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Water Quality of the Hauraki Rivers and Southern Firth of Thames, 2000–09

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Disclaimer

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Over the past 20 years, many members of Waikato Regional Council's Environmental Monitoring team have helped with the collection of surface water quality and river flow information that is reviewed and analysed here. Team members Stuart Beard and Nathan Singleton also helped with the estuarine and coastal water studies reported here. Donna Jones, Ed Prince, Melissa Purcell and Bruce Willoughby helped locate and collate the consent monitoring information that is analysed here. Karl Safi (NIWA) analysed the algal samples collected from the lower Waihou River. Clint Prior prepared the maps used in this report, and Peter Singleton made helpful comments on a draft of it.

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Abstract

Several rivers in the Hauraki area flow in a generally northerly direction into the Southern Firth of Thames. Information from recent studies of the water quality of these rivers and the Southern Firth was collated and analysed. Water quality has been monitored monthly at 17 sites on the Hauraki rivers, beginning during 1990–94. The water quality of the Southern Firth of Thames was studied during 2006–07, while that of the extensive estuarine section of one of the rivers was studied during 2009–10. Information is also available for the 22 moderate-to-large discharges of sewage or industrial wastewaters that enter the rivers.

The quality of the water in the Kauaeranga River was mostly excellent, being well-oxygenated and clear, and containing low concentrations of total nitrogen (N) and total phosphorus (P), and moderate concentrations of *Escherichia coli* bacteria. However, this river accounted for just 8% of the combined flow of the Hauraki rivers. Conversely, the water quality of the Piako (10% of the combined flow) and Waitoa (7%) Rivers was generally poor, being somewhat oxygen-depleted and murky, and with particularly high concentrations of total N and total P (5–7 times higher than guideline values). Concentrations of *E. coli* were also high (6 times higher than guideline values). The water quality of the largest river, the Waihou (75% of the combined flow), was intermediate: at the most downstream site on the main-stem the water was often well-oxygenated, but was murky, and concentrations of total N, total P and *E. coli* were 2–3 times higher than guideline values. The water quality of its main tributary the Ohinemuri River, however, was generally good.

Many (67%) of the records of river water quality at the 17 sites have been reasonably-stable over the past 20 years. Some 18% of the records showed important improvements, while 15% showed deteriorations. Several of the improvements have resulted from improved treatment of the wastewaters that are discharged to the rivers. In some cases these appear to have offset the effects of more intensive farming on the concentrations of total N and total P that are found in the rivers. At other sites, however, concentrations of total N have increased, probably as a result of the overall intensification of farming in the catchments of these rivers.

Moderately-high concentrations of algal chlorophyll *a* were found in the estuarine section of the lower Waihou River, near the zone of the “estuarine turbidity maximum”. However, the species found here were mostly coastal, and so were unlikely to be actively-growing as the water was fresh and highly turbid; furthermore, there was no evidence of any biological uptake of N or P. Naturally-occurring processes associated with the mixing of fresh and saline waters can retain and concentrate small particles, and are probably responsible for the high concentrations of both suspended solids and chlorophyll found in this section of the river.

Mass flows of total N and total P during 2000–09 were determined at 11 sites on the Hauraki rivers. Altogether the rivers carried about 3360 t/yr of nitrogen and 270 t/yr of phosphorus to the Southern Firth of Thames. The Waihou River carried 50–60% of the combined mass flows while the Kauaeranga River carried 2–4%; the Piako and Waitoa Rivers each carried about 20%. The 22 point source discharges contributed about 8% of the nitrogen and 25% of the phosphorus that was carried by the rivers. Background sources were estimated to contribute about 23% of the combined mass flow of total N and 28% of the total P. The remaining 70% of the combined mass flow of total N and 46% of the total P is likely to have come from diffuse agricultural sources in the rivers' catchments. During 2000–09 the combined mass flow of nitrogen carried by the rivers increased at a rate of about 1% per year, while the combined mass flow of phosphorus decreased at a rate of about 5% per year.

The water quality of the Southern Firth of Thames was generally good. The water there was mainly seawater, indicating that the freshwater inflows from the Hauraki

rivers were generally highly-diluted. The water column was weakly-stratified and well-oxygenated. Although murky, it was probably sufficiently well-lit to support algal growth. The water contained moderate concentrations of N and P, and low-to-moderate concentrations of algal chlorophyll *a*, with values being substantially lower than those found in nutrient-enriched coastal waters elsewhere (e.g. Auckland's Manukau Harbour).

1 Introduction

The Firth of Thames is the largest semi-enclosed coastal waterbody in the Waikato region (Figure 1). There are four moderately-large rivers that flow into the southern part of the Firth: the Kauaeranga, Piako, Waitoa and Waihou Rivers (Figure 1).[1] The Waitoa joins the Piako River about 40 km upstream of its mouth. A fifth river, the Ohinemuri, is a major tributary of the Waihou River. In this report these rivers are collectively called the “Hauraki rivers”. Altogether the area of the land that drains to the Firth is about 4200 km^2; about 65% of this area is in pasture, with about 20% in native bush (Turner et al. 2006). About 60,000 people live in this catchment,[2] many (c. 60%) in one of seven moderate-sized towns (c. 3500–7000 people each).

Table 1 lists some important characteristics of the catchments of the Hauraki rivers, showing that the pressures on them differ markedly. At one extreme the catchment of the Kauaeranga River is mostly covered by indigenous vegetation (89%), and there are no point source discharges to the river. By contrast, the catchments of the Piako and Waitoa Rivers are mostly covered in pasture (90%; mainly dairy), and there are several point source discharges to these rivers.

The Firth of Thames is approximately 30 km long and 20 km wide, and covers an area of about 600 km^2. The depth of the water increases progressively towards the north where it approaches about 30 m, resulting in a generally wedge-shaped bathymetry. Little is known about the water quality of the Firth, in particular about the concentrations of the plant nutrients nitrogen (N) and phosphorus (P), and the biomass of freely-floating, microscopic algae (or “phytoplankton”) whose growth they support (Williamson et al. 2003).

The Waikato Regional Council operates a routine river water quality monitoring programme that includes a number of sites on the Hauraki rivers. It also issues the resource consents that permit the discharge of treated wastewaters to these rivers; consent holders are required to monitor the flow and water quality of these discharges and to provide the information to the Council. Vant (1999) used this information to make some preliminary estimates of the relative importance of the various sources of the N and P that was carried by the Hauraki rivers in the 1990s. Finally, in recent years the Council has undertaken special studies on the water quality of the estuarine section of one of the rivers (Waihou River) and of the southern part of the Firth of Thames.

This report collates, analyses and interprets the available information to address the following matters:

- What is the current water quality of the Hauraki rivers?
- Has this changed in the past 20 years, and if so how?
- What mass flows of N and P do the Hauraki rivers currently carry into the Southern Firth of Thames?
- What are the main sources of these mass flows of N and P—how important are consented discharges of wastewaters?
- What is the current water quality of the Southern Firth of Thames, in particular what are the concentrations of N and P, and what level of algal biomass do these nutrients support?

[1] The north-western part of the Hauraki Plains is drained by a network of canals that enter the Firth near Waitakaruru. The flows and water quality of these canals are not monitored, however, and so are not discussed here.
[2] Results of 2006 census, http://www.stats.govt.nz/Census/2006CensusHomePage/QuickStats/AboutAPlace.aspx

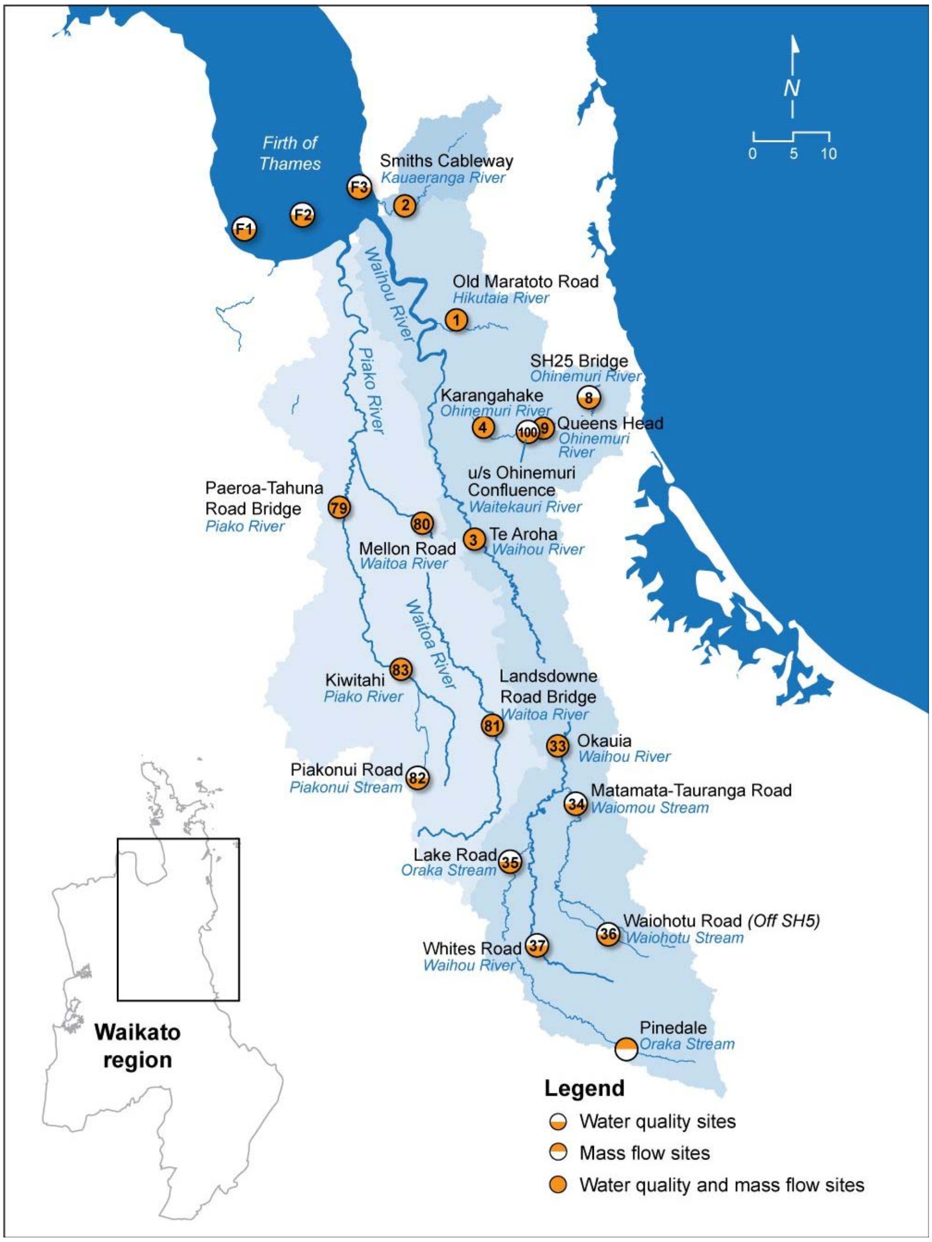

Figure 1: The Firth of Thames and the main rivers that flow into it, showing 17 sites at which river water quality is routinely monitored, 11 river sites at which the mass flows of nitrogen and phosphorus were determined and three sites in the Southern Firth where water quality was monitored during 2006–07.

Table 1: Average river flows during 2000–09 and important catchment characteristics at key sites on the Hauraki rivers (see Fig. 1). The number of moderate-to-large point sources discharging to each river as a whole is also shown (see later). The land use information is from Jenkins & Vant (2007).

	Kauaeranga at Smiths	**Piako at Paeroa-Tahuna Rd**	**Waitoa at Mellon Rd**	**Ohinemuri at Karangahake**	**Waihou at Te Aroha**
Flow (m^3/s)	5.8	6.9	4.8	11.1	37.2
Catchment area (km^2)	120	540	410	285	1100
Indigenous vegetation	89%	5%	3%	47%	24%
Exotic forest	5%	<1%	<1%	<1%	16%
Dairy pasture	0%	66%	69%	32%	44%
Drystock pasture	5%	25%	21%	14%	14%
Other	1%	4%	7%	6%	3%
Point source discharges	0	5	4	4	8

2 Water quality of the Hauraki rivers

Monitoring

Waikato Regional Council operates 15 routine water quality monitoring sites on the Hauraki rivers (Beard 2010).[3] A further two sites are monitored as part of NIWA's national river water quality network (Ohinemuri River at Karangahake and Waihou River at Te Aroha). The river network and the locations of the monitoring sites are shown in Figure 1. Monitoring of the 17 sites began in during 1990–94. The sites are visited monthly, with field measurements being made (water temperature, dissolved oxygen and water clarity), and samples being collected for analysis in the laboratory.

2.1 Current condition

Waikato Regional Council uses a range of water quality variables to assess river water quality (e.g. Beard 2010). The suitability of water to support a healthy ecosystem is assessed based on the following seven variables: dissolved oxygen, pH, turbidity, water temperature, total ammonia, total phosphorus and total nitrogen. The suitability of the water for swimming is assessed based on levels of horizontal water clarity and *Escherichia coli* bacteria. Specified criteria are used to distinguish water that is unsatisfactory, satisfactory or excellent for these uses.[4] Results for these variables for the decade 2000–09 are used here to assess the water quality in the Hauraki rivers.

Summary statistics for the water quality variables for all 17 sites are listed in Appendix 1. The median values for the five most downstream sites that are monitored on the Hauraki rivers are listed in Table 2, with the corresponding boxplots being shown in Figure 2. These are the sites where the effects of the various pressures on river water quality are likely to be greatest. Generally-speaking, water quality was better, and was often much better, at sites further upstream. For example, Appendix 1 shows that the water clarity of the Waihou River was substantially higher at the site at Whites Rd (median water clarity 6.1 m) than at Okauia (1.1 m) or at the most-downstream site at Te Aroha (0.7 m).

Table 2: Median water quality at selected sites on the Hauraki rivers, 2000–09 (see Fig. 1 for site locations). See Appendix 1 and Figure 2 for further details. Guideline values for satisfactory water quality are also shown (see footnote #4 for details). "DO", dissolved oxygen (% of saturation concentration); "NTU", turbidity (nephelometric turbidity units); "NH4", ammoniacal-nitrogen (mg/m^3); "TP", total phosphorus (mg/m^3); "TN", total nitrogen (mg/m^3); "Clar", horizontal water clarity (m); "Ecoli", *E. coli* (cfu/100 mL).

