Appendix 13: Water Quality

1. Introduction

What are the issues requiring action?

This appendix evaluates the Waikato River's water quality, specifically the nutrients nitrogen (N) and phosphorus (P), phytoplankton (measured as chlorophyll a), clarity and colour under existing and possible future management options. Water clarity and colour are degraded compared with upstream values and targets in the lower Waikato, Waipa River and tributaries that drain farmland. Base flow water clarity affects: the safety and enjoyment of people using the river for recreation, the ability of animals to see and capture their prey (Rowe et al., 2002), the amount of light reaching aquatic plants growing under the water and, together with colour, the appearance and aesthetic appeal of the river. Sensitive native fish avoid tributaries with high suspended solids concentrations (Boubée et al., 1997). The change in water colour (from blue in Lake Taupoo to yellow-brown at Te Puuaha near the mouth) makes the lower Waikato River less attractive to people using the river.

The concentrations of nutrients are high in the hydro dams, lower Waikato and shallow lakes compared with upstream values and targets. High nutrient concentrations increase the growth rate of phytoplankton (microscopic plants suspended in the water column), which contributes to low clarity and colour change. High concentrations of cyanobacteria (also called blue-green algae, a type of phytoplankton) in the hydro lakes, lower Waikato and shallow lakes pose a significant public health risk because they may release toxins.

What are the causes of the problems?

Water clarity decreases, and colour changes, because of increases in the concentration of one or more of the following constituents: fine suspended sediment, dissolved organic compounds (yellow substance) and phytoplankton pigments (chlorophyll). Chlorophyll concentrations increase between Taupoo and Te Puuaha because of the increase in nutrient concentrations (nitrogen and phosphorus), and because the long residence time in the hydro lakes allows time for phytoplankton to grow to high concentrations.

All four constituents (turbidity, yellow substance, nutrients, chlorophyll) need to be considered together, although their relative importance varies within the catchment – turbidity dominates colour and clarity in the Waipa River, nutrients and chlorophyll dominate in the hydro lakes, and the combination of all four are important in the lower Waikato.

Clarity and colour would have changed naturally between Taupoo and Te Puuaha prior to development in the catchment because of natural erosion and inflows from peat areas. However, pastoral farming, towns and waste discharges have caused significant increases to the inputs of fine sediment, nutrient and yellow substance which have degraded clarity and colour. For example, where peat soils predominate (notably in the lower Waikato basin), lake and tributary waters were historically stained by yellow substance, but in their undisturbed state they were clear. Farming of peat land has increased the input of fine sediment and its combination with yellow substance now degrades the appearance of these waters.

High concentrations of phytoplankton chlorophyll (notably in the lakes) reduce clarity and make the water green. Most of the time, phytoplankton affects aesthetics in a relatively minor way. However, some species of cyanobacteria can release toxins. Blooms of such species occur only very occasionally, but when they do occur they threaten the safety of water supplies taken from the river and pose a health risk to river users.

What this section covers

This section describes:

1. Modelling the effects that waste discharges and runoff from farmland, forest and towns have on clarity, colour, nutrients and chlorophyll.
2. Predicting the effects of several scenarios of proposed actions (e.g., farming practice, land use change, improved waste treatment).
3. Comparing predictions with targets for health and wellbeing.
4. Hence, determining the actions required to restore the health and wellbeing of the Waikato.

The issue of phytoplankton blooms; is considered in this Section rather than the appendices dealing with public health (see Appendix 10: Faecal Contamination; Appendix 20: Cyanotoxin treatment; Appendix 21: Toxic contaminants), because it is strongly linked to nutrients and clarity.

A computer model, the Waikato Catchment Model (WCM) (Rutherford et al., 2001), is used to quantify the cumulative effects of the numerous point sources (waste discharges) and non-point sources (run-off from farmland, forest and urban areas) in the Waikato and Waipa catchments. A description of the WCM model and its application to this Study is given at the end of this appendix in Section 5.3.

While water clarity is lowest during wet weather – when sediment is washed into rivers, re-suspended from the riverbed, and/or released by bank erosion – the greatest use is made of the river for recreation during base flows. Moreover, phytoplankton blooms tend only to occur during summer low flows. Thus, in this section we focus on modelling clarity, colour and chlorophyll at base flow, but mean flow is also modelled since this may be affected by events such as floods and droughts.

Section 4 of the main Report describes the targets used in this project which, if attained, will restore the health and wellbeing of the Waikato. Those relevant to clarity, nutrients, colour and chlorophyll are shown in Table 1.

Table 1: Targets for nutrients, chlorophyll, clarity and colour. Refer to Section 4 for details of how these targets are derived. Along the Waikato, distance is measured downstream from Lake Taupoo. 190 kilometres is Karaapiro; 240 kilometres is where the Waipa joins the Waikato.

			Waikato River			**Waipa River**
			Upper (0–190 km)	**Middle (190–240 km)**	**Lower (> 240 km)**	
Phosphorus	TP	mg/m^3	20	35	35	35
Nitrogen	TN	mg/m^3	300	500	500	500
Chlorophyll – trigger	CHL	mg/m^3	5	5	5	5
Chlorophyll – warning	CHL	mg/m^3	10	10	10	10
Chlorophyll – filters	CHL	mg/m^3		20	20	20
Clarity	BD	m	4	1.6	1.6	1.6
Colour	Munsell		10 Munsell units below the values that are predicted to have existed in the river in the 1920s prior to the hydro dams being built.			

Section 6 of the main Report describes possible combinations of actions (i.e., scenarios) to restore the health and wellbeing of the Waikato River. The Current State is the present situation both in terms of farming practice and land use.

- Scenario 1 (current best practice) involves the uniform adoption of standard farming practices that should be being utilised at present to meet existing rules in the regional plan, and industry codes of practice (e.g., Dairying and Clean Streams Accord practices).
- Scenario 2 involves all of the actions of Scenario 1 plus an “optimised” combination of proven, but more costly practices than Scenario 1, with the aim of achieving significant rehabilitation to acceptable levels of many of the desired values identified in the consultation processes.
- Scenario 3 is the same as Scenario 2 with the addition of riparian buffers on sheep-beef farms, and 60 percent of sheep-beef farming on steep hill country, and 25 percent of sheep-beef farming on easy hill country being converted to forestry (170,900 hectares). The changes in land use are aimed at achieving a higher level of restoration.

Tables 2 and 3 give the percentage reductions from the Current State in total nitrogen (TN), total phosphorus (TP), suspended sediment (SS), fine suspended sediment (FSS) and dissolved colour (G440) for Scenarios 1, 2 and 3 respectively for the various land uses. These reductions are calculated from the yields in Table 7

Appendix 9: Farms, estimated by Dr. Ross Monaghan (AgResearch, Invermay). Note that the Monaghan table reports the expected reductions in suspended sediment (SS) yield but similar reductions are expected for fine suspended sediment (FSS) (Dr. Ross Monaghan, AgResearch, Invermay, pers. comm.). The SS reductions have also been assumed to apply to G440.

Table 2: Scenario 1 – percentage reductions from the Current State in the yields of nitrogen, phosphorus, suspended sediment, fine suspended sediment and dissolved colour.

