Management Strategies to Mitigate Faecal Contamination Inferred from Analysis of Data from the Waikato Region

MAF Technical Paper No: 2002/15

Prepared for MAF Policy
by Rob Collins, NIWA

ISBN No: 0-478-07695-9
ISSN No: 1171-4662

December 2002

Disclaimer

While every effort has been made to ensure the information in this publication is accurate, the Ministry of Agriculture and Forestry does not accept any responsibility or liability for error or fact omission, interpretation or opinion which may be present, nor for the consequences of any decisions based on this information.

Any view or opinions expressed to not necessarily represent the official view of the Ministry of Agriculture and Forestry.

The information in this report and any accompanying documentation is accurate to the best of the knowledge and belief of the Consultant acting on behalf of MAF Policy. While the Consultant has exercised all reasonable skill and care in the preparation of information in this report, neither the Consultant nor MAF Policy accept any liability in contract, tort or otherwise for any loss, damage, injury, or expense, whether direct, indirect or consequential, arising out of the provision of information in this report.

Requests for further copies should be directed to:

Publication Adviser
MAF Information Bureau
P O Box 2526
WELLINGTON

Telephone: (04) 474 4100
Facsimile: (04) 474 4111

This publication is also available on the MAF website at www.maf.govt.nz/publications

Executive Summary

Environment Waikato has collected *E. coli* data from 73 stream sites across the Waikato region that encompass a diverse range of faecal contaminant sources. Examination of this microbial dataset has been conducted in conjunction with a range of environmental factors including the physical characteristics of each catchment, the land management practices within it, and dynamic processes such as hydrological and meteorological conditions. This approach has highlighted the key processes determining faecal contamination of waterways, and identified some mitigating practices.

With the exception of a few sites, the discharge of point sources direct to waterways appears not to influence median *E. coli* concentrations. This is attributed to the relatively low number of consented discharges that cause faecal contamination, and to improvements in the treatment of waste water.

Median *E. coli* concentrations across the region range from 1 to 1300 cfu/100mL and, at 53 of the 73 sites sampled, they exceed the guideline for freshwater recreation (a median value of 126 cfu/100mL). The pattern of contamination across the Waikato is dominated by the presence of grazing livestock and the highest median *E. coli* concentrations are associated with the most intensive dairy farming in the centre of the region. Conversely, the lowest median values are found in forested catchments, although *E. coli* concentrations are always measurable, indicating contamination by wild animals.

Strategies to reduce faecal contamination of streams and rivers in the Waikato region should focus upon grazing livestock. Cattle access to streams and near-channel areas is likely to dominate faecal contamination, and mitigation measures may, therefore, be best directed at riparian zones. Permanent fencing to exclude livestock from stream channels and a proportion of riparian land is likely to be the most effective means of reducing faecal contamination by grazing cattle. There are also a number of riparian management alternatives to permanent fencing that may not be as effective but should still reduce faecal contamination.

The percentage of poorly drained soil within a watershed is a relatively strong predictor of median *E. coli*. This is probably attributable to the generation of appreciable overland flow that can rapidly transport faecal material to waterways. It is also likely that artificial drainage in poorly drained soils accelerates the transport of faecal microbes to streams. The bacterial water quality of streams draining such soils is likely to be particularly sensitive to livestock grazing and the application of effluent to land. Appropriate mitigation measures on land underlain by poorly drained soils may include the adoption of less intensive farming practices, optimising the timing of effluent application to land to avoid periods when the soil is saturated, wetland treatment of wastes, surface runoff and sub-surface drainage, and retirement of riparian areas from grazing.

A weak inverse relationship was found between the presence of a wetland within a catchment and median *E. coli*. A tentative inference is drawn therefore that wetlands may act to attenuate faecal contamination.

A statistical model explains almost 70% of the observed variance in median *E. coli* across the region. There are 3 explanatory variables: the percentage of poorly drained soil, density of cattle, and median turbidity at the catchment outlet. The model potentially provides a means of predicting faecal contamination through the use of basic environmental data.

Some future directions for research are identified. A major challenge for researchers and resource managers alike will be to develop a method of characterising riparian zones with respect to livestock access to channels and the function of vegetation in trapping overland flow of faecal contamination.

Contents

Page

1. Introduction

In recent years the contamination of New Zealand's freshwaters by a range of indicator and pathogenic microorganisms has been studied under the Freshwater Microbiological Research Programme (McBride 2002). The results from this and earlier studies (for example, Smith et al. 1993) have confirmed that microbial contamination of lakes and rivers is widespread in New Zealand, with concentrations of the faecal indicator Escherchia coli (*E. coli*) often exceeding 1000 cfu per 100mL. Such findings, coupled with the high incidence of notified campylobacteriosis (Savill et al. 2001) and cryptosporidiosis (Duncanson et al. 2000) compared to other developed countries, has raised concerns over the public health risk from pathogens of faecal origin (including *Campylobacter*, *Cryptosporidium* oocysts, *Giardia* cysts, and Salmonellae) in New Zealand's fresh waters. This risk to public health has substantial implications for land management practices, and for New Zealand's international image with respect to trade and tourism. Furthermore, faecal contamination also restricts the recreational use of freshwaters, use for potable treatment, and shellfish aquaculture in estuaries receiving agricultural drainage.

The sources of faecal contamination of freshwaters are diverse and vary both spatially and temporally. Numerous studies (Wilcock 1986, Davies-Colley and Stroud 1995, and Gary et al. 1983) have demonstrated that grazing livestock cause faecal bacterial contamination of streams. This contamination arises through the delivery of faecal material in overland (Doran and Linn 1979) and subsurface (Collins 2002) flows to a watercourse and, where livestock have access to a stream, direct deposition of faecal material (Gary et al. 1983, Davies-Colley et al. 2002). Wild animals also contribute to faecal contamination of waterways (Niemi and Niemi 1991). Point source discharges of wastewater from sewage treatment and animal processing plants have also been shown to impair the bacterial quality of receiving waters (Smith 2001). Discharge of effluent to land, although considered preferable to discharge direct to a watercourse, leads to contamination of soil and soil water (Trevisan et al. 2002), which may, ultimately flow to surface waters.

The impact of each source of faecal contamination upon freshwater is influenced by a range of interacting environmental factors. These factors include the physical characteristics of a catchment, the land management practices within it, and dynamic processes such as rainfall, stream flow and recent climatic conditions. Understanding of the interactions between sources of contamination, and the watershed processes acting upon them remains, however, incomplete. This, in turn, may limit identification and application of land management strategies to minimise faecal contamination.

In an attempt to advance understanding and identify mitigating practices, stream water *E. coli* concentrations, collected from a regional monitoring program, were analysed in conjunction with a range of environmental variables. The microbial data, provided by Environment Waikato (EW), was collected from 73 stream sites throughout the Waikato region that encompass a diverse range of contaminant sources, catchment characteristics and land management practices. As part of the analysis a statistical model was developed to predict median *E. coli* concentrations across the region using basic environmental data. The modelling aids evaluation of the relative importance of sources and processes and provides a means of predicting likely faecal contamination at sites not currently monitored for *E. coli*.

This approach to improving prediction and management of faecal contamination through the use of environmental datasets has had recent, but limited, application elsewhere. Smith et al.

(2001) used land cover and digital elevation data to analyse faecal contamination in South Carolina, and Crowther et al. (2001) used river discharge, tide, wind and sunshine data to provide insight into the factors affecting microbial water quality in coastal recreational waters in the U.K. The analysis of the EW dataset is, however, the most comprehensive to date in New Zealand

As part of this study AgResearch were subcontracted to undertake a field survey of selected watersheds (Longhurst and O'Connor, 2002). The objective of this survey was to identify and correct any major discrepancies in the data set, for example, in the delineation of catchment boundaries and/or descriptions of land use. The presence of riparian planting within a catchment was also noted, and an assessment made of the accessibility of streams to cattle. Direct deposition of faecal material into streams is likely to be an important process contributing to contamination, and riparian planting may attenuate microbes in overland flow and (if fenced) exclude stock from streams.

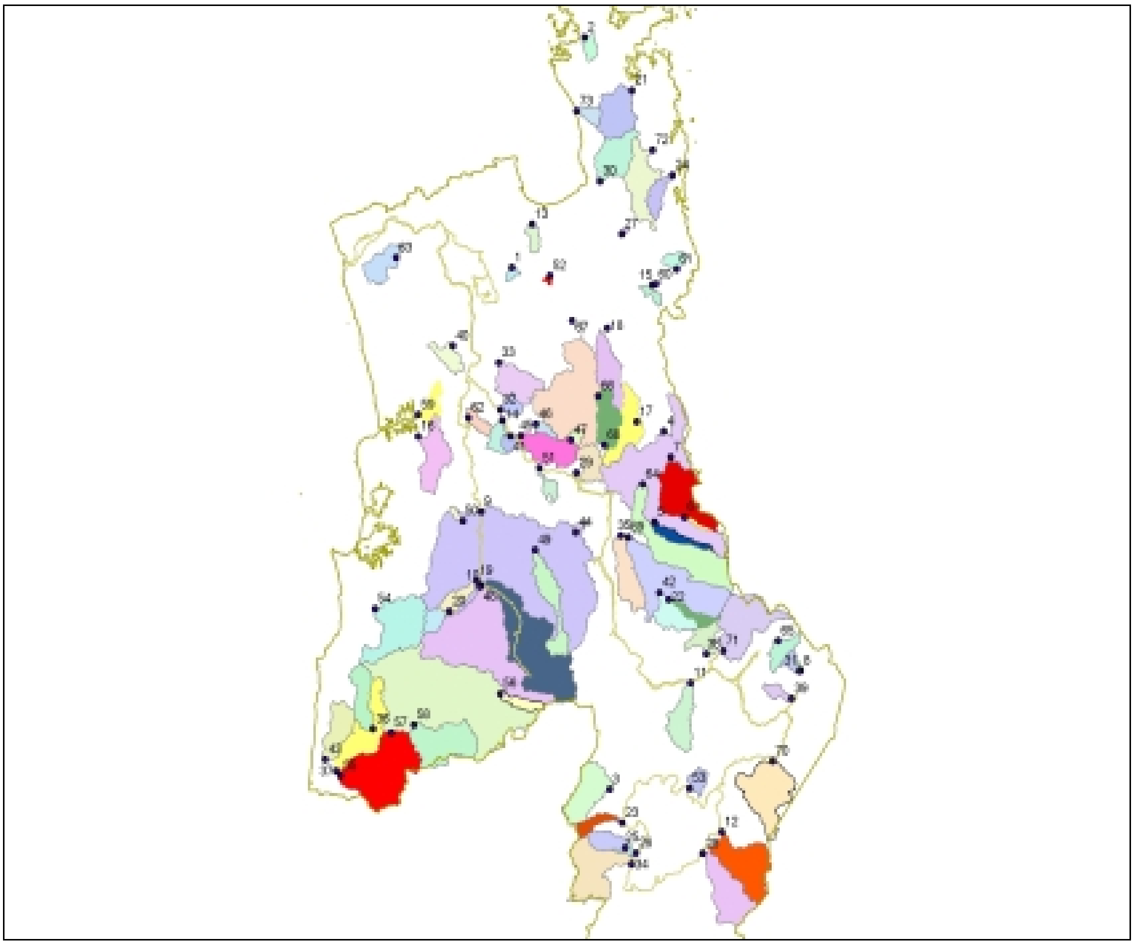
2. Data Sources

2.1 WATERSHED DERIVATION

From the NIWA 30m digital elevation model (which encompasses the whole of NZ), the catchment boundaries upstream of each of the 73 EW sampling points were identified (by NIWA) using a GIS. These boundaries were then passed to EW and overlain on GIS maps of land use, livestock, soil drainage, rainfall, and land management to provide summary statistics (eg. the percent of catchment area by land use). The data provided by this approach gave no indication of the spatial patterns within watersheds. For example, if a watershed was partially forested, it was not known how many stands of trees there were, or their location within the catchment. The field survey identified inaccuracies associated with the derived watershed boundaries. These were attributed to the relatively coarse resolution (30 m) of the DEM.

The watersheds ranged from 2 to 2270 km^2 in size and covered c. 50% of the Waikato region (Figure 1). They encompass a range of land uses, soil types, and potential sources of faecal contamination.

Figure 1. Sampling locations (obtained from the Environment Waikato's Regional River Monitoring Programme, copyright Environment Waikato) and their watersheds, within the Waikato region. The colours are used only to illustrate the extent of each watershed.



2.2 SLOPE ANGLE

The digital elevation model (section 2.1) was used to derive the dominant slope angle in each watershed. This was achieved by classifying the slope angle in each 30×30m cell into one of 7 ranges, with the midpoint of the most frequently occurring range in a catchment being the dominant slope. Additionally, the percentage of steep slopes (>15°) within each watershed was derived.