	Site	DO	pH	NTU	NH4	TP	TN	Clar	Ecoli
	Kauaeranga								
2	Kauaeranga at Smiths	99	7.1	1.1	5	4	100	3.1	95
	Piako								
79	Piako at Paeroa-Tahuna Rd	82	7.2	10	60	280	2450	0.7	700
	Waitoa								
80	Waitoa at Mellon Rd	75	7.2	7.6	60	270	2800	0.9	730
	Waihou								
4	Ohinemuri at Karangahake	106	7.8	1.1	14	14	630	2.5	45
3	Waihou at Te Aroha	93	7.3	5.1	30	100	1260	0.7	250
	Guideline for satisfactory water quality	>80	6.5–9	<5	<880	<40	<500	<1.6	<126

[3] There is also a site on the Waitakaruru River which flows into the western site of the Southern Firth of Thames; plus a site on the Mangawhero Stream, a small tributary of the Piako River. However, these waterbodies are regarded as relatively-minor (catchment areas 2–50 km^2) and are not discussed here.

[4] Water quality guidelines to support healthy ecosystems, see Table 2 at this link, and Water quality guidelines for contact recreation, see Table 2 at this link.

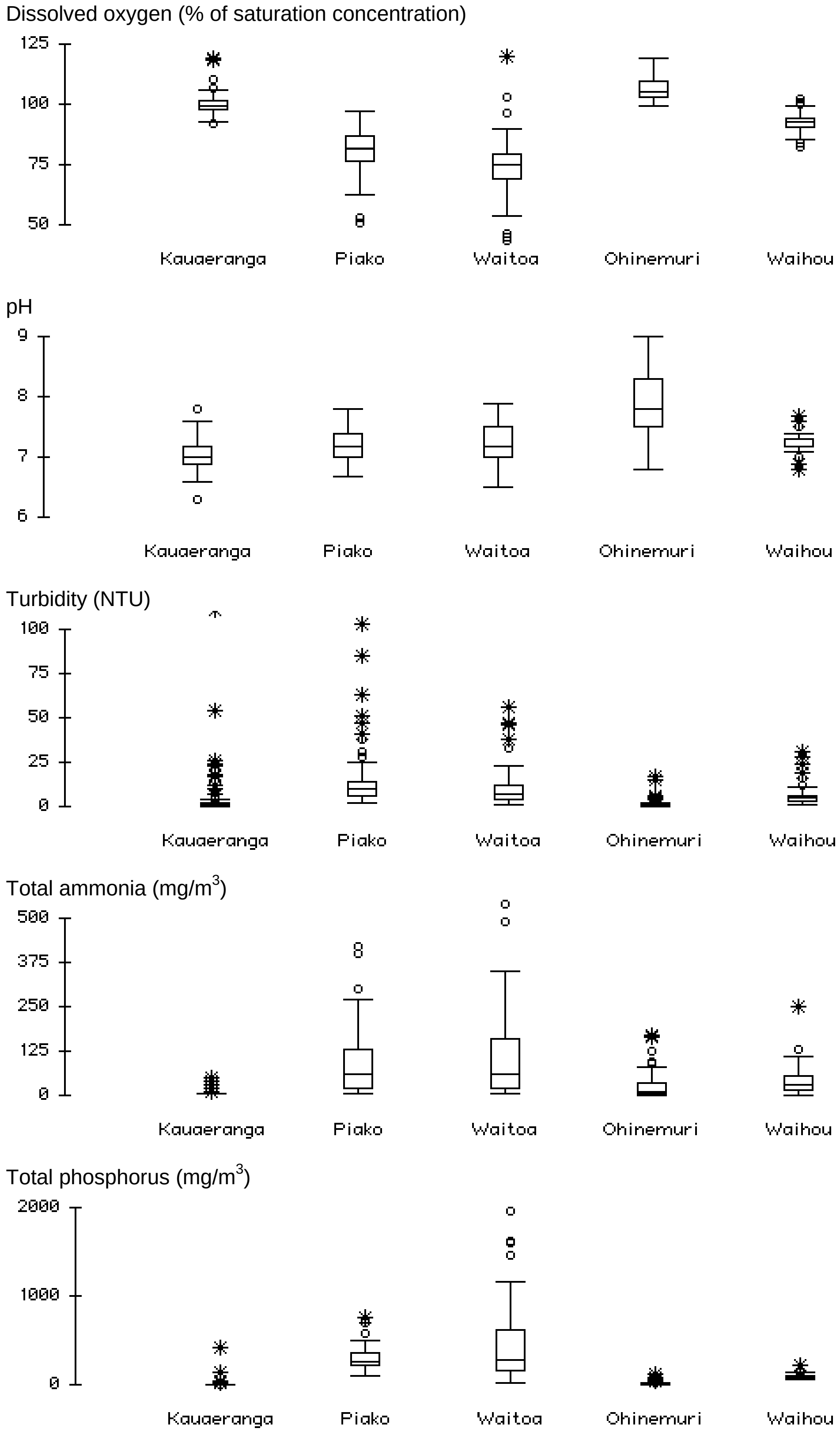

Figure 2: Boxplots of water quality during 2000–09 at selected river sites (Kauaeranga at Smiths, Piako at Paeroa-Tahuna Rd, Waitoa at Mellon Rd, Ohinemuri at Karangahake and Waihou at Te Aroha). The central box spans the inter-quartile range with the line in the middle being the median (see Table 2 also); the whiskers encompass most of the data, but outliers are shown as circles and extreme outliers as stars.

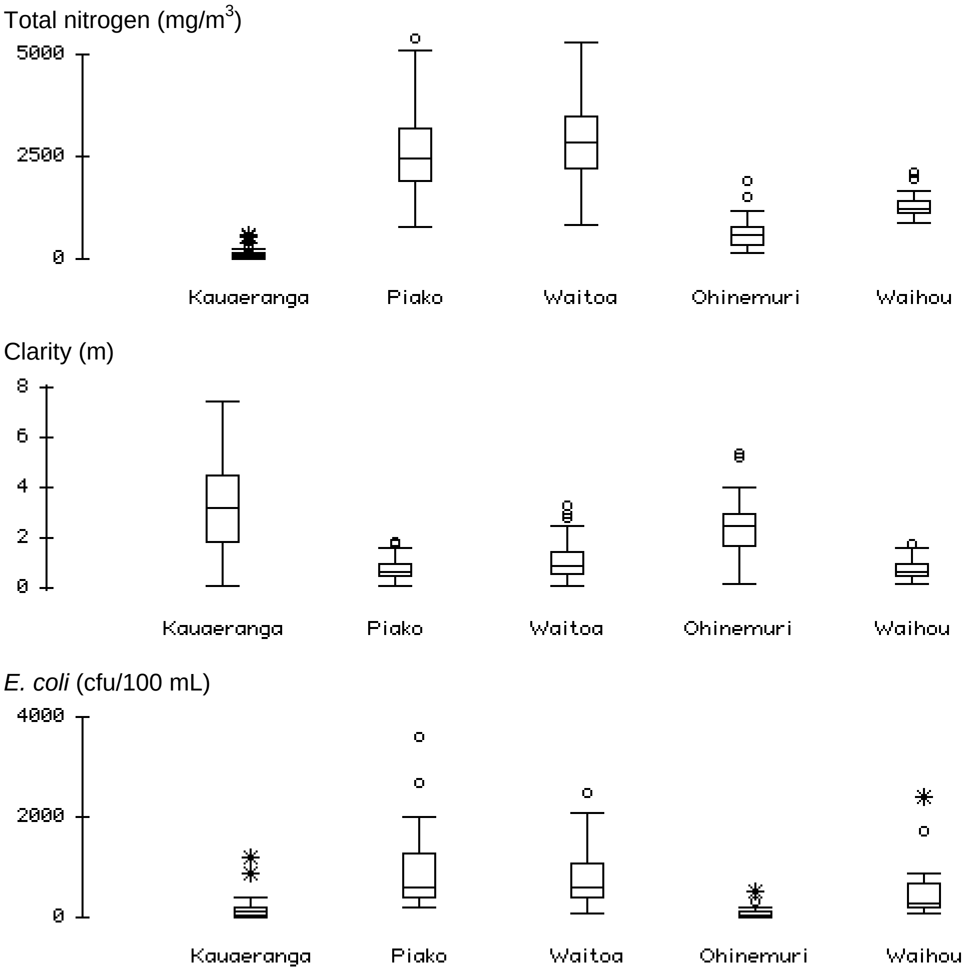

Figure 2 (continued): Boxplots of water quality during 2000–09 at selected river sites (Kauaeranga at Smiths, Piako at Paeroa-Tahuna Rd, Waitoa at Mellon Rd, Ohinemuri at Karangahake and Waihou at Te Aroha). The central box spans the inter-quartile range with the line in the middle being the median (see Table 2 also); the whiskers encompass most of the data, but outliers are shown as circles and extreme outliers as stars.

Water quality varied markedly between the five sites (Table 2, Figure 2). Overall, many aspects of the water quality of the Kauaeranga River were excellent, whereas several aspects of the water quality of the Piako and Waitoa Rivers were unsatisfactory.

Dissolved oxygen

The water in the Kauaeranga, Ohinemuri and Waihou Rivers was generally well-oxygenated, with all of the measurements from the Kauaeranga and Ohinemuri exceeding 90% of the saturation concentration (and thus being classified as "excellent"). Some 80% of the measurements from the Waihou River were excellent. For the Piako and Waitoa Rivers, by contrast, many of the measurements—37% and 78%, respectively—were classified as unsatisfactory (i.e. less than 80% of the saturation concentration).

pH

Measurements of pH at all five river sites were mostly at least satisfactory; indeed in all cases between 60% and 90% of the measurements showed that pH was excellent (being in the range 7 to 8).

Turbidity

The water in the Kauaeranga and Ohinemuri Rivers was generally clear, as indicated by the low turbidity (with 73–80% of measurements being classified as excellent). By contrast, the water of the Piako and Waitoa Rivers was often murky, and 70–85% of measurements were classified as unsatisfactory. The turbidity of the Waihou River was intermediate, with about half of the measurements being classified as satisfactory and half being unsatisfactory. The appearance of the river waters was also affected by the differing amounts of dissolved organic compounds that they contained (results not shown). Concentrations of these compounds were relatively-high in the Piako and Waitoa Rivers, reflecting the large areas of peat wetland that these rivers drain. Concentrations were relatively-low at the sites on the Kauaeranga, Ohinemuri and Waihou Rivers.[5]

Ammonia

Concentrations of a toxic form of nitrogen, total ammonia (or ammoniacal-N), were relatively low at the five sites. Very few of the results were classified as unsatisfactory (2% of samples from the Waitoa River). Concentrations were particularly-low in the Kauaeranga (100% excellent), Ohinemuri (97%) and Waihou (97%) Rivers. Many results from the Piako (65%) and Waitoa (60%) Rivers were excellent as well.

Nitrogen and phosphorus

Concentrations of total nitrogen and total phosphorus varied markedly between the five sites, with concentrations generally being low in the Kauaeranga and Ohinemuri Rivers, and high or very high in the Piako, Waitoa and Waihou Rivers. The results from the latter three sites were almost always classified as unsatisfactory. By contrast, in the Kauaeranga River 85% of the results for total P and 50% of those for total N were classified as excellent.

Horizontal clarity

The results for water clarity as measured by the visibility of a black disc were similar to those described above for turbidity. Water clarity was moderate-to-high in the Kauaeranga and Ohinemuri Rivers, and poor in the Piako, Waitoa and Waihou Rivers.

E. coli

Concentrations of *E. coli* were lowest in the Kauaeranga and Ohinemuri Rivers, and highest in the Piako and Waitoa Rivers. While the median concentrations in the Kauaeranga and Ohinemuri Rivers met the guideline value for safe swimming (namely 126 *E. coli*/100 mL), the 95 percentile concentrations exceeded the 550 per 100 mL guideline (with the values being 1100 and 1200 per 100 mL, respectively). Water quality at these sites can therefore be described borderline for safe swimming, while conditions at the other three sites were unsuitable for swimming.[6]

In summary, during 2000–09 the water quality of the Hauraki rivers was excellent in some respects at some sites, and poorer in some respects at others:

- The water in the Kauaeranga, Ohinemuri and Waihou Rivers was well-oxygenated; that in the Piako and Waitoa Rivers was often somewhat oxygen-depleted.
- The water in the Kauaeranga and Ohinemuri Rivers was generally clear, while that in the Piako and Waitoa Rivers was often murky. Although the headwaters of the Waihou River were particularly clear, the water further downstream was rather murky.
- Concentrations of ammoniacal-N were relatively-low in all rivers; they were particularly-low in the Kauaeranga, Ohinemuri and Waihou Rivers.
- Concentrations of total nitrogen and total phosphorus were generally low in the Kauaeranga and Ohinemuri Rivers, but were high or very high in the Piako, Waitoa and Waihou Rivers.
- Concentrations of *E. coli* bacteria were lowest in the Kauaeranga and Ohinemuri Rivers, although they were only borderline for safe swimming. *E. coli* concentrations in the Piako and Waitoa Rivers were high.

[5] Very low concentrations of dissolved organic compounds were found in the spring-fed waters found at the Whites Rd site on the Waihou River. This site also had the lowest turbidity and highest clarity (Appendix 1).

[6] The spring-fed waters of the site on the Waihou River at Whites Rd had the lowest concentrations of *E. coli* (Appendix 1), with the values for both the median (45 per 100 mL) and 95 percentile (370 per 100 mL) meeting the guidelines for safe swimming.

2.2 Long-term changes

Vant (2008) analysed the water quality records from 1990–94 to the end of 2007 for all of the routine monitoring sites in the region. That analysis has now been updated to the end of 2009 for the 17 sites on the Hauraki Rivers. The key trend statistics—*p*-values and slopes (or rate of change in water quality)—for each site are shown in Appendix 2. Table 3 shows the slopes at the five most downstream sites described above.

This discussion focuses on statistically significant trends (*p*-value <5%) where the absolute value of the slope is greater than 1% per year. Following Vant (2008), these trends are regarded as being important. Records where dissolved oxygen and water clarity have increased over time represent an improvement, while a decrease represents a deterioration; for all other variables an increase over time represents a deterioration (and vice versa).