	Nitrogen (TN)	Phosphorus (TP)	Suspended sediment (SS)	Fine suspended sediment (FSS)	Dissolved colour (G440)
Dairy on well-drained soils	16	75	15	15	15
Dairy on poorly-drained soils	17	61	15	15	15
Dairy on peat soils	26	35	7	7	7
Sheep-beef on steep hill country	4	6	18	18	18
Sheep-beef on easy hill country	4	6	18	18	18
Sheep-beef on easy rolling country	4	6	18	18	18
Horticulture & cropping	68	79	50	50	50
Forestry (planted forest)	10	15	20	20	20

Table 3: Scenarios 2 and 3 – percentage reductions from the Current State in the yields of nitrogen, phosphorus, suspended sediment, fine suspended sediment and dissolved colour.

	Nitrogen (TN)	Phosphorus (TP)	Suspended sediment (SS)	Fine suspended sediment (FSS)	Dissolved colour (G440)
Dairy on well-drained soils	62	89	42	42	42
Dairy on poorly-drained soils	44	74	43	43	43
Dairy on peat soils	64	63	73	73	73
Sheep-beef on steep hill country	6	9	34	34	34
Sheep-beef on easy hill country	6	9	34	34	34
Sheep-beef on easy rolling country	6	9	34	34	34
Horticulture and cropping	68	79	50	50	50
Forestry (planted forest)	10	15	20	20	20

Inputs from the 29 point source discharges into the Waipa and Waikato are given in the Tables 5 and 6 below. Currently, point source discharges contribute approximately five percent of the combined annual yield of total nitrogen load to the river from point sources plus diffuse sources from production land (farms, forests and horticulture) and 11 percent of the total phosphorus load. These percentages are higher at baseflow – 18 percent for total nitrogen and 22 percent for total phosphorus. Sewage accounts for 30 percent of the point source nitrogen load and 50 percent of the point source phosphorus load, with the balance from industrial inputs.

River iwi have expressed a desire for sewage discharges to be discharged to land/wetlands to meet cultural requirements and this has potential co-benefits for nutrient reduction. Scenario 2 includes land/wetland treatment of priority discharges from Hamilton City (largest discharge to river) and Te Kauwhata (discharged to a riverine lake) and Scenario 3 includes all sewage being discharged to land/wetlands. These actions have co-benefits for nutrient management. For the purposes of this Study we assumed that discharge to land/wetlands will reduce the nitrogen and phosphorus loads from sewage point sources by 70 percent. It should be noted that chemical or biological treatment could be used to further reduce nutrient loads, and may be more cost-effective than wetland or land disposal. However, this would not have the co-benefit of meeting cultural aspirations.

The following describes results of the WCM modelling of the cumulative effect of the actions in each of the three scenarios that will reduce the inputs of nutrient, sediment and dissolved colour. The model predicts the benefits in terms of increased clarity, improved colour and reduced nutrient and phytoplankton chlorophyll concentrations – all of which are important water quality parameters that strongly influence the health and wellbeing of the Waikato River. For the Current State the WCM is calibrated to match the measured data for both mean and base flow. Results are presented first for the Waipa River, since it is the largest tributary of the Waikato and its outputs become inputs for the main stem Waikato model.

2. Waipa River

2.1 Current State of Waipa River water quality

Figures 1 and 2 show the current state of water quality in the Waipa River, assessed from measurements and WCM predictions at base and mean flow respectively.

Water clarity (BD)

Degraded water clarity is one of the most important issues for the Waipa identified by Maniapoto, science and community consultation.

At the top site (Mangaookewa Road eight kilometres), where the catchment is mostly native or exotic forest, the measured clarity averages 1.6 metres at base flow and 1.7

metres at mean flow. Clarity declines with distance downstream from Otewa. There is a large step decrease in clarity at Otorohanga (60 kilometres) (Figures 1 and 2) which is caused by dirty water from the Mangapuu (0.9 ± 0.4 metres at base flow) and Waitomo (1.0 ± 0.5 metres at base flow) joining the Waipa River. At Whatawhata (127 kilometres) clarity is degraded at base flow (0.7 ± 0.3 metres, average ± standard deviation) and severely degraded at mean flow (0.4 ± 0.2 metres). In the lower Waipa, the main contributors to low clarity are farm roads and animal tracks, exposed soils, streambanks and the streambed.

Clarity values predicted by the WCM at base flow are close to the measured values in the upper part of the catchment but slightly under predict measured values in the lower catchment (Figure 1). At mean flow, the model predicts the measured clarity values well at all sites except at the top site (Mangaookewa Road eight kilometres) (Figure 2).

Clarity is significantly better at base flow (Figure 1) than at mean flow (Figure 2) – possible reasons are bank and bed erosion, release of material from the Tunawaea slip (see below) and run-off from pasture. Figure 1 shows that at base flow the measured black disc water clarity (BD) meets the 1.6 metres clarity target at the top two monitoring sites (Mangaookewa Road eight kilometres, Otewa 43 kilometres) but not at the remaining three monitoring sites (Otorohanga 60 kilometres, Pirongia-Ngutunui Bridge 95 kilometres, Whatawhata 127 kilometres). Figure 2 shows that at mean flow the measured BD only meets the target at the top site (Mangaookewa Road eight kilometres).

Sedimentary rocks in parts of the catchment (notably near Te Kuuiti, Waitomo and in the Rangitoto Ranges) are associated with low clarity even when covered by undisturbed native forest. Because water clarity is naturally low in such lithology, it will be difficult to achieve very high water clarity throughout the Waipa catchment and may be unrealistic when the cost/benefits are considered. The highest clarity in any Waipa tributary occurs in the Mangauuika Stream, which is 95 percent native forest on the slopes of Pirongia, where base flow clarity averages 3.5 metres. Elsewhere in the Waikato catchment, clarity in native and exotic forest streams ranges from 1.0–4.5 metres. We would expect forested streams in the Waipa catchment to have a base flow clarity of 1.7–3.5 metres based on monitoring results in similar lithology.

A major contributor to low water clarity in the steep, upper reaches of the Waipa River is fine sediment from slips (landslides). In 1991 the Tunawaea slip deposited a large volume of sediment into the Tunawaea Stream. Environment Waikato and other stakeholders have stabilised the slip area but material that slipped into the river is likely to still be releasing fine sediment especially at mean flow and above. Over time, the effects of the Tunawaea slip are expected to decline, but this may take decades.

Colour (G440 and Munsell)

Measured dissolved colour (G440) does not vary significantly with flow or distance (Figures 1 and 2). The WCM predictions are close to the measurements. Note that there is no guideline value for dissolved colour. G440 makes a relatively small contribution to clarity in the Waipa River.

Munsell colour is not measured in the Waipa River and there are no data points to compare with WCM predictions. Munsell colour is a function of chlorophyll (CHL), G440 and FSS. There is a large step decrease in Munsell colour at 60 kilometres where the Mangapuu Stream joins the Waipa River (Figures 1 and 2). FSS and G440 are larger at mean flow than at base flow, resulting in Munsell colour being lower at mean flow. The WCM predicts that Munsell colour decreases (viz., colour becomes less blue and more brown) with distance from the headwaters.

