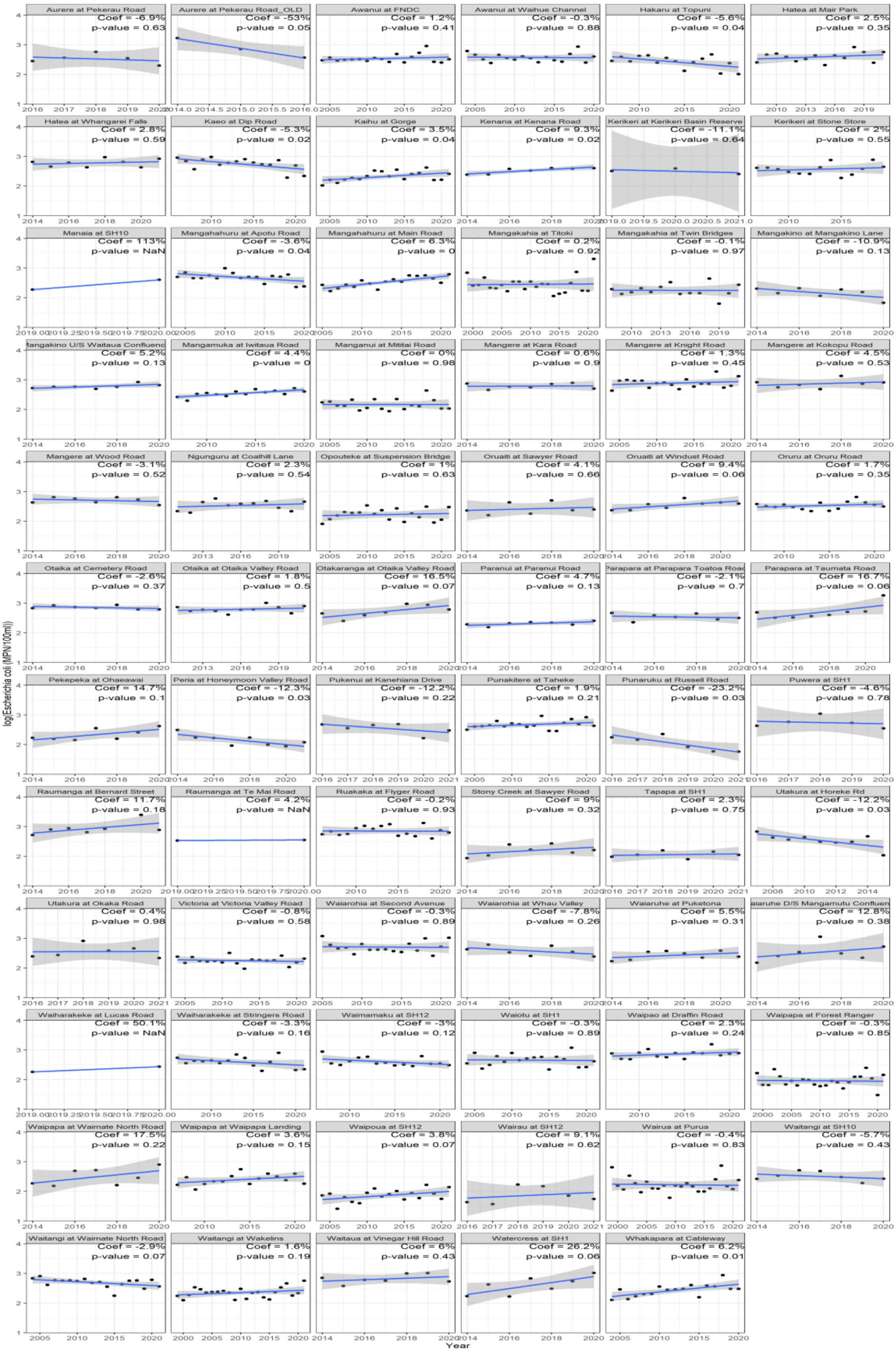
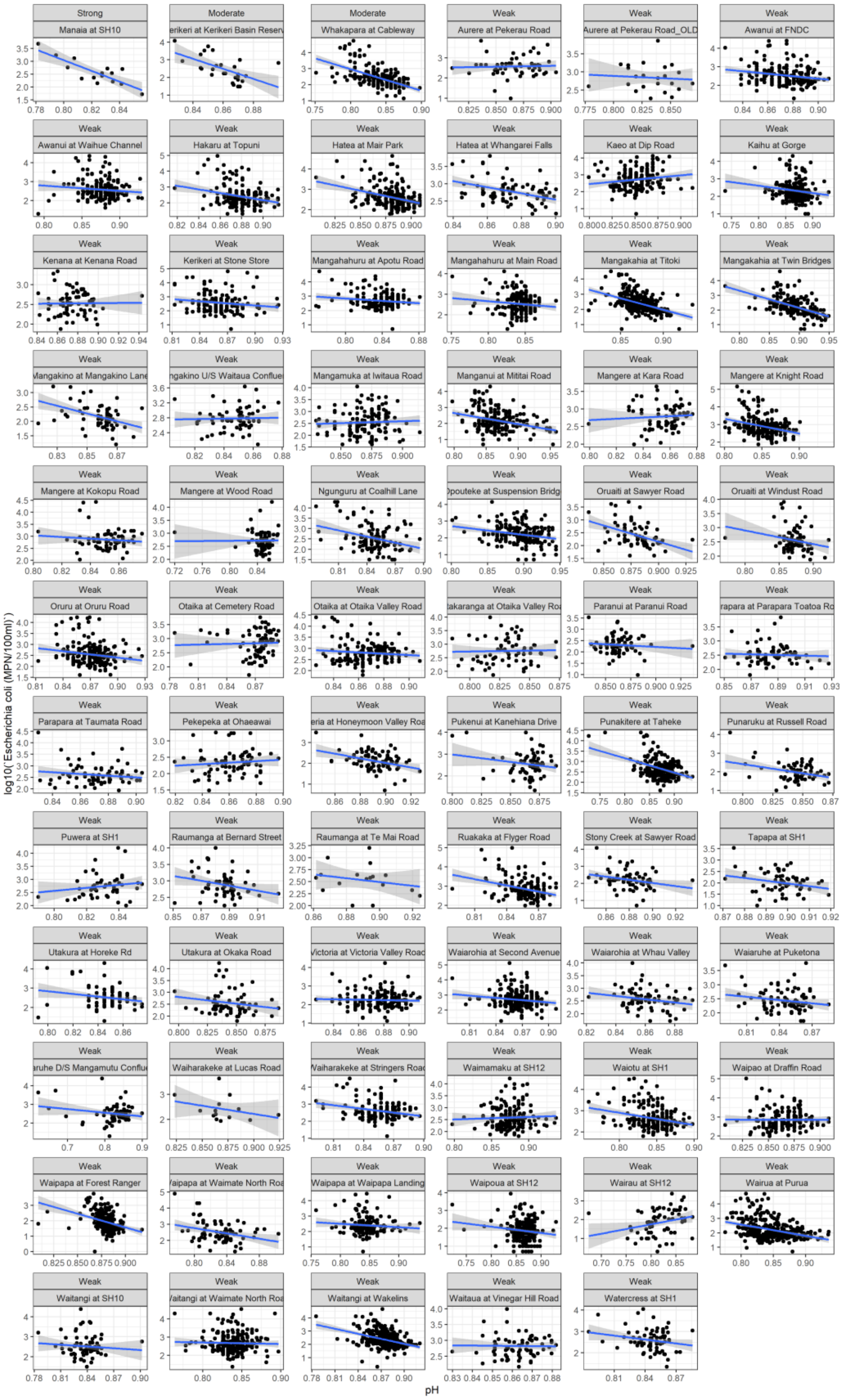
Appendices

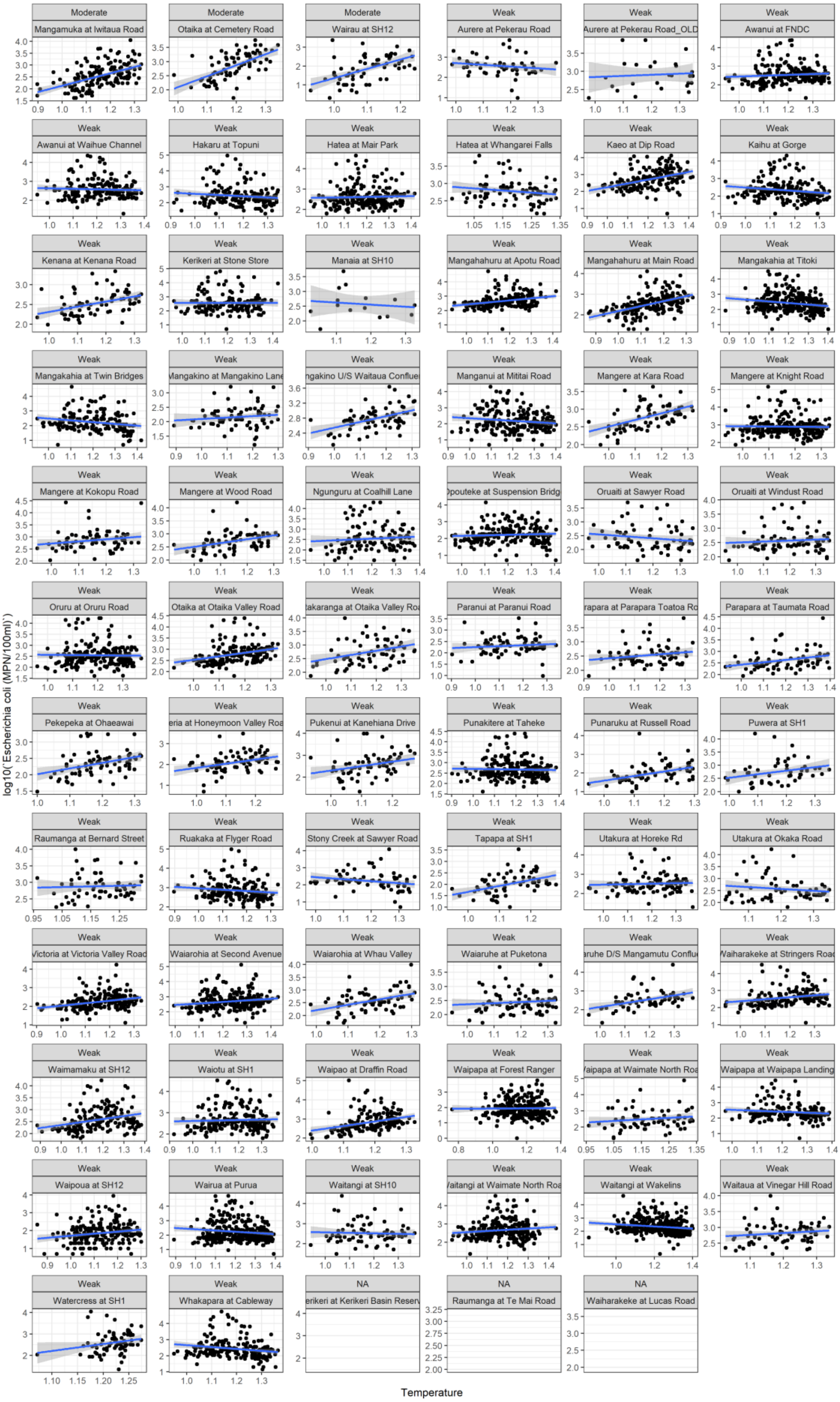
Note – Many of the figures presented in these appendices have so much information they are difficult to read on an A4 page. All of these figures have been provided to NRC in an email so that they can be printed on a larger page or zoomed in on a screen for better clarity.

