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Visual clarity of the Waikato and Waipa Rivers

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Note: This report was originally published in May 2015. This revised version corrects minor errors in Tables 2, 3 and 4 (and the accompanying text) of the original report. These corrections have made little or no difference to the interpretation or conclusions.

Acknowledgement

The analysis presented here arose from a discussion at a workshop convened by the Healthy Rivers Technical Leaders Group in December 2014. The other workshop participants—Bryce Cooper, Rob Davies-Colley, Sandy Elliott, John Quinn and Mike Scarsbrook—all contributed to the ideas discussed here, and Rob reviewed and helpfully commented-on a draft of this report (see WRC document #3306943).

Table of contents

Summary

1. The visual clarity of the water in the Waikato and Waipa Rivers reflects the varying concentrations of the light-attenuating constituents present in it. The main constituents are dissolved yellow substance, phytoplankton, organic detritus and suspended silts and clays. The concentrations of these constituents vary in both time and space, and so too does the visual clarity of the river waters.

2. Routine measurements of the horizontal sighting range of a black disc, a robust measure of water clarity, can be used to determine the underwater attenuation of light, characterised by the beam attenuation coefficient. Over the past decade (2005–14), average beam attenuation was particularly low in the clear blue waters leaving Lake Taupo, and increased progressively moving down the length of the Waikato River. Beam attenuation was moderately-high in even the upper reaches of the Waipa River, with the highest values in the two rivers being observed in the lower reach of the Waipa.

3. Concentrations of phytoplankton (as chlorophyll *a*) and yellow substance also increased progressively down the length of the Waikato River. The highest concentration of yellow substance in the Waipa River, however, occurred in its upper reaches. Although there is little or no information about the presence of phytoplankton in the Waipa River, they are likely to be uncommon there.

4. Concentrations of chlorophyll *a* were highest in the Waikato River during summer (October-to-March). Some 25–30% of the summer-average chlorophyll *a* in the lower reach of the Waikato River is likely to have come from the large shallow lakes present in the river's floodplain.

5. On average, yellow substance was a minor contributor (c. 2%) to beam attenuation in the Waikato River during 2005–14. Even in the Waipa River its contribution was usually small (<5%), apart from at the most upstream site (where it was c. 8%).

6. On average, phytoplankton contributed an estimated 50–60% of the observed beam attenuation in the section of the Waikato River upstream of the confluence with the Waipa River (at Ngaruawahia). Further downstream, phytoplankton contributed about one-third of beam attenuation on average.

7. Non-algal beam attenuation, which can be mainly attributed to suspended silts and clays, is apparently responsible for the other 40–50% of the beam attenuation in the section of the Waikato River upstream of Ngaruawahia, and most of the beam attenuation in the reach downstream of there. Non-algal attenuation is expected to dominate beam attenuation in the Waipa River.

8. Over the past decade or so, chlorophyll *a* concentrations in the Waikato River have declined. However, this has had only a minor effect on the visual clarity of the river water, and then only in certain parts of the river (e.g. Narrows). Somewhat unexpectedly, water clarity at Lake Ohakuri was actually *poorer* during the period of *lower* chlorophyll than it had been previously. Although phytoplankton can be an important cause of beam attenuation in the river, so too are other constituents (e.g. silts and clays), and it appears that these often mask the effects of the phytoplankton.

1 Introduction

The visual clarity of a waterbody—how far an observer can see through the water—is primarily determined by its water quality; in particular, by the concentrations of the various constituents that absorb or scatter light (Davies-Colley et al. 1993). The main light-attenuating constituents of natural waters are (1) yellow substance—coloured dissolved organic material, (2) inorganic suspended particles (silts and clays), (3) organic suspended particles including phytoplankton and biological detritus, and (4) water itself. Table 1 summarises the main optical effects of each of these constituents.

These light-attenuating constituents are present in different amounts in the Waikato and Waipa Rivers, resulting in the marked differences in time and space in the appearance of the water of these rivers. Vant (2010) commented on the appearance of the Waikato River as follows,

> *"The most striking changes in the river's water quality are those that occur longitudinally. Downriver changes in turbidity, dissolved colour and phytoplankton chlorophyll cause the appearance of the river to change from clear and blue as it leaves Lake Taupo to green and murky as it passes through Hamilton, and brown and muddy at Tuakau."*

In this report, results from Waikato Regional Council's and NIWA's long-term routine water quality monitoring programmes for the Waikato and Waipa Rivers are used to characterise the visual clarity of the rivers and to identify the main causes of it.

Figure 1 shows the location of most of the routine water quality monitoring sites on the Waikato and Waipa Rivers considered in this analysis. It also summarises the variation in turbidity—mostly due to the scattering of light by fine particles—in the rivers. Turbidity is fairly closely inversely-related to visual clarity in rivers (Davies-Colley & Smith 2001), and Figure 1 shows that the typical turbidity of the upper reaches of the Waikato is low, while the lower reaches of both the Waikato and the Waipa are substantially more turbid.

Table 1: Categories of light-attenuating constituents in natural waters (adapted from Davies-Colley et al. 1993).

Constituent	Optical character	Measured by
Water itself	Absorbs light, mainly red. Scatters light very weakly.	Specific optical measurements.
Dissolved constituents		
Yellow substance	Strongly absorbs light, particularly blue light. Scattering is negligible.	Absorption of filtered sample, e.g. at 440 nm.
Particulate constituents		
Total suspended particles	Responsible for almost all scattering. Organic solids may also absorb light.	Total suspended solids (TSS).
Mineral or inorganic suspended particles	Scatter light intensely, but usually absorb light weakly.	Ash content of TSS (or "non-volatile suspended solids")
Detritus	Spectral absorption similar to yellow substance. Also scatters light.	Volatile suspended solids, corrected for living biomass.
Phytoplankton	Absorb light strongly (with spectral sensitivity). Scatter light strongly.	Chlorophyll *a* concentration.

Figure 1: Median turbidity in the Waikato and Waipa Rivers, 2010–14. From [WRC website](#).

2 Current water clarity and constituent concentrations

Information used
Up-to-date information on the location of the WRC water quality monitoring sites, the water quality variables measured, the methods used and the general nature of the results obtained are provided in the annual reports on the monitoring programmes (Tulagi 2014a,b).

The water quality results considered here are as follows (see Davies-Colley et al. 1993 for details):

– horizontal sighting range of a black disc (y_{BD}), a robust measure of visual water clarity (Zanevald & Pegau 2003)
– beam attenuation coefficient (c)[1], estimated as $4.8/y_{BD}$
– laboratory turbidity
– chlorophyll *a*
– yellow substance, as the absorption coefficient at 440 nm (g_{440})

Average visual clarity and constituent concentrations in the rivers
Table 2 lists the average values of these variables at the routine monitoring sites (Figure 1) during the past ten years.

[1] Actually, the beam attenuation coefficient at 550 nm, in the middle of the visible spectrum (400–700 nm), at which wavelength the human eye is most sensitive.

Table 2: Average water clarity, beam attenuation coefficient and constituent concentrations at 13 sites on the Waikato River and five sites on the Waipa River during 2005–14. Site locations are shown in Fig. 1. Results for a deep-water site in the centre of Lake Taupo are also shown.

	y_{BD} (m)	c (m^{-1})	Turbidity (NTU)	Chlorophyll *a* (mg/m^3)	g_{440} (m^{-1})
Lake Taupo	12.3	0.4	–	1	0.1*
Waikato River					
Taupo Gates	–	–	0.6	<3	<0.1
Reids Farm (NIWA)	7.6	0.7	0.4	–	0.1[§]
Ohaaki Bridge	4.5	1.2	1.0	<3	<0.1
Ohakuri tailrace	2.4	2.3	1.2	4	<0.1
Whakamaru tailrace	2.1	2.6	1.3	10[†]	0.1
Waipapa tailrace	1.9	2.7	1.4	6	0.3
Narrows	1.5	3.7	2.5	8	0.4
Hamilton (NIWA)	1.2	4.4	2.5	–	0.8
Horotiu Bridge	1.3	4.2	3.0	9	0.5
Huntly Bridge	0.8	7.2	8.7	8	0.8
Rangiriri (NIWA)	0.7	8.0	7.0	–	1.2
Mercer Bridge	–	–	11.4	13	1.0
Tuakau Bridge	0.6	9.4	11.2	16	1.1
Waipa River					
Mangaokewa Rd	1.5	4.0	3.1	–	2.1
Otewa (NIWA)	1.6	7.5	8.0	–	1.2
Otorohanga	1.2	6.7	9.0	–	1.2
Pirongia	0.7	10.0	16.2	–	1.2
Whatawhata (NIWA)	0.5	13.0	13.9	–	1.8

*Estimated from the result for Reids Farm

[§]NIWA uses a more sensitive method to determine g_{440} (40 mm spectrophotometric cell, rather than 10 mm), so the NIWA results for this part of the river in particular are more precise than the WRC results.

[†]Some of the chlorophyll at this site is likely to be associated with filamentous algae rather than phytoplankton (Vant 2013a)

Table 2 also shows the beam attenuation coefficient and constituent concentrations for Lake Taupo, from measurements made at a deep-water site in the middle of the lake (Gibbs 2014). In that case c was estimated from the measured Secchi disc depth, z_{SD}, and the relationship $y_{BD} = z_{SD}/1.25$ (from Davies-Colley et al. 1993, section 5.3.2).

The average black disc sighting range (y_{BD}) decreased progressively down both the Waikato and Waipa Rivers (Table 2). The upper reaches of the Waikato River were particularly clear (y_{BD} > 4 m), reflecting the high visual clarity of the water in Lake Taupo. The upper reaches of the Waipa River were also clearer than further downstream in this tributary, but were not as clear as the Upper Waikato. The lower reaches of both rivers were relatively turbid (y_{BD} < 1 m). Conversely, beam attenuation was low in the Upper Waikato (c. 1 m^{-1}), and relatively high in the lower reaches of both rivers (> 7 m^{-1}).