2.3 LAND USE AND STOCK DENSITY

Land cover data for each of the 73 watersheds was supplied by EW from the 1996 Land Cover database derived by Terralink New Zealand Ltd. Reference to the map of land cover for the whole region (Figure 2) illustrates the predominance (56%) of pastoral farming. Large areas of plantation forest and indigenous vegetation are also evident, particularly on the Coromandel peninsula, the western fringes, and the south east of the region. Sheep and beef cattle are farmed on the steeper hillslopes, but dairying dominates and is most intensive in the centre of the region near Hamilton (Figure 3). The numbers of beef cattle, dairy cattle, sheep, and deer in each watershed were provided by EW. This data was derived from an agricultural database (Agribase) under licence to AgriQuality New Zealand Ltd. Animal numbers were converted to stock units (Fleming and Burtt 1991) to account for variation in the supply of faecal material with animal type. This approach could not, however, account for differences in the content of *E.coli* (per unit weight of faecal material) between different animal types. The stock records provided were based upon data collected in 2001, whereas water quality was monitored in 1998-2001 and land use surveyed in 1996-97**.**

2.4 SOIL DRAINAGE

The soil drainage characteristics of each watershed (Figure 4) were provided by EW and derived from the New Zealand soil classification database, Landcare Research New Zealand Ltd. (Hewitt 1993). Within this dataset, soil drainage is classified into 1 of 5 categories, ranging from very poorly drained (Class 1) to well drained (Class 5).

2.5 RAINFALL

The distribution of mean annual rainfall across the region was supplied by NIWA – Wellington in a grid format. This data was derived by interpolating a surface of point measurements of annual rainfall, a process that also accounted for the influence of altitude upon rainfall. From the resulting grid, mean annual rainfall was derived for each watershed. The region has an average annual rainfall of 1,250 mm, but this ranges from in excess of 3,000 mm in the Coromandel peninsula, and parts of the south-west of the region, to less than 1,200 mm in the lower Waikato lowlands, the Hauraki plains, Taupo and the Reporoa valley.

Figure 2. Land Cover for the Waikato region, sourced from the Waikato State of the Environment report 1988. Copyright Environment Waikato.

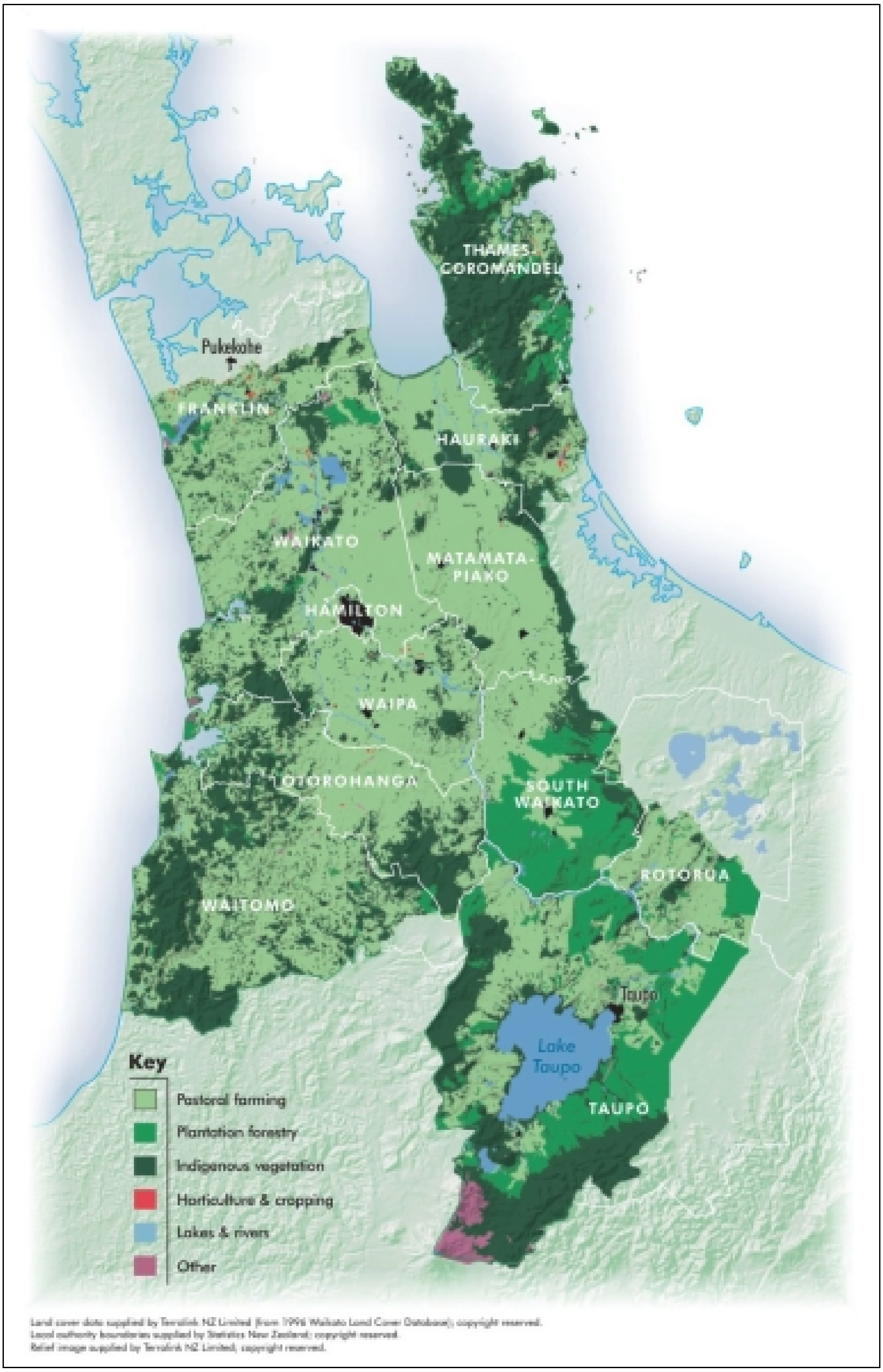


Figure 3. Cattle density and median *E.coli* across the Waikato region, sourced from the Waikato State of the Environment report 1988. Copyright Environment Waikato.

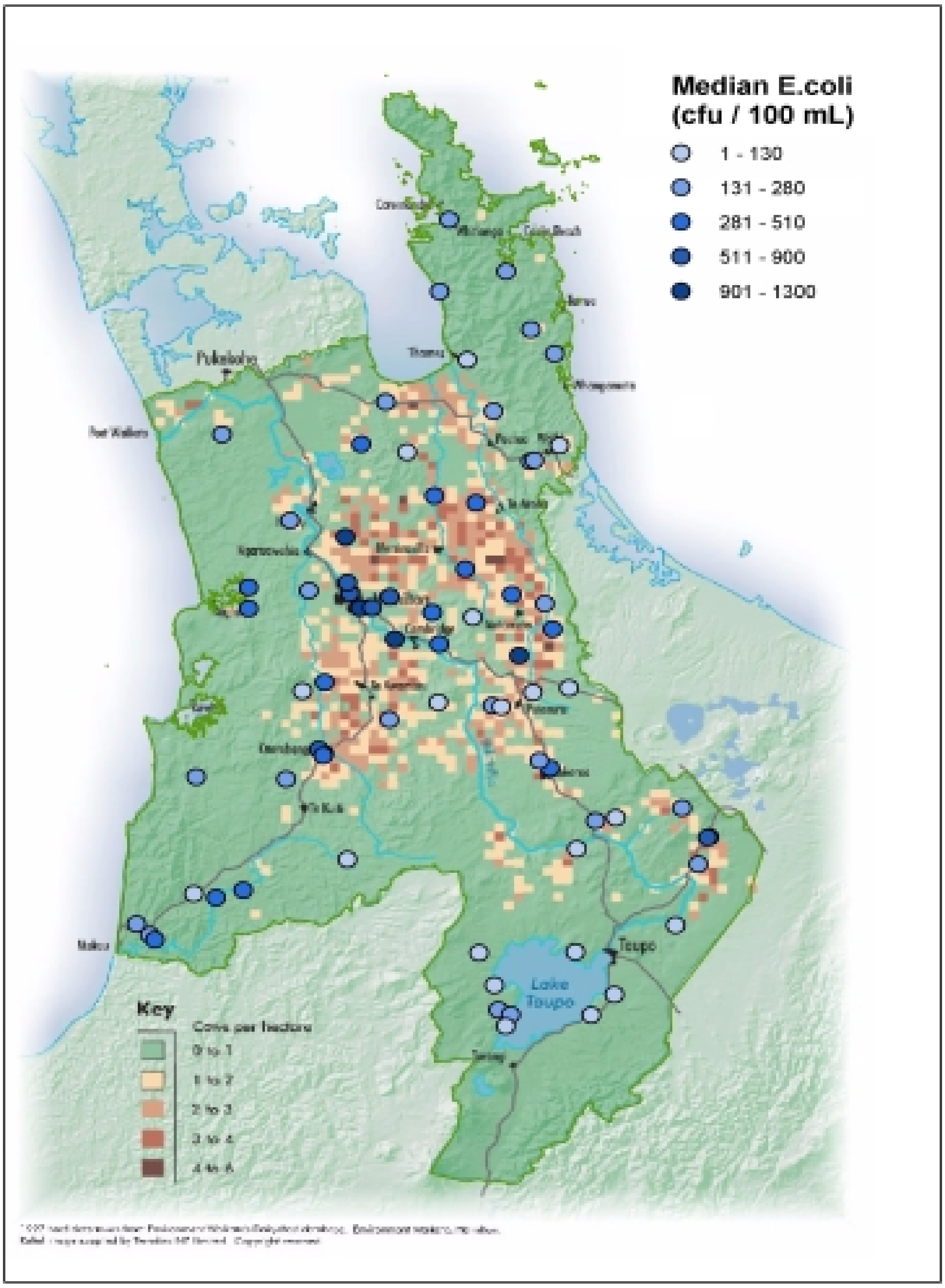
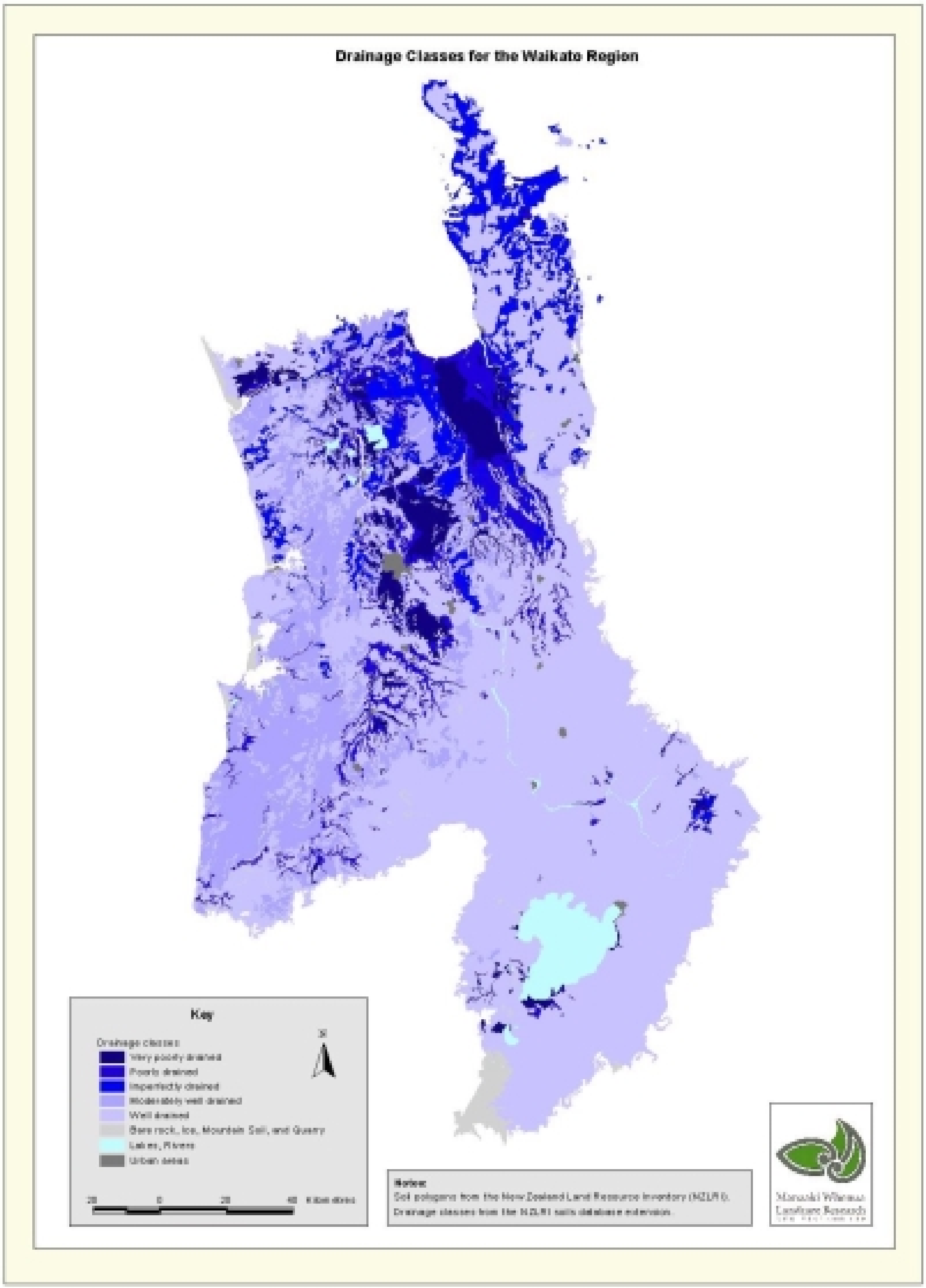


Figure 4. Soil drainage class across the Waikato (Landcare Research New Zealand Ltd.)