Chlorophyll (CHL)

Phytoplankton chlorophyll (CHL) concentration is not routinely measured in the Waipa River although there are few measurements at the top site (Mangaookewa Road eight kilometres) – mean at base flow 6.3 milligrams per cubic metre (Figure 1). Phytoplankton numbers are low in the Waipa because the waters are turbid, their growth rates are low and water does not remain in the Waipa long enough for numbers to build up. The WCM has assumed that there is no growth of CHL in the Waipa and assigned it a constant concentration of five milligrams per cubic metre at both base and mean flow.

Nutrients (TP and TN)

The principal sources of phosphorus in the Waipa River are farm run-off, soil erosion and treated sewage. The principal source of nitrogen is leaching of nitrate from farmland.

Figure 1 shows that at base flow the measured total phosphorus (TP) and total nitrogen (TN) meet the targets (35 milligrams per cubic metre for TP, 500 milligrams per cubic metre for TN) in the upper part of the Waipa River (Mangaookewa Road eight kilometres, Otewa 43 kilometres, Otorohanga 60 kilometres). At the lower two sites (Pirongia-Ngutunui Bridge 95 kilometres, Whatawhata 127 kilometres), the guideline concentrations are exceeded. TP and TN concentrations increase significantly with flow – at mean flow the measured data only meet the guideline at the top site (eight kilometres) for TP (Figure 2) and at the top two sites (eight kilometres and 43 kilometres) for TN. The measured data at mean flow exceed the targets for the sites downstream (Figure 2) being over twice the guideline values in the lower part of the river.

At base flow the WCM predicts measured nutrient values well except at Mangaookewa Road in the headwaters (Figure 1). At mean flow, the WCM predicts the measured values well at all sites (Figure 2).

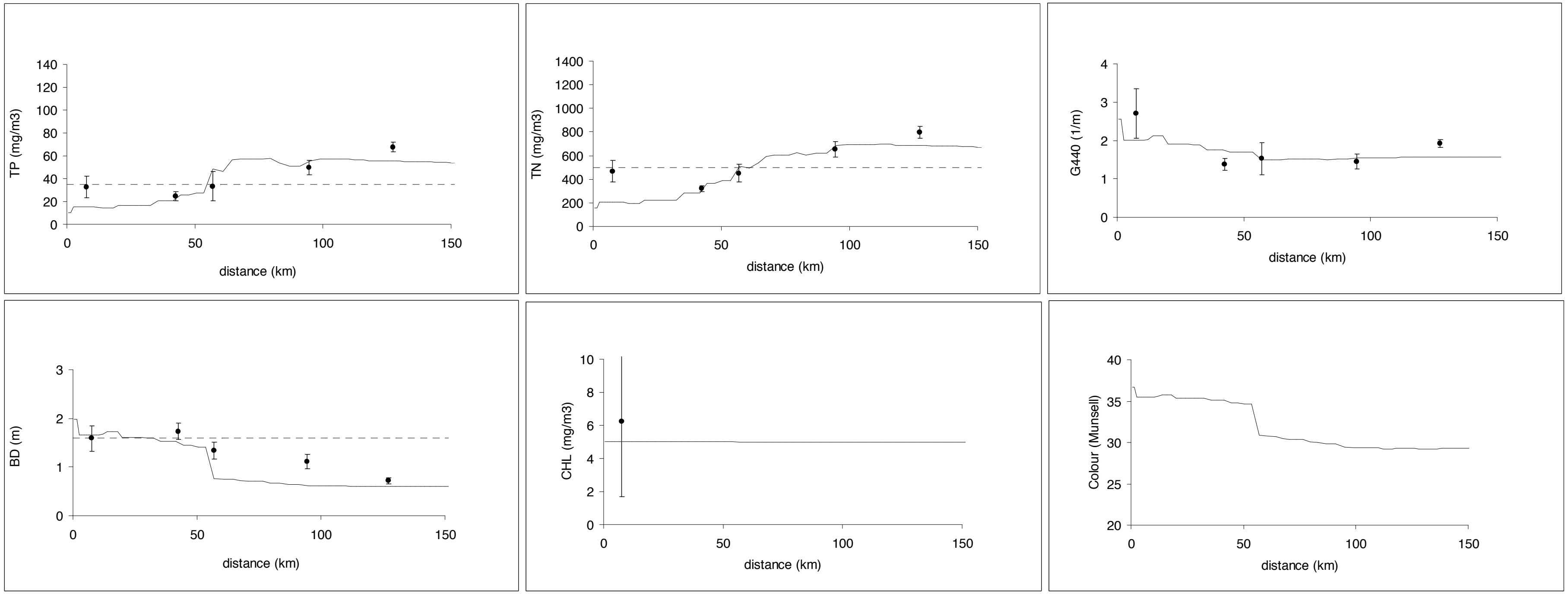

Figure 1: Current State (current farming practice and land use) of water quality at **base flow** in the **Waipa River** – variation with distance downstream of phosphorus (TP), nitrogen (TN), dissolved colour (G440), water clarity (BD), chlorophyll (CHL) and colour (Munsell). Black circles are observed data (mean ± 95 percent confidence interval) (Source: NIWA and EW monitoring). The dashed lines are targets (Table 1). The solid lines are predicted by the WCM model.

