Healthy Rivers | Wai Ora
PLAN FOR CHANGE | HE RAUTAKI WHAKAPAIPAI

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A methodology for chlorophyll and visual clarity modelling of the Waikato and Waipa Rivers

This report was commissioned by the Technical Leaders Group for the Healthy Rivers Wai Ora Project

The Technical Leaders Group approves the release of this report to Project Partners and the Collaborative Stakeholder Group for the Healthy Rivers Wai Ora Project.

Signed by:

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NIWA
Taihoro Nukurangi

A methodology for chlorophyll and visual clarity modelling of the Waikato and Waipa Rivers

Information to support scenario modelling for the Healthy Rivers Wai Ora Project

Prepared for the Technical Leaders Group of the Waikato-Waipa Healthy Rivers Wai Ora Project

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Executive summary

Waikato Regional Council (WRC), together with Waikato and Waipa River iwi, are partners in the "Healthy Rivers: Plan for Change/Wai Ora: He Rautaki Whakapaipai" project, which aims to develop changes to the Waikato Regional Plan in order to help restore and protect the health of the Waikato and Waipa rivers. Once developed, these plan changes will assist, over time, in reducing inputs of sediment, bacteria and nutrients (primarily nitrogen and phosphorus) entering water bodies in the Waikato and Waipa River catchments.

This report, one in a series commissioned by the Healthy Rivers/Wai Ora Technical Leaders Group, describes the methodology used to estimate changes in chlorophyll concentrations and visual clarity in the Waikato and Waipa Rivers in response to changes in nutrient concentrations and sediment loads under various scenarios of land management and land use change. The scope of the report is limited to the development of the methodology – the actual modelling of changes to chlorophyll concentrations and visual clarity will be undertaken as part of the scenario modelling used to assess both the water quality improvements and the costs associated with each scenario (to be reported elsewhere).

To facilitate calculation of changes to visual clarity as part of the scenario modelling, estimates of current visual clarity have been derived for main-stem and tributary sites in the Waikato and Waipa rivers.

For the purposes of this study, the key contributors to visual clarity are considered to be yellow substance (a type of dissolved organic material), phytoplankton (floating algae) and 'other' (assumed to be dominated by fine sediment). Changes to nutrient concentrations bring about changes to visual clarity through increased or decreased phytoplankton growth (as measured by chlorophyll *a* concentrations). Changes to sediment loads affect changes to visual clarity through the 'other' contributor.

An empirical relationship is developed to predict changes in annual median chlorophyll concentrations in response to changes in annual median total nitrogen (TN) and phosphorus (TP) concentrations for sites on the main-stem of the Waikato River. The coefficients are weighted as a function of the TN/TP ratio, which allows the model to respond to changes in both nutrients at different levels of sensitivity under different nutrient-limitation regimes. Separate models are fitted for individual sites. Chlorophyll concentrations are not measured in the tributaries or along the main-stem of the Waipa River, and contributions to visual clarity resulting from phytoplankton are considered negligible for these sites.

Sediment loads lost from the land are routed through the river network to estimate changes in in-stream sediment loads. The routing includes retention of sediment in hydro-reservoirs along the main-stem of the Waikato River. Equations are produced that relate the magnitude of predicted changes in in-stream chlorophyll concentrations and sediment loads to associated changes in visual clarity.

1 Introduction

1.1 Preamble

Waikato Regional Council (WRC), together with Waikato and Waipa River iwi, are partners in the "Healthy Rivers: Plan for Change/Wai Ora: He Rautaki Whakapaipai" project, which aims to develop changes to the Waikato Regional Plan ("the regional plan") in order to help restore and protect the health of the Waikato and Waipa rivers. Once developed, these plan changes will assist, over time, in reducing inputs of sediment, bacteria and nutrients (primarily nitrogen and phosphorus) entering water bodies in the Waikato and Waipa River catchments.

This report, one in a series commissioned by the Healthy Rivers/Wai Ora Technical Leaders Group (TLG), describes the methodology used to estimate changes in chlorophyll concentrations and visual clarity in the Waikato and Waipa Rivers in response to changes in nutrient (i.e. nitrogen and phosphorus) concentrations and sediment load inputs under various scenarios. The scope of this report is limited to the development of the methodology and, as such, no results are included for chlorophyll and visual clarity under the scenarios. The actual modelling of chlorophyll concentrations and visual clarity in response to estimated changes in nutrient and sediment concentrations will be undertaken as part of scenario modelling to assess the water quality improvements and costs associated with implementing various mitigation activities (Doole et al. In preparation).

1.2 Background Information

For modelling purposes, the catchment area of the Waikato and Waipa rivers is divided into 74 sub-catchments, referred to as the Healthy Rivers Wai Ora (HRWO) sub-catchments. The boundaries of these sub-catchments have been delineated largely on the basis of existing water quality monitoring sites. As such, each sub-catchment represents the contributing area draining to a particular site location. More information on the HRWO sub-catchments is available in Semadeni-Davies et al. (2015).

Visual clarity is measured at the monitoring sites as the horizontal sighting range of a black disc, as discussed in Section 2. For the purposes of this study, the key contributors to visual clarity are considered to be yellow substance, phytoplankton (floating algae) and fine sediment (Vant 2015). The contribution to visual clarity from yellow substance at each site is assumed to remain constant and is usually quite low (Vant 2015). Changes in nutrient concentrations predicted for the HRWO sub-catchments under different scenarios affect visual clarity through increased or decreased algal biomass (measured as chlorophyll *a*; hereafter referred to simply as chlorophyll), whilst changes in sediment inputs from the land and stream banks will affect visual clarity directly.

1.3 Scope

This report describes the methodology used to estimate changes in chlorophyll concentrations and visual clarity for the HRWO sub-catchments in response to changes in nutrient and sediment concentrations. Estimates of the current nutrient concentrations and sediment loads for the HRWO sub-catchments under existing conditions are described separately in Semadeni-Davies et al. (2015) and Hughes (2015). In addition, the actual modelling of changes to nutrient and sediment concentrations under the scenarios and the resulting estimates of changes in visual clarity will be undertaken as part of the scenario modelling (to be reported elsewhere). As such, the scope of this report is limited to the development of the methodology and includes:

- Estimating current chlorophyll concentrations and visual clarity for the HRWO sub-catchments consistent with the Waikato Objectives Framework (Section 2);
- Developing an empirical model to relate nutrient concentrations to chlorophyll concentrations (Section 3.2);
- Collating information on the routing of sediment load estimates lost from the land through the river network to produce sediment loads discharged at the reach outlets (Section 3.3); and
- Relating changes in chlorophyll and sediment concentrations under the scenarios to changes in black disc visual clarity (Section 3.4).

The nutrient-phytoplankton model predicts median chlorophyll concentrations in response to median concentrations of nitrogen and phosphorus. In addition, the sediment loads routed through the stream network represent annual average sediment loads lost from the land. This 'average' approach is consistent with the needs of the HRWO project, which uses the attribute bands and associated median statistics in the National Objectives Framework to describe both the current water quality and that of scenarios for water quality improvement. Furthermore, the scenarios developed by the Collaborative Stakeholder Group specify that these median attributes must include the water quality of all seasons (with summer extremes represented by the attribute of maximum chlorophyll).

2 Visual Clarity of the Waikato and Waipa Rivers

This section describes current visual clarity estimates for the HRWO sub-catchments as well as the relative contributions to visual clarity from the each of the key constituents.

2.1 Background Information

Visual clarity in the Waikato and Waipa rivers is discussed in Vant (2015). The visual clarity of a waterbody – how far an observer can see through the water – is primarily determined by the concentrations of the various constituents that absorb or scatter light (Davies-Colley et al. 1993). The main optically-active constituents of natural waters are:

- Yellow substance (a type of dissolved organic material);
- Inorganic suspensoids, e.g. silts and clays;
- Organic suspensoids, e.g. phytoplankton and biological detritus; and
- Water itself

As discussed by Vant (2015), these substances are present in contrasting amounts in the Waikato and Waipa rivers, resulting in marked differences in the appearance of the water in each. For the purposes of this study, the key constituents contributing to visual clarity in the Waikato and Waipa rivers are divided into:

1. Yellow substance;
2. Phytoplankton, measured by chlorophyll concentrations; and
3. 'Other', assumed to be dominated by fine sediment.