Appendix 1: Long-term trend analysis for the river water quality sites in Northland. The blue line is the trend line and the grey areas the 95% confidence interval of the trend.

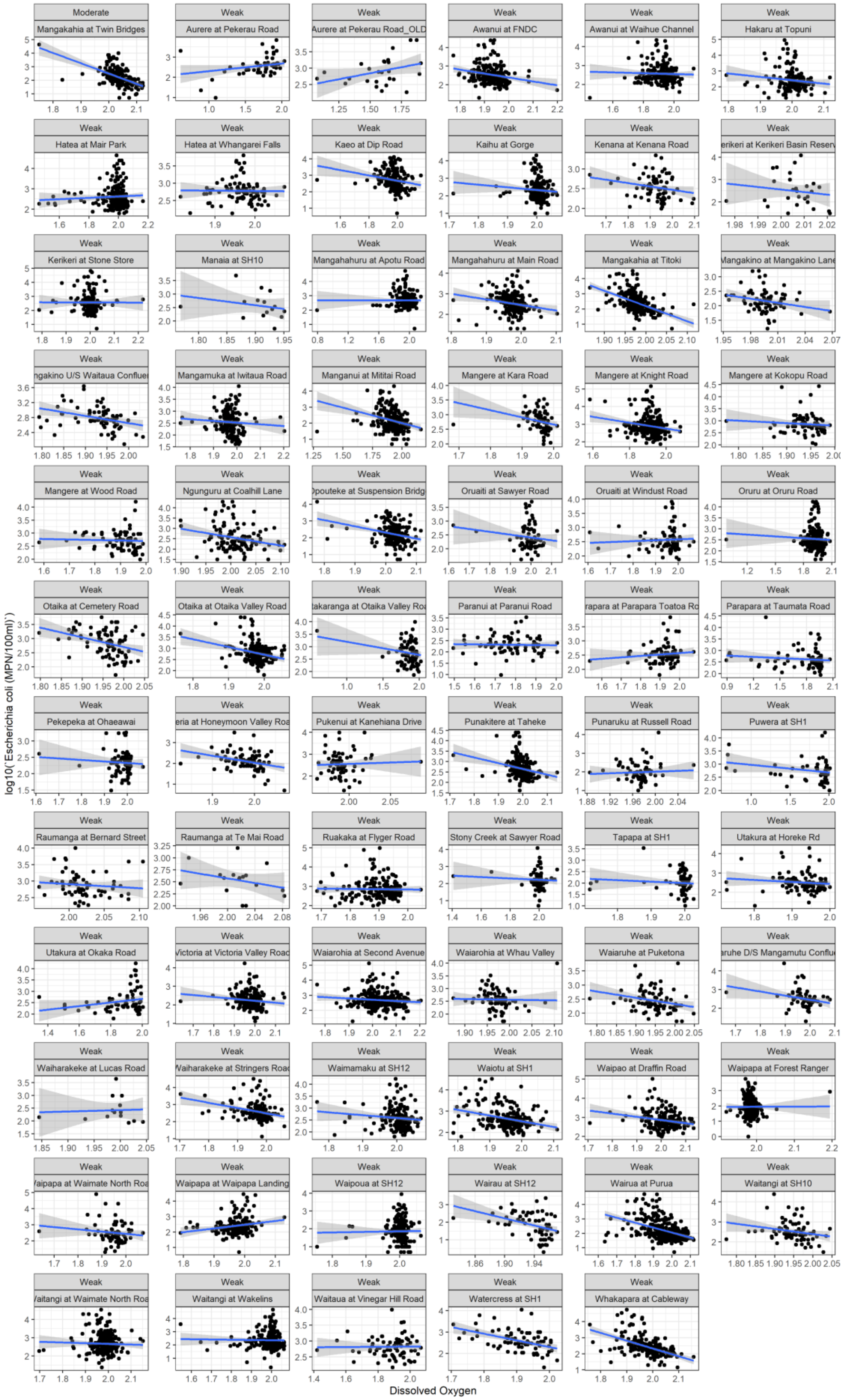


Appendix 2: Correlation graphs for each site between the Log_{10} *E. coli* 100 mL^{-1} and other water quality parameters (pH, temperature, dissolved oxygen, dissolved reactive phosphorus, total phosphorus, ammoniacal nitrogen, total nitrogen, total suspended solids, black disc and turbidity).





Moderate
Mangamuka at Iwitaua Road
Moderate
Otaika at Cemetery Road
Moderate
Wairau at SH12
Weak
Aurere at Pekerau Road
Weak
Aurere at Pekerau Road_OLD
Weak
Awanui at FNDC
Weak
Awanui at Waihue Channel
Weak
Hakaru at Topuni
Weak
Hatea at Mair Park
Weak
Hatea at Whangarei Falls
Weak
Kaeo at Dip Road
Weak
Kaihu at Gorge
Weak
Kenana at Kenana Road
Weak
Kerikeri at Stone Store
Weak
Manaia at SH10
Weak
Mangahahuru at Apotu Road
Weak
Mangahahuru at Main Road
Weak
Mangakahia at Titoki
Weak
Mangakahia at Twin Bridges
Weak
langakino at Mangakino Lane
Weak
ngakino U/S Waitaua Conflue
Weak
Manganui at Mititai Road
Weak
Mangere at Kara Road
Weak
Mangere at Knight Road
Weak
Mangere at Kokopu Road
Weak
Mangere at Wood Road
Weak
Ngunguru at Coalhill Lane
Weak
)pouteke at Suspension Bridg
Weak
Oruaiti at Sawyer Road
Weak
Oruaiti at Windust Road
Weak
Oruru at Oruru Road
Weak
Otaika at Otaika Valley Road
Weak
takaranga at Otaika Valley Ro
Weak
Paranui at Paranui Road
Weak
rapara at Parapara Toatoa Ro
Weak
Parapara at Taumata Road
Weak
Pekepeka at Ohaeawai
Weak
eria at Honeymoon Valley Roa
Weak
Pukenui at Kanehiana Drive
Weak
Punakitere at Taheke
Weak
Punaruku at Russell Road
Weak
Puwera at SH1
Weak
Raumanga at Bernard Street
Weak
Ruakaka at Flyger Road
Weak
Stony Creek at Sawyer Road
Weak
Tapapa at SH1
Weak
Utakura at Horeke Rd
Weak
Utakura at Okaka Road
Weak
Victoria at Victoria Valley Road
Weak
Waiarohia at Second Avenue
Weak
Waiarohia at Whau Valley
Weak
Waiaruhe at Puketona
Weak
aruhe D/S Mangamutu Conflu
Weak
Vaiharakeke at Stringers Road
Weak
Waimamaku at SH12
Weak
Waiotu at SH1
Weak
Waipao at Draffin Road
Weak
Waipapa at Forest Ranger
Weak
/aipapa at Waimate North Roa
Weak
Waipapa at Waipapa Landing
Weak
Waipoua at SH12
Weak
Wairua at Purua
Weak
Waitangi at SH10
Weak
/aitangi at Waimate North Roa
Weak
Waitangi at Wakelins
Weak
Waitaua at Vinegar Hill Road
Weak
Watercress at SH1
Weak
Whakapara at Cableway
NA
erikeri at Kerikeri Basin Reserv
NA
Raumanga at Te Mai Road
NA
Waiharakeke at Lucas Road
log10(`Escherichia coli (MPN/100ml)`)
Temperature