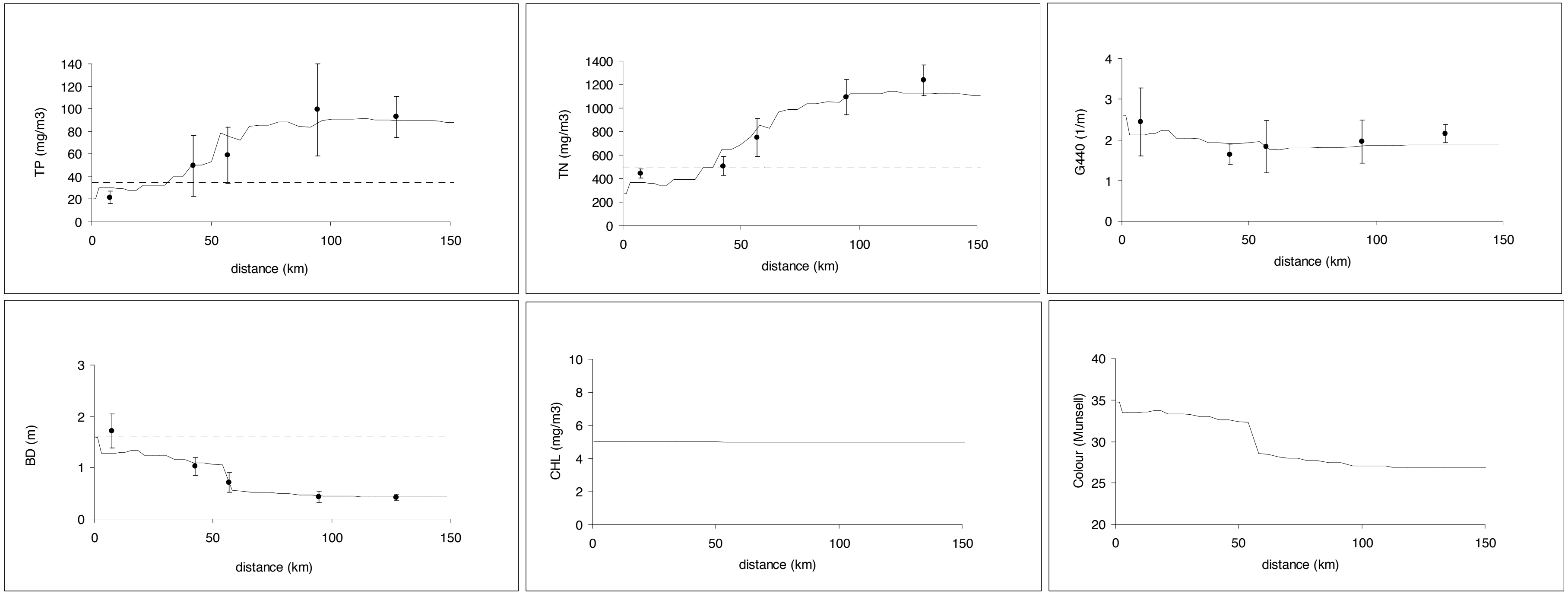

Figure 2: Current State (current farming practice and land use) of water quality at **mean flow** in the **Waipa River** – variation with distance downstream of phosphorus (TP), nitrogen (TN), dissolved colour (G440), water clarity (BD), chlorophyll (CHL) and colour (Munsell). Black circles are observed data (mean ± 95 percent confidence interval) (Source: NIWA and EW monitoring). The dashed lines are targets (Table 1). The solid lines are predicted by the WCM model.

2.2 Priority actions to restore the Waipa River

Major issues for water quality in the Waipa River are high suspended sediment and nutrient concentrations and low water clarity. Actions likely to improve water quality in the Waipa River are:

1. Reducing phosphorus content of point source discharges.
2. Changing farming practice to reduce the loss of fine sediment and nutrients to streams.
3. Retiring and reforesting pasture to reduce erosion.
4. Revegetating streambanks to reduce bank erosion.

2.2.1 Reducing point source discharges

One action suggested by the community is the further treatment (possibly including land disposal) of municipal sewage and industrial discharges. Point source waste discharges contribute to low clarity and high nutrient concentrations in some Waipa tributaries (notably in the Mangaookewa Stream at Te Kuuiti and the Mangapiko Stream at Te Awamutu). Figure 3 shows, however, that point source discharges have only a minor impact on TN, G440, BD, CHL and Munsell colour in the main stem of the Waipa River at base flow.

The point sources do, collectively, make a significant contribution to TP concentrations in the lower reaches of the Waipa. The same is true at mean flow (details omitted for brevity). Therefore phosphorus removal from waste discharges would reduce TP concentrations in the Waipa River. This is unlikely to benefit water clarity or chlorophyll concentrations in the Waipa River because phytoplankton appear not to grow to high concentrations in the swift and turbid waters of the Waipa. Reducing nutrient inputs is also unlikely to affect the abundance of aquatic weeds which is more strongly influenced by current, habitat and shading than by nutrient concentration in the Waipa River. A reduction of nutrient input will, however, has some benefits in the lower Waikato below its confluence with the Waipa River – as is discussed in the next Section.

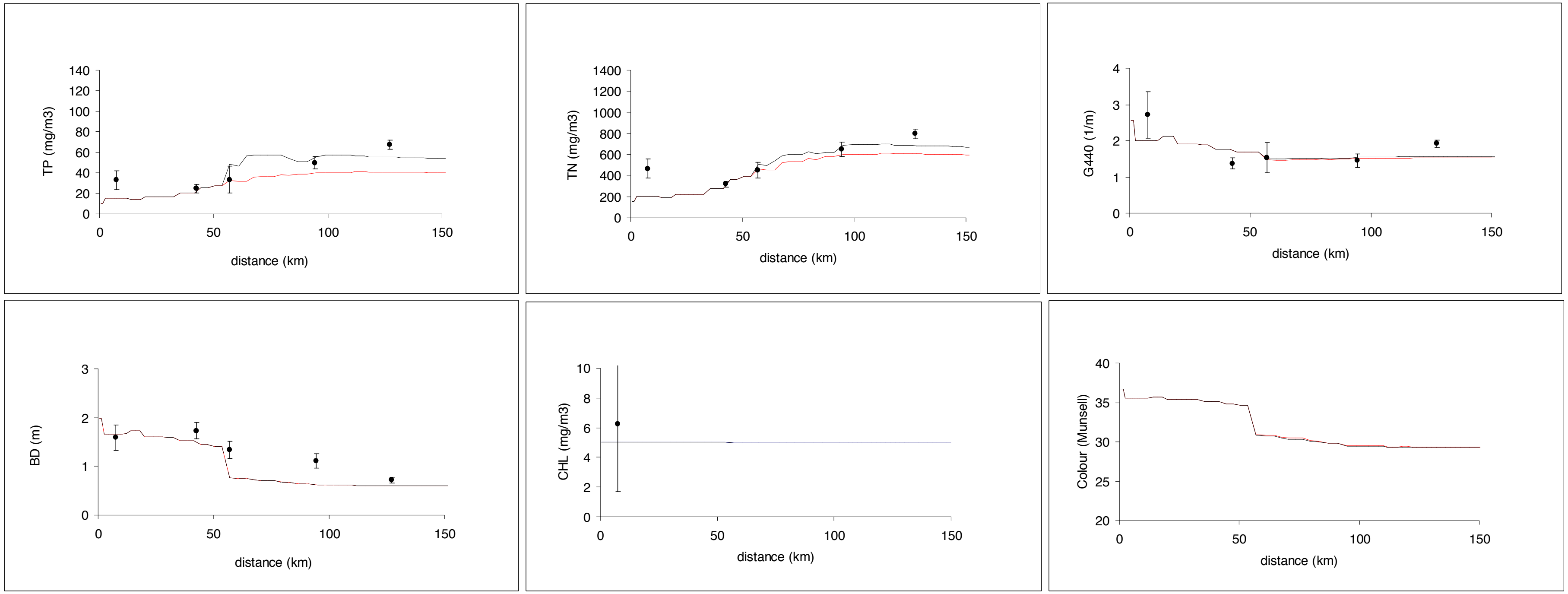

Figure 3: Predicted effects of point source discharges on the **Waipa River** water quality at **base** flow – predicted phosphorus (TP), nitrogen (TN), dissolved colour (G440), water clarity (BD), chlorophyll (CHL) and colour (Munsell) with (black line) and without (red line) the point source discharges. Black circles are observed data (mean ± 95 percent confidence interval) (Source: NIWA and EW monitoring).