In most cases Appendix 2 shows the trend statistics for two periods: (1) from the beginning of the record (during 1990–94) to 2009, and (2) for the decade 2000–09. In many cases (70%) the results for the two periods were similar, with no important trend in either period (57%; e.g. records of *E. coli* at all sites), improvements in both periods (7%) or deteriorations in both periods (6%). In other cases (28%) there was a trend in one of the periods, but not the other: either a trend that was apparent in the whole period was too weak to be detected in the latter decade, or a marked change in water quality occurred just during the latter decade. Finally in a small number of cases (2%) contrasting trends occurred in the two periods. In each of these there was an overall improvement in the whole record, accompanied by a distinct short-term deterioration during the latter decade (e.g. total N concentrations in the Piako River at Paeroa-Tahuna Rd).

The analyses for the whole period for all 17 sites showed that many (67%) of the records showed no important trends (Appendix 2), so that average water quality was broadly stable throughout the two decades. However, 18% of the records showed important improvements, while 15% showed deteriorations. The improvements included reductions in total ammonia concentrations at seven sites, reductions in total phosphorus at five sites (e.g. Fig. 3) and reductions in total nitrogen at five sites. Several of these improvements are likely to be the result of improved treatment of the wastewaters that are discharged to the rivers. For example, the loads of total P discharged from the Waitoa dairy factory and the Waihi sewage treatment plant have decreased markedly (see later), resulting in the improvements in river water quality shown in Figure 3. The deteriorations included increases in total nitrogen concentrations at six sites and in conductivity at five sites, and a decrease in water clarity at five sites. The increases in total nitrogen and conductivity are likely to reflect the overall intensification of farming in the catchments of these rivers (see Vant [2008] for further details).

At two sites, namely the Piakonui Stream and the Piako River at Kiwitahi, there were improvements in several water quality variables and little if any deterioration (Appendix 2). This indicates that there has been an overall improvement in water quality at these sites over the past two decades. By contrast, a number of variables deteriorated in the Kauaeranga River, and no variables improved (Table 3). This is somewhat disturbing given the generally excellent conditions in this river (see earlier); that is, although the water quality is mostly excellent, it has deteriorated in several respects.

At the other four downstream or “bottom of the catchment” sites the majority of variables were largely stable, with either no trend or a rate of change less than 1% per year (Table 3). Where there were changes, there were similar numbers of improvements and deteriorations. Although conductivity deteriorated at three of the five downstream sites, probably reflecting an increase in the intensity of land

Table 3: Slopes (% per year) of statistically significant ($p < 5\%$) trends at sites on four Hauraki rivers during 1990–2009 (see Appendix 2 for further details). Important improvements are shown in bold; important deteriorations are bold underlined; "ns", not significant. "Cond", conductivity; other abbreviations as in Table 2.

	Site	DO	Cond	NTU	NH4	TP	TN	Clar	Ecoli
	Kauaeranga								
2	Kauaeranga at Smiths	ns	<u>**1.0**</u>	<u>**2.4**</u>	ns	ns	<u>**3.6**</u>	<u>**–2.3**</u>	ns
	Piako								
79	Piako at Paeroa-Tahuna Rd	ns	0.9	ns	**–5.1**	ns	**–1.3**	<u>**–1.3**</u>	ns
	Waitoa								
80	Waitoa at Mellon Rd	0.6	<u>**1.1**</u>	ns	**–6.6**	**–10.4**	**–1.2**	ns	ns
	Waihou								
4	Ohinemuri at Karangahake	–0.1	<u>**1.3**</u>	**–1.1**	ns	**–2.9**	ns	ns	ns
3	Waihou at Te Aroha	–0.2	0.5	ns	<u>**3.8**</u>	ns	0.5	ns	ns

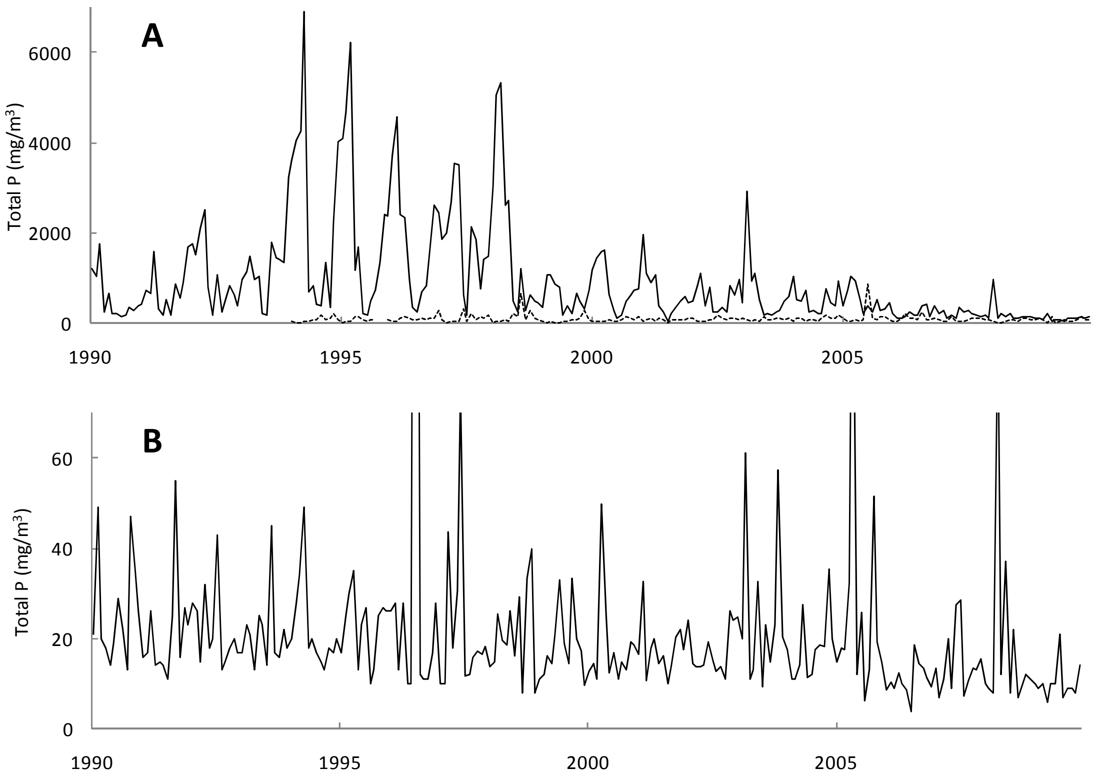

Figure 3: Concentrations of total phosphorus in **A**, the Waitoa River (solid line, Mellon Rd, site 80; dashed line, Landsdowne Rd, site 81), and **B**, the Ohinemuri River at Karangahake at monthly intervals during 1990–2009. Note the very different vertical scales.

disturbance (Vant 2008), concentrations of ammonia, total P and total N improved in several cases. Improved treatment of sewage and industrial wastewaters is likely to be responsible for much of this (see later).

In summary, these results show that the overall quality of the water at the downstream sites on the Hauraki rivers has remained broadly stable over the past two or so decades. In these catchments the effects of more intensive farming appear to have been offset by improved treatment of sewage and industrial wastewaters. This contrasts with the situation found elsewhere in the Waikato region where although many variables have remained stable, of those that have changed there have been more deteriorations than improvements, with concentrations of total P and total N in particular having slowly increased over this period (Vant 2008).

2.3 Lower Waihou River

Study design

An investigation of the water quality of the estuarine section of the Waihou River was undertaken between November 2009 and July 2010. On four occasions a boat was used to visit up to 23 separate sites on a transect between the mouth of the river near Thames and Puke Bridge near Paeroa (Fig. 4). The average distance between consecutive sites was 1.7 km (range 1.0–2.3 km). Surveys began at the river mouth near the time of high water, and took about 3 hours to complete. The time of local high water at any point in the river channel is progressively delayed as the incoming tide moves upstream. This meant that all the sites were visited at roughly the time of local high water.

At each site the salinity, water temperature, dissolved oxygen and turbidity was measured in both the near-surface and the near-bottom waters. At every second site water samples were collected from the near-surface layer, stored on ice and returned to the laboratory for analysis by Hills Laboratories for suspended solids, particulate and dissolved forms of nitrogen (N) and phosphorus (P) and dissolved silica; additional samples were analysed for chlorophyll *a* and its phaeopigment degradation products (by NIWA), using a sensitive fluorometric method. On two trips (2 February and 2 March) samples from selected sites were preserved with Lugols iodine and the species composition of the algal assemblage was determined by NIWA.

Table 4 summarises the results for the four surveys, while Figure 5 shows the transect results for selected variables for the survey of 2 March 2010. River flow and tide range at the time of each of the surveys were as follows (Table 4):

- 23 November, low river flow, average tide
- 2 February, high river flow, spring tide
- 2 March, low river flow, spring tide
- 15 July, average river flow, spring tide

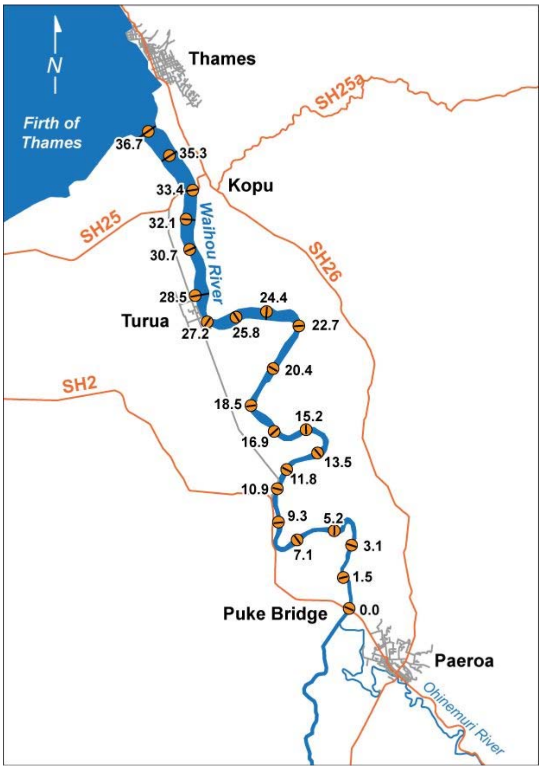

Figure 4: Sites on the Lower Waihou River that were sampled on four occasions during November 2009 to July 2010. The distance (km) that each site is from Puke Bridge is also shown.

Table 4: Water quality of the lower Waihou River on four occasions during 2009–10. For several variables (turbidity, suspended solids, chlorophyll *a* and phaeopigment), the distance downstream of Puke Bridge (in km; see Fig. 4) where the maximum value was observed is shown in italics in brackets after the value itself. Otherwise values in brackets refer to concentrations of inorganic forms of N and P.

	23 Nov 2009		**2 Feb 2010**		**2 Mar 2010**		**15 Jly 2010**	
River flow* (m^3/s)	30		106		27		41	
Tide range (m)	2.1		3.4		3.4		3.0	
Salinity (near-surface)								
Puke Bridge	0		0		0		0	
25 km downstream	1		1		6		1	
River mouth	22		27		28		25	
Turbidity (NTU)								
Puke Bridge	9		64		14		10	
Turb-max (*distance*)	730	(*24*)	810	(*23*)	>1000	(*13–20*)	800	(*23*)
River mouth	23		47		45		73	
Suspended solids (g/m^3)								
Puke Bridge	–		–		18		8	
SS-max (*distance*)	–		450	(*20*)	1500	(*17*)	650	(*24*)
River mouth	–		–		50		90	
Total N (TIN) (mg/m^3)								
Puke Bridge	1200	(1100)	1030	(570)	1140	(900)	1400	(1280)
River mouth	810	(460)	520	(190)	550	(110)	1300	(880)
Total P (DRP) (mg/m^3)								
Puke Bridge	110	(80)	160	(45)	80	(60)	50	(32)
River mouth	110	(80)	100	(40)	110	(60)	110	(45)
Dissolved silica (g SiO_2/m^3)								
Puke Bridge	61		21		62		46	
River mouth	23		6		13		16	
Chlorophyll *a* (mg/m^3)								
Puke Bridge	<1		1		1		<1	
Chl*a*-max (*distance*)	26	(*17*)	10	(*37*)	34	(*11*)	6	(*37*)
River mouth	4		10		18		6	
Phaeopigment (mg/m^3)								
Puke Bridge	<1		1		1		<1	
Phae-max (*distance*)	13	(*17*)	5	(*20*)	21	(*13*)	5	(*24*)
River mouth	3		4		7		2	

*Sum of the flows of the Waihou River at Te Aroha and the Ohinemuri River at Karangahake

Salinity and mixing

The differing hydraulic conditions on the four surveys meant that the extent to which seawater penetrated up the river channel varied. The greatest degree of penetration was on 2 March when a spring tide occurred at a time of low river flow. On this occasion near-surface salinity was >1 between a point about 20 km downstream of Puke Bridge and the river mouth (Fig. 5A), a distance of about 15 km. There was also evidence of a weak salt wedge in the channel, with salinity in the near-bottom waters being slightly higher than that in the near-surface waters, particularly in the area just upstream of the mouth of the river (Fig. 5A).

It is interesting to note that on 2 March the water in the river channel was observed to be moving upstream at the time of local high water at locations as far inland as Puke Bridge (with the velocity there being estimated to be in the range 0–1 m/s). Note, however, that the water there was entirely fresh (Table 4, Fig. 5A).