The relative contributions of each of these three key constituents to visual clarity in the HRWO sub-catchments is discussed in Section 2.2 below.

2.2 Current Visual Clarity and Constituent Contributions

As specified under the Waikato Objectives Framework, recommended and accepted by the Collaborative Stakeholder Group for the HRWO project, visual clarity for the Waikato and Waipa rivers is assessed in terms of the median black disc horizontal sighting range under baseflow conditions (i.e., excluding any measurements taken during the top 10 % of flows). Table 2-1 summarises current black disc visual clarity for the HRWO sub-catchments estimated from monitoring data provided by WRC as well as from the National Rivers Water Quality Network (NRWQN) run by NIWA. For consistency with the analysis of current nutrient concentrations elsewhere in the project (Semadeni-Davies et al. 2015), the median black disc values are calculated over the 5-year period 2010 – 2014.

Flows associated with each of the black disc measurements were assigned by interpolating nearby flow site records at each of the water quality sampling times. The flow sites assigned were the same as those used in analysis of current nutrient concentrations and loads (Semadeni-Davies et al. 2015) where possible, or were otherwise drawn from Vant (2013, Table 3). Black disc measurements associated with the top decile of the flow record were excluded from the analysis.

In addition to black disc measurements, beam attenuation coefficients were also calculated from the monitoring data in order to assess the contribution to visual clarity from each of the three key constituents noted in Section 2.1. For each black disc measurement y_{BD} [m], the beam attenuation coefficient [m^{-1}] is calculated as $c = 4.8/y_{BD}$. The contribution to beam attenuation from each of the key constituents may be considered additive, so that

$$c = c_Y + c_B + c_S, \tag{2.1}$$

where c_Y is the contribution due to yellow substance [m^{-1}], c_B is the contribution due to phytoplankton [m^{-1}] and c_S is the contribution due to 'other' which in this case is assumed to be dominated by fine sediment [m^{-1}]. Table 2-1 summarises current beam attenuation values for the HRWO sub-catchments as well as the average contributions to beam attenuation from each of the three key constituents, estimated following the methodology in Vant (2015) as outlined below:

- The contribution to beam attenuation from yellow substance is estimated as $c_Y = 0.13g_{440}$, where g_{440} is calculated from the absorbance measured at 440 nm (Davies-Colley et al. 1993, Equation A2.4).
- The contribution to beam attenuation from phytoplankton is estimated as $c_B = 0.47(Chl)^{0.65}$, where Chl is the chlorophyll concentration in mg m^{-3}.
- The contribution to beam attenuation from sediment is estimated as the remainder , i.e. $c_S = c - (c_Y + c_B)$.

The contribution due to yellow substance is a little higher for the main-stem Waipa River sites than the main-stem Waikato River sites, though for all sites the contribution due to yellow substance is not particularly significant (ranging between 0 – 11 %). The contribution due to phytoplankton for the main-stem Waikato River sites generally decreases with distance downstream from Lake Taupo, with the exception of Ohakuri (44 %) and Waipapa (36 %), which are a little lower than Narrows (52 %). Beam attenuation for the main-stem Waipa River sites and the tributary sites is dominated by sediment (generally in excess of 90 %).

Table 2-1: Median visual clarity and percent contributions to beam attenuation from each of the three key constituents for the HRWO sub-catchments. Sub-catchments without values are not associated with monitoring sites.

HRWO sub-catchment	Visual clarity		Constituent contribution (%)		
	y_{BD} (m)	c (m^{-1})	c_Y	c_B[1]	c_S
Awaroa (Rotowaro) at Harris/Te Ohaki Br	-	-	-	-	-
Awaroa (Rotowaro) at Sansons Br	0.8	5.9	1	0	99
Awaroa (Waiuku)	0.4	13.0	1	0	99
Firewood	-	-	-	-	-
Kaniwhaniwha	-	-	-	-	-
Karapiro	0.9	5.2	5	0	95
Kawaunui	1.3	3.6	4	0	96
Kirikiriroa	0.4	12.0	2	0	98
Komakorau	-	-	-	-	-
Little Waipa	1.5	3.1	2	0	98
Mangaharakeke	1.1	4.4	3	0	97
Mangakara	-	-	-	-	-
Mangakino	1.6	2.9	1	0	99
Mangakotukutuku	0.4	11.7	11	0	89
Mangamingi	0.8	5.9	3	0	97
Mangaohoi	1.6	3.0	1	0	99
Mangaokewa	1.0	4.9	5	0	95
Mangaone	1.0	5.0	5	0	95
Mangaonua	0.9	5.1	3	0	97
Mangapiko	0.6	8.0	6	0	94
Mangapu	0.8	6.0	2	0	98
Mangarama	-	-	-	-	-
Mangarapa	-	-	-	-	-
Mangatangi	0.6	8.7	3	0	97
Mangatawhiri	1.6	2.9	5	0	95
Mangatutu	1.5	3.1	3	0	97
Mangauika	-	-	-	-	-
Mangawara	0.3	19.2	3	0	97
Mangawhero	0.3	18.8	3	0	97
Matahuru	0.3	15.5	3	0	97
Moakurarua	-	-	-	-	-
Ohaeroa	0.8	5.9	3	0	97

[1] Chlorophyll concentrations are not measured in the tributaries of the Waikato and Waipa rivers or in the main-stem of the Waipa River. Contributions to visual clarity resulting from phytoplankton are considered negligible for these sites (i.e., $c_B = 0$).

Table 2-1 cont.

HRWO sub-catchment	Visual clarity		Constituent contribution (%)		
	y_{BD} (m)	c (m^{-1})	c_Y	c_B	c_S
Ohote	-	-	-	-	-
Opuatia	0.5	9.1	2	0	98
Otamakokore	1.1	4.4	6	0	94
Pokaiwhenua	1.3	3.7	2	0	98
Pueto	1.6	2.9	0	0	100
Puniu at Bartons Corner Rd Br	0.9	5.1	4	0	96
Puniu at Wharepapa	-	-	-	-	-
Tahunaatara	1.2	4.0	4	0	96
Torepatutahi	-	-	-	-	-
Waerenga	0.8	5.8	3	0	97
Waikare	-	-	-	-	-
Waikato at Bridge St Br[2]	1.4	3.5	1	52	47
Waikato at Horotiu Br	1.4	3.6	1	47	52
Waikato at Huntly-Tainui Br	0.9	5.5	2	31	67
Waikato at Karapiro	-	-	-	-	-
Waikato at Mercer Br[3]	0.6	8.0	1	28	71
Waikato at Narrows	1.6	3.0	1	52	47
Waikato at Ohaaki[4]	-	-	-	-	-
Waikato at Ohakuri	2.0	2.4	0	44	56
Waikato at Port Waikato	-	-	-	-	-
Waikato at Rangiriri[5]	0.8	6.2	1	31	68
Waikato at Tuakau Br	0.5	9.4	1	27	72
Waikato at Waipapa	1.6	3.0	1	36	63
Waikato at Whakamaru[6]	-	-	-	-	-
Waiotapu at Campbell	1.2	4.1	0	0	100
Waiotapu at Homestead	0.7	7.2	2	0	98
Waipa at Mangaokewa Rd	1.5	3.2	8	0	92
Waipa at Otewa	2.2	2.2	2	0	98
Waipa at Otorohanga	1.1	4.3	4	0	96
Waipa at Pirongia-Ngutunui Rd Br	0.8	6.2	3	0	97

Table 2-1 cont.

[2] Chlorophyll is not measured at this site. The contribution to visual clarity resulting from phytoplankton is assumed to be the same as for Waikato at Narrows.

[3] Black disc measurements are not available for this site. Median black disc visual clarity is estimated from Waikato at Huntly-Tainui Br.

[4] Measured chlorophyll concentrations are consistently below detection at this site.