log10(`Escherichia coli (MPN/100ml)`)
Dissolved Oxygen
Moderate
Mangakahia at Twin Bridges
Weak
Aurere at Pekerau Road
Aurere at Pekerau Road_OLD
Awanui at FNDC
Awanui at Waihue Channel
Hakaru at Topuni
Hatea at Mair Park
Hatea at Whangarei Falls
Kaeo at Dip Road
Kaihu at Gorge
Kenana at Kenana Road
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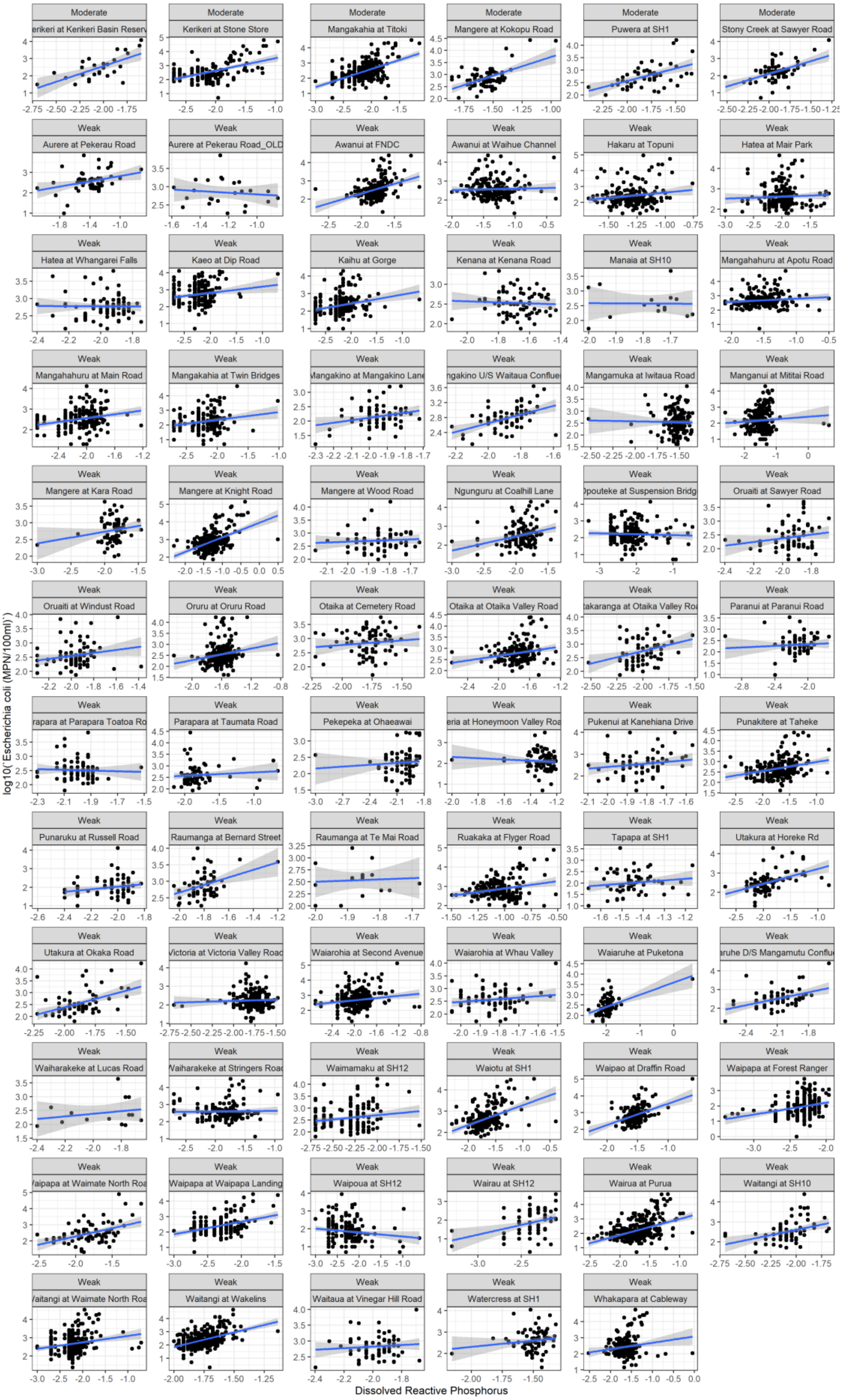
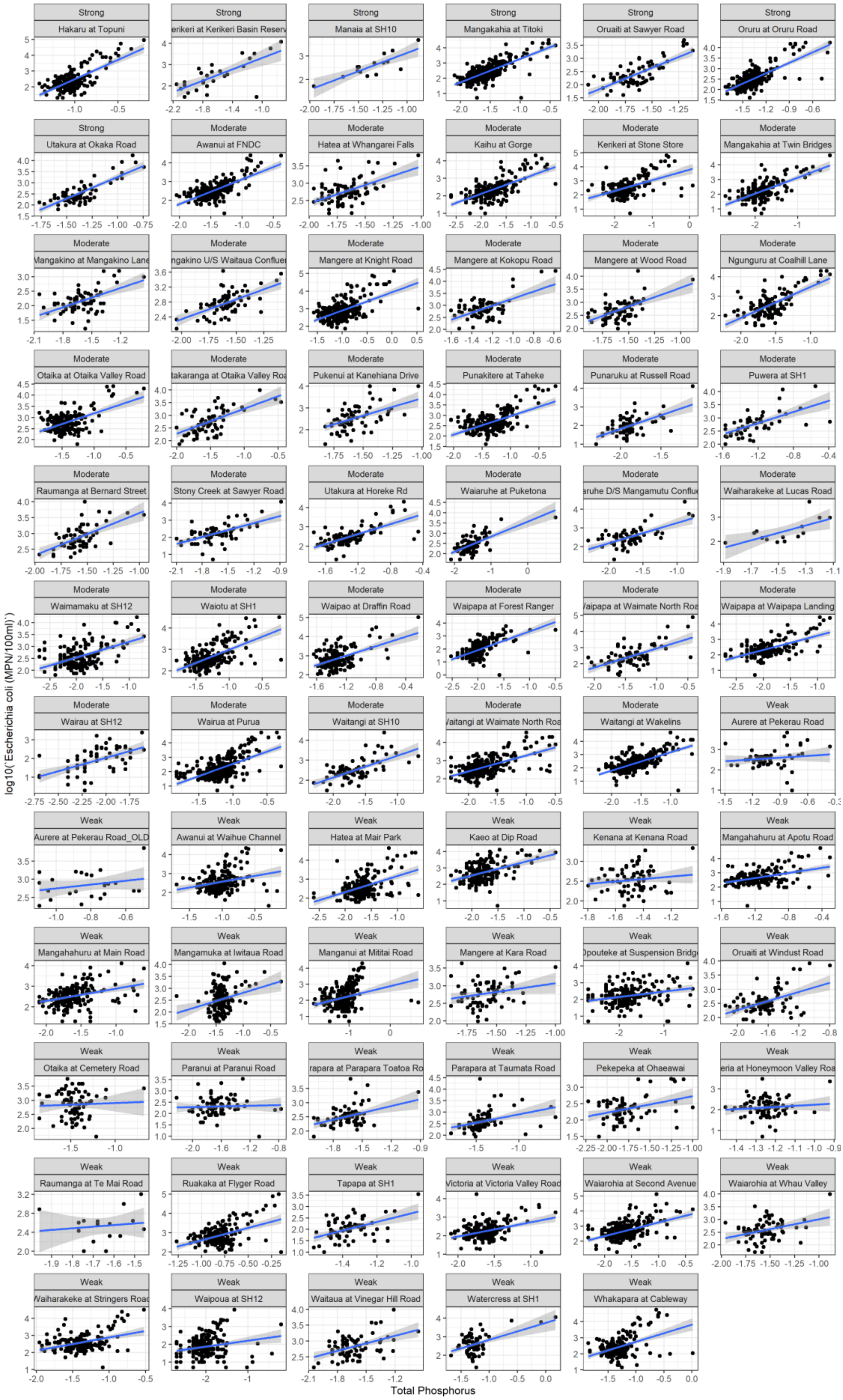
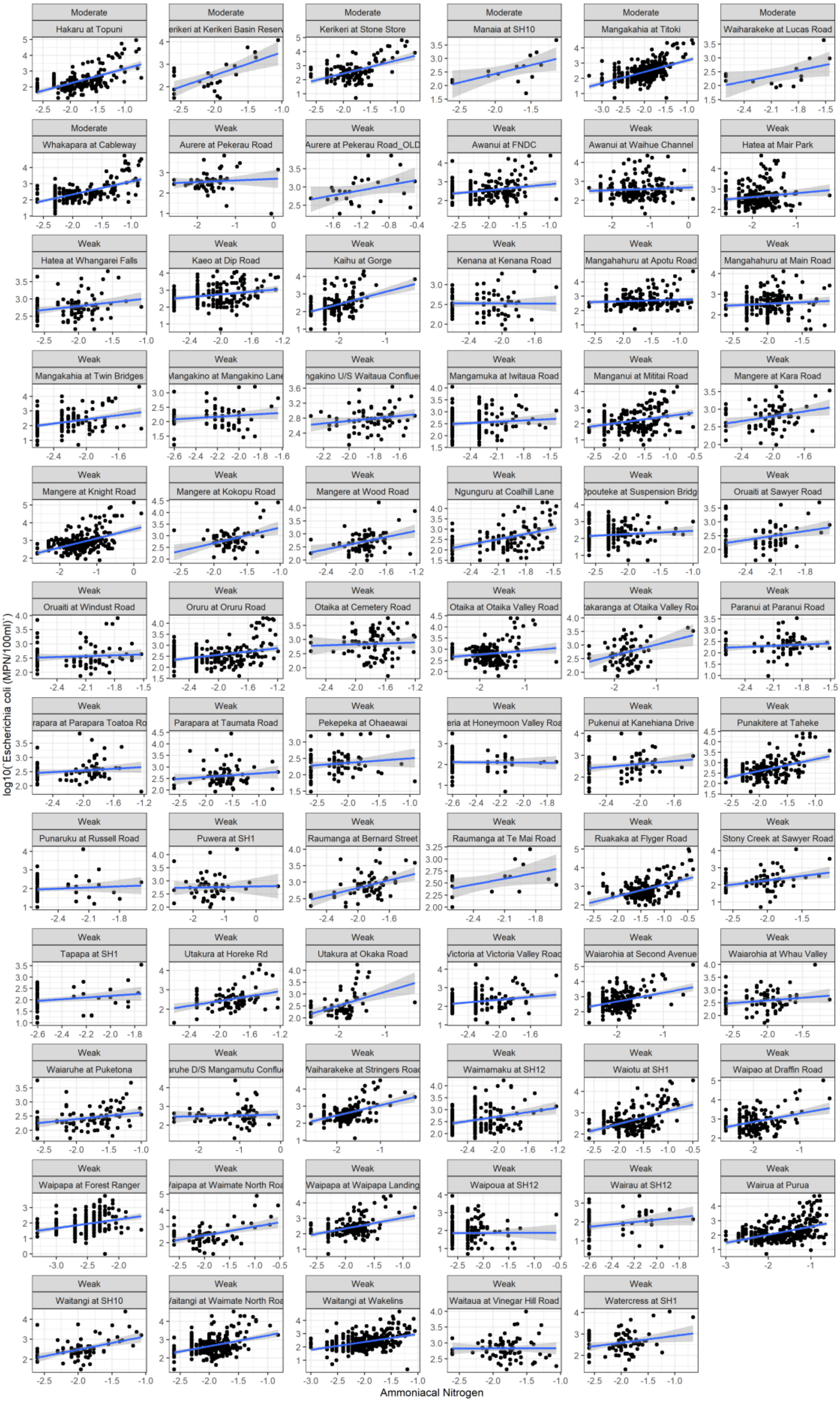
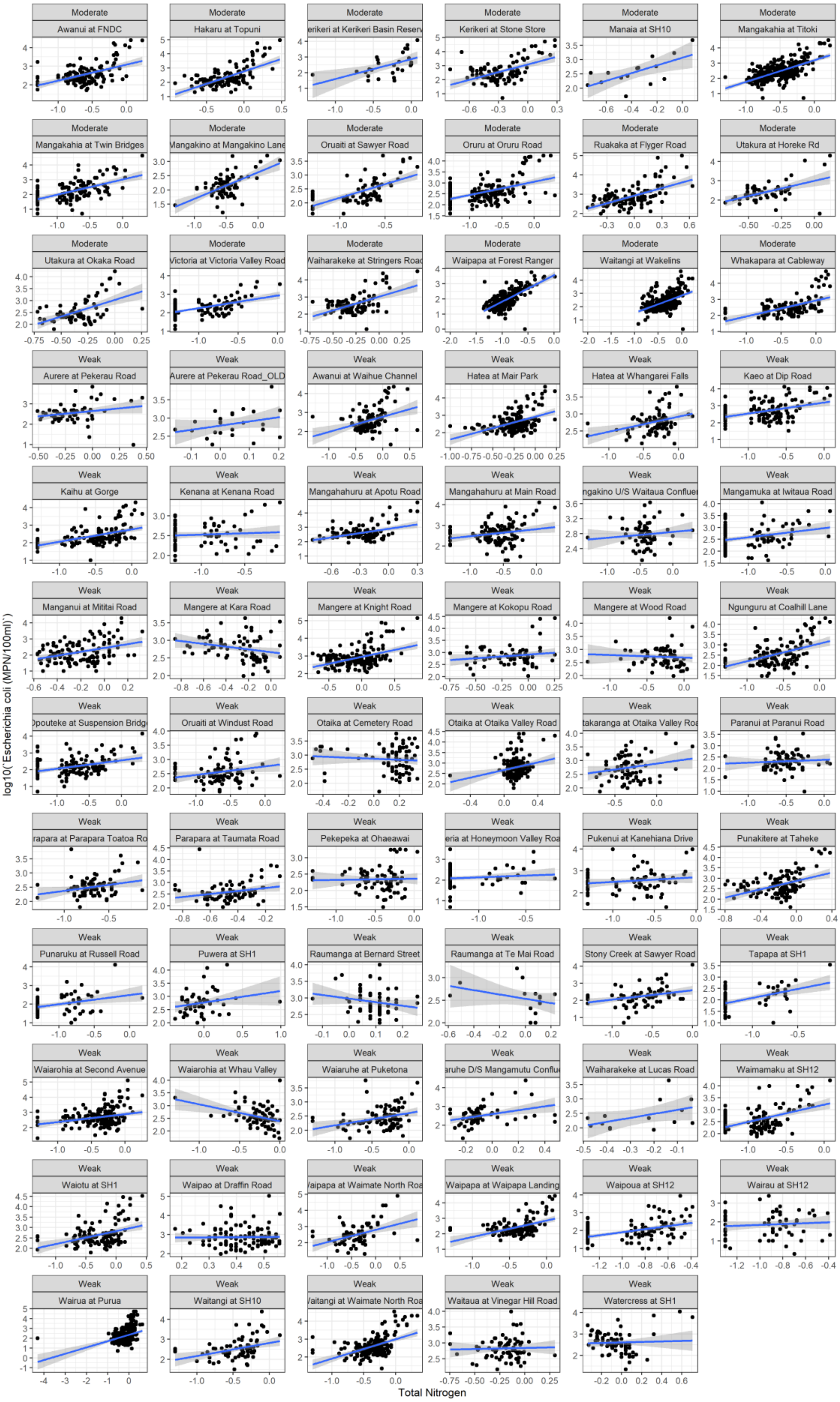
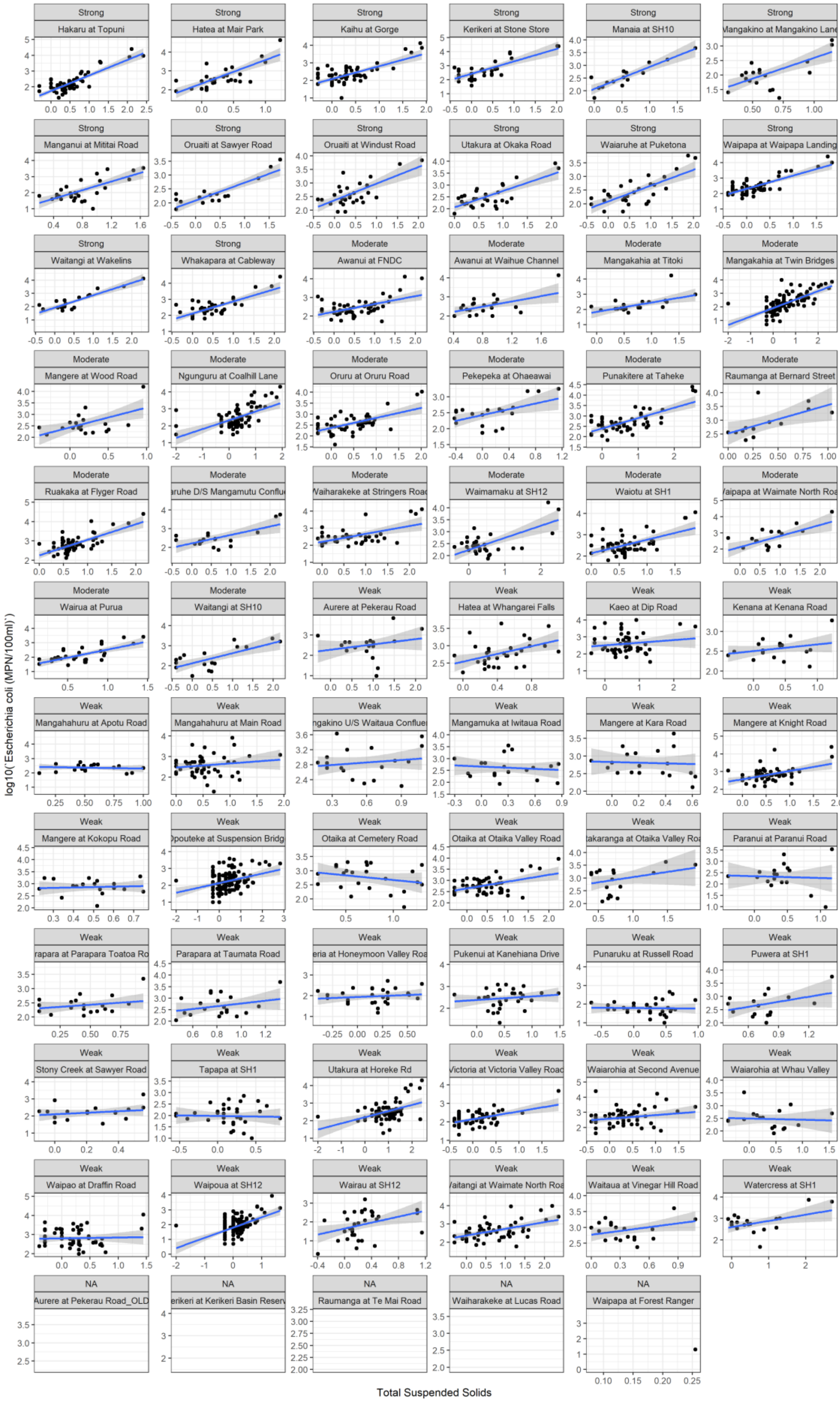
Manaia at SH10
Mangahahuru at Apotu Road
Mangahahuru at Main Road
Mangakahia at Titoki
Mangakino at Mangakino Lane
ngakino U/S Waitaua Conflue
Mangamuka at Iwitaua Road
Manganui at Mititai Road
Mangere at Kara Road
Mangere at Knight Road
Mangere at Kokopu Road
Mangere at Wood Road
Ngunguru at Coalhill Lane
Opouteke at Suspension Bridg
Oruaiti at Sawyer Road
Oruaiti at Windust Road
Oruru at Oruru Road
Otaika at Cemetery Road
Otaika at Otaika Valley Road
takaranga at Otaika Valley Ro
Paranui at Paranui Road
rapara at Parapara Toatoa Ro
Parapara at Taumata Road
Pekepeka at Ohaeawai
eria at Honeymoon Valley Ro
Pukenui at Kanehiana Drive
Punakitere at Taheke
Punaruku at Russell Road
Puwera at SH1
Raumanga at Bernard Street
Raumanga at Te Mai Road
Ruakaka at Flyger Road
Stony Creek at Sawyer Road
Tapapa at SH1
Utakura at Horeke Rd
Utakura at Okaka Road
Victoria at Victoria Valley Road
Waiarohia at Second Avenue
Waiarohia at Whau Valley
Waiaruhe at Puketona
aruhe D/S Mangamutu Conflu
Waiharakeke at Lucas Road
Vaiharakeke at Stringers Roa
Waimamaku at SH12
Waiotu at SH1
Waipao at Draffin Road
Waipapa at Forest Ranger
aipapa at Waimate North Ro
Waipapa at Waipapa Landing
Waipoua at SH12
Wairau at SH12
Wairua at Purua
Waitangi at SH10
aitangi at Waimate North Roa
Waitangi at Wakelins
Waitaua at Vinegar Hill Road
Watercress at SH1
Whakapara at Cableway