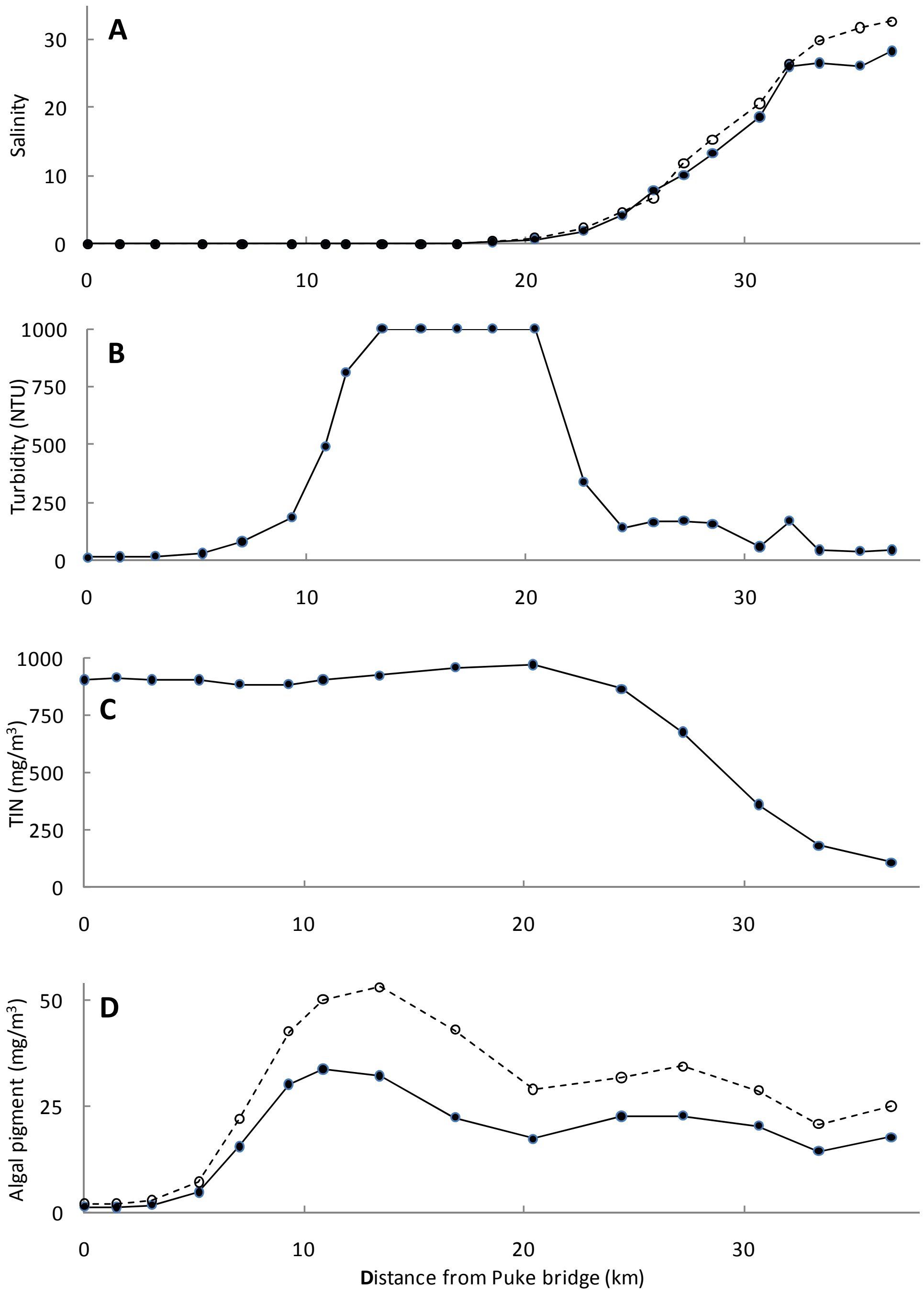

Figure 5: Water quality along a transect in the Lower Waihou River, 2 March 2010. **A**, salinity in the near-surface (solid circles) and near-bottom (open circles) water; **B**, turbidity; **C**, total inorganic nitrogen (see text); and **D**, chlorophyll *a* (solid circles) and chlorophyll plus phaeopigment (open circles).

Turbidity and suspended solids

A zone of high turbidity was observed in the river downstream of Puke Bridge on each survey. On three occasions this occurred in the region 20–25 km downstream of Puke Bridge (Table 4). But on 2 March the turbid zone was even further from the sea, being located 13–20 km downstream of Puke Bridge (Fig. 5B). This zone is called the "estuarine turbidity maximum" (Dyer 1995, Uncles et al. 2002). In this zone, located in regions of low salinity, both turbidity and the concentrations of suspended solids are much higher than in either the upstream river or the increasingly saline water towards the sea (see Table 4).

Turbidity maxima occur when catchment-derived particles are carried downriver in the light, fresh surface waters until decreasing current velocities and saline-induced flocculation near the head of the estuary cause them to settle into the denser, more saline, bottom waters (i.e. the salt wedge). These bottom waters then carry the particles back upstream. Suspended solids are thus recycled and concentrated in a conspicuous zone of turbidity near the head of the estuary. This zone moves seawards with the ebbing tide, and also with increases in the freshwater inflow. The low gradient of the Hauraki Plains means the estuarine zone of the Waihou River is substantially longer than that in many New Zealand rivers, such that a particularly well-developed turbidity maximum occurs there.

The maximum suspended solids concentration observed in the zone of the turbidity maximum on 2 March was 1500 g/m^3. By contrast, the concentration further upstream at Puke Bridge was 18 g/m^3, while that at the mouth of the river was 50 g/m^3. And as shown later (section 4), the median concentrations found further seawards in the Southern Firth of Thames were lower still at 5–26 g/m^3 (see Table 8).

Nitrogen, phosphorus and silica

On each occasion, concentrations of total N were higher at Puke Bridge than at the mouth (Table 4). However, on two occasions concentrations of total P were higher at the mouth than at Puke Bridge. On 2 March the concentrations of total inorganic N (TIN), the sum of nitrate, nitrite and ammoniacal N, steadily decreased over the lower 15 km of the river (Fig. 5C), mirroring the increase in salinity (Fig. 5A). These variables were highly correlated (r=0.99), indicating that the decrease in TIN concentration was simply due to dilution of the high-TIN river water with low-TIN seawater; that is, there was no evidence of biological uptake of TIN in this part of the estuary. Similar patterns were observed on the other three surveys as well.

The concentrations of both total N and total P at the mouth of the river were higher than those typically observed further seaward in the Southern Firth of Thames (see later: Table 8). Dilution with low-nutrient seawater is likely to account for some of this difference, but particulate nutrients present in the suspended solids in the river mouth water—including those re-suspended from the bottom in the shallow area near there—are likely to be important too.

Concentrations of dissolved silica were higher at Puke Bridge than at the river mouth (Table 4), and were highly correlated with salinity in the estuarine zone (with r being in the range 0.83–0.99 on each survey), indicating there was no evidence of any biological uptake of silica. The concentrations at Puke Bridge varied with river flow, being highest when flows were low, suggesting that silica is dissolved from the volcanic soils at the head of the Waihou catchment at a reasonably-constant rate, and is diluted by the additional low-silica runoff that is present in the river at times of high flow.

Algae and the chlorophyll maxima

Estuarine maxima were also observed in concentrations of chlorophyll *a* and its phaeopigment degradation products (Table 4, Fig. 5D). On the two low river flow occasions (23 November and 2 March) these maxima were located upstream of the turbidity maxima. Microscopic examination of the algal assemblage present at several sites on the survey of 2 March showed that marine species were dominant. These included various diatoms (e.g. *Coscinodiscus* sp., *Podosira* sp., *Thalassiosira* sp.) and small flagellates/unicells. At the chlorophyll maximum, 11 km downstream of Puke Bridge (Fig. 5D), the marine diatom *Podosira* sp. and various small flagellates were co-dominant. These taxa, together with the diatom *Navicula* sp., were also co-dominant at the phaeopigment maximum, a further 2 km downstream (although the large amount of sediment present in the sample from this site made identification and counting difficult).

The large numbers of marine algae found in this freshwater section of the river, together with the relatively-high concentrations of chlorophyll *a* and its degradation products were somewhat surprising. The negligible salinity and the high turbidity suggests that the cells were unlikely to be actively growing. Furthermore, TIN concentrations were high and stable in this part of the river (Fig. 5C), showing no sign of the biological uptake that would be expected if the algal assemblage was healthy.

This suggests that the algae present in the chlorophyll maxima were dead or dying cells that had been trapped by the same estuarine circulation cell that led to the formation of the turbidity maxima.

Although microscopic examination indicated that high numbers of marine species were present, some freshwater green algae and euglenoids were also observed in some samples. An oxidation pond is part of the wastewater treatment system at Thames, discharging into the lower Waihou River near the mouth. It is therefore possible that freshwater algae from this pond are also transported upriver and are trapped by the estuarine circulation cell, contributing to the observed chlorophyll maxima.

In summary,

- Salt water penetrated up to 15 km up the Waihou River from the Southern Firth of Thames.
- Near the limit of salt intrusion, river-borne sediments were trapped in a “turbidity maximum” where the turbidity was much higher than in the upstream river or in the coastal waters beyond. The physical processes responsible for this were probably naturally-occurring.
- Algae from the adjacent coastal waters were also trapped—in this case in a zone slightly upstream of the turbidity maximum. Although the chlorophyll concentration in this zone was high, the algae were unlikely to be actively-growing.
- There was little indication of any biological uptake of N or P in the lower section of the river. Instead the high-nutrient river waters were generally diluted by the lower-nutrient seawaters. The high concentrations of particulate forms of P found near the river mouth were likely to be associated with the suspended solids there, including those that were likely to be re-suspended from the bottom in this area which is exposed to wind waves and tidal currents.

3 Sources of nitrogen and phosphorus in the rivers

3.1 Mass flows carried by the rivers

Mass flows of nitrogen and phosphorus during 2000–09 were determined at a total of 11 sites on the Hauraki rivers (Figure 1). At nine of these sites the mass flows were calculated using monthly measurements of total N and total P concentrations together with continuous records of river flow. At two of the sites less information was available, and the mass flows were estimated (see below).

The following procedure was used to calculate mass flows at the nine sites with continuous records of flow: (1) identify the river flow at the time each of the monthly water quality samples was collected (n=120 in most cases), (2) determine the relationships between river flow and the concentrations of total N and total P, (3) use these relationships to calculate the mass flow at each half-percentile interval (i.e. 0.5%) of the site’s flow distribution curve, and (4) add the 200 estimates of mass flow thus obtained to give the combined mass flow at all river flows. These calculations were made with the “Sedrate” software, using its bias correction procedures.

In most cases there was a statistically significant relationship between the logarithms of river flow and nutrient concentration, with the correlation coefficients being between about 0.2 and 0.9. The one exception was for the Ohinemuri River at Karangahake site where there was little or no dependence of total nitrogen concentration on river flow (r=0.03). Figure 6 shows how the concentrations of total N and total P varied with flow in the Kauaeranga River. In each case increased flows tended to be associated with higher concentrations, with the log-log correlation coefficients being 0.65 and 0.57 for total N and total P, respectively.

The extent to which the mass flows of total N and total P varied at each site also depended on the extent to which flows themselves varied, with some sites exhibiting less flow variability than others. For example, high flow (95%ile) in the Piako River at Paeroa-Tahuna Rd was about 40 times higher than low flow (5%ile); but in the Waihou River at Te Aroha high flow was just three times higher than low flow. The seasonal variation in mass flows of total N and total P at these two sites is shown in Figure 7. Mass flows of both total N and total P tended to be 10–100 times higher in the winter than in the summer at the Piako River site, whereas the mass flows at the Waihou River site showed much less seasonal variability.

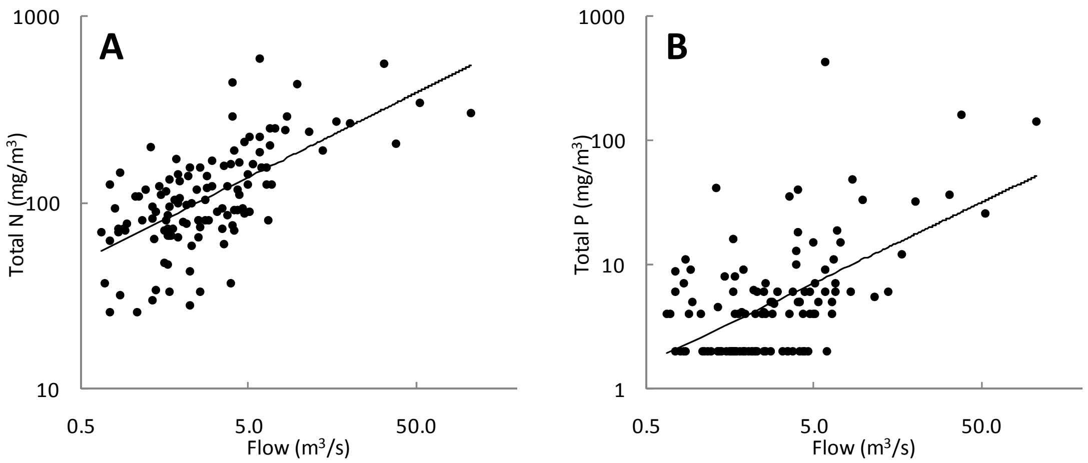

Figure 6: Monthly measurements of flow and **A**, total nitrogen, and **B**, total phosphorus in the Kauaeranga River, 2000–09.

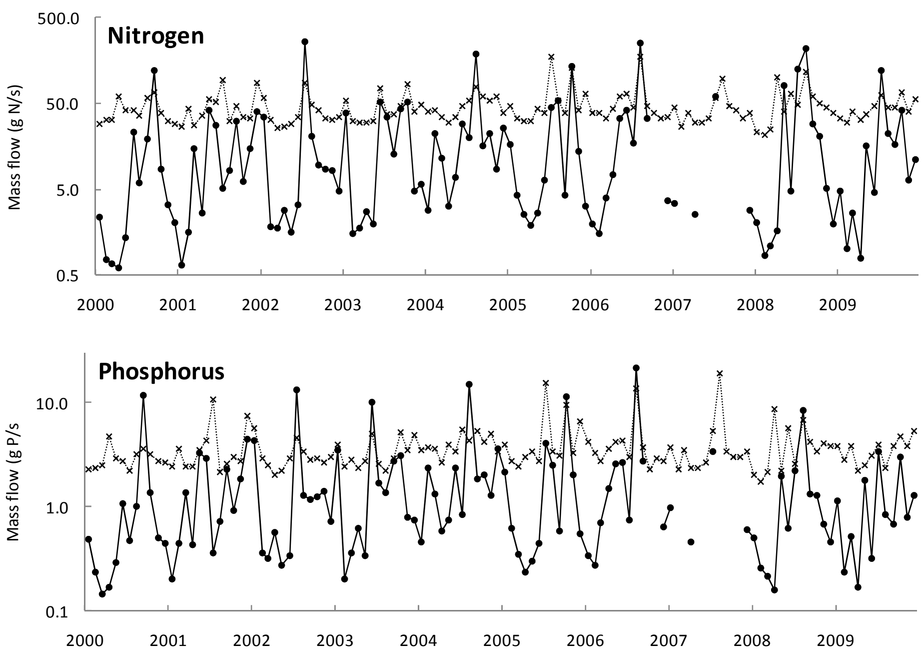

Figure 7: Mass flows of nitrogen and phosphorus in the Piako River (Paeroa-Tahuna Rd; circles, solid line) and the Waihou River (Te Aroha; crosses, dotted line) at monthly intervals during 2000–09.