2.6 EFFLUENT DISCHARGES TO LAND

The location of licensed effluent discharges to land between 1998 and present day (and the volume of discharge per day) were supplied by EW. Three sources of effluent with the potential to contain faecal material were identified: dairy farms, non-dairy agriculture, and utilities (treated sewage waste water). The number of consents per watershed in each of these categories, was determined. Data describing the volume of discharge was incomplete and therefore not used. Figure 5 illustrates all of the consented effluent discharges to land, regardless of category, with their location appearing to broadly correlate with dairying and urban areas.

2.7 POINT SOURCE DISCHARGES TO WATER

The location and volume (m^3/day) of licensed point source discharges to surface waters were provided by EW. From this, the total volume of point source discharge with a potential to cause faecal contamination was determined for each watershed. Again, the data was divided into three categories – dairy farms, non-dairy agriculture, and utilities, with the latter including stormwater. The bacterial quality of treated sewage waste water was unknown, and it may have varied between sites due to differences in treatment techniques. The pattern of point source discharges across the region (Figure 6) is broadly similar to that of the land discharge of effluent. Since the point source data was from 1997, changes in the type, location and volume of discharge may have occurred during the faecal contamination monitoring program which was initiated in 1998 (section 3.1).

2.8 PONDS

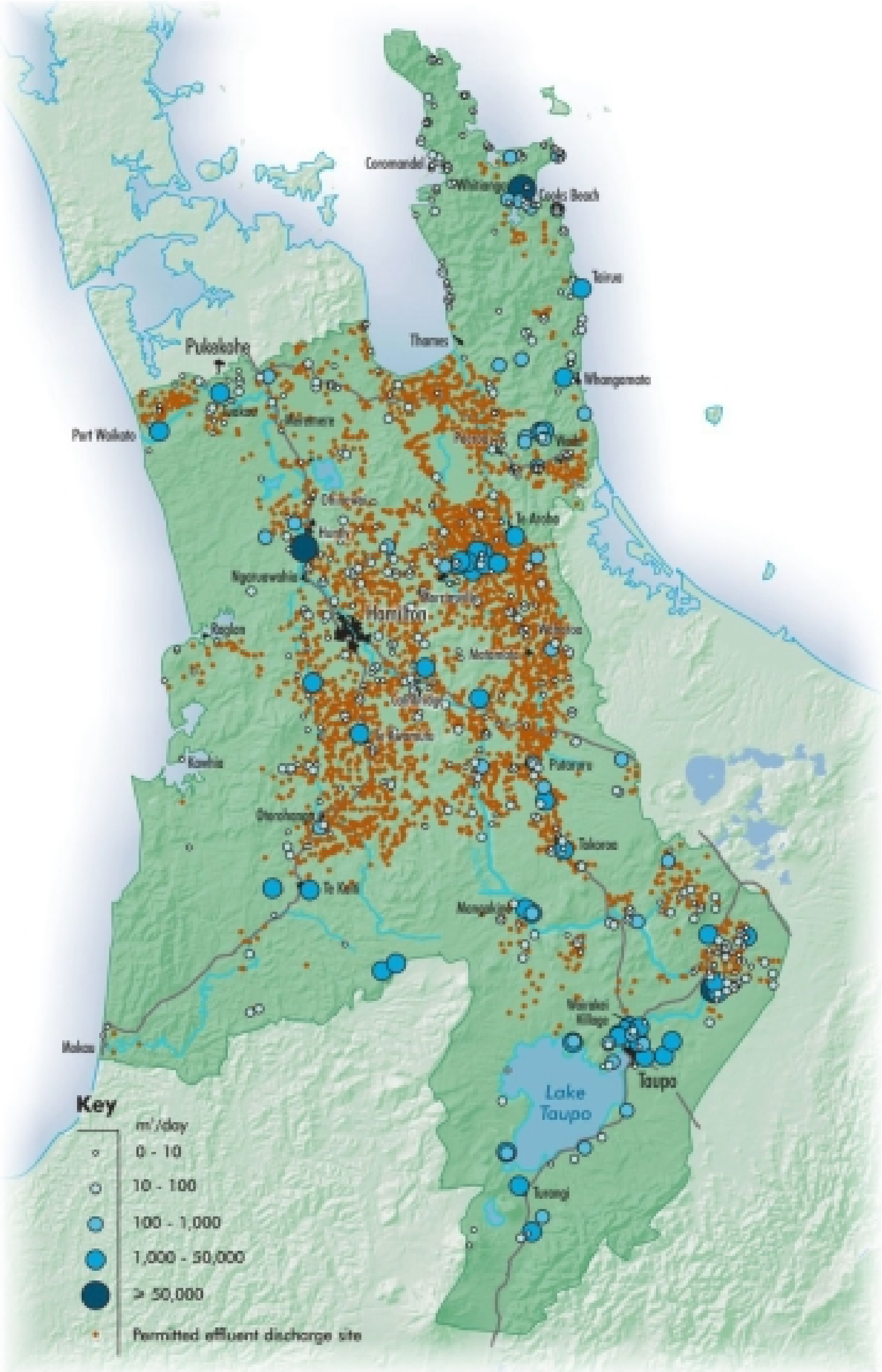
Consent to discharge dairy effluent direct to a watercourse requires that the effluent is first stored within a pond. This practice promotes indicator and pathogen die-off prior to discharge (Sukias et al. 2001). Locations of all consented dairy ponds within the region were provided by EW, and this data was used to determine the number of ponds in each watershed.

2.9 RIPARIAN DATA

Field survey of 8 selected watersheds (sites 17, 18, 24, 41, 46, 64, 66, and 67) indicated that riparian planting and stock exclusion from streams is highly variable both within and between watersheds. On one farm, for example, livestock were fenced off from the streambank except for a dedicated access point that was regularly visited by cattle. The length of fenced streambank may be irrelevant in determining faecal contamination if the total visitation rate of cattle to the stream is unaffected by the fencing. At site 41 a network of unfenced open drains was observed. These are known to attract cattle, and provide a pathway for the rapid transport of faecal contamination to the stream network during storm events. Such drains are likely to be present at other sites, particularly on flat land.

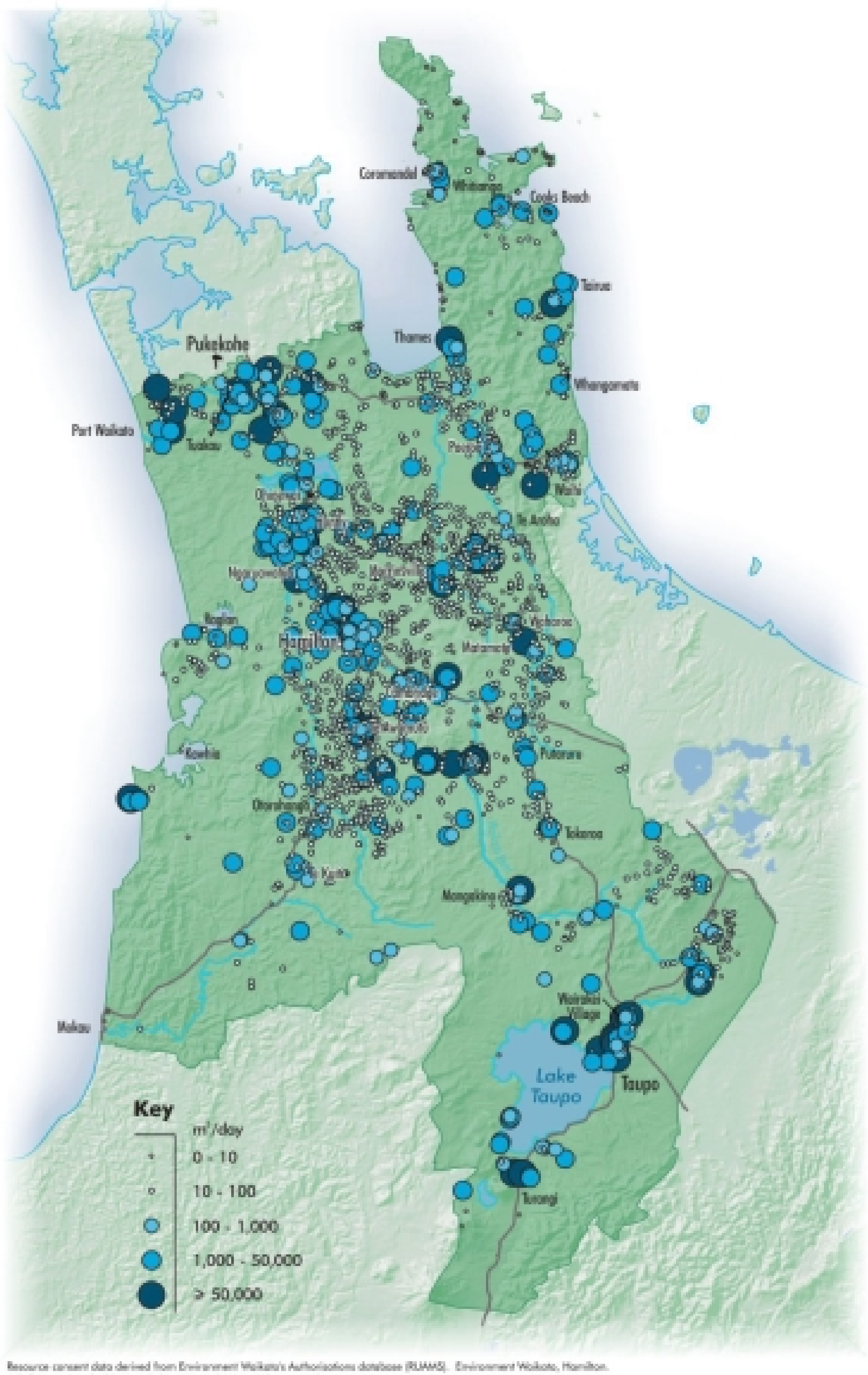
Riparian survey of all 73 watersheds was beyond the scope of this study and has, therefore, precluded the analysis of riparian planting and/or stock access in explaining faecal contamination across the region. The survey of selected watersheds has, however, highlighted the difficulties associated with the acquisition of riparian data at a regional scale.

Figure 5. Effluent discharge to land throughout the Waikato, sourced from the Waikato State of the Environment report 1988. Copyright Environment Waikato.



Resource consent data derived from Environment Waikato's Authorisations database (RUAMS). Environment Waikato, Hamilton.
Relief image supplied by Terralink NZ Limited. Copyright reserved.

Figure 6. Point source discharges to water throughout the region, sourced from the Waikato State of the Environment report 1988. Copyright Environment Waikato.



Resource consent data derived from Environment Waikato's Authorisations database (RUAMS). Environment Waikato, Hamilton.
Relief image supplied by Terralink NZ Limited. Copyright reserved.