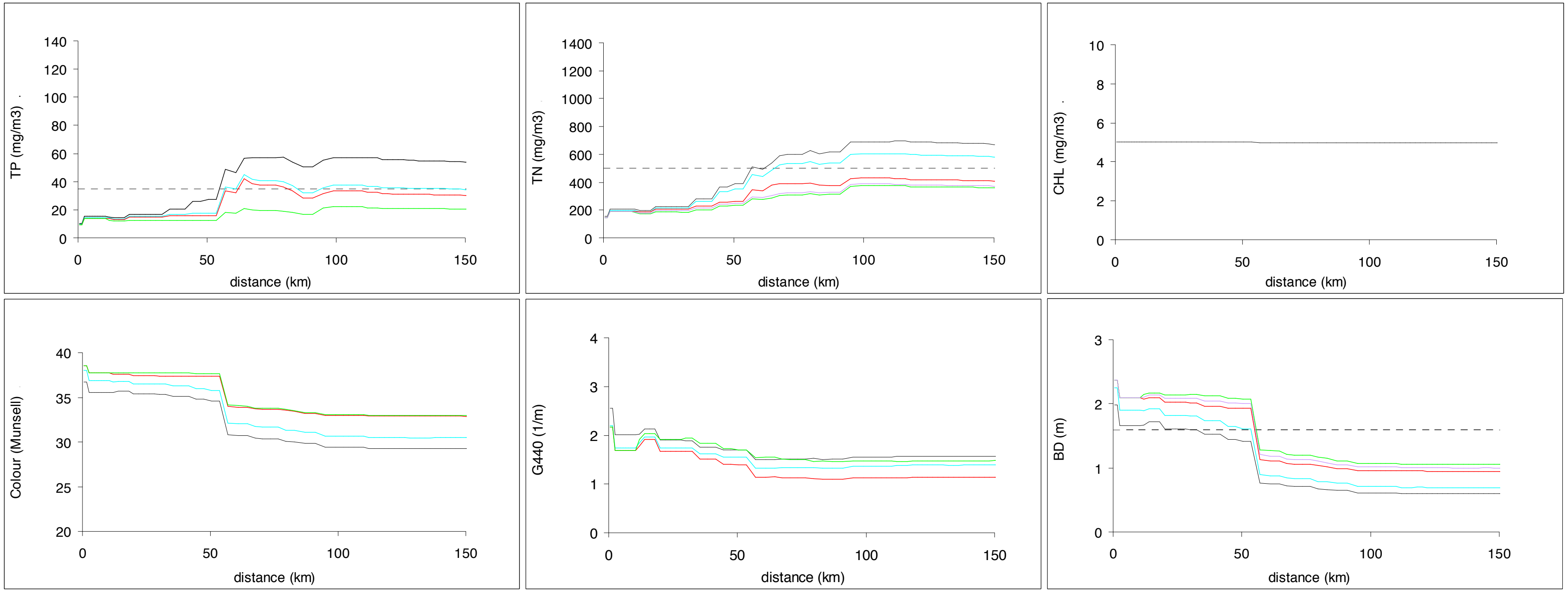

Figure 4: Predicted variation in **Waipa River** water quality with distance downstream at **base flow**: phosphorus (TP), nitrogen (TN), dissolved colour (G440), water clarity (BD), chlorophyll (CHL) and colour (Munsell) for the Current State (black line), Scenario 1 (blue line), Scenario 2 (red line) and Scenario 3 (green line). The dashed lines are targets (Table 1).

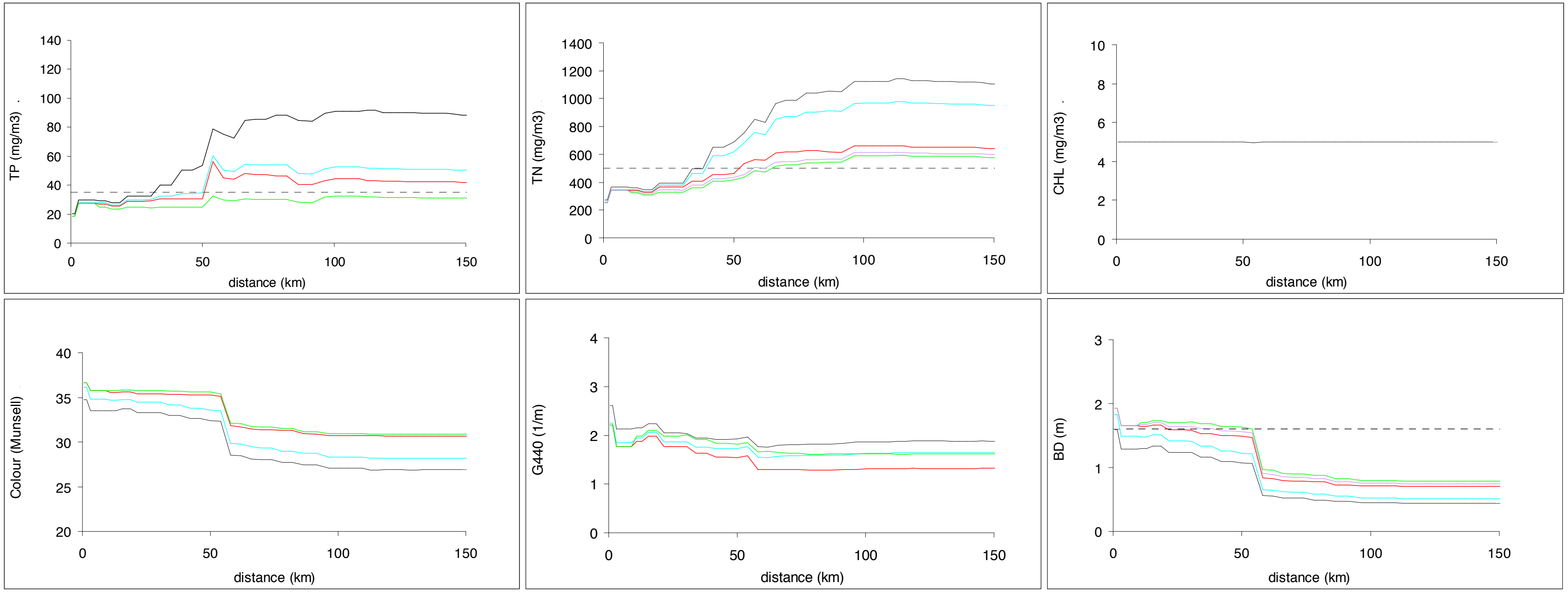

Figure 5: Predicted variation in the **Waipa River** water quality at **mean flow** with distance downstream: phosphorus (TP), nitrogen (TN), dissolved colour (G440), water clarity (BD), chlorophyll (CHL) and colour (Munsell) for the Current State (black line), Scenario 1 (blue line), Scenario 2 (red line) and Scenario 3 (green line). The dashed lines are targets (Table 1).

2.2.2 Changing farming practice and land use

Figures 4 and 5 compare WCM predictions for the Current State with the changes in farming practice and land use described earlier for Scenarios 1 – 3.

Water clarity (BD)

Because BD water clarity is a function of CHL, G440 and FSS (Section 5.3) and there are reductions in FSS and G440 from the Current State for Scenarios 1, 2 and 3 for all land uses (except native forest, scrub, and urban – see Table 2), there are improvements in water clarity along the entire length of the Waipa River at both base flow (Figure 4) and mean flow (Figure 5). Note that it is assumed there is no growth of CHL in the Waipa and that its concentration is 5 mg/m^3 at both base and mean flow.

For Scenario 1 the 1.6 metre clarity guideline is met everywhere upstream from where the Mangapuu Stream joins the Waipa (57 kilometres) at base flow. However, at mean flow the clarity guideline is only attained in the headwaters (Figure 5). Downstream from Mangapuu, BD remains below the 1.6 metre guideline at both base and mean flow (Figures 4 and 5).