There was no record of river flow at the Hikutaia River site (catchment area 73 km^2). In this case the flow at the time each of the monthly water quality samples was collected was estimated from the corresponding flow in the Kauaeranga River, taking account of the catchment areas at the two locations. The estimated flows and measured concentrations were used to calculate flow-weighted average concentrations of total N and total P at the Hikutaia River site. Following Littlewood et al. (1998), mass flows were then calculated by multiplying the flow-weighted average concentrations by the average flow in the Hikutaia River during 2000–09 (which was also estimated from the average flow in the Kauaeranga, taking account of the respective areas).

A similar approach was used to calculate the mass flows at the Oraka Stream (at Pinedale) site. In this case water quality was only measured at monthly intervals from July 2005 to August 2006 (n=14), although flow was measured more-or-less continuously throughout 2000–09. Mass flows of total N and total P were calculated by multiplying the flow-weighted average concentrations for 2005–06 by the average flow for 2000–09.

Table 5 shows the average mass flows of nitrogen and phosphorus at the 11 river monitoring sites during 2000–09. The average flow of the Hauraki rivers combined was about 69 m^3/s, with the combined mass flows of total N and total P being about 3295 t/yr and 261 t/yr, respectively (but see later for more comprehensive estimates). The Waihou River system was the largest, and carried the greatest share of the nutrients. While the Kauaeranga River carried about 8% of the combined flow, it only carried 2% of the mass flow of nitrogen and 4% of the mass flow of phosphorus. Conversely, the Piako and Waitoa Rivers each carried 7–10% of the combined flow, but between 16% and 24% of the mass flows of nitrogen and phosphorus. These differences largely reflected the lower concentrations of total N and total P found in the Kauaeranga River (Table 2). The Ohinemuri River also had relatively low nutrient concentrations and carried a disproportionately-low share of the nutrient mass flows.

Table 5: Average flows and mass flows of nitrogen and phosphorus in four Hauraki river systems, 2000–09 (site locations in Fig. 1). The most downstream sites are shown underlined. Values in italics are estimated: see text. Note that the totals are lower than the more comprehensive values shown in Table 7.

	Flow (m^3/s)		Nitrogen (t/yr)		Phosphorus (t/yr)	
Kauaeranga						
<u>Kauaeranga at Smiths</u>	5.8	(8%)	67	(2%)	10	(4%)
Piako						
Piako at Kiwitahi	1.7		212		7	
<u>Piako at Paeroa-Tahuna Rd</u>	6.9	(10%)	775	(24%)	55	(21%)
Waitoa						
Waitoa at Landsdowne Rd	1.4		123		6	
<u>Waitoa at Mellon Rd</u>	4.8	(7%)	535	(16%)	58*	(22%)
Waihou						
<u>Hikutaia at Maratoto Rd</u>	*3.5*		*38*		*4*	
Ohinemuri at Queens Head	5.0		265		8	
<u>Ohinemuri at Karangahake</u>	11.1		299		9	
Oraka at Pinedale	2.7		*147*		*5*	
Waihou at Okauia	26.6		1246		89	
<u>Waihou at Te Aroha</u>	37.2		1581		125	
<u>Waihou combined</u>	51.8	(75%)	1918	(58%)	138	(53%)
All four rivers	69.3	(100%)	3295	(100%)	261	(100%)

*Note that the concentration—and thus the mass flow—of total P at this site fell markedly during the decade (Fig. 3B), with the average monthly value during 2006–09 being 70% lower than that during 2000–05. During the last year of the decade (2009), the mass flow estimated following Littlewood et al. (1998; see text) was 20 t/yr, or about one-third of the value shown here.

The rates of change in nutrient concentration during 2000–09 that were determined for the various monitoring sites (see Appendix 2) can be applied to the mass flows in Table 5. For example, total N concentrations in the Piako River at Paeroa-Tahuna Rd increased at an average rate of about 3.4% per year during 2000–09 (Appendix 2). Applying this to the average mass flow of N at this site (775 t/yr) gives a change in mass flow of +26 t/yr. The corresponding changes at the Waitoa River at Mellon Rd and Waihou River at Te Aroha sites were –10 t/yr and +16 t/yr, respectively (noting that the trends at the other two downstream sites were not statistically significant). This gives a combined change for the Hauraki rivers of +32 t/yr, so that the combined mass flow of nitrogen increased by about 1% per year during 2000–09. The combined change in phosphorus was –12 t/yr, so the combined mass flow of this nutrient in the Hauraki rivers decreased by about 5% per year.

3.2 Mass flows from point sources

Monitoring information

Figure 8 shows the location of 22 sites where contaminants are discharged to the rivers that flow into the Southern Firth of Thames. Each can be regarded as a moderate-to-large point source of nitrogen and phosphorus. Some 14 of these locations are sites where sewage wastewaters from towns and other smaller settlements are treated, while the remaining eight are various industrial sites, mainly dairy factories and meatworks (Table 6). In each case the discharge of treated wastewater is permitted by a resource consent issued by the Regional Council. The terms of these consents generally limit both the volume and the water quality of the effluent that may be discharged; they also require the consent holder to regularly monitor these variables and to provide this information to the Council.

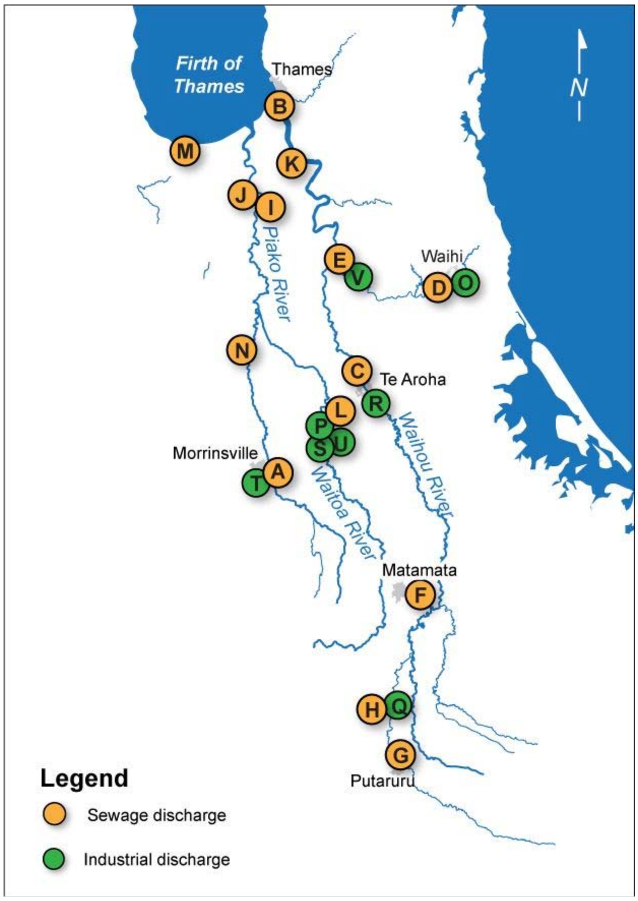

Figure 8: Location of 22 discharges of wastewaters discharging to the Hauraki rivers. See Table 6 for further details.

This consent monitoring information was used to determine the average mass flows of nitrogen and phosphorus that were discharged from each of the point sources during 2000–09. In most cases electronic copies of the monitoring information were available in the Council's document management system, although in a small number of cases hardcopies needed to be located in physical files. These records were retrieved, collated and checked for errors.

Comprehensive records were available for some sites—particularly some industrial sites—with daily wastewater volumes being recorded throughout the decade, and water quality analyses undertaken at least monthly (or more often in some cases). Rather less information was available for other sites, particularly the discharges of sewage wastewaters from the smaller settlements (e.g. 1–3 years of data for Kerepehi, Tahuna, Turua and Waitakaruru). In most cases samples of the wastewaters had been analysed for total nitrogen and total phosphorus, but in some cases these variables needed to be estimated from the results of other analyses: ammoniacal-N (Waihou sewage, Waihi gold mine), Kjeldahl-N (Waihi sewage) and dissolved reactive P (Te Aroha and Waihou sewage).

Wastewater flows and nutrient concentrations

Where possible, the results were used to determine whether the calculated mass flows were likely to be biased by any covariance between wastewater flow and nutrient concentration. This was done by estimating the mass flow of nutrient for each month as the product of the monthly averages of flow and concentration, then comparing the average value of this measure for all months ("average of the products") with the product of the overall averages of flow and concentration ("product of the averages"). When concentrations and flows covary to a marked degree, these measures will be rather different, with the latter value ("product of the averages") providing a biased estimate of the true mass flow.

At eight sites, including the seven smallest sewage treatment sites, there was insufficient information to be able to check for bias, while at the other 14 sites some test for bias was able to be made. At two of these (Morrinsville sewage and Tirau dairy factory) a moderate degree of bias was apparent, with the product of the averages being up to 40% greater than the average of the products. In both these cases wastewater volumes varied seasonally—with highest flows during winter at Morrinsville sewage and during summer at Tirau dairy factory—and nutrient concentrations tended to be lower at higher flows, presumably reflecting simple dilution (e.g. Fig. 9). At these sites, and at eight other sites for which there was sufficient information (Table 6), the nutrient mass flows were estimated as the average value (n=11–114) of the products of individual values of monthly average flow and monthly average concentration. At the other 12 sites the nutrient mass flows were simply estimated as the product of the decadal average flow of wastewater and the decadal average concentration of total nitrogen or total phosphorus.

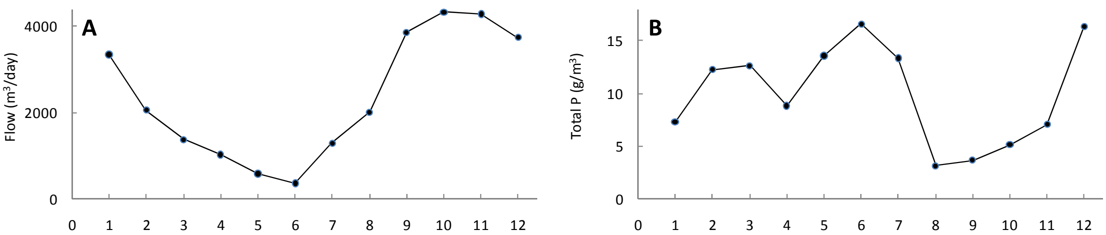

Figure 9: Monthly average values of (A) wastewater flow, and (B) total phosphorus concentration at the Tirau dairy factory during 2000–09. "1", January; "12", December.

Table 6 shows the information on wastewater flows and nitrogen and phosphorus concentrations in the 22 discharges of wastewater. Average flows of wastewater varied markedly between the different sites, reflecting differences in the number of people living in each town or settlement, and the nature and scale of the different industries. For example, large volumes of groundwater and stormwater collect in the pit at the Waihi gold mine and are pumped to a treatment plant, whereas the Paeroa meatworks is closed for several months each year.

The average concentrations of nitrogen and phosphorus in the wastewaters also varied markedly, reflecting both the nature of the activity and the efficiency of wastewater treatment. For example, the wastewater from the Te Aroha and Waitoa meatworks contained much higher nutrient concentrations than those from the Waihi mine and the Morrinsville dairy factory, mainly due to the different nature of the operations at each site. Note that the "high strength" wastewater from the Morrinsville dairy factory is routed to the town's sewage treatment plant (and is thus included in the discharge from that site); only "low strength" condensate and boiler water is discharged directly from the factory. The wastewaters from the Tirau and Waitoa dairy factories, by contrast, come from a wider range of factory processes.

During 2000–09 there were a number of changes in the treatment processes used at several of sites. As a result the concentrations and mass flows of nitrogen and phosphorus have varied over time, but these changes are masked by the decadal-averaging used to obtain the values in Table 6. For example, substantial reductions in nutrient concentrations occurred at both Waihi sewage and the Waitoa dairy factory. Concentrations of total P in the wastewater from the Waihi sewage treatment plant fell by about 20-fold following changes to the treatment system in 2005, while concentrations of total N more than halved. This is probably responsible for the improvement in the Ohinemuri River that is shown in Figure 3B.

Table 6: Average flows of wastewater and average concentrations and mass flows of nitrogen (N) and phosphorus (P) from 22 consented discharges to Hauraki rivers, 2000–09. Site locations are shown in Figure 8. At sites labelled "m", the mass flows were calculated from monthly records, rather than from the decadal averages shown here (see text).

	Site	Flow (m^3/day)	Concentration (g/m^3) Total N	Total P	Mass flow (t/yr) Total N	Total P
	Sewage wastewater					
A	Morrinsville (m)	4150	11	6.6	13	6.3
B	Thames (m)	3880	28	3.5	42	4.6
C	Te Aroha	2090	21	2.1	16	1.6
D	Waihi	1870	12	4.2	8	2.9
E	Paeroa (m)	1790	13	3.2	7	1.9
F	Matamata	1640	25	8.8	15	5.3
G	Putararu (m)	1200	26	7.3	11	3.2
H	Tirau	290	36	5.6	4	0.6
I	Kerepehi	170	13	6.6	1	0.4
J	Ngatea	90	24	6.5	1	0.2
K	Turua	70	18	9.9	<1	0.2
L	Waihou	40	30	9.2	<1	0.1
M	Waitakaruru	20	47	10.8	<1	0.1
N	Tahuna	20	11	6.6	<1	<0.1
	Sub-total sewage				**120**	**27**
	Industrial wastewater					
O	Waihi gold mine (m)	8930	2	–	9	–
P	Waitoa dairy factory	5450	14	10.7	27	20.9
Q	Tirau dairy factory (m)	2390	36	9.8	40	7.1
R	Te Aroha meatworks (m)	640	112	25.9	27	6.5
S	Waitoa meatworks (m)	450	209	32.1	34	5.9
T	Morrinsville dairy factory	370	1	0.2	<1	<0.1
U	Waitoa poultry processor (m)	260	25	2.4	2	0.3
V	Paeroa meatworks (m)	110	87	7.7	3	0.3
	Sub-total industrial				**142**	**41**
	Total				**262**	**68**

At the Waitoa dairy factory, concentrations and mass flows of total P reduced progressively over the decade (Fig. 10), with the levels at the end of the period being 100 times lower than those at the beginning (and about 400 times lower than those recorded during 1995–97: Vant 1999). This is almost certainly responsible for the improvement in the Waitoa River that is shown in Figure 3A, with concentrations at the downstream site (Mellon Rd) now being similar to those upstream of the factory (Landsdowne Rd: Fig. 3A). Concentrations and mass flows of total N in the dairy factory wastewater also fell markedly, but somewhat erratically and to a smaller extent overall (Fig. 10).