3. Water Quality Monitoring Data

3.1 *E.COLI* CONCENTRATIONS

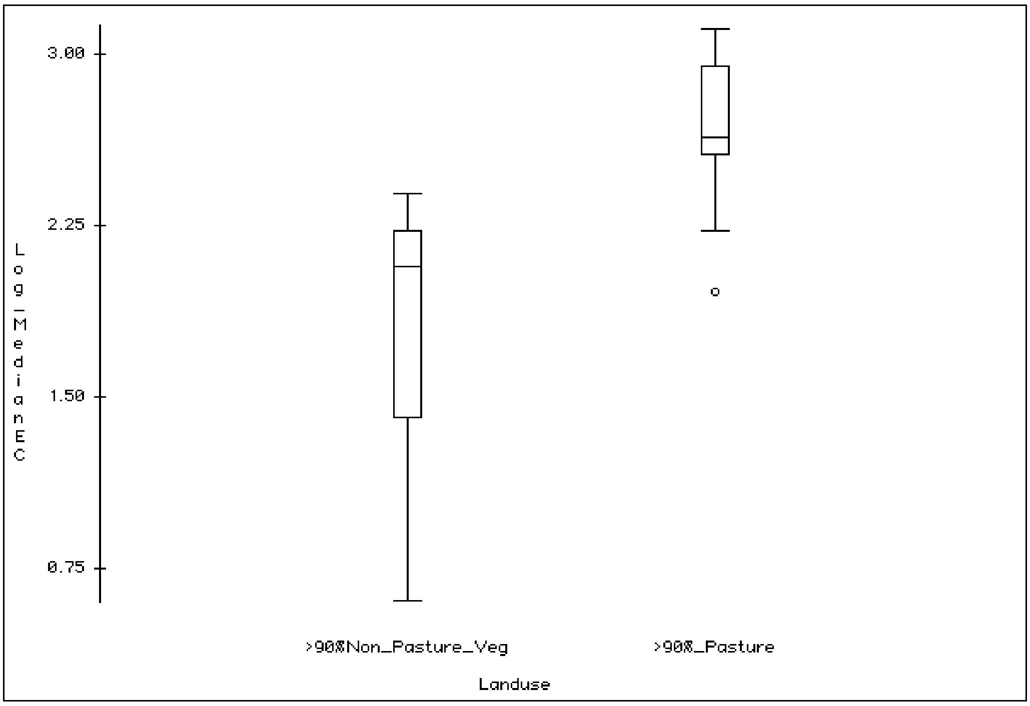
Since early 1998, quarterly spot samples have been collected at the 73 stream and river sites across the Waikato region for *E.coli* analysis. This analysis is done by membrane filtration with a count on MFC agar at 44.5°C after 24 hours, following the American Public Health Association method 9222G. At most locations 15 samples have been collected to date. Mean values are often markedly higher than median values (Table 1) reflecting the strong positive skewness of the data distributions. Analysis is therefore focused upon the median values as they better describe the central tendency of the data. Median concentrations range from 1 to 1300 cfu/100mL (Table 1) with the highest values generally associated with the most intensive dairy farming in the centre of the region (Figure 3), for example the Komakorau, Mangakotukutuku, Mangaone, Mangawhero and Oraka streams (sites 33, 41, 45, 51, and 64 respectively). The lowest median values are generally found in forested catchments bordering Lake Taupo in the south, for example, the Waihaha, Hinemaiaia, and Kuratau rivers, and the Whanganui and Mapara streams (sites 3, 28, 34, 23, and 53 respectively). The impact of land use upon median *E. coli* concentration is illustrated in Figure 7. Of the 73 sites, median values at 53 of them exceed the guideline for freshwater recreation (126 cfu/100mL). The range in values found at a site (Table 1) can be extremely large (for example at the Waitawhiriwhiri stream and the Waitoa and Mokau rivers, sites 14, 17, and 57 respectively) reflecting significant temporal variation in factors contributing to faecal contamination (and die-off), for example, point sources, stock density, the magnitude of streamflow, and insolation.

Table 1. Statistical summary of spot sampled *E. coli* and turbidity at the 73 sites. IQR = Interquartile Range.

			E. coli (cfu/100mL)				Turbidity (NTU)			
Num	Site	N	Mean	Median	StdDev	IQR	Mean	Median	StdDev	IQR
1	Waerenga Stm	15	1266	400	3251	348	15	4	41	4
2	Waiau River	15	767	140	2204	160	13	3	29	7
3	Waihaha River	15	20	4	36	15	1	0	0	0
4	Waihou River	15	251	230	106	168	3	3	2	2
5	Waihou River	15	61	33	88	32	0	0	0	0
6	Waiohotu Stm	15	230	110	340	228	3	3	1	1
7	Waiomou Stm	15	328	330	158	220	3	3	1	2
8	Waiotapu Stm	15	3	1	6	2	7	6	3	3
9	Waipa River	15	1129	390	1596	1183	22	10	33	15
10	Waipa River	15	501	200	963	253	6	4	8	6
11	Waipapa Stm	15	110	89	118	45	3	3	1	1
12	Waitahanui River	15	70	60	46	55	1	1	0	0
13	Waitakaruru River	15	1502	230	4570	330	17	10	30	10
14	Waitawhiriwhiri Stm	15	2753	700	3364	3774	48	29	52	12
15	Waitekauri River	15	382	180	773	258	2	1	4	1
16	Waitetuna River	15	625	380	481	543	14	8	13	13
17	Waitoa River	15	1701	370	2523	2556	8	5	9	5
18	Waitoa River	15	1140	430	1820	970	9	6	11	8
19	Waitomo Stm	15	1753	740	3211	1270	20	12	24	14
20	Waitomo Stm	15	1731	190	4313	1053	12	6	13	11
21	Waiwawa River	15	2270	170	7951	360	9	2	25	1
22	Whakauru Stm	15	677	300	1280	353	3	3	1	1
23	Whanganui Stm	3	38	28	25	35	1	1	0	0
24	Wharekawa River	15	1425	250	4314	430	4	2	4	1

			E. coli (cfu/100mL)				Turbidity (NTU)			
Num	**Site**	**N**	**Mean**	**Median**	**StdDev**	**IQR**	**Mean**	**Median**	**StdDev**	**IQR**
25	Whareroa Stm	3	102	140	65	85	3	2	1	1
26	Whareroa Stm	3	114	160	88	119	3	3	1	2
27	Hikutaia River	15	648	280	1036	458	3	1	6	2
28	Hinemaiaia River	15	28	26	16	23	1	1	0	0
29	Karapiro Stm	15	695	440	820	678	10	4	14	4
30	Kauaeranga River	15	330	120	747	237	2	1	4	1
31	Kawaunui Stm	15	868	600	755	1380	4	4	1	2
32	Kirikiriroa Stm	15	1366	600	2225	516	49	33	52	15
33	Komakorau Stm	15	127769	1300	490273	923	53	55	18	30
34	Kuratau River	3	21	28	15	21	9	2	14	18
35	Little Waipa Stm	15	160	140	80	85	2	1	1	1
36	Awakino River	14	136	70	138	120	9	2	17	7
37	Awakino River	14	873	220	1416	840	75	5	187	25
38	Mangaharakeke Stm	15	160	160	85	85	4	4	1	1
39	Mangakara Stm	15	226	160	196	165	4	4	1	2
40	Awaroa Stm	15	25007	240	95440	320	8	5	9	4
41	Mangakotukutuku Stm	15	1637	1200	1898	1301	30	24	20	16
42	Mangamingi Stm	15	660	250	771	643	3	3	0	1
43	Manganui River	14	536	176.5	899	450	58	3	109	30
44	Mangaohoi Stm	14	160	78	232	60	5	2	10	2
45	Mangaone Stm	15	1143	900	822	1183	10	6	15	4
46	Mangaonua Stm	15	2216	900	2977	1233	23	11	30	6
47	Mangaonua Stm	15	6517	400	22561	436	71	3	257	2
48	Mangapu River	15	2296	370	7120	597	26	8	64	11
49	Mangatutu Stm	14	575	235	521	890	9	3	13	5
50	Mangauika Stm	15	277	12	592	31	4	1	11	1
51	Mangawhero Stm	15	1788	1000	1837	1998	49	41	29	10
52	Mangawhero Stm	15	330	90	558	357	25	7	61	7
53	Mapara Stm	15	105	92	55	72	4	3	1	1
54	Marokopa River	15	634	190	798	1148	12	4	22	8
55	Mokau River	14	872	315	1106	1400	449	41	1161	80
56	Mokau River	15	620	100	1409	122	3	3	3	2
57	Mokau River	14	2053	450	3996	2580	80	10	132	133
58	Mokauiti Stm	14	2745	355	5428	1360	158	16	294	44
59	Ohautira River	15	2495	450	7354	493	19	10	29	7
60	Ohinemuri River	15	1110	170	2462	569	5	2	7	2
61	Ohinemuri River	15	1452	97	4590	530	4	1	11	1
62	Ohote Stm	15	613	266	840	483	16	9	12	21
63	Opuatia Stm	15	1297	240	2590	450	18	8	35	10
64	Oraka Stm	15	1213	1300	667	1010	4	3	2	3
65	Otamakokore Stm	15	213	190	112	125	2	2	1	1
66	Piako River	15	1218	330	2761	804	9	4	12	3
67	Piako River	15	1106	510	1339	1040	14	9	14	5
68	Piakonui Stm	15	588	110	1166	360	8	4	8	3
69	Pokaiwhenua Stm	15	168	130	113	176	2	2	1	1
70	Pueto Stm	15	48	32	59	15	2	2	1	1
71	Tahunaatara Stm	15	107	93	73	64	2	2	0	0
72	Tairua River	15	609	140	1719	231	4	2	5	1
73	Tapu River	15	608	190	1103	278	4	2	6	1

Figure 7. Boxplots illustrating log transformed median *E. coli* statistics from sites characterised by greater than 90% non-pastoral vegetation, and those characterised by greater than 90% pastoral vegetation. The outlined central box depicts the middle half of data between the 25th and 75th percentiles, the horizontal line across the box marks the median, the whiskers extend from the top and bottom of the box to depict the extent of the main body of data. Outliers are plotted individually as a circle.



3.2 TURBIDITY

Sampling for turbidity was undertaken at the same time as sampling for microbial analysis (section 3.1) for each of the 73 sites. As with the microbial dataset considerable variance is evident within many sites (Table 1). Median turbidity varies significantly across the region, ranging from < 1 to 55 Nephelometric Turbidity Units (NTU). This range reflects the spatial and temporal diversity of processes determining hillslope and channel sediment dynamics.

4. Relationships between environmental factors and faecal contamination

Analysis of the factors determining faecal contamination was undertaken both within individual sites and, through the use of median values, between sites across the region. The intra-site variability was assumed to be determined by those factors that vary on a temporal basis, whilst differences between sites are attributed to spatial variability. In the following analysis, flow, turbidity and seasonality were assumed to be the dominant controls upon variability within a site. Clearly though, other factors vary in a temporal manner, for example, the discharge of point sources, and stock density. Data describing these, however, was either provided in a mean annual format, or collated from one-off surveys (section 2). Consequently, in the analysis such data is necessarily treated as invariant in a temporal sense.

Bivariate relationships were used to examine the impact of each spatially varying factor upon median *E. coli* across the region. Pearson product-moment correlation (R) and the coefficient of determination (R^2) are given in Table 2 for each relationship. Since not all the independent variables are necessarily linearly related to median *E. coli* (for example, the percentage of all non-pastoral vegetation, Figure 11b), the Spearman Rank correlation (Rs) was also derived (Table 2) as this measures the degree of monotonicity in a relationship, rather than the degree of linearity. The Spearman Rank correlation is also able to better account for extreme values that increase the skewness of a dataset. Correlation between the environmental factors is given in Table 3.

All **median** *E. coli* concentrations are expressed as cfu/100 mL since Log_{10} transformations resulted in a poorer prediction of **median** faecal contamination by all the environmental variables examined. Non-median concentrations used in the *E. coli* – flow – turbidity relationships (Figures 8, 9 and 10) have been log transformed.

Table 2. Summary of the coefficient of determination (R^2), Pearson product-moment correlation (R), and Spearman Rank correlation (Rs) between median *E. coli* and each independent variable.

Independent factor	R^2	R	Rs
%_Pasture	0.23	0.48	0.59
Total_stockunits/km^2	0.29	0.54	0.58
Cattle_stockunits/km^2	0.34	0.58	0.60
%Indigenous_forest	0.15	-0.39	-0.38
%Non-Pastoral_Vegetation	0.27	-0.52	-0.63
%Wetland (all watersheds)	0.02	- 0.15	0.014
%Wetland (only watersheds with wetlands)	0.10	-0.32	-0.47
%Urban	0.15	0.39	0.47
%Well-drained_soil	0.18	-0.42	-0.57
%Poor_drained_soil	0.48	0.69	0.61
Rainfall	0.11	-0.33	-0.28
DominantSlope	0.17	-0.41	-0.29
%SteepSlope	0.24	-0.49	-0.32
Catchment_area	0.03	0.17	0.08
Median_turbidity	0.42	0.65	0.71
%Inland_water	0.01	0.10	0.06
Num_Dairy_effluent_discharges_to_land/km^2	0.02	0.14	0.3
Num_Non_Dairy_effluent_discharges_to_land/km^2	0.21	0.46	0.51
Num_Utility_effluent_discharges_to_land/km^2	0.03	0.17	0.18
Volume_Dairy_Point_Sources/km^2	0.10	0.32	0.51
Volume_Non_Dairy_Point_Sources/km^2	0.15	0.39	0.34
Volume_Utility_Point_Sources/km^2	0.05	0.22	0.36
Num_DairyPonds/km^2	0.11	0.33	0.58

Table 3. Correlation (R) between the independent variables.