For Scenario 2 there is more of an improvement in BD because of further reductions in FSS and G440 input for farmland (Tables 2 and 3). At both base flow and mean flow BD clarity is complies with the 1.6 metre guideline upstream from the Mangapuu (57 kilometres) (Figures 4 and 5). However, downstream from the Mangapuu, BD clarity remains below the 1.6 metre guideline at base and mean flow (Figures 4 and 5).

Scenario 3 includes all the changes in farming practice in Scenario 2 plus the retirement and reforestation of 60 percent of sheep-beef farming on steep hill country and 25 percent of sheep-beef farming on easy hill country. Figures 4 and 5 show that the actions of Scenario 3 result in further improvement in BD clarity. However, downstream from the Mangapuu BD clarity remains below the 1.6 metre guideline at both base and mean flow.

Colour (G440 and Munsell)

As with the Current State, dissolved colour (G440) does not vary significantly with flow across Scenarios 1–3 (Figures 4 and 5). The actions of Scenarios 1 and 3 produce similar, small reductions from the Current State at both base (Figure 4) and mean flow (Figure 5). Scenario 2 results in a larger reduction in G440 at both flows.

There is a small improvement in Munsell colour as a result of the actions of Scenario 1 (Figures 4 and 5). The actions of Scenario 2 result in a significant improvement in Munsell colour at both base and mean flow. Scenario 3 produces approximately the same reductions as Scenario 2 (Figures 4 and 5).

Nutrients (TP and TN)

At base flow, Scenario 1 results in significant decreases in TP concentrations such that compliance with the 35 milligrams per cubic metre guideline is achieved along the entire length of the Waipa River (Figure 4). At mean flow, Scenario 1 reduces TP concentrations, but the guideline is not achieved downstream from Otorohanga (60 kilometres) (Figure 5). Scenario 1 also results in reduced TN concentrations, but they are not as large as for TP. However, at base flow TN achieves the guideline (500 mg/m^3) upstream from Pirongia-Ngutunui Bridge (95 kilometres), and is only just above it downstream from Pirongia-Ngutunui Bridge (Figure 4). At mean flow TN remains non-compliant with the guideline downstream from Otewa (43 kilometres).

At base and mean flow, Scenarios 2 and 3 both result in further slight reductions in TP concentrations (Figure 4). The differences between Scenarios 1 and 2 and between Scenarios 2 and 3 are small compared to the differences between Current State and Scenario 1 (Figure 5). At mean flow Scenario 3 achieves compliance with the TP guideline (35 milligrams per cubic metre) everywhere except at Otorohanga (60 kilometres) where the TP concentration spikes to 50 milligrams per cubic metre (Figure 5).

The decrease in TN concentrations between Scenarios 1 and 2 is larger than that between Current State and Scenario 1 at both base and mean flows (Figures 4 and 5). At base flow, Scenario 2 achieves compliance with the TN guideline (500 milligrams per cubic metre) along the entire length of the Waipa River (Figure 4). At mean flow Scenario 2 achieves compliance upstream from Otorohanga (60 kilometres) and TN concentrations are much closer to the 500 milligrams per cubic metre guideline downstream from Otorohanga. The actions of Scenario 3 result in a further small reduction in TN at both flows – compliance remains as for Scenario 2.

3. Waikato River

3.1 Current state of Waikato River water quality

The current state of water quality along the main stem of the Waikato River, assessed from measurements and WCM predictions at base and mean flow, are shown in Figures 6 and 7 respectively.

Water clarity (BD)

Observed clarity is similar at base flow (Figure 6) and mean flow (Figure 7) – unlike the Waipa where clarity is significantly lower at mean flow than at base flow. Measured water clarity is high in water leaving Lake Taupoo, but decreases with distance downstream (Figures 6 and 7). Observed clarity currently exceeds the 4 metre guideline upstream from the hydro lakes but not in the hydro lakes themselves (50–190 kilometres). Downstream from the hydro lakes observed clarity is just below the 1.6 metre guideline, and downstream from the Waipa confluence (240 kilometres) is below one metre.

Rutherford et al., (2001) showed that water clarity in the hydro lakes and lower Waikato River is strongly influenced not only by fine suspended sediment (as in the Waipa River), but also by dissolved colour (yellow substance) and phytoplankton chlorophyll. The hydro lakes slow the Waikato River and allow sediment to settle out, thereby increasing water clarity. However, this is counteracted by a decrease in water clarity and a change in colour caused by phytoplankton spending enough time in the hydro lakes to grow and increase the phytoplankton chlorophyll concentration. The Kinleith mill (117 kilometres) discharges dissolved colour into Lake Maraetai and, even though colour inputs have been reduced by c. 50 percent since the early 1990s, this point source has a detectable effect on dissolved colour (G440), Munsell colour and clarity.

The BD values predicted by the WCM are close to the observed values along the entire length of the Waikato River at both base and mean flow (Figures 6 and 7).

Colour (G440 and Munsell)

Unlike the Waipa River, the observed dissolved colour (G440) increases with distance downstream at both base and mean flow (Figures 6 and 7). There is a step increase around the Kinleith mill discharge site (117 kilometres) and another step increase at the Waipa confluence (240 kilometres). WCM overestimates the increase in G440 at Kinleith and in the lower Waikato (Figures 6 and 7) but this has only a minor impact on predicted clarity and Munsell colour.

Similar to water clarity, measured Munsell colour decreases with distance downstream, with the highest values occurring in the headwaters (Figures 6 and 7). Colour changes significantly between Taupoo (Munsell 55 – blue), the lower hydro lakes (Munsell 40 – green-brown) and Te Puuaha (Munsell 35 – yellow-brown). There is little change in observed colour between mean and base flow. The guideline for colour is a change of no more than 10 Munsell (Ministry for the Environment, 1994)[1]. In this Study, the colour guideline is set to 10 Munsell units below the values that are predicted to have existed in the river in the 1920s prior to the hydro dams being built – these 1920 values are reported in Rutherford et al., (2001). The observed colour easily complies with this guideline throughout the length of the river at both base and mean flow (Figures 6 and 7). The predicted values are close to the observed.

Chlorophyll (CHL)

The measured phytoplankton chlorophyll concentration does not change much in the first 50 kilometres downstream from the river's source at Taupoo but then increases significantly in the hydro lakes (50–190 kilometres) at base flow (Figure 6) and mean

[1] Water Quality Guidelines No. 2. Guidelines for the management of water colour and clarity. June 1994. Ministry for the Environment. www.mfe.govt.nz/publications/water/water-quality-guidelines-2.pdf

flow (Figure 7). Near Taupoo the observed chlorophyll concentration complies with both the trigger (five milligrams per cubic metre) and warning (10 milligrams per cubic metre) guideline for cyanobacteria blooms at both flows. In the hydro lakes the warning guideline is met at both flows, but not the trigger guideline. At base flow measured CHL lies between the warning guideline of 10 milligrams per cubic metre and the filters guideline of 20 milligrams per cubic metre downstream from the hydro lakes (Figure 6) until Rangiriri (265 kilometres), after which the filters guideline is exceeded. At mean flow measured CHL lies between the warning and filters guidelines all the way to Te Puuaha (Figure 7). Measured CHL is higher at base flow than mean flow, because at base flow phytoplankton spend longer in the hydro lakes and lower Waikato and grow to higher concentrations.