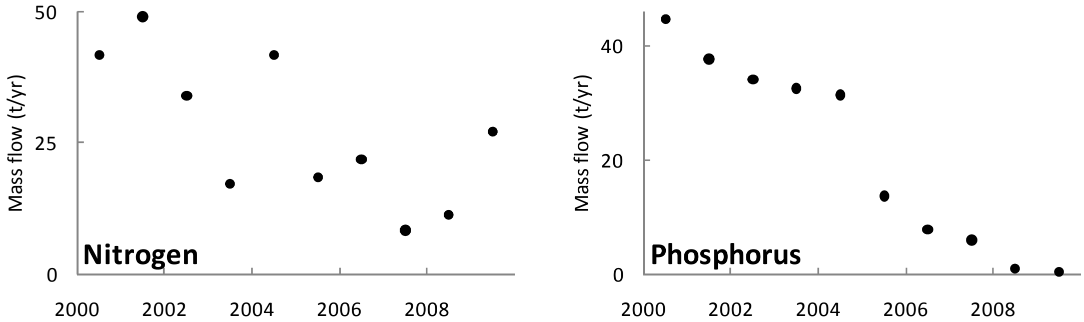

Figure 10: Annual average mass flows of nitrogen and phosphorus discharged from the Waitoa dairy factory during 2000–09.

<u>Mass flows</u>

The combined mass flow of nitrogen discharged from the 22 moderate-to-large point sources during 2000–09 averaged about 260 t/yr (Table 6). Two-thirds of this came from five sites: Thames sewage (16%), Tirau dairy factory (15%), Waitoa meatworks (13%), Te Aroha meatworks (10%) and Waitoa dairy factory (10%). By contrast, eight sites each contributed less than 1% of the total.

For phosphorus the combined mass flow averaged about 68 t/yr (Table 6). Two-thirds of this came from five sites: Waitoa dairy factory (31%, but see the information above about the substantial reduction in mass flow during the decade), Tirau dairy factory (10%), Te Aroha meatworks (10%), Morrinsville sewage (9%) and Waitoa meatworks (9%). By contrast, 10 sites each contributed less than 1% of the total.

3.3 Components of the total mass flows in rivers

The mass flows of nitrogen and phosphorus discharged from the point sources described above (Table 6) may now be compared with the total mass flows of these nutrients that are carried by the Hauraki rivers (Table 5). Furthermore, by estimating the contributions from background—that is, the mass flows that would have been carried by the rivers prior to development of their catchments—it is possible to also estimate the mass flows that have resulted from the development of the land.

For the Kauaeranga, Piako and Waitoa Rivers there is no mass flow information available for river locations downstream of the respective monitoring sites at Kauaeranga River at Smiths, Piako River at Paeroa-Tahuna Rd and Waitoa River at Mellon Rd. The individual components of the overall mass flows were therefore calculated for these sites. The most downstream monitoring site on the Waihou River is at Te Aroha, but this site is more than 65 km from the mouth of the river. Furthermore, various tributaries (Fig. 1)—including the moderately-large Ohinemuri River—and several point source discharges (Fig. 8) enter the river downstream of the monitoring site at Te Aroha. The nutrient mass flows at the mouth of the Waihou River were therefore estimated as the sum of the values for the following sites: Waihou River at Te Aroha, Ohinemuri River at Karangahake and Hikutaia Stream at Maratoto Rd, plus Te Aroha sewage, Paeroa sewage, Paeroa meatworks and Thames sewage.

Table 7 shows the average mass flows of nitrogen and phosphorus carried by the four Hauraki rivers during 2000–09. The contributions to these mass flows from the various point sources listed in Table 6 are also shown.[7] Following Vant (1999), pre-development or background mass flows were calculated from the respective catchment areas (Table 1) and estimates of the specific yields from undeveloped land, namely 3 kg/ha/yr for nitrogen and 0.3 kg/ha/yr for phosphorus, based on the information in Jenkins & Vant (2007, see their Table 2). Subtracting the point source and background mass flows from the total mass flow gives an estimate of the mass flow that is associated with the areas of the catchment that have been developed (generally for pastoral farming).

Altogether the four rivers carried about 3360 t/yr of nitrogen and 270 t/yr of phosphorus to the Southern Firth of Thames (Table 7). The Waihou River carried 50–60% of the combined mass flows while the Kauaeranga River carried 2–4%; the Piako and Waitoa Rivers each carried about 20%.

Point source discharges contributed 9–12% of the mass flows of nitrogen carried by the Waihou and Waitoa Rivers, but just 2% of that carried by the Piako River. There were no consented discharges of nitrogen (or phosphorus) to the Kauaeranga River. Overall, point sources contributed about 8% of the mass flow of nitrogen that was carried by the Hauraki rivers into the Southern Firth of Thames.

Point sources were moderately-important sources of the mass flow of phosphorus carried by the rivers, accounting for 13%, 23% and 47% of the overall mass flows in the Piako, Waihou and Waitoa Rivers, respectively. Overall, point sources contributed about 25% of the mass flow of phosphorus that was carried by the Hauraki rivers into the Southern Firth of Thames.

Between 47% (Kauaeranga River) and 77% (Piako River) of the mass flows of nitrogen carried by the rivers is estimated to have come from diffuse agricultural sources, with these sources accounting for about 70% of the combined mass flow of nitrogen carried by the Hauraki rivers into the Southern Firth of Thames. Background and point source mass flows of phosphorus were somewhat more important than those of nitrogen, so that overall diffuse agricultural sources accounted for about 46% of the combined mass flow of phosphorus carried by the Hauraki rivers into the Southern Firth of Thames.

Table 7: Mass flows of nitrogen and phosphorus in the lower reaches of four Hauraki rivers during 2000–09. The combined mass flows from the various moderate-to-large point source discharges are shown, as are estimates of the pre-development or background mass flows, and the mass flows resulting from catchment land use (see text). Values are rounded; note that the totals differ from those in the less comprehensive analysis in Table 5.

	Kauaeranga	Piako	Waitoa	Waihou	All four rivers
Nitrogen (t/yr)					
Overall	67	775	535	1987	3360
Point sources	0 (0%)	15 (2%)	63 (12%)	183 (9%)	260 (8%)
Background	36 (53%)	161 (21%)	123 (23%)	438 (22%)	760 (23%)
Landuse	32 (47%)	599 (77%)	349 (65%)	1366 (69%)	2340 (70%)
Phosphorus (t/yr)					
Overall	10	55	58	146	270
Point sources	0 (0%)	7 (13%)	27 (47%)	34 (23%)	70 (25%)
Background	4 (37%)	16 (29%)	12 (21%)	44 (30%)	75 (28%)
Landuse	6 (63%)	32 (58%)	18 (32%)	68 (47%)	125 (46%)

[7] The information in Tables 5 and 6 can also be used to calculate the point source contribution to mass flows in particular parts of the various rivers. For example, the mass flow of phosphorus in the Oraka Stream at Pinedale, (well) upstream of Tirau, was about 5 t/yr (Table 5), but additions from Tirau dairy factory (7 t/yr, Table 6) and Tirau sewage (0.6 t/yr) mean that the mass flow downstream of the town was more than twice this.

4 Water quality of the Southern Firth of Thames

Study design

Waikato Regional Council operates a modest estuarine water quality monitoring programme. As part of this, water quality was monitored at three sites in the Southern Firth of Thames at monthly intervals from November 2006 to December 2007. The site locations are shown in Figure 1. This part of the Firth is shallow, with water depths being in the range 0–2 m below chart datum.[8] At the time of sampling, the total depth at each site was typically 2–4 m.

Monitoring was undertaken on an outgoing tide, with each site being visited within an hour of mid-tide. On visits up to and including that in March 2007, measurements of temperature, salinity and dissolved oxygen were made in samples collected from near the surface and the bottom of the water column. From April 2007 onwards profiles of these variables were measured at 0.5 m intervals down through the water column. The Secchi disc depth was also measured at each site.

On the first visit (November 2006) near-surface and near-bottom water samples were collected, but as the laboratory results for these samples were similar, only near-surface samples were collected on subsequent visits. The water samples were analysed by Hills Laboratories for pH, suspended solids, turbidity, biochemical oxygen demand, particulate and dissolved forms of nitrogen (N) and phosphorus (P) and faecal bacteria (faecal coliforms, *Escherichia coli* and enterococci); and further samples were analysed for chlorophyll *a* by NIWA, using the sensitive fluorometric method.

The water quality results at each site are summarised in Table 8, with the seasonal changes for selected variables being shown in Figure 11. Figure 11F shows the combined inflow of freshwater from the Hauraki rivers during the period of the study.

Salinity, temperature and dissolved oxygen

The median salinity was relatively-high at all three sites (31–32 salinity units, noting that the salinity of seawater is about 35). Freshwater was therefore only a minor component of the mixture (overall average 11%, range 1–33%). Salinity varied seasonally, with lowest values occurring during July and August, when river flows were highest (Figs 11A, F). Comparison of the near-surface and near-bottom salinity results on each occasion showed that the water column was generally only weakly-stratified. On average, the salinity of the bottom waters was 1, 2 and 2 salinity units higher than that of the surface waters at sites F1, F2 and F3, respectively. In November 2006, there was no difference in salinity between the surface and bottom waters at sites F1 and F2 (and furthermore, the salinity at these sites was the same: Fig. 11A), while in July 2007 surface and bottom salinities at site F3 were 24 and 32, respectively—a difference of 8 salinity units.

Water temperature also varied seasonally (results not shown), ranging from an average of about 23°C in February to about 11°C in July. The temperature profiles also confirmed that the water column was usually only weakly-stratified, with most differences between surface and bottom temperatures being less than 1°C. The exceptions to this occurred in October, when the surface temperature was 1.9°C higher than the bottom temperature at site F2, and 1.5°C higher at site F3 (but only 0.4°C higher at site F1).

The water was mostly well-oxygenated, with most measurements exceeding 90% of the saturation concentration (Table 8). In particular, all dissolved oxygen measurements in the bottom waters exceeded 90% of saturation (but note that no

[8] Land Information New Zealand chart NZ533.

Table 8: Water quality at three sites in the Southern Firth of Thames during 2006–07 (see Fig. 1). Values are medians (with the minimum and maximum values shown in brackets).

	Site F1	**Site F2**	**Site F3**
Salinity (depth-averaged)	32 (24–35)	32 (22–34)	31 (19–35)
Dissolved oxygen (% saturation)	100 (89–115)	103 (91–115)	95 (86–112)
pH	8.0 (7.6–8.1)	8.0 (7.7–8.2)	7.9 (7.7–8.1)
Secchi depth (m)	1.6 (0.8–3.0)	1.6 (0.9–2.3)	0.6 (0.4–1.1)
Underwater light (% subsurface)	30 (15–50)	30 (20–40)	25 (20–40)
Suspended solids (g/m^3)	5 (<3–14)	6 (3–39)	26 (9–43)
Total phosphorus (mg/m^3)	40 (20–60)	40 (30–50)	60 (40–100)
Dissolved reactive P (mg/m^3)	20 (10–60)	20 (10–50)	30 (10–50)
Total N (mg/m^3)	200 (60–1400)	200 (100–530)	400 (170–1200)
Total inorganic N (mg/m^3)	6 (6–620)	25 (6–940)	45 (6–670)
Chlorophyll *a* (mg/m^3)	2.3 (0.4–9.2)	2.3 (0.8–8.4)	4.0 (1.0–9.3)
Faecal coliforms (cfu/100 mL)	<1 (<1–18)	<1 (<1–42)	3 (<1–120)
Enterococci (cfu/100 mL)	<1 (<1–8)	<1 (<1–5)	<1 (<1–21)

results were obtained for these waters on four of the trips). Dissolved oxygen concentrations were well above saturation concentrations at times (110–120%), presumably because rates of photosynthesis in the water column were high then.

Concentrations of biochemical oxygen demand were low (results not shown), with all but one result being 1 g/m^3 or less (the exception being the June sample for site F2 where the concentration was 2 g/m^3). At each of the sites the median concentration of biochemical oxygen demand was <1 g/m^3, indicating good water quality with no evidence of organic wastes.

Water clarity and suspended solids

The water was typically rather murky, with median Secchi disc depths ranging from 0.6 m at site F3 to 1.6 m at the other two sites. Median suspended solids concentrations ranged from 5 g/m^3 at site F1 to 26 g/m^3 at site F3. In September 2007, however, the water at site F1 was unusually clear (Secchi depth 3.0 m, suspended solids <3 g/m^3). At the other extreme, the water at site F3 was particularly murky in both June 2007 (Secchi depth 0.4 m, suspended solids 38 g/m^3) and December 2007 (Secchi depth 0.4 m, suspended solids 43 g/m^3). Although the poorer clarity at site F3 is undoubtedly associated with the plume of turbid water often present in the nearby Waihou River (Table 4, Fig. 5B), on both occasions river flows were below average (Fig. 11F).

The range of suspended solids concentrations observed were consistent with those reported for this part of the Firth of Thames by van Leeuwe (1991, e.g. her Fig. 5.5c), but note that the lowest category shown in her maps was where suspended solids concentrations were less than 0.1 g/L or 100 g/m^3, and that all of the concentrations found in this study were lower than this, and many were substantially lower (Table 8).