[5] Chlorophyll is not measured at this site. The contribution to visual clarity resulting from phytoplankton is assumed to the same as for Waikato at Huntly-Tainui Br.

[6] Measured chlorophyll concentrations are considered unreliable for this site (see Verburg, 2015).

HRWO sub-catchment	Visual clarity		Constituent contribution (%)		
	y_{BD} (m)	c (m^{-1})	c_Y	c_B	c_S
Waipa at SH23 Br Whatawhata	0.6	7.9	1	0	99
Waipa at Waingaro Rd Br	-	-	-	-	-
Waipapa	1.1	4.3	1	0	99
Waitawhiriwhiri	0.4	12.6	6	0	94
Waitomo at SH31 Otorohanga	0.6	8.1	2	0	98
Waitomo at Tumutumu Rd	1.0	5.1	1	0	99
Whakapipi	1.1	4.4	5	0	95
Whakauru	0.8	6.2	2	0	98
Whangamarino at Island Block Rd	0.2	24.0	3	0	97
Whangamarino at Jefferies Rd Br	0.5	9.6	2	0	98
Whangape	-	-	-	-	-
Whirinaki	2.7	1.8	0	0	100

3 Estimating Changes to Chlorophyll Concentrations and Visual Clarity

This section details the methodology used to estimate changes in chlorophyll concentrations and visual clarity for each of the HRWO sub-catchments in response to changes in nutrient concentrations and sediment loads under various scenarios.

3.1 Outline

Figure 3-1 illustrates how changes in nutrient concentrations and sediment loads predicted for the HRWO sub-catchments under various scenarios are related to changes in visual clarity through the contributions from yellow substance, phytoplankton and 'other' (assumed to be dominated by fine sediment). Under each scenario:

- Concentrations of yellow substance are assumed to remain constant.
- Changes in nutrient (i.e. nitrogen and phosphorus) concentrations for the river reaches are related to changes in chlorophyll concentrations, which provide an indicator of phytoplankton growth; and
- Changes in sediment loads lost from the land are routed through the river network to assess sediment loads discharged from each reach outlet.

The sections below provide further details of the nutrient-chlorophyll relationships used in this study, the routing of sediment loads through the river reaches and the translation of these quantities into changes in visual clarity.

3.2 Nutrient-Chlorophyll Relationships

Model Structure

Nutrient (i.e. nitrogen and phosphorus) concentrations for the river reaches are modelled separately (Semadeni-Davies et al. 2015). The relationship between chlorophyll, total nitrogen (TN) and total phosphorus (TP) concentrations used in this study is of the form

$$Chl = a_0 + a_1 w_1(r)N + a_2 w_2(r)P, \tag{3.1}$$

where Chl is the predicted (median) chlorophyll concentration [mg L^{-1}], N is the median TN concentration [mg L^{-1}], P is the median TP concentration [mg L^{-1}] and $r = N/P$ is the ratio of total nitrogen to phosphorus concentrations [dimensionless]. The parameter a_0 [mg L^{-1}] represents the contribution to chlorophyll not related to TN and TP, whilst a_1 and a_2 [dimensionless] reflect the maximum sensitivity of the model to changes in TN and TP under completely nitrogen- and phosphorus-limited regimes, respectively. For example, under a completely nitrogen-limited regime (low N/P ratio), a 1 mg L^{-1} increase in TN would result in a predicted increase in chlorophyll of a_1 mg L^{-1}, whilst changes in TP would have no effect. Likewise, under a completely phosphorus-limited regime (high N/P ratio), a 1 mg L^{-1} increase in TP would result in a predicted increase in chlorophyll of a_2 mg L^{-1}, whilst changes in TN would have no effect. Realistically, however, the predicted responses to changes in TN and TP would be some fractions of a_1 and a_2 due to scaling by the weight functions $w_1(r)$ and $w_2(r)$ as discussed below.

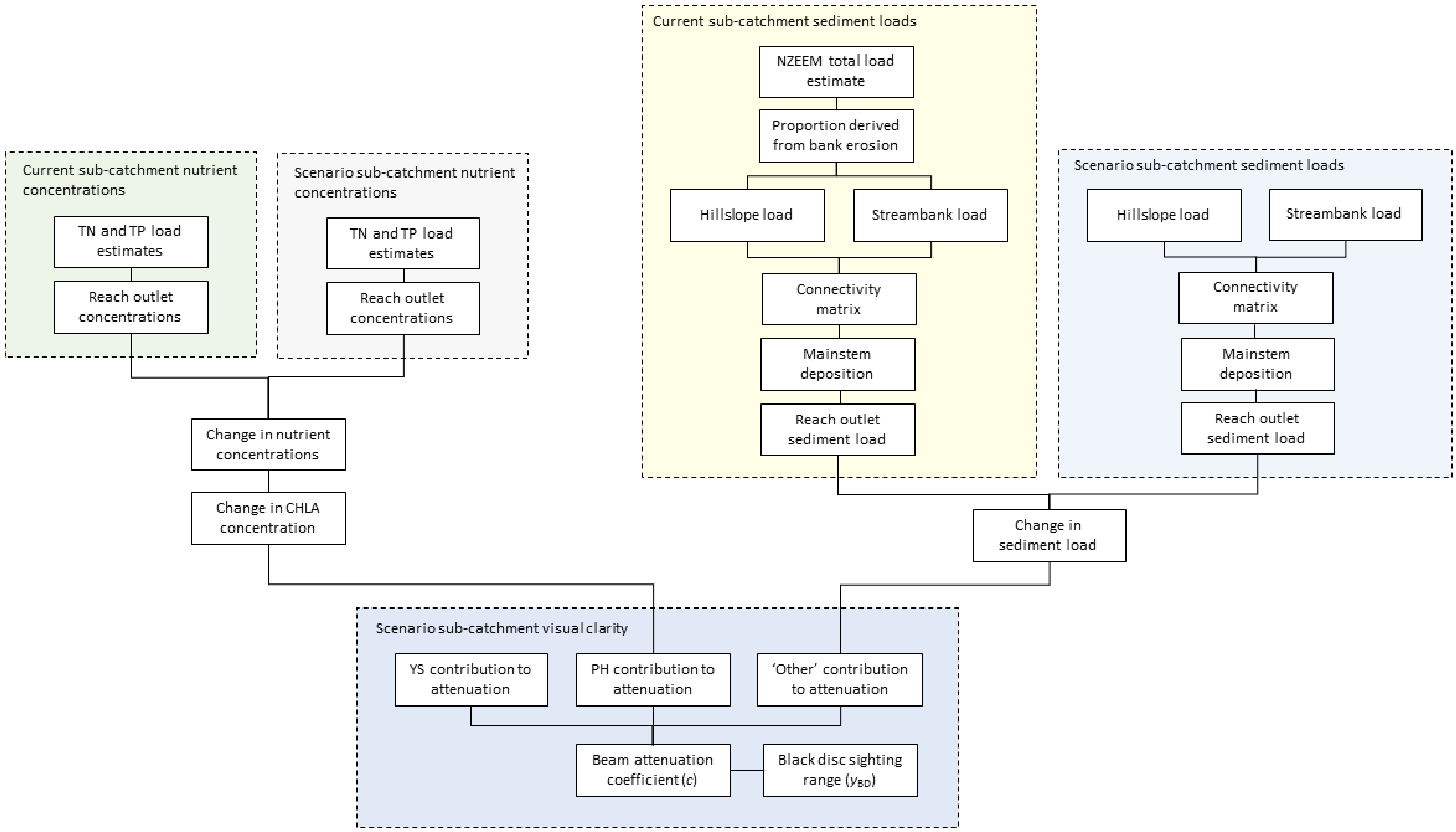

Figure 3-1: Illustrative relationship between changes in nutrient concentrations and sediment loads and associated changes in visual clarity. YS = yellow substance and PH = phytoplankton

The weight functions $w_1(r)$ and $w_2(r)$ are dimensionless weight functions which allow the sensitivity of the model to changes in TN and TP to vary at different nutrient ratios. They represent a pair of logistic curves centred around $r = r_0$ with steepness k, i.e.

$$w_1(r) = \frac{1}{1 + e^{k(r-r_0)}} \tag{3.2}$$

and

$$w_2(r) = \frac{1}{1 + e^{-k(r-r_0)}} \tag{3.3}$$

An example of these curves for $r_0 = 10$ and $k = 0.5$ is shown in Figure 3-2. For very low TN/TP ratios, w_1 is approximately equal to 1 whilst w_2 is approximately zero. In that case, the model will behave as for the completely nitrogen-limited regime discussed in the previous paragraph. As the TN/TP ratio increases, the weighting for TN decreases whilst the weighting for TP increases, meaning the proportional response of the model to changes in TN will reduce until, at very high TN/TP ratios, w_1 is approximately zero and w_2 is approximately 1 and the model will behave as for the completely phosphorus-limited regime. The weights are equal at $r = r_0$, meaning the proportional response of the model to changes in TN and TP will also be equal at this point. The steepness parameter k defines the width of the transition region between nitrogen- and phosphorus-limited regimes, with higher k values indicating a sharper transition (narrower bandwidth).