Average turbidity showed a similar pattern of variation to beam attenuation (Table 2), with very low values in the water leaving Lake Taupo, and high values in the lower reaches of both rivers (see also Fig. 1). Figure 2 shows the monthly results for y_{BD} and turbidity at four Waikato River sites during 2014. Between Taupo and Ohakuri, turbidity tended to be low (< 2 NTU), and black disc range was high (> 2 m). Further downstream, turbidity was higher and y_{BD} was lower. Figure 2 also shows that both y_{BD} and turbidity varied markedly during the year, particularly at Ohaaki and at Tuakau (i.e. the opposite ends of the river). The measured turbidity was mostly due to scattering by suspended particles, so the turbidity measurements provide a crude surrogate for suspended solids concentrations (ignoring the effects of particle size, shape and composition: see later).

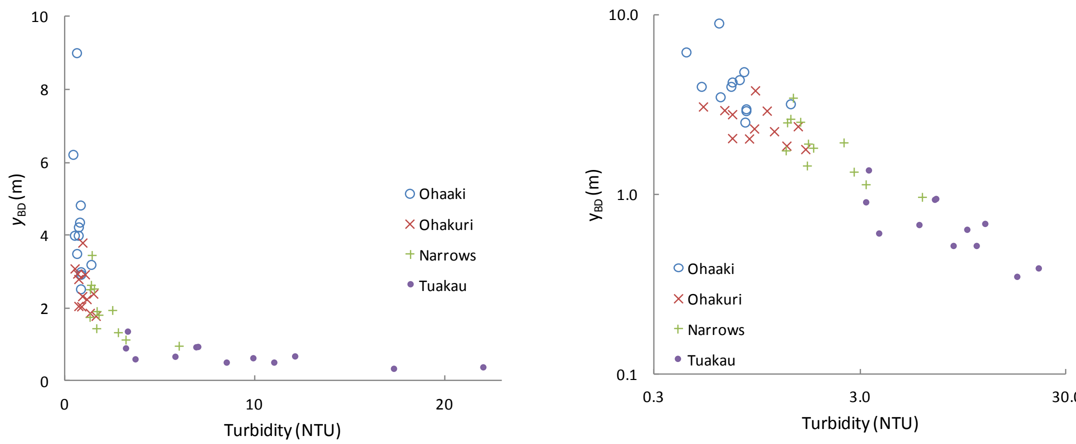

Figure 2: Black disc sighting range (y_{BD}) and turbidity in monthly samples from four sites on the Waikato River, January-December 2014. Results are plotted on both normal axes (left) and logarithmic axes (right).

Average concentrations of phytoplankton chlorophyll *a* also increased progressively down the Waikato River (Table 2), with phytoplankton being carried out of Lake Taupo, then growing in the Waikato hydrolakes and beyond. By contrast, phytoplankton are uncommon in "normal" rivers in New Zealand (Davies-Colley et al. 1993, Smith et al. 1997), so chlorophyll concentrations are not measured in the Waipa River monitoring programmes. In this analysis, concentrations there are assumed to be negligible.

Some of the chlorophyll measured in the Waikato River at Mercer and Tuakau is likely to have been carried downstream from the large shallow lakes found in the river's floodplain. Calculations shown in Appendix 1 indicate that about 27% of the chlorophyll measured at Mercer in summer periods during 2003–14 is likely to have come from Lakes Waikare and Whangape. That is, not all of the chlorophyll observed at the lower river sites in Table 2 will have grown in the river itself.

Average concentrations of yellow substance—measured as g_{440}—were also low in the water leaving Lake Taupo, and increased progressively down the river (Table 2). Average concentrations at all sites on the Waipa River, however, were somewhat higher. Interestingly, the highest average value of g_{440} in the Waipa River was observed at the most upstream site at Mangaokewa Rd, where the relatively small catchment (48 km^2) is largely covered in native bush/shrubland (30%) and planted forest (44%). The elevated concentration of yellow substance at this site may well result from the natural decay of plant materials produced in these areas.

Seasonal differences in visual clarity and constituent concentrations in the rivers

Figure 3 shows the seasonal changes in the black disc sighting range at selected sites in the Waikato and Waipa Rivers during 2005–14, as follows (Figure 1):

– Waikato River at Ohakuri, the first large hydrolake
– Waikato River at Narrows, downstream of the last hydrolake
– Waikato River at Tuakau, the last monitoring site
– Waipa River at Mangaokewa Rd, the first site on this major tributary
– Waipa River at Whatawhata, the last Waipa site

At Ohakuri a reasonably-pronounced seasonal pattern in y_{BD} was apparent, with water clarity being greatest during the middle of the year (roughly the middle third, May-to-August). At Narrows and Tuakau, seasonality was less pronounced, but greatest clarity did occur around April-May, with lowest clarity occurring several months later (October-to-November).

Waikato River

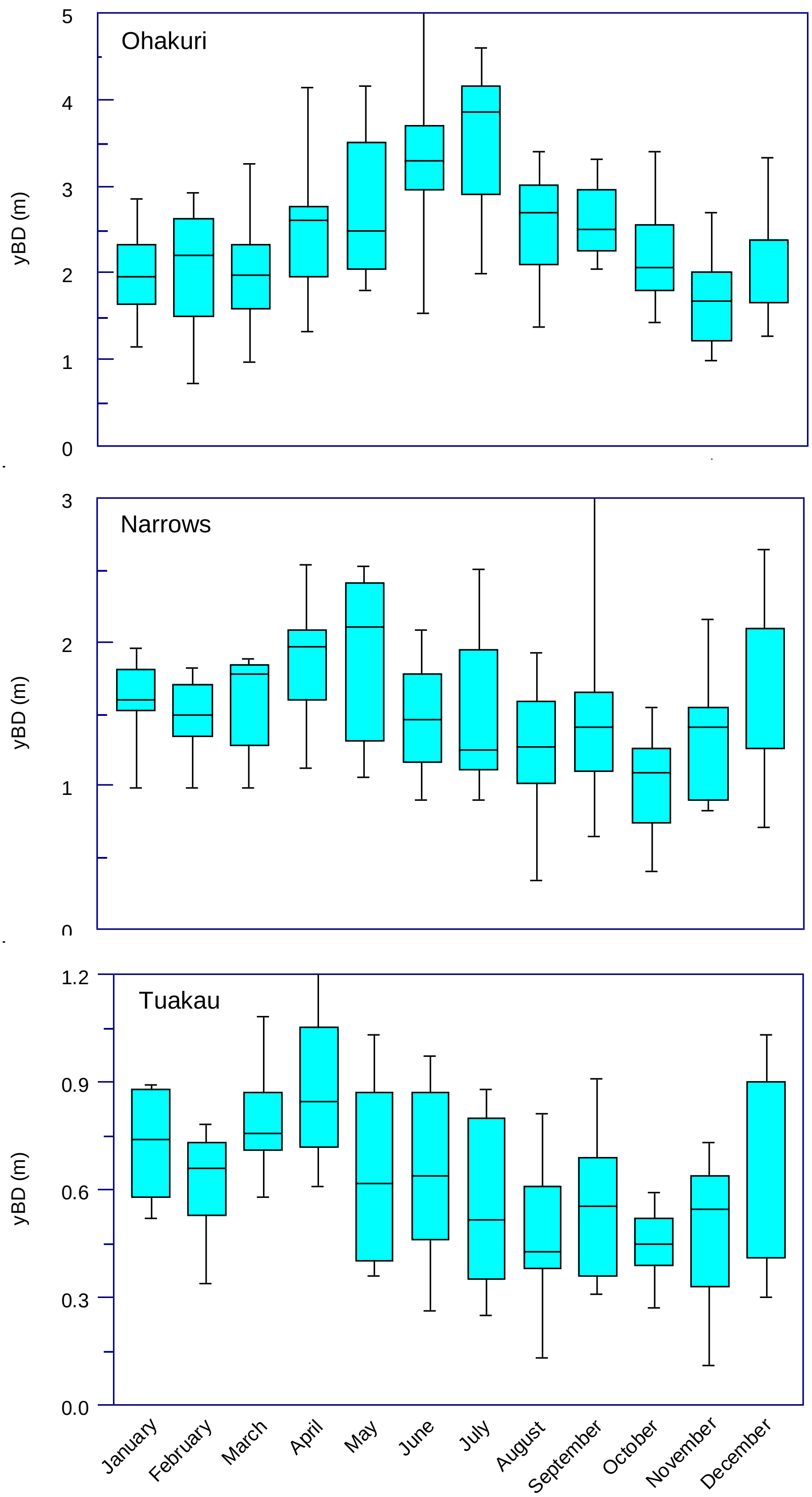

Figure 3: Seasonal boxplots of black disc sighting range at selected sites on the Waikato and Waipa Rivers, 2005–14