The CHL values predicted by the WCM are close to the observed values at both base and mean flow (Figures 6 and 7). Predicted chlorophyll concentrations decrease near each of the hydro dams – this is particularly noticeable at base flow – because of settling in the tranquil and deep water. Predicted chlorophyll concentrations increase in the lower Waikato River where nutrient concentrations are high – especially at base flow when the residence time is high.

Nutrients (TP and TN)

Figures 6 and 7 show that observed TP concentrations comply with the guideline of 20 mg/m^3 in the upper Waikato but exceed it in the hydro lakes (50–190 kilometres) – more so at base than at mean flow. Measured TP continues to increase downstream from the hydro lakes at both flows with a large increase just downstream from Hamilton (219 kilometres) where there are three significant point source discharges – Hamilton City, Te Raapa dairy factory and Horotiu meatworks. There is an increase in the observed TP below the confluence of the Waikato and the Waipa (240 kilometres). This is because the TP concentration in the lower Waipa (70 ± 20 milligrams per cubic metre at base flow, Figure 1) is higher than that in the Waikato River at the Waipa confluence (50 ± 11 milligrams per cubic metre, Figure 6). Observed TP exceeds the 35 milligrams per cubic metre guideline for the reaches below the hydro lakes (more than 190 kilometres) at both base flow and mean flow (Figures 6 and 7).

Measured TN concentrations increase steadily downstream from Taupoo until Hamilton (219 kilometres) at both base flow and mean flow (Figures 6 and 7). Just downstream from Hamilton there is a large increase in TN concentration associated with point source discharges from Hamilton City, Te Raapa dairy factory and Horotiu meatworks (Figures 6 and 7). There is also a large increase in observed TN concentrations below the confluence of the Waikato and Waipa Rivers (240 kilometres) which occurs because the concentration of TN at the mouth of the Waipa (800 ± 220 milligrams per cubic metre at base flow, Figure 1) is higher than that in the Waikato River at the Waipa confluence (400 ± 80 milligrams per cubic metre, Figure 6). At base flow, observed TN concentrations are below the 300 milligrams per cubic metre guideline in the hydro lakes, and below the 500 milligrams per cubic metre guideline for the entire length of the Waikato River (Figure 6). At mean flow observed TN concentrations are below the 300 milligrams per cubic metre guideline in the hydro lakes, but exceed the 500 milligrams per cubic metre downstream from the Waipa confluence (Figure 7).

The WCM's predictions of TP and TN concentration are good at mean flow but slightly over estimate concentrations in the lower Waikato at base flow (Figures 6 and 7).

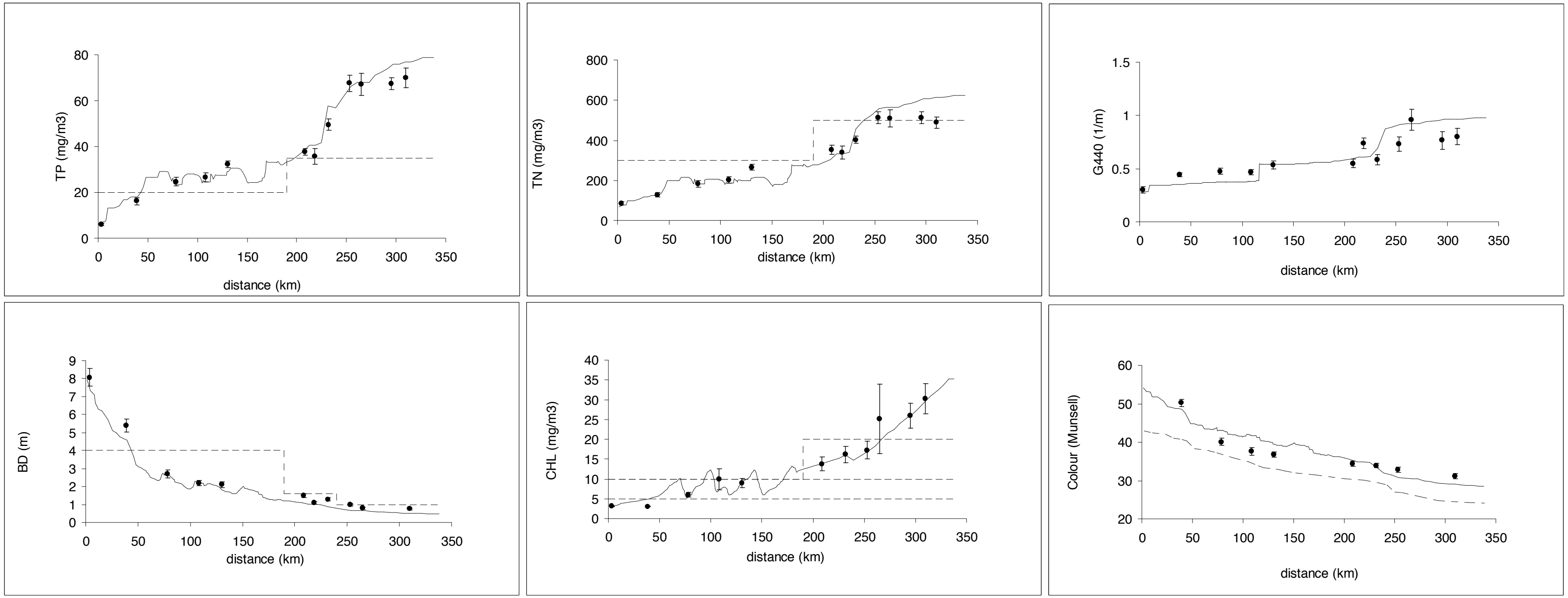

Figure 6: Current State (current farming practice and land use) of water quality in the Waikato River at **base flow** showing variation with distance downstream of phosphorus (TP), nitrogen (TN), dissolved colour (G440), water clarity (BD), chlorophyll (CHL) and colour (Munsell). Black circles are observed data (mean ± 95percent confidence interval) (Source: NIWA and EW monitoring). The dashed lines are targets (Table 1). The solid lines are predicted by the WCM model.