Moderate
erikeri at Kerikeri Basin Reserv
Moderate
Kerikeri at Stone Store
Moderate
Mangakahia at Titoki
Moderate
Mangere at Kokopu Road
Moderate
Puwera at SH1
Moderate
Stony Creek at Sawyer Road
Weak
Aurere at Pekerau Road
Weak
Aurere at Pekerau Road_OLD
Weak
Awanui at FNDC
Weak
Awanui at Waihue Channel
Weak
Hakaru at Topuni
Weak
Hatea at Mair Park
Weak
Hatea at Whangarei Falls
Weak
Kaeo at Dip Road
Weak
Kaihu at Gorge
Weak
Kenana at Kenana Road
Weak
Manaia at SH10
Weak
Mangahahuru at Apotu Road
Weak
Mangahahuru at Main Road
Weak
Mangakahia at Twin Bridges
Weak
langakino at Mangakino Lane
Weak
ngakino U/S Waitaua Confluen
Weak
Mangamuka at Iwitaua Road
Weak
Manganui at Mititai Road
Weak
Mangere at Kara Road
Weak
Mangere at Knight Road
Weak
Mangere at Wood Road
Weak
Ngunguru at Coalhill Lane
Weak
pouteke at Suspension Bridg
Weak
Oruaiti at Sawyer Road
Weak
Oruaiti at Windust Road
Weak
Oruru at Oruru Road
Weak
Otaika at Cemetery Road
Weak
Otaika at Otaika Valley Road
Weak
akaranga at Otaika Valley Roa
Weak
Paranui at Paranui Road
Weak
rapara at Parapara Toatoa Ro
Weak
Parapara at Taumata Road
Weak
Pekepeka at Ohaeawai
Weak
eria at Honeymoon Valley Roa
Weak
Pukenui at Kanehiana Drive
Weak
Punakitere at Taheke
Weak
Punaruku at Russell Road
Weak
Raumanga at Bernard Street
Weak
Raumanga at Te Mai Road
Weak
Ruakaka at Flyger Road
Weak
Tapapa at SH1
Weak
Utakura at Horeke Rd
Weak
Utakura at Okaka Road
Weak
Victoria at Victoria Valley Road
Weak
Waiarohia at Second Avenue
Weak
Waiarohia at Whau Valley
Weak
Waiaruhe at Puketona
Weak
aruhe D/S Mangamutu Conflu
Weak
Waiharakeke at Lucas Road
Weak
Vaiharakeke at Stringers Road
Weak
Waimamaku at SH12
Weak
Waiotu at SH1
Weak
Waipao at Draffin Road
Weak
Waipapa at Forest Ranger
Weak
aipapa at Waimate North Roa
Weak
Waipapa at Waipapa Landing
Weak
Waipoua at SH12
Weak
Wairau at SH12
Weak
Wairua at Purua
Weak
Waitangi at SH10
Weak
aitangi at Waimate North Roa
Weak
Waitangi at Wakelins
Weak
Waitaua at Vinegar Hill Road
Weak
Watercress at SH1
Weak
Whakapara at Cableway
log10(`Escherichia coli (MPN/100ml)`)
Dissolved Reactive Phosphorus