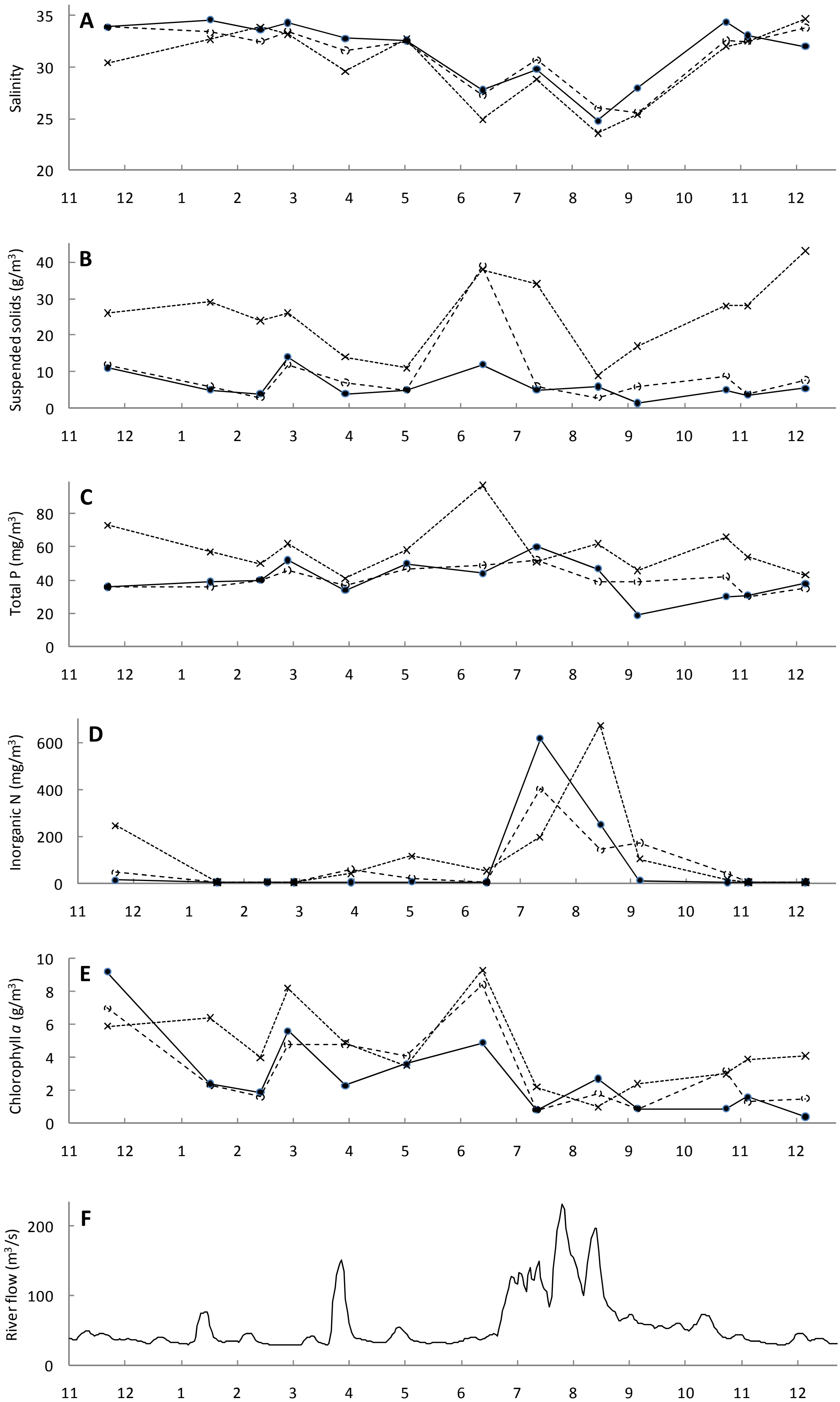

Figure 11: **A-E**, Water quality at three sites in the Southern Firth of Thames, November 2006 to December 2007 (site F1, closed circles, solid line; site F2, open circles, dashed line; site F3, crosses, dotted line). **F**, 7-day running mean of the combined flow of the Hauraki rivers.

Using a relationship developed for the similarly murky waters of Auckland's Manukau Harbour (Vant 1991), measurements of Secchi depth can be used to estimate the rate at which underwater light is attenuated. Together with the measured depth of the water column, these can be used to calculate the depth-averaged level of underwater light for plant growth (as a percent of the value just below the water surface). The median level of underwater light at the three sites was moderate, being in the range 25–30% of the near-surface value (Table 8). The poorer clarity and greater attenuation at site F3 was offset by the shallower water depth there, so the underwater light levels at all three sites are likely to have been sufficient to support plant growth. That is, despite the murky appearance of the water, algal growth is unlikely to have been light-limited.

Nitrogen and phosphorus

Median concentrations of total P were in the range 40–60 mg/m^3, while those for total N were 200–400 mg/m^3. The values of the corresponding ANZECC guidelines are 30 and 300 mg/m^3, respectively. These guidelines are based on concentrations found in estuaries in south-east Australia (as there are no values for New Zealand estuaries). The concentrations found at site F3 were typically higher than those at sites F1 and F2, presumably reflecting the input from the nearby Waihou River (Tables 4, 7).

Concentrations of total P showed little seasonal variation (Fig. 11C). However, concentrations of total inorganic nitrogen (TIN) varied markedly during the year (Fig. 11D). Concentrations were highest during July and August, when concentrations of algal chlorophyll *a* were low (Fig. 11E). River flows, and thus the mass flows of nitrogen to the Southern Firth, were highest during these months (Fig. 11F) and this, together with minimal uptake by the low biomass of algae present in the water column probably accounts for the elevated concentrations found in the waters of the Southern Firth then.

Concentrations of TIN were generally low during the rest of the year. In particular, they were low in November 2006 and June 2007 when chlorophyll *a* levels were high (Figs 11D, E). River flows, and thus mass flows of nitrogen, were relatively low then and algal uptake was presumably relatively-high. Concentrations of dissolved reactive P (DRP), however, did not show the same inverse patterns with chlorophyll *a*; instead DRP was less variable and only occasionally fell to low values. This suggests that algal growth was related more to the concentrations of TIN than to those of DRP. This is consistent with the widespread finding that algal growth in estuarine waters is more dependent on N than on P (e.g. Williamson et al. 2003; Paerl 2009).

Concentrations of TIN and DRP have been extensively-studied in Manukau Harbour, particularly in the north-east part of the harbour where the discharge of large volumes of treated sewage wastewaters means the water is enriched in N and P, and algal blooms have been common (Williamson et al. 2003). Table 9 lists the concentrations found during summer and winter in four separate parts of the harbour during 1991–94 (Vant & Safi 1996), together with the corresponding values for the Southern Firth of Thames.

The average concentrations of TIN found in the Southern Firth during summer were all lower than those found anywhere in Manukau Harbour, while the concentrations found in winter were similar to those found in the north-west and southern parts of the harbour (Table 9). The average concentrations of DRP in the Southern Firth were similar to those found in the southern part of Manukau Harbour. The concentrations of both TIN and DRP in the Southern Firth of Thames were thus much lower than those found in the north-east part of Manukau Harbour that is nutrient-enriched due to the discharge of sewage wastewaters, and instead were similar to those found in the southern part of the harbour, well away from the discharge, and where algal blooms have not been recorded.

Table 9: Average concentrations of total inorganic nitrogen and dissolved reactive phosphorus in summer (December to February) and winter (June to August) at sites in the Southern Firth of Thames (this study) and Manukau Harbour (Vant & Safi 1996).

	Total inorganic N (mg/m^3)		Dissolved reactive P (mg/m^3)	
	Summer	**Winter**	**Summer**	**Winter**
Southern Firth of Thames				
Site F1	6	290	29	35
Site F2	6	185	20	35
Site F3	6	310	15	35
Manukau Harbour				
Entrance	27	58	14	15
Southern	20	220	20	25
North-west	96	307	56	67
North-east	703	1350	231	227

Algae and faecal bacteria

The median concentrations of chlorophyll *a* were in the range 2.3–4.0 mg/m^3 (Table 8, Fig. 11E), with maximum values being below 10 mg/m^3, a value suggested as a threshold for coastal algal blooms elsewhere (Cloern 1996, 2001). The value of the ANZECC guideline for chlorophyll *a* in estuarine waters is 4 mg/m^3, but it is not clear whether this is intended as a maximum value or an average. The concentrations observed in the Southern Firth were also substantially-lower than those found in the lower Waihou River (Table 4, Fig. 5D). As noted above, however, the algae in the lower river are likely to have been trapped and concentrated by the physical processes associated with estuarine mixing, and are unlikely to have been actively-growing.

Estuarine waters elsewhere in the region have also been found to contain relatively-low concentrations of chlorophyll *a*, with maximum values being 4, 8, 6 and 2 mg/m^3 at Kawhia, Raglan, Whangapoua and Whitianga Harbours, respectively (*n*=40–70 in each case; Waikato Regional Council, unpublished data). By way of comparison, in the nutrient-rich north-east part of Manukau Harbour (Table 9) concentrations of algal chlorophyll *a* in excess of 50 mg/m^3 have been recorded during several summers over the past two decades (Vant & Budd 1993; Watercare Services, unpublished data).

Finally, concentrations of faecal bacteria were mostly low, with median concentrations of faecal coliforms in the range <1 to 3 cfu/100 mL, and median concentrations of enterococci being <1 cfu/100 mL at all three sites (Table 8). The concentrations were much lower than those in the Hauraki rivers, indicating that both dilution (c. 10-fold) and die-off in the coastal waters were responsible for the low values seen there.

In summary, during 2006–07 the estuarine water in the Southern Firth of Thames:

- Was dominated by seawater, with freshwater generally representing a minor proportion of the mixture.
- Was reasonably well-mixed vertically with salinity stratification generally being weak.
- Was well-oxygenated.
- Although relatively-murky, was probably sufficiently well-lit to support algal growth (due to the relative shallowness of the water).
- Contained moderate concentrations of the plant nutrients N and P (with concentrations of total N being broadly-similar to guideline values).
- Contained low-to-moderate concentrations of algal chlorophyll *a* (with values being substantially lower than in the nutrient-enriched waters of Manukau Harbour).
- Contained low concentrations of faecal bacteria.

The water quality of the Southern Firth was thus reasonably-good, with no obvious grounds for concern being apparent.

5 Summary and conclusions

1. The water quality of the Hauraki rivers has been routinely monitored at 17 sites for about 20 years (with records beginning during 1990–94). During the past decade (2000–09) the water quality at these sites was excellent in several respects at some sites, and poorer in some respects at others.

2. The Kauaeranga and Ohinemuri Rivers had generally good water quality; indeed that of the Kauaeranga River was excellent in many respects. The water of both rivers was generally well-oxygenated and clear, contained low concentrations of the plant nutrients total N and total P, and moderate concentrations of the faecal bacteria *E. coli*.

3. The Piako and Waitoa Rivers had poorer water quality. The water was often somewhat oxygen-depleted and murky, and contained particularly high concentrations of total N and total P. *E. coli* concentrations were also high.

4. The Waihou River had intermediate water quality. The water was often well-oxygenated, but apart from at headwater sites near large springs, it was murky. Concentrations of total N, total P and *E. coli* were high.

5. The records of water quality at the 17 river sites were analysed for long-term changes (or "trends"). Many (67%) of the records showed no important trends, so that average water quality was broadly stable over the 20 years. However, 18% of the records showed important improvements while 15% showed deteriorations.

6. Notable reductions in total N and total P concentrations at some monitoring sites have resulted from the improved treatment of the wastewaters that are discharged to the rivers. At other sites, however, concentrations of total N increased, probably as a result of the overall intensification of farming in the catchments of these rivers. Even so, over the past 20 years the effects of more intensive farming on nutrient concentrations in the Hauraki rivers as a whole have probably been offset by improved treatment of sewage and industrial wastewaters.

7. A study of the lower, estuarine section of the Waihou River during 2009–10 found that suspended sediments were trapped in a zone near the limit of salt intrusion, up to 20 km from the river mouth. In this "turbidity maximum" the turbidity was higher than in the river upstream or in the coastal waters beyond. The physical processes responsible for this were probably naturally-occurring.

8. Algae from the adjacent coastal waters were also trapped in the lower river, in this case in a zone slightly upstream of the turbidity maximum. Although the concentrations of chlorophyll *a* were high, the negligible salinity and high turbidity mean the algae were unlikely to be actively-growing here. Furthermore, there was no sign of any biological uptake of N or P in the lower section of the river. Instead the high-nutrient river waters appear simply to have been diluted by the lower-nutrient coastal water.

9. Mass flows of total N and total P during 2000–09 were determined at 11 sites on the Hauraki rivers. Altogether the rivers carried about 3360 t/yr of nitrogen and 270 t/yr of phosphorus to the Southern Firth of Thames. The Waihou River carried 50–60% of the combined mass flows while the Kauaeranga River carried 2–4%; the Piako and Waitoa Rivers each carried about 20%. Mass flows were also determined at 22 locations where treated sewage or industrial wastewaters are discharged to the rivers. Overall, these moderate-to-large point sources contributed about 8% of the nitrogen and 25% of the phosphorus that was carried by these rivers into the Southern Firth of Thames.

10. During 2000–09 the combined mass flow of nitrogen carried by the Hauraki rivers increased at a rate of about 1% per year, while the combined mass flow of phosphorus decreased at a rate of about 5% per year.

11. The combined discharge of total N from the 22 point sources was about 260 t/yr. Much of this came from five sites: Thames sewage (16%), Tirau dairy factory (15%), Waitoa meatworks (13%), Te Aroha meatworks (10%) and Waitoa dairy factory (10%). The combined discharge of total P was about 68 t/yr, much of which came from five sites: Waitoa dairy factory (31%), Tirau dairy factory (10%), Te Aroha meatworks (10%), Morrinsville sewage (9%) and Waitoa meatworks (9%). Note, however, that the load of total P discharged from the Waitoa dairy factory fell markedly during the decade.

12. Background (or "natural") sources in the catchments of the rivers were estimated to contribute about 23% of the combined mass flow of total N and 28% of the total P. The remaining 70% of the combined mass flow of total N and 46% of the total P is likely to have come from diffuse agricultural sources in the rivers' catchments. That is, losses of N and P due to the development of land for farming contributed much of the nutrient mass flow entering the Firth of Thames in the Hauraki rivers.