Waipa River

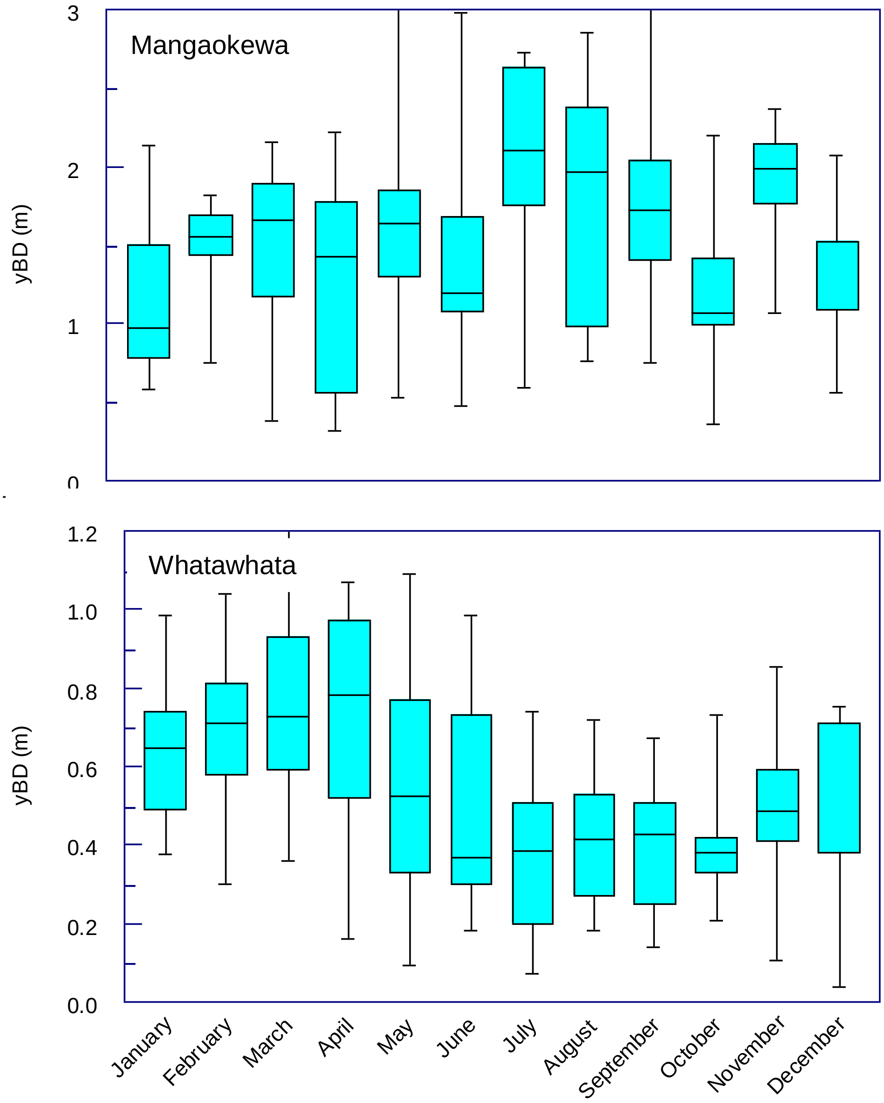

Figure 3 (continued): Seasonal boxplots of black disc sighting range at selected sites on the Waikato and Waipa Rivers, 2005–14

Waikato River

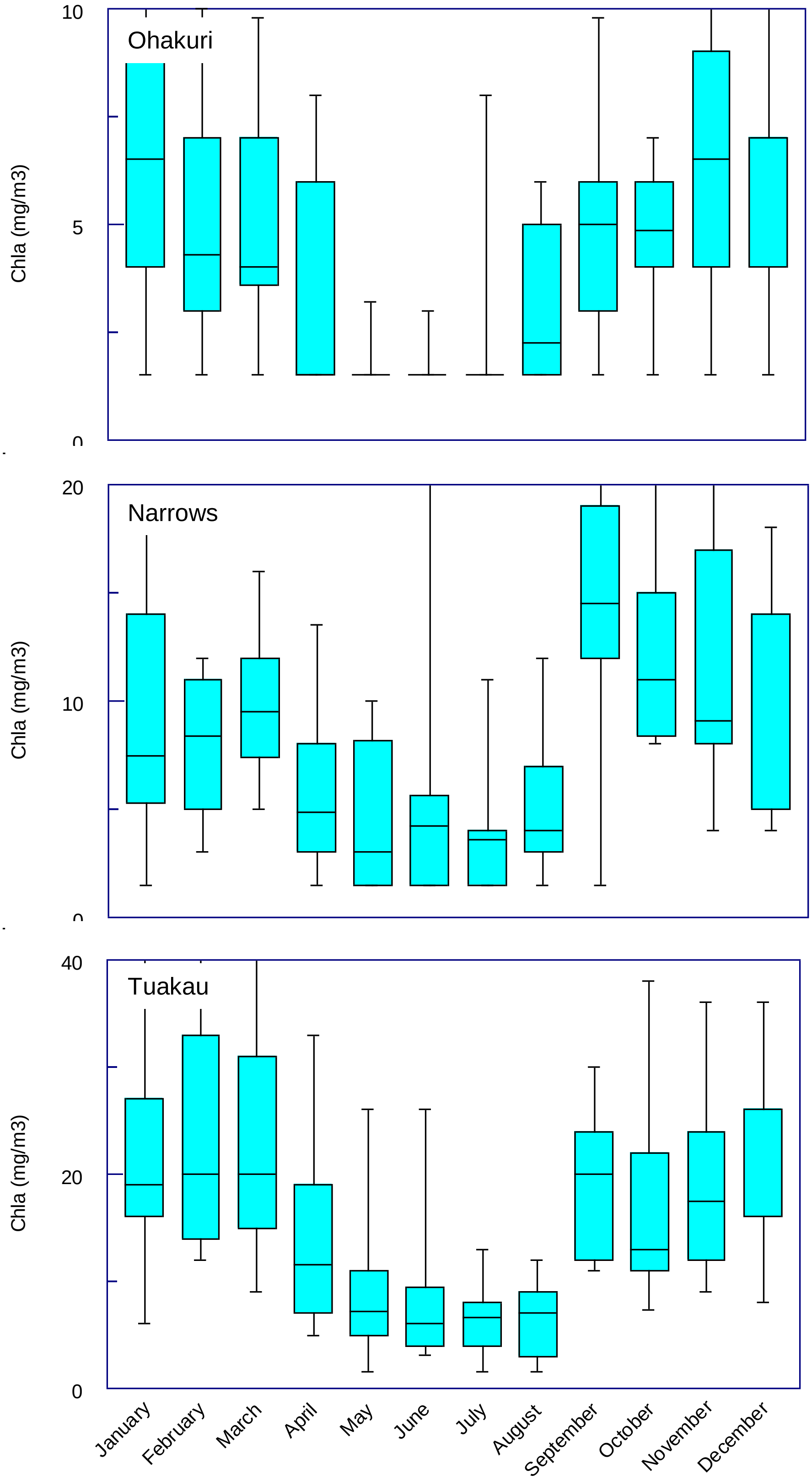

Figure 4: Seasonal boxplots of chlorophyll *a* concentration at selected sites on the Waikato River, 2005–14

A broadly similar pattern of seasonality in y_{BD} was also seen in the Waipa River at Whatawhata (but not at Mangaokewa), suggesting that the causes of seasonality in the Waikato River were not necessarily connected with the presence of hydrolakes.

Figure 4 shows the seasonal changes in chlorophyll *a* concentration at the selected sites on the Waikato River. In this case, highest concentrations of chlorophyll tended to occur during the summer months, particularly the period October-to-March.

3 Contribution of constituents

Yellow substance

Vant & Davies-Colley (1984) studied the optical properties and water quality of 27 diverse New Zealand lakes. They found that the contribution of yellow substance to the absorption coefficient, *a*, could be calculated as $0.13 \times g_{440}$. As dissolved yellow substance produces negligible light scattering (Table 1), and since $c = a + b$, where *b* is the scattering coefficient, it follows that the contribution of yellow substance to beam attenuation (c_Y), can be calculated as $c_Y = 0.13 \times g_{440}$. This equation was used to calculate c_Y each month at all of the Waikato and Waipa monitoring sites, with the result being compared with the corresponding estimate of *c* for that month. The ratio c_Y/c provides an estimate of the relative contribution of yellow substance to beam attenuation on each sampling occasion.

Table 3 shows the average contribution of yellow substance to beam attenuation at the Waikato and Waipa River monitoring sites during the past 10 years. Yellow substance was generally a minor cause of beam attenuation at the Waikato River sites, with average contributions being about 2%. At the Waipa River sites, the contributions of yellow substance were somewhat larger, but apart from Waipa at Mangaokewa (8%), were still reasonably small (2–4%). As noted above, the elevated concentration of yellow substance at the Mangokewa site may well result from the decay of the plant materials produced in the relatively large areas of forest in this part of the catchment. The vegetation cover is likely to help minimise soil erosion as well, so this source of beam attenuation will be minimised, further increasing the relative importance of yellow substance here.

In general, yellow substance was a relatively minor cause of beam attenuation in the Waikato and Waipa Rivers, and as a result will not be considered further in this analysis.

Table 3: Average contribution of yellow substance to beam attenuation at sites on the Waikato and Waipa Rivers during 2005–14.

	c (m^{-1})	g_{440} (m^{-1})	c_Y/c
Waikato River			
Taupo Gates	–	not detected	–
Reids Farm (NIWA)	0.7	0.1*	2%
Ohaaki Bridge	1.2	not detected	–
Ohakuri tailrace	2.3	not detected	–
Whakamaru tailrace	2.6	0.1	1%
Waipapa tailrace	2.7	0.3	1%
Narrows	3.7	0.4	2%
Hamilton (NIWA)	4.4	0.8	3%
Horotiu Bridge	4.2	0.5	2%
Huntly Bridge	7.2	0.8	2%
Rangiriri (NIWA)	8.0	1.2	2%
Mercer Bridge	–	1.0	–
Tuakau Bridge	9.4	1.1	2%
Waipa River			
Mangaokewa Rd	4.0	2.1	8%
Otewa	7.5	1.2	4%
Otorohanga	6.7	1.2	4%
Pirongia	10.0	1.2	2%
Whatawhata	13.0	1.8	3%

Phytoplankton

A similar approach was used to determine the contributions of phytoplankton to beam attenuation at WRC's Waikato River sites (only). In this case the *upper bound* to the contribution of phytoplankton biomass to beam attenuation (c_B) was estimated as:

$$c_B = 0.47\times[\text{Chlorophyll } a]^{0.65}$$

(from Davies-Colley et al. 1993, see their Fig. 5.11).