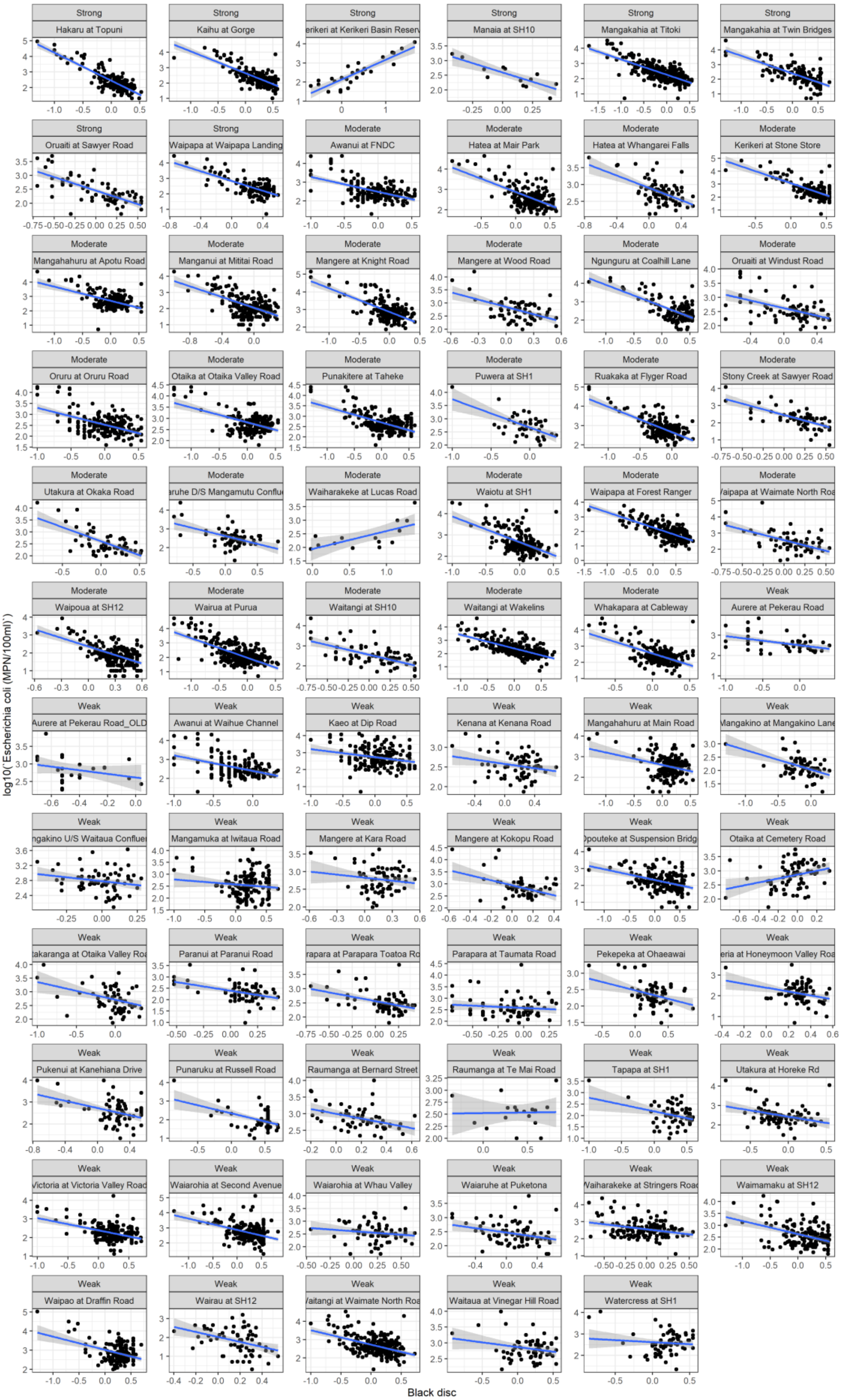

Strong
Hakaru at Topuni
Strong
erikeri at Kerikeri Basin Reserv
Strong
Manaia at SH10
Strong
Mangakahia at Titoki
Strong
Oruaiti at Sawyer Road
Strong
Oruru at Oruru Road
Strong
Utakura at Okaka Road
Moderate
Awanui at FNDC
Moderate
Hatea at Whangarei Falls
Moderate
Kaihu at Gorge
Moderate
Kerikeri at Stone Store
Moderate
Mangakahia at Twin Bridges
Moderate
Mangakino at Mangakino Lane
Moderate
ngakino U/S Waitaua Confluer
Moderate
Mangere at Knight Road
Moderate
Mangere at Kokopu Road
Moderate
Mangere at Wood Road
Moderate
Ngunguru at Coalhill Lane
Moderate
Otaika at Otaika Valley Road
Moderate
takaranga at Otaika Valley Roa
Moderate
Pukenui at Kanehiana Drive
Moderate
Punakitere at Taheke
Moderate
Punaruku at Russell Road
Moderate
Puwera at SH1
Moderate
Raumanga at Bernard Street
Moderate
Stony Creek at Sawyer Road
Moderate
Utakura at Horeke Rd
Moderate
Waiaruhe at Puketona
Moderate
aruhe D/S Mangamutu Conflue
Moderate
Waiharakeke at Lucas Road
Moderate
Waimamaku at SH12
Moderate
Waiotu at SH1
Moderate
Waipao at Draffin Road
Moderate
Waipapa at Forest Ranger
Moderate
aipapa at Waimate North Roa
Moderate
Waipapa at Waipapa Landing
Moderate
Wairau at SH12
Moderate
Wairua at Purua
Moderate
Waitangi at SH10
Moderate
aitangi at Waimate North Roa
Moderate
Waitangi at Wakelins
Weak
Aurere at Pekerau Road
Weak
Aurere at Pekerau Road_OLD
Weak
Awanui at Waihue Channel
Weak
Hatea at Mair Park
Weak
Kaeo at Dip Road
Weak
Kenana at Kenana Road
Weak
Mangahahuru at Apotu Road
Weak
Mangahahuru at Main Road
Weak
Mangamuka at Iwitaua Road
Weak
Manganui at Mititai Road
Weak
Mangere at Kara Road
Weak
Opouteke at Suspension Bridg
Weak
Oruaiti at Windust Road
Weak
Otaika at Cemetery Road
Weak
Paranui at Paranui Road
Weak
rapara at Parapara Toatoa Ro
Weak
Parapara at Taumata Road
Weak
Pekepeka at Ohaeawai
Weak
eria at Honeymoon Valley Roa
Weak
Raumanga at Te Mai Road
Weak
Ruakaka at Flyger Road
Weak
Tapapa at SH1
Weak
Victoria at Victoria Valley Road
Weak
Waiarohia at Second Avenue
Weak
Waiarohia at Whau Valley
Weak
Vaiharakeke at Stringers Road
Weak
Waipoua at SH12
Weak
Waitaua at Vinegar Hill Road
Weak
Watercress at SH1
Weak
Whakapara at Cableway
log10(`Escherichia coli (MPN/100ml)`)
Total Phosphorus

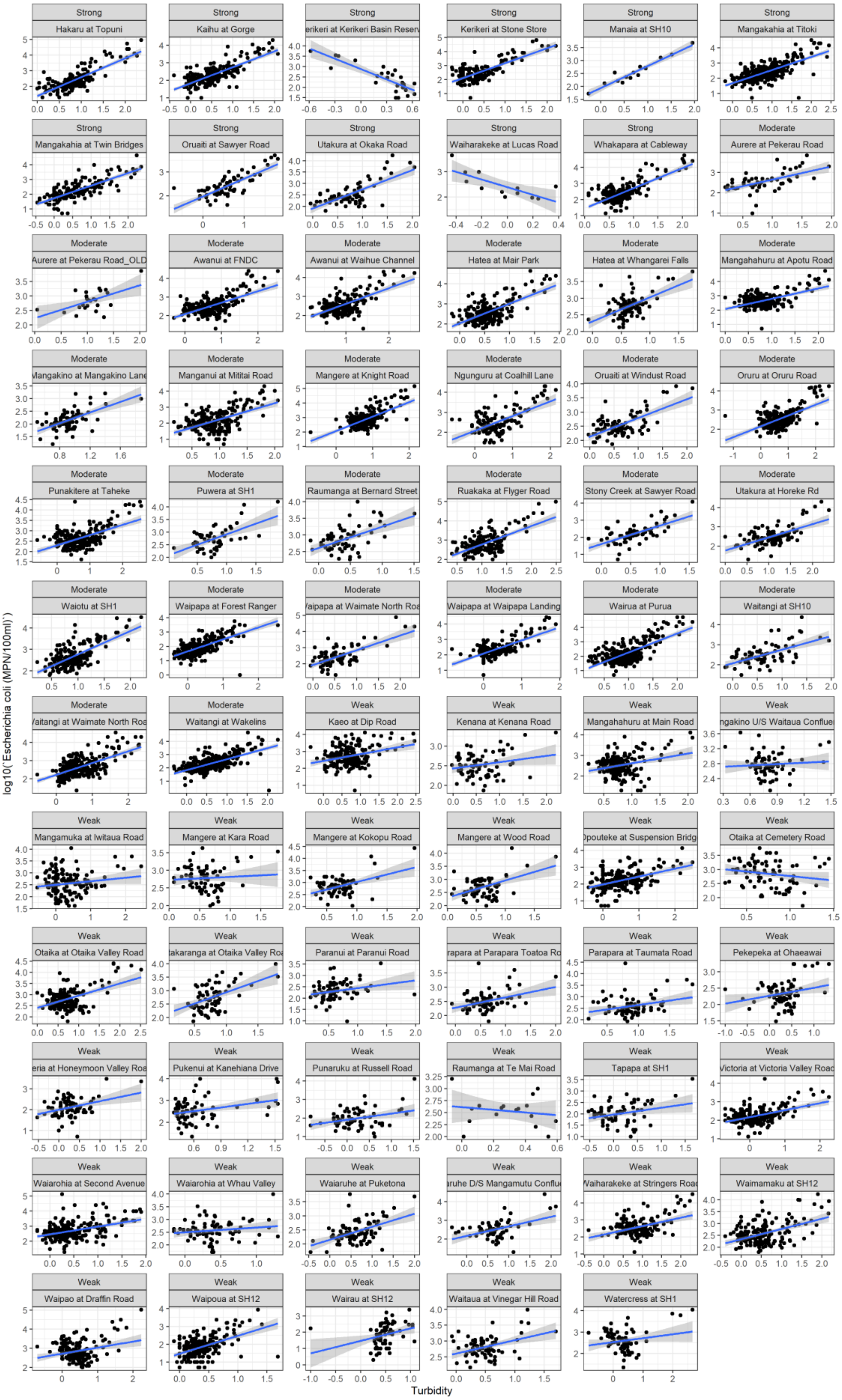

Moderate
Hakaru at Topuni
Moderate
erikeri at Kerikeri Basin Reser
Moderate
Kerikeri at Stone Store
Moderate
Manaia at SH10
Moderate
Mangakahia at Titoki
Moderate
Waiharakeke at Lucas Road
Moderate
Whakapara at Cableway
Weak
Aurere at Pekerau Road
Weak
Aurere at Pekerau Road_OLD
Weak
Awanui at FNDC
Weak
Awanui at Waihue Channel
Weak
Hatea at Mair Park
Weak
Hatea at Whangarei Falls
Weak
Kaeo at Dip Road
Weak
Kaihu at Gorge
Weak
Kenana at Kenana Road
Weak
Mangahahuru at Apotu Road
Weak
Mangahahuru at Main Road
Weak
Mangakahia at Twin Bridges
Weak
langakino at Mangakino Lane
Weak
ngakino U/S Waitaua Confluer
Weak
Mangamuka at Iwitaua Road
Weak
Manganui at Mititai Road
Weak
Mangere at Kara Road
Weak
Mangere at Knight Road
Weak
Mangere at Kokopu Road
Weak
Mangere at Wood Road
Weak
Ngunguru at Coalhill Lane
Weak
)pouteke at Suspension Bridg
Weak
Oruaiti at Sawyer Road
Weak
Oruaiti at Windust Road
Weak
Oruru at Oruru Road
Weak
Otaika at Cemetery Road
Weak
Otaika at Otaika Valley Road
Weak
akaranga at Otaika Valley Roa
Weak
Paranui at Paranui Road
Weak
rapara at Parapara Toatoa Ro
Weak
Parapara at Taumata Road
Weak
Pekepeka at Ohaeawai
Weak
eria at Honeymoon Valley Roa
Weak
Pukenui at Kanehiana Drive
Weak
Punakitere at Taheke
Weak
Punaruku at Russell Road
Weak
Puwera at SH1
Weak
Raumanga at Bernard Street
Weak
Raumanga at Te Mai Road
Weak
Ruakaka at Flyger Road
Weak
Stony Creek at Sawyer Road
Weak
Tapapa at SH1
Weak
Utakura at Horeke Rd
Weak
Utakura at Okaka Road
Weak
Victoria at Victoria Valley Road
Weak
Waiarohia at Second Avenue
Weak
Waiarohia at Whau Valley
Weak
Waiaruhe at Puketona
Weak
aruhe D/S Mangamutu Conflu
Weak
Vaiharakeke at Stringers Road
Weak
Waimamaku at SH12
Weak
Waiotu at SH1
Weak
Waipao at Draffin Road
Weak
Waipapa at Forest Ranger
Weak
/aipapa at Waimate North Roa
Weak
Waipapa at Waipapa Landing
Weak
Waipoua at SH12
Weak
Wairau at SH12
Weak
Wairua at Purua
Weak
Waitangi at SH10
Weak
/aitangi at Waimate North Roa
Weak
Waitangi at Wakelins
Weak
Waitaua at Vinegar Hill Road
Weak
Watercress at SH1
log10(`Escherichia coli (MPN/100ml)`)
Ammoniacal Nitrogen