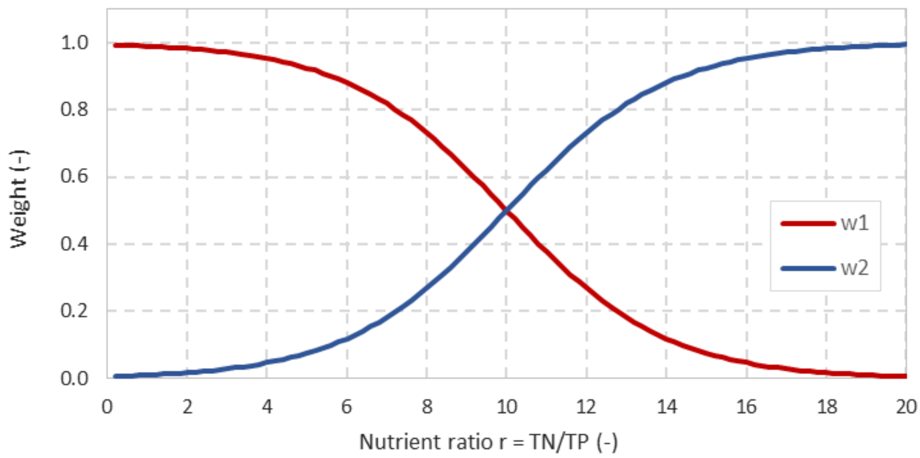

Figure 3-2: Weight functions for TN and TP with r_0 = 10 and k = 0.5.

Parameterisation

Chlorophyll concentrations are not measured in the tributaries of the Waikato and Waipa rivers, or in the main-stem of the Waipa River, and contributions to visual clarity resulting from phytoplankton are assumed to be negligible for these sites. Hence, nutrient-chlorophyll relationships are required only for the main-stem Waikato River sites.

We attempted to fit parameters for the individual main-stem Waikato River sites using annual median TN, TP and chlorophyll concentrations derived from monitoring data over the period 1990 – 2014. The data lacked a strong signal however, and the resulting parameter estimates (produced using non-linear least squares curve fitting routines in Matlab®) were uncertain, with large standard errors and a high degree of interaction, particularly between the TN and TP coefficients a_1 and a_2. Instead, by examining the sensitivity of the model, we have selected parameters which provide a good approximation of current conditions (to within 0.3 – 0.4 % of measured values) and produce model behaviour consistent with expert advice under variations of TN and TP (J. Quinn, 2015, pers. comm. 14 July). For example, under current conditions, the model predicts an average contribution to median chlorophyll concentrations of 16 % for all sites for TN and 69 % for all sites for TP. Table 3-1 summarises the model parameters for the individual sites. For each site, fixed values of $r_0 = 10$ and $k = 0.5$ were used as discussed below. Model relationships were not produced for Ohaaki or Whakamaru due to issues with the monitoring data at those sites (see Verburg, 2015). The parameters for Huntly-Tainui were used as a surrogate for the Rangiriri site, and the average of the parameter values for Narrows and Horotiu were used for the Bridge St site in the absence of monitoring data at these locations.

Literature suggests that phytoplankton growth is likely to be nitrogen-limited when the TN/TP ratio is less than about 10 (by mass), and phosphorus-limited when the TN/TP ratio is greater than about 17 (e.g. Pridmore, 1987 and Abell et al. 2010; as cited by Vant, 2015). For intermediate ratios, phytoplankton growth is likely to be co-limited (i.e. influenced by both TN and TP). Intuitively, this suggests that r_0 should lie somewhere within the range 10 – 17. In an analysis of nutrient and chlorophyll concentrations in the Waikato River over the period 1990 – 2014, Verburg (2015) states that "there is abundant evidence that algal biomass in the Waikato River is primarily limited by phosphorus, and not by nitrogen" (p. 5). This view is also supported by the results of bioassay studies at selected sites in the river (Gibbs et al. 2015), which showed little to no response to the addition of N, but small to large responses to the addition of P (either by itself or in combination with N). Current TN/TP ratios for the sites (Table 3-1) are between 10.6 and 14.3. Based on these ratios, we have selected a fixed value for r_0 equal to 10, which is at the low end of the co-limited range suggested by the literature, but reflects the evidence that the phytoplankton response is currently dominated by phosphorus.

Table 3-1: Model parameters for the Waikato River sites. The right-hand columns indicate the median measured TN, TP and chlorophyll (Chl) concentrations over the period 2010-2014. Sites are arranged in order of distance down the catchment. Parameters a_1 and a_2 have no unit.

HRWO sub-catchment	a_0 (mg L^{-1})	a_1	a_2	TN (mg L^{-1})	TP (mg L^{-1})	TN/TP ratio	Chl (mg L^{-1})
Waikato at Ohakuri	0.001	0.010	0.122	0.215	0.018	11.9	0.0032
Waikato at Waipapa	0.001	0.010	0.120	0.336	0.026	13.1	0.0041
Waikato at Narrows	0.001	0.011	0.158	0.410	0.029	14.3	0.0055
Waikato at Bridge St Br	0.001	0.011	0.149	0.437	0.035	12.5	-
Waikato at Horotiu Br	0.001	0.012	0.140	0.441	0.038	11.8	0.0062
Waikato at Huntly-Tainui Br	0.001	0.007	0.111	0.585	0.047	12.5	0.0060
Waikato at Rangiriri	0.001	0.007	0.111	0.602	0.056	10.8	-
Waikato at Mercer Br	0.001	0.015	0.175	0.662	0.054	12.2	0.0105
Waikato at Tuakau Br	0.001	0.017	0.207	0.595	0.056	10.6	0.0120

For the steepness parameter k, little information is available with which to guide selection. A value of 0.5 was chosen as it provides a reasonable differentiation between regimes (too low a value would result in TN and TP being fairly equally weighted for all nutrient ratios), yet does not result in too sharp a transition. Advice from ecologists (P. Verburg, 2015, pers. comm. 14 July) is that such sharp transitions between regimes do not occur in nature.

Figure 3-3 shows an example of the predicted chlorophyll concentrations for Waikato at Narrows in response to various TN and TP concentrations. The three solid black lines indicate TN/TP ratios of 5, 10 and 15. For low TN/TP ratios (upper left corner of the plot) the model is nitrogen-limited and the predicted chlorophyll concentrations have little sensitivity to TP. In contrast, for high TN/TP ratios (lower right corner of the plot) the model is phosphorus-limited and the predicted chlorophyll concentrations have little sensitivity to TN. Plots for all of the sites are shown in Appendix A.