As shown previously (Fig. 4), phytoplankton are most abundant in the Waikato River during the summer (October-to-March). So c_B will also be highest during the summer. Figure 5 shows the average concentrations of chlorophyll *a* and the average beam attenuation coefficient at the three selected Waikato River sites during nine recent summers. The dashed line shows how c_B varies across the range of chlorophyll *a* concentrations plotted. One of the results for Ohakuri, namely the summer of 2005–06, lies close to the plotted line, indicating that in that period much (c. 90%) of the average attenuation was associated with the average concentration of phytoplankton. However, in the other summers the beam attenuation coefficient plotted well above the line, suggesting that non-algal sources of attenuation were important then.

On average, c_B contributed about half (55%) of the average beam attenuation at Ohakuri during the nine summers (range 45–91%), with non-algal sources contributing the remaining 45%. Similar results were obtained at Narrows, where, on average, c_B contributed 55% of average beam attenuation (range 34–72%). At Tuakau, however, non-algal sources of beam attenuation were substantial, with c_B typically contributing just 35% of summer-average *c* (range 23–50%).

So even though phytoplankton were most abundant in the Waikato River during summer (Fig. 4), other causes of beam attenuation were also important then, particularly in the reach downstream of the confluence with the Waipa River. Note that an unknown fraction of the "non-algal" attenuation was probably caused by organic detritus associated with dead and decaying phytoplankton and other plant material. Most of the remaining non-algal attenuation was probably caused by inorganic silts and clays suspended in the water. In the lower river, downstream of its confluence with the Waipa, the typically brown and muddy appearance of the water suggests that in this area at least, inorganic suspended solids probably dominate the non-algal attenuation (and thus dominate total beam attenuation).

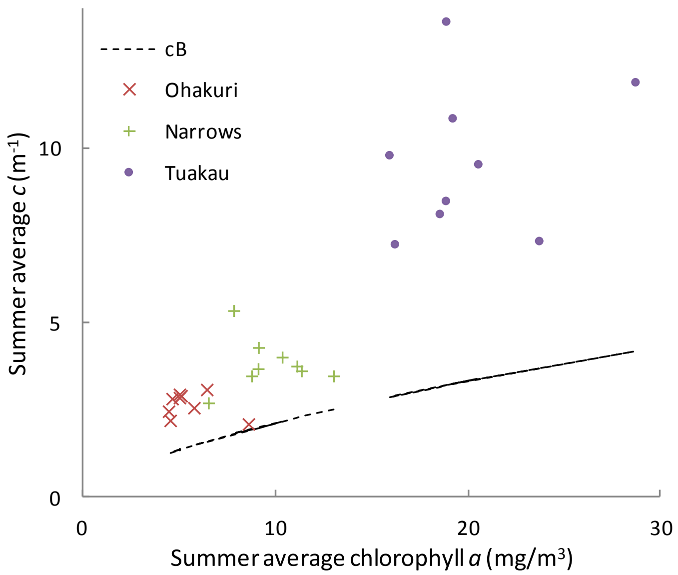

Figure 5: Summer-average chlorophyll *a* and beam attenuation at three Waikato River sites during 2005–14 (summer: October-to-March). The dashed line shows the upper bound to the contribution of phytoplankton to attenuation (as $c_B = 0.47\times[\text{ Chlorophyll } a]^{0.65}$: see text).

As noted earlier, both water clarity and phytoplankton biomass vary throughout the year in the Waikato River (see Figs 3 and 4). Figure 6 shows the monthly-average values of c and c_B at three sites on the river during the past ten years. At Ohakuri, average beam attenuation was highest during the summer, and so too was the contribution from phytoplankton. The *relative* contribution of phytoplankton to beam attenuation (i.e. c_B/c) averaged 54% over the 12 months, with the lowest value (41%) in May, and the highest (69%) in September.

At Narrows, both c and c_B were highest in October, with the ratio c_B/c averaging 53% over the 12 months, and with lowest (31%) and highest (85%) values falling in July and September, respectively. Finally, at Tuakau, c was highest during August-to-November and c_B was lowest during May-to-August, with the ratio c_B/c averaging 35% over the 12 months, and with the lowest value (15%) in August, and the highest (56%) in March.

Figure 6: Monthly-average beam attenuation (c) at three sites on the Waikato River, 2005–14, showing the estimated contributions of phytoplankton (c_B, green) and the other constituents (brown).

Table 4: Average visual clarity, beam attenuation coefficient and estimated constituent contributions to attenuation at seven sites on the Waikato River and five sites on the Waipa River during 2005–14. Results for a deep-water site in the centre of Lake Taupo are also shown. :"YS", yellow substance. The estimated constituent contributions depend critically on the use of the previously-derived equation for the effect of phytoplankton on beam attenuation (Figure 5).

	y_{BD} (m)	c (m^{-1})	YS	Phytoplankton	Other
Lake Taupo	12.3	0.4	–	99%	1%
Waikato River					
Ohaaki Bridge	4.5	1.2	–	59%	41%
Ohakuri tailrace	2.4	2.3	–	54%	46%
Waipapa tailrace	1.9	2.7	1%	54%	45%
Narrows	1.5	3.7	2%	53%	45%
Horotiu Bridge	1.3	4.2	2%	48%	50%
Huntly Bridge	0.8	7.2	2%	32%	66%
Tuakau Bridge	0.6	9.4	2%	35%	63%
Waipa River					
Mangaokewa Rd	1.5	4.0	8%	–	92%
Otewa (NIWA)	1.6	7.5	4%	–	96%
Otorohanga	1.2	6.7	4%	–	96%
Pirongia	0.7	10.0	2%	–	98%
Whatawhata (NIWA)	0.5	13.0	3%	–	97%

Table 4 shows the average contributions of the various constituents that can be estimated for the Waikato and Waipa River sites for which suitable data was available. It also shows the beam attenuation and constituent contributions calculated for Lake Taupo. It is clear that beam attenuation in Lake Taupo was dominated by phytoplankton; indeed, it was not uncommon for calculated c_B (see earlier) to exceed estimated c. These results suggest that the calculated values of c_B for the river sites downstream of Lake Taupo are likely to be reasonably robust—and so too are the estimates of non-algal attenuation (by difference).

Overall, these results indicate that phytoplankton were an important—but not always dominant—cause of beam attenuation in the Waikato River hydrolakes, and in the reach between the last of these and the confluence with the Waipa River at Ngaruawahia. Non-algal causes of beam attenuation were also important in this part of the river, and at times they were dominant (e.g. Narrows, June-to-August: Fig. 6). In the Waikato downstream of Ngaruawahia, and in the Waipa River, however, non-algal causes of beam attenuation were usually or always dominant.

The constituent contributions shown in Table 4 can be used to estimate the effects on the visual clarity at each of the monitoring sites of interventions that might alter the average concentrations of the different constituents. If each contribution is expressed as a proportion, p, where p is the percent contribution divided by 100 (e.g. "59%" becomes "0.59"), and the intervention is expected to change the average constituent concentration by x percent, then as a first approximation, the change in visual clarity (y_{BD}) resulting from the intervention can be estimated as:

$$\text{Change in visual clarity (\%)} = 100.[\{1/(1 + p.x/100)\} - 1]$$

For example, doubling the phytoplankton concentration (i.e. x = +100%) in the Waikato River at Narrows, where p for phytoplankton is 0.53, would result in a –36% change in visual clarity there (i.e. a deterioration). At Tuakau, however, where p for phytoplankton is 0.35, doubling the phytoplankton concentration would result in a smaller deterioration, namely –26%. Conversely, halving the suspended sediment concentration (i.e. x = –50%) in the Waipa River at Whatawhata, where p for this constituent is probably about 0.97, would result in a +94% change in visual clarity there. But halving the suspended sediment concentration at Tuakau, where p for this constituent is probably about 0.63, would result in a smaller percentage change (+46%).

4 Long-term changes

During the past 20 years, concentrations of phytoplankton—and the plant nutrients that support their growth—have changed in the Waikato River (Vant 2013a). In particular, concentrations of chlorophyll *a* have declined at several locations, while those of total nitrogen have increased (Appendix 2 provides additional information on this). This section examines how these changes may have affected the visual clarity of the water (noting that the plant nutrients do not themselves attenuate light—but simply support the growth of the phytoplankton that do).

Figure 7 shows the monthly estimates for beam attenuation at the Ohakuri, Narrows and Tuakau monitoring sites. In each case, the record began in 1995. Figure 8 shows the corresponding information for chlorophyll *a*, in this case from 1990 onwards (although some data is also available for a few years prior to that). Plots of long-term changes in the concentrations of total nitrogen and total phosphorus at these sites are included in Appendix 2.

The main changes that can be seen at each site are as follows:

- Ohakuri. Beam attenuation was lower for several years during 2000–06, and higher for several years following that (Fig. 7). Water clarity was thus poorer towards the end of the period shown. Chlorophyll *a*, however, was higher for several years during 2000–06, and fell after that (Fig. 8). That is, the period of better visual clarity (i.e. lower attenuation) occurred when phytoplankton levels were higher. This somewhat surprising result underlines the fact that, while being important, phytoplankton are only one of several causes of beam attenuation. The results imply that during 2000–06, non-algal causes of beam attenuation must have been *relatively-low*, more than offsetting the effect of the *relatively-high* levels of phytoplankton that occurred then.

- Narrows. Beam attenuation was reasonably stable throughout much of the period, but declined from about 2011. Chlorophyll *a* showed a slight peak during 2000–05, but declined after that. In this case, the reduction in phytoplankton in the latter part of the record may have contributed to some of the observed improvement in water clarity (even though as noted above, non-algal sources of beam attenuation were also important at this site).