Moderate
Awanui at FNDC
Moderate
Hakaru at Topuni
Moderate
erikeri at Kerikeri Basin Reserv
Moderate
Kerikeri at Stone Store
Moderate
Manaia at SH10
Moderate
Mangakahia at Titoki
Moderate
Mangakahia at Twin Bridges
Moderate
Mangakino at Mangakino Lane
Moderate
Oruaiti at Sawyer Road
Moderate
Oruru at Oruru Road
Moderate
Ruakaka at Flyger Road
Moderate
Utakura at Horeke Rd
Moderate
Utakura at Okaka Road
Moderate
Victoria at Victoria Valley Road
Moderate
Vaiharakeke at Stringers Road
Moderate
Waipapa at Forest Ranger
Moderate
Waitangi at Wakelins
Moderate
Whakapara at Cableway
Weak
Aurere at Pekerau Road
Weak
Aurere at Pekerau Road_OLD
Weak
Awanui at Waihue Channel
Weak
Hatea at Mair Park
Weak
Hatea at Whangarei Falls
Weak
Kaeo at Dip Road
Weak
Kaihu at Gorge
Weak
Kenana at Kenana Road
Weak
Mangahahuru at Apotu Road
Weak
Mangahahuru at Main Road
Weak
ngakino U/S Waitaua Confluer
Weak
Mangamuka at Iwitaua Road
Weak
Manganui at Mititai Road
Weak
Mangere at Kara Road
Weak
Mangere at Knight Road
Weak
Mangere at Kokopu Road
Weak
Mangere at Wood Road
Weak
Ngunguru at Coalhill Lane
Weak
)pouteke at Suspension Bridge
Weak
Oruaiti at Windust Road
Weak
Otaika at Cemetery Road
Weak
Otaika at Otaika Valley Road
Weak
takaranga at Otaika Valley Roa
Weak
Paranui at Paranui Road
Weak
rapara at Parapara Toatoa Ro
Weak
Parapara at Taumata Road
Weak
Pekepeka at Ohaeawai
Weak
eria at Honeymoon Valley Roa
Weak
Pukenui at Kanehiana Drive
Weak
Punakitere at Taheke
Weak
Punaruku at Russell Road
Weak
Puwera at SH1
Weak
Raumanga at Bernard Street
Weak
Raumanga at Te Mai Road
Weak
Stony Creek at Sawyer Road
Weak
Tapapa at SH1
Weak
Waiarohia at Second Avenue
Weak
Waiarohia at Whau Valley
Weak
Waiaruhe at Puketona
Weak
aruhe D/S Mangamutu Confluer
Weak
Waiharakeke at Lucas Road
Weak
Waimamaku at SH12
Weak
Waiotu at SH1
Weak
Waipao at Draffin Road
Weak
aipapa at Waimate North Roa
Weak
Waipapa at Waipapa Landing
Weak
Waipoua at SH12
Weak
Wairau at SH12
Weak
Wairua at Purua
Weak
Waitangi at SH10
Weak
aitangi at Waimate North Roa
Weak
Waitaua at Vinegar Hill Road
Weak
Watercress at SH1
log10(`Escherichia coli (MPN/100ml)`)
Total Nitrogen



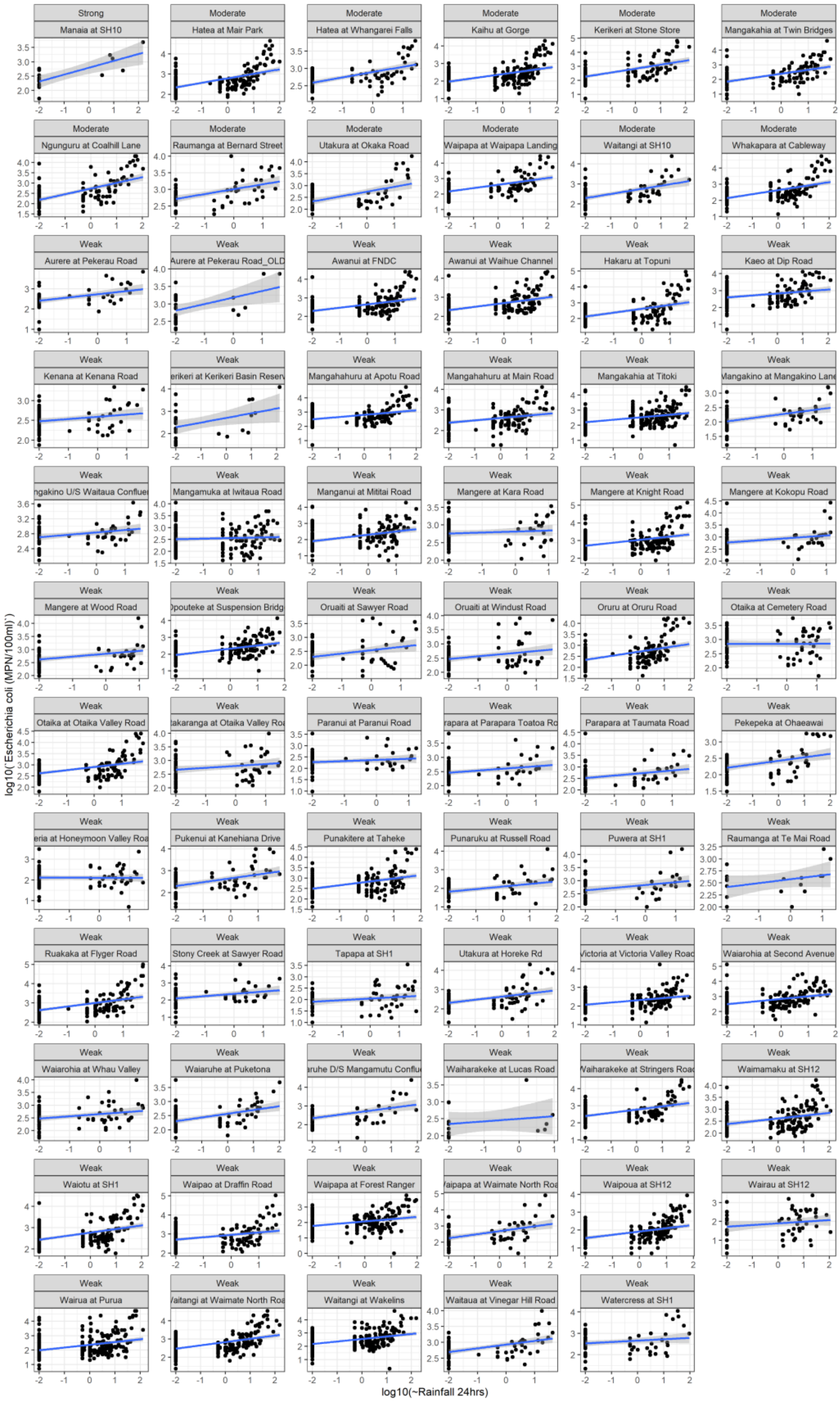
Strong
Hakaru at Topuni
Strong
Hatea at Mair Park
Strong
Kaihu at Gorge
Strong
Kerikeri at Stone Store
Strong
Manaia at SH10
Strong
Mangakino at Mangakino Lan
Strong
Manganui at Mititai Road
Strong
Oruaiti at Sawyer Road
Strong
Oruaiti at Windust Road
Strong
Utakura at Okaka Road
Strong
Waiaruhe at Puketona
Strong
Waipapa at Waipapa Landing
Strong
Waitangi at Wakelins
Strong
Whakapara at Cableway
Moderate
Awanui at FNDC
Moderate
Awanui at Waihue Channel
Moderate
Mangakahia at Titoki
Moderate
Mangakahia at Twin Bridges
Moderate
Mangere at Wood Road
Moderate
Ngunguru at Coalhill Lane
Moderate
Oruru at Oruru Road
Moderate
Pekepeka at Ohaeawai
Moderate
Punakitere at Taheke
Moderate
Raumanga at Bernard Street
Moderate
Ruakaka at Flyger Road
Moderate
aruhe D/S Mangamutu Conflu
Moderate
Vaiharakeke at Stringers Roac
Moderate
Waimamaku at SH12
Moderate
Waiotu at SH1
Moderate
/aipapa at Waimate North Roa
Moderate
Wairua at Purua
Moderate
Waitangi at SH10
Weak
Aurere at Pekerau Road
Weak
Hatea at Whangarei Falls
Weak
Kaeo at Dip Road
Weak
Kenana at Kenana Road
Weak
Mangahahuru at Apotu Road
Weak
Mangahahuru at Main Road
Weak
ngakino U/S Waitaua Conflue
Weak
Mangamuka at Iwitaua Road
Weak
Mangere at Kara Road
Weak
Mangere at Knight Road
Weak
Mangere at Kokopu Road
Weak
Opouteke at Suspension Bridg
Weak
Otaika at Cemetery Road
Weak
Otaika at Otaika Valley Road
Weak
akaranga at Otaika Valley Ro
Weak
Paranui at Paranui Road
Weak
rapara at Parapara Toatoa Ro
Weak
Parapara at Taumata Road
Weak
eria at Honeymoon Valley Roa
Weak
Pukenui at Kanehiana Drive
Weak
Punaruku at Russell Road
Weak
Puwera at SH1
Weak
Stony Creek at Sawyer Road
Weak
Tapapa at SH1
Weak
Utakura at Horeke Rd
Weak
Victoria at Victoria Valley Road
Weak
Waiarohia at Second Avenue
Weak
Waiarohia at Whau Valley
Weak
Waipao at Draffin Road
Weak
Waipoua at SH12
Weak
Wairau at SH12
Weak
/aitangi at Waimate North Roa
Weak
Waitaua at Vinegar Hill Road
Weak
Watercress at SH1
NA
Aurere at Pekerau Road_OLD
NA
erikeri at Kerikeri Basin Reser
NA
Raumanga at Te Mai Road
NA
Waiharakeke at Lucas Road
NA
Waipapa at Forest Ranger
log10(`Escherichia coli (MPN/100ml)`)
Total Suspended Solids