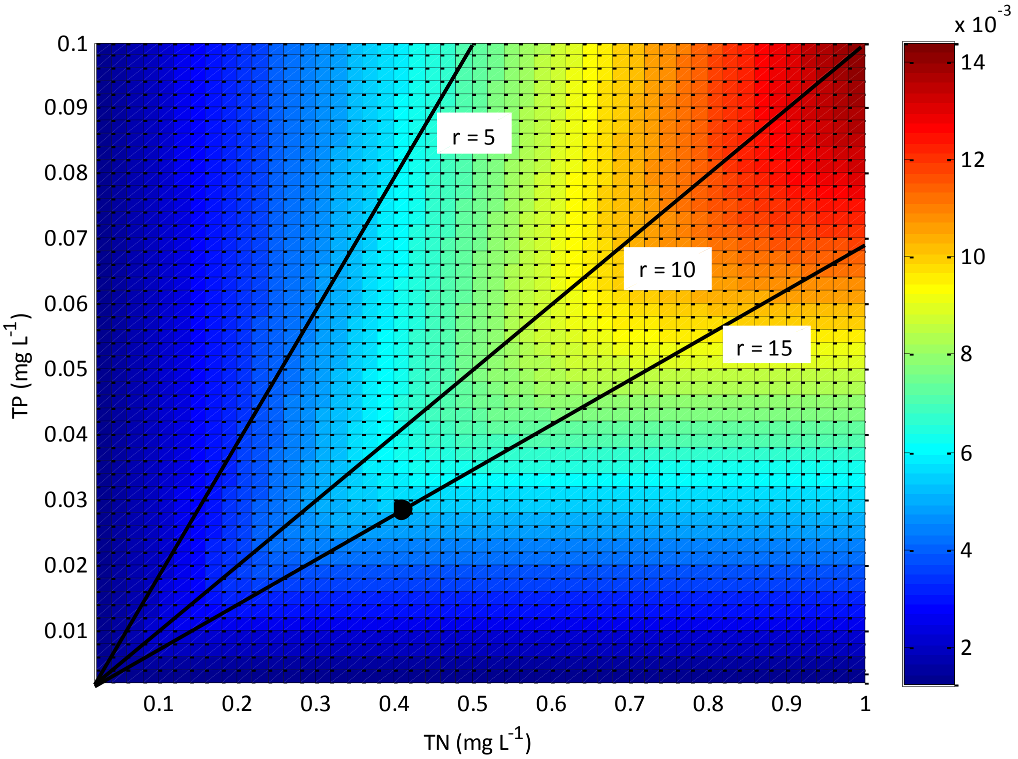

Figure 3-3: Predicted chlorophyll concentration for the Waikato at Narrows site in response to TN and TP concentrations. The colour scale to the right indicates the chlorophyll concentration (mg L^{-1}). The three solid black lines indicate r = TN/TP ratios of 5, 10 and 15, and the solid black circle indicates the current median TN and TP conditions.

Current conditions in Figure 3-3 are indicated by the solid black circle. Based on the current median TN and TP concentrations (Table 3-1), the TN/TP ratio at Narrows is $r = 14.3$. It follows that the weighting for TN in Equation (3.1) is $w_1 = 0.1$ and the weighting for TP is $w_2 = 0.9$. Thus, under current conditions, the coefficient for TN is 10 % of a_1 and the coefficient for TP is 90 % of a_2. Equation (3.1) then becomes

$$Chl = a_0 + 0.1a_1N + 0.9a_2P, \quad (3.4)$$

which gives a predicted median chlorophyll concentration of 0.0055 mg L^{-1}. As an example of the sensitivity of Equation (3.1) to different scenarios at this site:

- An increase of 10 % TN results in a less than 1 % increase in chlorophyll
- An increase of 10 % TP results in a 6.5 % increase in chlorophyll
- An increase of 10 % TN and 10 % TP results in an 8.2 % increase in chlorophyll

These values are reasonably consistent with the responses predicted by the regression relationship between annual median chlorophyll and TP derived from monitoring data at the Narrows site in Verburg (2015). This relationship (R^2 = 0.32) predicts a 7.5 % increase in chlorophyll in response to a 10 % increase in TP.

In addition to the median chlorophyll as predicted by Equation (3.1), maximum chlorophyll concentrations under the scenarios can be predicted using a regression relationship between annual maximum chlorophyll concentrations at the sites and annual median chlorophyll concentrations (Verburg, 2015). This relationship (R^2 = 0.91) is given as

$$Chl_{\max} = 2.1558 Chl + 4.9427, \qquad (3.5)$$

where $Chl_{\max}$ is the predicted maximum chlorophyll concentration (in mg m^{-3}) and Chl is the median chlorophyll concentration as given by Equation (3.1), also converted to mg m^{-3}.

3.3 Sediment Routing

Annual sediment loads lost from the land are modelled separately for the sub-catchments using the New Zealand Empirical Erosion Model[7] (NZeem®). As shown in Figure 3-1, the total sediment loads are divided into streambank and hillslope components, since these components may vary separately under the different scenarios. The percentage of the NZeem® total sediment loads estimated as being derived from bank erosion for each of the HRWO sub-catchments is listed in Hughes (2015).

The NZeem® total sediment loads lost from the land are routed through the stream network, allowing for retention of sediment in hydro-reservoirs along the main-stem of the Waikato River. The locations of the hydro-reservoirs and their associated retention efficiencies are shown in Table 3-2. Retention efficiencies for the individual reservoirs are drawn from Hughes (2015). Where multiple reservoirs are located in the same sub-catchment, a combined retention efficiency is calculated assuming sediment is transported through the lakes in series.

Table 3-2: Locations and sediment retention efficiencies of hydro-reservoirs along the Waikato River. Combined retention efficiencies for HRWO sub-catchments with multiple reservoirs are shown in brackets.

Reservoir type	HRWO sub-catchment	Name	Retention efficiency (%)
Hydro-lake	Waikato at Ohaaki	Lake Aratiatia	0
	Waikato at Ohakuri	Lake Ohakuri	66
	Waikato at Whakamaru	Lake Atiamuri, Lake Whakamaru	34, 50 (67)
	Waikato at Waipapa	Lake Maraetai, Lake Waiapapa	60, 18 (67)
	Waikato at Karapiro	Lake Arapuni, Lake Karapiro	58, 45 (77)

3.4 Changes to Visual Clarity

As discussed in Section 2.2, the beam attenuation coefficient c is represented as the sum of the individual contributions due to yellow substance, phytoplankton and 'other'. Under each scenario, the contribution due to yellow substance is assumed to remain constant. Then, as a first approximation in each reach:

[7] http://tools.envirolink.govt.nz/dsss/new-zealand-empirical-erosion-model/

- The contribution due to phytoplankton, c_B, is assumed to be proportional to the chlorophyll concentration. Thus, the percentage change in chlorophyll estimated for the scenario produces an equivalent percentage change in c_B.
- The contribution due to 'other', c_S, is assumed to be proportional to the total sediment load discharged at the reach outlet. Thus, the percentage change in sediment load at the reach outlet estimated for the scenario produces an equivalent percentage change in c_S.

Mathematically, the new beam attenuation coefficient under the scenario is then given by

$$c_{\text{new}} = c\big(\sigma_Y + \sigma_B(1 + p_B) + \sigma_S(1 + p_S)\big), \tag{3.6}$$

where c is the existing beam attenuation coefficient under current conditions (Table 2-1), σ_Y, σ_B and σ_S are the existing percentage contributions to beam attenuation due to yellow substance, phytoplankton and 'other' (also from Table 2-1), expressed as fractions, and p_B and p_S are the percentage changes in chlorophyll concentration and reach outlet sediment load, also expressed as fractions. It follows that the percentage change in beam attenuation, expressed as a fraction, is

$$p = \frac{c_{\text{new}}}{c} - 1 \tag{3.7}$$

and the new black disc horizontal sighting range under the scenario is

$$y_{BD,\text{new}} = \frac{y_{BD}}{1 + p} \tag{3.8}$$

where y_{BD} is the existing black disc horizontal sighting range under the current conditions.

4 Limitations and Recommendations for Further Work

It should be noted that the nutrient-chlorophyll relationships described for the individual sites in Section 3.2 remain a significant source of uncertainty:

- The model structure was developed to be flexible enough to represent different nutrient-limitation regimes whilst ensuring that the predicted chlorophyll concentrations are both continuous and differentiable, as required by the scenario modelling. This model structure is consistent with evidence from an in-depth analysis of monitoring data and bioassays that phytoplankton in the river are predominantly limited by phosphorus, but can occasionally be limited by nitrogen.