- Tuakau. Beam attenuation was stable throughout much of the period, but did show a slight decline in the last 2–3 years. Chlorophyll *a* at this site also showed a slight peak during 2000–05, but declined over the period as a whole. At this site, however, non-algal causes of beam attenuation were usually dominant (Table 4), so the decline in phytoplankton from 2005 is likely to have made little if any contribution to the slight improvement in water clarity that has occurred recently.

Overall, this indicates that the widespread reduction in chlorophyll *a* concentrations in the Waikato River over the past decade or so had only a minor effect on the visual clarity of the river water, and then only in certain parts of the river (e.g. Narrows). Indeed, elsewhere (i.e. Ohakuri), over the same period water clarity was *poorer* than it had been previously. Although phytoplankton are an important cause of beam attenuation in the river, so too are other constituents (e.g. silts and clays), and it appears that these often mask the effects of the phytoplankton.

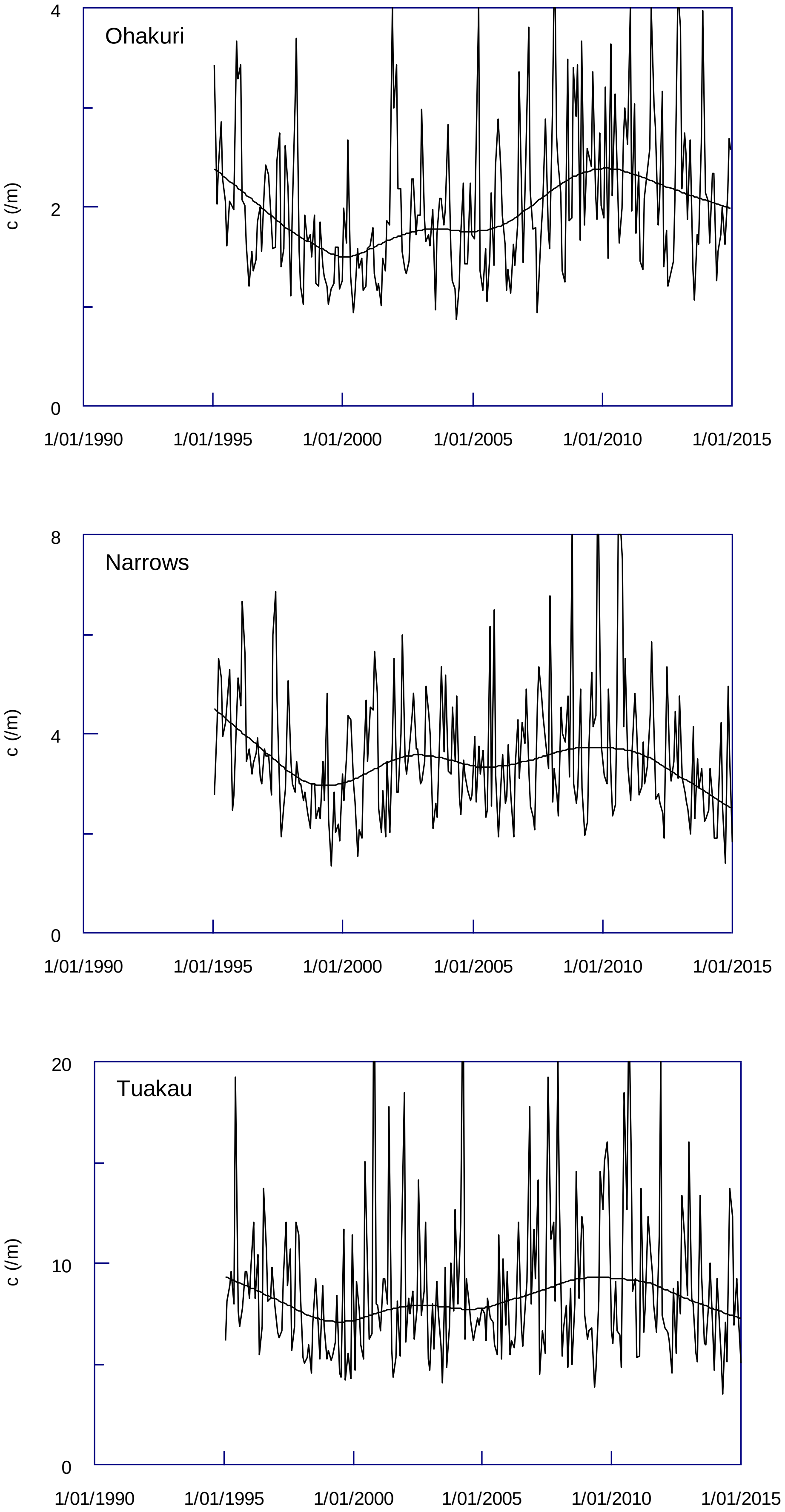

Figure 7: Monthly estimates of beam attenuation (*c*) in the Waikato River at Ohakuri, Narrows and Tuakau, 1995–2014. LOWESS smoothing curves have been fitted to the data.

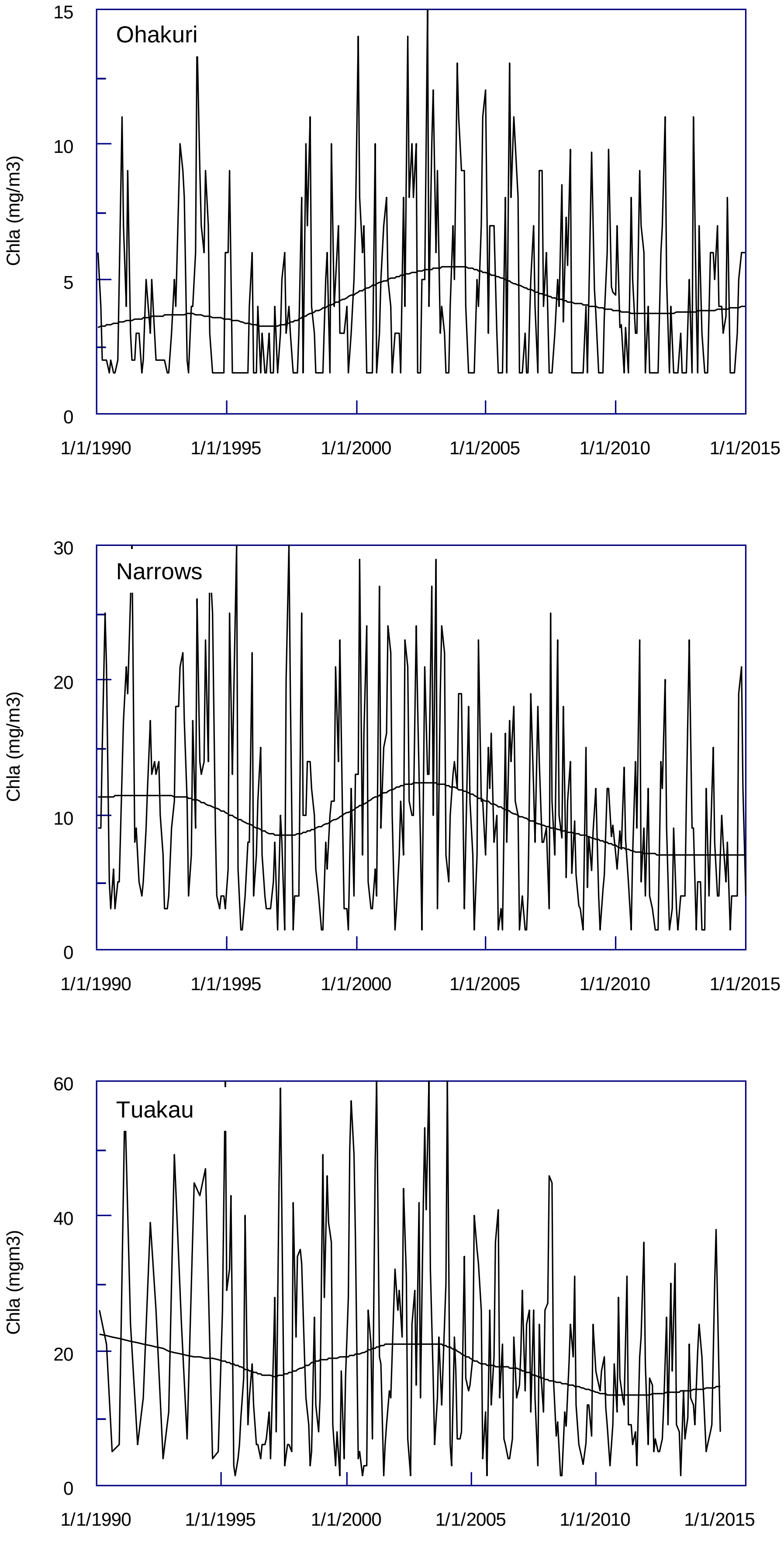

Figure 8: Monthly measurements of chlorophyll *a* in the Waikato River at Ohakuri, Narrows and Tuakau, 1990–2014. LOWESS smoothing curves have been fitted to the data.

5 Sources of constituents

Yellow substance

Yellow substance generally results from the decay of plant material. As such, it can be produced anywhere plants grow. Important terrestrial sources include wetlands and wet climate forests (e.g. as found on the West Coast of the South Island), from where it can enter waterbodies in runoff. It is also produced within waterbodies following the decay of plant material produced therein. In the Waikato catchment, the Kinleith pulp and paper mill discharges coloured organic material that is produced in the wood-pulping process. This material is optically-similar to natural yellow substance, and the mill is the largest single source of dissolved organic matter to the river.