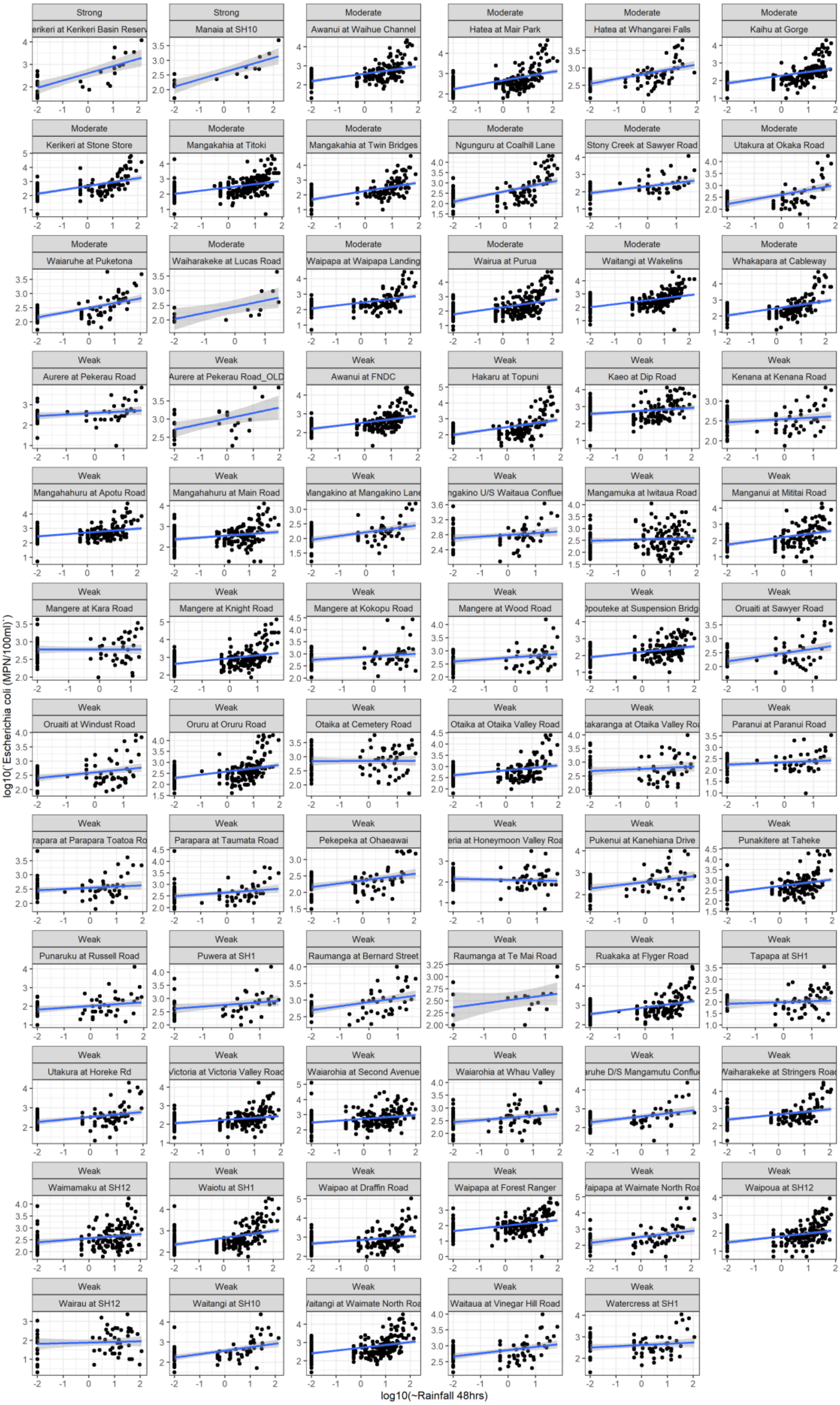

Strong
Hakaru at Topuni
Strong
Kaihu at Gorge
Strong
erikeri at Kerikeri Basin Reserv
Strong
Manaia at SH10
Strong
Mangakahia at Titoki
Strong
Mangakahia at Twin Bridges
Strong
Oruaiti at Sawyer Road
Strong
Waipapa at Waipapa Landing
Moderate
Awanui at FNDC
Moderate
Hatea at Mair Park
Moderate
Hatea at Whangarei Falls
Moderate
Kerikeri at Stone Store
Moderate
Mangahahuru at Apotu Road
Moderate
Manganui at Mititai Road
Moderate
Mangere at Knight Road
Moderate
Mangere at Wood Road
Moderate
Ngunguru at Coalhill Lane
Moderate
Oruaiti at Windust Road
Moderate
Oruru at Oruru Road
Moderate
Otaika at Otaika Valley Road
Moderate
Punakitere at Taheke
Moderate
Puwera at SH1
Moderate
Ruakaka at Flyger Road
Moderate
Stony Creek at Sawyer Road
Moderate
Utakura at Okaka Road
Moderate
aruhe D/S Mangamutu Conflu
Moderate
Waiharakeke at Lucas Road
Moderate
Waiotu at SH1
Moderate
Waipapa at Forest Ranger
Moderate
/aipapa at Waimate North Roa
Moderate
Waipoua at SH12
Moderate
Wairua at Purua
Moderate
Waitangi at SH10
Moderate
Waitangi at Wakelins
Moderate
Whakapara at Cableway
Weak
Aurere at Pekerau Road
Weak
Aurere at Pekerau Road_OLD
Weak
Awanui at Waihue Channel
Weak
Kaeo at Dip Road
Weak
Kenana at Kenana Road
Weak
Mangahahuru at Main Road
Weak
/angakino at Mangakino Lane
Weak
ngakino U/S Waitaua Conflue
Weak
Mangamuka at Iwitaua Road
Weak
Mangere at Kara Road
Weak
Mangere at Kokopu Road
Weak
)pouteke at Suspension Bridg
Weak
Otaika at Cemetery Road
Weak
takaranga at Otaika Valley Ro
Weak
Paranui at Paranui Road
Weak
rapara at Parapara Toatoa Ro
Weak
Parapara at Taumata Road
Weak
Pekepeka at Ohaeawai
Weak
eria at Honeymoon Valley Roa
Weak
Pukenui at Kanehiana Drive
Weak
Punaruku at Russell Road
Weak
Raumanga at Bernard Street
Weak
Raumanga at Te Mai Road
Weak
Tapapa at SH1
Weak
Utakura at Horeke Rd
Weak
/ictoria at Victoria Valley Road
Weak
Waiarohia at Second Avenue
Weak
Waiarohia at Whau Valley
Weak
Waiaruhe at Puketona
Weak
/aiharakeke at Stringers Roa
Weak
Waimamaku at SH12
Weak
Waipao at Draffin Road
Weak
Wairau at SH12
Weak
/aitangi at Waimate North Roa
Weak
Waitaua at Vinegar Hill Road
Weak
Watercress at SH1
log10(`Escherichia coli (MPN/100ml)`)
Black disc



log10(`Escherichia coli (MPN/100ml)`)
Turbidity
Strong
Hakaru at Topuni
Strong
Kaihu at Gorge
Strong
erikeri at Kerikeri Basin Reserv
Strong
Kerikeri at Stone Store
Strong
Manaia at SH10
Strong
Mangakahia at Titoki
Strong
Mangakahia at Twin Bridges
Strong
Oruaiti at Sawyer Road
Strong
Utakura at Okaka Road
Strong
Waiharakeke at Lucas Road
Strong
Whakapara at Cableway
Moderate
Aurere at Pekerau Road
Moderate
Aurere at Pekerau Road_OLD
Moderate
Awanui at FNDC
Moderate
Awanui at Waihue Channel
Moderate
Hatea at Mair Park
Moderate
Hatea at Whangarei Falls
Moderate
Mangahahuru at Apotu Road
Moderate
Mangakino at Mangakino Lane
Moderate
Manganui at Mititai Road
Moderate
Mangere at Knight Road
Moderate
Ngunguru at Coalhill Lane
Moderate
Oruaiti at Windust Road
Moderate
Oruru at Oruru Road
Moderate
Punakitere at Taheke
Moderate
Puwera at SH1
Moderate
Raumanga at Bernard Street
Moderate
Ruakaka at Flyger Road
Moderate
Stony Creek at Sawyer Road
Moderate
Utakura at Horeke Rd
Moderate
Waiotu at SH1
Moderate
Waipapa at Forest Ranger
Moderate
aipapa at Waimate North Roa
Moderate
Waipapa at Waipapa Landing
Moderate
Wairua at Purua
Moderate
Waitangi at SH10
Moderate
aitangi at Waimate North Roa
Moderate
Waitangi at Wakelins
Weak
Kaeo at Dip Road
Weak
Kenana at Kenana Road
Weak
Mangahahuru at Main Road
Weak
ngakino U/S Waitaua Conflue
Weak
Mangamuka at Iwitaua Road
Weak
Mangere at Kara Road
Weak
Mangere at Kokopu Road
Weak
Mangere at Wood Road
Weak
)pouteke at Suspension Bridg
Weak
Otaika at Cemetery Road
Weak
Otaika at Otaika Valley Road
Weak
akaranga at Otaika Valley Ro
Weak
Paranui at Paranui Road
Weak
rapara at Parapara Toatoa Ro
Weak
Parapara at Taumata Road
Weak
Pekepeka at Ohaeawai
Weak
eria at Honeymoon Valley Roa
Weak
Pukenui at Kanehiana Drive
Weak
Punaruku at Russell Road
Weak
Raumanga at Te Mai Road
Weak
Tapapa at SH1
Weak
Victoria at Victoria Valley Road
Weak
Waiarohia at Second Avenue
Weak
Waiarohia at Whau Valley
Weak
Waiaruhe at Puketona
Weak
aruhe D/S Mangamutu Conflu
Weak
Vaiharakeke at Stringers Road
Weak
Waimamaku at SH12
Weak
Waipao at Draffin Road
Weak
Waipoua at SH12
Weak
Wairau at SH12
Weak
Waitaua at Vinegar Hill Road
Weak
Watercress at SH1

Appendix 3: Correlation analysis between Log_{10} *E. coli* 100 mL^{-1} and rainfall (Log_{10} in the last 24, 48 or 72 hours) and river flow.