- Other types of empirical nutrient-chlorophyll relationships in the literature tend to switch between separate linear regressions for TN and TP at a fixed nutrient ratio, resulting in discontinuities in predicted chlorophyll concentrations which are not physically realistic. Alternatively, a minimum operator type approach will ensure that predicted chlorophyll concentrations are continuous, however the model will only respond to changes in one nutrient.

- There is little precedent for the model structure adopted here in the literature, and as a result, no information is available to guide parameterisation.

- Parameter estimates derived from non-linear least squares curve fitting routines using existing monitoring data were uncertain and contained significant interactions, particularly between the TN and TP coefficients.

- Nevertheless, the flexibility of the adopted model presents several advantages over other empirical methods. Further examination of model sensitivity, or adjustments to the existing structure may yield more certainty in parameter estimates.

- Development of a dynamical model (e.g. Rutherford et al. 2001) was also considered, but rejected on the basis of insufficient time to gather the field and experimental data required to parameterise and calibrate such a model. Although we consider our empirical model 'fit for purpose' and able to predict median chlorophyll from TN and TP medians (as required for the scenario modelling), phytoplankton responses to changes in nutrients and other factors (e.g., temperature, residence time) will be far more dynamic. We recommend that consideration should be given to developing a dynamic model so that other processes, along with the temporal and spatial variability in nutrients, their ratios and phytoplankton can be represented.

Other sources of uncertainty are as follows:

- As a first approximation, the contributions to beam attenuation due to phytoplankton and 'other' are assumed to be proportional to chlorophyll concentrations and reach outlet sediment loads. These assumptions are subject to an unquantified level of uncertainty.

- We assume that the 'other' contribution to beam attenuation is dominated by fine sediment. For some sites there may be other influencing factors not covered by our analysis, e.g. sites where suspended particulate organic matter, such as decaying algal cells, is an issue.

5 Summary

This report has described the methodology used to estimate changes in chlorophyll concentrations and visual clarity in the Waikato and Waipa Rivers in response to changes in nutrient concentrations and sediment loads under various scenarios. The scope of the report is limited to the development of the methodology – the actual modelling of changes to chlorophyll concentrations and visual clarity will be undertaken as part of scenario modelling to assess the costs associated with achieving various water quality improvements (Doole et al. In preparation).

The key contributors to visual clarity in this study were considered to be yellow substance, phytoplankton and 'other' (assumed to be dominated by fine sediment). At any particular location, the contribution to visual clarity due to yellow substance was assumed to remain constant. Changes to nutrient concentrations affect changes to visual clarity through increased or decreased chlorophyll concentrations which provide an indicator of phytoplankton growth. Changes to sediment loads affect changes to visual clarity through the 'other' contributor.

An empirical relationship was developed to predict changes in median chlorophyll concentrations in response to changes in median TN and TP concentrations. The coefficients of this relationship are weighted as a function of the TN/TP ratio, which allows the model to respond to changes in both nutrients at different levels of sensitivity under different nutrient-limitation regimes. Separate models were fitted for individual sites along the main-stem of the Waikato River. Chlorophyll concentrations are not measured in the tributaries or along the main-stem of the Waipa River, and contributions to visual clarity resulting from phytoplankton are considered negligible for these sites.

Sediment loads lost from the land were routed through the river network to estimate changes in in-stream sediment loads. The routing included retention of sediment in hydro-reservoirs along the main-stem of the Waikato River. Equations were produced to relate the magnitude of predicted changes in chlorophyll concentrations and sediment loads to the associated changes in visual clarity.

6 Acknowledgements

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Appendix A Plots of Nutrient-Chlorophyll Relationships

The figures below show the predicted chlorophyll concentrations for the main-stem Waikato River sites in response to various TN and TP concentrations. Chlorophyll concentrations (in mg L^{-1}) are indicated by the colour scale to the right. The three solid black lines indicate r = TN/TP ratios of 5, 10 and 15. Current median TN and TP concentrations (calculated from monitoring data over the period 2010 – 2014) are indicated by the solid black circle in each plot.

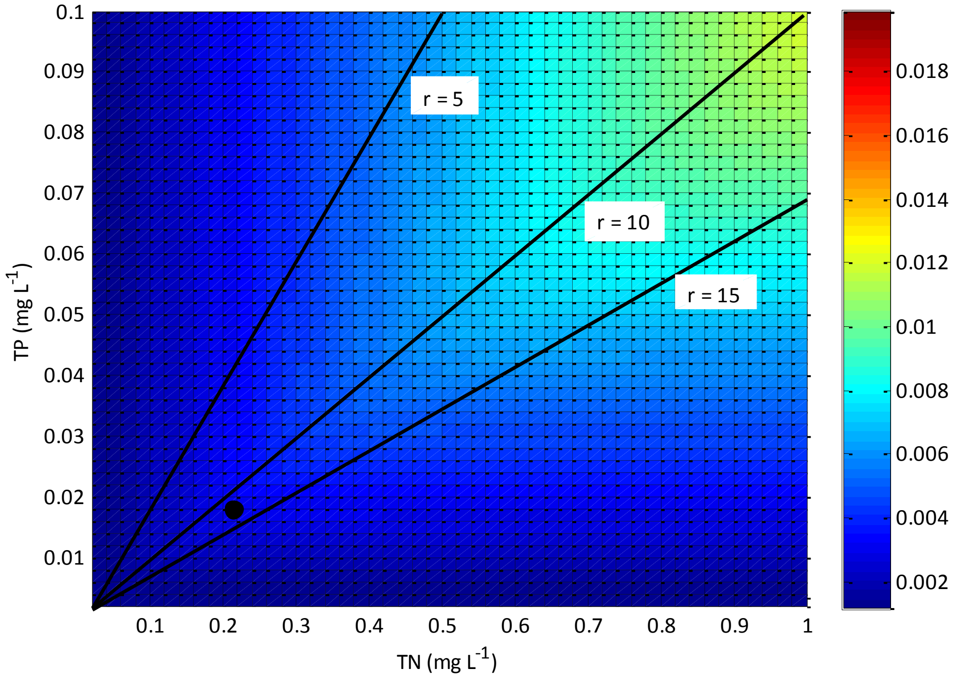

Figure A-1: Predicted chlorophyll concentrations for Waikato at Ohakuri.

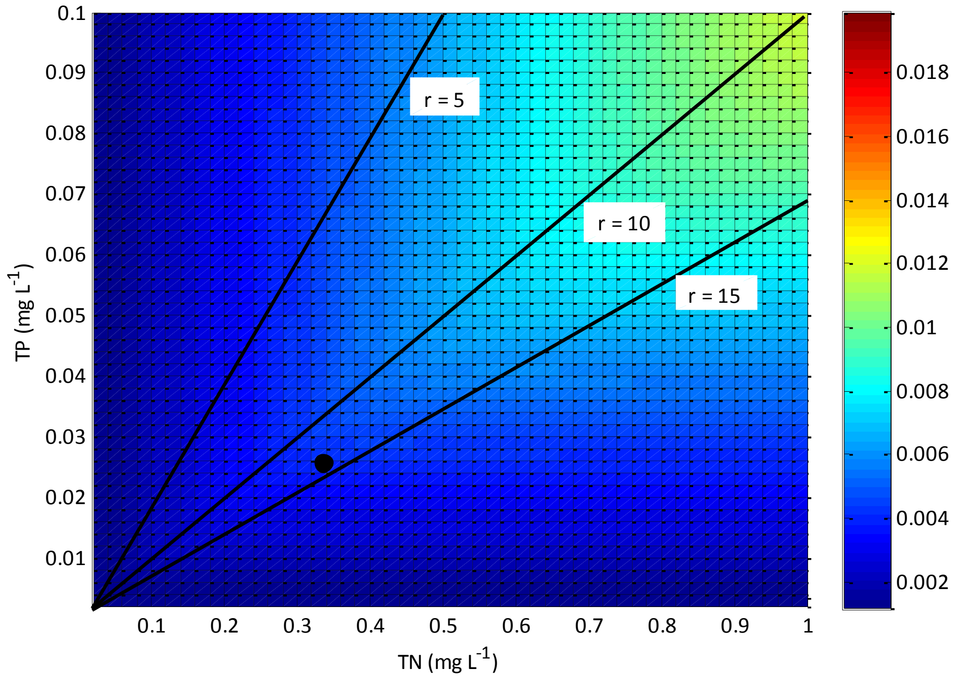

Figure A-2: Predicted chlorophyll concentrations for Waikato at Waipapa.