As noted above, the highest concentration of yellow substance in the Waikato and Waipa Rivers was at the Waipa at Mangaokewa site (Table 2). The catchment at this point is largely covered with native and planted forest, and the high concentration of yellow substance may well result from the natural decay of plant materials produced in these areas.

Apart from the Waipa at Mangaokewa site, yellow substance is generally only a minor source of beam attenuation in the Waikato and Waipa Rivers (c. 2% or less throughout the Waikato River, including at sites downstream of the Kinleith discharge: Table 3). Furthermore, apart from the Kinleith discharge, the sources of yellow substance to the rivers are essentially unmanageable.

Phytoplankton

Phytoplankton are carried into the Waikato River from Lake Taupo (Table 2), and from the shallow lakes in the floodplain of the lower river (Appendix 1). However, most of the phytoplankton present in the hydrolakes and the lower river have grown there. Impoundment in the hydrolakes means that the seed populations from Lake Taupo and other sources (e.g. Whirinaki Arm of Lake Ohakuri) have sufficient time to grow and reproduce, with their growth being supported by the nitrogen and phosphorus concentrations which progressively increase as the river flows downstream (e.g. Figs A2 and A3).

Over the past 20 years, concentrations of chlorophyll *a* in the river have generally declined (e.g. Figure 8). The analysis in Appendix 2 suggests that over this period, phytoplankton growth in the river has shifted from being N-limited, to being co-limited by both N and P. In this situation, the removal of *either* N or P is likely to reduce algal growth. And in the decade ending in 2014, total P concentrations declined significantly (p-value <1%) at all seven WRC sites downstream of Ohakuri (e.g. Fig. A3), with the average rate of decline being about 4% per year (WRC unpublished results).

Why have total P concentrations declined in the Waikato River? At the four sites downstream of Hamilton, this is probably due to the recent substantial reduction in the load of P discharged from the Hamilton wastewater treatment plant. Vant (2014) found that the load of P discharged during 2011–12 was half that discharged in the previous eight years, such that the amount of P in the river at Horotiu, downstream of the discharge point, was about 10% lower than it had been previously.

At the other three sites further up the river, the reasons for the decline in total P are less clear. The general shift towards disposing farm dairy effluent on the land rather than discharging it to water is likely to have contributed to the reduction. But so too is the maturing of the historic soil conservation works in the upper catchment; in the nearby Taupo catchment where there are only a few farm dairy discharges, a similar—and widespread—reduction in total P concentrations in streams and the lake has occurred (Vant 2013b), and can be plausibly linked to the soil conservation measures that were undertaken there in the 1980s.

These various reductions in the loads of TP entering the river are likely to have caused the decline in total P concentrations in the river. At the same time, concentrations of total N have increased, so that algal growth may have shifted to being co-limited by both N and P (Appendix 2). If so, the reductions in P are likely to have been responsible for some of the reduction in chlorophyll *a* observed in the river.

There are also some indications that the recent invasion of New Zealand waters by a North American species of zooplankton (Duggan et al. 2006) has increased the grazing pressure on phytoplankton in the Waikato River (Gibbs et al. 2015), and has thus also contributed to the observed reductions in chlorophyll *a*.

Sediment
With the exception of phytoplankton and organic detritus, the main source of light-attenuating suspended solids in water is accelerated soil erosion (Davies-Colley et al. 1993). Hicks & Hill (2010) described the main sources of sediment to Waikato and Waipa Rivers, and drew the following conclusions:

> *"The suspended loads measured at Hamilton and Rangiriri are 66,000 t/yr and 261,000 t/yr, respectively, with much of the difference being added by the Waipa River at Ngaruawahia. These loads have been substantially reduced by sedimentation in the hydrolakes. The Waipa is the largest single source of suspended sediment to the Waikato channel overall and it now supplies some two-thirds of the Waikato's suspended load downstream from Ngaruawahia. A substantial portion of the Waipa's suspended load originates from its upper catchment. Soil conservation efforts, including riparian retirement and re-vegetation, appear to be achieving some success in reducing suspended sediment loads in Waipa tributaries."*

That is, on average, at the confluence of the two rivers at Ngaruawahia, the Waipa carries about twice as much sediment as the Waikato—despite the average flow of the Waikato being nearly three times that of the Waipa at this point. And the observed water quality of the two rivers clearly reflects these differing sediment loads (e.g. Fig. 1).

However, it must be noted that suspended sediment loads are only an approximate indicator of optical effect, because different types of sediment particles in rivers—differing in size, shape, and composition—can vary appreciably in light attenuation per unit mass (or "optical cross-section"). For example, Davies-Colley et al. (2014) reported a fairly wide range of optical cross-sections for suspended sediment at the 77 river sites in NIWA's national water quality network. In a large catchment with complex geology, soils and land use, like the Waikato, we should expect appreciable within-catchment variation in optical properties of suspended particles. Sources of layer clays, which have an unusually high optical cross-section, are therefore a priority for soil conservation and riparian mitigations out of proportion to their mass load contribution.

6 Summary and conclusions

1. The visual clarity of the water in the Waikato and Waipa Rivers reflects the varying concentrations of the light-attenuating constituents present in it. The main constituents are dissolved yellow substance, phytoplankton, organic detritus and suspended silts and clays. The concentrations of these constituents vary in both time and space, and so too does the visual clarity of the river waters.

2. Routine measurements of the horizontal sighting range of a black disc, a robust measure of water clarity, can be used to determine the underwater attenuation of light, characterised by the beam attenuation coefficient. Over the past decade (2005–14), average beam attenuation was particularly low in the clear blue waters leaving Lake

Taupo, and increased progressively moving down the length of the Waikato River. Beam attenuation was moderately-high in even the upper reaches of the Waipa River, with the highest values in the two rivers being observed in the lower reach of the Waipa.

3. Concentrations of phytoplankton (as chlorophyll *a*) and yellow substance also increased progressively down the length of the Waikato River. The highest concentration of yellow substance in the Waipa River, however, occurred in its upper reaches. Although there is little or no information about the presence of phytoplankton in the Waipa River, they are likely to be uncommon there.

4. Concentrations of chlorophyll *a* were highest in the Waikato River during summer (October-to-March). Some 25–30% of the summer-average chlorophyll *a* in the lower reach of the Waikato River is likely to have come from the large shallow lakes present in the river's floodplain.

5. On average, yellow substance was a minor contributor (c. 2%) to beam attenuation in the Waikato River during 2005–14. Even in the Waipa River its contribution was usually small (<5%), apart from at the most upstream site (where it was c. 8%).

6. On average, phytoplankton contributed an estimated 50–60% of the observed beam attenuation in the section of the Waikato River upstream of the confluence with the Waipa River (at Ngaruawahia). Further downstream, phytoplankton contributed about one-third of beam attenuation on average.

7. Non-algal beam attenuation, which can be mainly attributed to suspended silts and clays, is apparently responsible for the other 40–50% of the beam attenuation in the section of the Waikato River upstream of Ngaruawahia, and most of the beam attenuation in the reach downstream of there. Non-algal attenuation is expected to dominate beam attenuation in the Waipa River.

8. Over the past decade or so, chlorophyll *a* concentrations in the Waikato River have declined. However, this has had only a minor effect on the visual clarity of the river water, and then only in certain parts of the river (e.g. Narrows). Somewhat unexpectedly, water clarity at Lake Ohakuri was actually *poorer* during the period of *lower* chlorophyll than it had been previously. Although phytoplankton can be an important cause of beam attenuation in the river, so too are other constituents (e.g. silts and clays), and it appears that these often mask the effects of the phytoplankton.

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8 Appendix 1—Phytoplankton from the shallow floodplain lakes

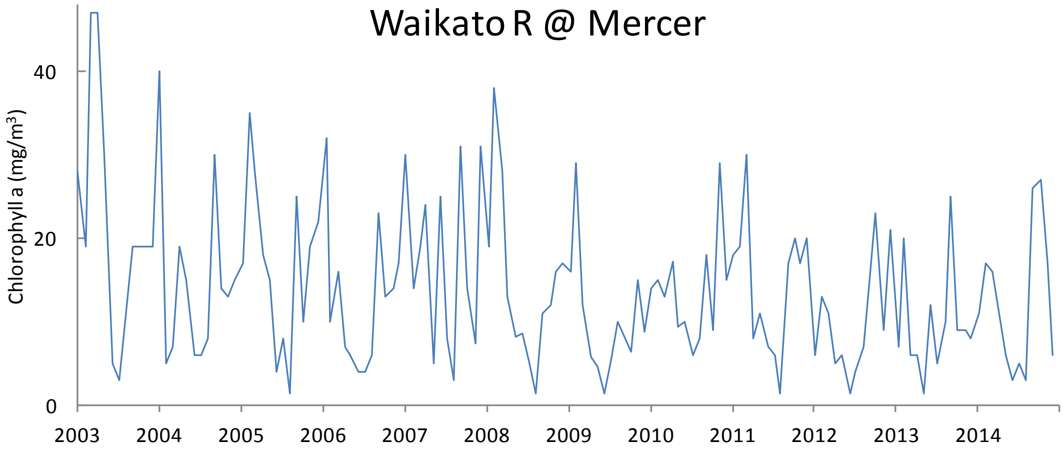
Several shallow lakes are present in the floodplain of the Lower Waikato River, and these generally drain into it. Lakes Waikare and Whangape are the largest, and both drain into the river upstream of the monitoring site at Mercer. Concentrations of chlorophyll *a* are very high in both lakes during the summer, so the water flowing out of them is likely to contribute an appreciable load of chlorophyll to the lower reaches of the river then. This appendix estimates the size of this load during the summer—when phytoplankton biomass in the river is typically highest (e.g. Fig. 3).