Pearson Product-Moment Correlation

No Selector

	Pasture	NonPa_	Cattle	PoorDr_	WellDr_	Wetland	Rainfall	Steeps_	Urban	D_Point	ND_Po_	NonDeff	Ponds	Turb__
Pasture	1.000													
NonPast Veg	-0.987	1.000												
Cattle	0.784	-0.785	1.000											
PoorDrain	0.519	-0.576	0.644	1.000										
WellDrain	-0.295	0.323	-0.222	-0.517	1.000									
Wetland	0.038	-0.037	-0.077	-0.029	0.158	1.000								
Rainfall	-0.409	0.432	-0.408	-0.445	-0.070	-0.099	1.000							
Steepslopes	-0.509	0.557	-0.645	-0.697	0.011	-0.113	0.595	1.000						
Urban	0.092	-0.250	0.168	0.455	-0.228	-0.068	-0.209	-0.381	1.000					
D_Point	0.508	-0.483	0.611	0.346	0.025	-0.093	-0.145	-0.473	0.005	1.000				
ND_Point	-0.023	0.023	0.051	-0.046	0.125	-0.012	-0.029	-0.000	-0.006	-0.014	1.000			
NonDeff	0.360	-0.349	0.592	0.421	-0.104	-0.024	-0.303	-0.449	-0.041	0.311	0.091	1.000		
Ponds	0.522	-0.514	0.628	0.361	-0.003	-0.002	-0.149	-0.500	0.053	0.955	0.029	0.355	1.000	
Turb_median	0.402	-0.440	0.440	0.706	-0.405	-0.072	-0.277	-0.463	0.353	0.256	-0.059	0.204	0.237	1.000

Figure 8. Relationships between *E. coli* concentration ($\log_{10}$ cfu/100mL) and flow (L/s). The prefix on each axis label indicates the site number.

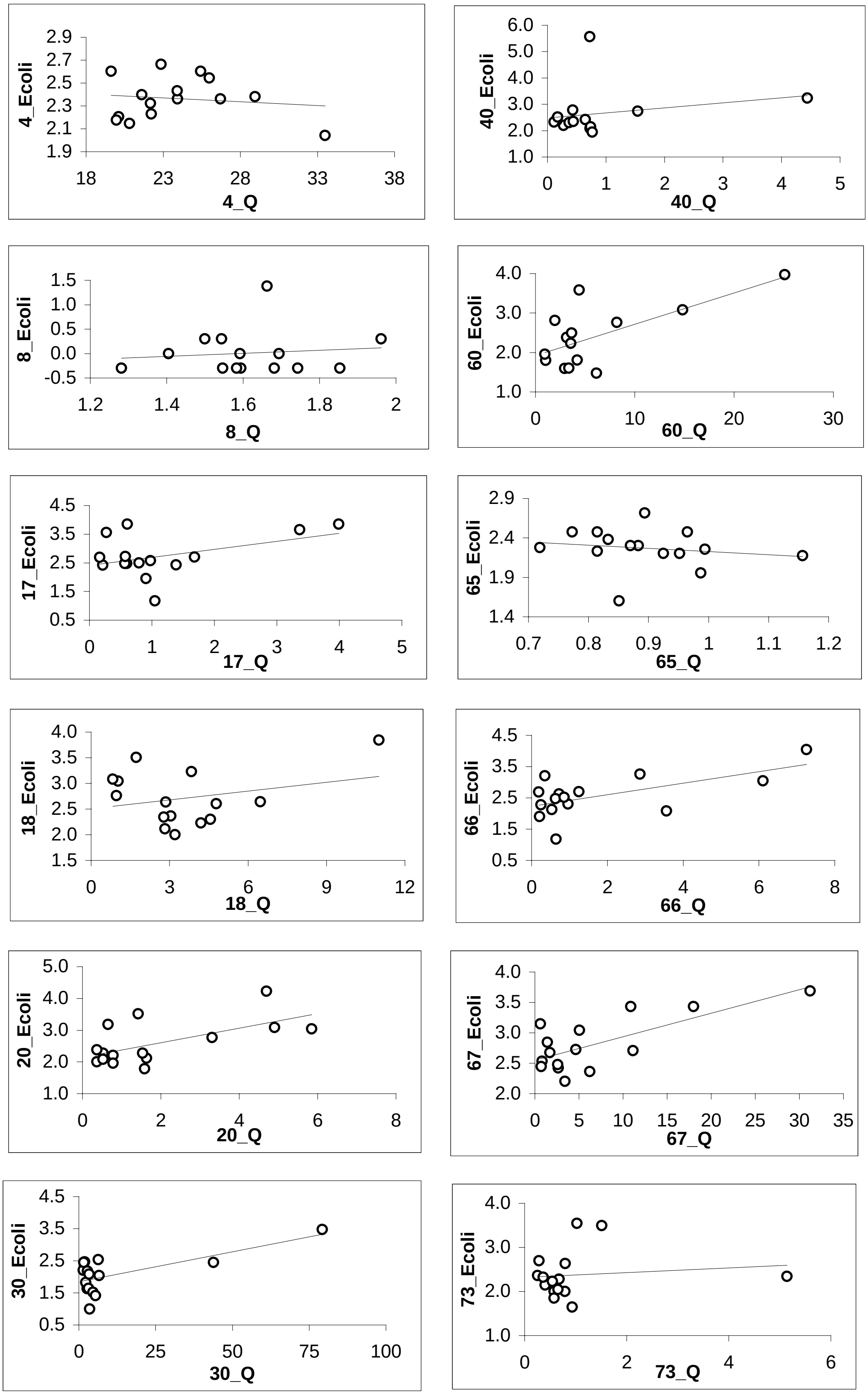


Figure 9. Relationships between turbidity (NTU) and flow (L/s). The prefix on each axis label indicates the site number.

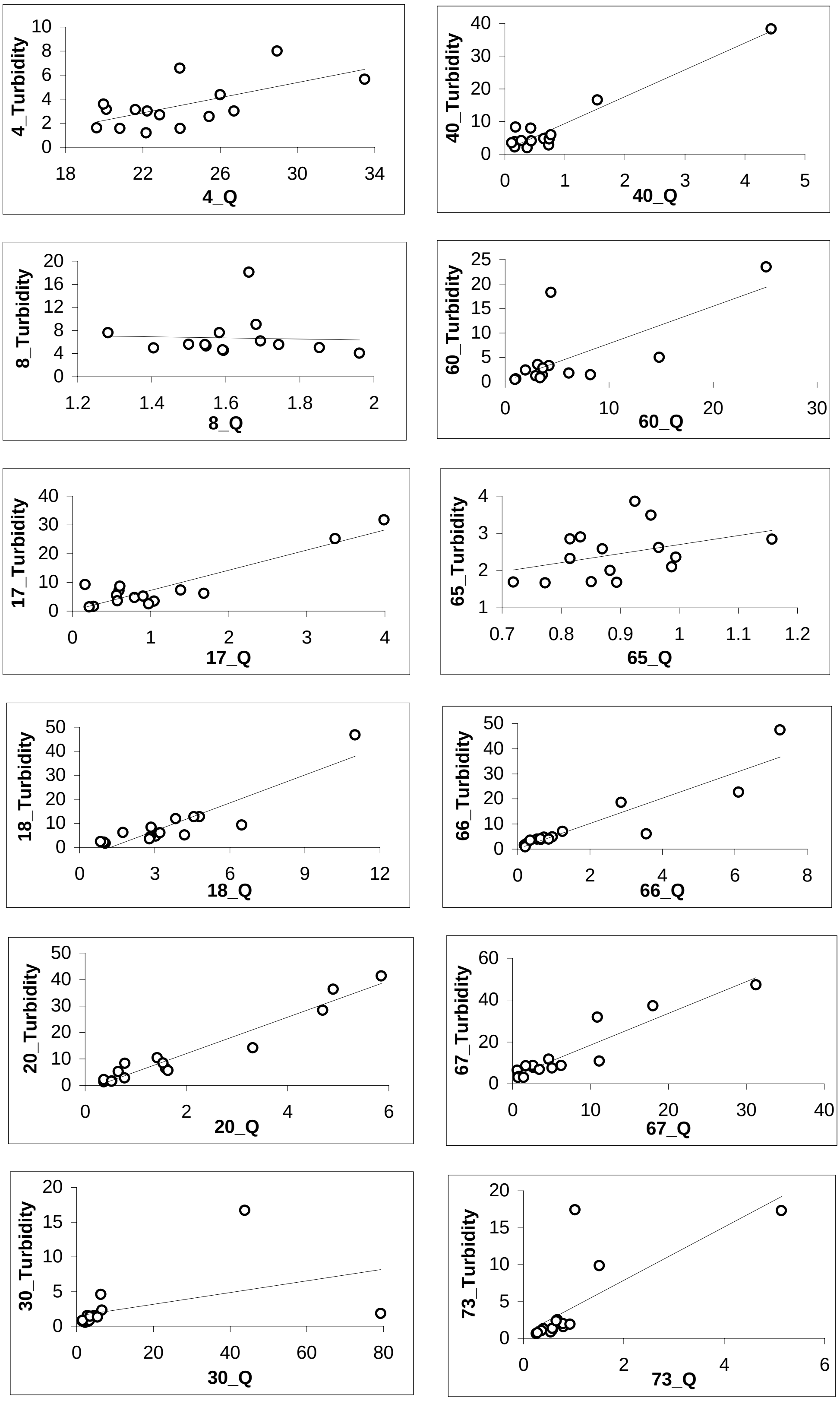
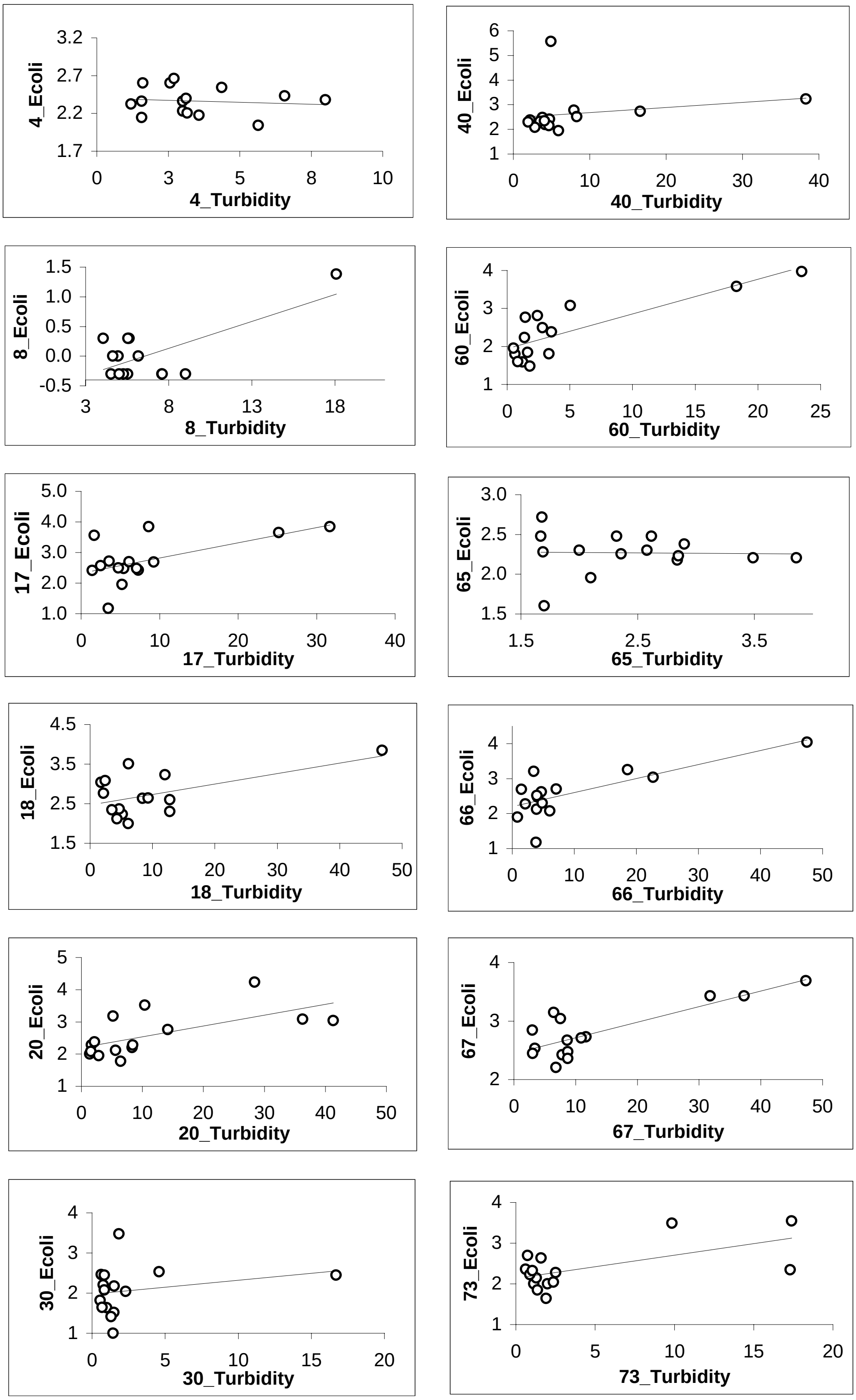


Figure 10. Relationships between *E. coli* ($\log_{10}$ cfu/100mL) and turbidity (NTU). The prefix on each axis label indicates the site number.