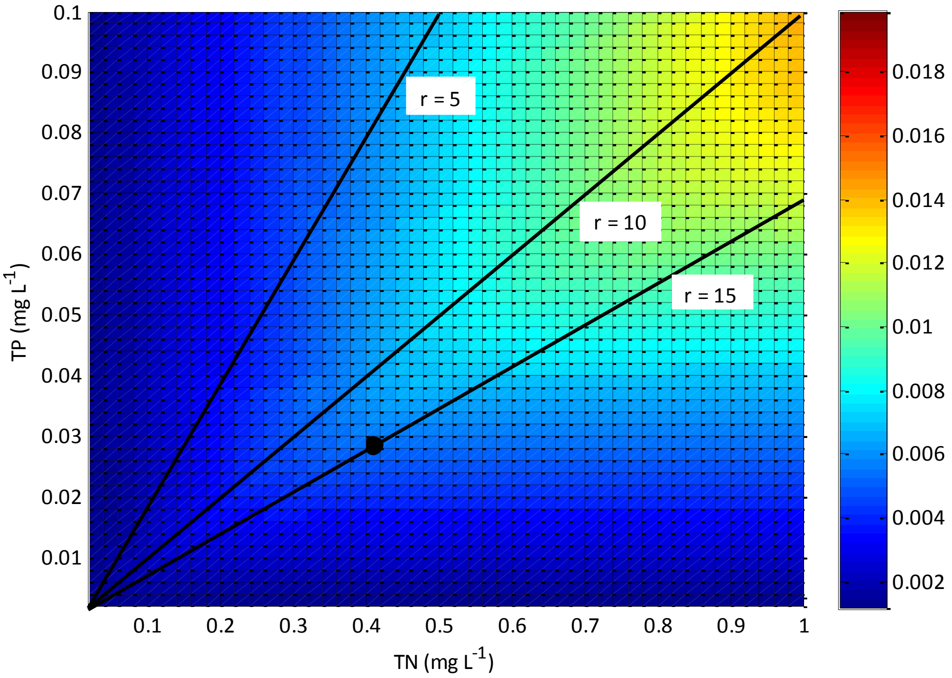

Figure A-3: Predicted chlorophyll concentrations for Waikato at Narrows.

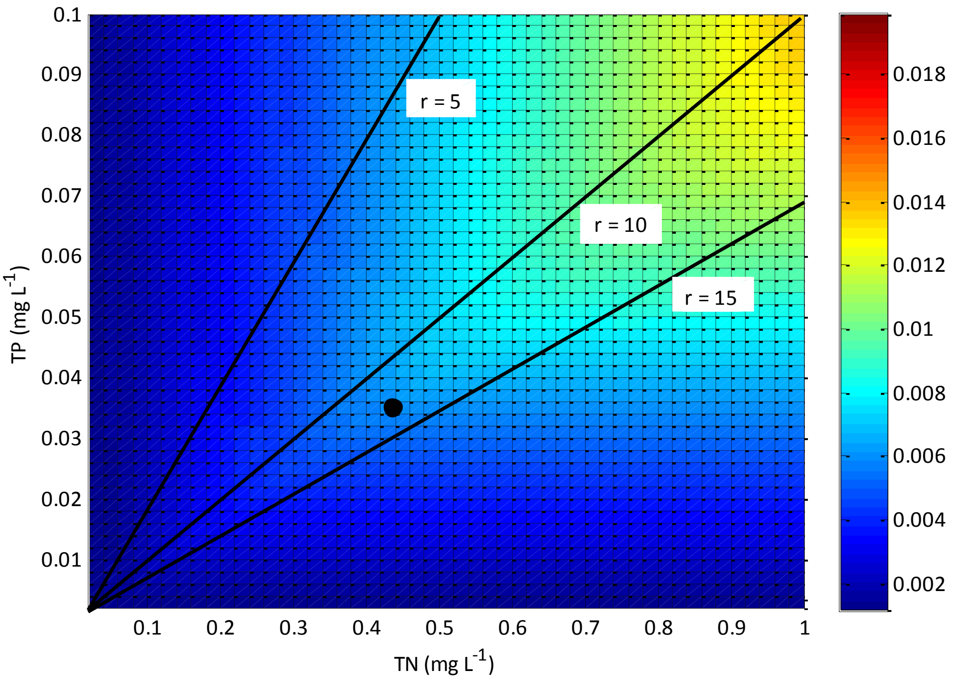

Figure A-4: Predicted chlorophyll concentrations for Waikato at Bridge St Br. Measured chlorophyll concentrations are not available at this site therefore the predicted chlorophyll concentrations are subject to an unquantified level of uncertainty.

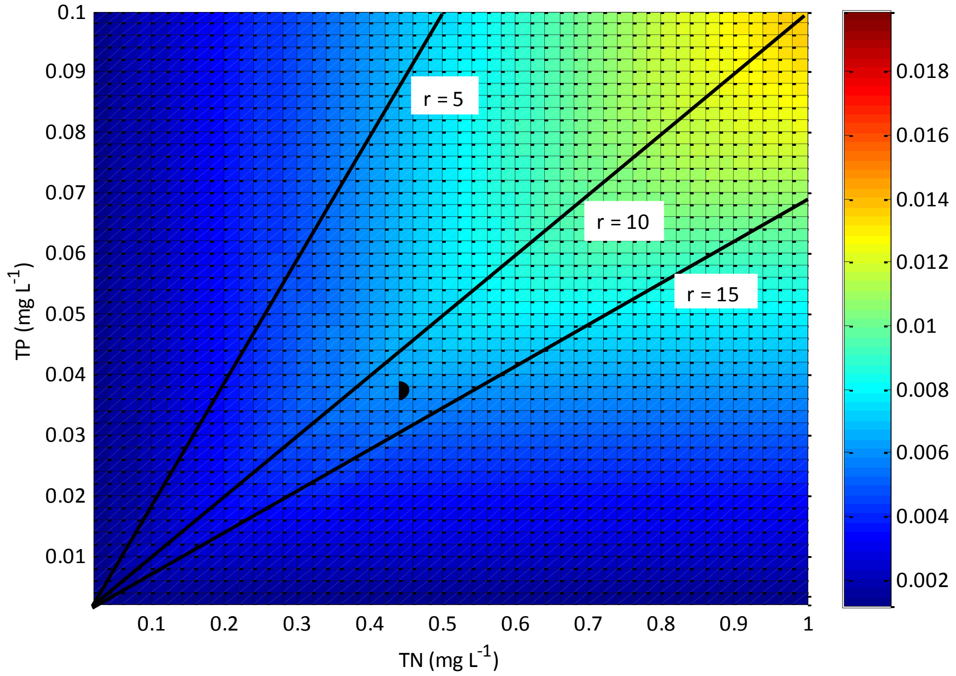

Figure A-5: Predicted chlorophyll concentrations for Waikato at Horotiu Br.