13. The water quality of the Southern Firth of Thames was studied at three sites during 2006–07, and was found to be generally-good. The water was predominantly seawater, with freshwater generally representing a minor proportion of the mixture, indicating that the inputs from the rivers (and direct rainfall) were substantially diluted with good quality seawater. The water column was weakly-stratified and was well-oxygenated. Although the water was generally murky, calculations showed that its relative shallowness meant it was probably sufficiently well-lit to support algal growth.

14. The water contained moderate concentrations of N and P, and low-to-moderate concentrations of chlorophyll *a*, with values being substantially lower than those found in nutrient-enriched estuarine waters elsewhere. Concentrations of inorganic N were highest during the winter (July and August) when mass flows from the Hauraki rivers were highest. Algal biomass was low at this time so biological uptake of N from the water was probably also low. Chlorophyll concentrations were highest in November and June, and concentrations of inorganic N were low then. This inverse pattern was not seen with concentrations of inorganic P, suggesting that algal growth in the Southern Firth of Thames depends more on the availability of N than P (as is commonly the case in coastal and estuarine waters elsewhere).

15. Overall then, the results presented here indicate that although the estuarine waters of the Southern Firth of Thames are probably sufficiently well-lit to support algal growth, dilution of the N and P inputs from the Hauraki rivers in the seawater present in the Southern Firth means that nutrient concentrations are not high there, and neither is the level of algal biomass.

16. In rivers elsewhere in the Waikato region, concentrations of N and P have slowly-increased over the past 20 years, largely as a result of intensifying farming. It is not clear whether or how algal growth in the Southern Firth of Thames would change if the mass flows of N and P in the Hauraki rivers were to increase in the future. To make useful predictions of this, more will need to be known about the dynamics of algal growth in this waterbody—where nutrients, light, flushing and grazing are all likely to affect algal biomass.

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Appendix 1: Water quality at sites in four Hauraki rivers, 2000–09 (see Fig. 1 for site locations). Values are medians (with the minimum and maximum values shown in brackets).

	Site	DO (% satn)	pH	Turbidity (NTU)	Ammonia (mg N/m^3)	Total P (mg/m^3)	Total N (mg/m^3)	Clarity (m)	Ecoli (cfu/100 mL)
	Kauaeranga								
2	Kauaeranga at Smiths	99 (92–120)	7.1 (6.3–7.8)	1.1 (0.5–510)	5 (5–50)	4 (2–420)	100 (26–600)	3.1 (0.1–7.5)	95 (1–1200)
	Piako								
82	Piakonui at Piakonui Rd	99 (90–125)	7.3 (6.5–7.8)	3.9 (1.6–65)	5 (5–190)	30 (7–340)	440 (220–2400)	1.2 (0.1–2.4)	85 (10–6400)
83	Piako at Kiwitahi	87 (22–120)	7.1 (6.6–7.6)	4.5 (0.8–100)	30 (5–1950)	110 (50–530)	1650 (260–5700)	1.5 (0.1–4.2)	500 (47–16,000)
79	Piako at Paeroa-Tahuna Rd	82 (51–98)	7.2 (6.7–7.8)	10 (2.3–100)	60 (5–420)	280 (110–780)	2450 (800–6300)	0.7 (0.1–1.9)	700 (150–14,000)
	Waitoa								
81	Waitoa at Landsdowne Rd	88 (55–130)	7.1 (6.7–7.7)	5.4 (0.5–230)	20 (5–310)	80 (15–860)	1970 (750–4600)	1.1 (0.1–4.4)	480 (15–33,000)
80	Waitoa at Mellon Rd	75 (43–120)	7.2 (6.5–7.9)	7.6 (1.0–55)	60 (5–1200)	270 (24–2900)	2800 (860–6100)	0.9 (0.1–3.3)	730 (100–25,000)
	Waihou								
1	Hikutaia at Maratoto Rd	95 (83–120)	7.1 (6.3–7.9)	1.5 (0.6–90)	5 (5–70)	11 (2–190)	150 (26–1400)	2.7 (0.1–5.2)	235 (23–1800)
8	Ohinemuri at SH25	105 (78–145)	7.0 (6.5–7.7)	1.0 (0.5–55)	5 (5–120)	15 (2–310)	640 (70–2200)	3.4 (0.3–9.0)	160 (7–37,000)
9	Ohinemuri at Queens Head	107 (87–130)	7.2 (6.5–8.2)	1.1 (0.4–55)	20 (5–260)	30 (2–250)	1240 (190–2400)	2.8 (0.1–6.1)	115 (17–15,000)
4	Ohinemuri at Karangahake	106 (100–120)	7.8 (6.8–9.0)	1.1 (0.5–17)	14 (1–170)	14 (4–130)	630 (140–1950)	2.5 (0.2–5.3)	45 (6–2000)
35	Oraka at Lake Rd	93 (55–101)	7.3 (6.7–8.3)	4.6 (1.4–160)	25 (5–890)	140 (90–990)	2300 (1700–5200)	1.0 (0.1–3.0)	850 (100–26,000)

Appendix 1 (continued)

	Site	DO (% satn)	pH	Turbidity (NTU)	Ammonia (mg N/m^3)	Total P (mg/m^3)	Total N (mg/m^3)	Clarity (m)	Ecoli (cfu/100 mL)
37	Waihou at Whites Rd	102 (93–112)	7.0 (6.5–7.5)	0.4 (0.2–3.6)	5 (5–60)	85 (70–120)	670 (430–1160)	6.1 (1.5–8.9)	45 (1–2300)
33	Waihou at Okauia	94 (88–106)	7.3 (6.7–8.1)	3.8 (1.1–55)	10 (5–110)	95 (70–260)	1300 (840–2600)	1.1 (0.2–2.4)	300 (90–5400)
3	Waihou at Te Aroha	93 (82–103)	7.3 (6.7–7.6)	5.1 (1.6–50)	30 (1–250)	100 (70–440)	1260 (900–2220)	0.7 (0.2–1.8)	250 (30–2400)
36	Waiohotu at Waiohotu Rd	95 (77–112)	7.2 (6.6–7.7)	4.6 (1.0–23)	5 (5–80)	30 (13–90)	350 (230–690)	no data	80 (10–1700)
34	Waiomou at Matamata-Tauranga Rd	96 (90–104)	7.1 (6.6–7.7)	3.5 (1.1–50)	14 (5–120)	45 (27–150)	700 (340–1900)	1.3 (0.1–2.9)	330 (10–2400)
100	Waitekauri at Ohinemuri	104 (94–120)	7.2 (6.5–8.2)	0.8 (0.4–80)	5 (5–100)	9 (2–630)	250 (30–2700)	3.3 (0.1–8.1)	110 (2–10,000)

Appendix 2: *p*-values (%) and, in brackets, slopes (% per year) of trends in flow-adjusted water quality at sites in four Hauraki rivers. Upper row, whole record; lower row, 2000–09. Important improvements (see text) are shown in bold; important deteriorations are bold underlined; "ns", not significant. "Cond", conductivity.

	Site	DO	Cond	Turbidity	Ammonia	Total P	Total N	Clarity	Ecoli
	Kauaeranga								
2	Kauaeranga at Smiths	6 (0.1)	**<1 (1.0)**	**1 (2.4)**	6 (0.0)	7 (0.0)	**<1 (3.6)**	**<1 (–2.3)**	97 (–0.4)
		49 (–0.1)	12 (0.5)	78 (0.6)	98 (0.0)	39 (–2.5)	25 (2.1)	**<1 (–3.8)**	40 (5.2)
	Piako								
82	Piakonui at Piakonui Rd	<1 (–0.3)	32 (0.1)	**<1 (–3.6)**	8 (–2.0)	**2 (–1.3)**	51 (–0.2)	**<1 (2.3)**	61 (–2.2)
		<1 (–0.3)	<1 (–0.7)	**5 (–2.4)**	**2 (–2.0)**	**<1 (–5.1)**	45 (–0.7)	99 (0.0)	45 (–6.4)
83	Piako at Kiwitahi	<1 (–0.9)	<1 (0.6)	**<1 (–3.4)**	**<1 (–5.0)**	**1 (–1.0)**	3 (–0.9)	**2 (1.6)**	6 (16.2)
		8 (–0.5)	19 (0.3)	13 (1.3)	82 (0.0)	**3 (–2.1)**	39 (0.8)	**<1 (–4.5)**	50 (9.1)
79	Piako at Paeroa-Tahuna Rd	89 (0.0)	<1 (0.9)	70 (0.3)	**<1 (–5.1)**	56 (–0.2)	**<1 (–1.3)**	**5 (–1.3)**	77 (3.1)
		5 (0.6)	**<1 (1.0)**	**5 (3.1)**	8 (–5.0)	34 (2.0)	**1 (3.4)**	**<1 (–5.3)**	67 (5.3)
	Waitoa								
81	Waitoa at Landsdowne Rd	86 (0.0)	<1 (0.9)	42 (–0.4)	23 (–2.0)	70 (–0.1)	18 (0.4)	**<1 (–2.0)**	35 (7.2)
		<1 (0.9)	<1 (0.5)	78 (0.4)	90 (1.0)	**3 (–2.1)**	16 (0.8)	**<1 (–5.2)**	99 (1.5)
80	Waitoa at Mellon Rd	<1 (0.6)	**<1 (1.1)**	71 (–0.2)	**<1 (–6.6)**	**<1 (–10.4)**	**<1 (–1.2)**	21 (–0.6)	97 (0.4)
		<1 (0.8)	34 (–0.8)	82 (–0.5)	**<1 (–8.5)**	**<1 (–22.5)**	**5 (–1.8)**	**4 (–2.2)**	62 (–1.6)
	Waihou								
1	Hikutaia at Maratoto Rd	37 (0.0)	59 (0.1)	67 (–0.5)	**<1 (–8.0)**	76 (0.0)	30 (–0.6)	38 (–0.7)	92 (–0.2)
		52 (0.1)	<1 (–0.5)	25 (–1.7)	**<1 (–16.0)**	**<1 (–6.4)**	6 (–2.8)	11 (–2.6)	62 (1.4)
8	Ohinemuri at SH25	1 (–0.2)	95 (0.0)	42 (–0.7)	**<1 (–4.0)**	23 (–1.2)	**<1 (–1.1)**	**<1 (–2.4)**	53 (1.2)
		<1 (–0.5)	1 (–0.4)	7 (2.4)	12 (–4.0)	75 (–0.7)	83 (–0.2)	**<1 (–7.6)**	40 (4.8)
9	Ohinemuri at Queens Head	1 (–0.2)	**<1 (2.1)**	**<1 (–3.5)**	7 (–3.3)	**<1 (–6.4)**	**5 (1.0)**	52 (0.3)	62 (2.7)
		<1 (–0.5)	**3 (1.9)**	6 (–2.3)	29 (2.5)	**<1 (–10.7)**	12 (1.1)	15 (–1.6)	99 (–0.2)
4	Ohinemuri at Karangahake	3 (–0.1)	**<1 (1.3)**	**2 (–1.1)**	9 (–1.5)	**<1 (–2.9)**	23 (–0.3)	11 (0.5)	–
		<1 (–0.3)	13 (0.6)	**2 (2.9)**	75 (0.7)	**<1 (–5.8)**	17 (1.1)	50 (0.5)	99 (–0.1)
35	Oraka at Lake Rd	20 (–0.1)	**<1 (1.3)**	**<1 (4.9)**	73 (–0.7)	24 (–0.7)	**<1 (1.0)**	74 (0.1)	92 (–0.6)
		31 (0.1)	39 (–0.2)	74 (1.0)	**5 (–6.9)**	29 (–0.7)	14 (0.6)	62 (–1.0)	69 (–2.1)

Appendix 2 (continued)

	Site	DO	Cond	Turbidity	Ammonia	Total P	Total N	Clarity	Ecoli
37	Waihou at Whites Rd	<1 (–0.2)	<1 (0.5)	7 (–1.5)	4 (0.0)	<1 (–0.4)	**<1 (1.5)**	1 (0.9)	35 (2.8)
		<1 (–0.3)	66 (0.0)	78 (–0.4)	78 (0.0)	<1 (–0.8)	**<1 (1.7)**	**1 (–1.6)**	89 (0.5)
33	Waihou at Okauia	69 (0.0)	<1 (0.9)	19 (1.1)	**3 (–2.0)**	5 (–0.5)	**<1 (1.1)**	91 (0.0)	16 (3.0)
		13 (0.1)	70 (–0.1)	94 (–0.2)	**4 (–2.0)**	5 (–0.7)	17 (0.6)	26 (–1.2)	56 (–2.5)
3	Waihou at Te Aroha	<1 (–0.2)	<1 (0.5)	62 (–0.2)	**<1 (3.8)**	77 (0.1)	<1 (0.5)	89 (0.0)	–
		71 (0.0)	<1 (0.6)	7 (1.9)	**<1 (6.3)**	**<1 (1.3)**	**2 (1.0)**	27 (–0.9)	99 (–1.3)
36	Waiohotu at Waiohotu Rd	36 (0.0)	50 (0.0)	11 (1.4)	27 (0.0)	27 (0.3)	**<1 (2.1)**	no data	97 (0.3)
		<1 (–0.4)	<1 (–0.4)	**1 (–4.5)**	66 (0.0)	**<1 (–3.1)**	78 (0.3)		56 (–6.9)
34	Waiomou at Matamata-Tauranga Rd	15 (0.0)	<1 (0.5)	25 (0.8)	29 (1.0)	<1 (0.9)	**<1 (1.6)**	35 (0.5)	26 (3.0)
		59 (–0.4)	<1 (–0.7)	29 (1.1)	22 (–3.0)	8 (–0.9)	99 (0.0)	**2 (–2.9)**	50 (0.8)
100	Waitekauri at Ohinemuri	20 (0.1)	**<1 (–2.7)**	40 (1.0)	**<1 (–18.0)**	**3 (1.3)**	**<1 (–5.6)**	**<1 (–1.7)**	14 (–4.6)
		2 (–0.3)	12 (–0.6)	**3 (5.0)**	31 (–2.0)	39 (–2.2)	49 (0.9)	**<1 (–6.1)**	52 (–2.4)