4.1 INTRA-SITE VARIABILITY

4.1.1 Flow and Turbidity

At 12 (of the 73) sites, instantaneous flow was recorded at the time samples were collected for *E. coli* analysis, enabling the relationship between these two variables to be examined. The resultant scatter plots (Figure 8) generally exhibit a positive linear relationship between log-transformed *E. coli* concentration and flow, although 2 sites, (4 and 65) exhibit an inverse relationship. The data at most sites are strongly skewed as most samples were collected at low to medium flow with just 2 or 3 samples collected at high flow. This skewness is also evident within the turbidity data (Figures 9 and 10). The increase in *E.coli* concentration with increasing flow generally observed at these sites is in accordance with findings from a number of other studies (for example, Nagels et al. 2001). This behaviour can be attributed to the wash-in of faecal material from grazed paddocks, and the entrainment of bacteria, previously deposited, from within bed sediments. As flow rises, turbidity increases and sunlight inactivation of bacteria suspended in the water column is decreased. In contrast, however, faecal bacteria discharged from point sources will tend to **decrease** in concentration with increasing flow, due to dilution. Watershed 4 (upstream of Okauia on the Waihou river) is characterised by significant point sources, and this may be the reason for the inverse relationship observed. Watershed 65 does not have any significant discharge of point sources. It should be noted, however, that sampling at both these sites encompassed a relatively limited range of flow, and it may be that over a greater flow range, a positive correlation between faecal bacteria and flow may be apparent. Intermittent cattle access to streams may contribute, at some sites, to the relatively high variance in faecal contamination observed at low flows (Figure 8). Cattle within a stream have been shown to increase turbidity and concentrations of faecal contamination by 2-3 orders of magnitude (Davies-Colley et al. 2002). Sampling undertaken downstream of an access point clearly, therefore, has the potential to record high levels of faecal contamination even at relatively low flow.

The relationships illustrated in Figure 8 indicate that some of the variance within a site can be attributed to variations in flow at the time of sampling. As a consequence, in order to aid interpretation and prediction of faecal contamination, attempts were made to minimise the flow-induced variance within the data. Two approaches were used. The first excluded from the analysis those *E. coli* samples that had been collected at greater than mean flow. This required that a flow record be available for each site. At 12 sites flow is recorded directly. For the remaining 61 sites a surrogate flow record was derived from a nearby stream or river. These surrogate records were obtained from FoSRT, Mighty River Power, Emco, Contact Energy, and Carter Holt Harvey. This approach typically led to 2 or 3 *E.coli* values being excluded from each site, resulting in a new set of (lower) median values for the region. Although this modified dataset was characterised by a lower variance, use of it resulted in a poorer relationship between **median** *E. coli* and all of the environmental variables. The use of surrogate flow data that was often derived from a river tens of kilometres from the sampling site was probably a key reason for this. Such a distance would have given rise to differences in the state of flow (at least on occasions) between the surrogate and actual sites.

The second approach used the turbidity dataset to discriminate those values statistically defined as an outlier or extreme outlier. It was assumed that high turbidity samples were collected at high flow and the corresponding *E.coli* concentration was, therefore, excluded from the faecal dataset. Evidence that this assumption was valid is provided by the flow-turbidity and *E. coli*-turbidity relationships derived for those 12 sites where instantaneous flow was recorded (Figures 9 and 10). Both sets of relationships are characterised by considerable scatter. However, they do illustrate a correlation between high flow, and high turbidity and *E. coli* concentrations. This suggests that turbidity may be a useful surrogate variable for *E. coli*, and that processes of entrainment of fine sediment generally may be similar to those mobilising bacteria. As with the mean flow criteria of the first approach, however, this second method led to no improvement in prediction of median *E. coli* values from the range of environmental factors. The inability of either method of accounting for flow-induced variance to improve explanation of faecal contamination, probably relates, in part, to the generally small reduction in median *E.coli* values that resulted.

4.1.2 SEASONALITY

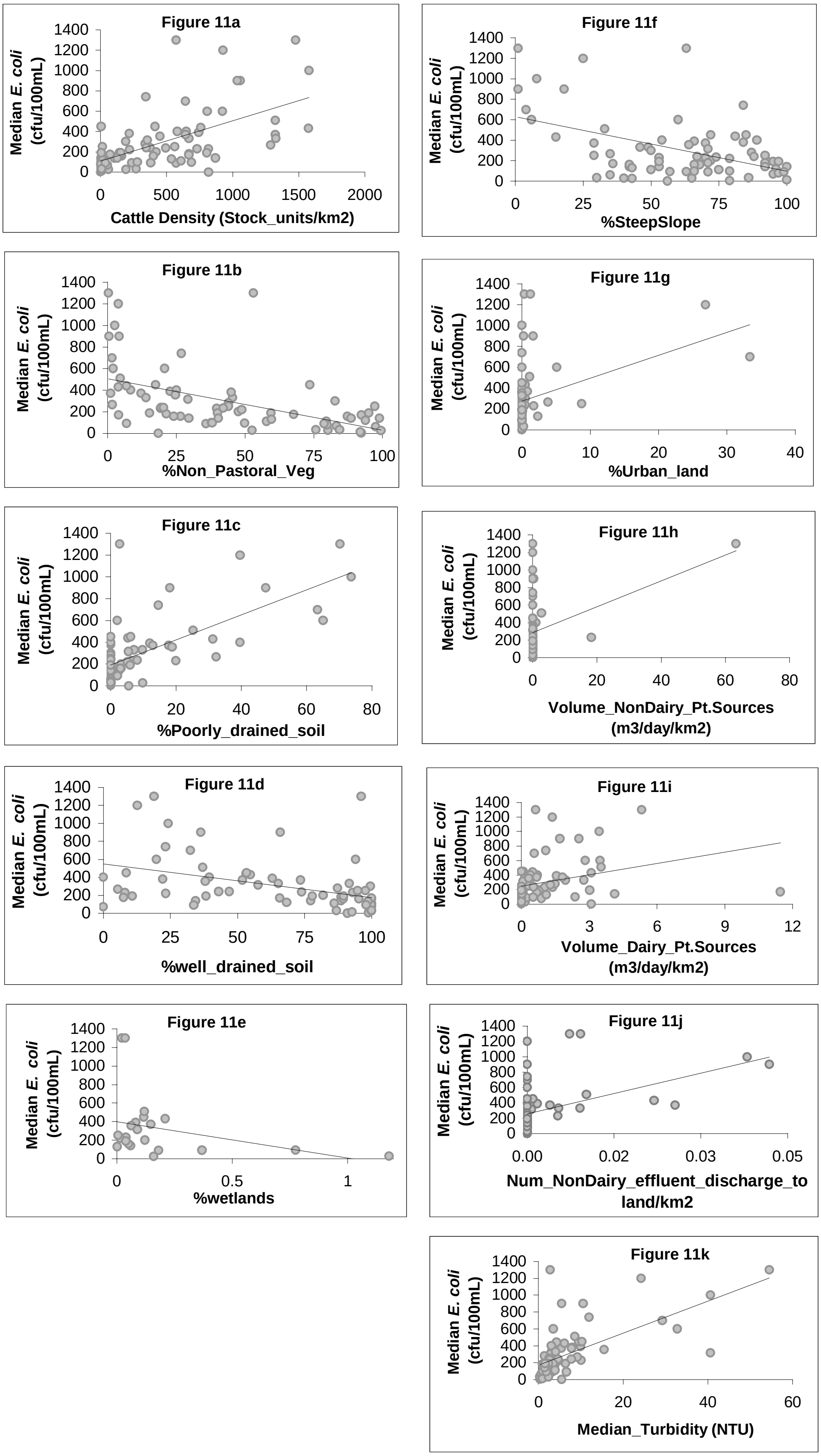
To assess the impact of season upon faecal contamination, *E. coli* concentrations at 12 sites were divided into winter (collected between April and September) and summer (collected between October and March) samples. No seasonal differences were found at these sites possibly because these were masked by the impact of flow variations. At five sites (15, 60, 61, 65, and 67) daily solar radiation data was available from one of 3 automatic weather stations located within 20km. At four of these sites a weak inverse relationship (R^2 ranged between 0.006 and 0.14) was found between *E. coli* concentration and mean daily solar radiation averaged over the day, and preceding day, of sampling. These relationships are consistent with die-off due to solar radiation.

4.2 INTER-SITE VARIABILITY

4.2.1 Livestock

It has been well established that grazing animals are an important causal factor in the faecal contamination of streams (section 1). This is reflected within the Waikato dataset through a comparison of median *E. coli* concentrations in streams draining pastoral catchments (>90% pasture) with those draining forested (>90% forest) ones (Figure 7). Furthermore, a correlation (R = 0.48, Rs = 0.59) exists between median *E. coli* concentration and the percentage of pastoral land within a catchment, across the region. This relationship strengthens (R = 0.54, Rs = 0.58) when stock density (stock units per km^2) rather than pastoral land is used as the independent variable. A further slight strengthening of this relationship (R = 0.58, Rs = 0.60) occurs when just cattle stock density is used as the predictor (Figure 11a), probably because cattle are attracted to water, depositing faecal material directly to streams. It is likely that the presence of livestock would be a stronger prediction of faecal contamination if cattle access to streams, or conversely, their exclusion from them, were known for each watershed. The acquisition of such data was not feasible at a regional scale in the present study.

Figure 11a-k. Relationships between environmental factors and median *E. coli*



4.2.2 Forest and Non-pastoral Vegetation

Catchments characterised by forest or non-pastoral vegetation exhibit relatively low median *E. coli* concentrations (Figure 7), and a weak inverse relationship exists (R = -0.39) between the percentage of land under indigenous vegetation and median *E. coli*, across the region. This linear relationship strengthens (R = -0.52) when the percentage of all non-pastoral vegetation is used as the independent variable (Figure 11b). The Spearman Rank correlation coefficient (Rs) is –0.63, indicating a relatively strong degree of monotonicity between non-pastoral vegetation and median *E. coli*. Figure 11b suggests this relationship may be non-linear. The exclusion of livestock from such land is clearly the principle reason for this correlation. Non-zero *E. coli* concentrations are observed, however, even in fully forested catchments (e.g. site 28), and this background level of contamination can probably be attributed to birds and mammals such as pigs, deer, possums and rats. This contamination from wild animals may be accentuated by the scarcity of ground vegetation under the shade of riparian trees, which might otherwise attenuate faecal material entrained in overland flow (R. Davies-Colley pers. comm.). Furthermore, shading by riparian vegetation will reduce, relative to pastoral catchments, the rate of sunlight die-off on land and in the water.

4.2.3 Soil Drainage

A relatively strong correlation (R = 0.69, Rs = 0.61) exists (Figure 11c) between median *E. coli* and the percentage of a catchment characterised by poorly drained soil (soil drainage classes 1 and 2). This is consistent with the hydrological characteristics of such soils whereby a relatively large volume of surface runoff is generated, rapidly transporting entrained faecal material to surface waters. Where such soils underlie grazed pastoral land, stock trampling may further impede the infiltration of water (Nguyen et al. 1998). The rapid hydrological response of such soils may also act to increase peak flows in receiving waters. Higher flow velocities associated with such a response would in turn lead to a greater relative entrainment of faecal material within such streams.

The analysis of soil drainage properties in this study did not account for the presence of subsurface drains, often installed under otherwise poorly drained dairying land. Although these drains reduce ponding and overland flow of surface water, they may also act to provide a flowpath by which subsurface faecal contamination can be rapidly transported to the channel network. Such an inference is supported by the recovery of *E. coli* concentrations in excess of 10,000 cfu/100mL from subsurface drains in Northland (L. Nguyen pers. commun.). Consequently, the correlation between median *E. coli* and poorly drained soil may, in part, be explained by the presence of subsurface drains.