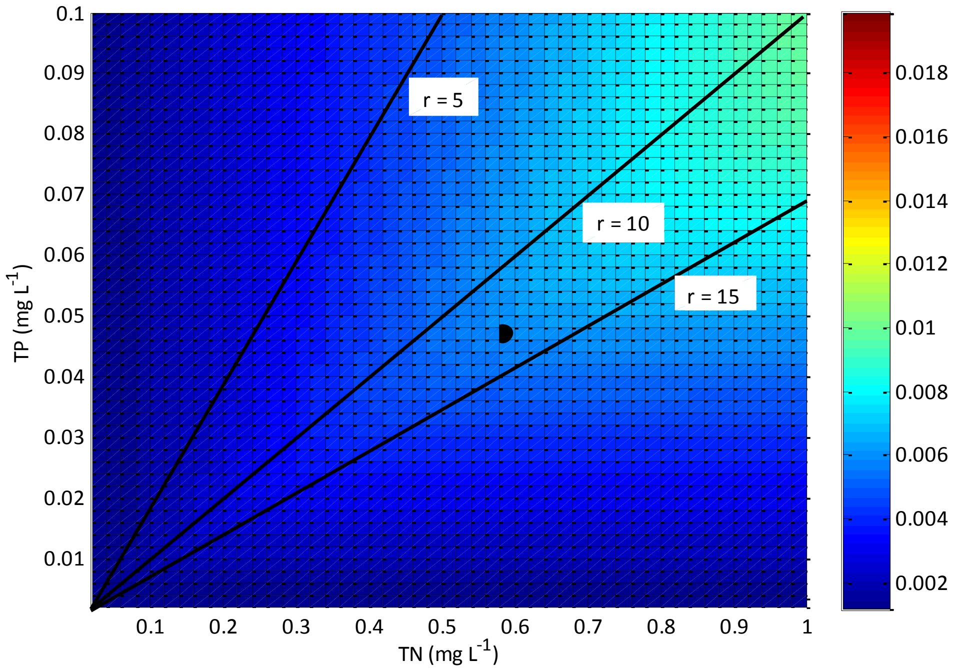

Figure A-6: Predicted chlorophyll concentrations for Waikato at Huntly-Tainui Br.

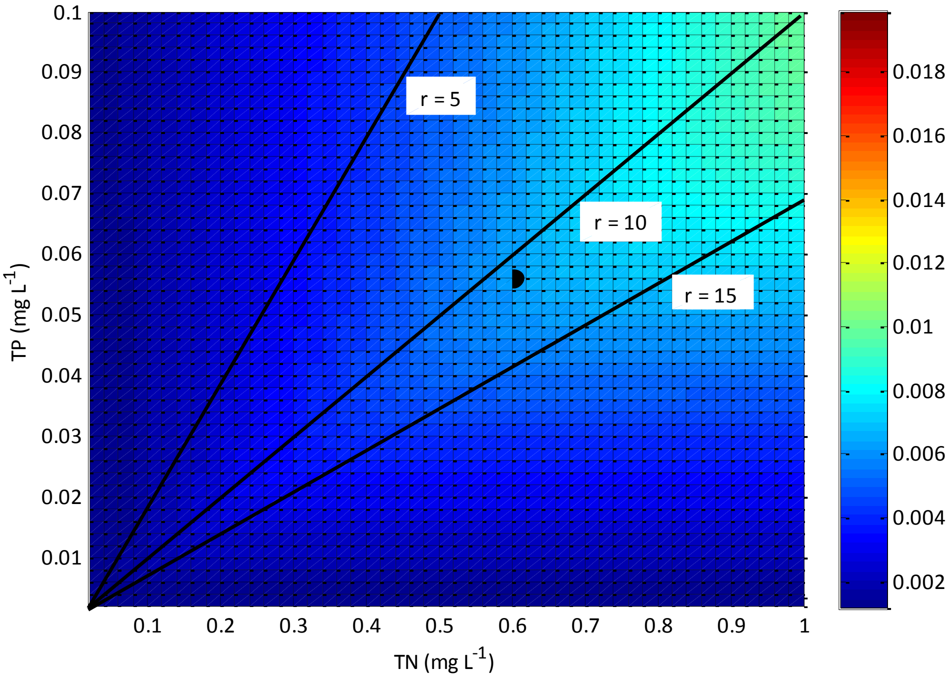

Figure A-7: Predicted chlorophyll concentrations for Waikato at Rangiriri. Measured chlorophyll concentrations are not available at this site therefore the predicted chlorophyll concentrations are subject to an unquantified level of uncertainty.

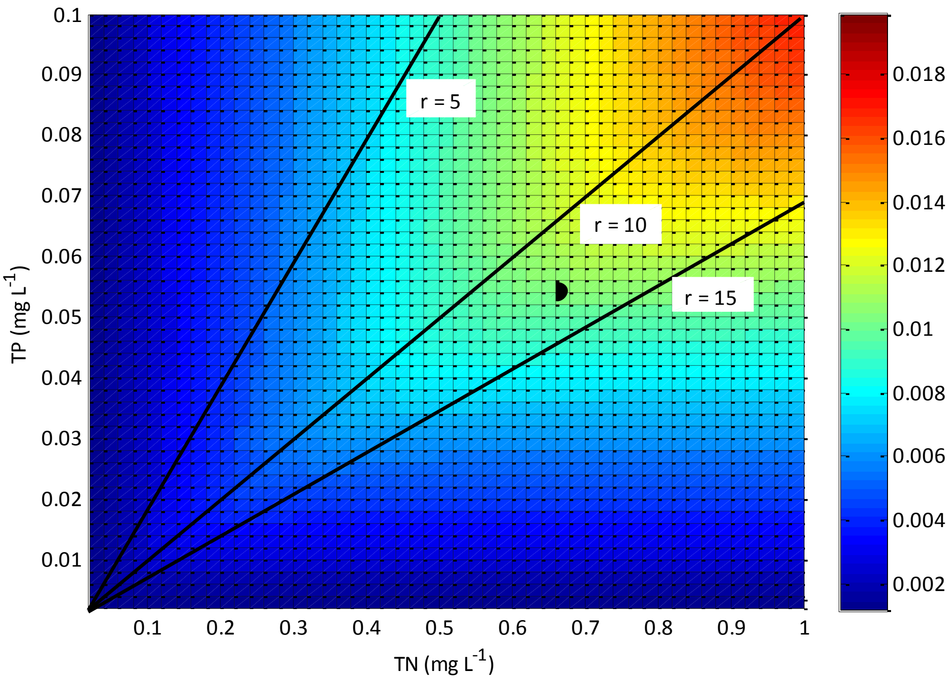

Figure A-8: Predicted chlorophyll concentrations for Waikato at Mercer Br.

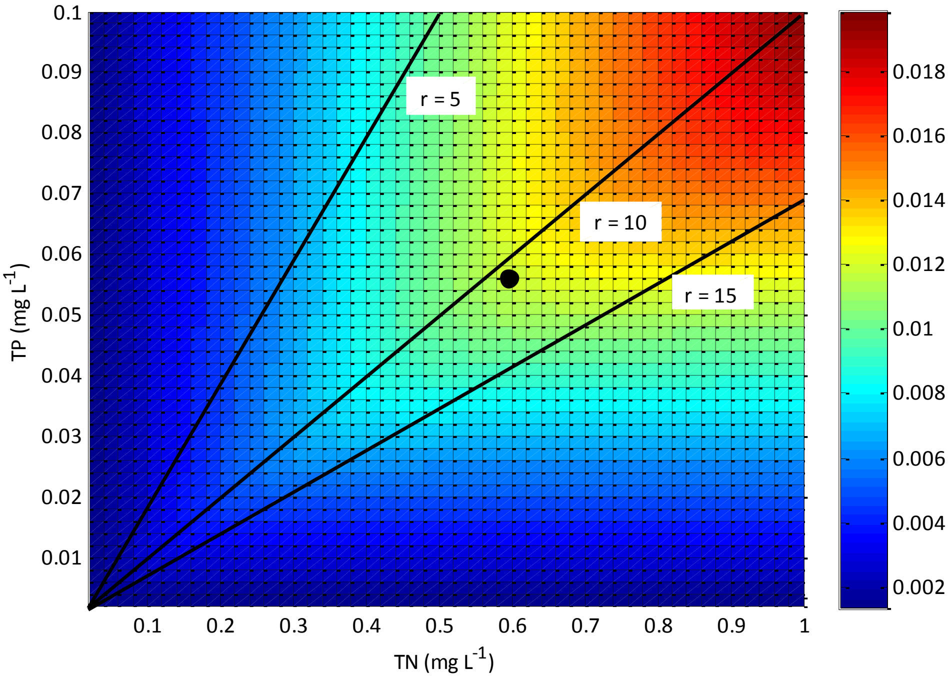

Figure A-9: Predicted chlorophyll concentrations for Waikato at Tuakau Br.