Strong
erikeri at Kerikeri Basin Reserv
Strong
Manaia at SH10
Moderate
Awanui at Waihue Channel
Moderate
Hatea at Mair Park
Moderate
Hatea at Whangarei Falls
Moderate
Kaihu at Gorge
Moderate
Kerikeri at Stone Store
Moderate
Mangakahia at Titoki
Moderate
Mangakahia at Twin Bridges
Moderate
Ngunguru at Coalhill Lane
Moderate
Stony Creek at Sawyer Road
Moderate
Utakura at Okaka Road
Moderate
Waiaruhe at Puketona
Moderate
Waiharakeke at Lucas Road
Moderate
Waipapa at Waipapa Landing
Moderate
Wairua at Purua
Moderate
Waitangi at Wakelins
Moderate
Whakapara at Cableway
Weak
Aurere at Pekerau Road
Weak
Aurere at Pekerau Road_OLD
Weak
Awanui at FNDC
Weak
Hakaru at Topuni
Weak
Kaeo at Dip Road
Weak
Kenana at Kenana Road
Weak
Mangahahuru at Apotu Road
Weak
Mangahahuru at Main Road
Weak
Mangakino at Mangakino Lane
Weak
ngakino U/S Waitaua Conflue
Weak
Mangamuka at Iwitaua Road
Weak
Manganui at Mititai Road
Weak
Mangere at Kara Road
Weak
Mangere at Knight Road
Weak
Mangere at Kokopu Road
Weak
Mangere at Wood Road
Weak
Opouteke at Suspension Bridg
Weak
Oruaiti at Sawyer Road
Weak
Oruaiti at Windust Road
Weak
Oruru at Oruru Road
Weak
Otaika at Cemetery Road
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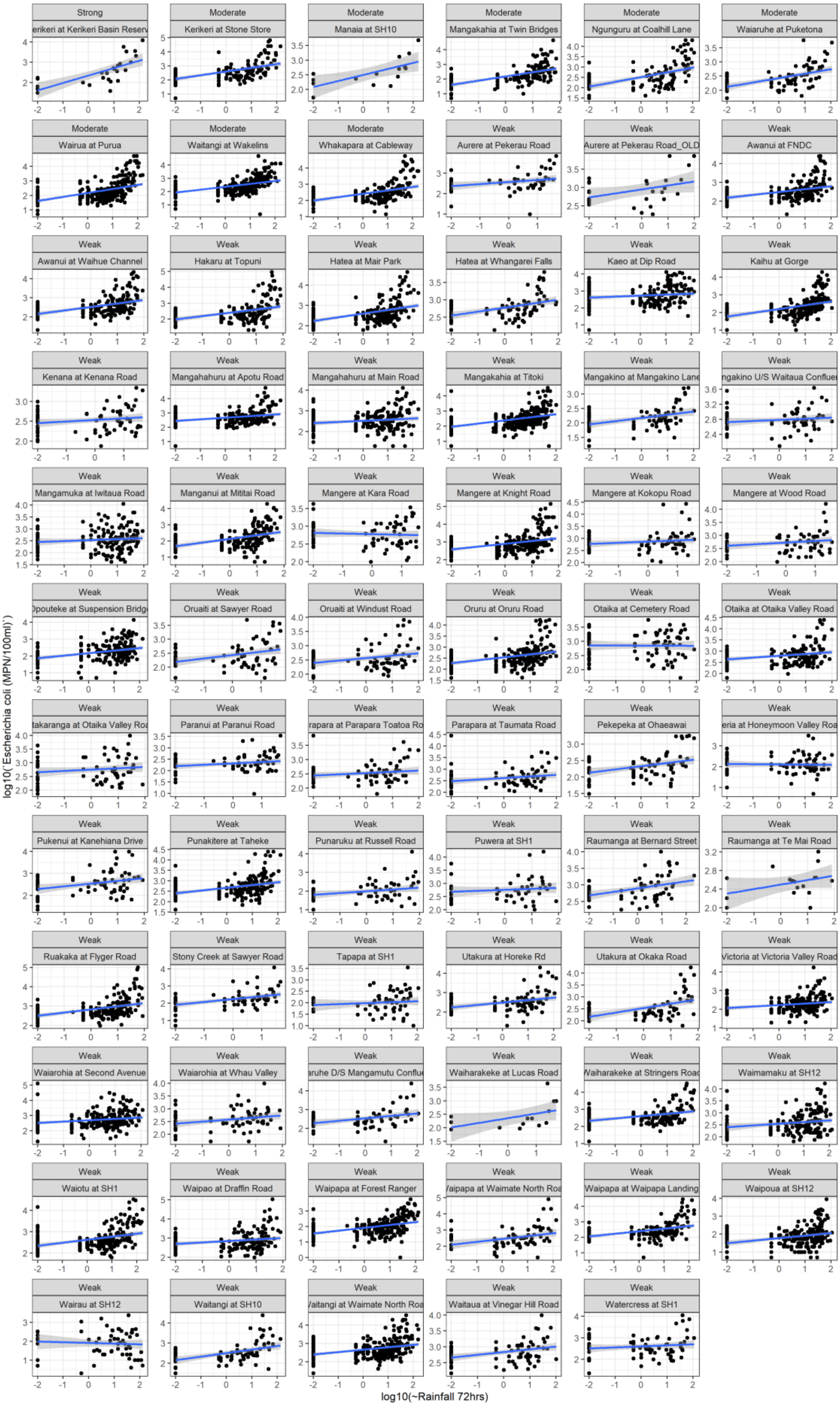
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Waitaua at Vinegar Hill Road
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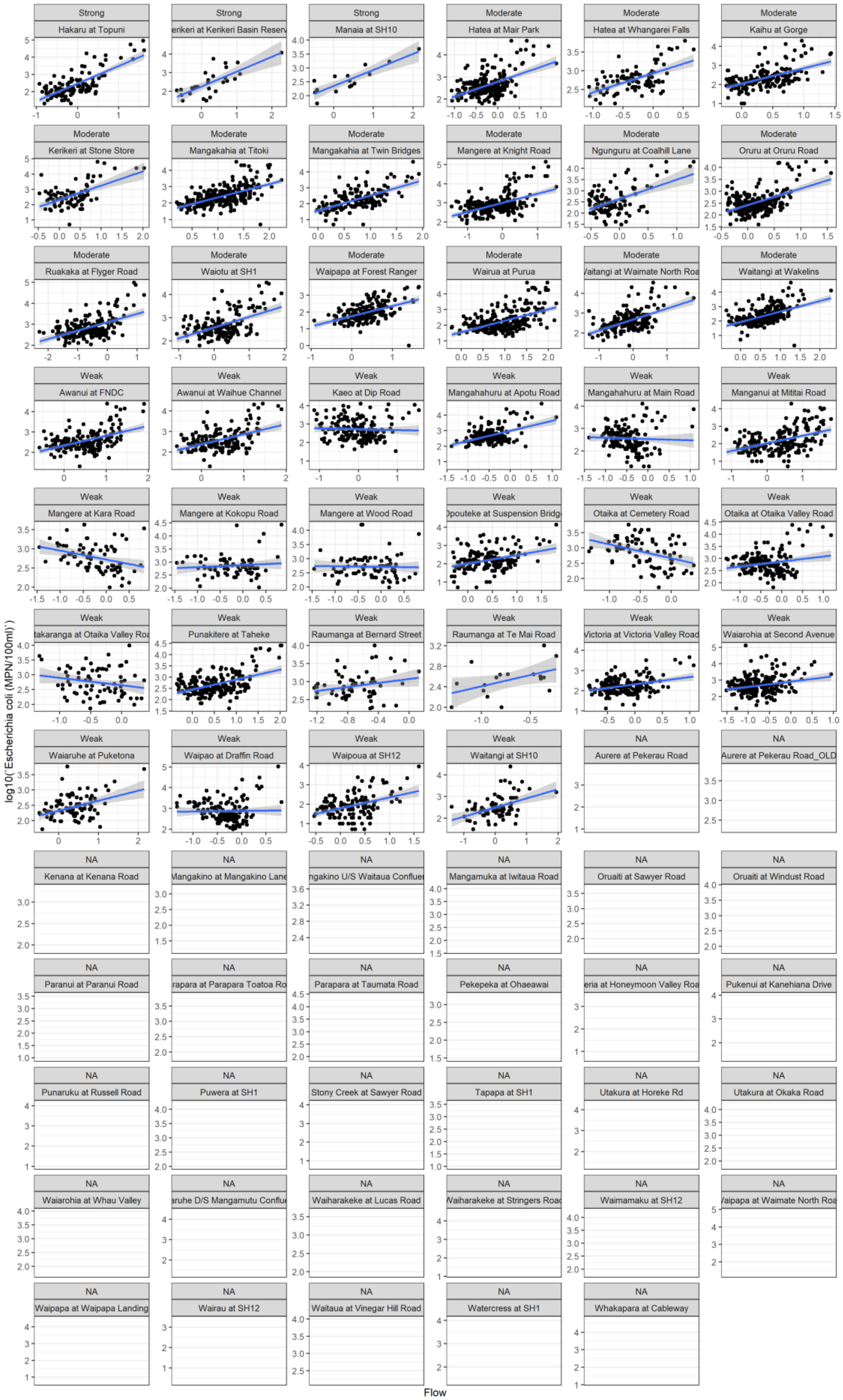
Watercress at SH1
log10(`Escherichia coli (MPN/100ml)`)
log10(~Rainfall 72hrs)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Wairau at SH12
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Waitaua at Vinegar Hill Road
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Watercress at SH1
NA
Whakapara at Cableway
log10(`Escherichia coli (MPN/100ml)`)
Flow

Appendix 4. Correlation analysis between Log_{10} *E. coli* 100 mL^{-1} and land use. The data shows the r and r^2 (r^2) values for the individual water quality metrics. N present is the number of catchments that contained that land-use and Mean Proportion is the mean proportion of the catchment in that land use. Rows are colour coded: grey for unreliable, blue for neutral and white for reliable data based on the number of catchments that contained that land use.

River water quality monitoring sites:

Landcover	Median E. coli_r	% >260_r	%>540_r	95th Percentile_r	Median E. coli_r^2	% >260_r^2	%>540_r^2	95th Percentile_r^2	N Present	Mean Proportion
Indigenous Forest	-0.3	-0.35	-0.32	-0.29	0.09	0.12	0.11	0.08	61	0.28
Exotic Forest	-0.08	-0.06	-0.08	-0.05	0.01	0	0.01	0	60	0.12
High Producing Exotic Grassland	0.3	0.31	0.36	0.37	0.09	0.09	0.13	0.14	59	0.43
Manuka and/or Kanuka	-0.19	-0.1	-0.25	-0.21	0.03	0.01	0.06	0.04	55	0.066
Broadleaved Indigenous Hardwoods	0.02	0.01	-0.01	-0.08	0	0	0	0.01	54	0.027
Low Producing Grassland	-0.1	-0.07	-0.09	0.16	0.01	0	0.01	0.03	48	0.0059
Forest - Harvested	-0.22	-0.22	-0.23	-0.05	0.05	0.05	0.05	0	43	0.014
Deciduous Hardwoods	0.05	0	0.05	0.04	0	0	0	0	40	0.0019
Gorse and/or Broom	-0.11	-0.08	-0.15	0.02	0.01	0.01	0.02	0	36	0.0034
Lake or Pond	-0.05	0.01	-0.04	-0.03	0	0	0	0	34	0.0051
Built-up Area (settlement)	0.34	0.38	0.33	0.02	0.11	0.15	0.11	0	31	0.022
Orchard, Vineyard or Other Perennial Crop	0.39	0.29	0.35	-0.01	0.15	0.08	0.13	0	29	0.011
Surface Mine or Dump	0.18	0.16	0.18	-0.05	0.03	0.03	0.03	0	28	0.0015
Herbaceous Freshwater Vegetation	-0.15	-0.11	-0.09	0.27	0.02	0.01	0.01	0.07	26	0.0035
Short-rotation Cropland	0.28	0.28	0.3	0.08	0.08	0.08	0.09	0.01	24	0.0022
Mixed Exotic Shrubland	-0.06	-0.02	-0.12	-0.06	0	0	0.01	0	23	0.00091
Urban Parkland/Open Space	0.33	0.33	0.32	0.17	0.11	0.11	0.1	0.03	18	0.0025
River	-0.12	-0.09	0.01	0.07	0.01	0.01	0	0.01	7	0.00019
Transport Infrastructure	-0.21	-0.24	-0.18	-0.08	0.04	0.06	0.03	0.01	6	2.4e-05
Fernland	-0.01	0.03	-0.02	0.23	0	0	0	0.05	4	2e-05
Depleted Grassland	-0.04	-0.01	-0.09	0.18	0	0	0.01	0.03	2	2.9e-05
Landslide	-0.1	-0.1	-0.09	0.04	0.01	0.01	0.01	0	2	2.3e-06
Gravel or Rock	-0.03	0.01	-0.04	-0.03	0	0	0	0	2	0.00018
Flaxland	-0.15	-0.11	-0.03	0.42	0.02	0.01	0	0.18	2	1.9e-05
Matagouri or Grey Scrub	-0.12	-0.16	-0.13	-0.1	0.01	0.02	0.02	0.01	1	3.6e-05
Sand or Gravel	-0.03	0.01	-0.04	-0.03	0	0	0	0	1	2.1e-05
Mangrove	-0.09	-0.11	-0.08	-0.04	0.01	0.01	0.01	0	1	3.9e-06

Swimming water quality sites:

Landcover	95th Percentile Hazen_r	95th Percentile Hazen_r^2	N Present	Mean Proportion
Surface Mine or Dump	0	0	8	0.003
Transport Infrastructure	0.42	0.18	4	1e-04
Manuka and/or Kanuka	-0.2	0.04	18	0.045
Forest - Harvested	0.43	0.19	16	0.017
High Producing Exotic Grassland	0.37	0.14	19	0.44
Indigenous Forest	-0.52	0.27	19	0.3
Lake or Pond	0.15	0.02	12	0.0037
Low Producing Grassland	0.01	0	18	0.004
Broadleaved Indigenous Hardwoods	0.26	0.07	19	0.024
Exotic Forest	0.28	0.08	18	0.089
Orchard, Vineyard or Other Perennial Crop	0.12	0.01	7	0.03
Built-up Area (settlement)	0.34	0.12	11	0.025
Deciduous Hardwoods	-0.01	0	13	0.0026
Urban Parkland/Open Space	0.84	0.71	4	0.0013
Short-rotation Cropland	0.22	0.05	8	0.0026
Gorse and/or Broom	0.13	0.02	12	0.0019
Mixed Exotic Shrubland	0.16	0.02	6	0.0012
Herbaceous Freshwater Vegetation	0.31	0.1	9	0.0021
Flaxland	0.06	0	2	2.2e-05
Fernland	0.64	0.41	2	4.4e-05
River	-0.04	0	5	0.00058
Sand or Gravel	0.02	0	2	0.00015
Mangrove	0.01	0	1	0.00017
Gravel or Rock	0.11	0.01	1	7.8e-05