An inverse relationship (R = -0.42, Figure 11d) is implied between median *E. coli* and the percentage of well-drained soils (soil drainage class 5) within a catchment, whilst the Spearman rank correlation coefficient (Rs = -0.57) indicates a relatively strong degree of monotonocity between the two variables. Reference to the matrix of correlation between independent variables (Table 3) suggests that this is partly an indirect relationship whereby the presence of well drained soil simply reflects the absence of poorly drained soil. It may, however, also indicate that well drained soils have a direct impact through minimising the generation of overland flow and enabling rainwater to infiltrate down through the soil horizons. This would lead to reduced contamination as the soil matrix is generally effective at filtering soil water through the attachment of faecal material to soil particles. It is important to note, however, that if a soil is exceptionally permeable due to macropores, then the filtration process will be minimal and subsurface flow may be of low bacterial quality.

4.2.4 Wetlands and Inland Water

A weak inverse relationship exists between the percentage of land within a catchment classified as wetland, and median *E. coli*. This relationship strengthens (R = -0.32, Rs = -0.47) if those catchments without any wetlands are excluded from the analysis (Figure 11e). With the exception of one site, all those catchments with wetlands are also characterised by > 40% pasture. These findings suggest that the presence of a wetland may act to trap faecal material, reducing levels of faecal contamination. It is likely that trapping efficiency will be dependent upon the rate of water moving through a wetland, decreasing with increasing flow.

The percentage of inland water (streams, rivers, ponds and lakes) within a catchment essentially exhibits no correlation with median *E. coli*. Although length of streambank may correlate positively with faecal contamination through influencing the degree to which cattle have access to waterways, such a relationship may be offset by the presence of lakes and ponds that may act to trap faecal material. However, no such conclusions can be drawn from this dataset.

4.2.5 Rainfall

An inverse relationship (R = -0.33, Rs = -0.28) exists between mean annual rainfall and median *E. coli*. This is probably because those areas within the region that receive high rainfall are also characterised by relatively low pastoral land use, as reflected by the negative correlation coefficient between these two variables (Table 3).

4.2.6 Slope and Catchment Area

A weak inverse relationship is apparent between dominant slope angle and median *E. coli*. This strengthens slightly when the percentage of steep slopes (Figure 11f) within a catchment is used as the independent variable (R = -0.49, Rs = -0.32). Steep slopes might be expected to exhibit a positive relationship with faecal contamination through increasing overland flow to streams. However, little pastoral land within the region lies on steep slopes, as indicated by the negative correlation coefficient between these two variables (Table 3).

It may be speculated that larger catchments, and therefore, a greater stream and river length may increase the time available for die-off and deposition of faecal material. In addition, the larger the catchment, the more likely it is to encompass flat land characterised by lower flow velocities that favour deposition. Catchment area, however, appears to have no influence upon median *E. coli* levels. This lack of a correlation may relate to the spatial distribution of contaminant sources within catchments. A point source discharge of faecal material located close to the catchment outlet, for example, will mask the impact of the processes outlined above.

4.2.7 Urban Area

The presence of urban areas (Figure 11g) appears to correlate weakly (R = 0.39, Rs = 0.47) with median *E. coli* concentrations. Urban runoff is known to have relatively high levels of faecal contamination, attributed, for example, to bird droppings and dog faeces. Furthermore, point source discharges from treated waste water (and some industries) within urban areas are likely to provide an appreciable input of faecal contamination direct to a stream or river.

4.2.8 Point Source Discharges

No strong correlation is apparent between median *E. coli* and the 3 categories of point sources across the region. The volume of non-dairy point sources (per day per km^2) apparently provides the strongest linear relationship (R = 0.39, Rs = 0.34), Figure 11h, primarily since this factor explains much of the variance caused by site 64, which has the joint highest median *E.coli* (1300 cfu/100mL) across the region. The stream network in watershed 64 directly receives 63 m^3/day/km^2 of non-dairy effluent, a far higher volume than any other watershed. Excluding site 64 from the bivariate relationship results in effectively no correlation between median *E. coli* and non-dairy point sources.

The direct discharge of dairy effluent to surface water is low, with a mean discharge of 1 m^3/day/km^2 across the region. This reflects a policy in recent years to reduce the direct discharge of effluent to surface water, and is the likely reason for the apparent lack of a strong correlation (R = 0.32, Rs = 0.51) with median *E. coli* concentrations (Figure 11i). The Spearman Rank correlation is stronger probably because it is better able to account for the skewed nature of the dairy point source data.

The lack of a strong correlation (R = 0.22, Rs = 0.36) between point source discharges from utilities and median *E. coli* may reflect the inclusion of discharges within this category that are not faecally-contaminated. In addition, recent improvements in the treatment of sewage and industrial waste-water (Waikato State of the Environment Report 1998, Vant 2001) may limit any relationship.

4.2.9 Effluent Discharges to Land

No strong correlation is apparent between the 3 sources of effluent discharge to land, and median *E. coli* across the region. Non-dairy effluent (Figure 11j) provides the strongest relationship (R = 0.46, Rs = 0.51). Expressing this data in terms of the number of occurrences, rather than the volume of discharge, may have masked a stronger correlation with the faecal contamination of streams. A tentative conclusion may be drawn, however, that effluent discharge to land does not markedly impact upon bacterial water quality.

4.2.10 Ponds

Since the presence of a pond generally reflects consent to discharge dairy effluent direct to a stream, a strong correlation exists between the two (Table 3). As with dairy point source discharges, the presence of dairy ponds shows no strong correlation (R = 0.33, Rs = 0.58) with median *E. coli* concentration. If climatic conditions are appropriate and effluent is contained within a pond for sufficient time, then significant microbial die-off may occur prior to discharge. This may act to weaken any correlation between ponds and discharge of dairy waste with faecal contamination of streams.

4.2.11 TURBIDITY

Median turbidity is a relatively strong predictor (R = 0.65, Rs = 0.71) of median *E. coli*, across the region (Figure 11k). A degree of correlation is to be expected given that both stream bed-sediments and the microbes settled within them are subject to entrainment as flow velocity increases. In addition, the processes by which overland flow detaches and transports soil particles on the hillslope are also applicable to faecal material. Median turbidity has a relatively strong correlation (R = 0.79) with the percentage of poorly drained soil within a catchment, and some correlation (R = 0.44) is apparent with the density of cattle (Table 3).

5. Development of statistical models

Multiple regression was used to examine relationships between median *E.coli* and environmental factors, and to derive a statistical tool with which to predict median concentrations across the region. Median *E.coli* concentration was used as the dependent variable, and the environmental factors in Table 2, the independent variables. The strength of relationships was assessed using the coefficient of determination (R^2), expressed as a percentage and adjusted for degrees of freedom. All environmental factors were examined in an interactive stepwise selection procedure, using DataDesk software, regardless of the strength of their bivariate relationship (section 4.2) with median *E.coli*. It is important to note that during this process independent variables were retained even if they were correlated with other independent variables in the model. The analysis derived a predictive model whereby four factors together explained 69% of the variance in median *E.coli* across the region. Each factor, and the partial R^2 associated with its addition to the regression model, is given in Table 4.

Table 4. The statistical model derived from all sites across the region.

Variable	Coefficient	Partial R^2	Comments
Constant	99.2		Intercept
%Poordrain	5.5	47.3	% of poorly drained soil
TurbMedian	9.4	49.2	Median turbidity
Cattle	0.14	52.6	Cattle stock units
NonDairyPtSource	15.6	69.2	Volume of non-dairy point sources

The factors were: the percentage of land with poorly drained soil, median turbidity, cattle density (stock units/km^2), and the volume of non-dairy point source discharge (m^3/day/km^2), providing the following relationship (Equation 1).

$$MedianE.coli = 99.2 + (5.5 \times \%Poordrain) + (9.4 \times TurbMedian) + (0.14 \times Cattle) + (15.6 \times NonDairyPtSource)$$

...Equation 1

The addition of non-dairy point sources to the statistical model increased the variance explained from 55% to 69%, but this was primarily attributed to the median value at just one site (site 64, see section 4.2.8). Since non-dairy point sources are not a strong predictor of median *E. coli* **across the region**, a second regression model was developed, which excluded site 64 from the analysis, whereby four factors explained 68% of variance (Equation 2 and Table 5), with the first 3 factors being common to both models.

$$MedianEcoli = 195.6 + (4.1 \times \%Poordrain) + (8.4 \times TurbMedian) + (0.17 \times Cattle) - (1.4 \times \%Welldrain)$$

…Equation 2

Co-linearity is apparent between the independent variables within the models (Table 3), notably between the percentage of poorly drained soil and median turbidity (R=0.79). Co-linearity means that equations 1 and 2 should not be used to draw inferences about the relative contributions to median *E. coli* concentrations made by each of the independent variables.

The equations will be most reliable for predicting *E. coli* concentrations in unmonitored catchments where the relationships between independent variables are similar to those in the original dataset. This is likely to hold in most places throughout the Waikato Region but may not apply elsewhere in the country. Both models are characterised by fairly high intercepts (99, 196) reflecting faecal contamination in the absence of grazing livestock (see section 4.2.2). Implications drawn from the statistical models are discussed in section 6.

Table 5. The statistical model derived excluding site 64 (with an unusually high point discharge).

Variable	Coefficient	Partial R^2	Comments
Constant	195.6		Intercept
%Poordrain	4.1	59.9	% of poorly drained soil
TurbMedian	8.4	62.9	Median turbidity
Cattle	0.17	65.9	Cattle stock units
%Welldrain	-1.4	67.5	% of well drained soil

6. Management Implications

Results from the EW in-stream monitoring programme indicate that *E. coli* concentrations generally increased with flow by roughly an order of magnitude over the flow range encountered. Results elsewhere from dedicated storm monitoring indicate, however, that a 2 or 3 order of magnitude increase in microbial concentration may occur over flood events (Muirhead 2001, Wilkinson et al. 1995). These findings suggest that low frequency sampling regimes, since they are unlikely to capture large storm events, preclude an accurate estimation of microbial flux. Where estimates of microbial loads are required (for example, in catchments supporting estuarine shellfish farming), high frequency sampling during storm events is necessary (Davies-Colley et al. 2001).

Bivariate relationships derived from the EW water quality monitoring program exhibit a correlation, at individual sites, between *E. coli* and turbidity. Within a site, therefore, turbidity data may be of use as a surrogate variable for *E. coli* offering a cheaper alternative to the direct monitoring of faecal contamination, especially if high frequency sampling is desirable. Across a region, however, turbidity may only provide a broad indication of median faecal contamination since, for example, highly erodible soils (that contribute to high turbidity) may not be subject to livestock grazing. Conversely, non-erosive soils may be subject to intensive grazing and point sources of faecal contamination.

The pattern of microbial contamination across the Waikato region is strongly influenced by the presence of grazing livestock. This finding supports the assertion of Vant (2001) that non-point agricultural sources now provide the dominant contribution to faecal contamination in the Waikato River. Strategies to reduce faecal contamination of streams and rivers must, therefore, address this primary, diffuse source. It is likely, although unproven within this study owing to data limitations, that the degree of cattle access to streams is important in determining the level of faecal contamination of waterways. This is because cattle deposit faecal material directly to streams, and onto stream banks where it is readily washed into the channel by overland flow or entrained by rising streamwater. Wash-in by overland flow may be accentuated by cattle treading which reduces the trapping efficiency of riparian soils (Nguyen et al. 1998). Permanent fencing to exclude livestock from stream channels and a proportion of riparian land is likely to be an effective measure to reduce faecal contamination by grazing cattle. Quantifying the effectiveness of this management intervention is difficult and, at present, the relative importance to faecal contamination of direct and near-channel deposition compared with overland flow from elsewhere in the catchment is not clear (Davies-Colley and Parkyn 2001). There are a number of riparian management alternatives to permanent fencing that may not be as effective, but could help reduce faecal contamination. These are summarised from Davies-Colley and Parkyn (2001), and illustrated in Table 6.

Table 6. Options for livestock management in riparian zones to reduce faecal contamination. Summarised from Davies-Colley and Parkyn (2001).