Figure A1 shows the chlorophyll *a* concentrations in the river and the two shallow lakes during 2003–14, with the average concentrations during summer shown in Table A1. Table A1 also shows the average flows at this time of the year. River flows are monitored in the Waikato River at Mercer, and at the outflow from Lake Waikare ("Northern Gate"; note that the outflow from this lake often includes stored floodwater, previously diverted into the lake from the Waikato River, so the average outflow is thus substantially higher than the natural inflow to the lake). The outflow from Lake Whangape is not monitored, and has been estimated here from the specific water yield of the 105 km^2 Matahuru catchment and the combined area of the Whangape catchment (307 km^2) and the lake (11 km^2); note that this implicitly assumes that areal evaporative losses from the lake are similar to the evaporation/transpiration losses from the land.

It is clear from Table A1 that flows are much higher in the river than in the outflows from the lakes during summer, with the combined outflow (9.0 m^3/s) being about 2.5% of the summer-average flow in the river. However, the chlorophyll *a* concentrations in the lakes are much higher than in the river (Table A1), so the lake's contributions to the mass of chlorophyll *a* in the river will be considerably larger than this.

For each of the summers from 2002/03 to 2013/14, the summer-average chlorophyll *a* concentrations at Mercer and in the two lakes was calculated from the records shown in Figure A1. Multiplying each of these concentrations by the overall summer-average outflow from the corresponding lake provided estimates of the summer-average loads of chlorophyll flowing out of the lakes and into the river. Similarly the loads of chlorophyll *a* carried by the river at Mercer during each summer were estimated by multiplying the summer-average flow in the river (Table A1) by the average chlorophyll *a* concentration in the river that summer (from Fig. A1).

The calculated loads of chlorophyll *a* in the river and the lake outflows are shown in Table A2. On average, during 2003–14 the combined load of chlorophyll *a* flowing out of the two lakes during summer was equivalent to 27% of the load carried in the river at Mercer (range 11–52%). The shallow lakes thus represent an important source of the chlorophyll *a* found in the lower river during summer, particularly the reach downstream of about Mercer. The contributions during the winter, however, will generally be much lower.



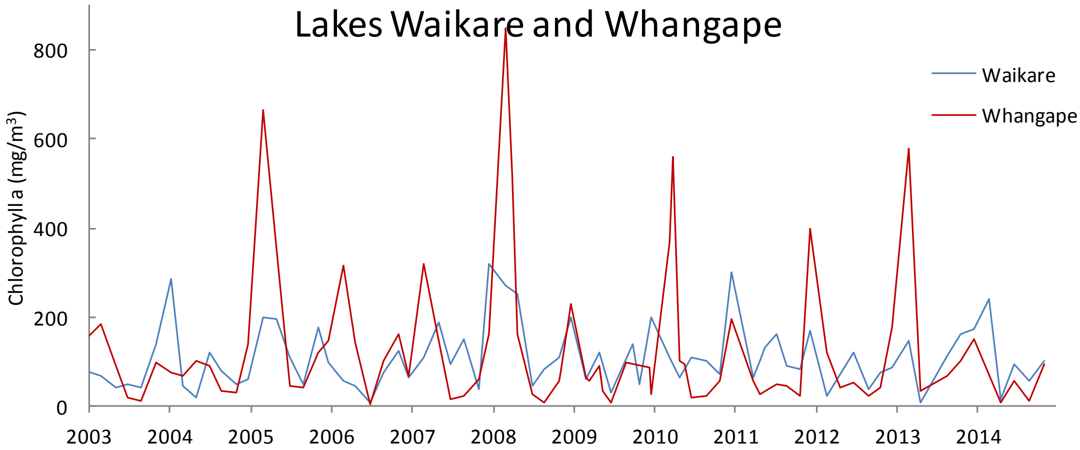


Figure A1: Monthly or bimonthly concentrations of chlorophyll *a* in the Waikato River at Mercer and in two nearby shallow lakes, 2003–14.

Table A1: Summer-average flows and chlorophyll *a* concentrations in the Waikato River at Mercer and in two nearby shallow lakes, 2003–12. Summer: October-to-March.

	Flow (m^3/s)	**Chlorophyll *a* (mg/m^3)**
Waikato R at Mercer	353	18
Lake Waikare outflow	3.8	127
Lake Whangape outflow	5.2	195

Table A2: Summer-average load of chlorophyll *a* (g/s) in the Waikato River at Mercer and in two nearby shallow lakes, 2003–14. Summer: October-to-March.

Summer	**Mercer**	**Waikare**	**Whangape**	**Both lakes**	**Lakes/Mercer**
2003	8.57	0.25	0.67	0.92	11%
2004	9.03	0.60	0.42	1.02	11%
2005	7.57	0.39	1.43	1.82	24%
2006	6.29	0.42	1.00	1.42	23%
2007	6.06	0.38	0.94	1.32	22%
2008	5.43	0.80	2.04	2.84	52%
2009	5.89	0.47	0.50	0.97	17%
2010	4.59	0.48	1.34	1.82	40%
2011	7.11	0.56	0.53	1.09	15%
2012	4.72	0.35	0.94	1.29	27%
2013	4.18	0.39	1.38	1.77	42%
2014	3.12	0.73	0.65	1.39	45%
Average	6.05	0.49	0.99	1.47	27%

9 Appendix 2—Long-term changes in nitrogen and phosphorus

Figures A2 and A3 show the monthly concentrations of total nitrogen (TN) and total phosphorus (TP) at the Ohakuri, Narrows and Tuakau monitoring sites during 1990–2004.

The main changes in average values that can be seen at each site are as follows:

- Ohakuri. TN concentrations fell in the first half of the 1990s, probably reflecting the diversion away from the river of wastewater from the Taupo sewage treatment plant. But from 1995 to 2010, TN concentrations steadily rose again, before flattening out and then decreasing slightly during the last few years (Fig. A2). TP concentrations also fell during 1990–95, rose slightly to 2008, then declined again (Fig. A3).

- Narrows. TN concentrations were steady during 1990–2000, then rose in the second half of the period. TP concentrations were reasonably steady for much of the period, but fell markedly from 2010 onwards.

- Tuakau. TN concentrations dipped slightly around 2000 then rose to 2010, before declining again. TP concentrations were reasonably steady until about 2010, then fell markedly.

Trends of rising TN concentrations and declining TP concentrations mean the ratio TN/TP will also rise. This is apparent in Figure A4 which shows the TN/TP ratios in summer months at the three sites during 1995–2014. Studies elsewhere have shown that where the TN/TP ratio is less than about 10 (by weight), plant growth is likely to be limited by the supply of N; if the ratio is greater than about 17, growth is likely to be limited by the supply of P (e.g. Pridmore 1987; Abell et al. 2010). If the ratio falls within the range 10–17, growth is regarded as being "balanced", with the two nutrients being co-limiting.

At Ohakuri and, in particular, at Narrows the TN/TP ratio began to regularly exceed 10 during the period shown. This suggests that whereas phytoplankton in the river could have been expected to be N-limited up until about 2000, it has become less so since then, and is now within the zone of "balanced" growth (i.e. N and P are co-limiting). In this transition zone, the removal of *either* N or P is likely to reduce algal growth. And in recent years, concentrations of TP have fallen at several sites. These reductions in TP are therefore likely to have contributed to the observed reductions in phytoplankton biomass (as chlorophyll *a*).

There are also some indications that the recent invasion of New Zealand waters by a North American species of zooplankton (Duggan et al. 2006) has increased the grazing pressure on phytoplankton in the Waikato River (Gibbs et al. 2015), and has thus also contributed to the observed reductions in chlorophyll *a*.