Management approach	Benefits	Notes
Permanent fencing, and therefore, growth of riparian vegetation	Removal of direct and near-channel deposition of faecal material. Increased trapping efficiency of microbes washed downslope in overland flow	Fencing costs, planting costs, weed and pest management required. Planting needed for best outcome ?
Temporary fencing	Temporary benefits as above. Can also be used to selectively control animal access, for example prevent access when soils are wet	Considerable management required for weed control and maintenance of grass sward
Rest-rotation grazing	Permits soil and grass recovery between grazing episodes aiding trapping efficiency of microbes in overland flow	Requires considerable fencing and stock management.
Off-stream watering	Removes one incentive for livestock to access streams. Reduced direct and near-channel deposition of faecal material	Water may not be the only or main reason for stock access to streams
Off-stream shade & shelter	Removes one incentive for livestock to access streams. Reduced direct and near-channel deposition of faecal material	Shade and shelter may not be the only or main reason for stock access to streams
Livestock bridges on farm races	Removes livestock access where raceway intercepts stream channel	Costly? Main application on dairy farms ?

Despite its likely importance, stock access to streams is difficult to quantify, particularly at a regional scale. Although riparian planting can be identified from land cover maps or aerial photos, its presence does not necessarily indicate stock exclusion. Field survey within this study indicated that cattle access to streams is highly variable within a catchment. Methods are required for characterising riparian zones across a region, with respect to livestock access and the entrapment of faecal material entrained within overland flow.

Soil drainage properties explain much of the variation in streamwater faecal contamination and the percentage of poorly drained soil within a watershed is a key factor within the statistical model that predicts median *E. coli* across the region. Two possible mechanisms giving rise to this correlation are: enhanced surface flow, and artificial drainage. It is not possible to determine which mechanism predominates in a statistical analysis of this kind and further experimental studies are desirable. Nevertheless, the strength of poorly drained land as an explanatory variable has important implications for land management, suggesting that bacterial water quality on poorly drained land would benefit from (1) better riparian protection to maximise filtering of faecal material within overland flow and, (2) better management of subsurface drainage systems, for example, through wetland treatment of drainage flows.

The importance of soil drainage properties is further illustrated through reference to the relationship between median *E. coli* and the discharge of dairy effluent to land (Figure 12). Here, the sites with the greatest discharge of dairy effluent (sites 8, 31 and 54) do not have particularly high median *E.coli* concentrations. Since these three sites are all characterised by well-drained soils (>90%) an inference may be drawn that the good soil drainage properties act to attenuate the transport of faecal material from land to the channel network. In contrast to poorly drained land where riparian planting may be particularly effective, on well-drained soils, faecal material is more likely to be attenuated by infiltration into the soil matrix.

Given the weak inverse relationship between the presence of wetlands within pastoral (> 40%) catchments, and median *E. coli* (section 4.2.4), it can be tentatively concluded that wetlands generally act to attenuate faecal contamination. Destruction of existing wetlands is, therefore, likely to have a detrimental impact on bacterial water quality. Such an inference may only be applicable to the wetlands large enough (> 1 ha) to be included in the land cover data used in this study, as they are unlikely to be substantially grazed by livestock. Studies of small (<10 m) hill-country wetlands (Collins 2002) indicate, however, that cattle are attracted to them to graze, and that they can be a source of faecal contamination. Management of these wetlands to exclude livestock from them may therefore be necessary to reduce faecal contamination of hill-country streams.

7. Conclusions

Analysis of the EW *E. coli* dataset has confirmed that faecal contamination of streams and rivers occurs throughout the region. Median concentrations range from 1 to 1,300 cfu/100 mL and, at 53 of the 73 sites sampled, they exceed the guideline of 126 cfu/100 mL for contact recreation. Bivariate relationships derived at individual sites were characterised by considerable scatter, but showed moderately high correlation between flow, *E. coli*, and turbidity. Some of the variance in *E. coli* concentration at a given site can be attributed to variations in flow. Turbidity may be a useful surrogate variable for *E. coli* at a given site although sampling a range of flows would be required to establish the correlation between *E. coli* and turbidity. Such correlations may still have a moderately high unexplained variance and generally cannot be transferred to other sites.

Examination of the microbial dataset in conjunction with a range of environmental factors, such as land use and soil type, has highlighted the key controls upon faecal contamination. The pattern of contamination across the Waikato is strongly influenced by the presence of grazing livestock and the highest median *E. coli* concentrations are generally associated with the most intensive dairy farming in the centre of the region. Conversely, the lowest median values are found in forested catchments, although concentrations are always detectable, indicating contamination by wild animals.

A relatively strong relationship exists between the percentage of a catchment characterised by poorly drained soil and median *E. coli* across the region. This is probably attributable to the generation of a relatively large volume of surface runoff on these soils that is able to entrain faecal material and quickly transport it to the stream network. It is also probable that the installation of sub-surface drains and drainage ditches in poorly drained soils accelerates the transport of faecal microbes to streams. The bacterial water quality of streams draining such soils is likely to be particularly sensitive to livestock grazing and the application of effluent to land. Appropriate mitigation measures on land underlain by poorly drained soils may include the adoption of less intensive farming practices, optimising the timing of effluent application to land to avoid periods when the soil is saturated, wetland treatment of wastes, surface runoff and drainage flows, and retirement of riparian areas.

Median turbidity is a relatively strong predictor of median *E. coli* across the region. This indicates that the processes mobilising fine sediment, both on the hillside and in-stream, apply also to bacteria.

A statistical model, developed to predict median *E. coli* concentrations at the regional scale, explains almost 70% of the observed variance. The percentage of poorly drained soil, the density of cattle within a catchment, and median turbidity at a catchment outlet, are the 3 key factors incorporated into the model.

With the exception of a few sites, the discharge of point sources direct to waterways appears not to influence **median** *E. coli* concentrations in the Waikato region. This is attributed to a relatively low number of consented discharges that can cause faecal contamination, and to recent improvements in the treatment of waste water.

Strategies to reduce faecal contamination of streams and rivers in the Waikato region should focus upon grazing livestock. Cattle access to streams and near-channel areas is likely to be important in determining the level of faecal contamination and mitigation measures may therefore be best directed at riparian zones. Permanent fencing to exclude livestock from stream channels and a proportion of riparian land is likely to be the most effective measure in reducing faecal contamination by grazing cattle. There are also a number of riparian management alternatives to permanent fencing that may not be as effective, but may still result in reduced faecal contamination.

A weak inverse relationship was derived between the presence of a wetland within a catchment and median *E. coli*. A tentative inference is drawn therefore, that those wetlands within the region that are large enough to be discriminated on the land cover map, act to attenuate bacteria. Protection of these wetlands is therefore likely to be beneficial in reducing faecal contamination. A distinction is made, however, between the larger lowland wetlands found, for example, on the Hauraki plains, and small hill-country wetlands. Studies elsewhere have shown that cattle are attracted to the latter, and that they can sometimes be a source rather than sink for faecal contamination to waterways.

8. Acknowledgements

This study was funded by the Ministry of Agriculture and Forestry – Sustainable Resource Use Policy.

Summary statistics for land use, animal numbers, soil drainage, point source and effluent discharges, and dairy ponds were provided by Environment Waikato for the 73 watersheds analysed in this study. Some of these statistics were derived from datasets purchased by Environment Waikato under formal licensing agreements with external agencies, as follows:

Landcover database – Terralink New Zealand Limited

Animal numbers – AgriQuality New Zealand Limited

Soil drainage – Landcare Research New Zealand Limited

Resource consent data (point source and effluent to land discharges) was derived from the Environment Waikato Authorisation database (RUAMS).

We are grateful to a number of Environment Waikato staff, and Len Brown in particular, for deriving the summary statistics for each watershed. Bill Vant (Environment Waikato) is also thanked for providing considerable background information and contributing to the design of the methodological approach. We would also like to thank Rob Davies-Colley, Kit Rutherford, and Graham McBride (NIWA) for reviewing the report.

9. References

Collins, R.P. (2002). Faecal contamination of subsurface soil water under pastoral land. NIWA Client Report EVW02239

Crowther, J.; Kay, D.; Wyer, M.D. (2001). Relationships between microbial water quality and environmental conditions in coastal recreational waters: the Fylde coast, UK. Water Research, 35, 17, 4029-4038

Davies-Colley, R.J; Nagels, J.W.; Donnison, A.M.; Muirhead, R.W. (2001). Faecal contamination of rural streams – implications for water quality monitoring and riparian management. 43rd annual conference of the New Zealand Water and Wastes Association, 19th-21st September, 2001. Wellington, New Zealand.

Davies-Colley, R.J.; Nagels, J.W.; Smith, R.; Young, R.; Phillips, C.R. (2002). Water quality impacts of cows crossing the Sherry River, Tasman District, New Zealand. In prep. For Water Science and Technology

Davies-Colley, R.J; Parkyn, S. (2001). Effects of livestock on streams and potential benefits of riparian management. Issues and options in the Auckland region. NIWA Client Report ARC01275/1

Davies-Colley, R.J.; Stroud, M.J. (1995). Water Quality Degradation by Pastoral Agriculture in the Whanganui River Catchment. NIWA Client Report DoC050/1

Doran, J.W.; Linn, D.M. (1979). Bacteriological quality of runoff water from pastureland. Applied and Environmental Microbiology, 37, 5, 985-991

Duncanson, M.; Russell, N.; Weinstein, P.; Baker, M.; Skelly, C.; Hearnden, M.; Woodward, A. (2000). Rates of notified Cryptosporidiosis and quality of drinking water supplies in Aotearoa, New Zealand. Water Research, 34, 15, 3804-3812.

Fleming, P.H; Burtt, E.S. (1991). Farm Technical Manual. Farm Mangement Department, Lincoln University, Canterbury, New Zealand.

Gary, H.L.; Johnson, S.R.; Ponce, S.L. (1983). Cattle grazing impact on surface water quality in a Colorado front range stream, Journal of Soil and Water Conservation, 38, 124-128

Hewitt, A. E; (1993). Methods and rationale of the New Zealand Soil Classification. Landcare Research Science Series 2. Lincoln, New Zealand, Manaaki Whenua Press 71p

Longhurst, R.D.; O'Connor, M.B. (2002). Watershed assessment in the Waikato region. AgResearch client report prepared for NIWA.

McBride, G.; Till.D.; Ryan, T.; Ball, A.; Lewis, G.; Palmer, S.; Weinstein, P. (2002). Freshwater Microbiology Research Programme. Pathogen occurrence and human health risk assessment analysis. Report in preparation

Muirhead, R.W. (2001). Faecal contamination and flood events in a rural stream. Unpublished Master of Science thesis. University of Waikato, Hamilton, New Zealand

Nagels, J. W.; Davies-Colley, R.J.; Donnison, A.M.; Muirhead, R.W. (2001). Faecal contamination over flood events in a pastoral agricultural stream in New Zealand. Water Science and Technology (in Press)

Nguyen, M.L.; Sheath, G.W.; Smith, C.M.; Cooper, A.B. (1998). Impact of cattle treading on hill land. 2. Soil physical properties and contaminant runoff. New Zealand Journal of Agricultural Research, 41, 279-290

Niemi, R.M.; Niemi, J.S. (1991). Bacterial pollution in pristine and agricultural lands. Journal of Environmental Quality, 20, 620-627

Savill, M.G; Hudson, J.A.; Ball, A; Klena, J.D.; Scholes, P.; Whyte, R.J.; McCormick, R.E; Jankovic, D. (2001). Enumeration of Campylobacter in New Zealand recreational and drinking waters. Journal of Applied Microbiology, 91, 38-46

Smith, J.H.; Wickham, J.D.; Norton, D.; Wade, T.G.; Jones, K.B. (2001). Utilization of landscape indicators to model potential pathogen impaired waters. Journal of the American Water Resources Association, 37, 4, 805-814.

Smith, C.M.; Wilcock, R.J.; Vant, W.N.; Smith, D.G.; Cooper, A.B. (1993). Towards sustainable agriculture: freshwater quality in New Zealand and the influence of agriculture. NIWA Ecosystems report for MAF Policy and Ministry for Environment.

Sukias, J. P. S.; Tanner, C.C.; Davies-Colley, R.J.; Nagels, J. W.; Wolters, R. (2001). Algal abundance, organic matter, and physico-chemical characteristics of dairy farm facultative ponds: implications for treatment performance. New Zealand Journal of Agricultural Research, 44, 279-296.

Trevisan, D.; Vansteelant, J.Y.; Dorioz, J.M. (2002). Survival and leaching of fecal bacteria after slurry spreading on mountain hay meadows: consequences for the management of water contamination risk. Water Research, 36, 275-283

Vant, W. N. (2001). New challenges for the management of plant nutrients and pathogens in the Waikato River, New Zealand. Water Science and Technology, 43, 5, 137-142

Waikato State of the Environment Report; (1998). Environment Waikato Regional Council

Wilcock, R.J. (1986). Agricultural run-off: a source of water pollution in New Zealand? New Zealand Agricultural Science 20, 2, 98-103

Wilkinson, J.; Jenkins, A.; Wyer, M.; Kay, D. (1995). Modelling faecal coliform dynamics in streams and rivers. Water Research, 29, 847-855