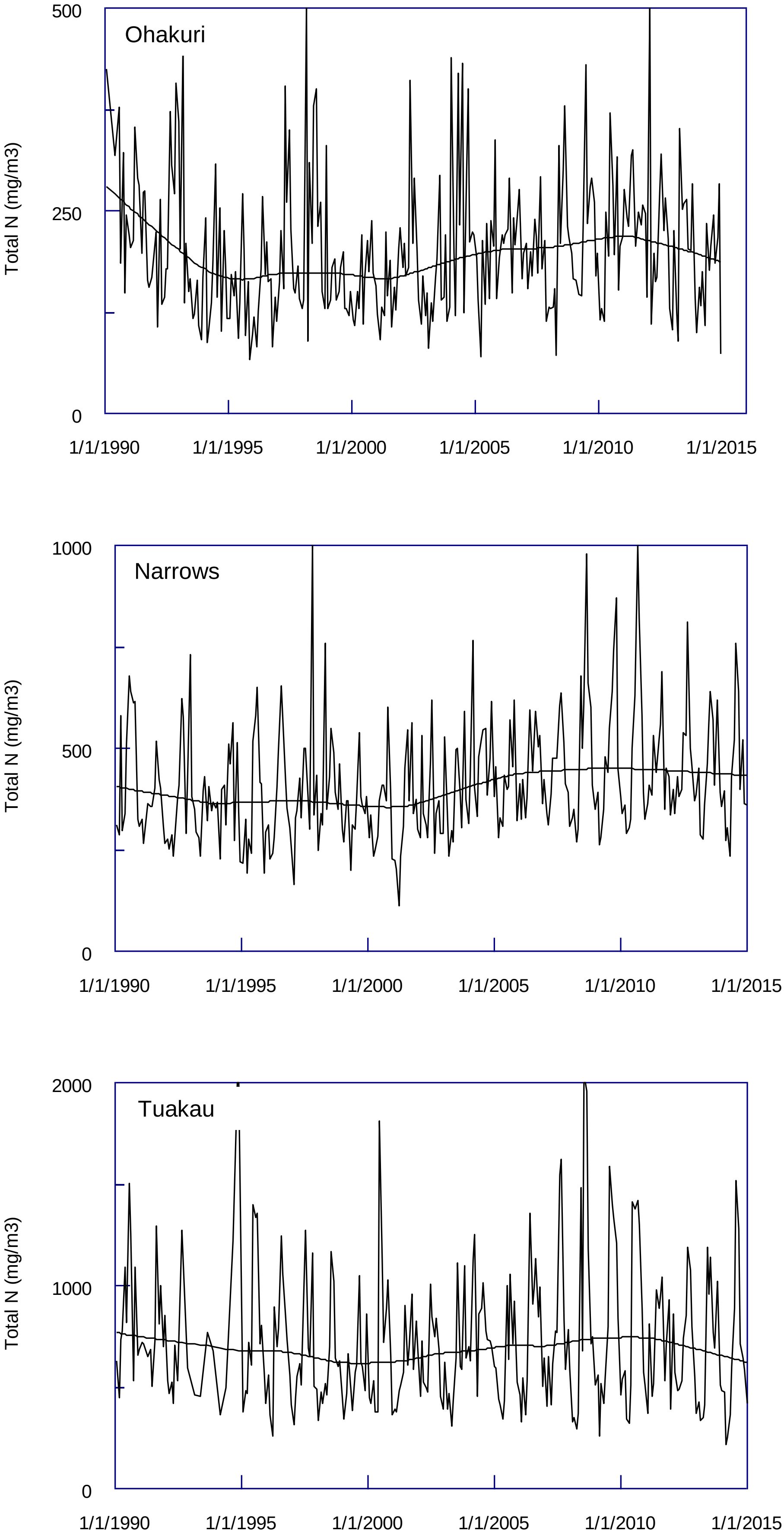


Figure A2: Monthly measurements of total nitrogen in the Waikato River at Ohakuri, Narrows and Tuakau, 1990–2014. LOWESS smoothing curves have been fitted to the data.

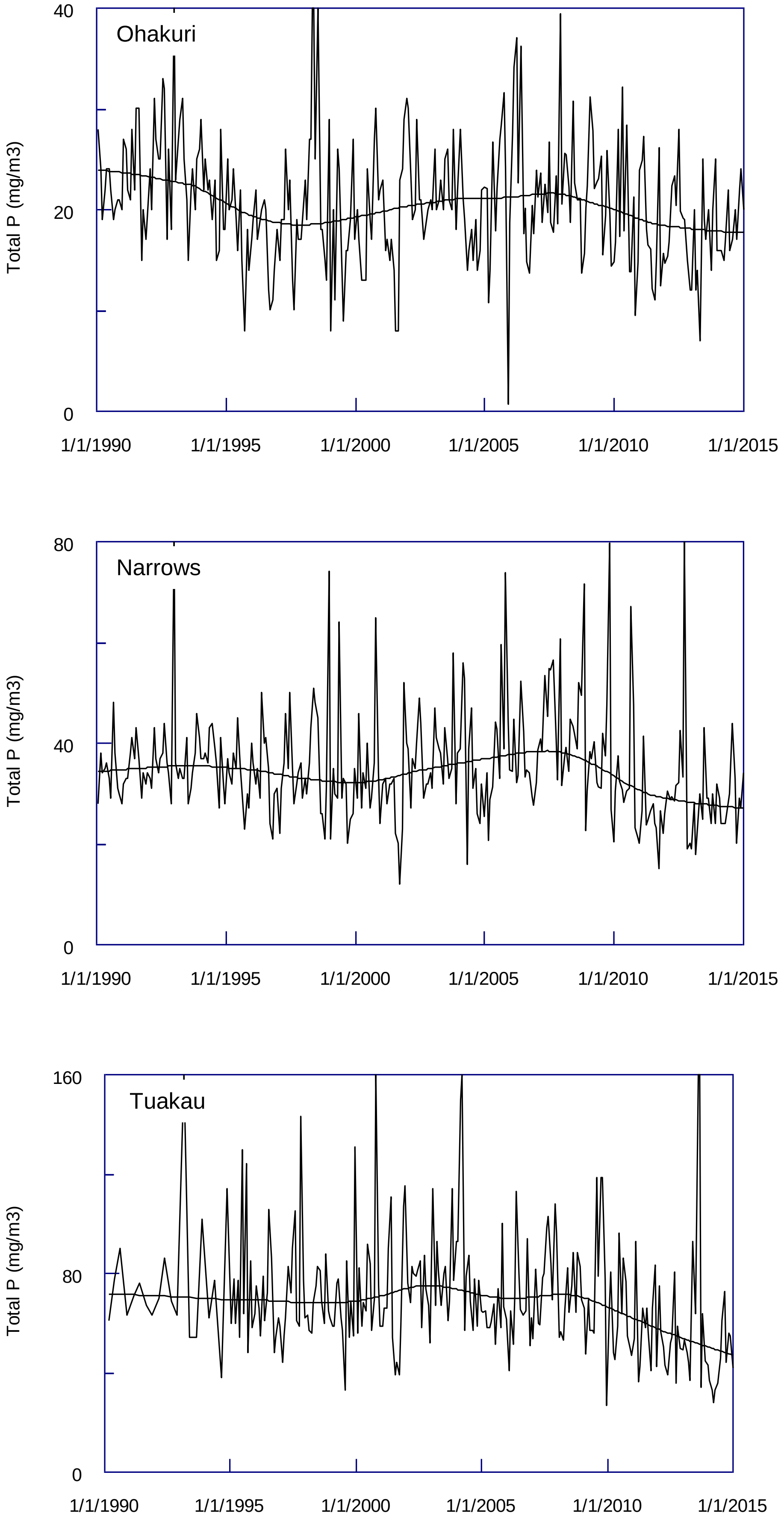


Figure A3: Monthly measurements of total phosphorus in the Waikato River at Ohakuri, Narrows and Tuakau, 1990–2014. LOWESS smoothing curves have been fitted to the data.

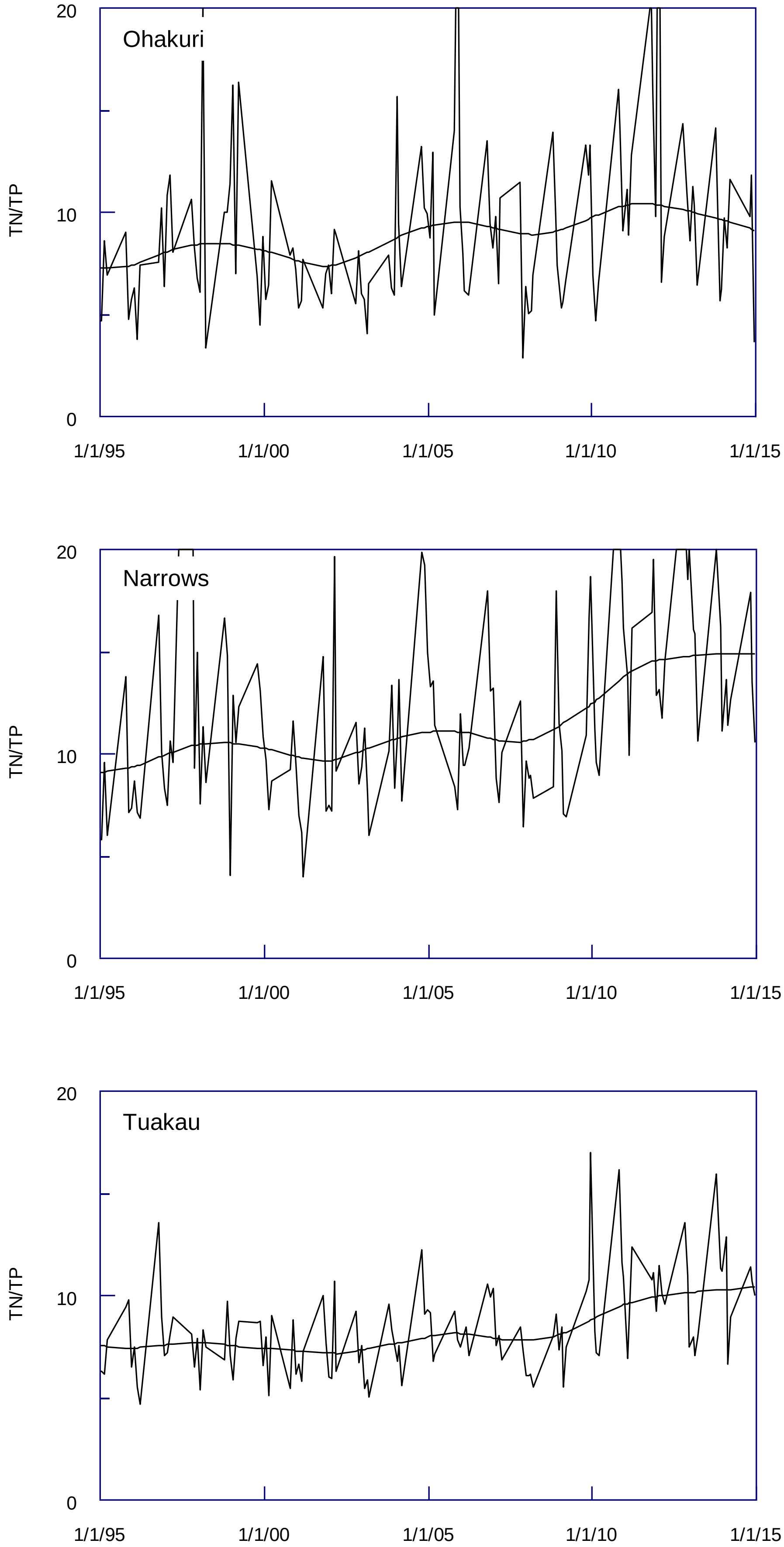


Figure A4: Monthly ratios of total nitrogen and total phosphorus in the Waikato River during summer at Ohakuri, Narrows and Tuakau, 1995–2014. Summer: October-to-March. LOWESS smoothing curves have been fitted to the data.