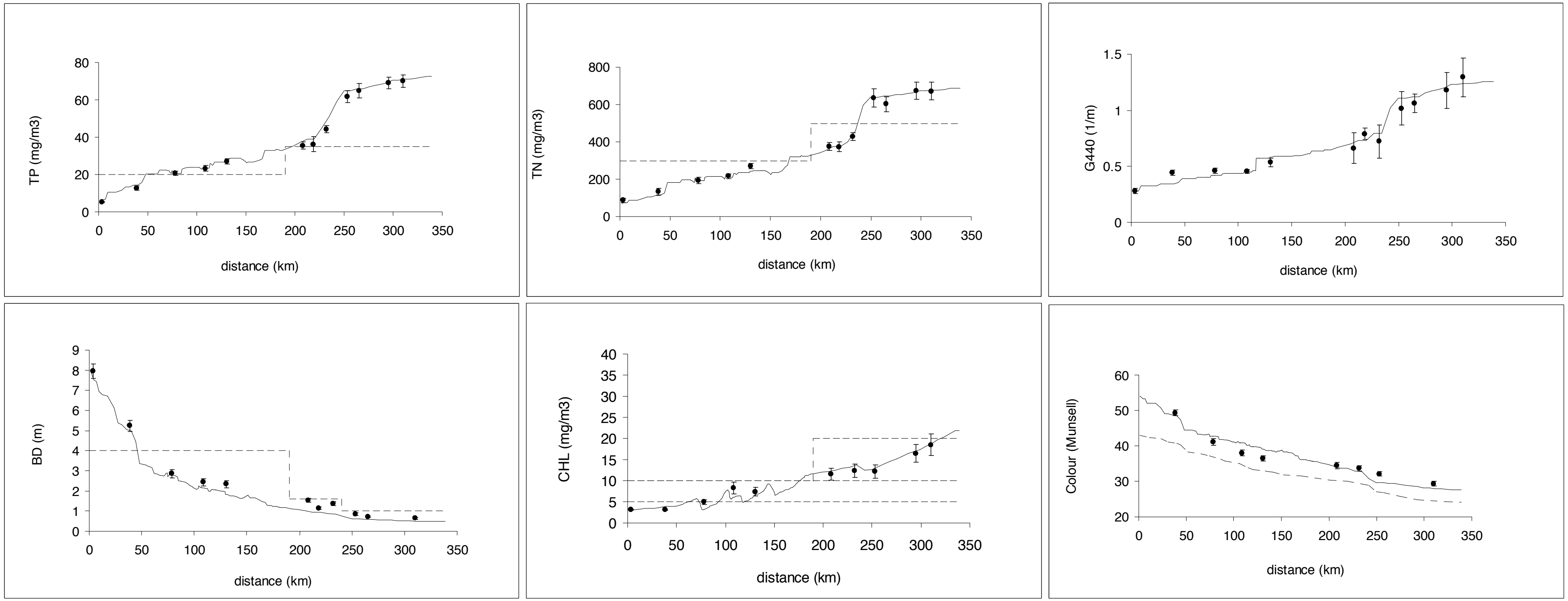

Figure 7: Current State (current farming practice and land use) of water quality in the Waikato River at **mean flow** – variation with distance downstream of phosphorus (TP), nitrogen (TN), dissolved colour (G440), water clarity (BD), chlorophyll (CHL) and colour (Munsell). . Black circles are observed data (mean ± 95 percent confidence interval) (Source: NIWA and EW monitoring). The dashed lines are targets (Table 1). The solid lines are predicted by the WCM model.

3.2 Priority actions to restore Waikato River water quality

Actions to improve water quality in the Waikato River include:

1. Further treatment of point source waste discharges.
2. Changing farming practice.
3. Retiring and reforesting erodible pasture.

3.3 Reducing point source waste discharges

There are 23 major point source discharges of waste along the length of the Waikato River (cf. 6 in the Waipa River) (Table 6). One action suggested by the community is the further treatment (possibly including land disposal) of municipal sewage and industrial discharges. Point source waste discharges contribute to low clarity and high nutrient concentrations in some Waikato tributaries. Figure 8 shows, however, that these point source discharges have only a minor impact on clarity and Munsell colour in the main stem of the Waikato River.

Point source discharges do not impact significantly on dissolved colour (G440) except for the Kinleith mill (117 kilometres) which has a high G440 concentration.

Therefore, further treatment of waste discharges to reduce sediment and nutrient inputs is not likely to have significant beneficial effects for water quality in the Waikato River, with the possible exception of phosphorus (see below). Note, however, that the further treatment (notably land disposal) of sewage may have benefits in terms of reducing public health risk and will help meet Maaori aspirations for zero discharge of human waste to waterways.

Discharges have a minor impact on TP and TN in the upper Waikato, but below Hamilton (228–232 kilometres) discharges from Hamilton City, Te Raapa dairy factory and the Horotiu meatworks cause an increase in TP and TN concentration. The point source discharges of nutrients contribute to the high CHL concentrations below Horotiu (232 kilometres) especially at base flow, and at the mouth the point sources are responsible for 20 percent of the base flow CHL concentration.

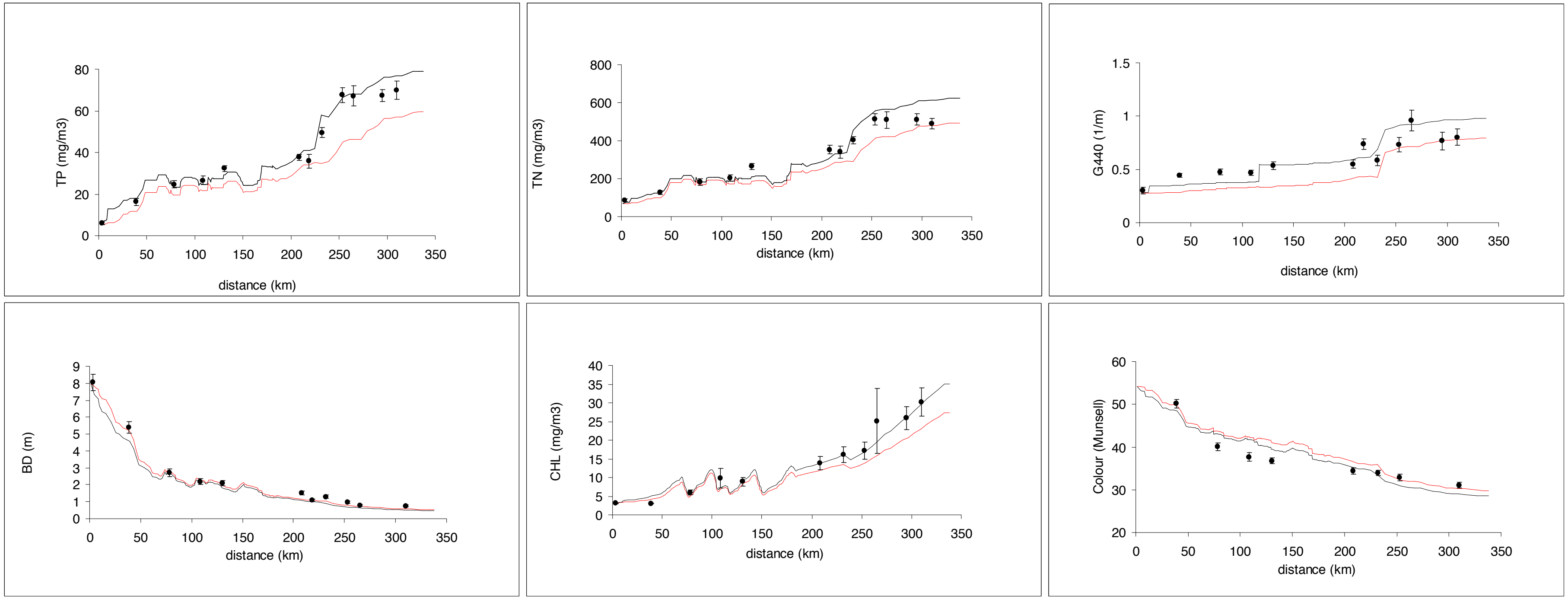

Figure 8: Effects of point source discharges on the Waikato River water quality at **base** flow – predicted phosphorus (TP), nitrogen (TN), dissolved colour (G440), water clarity (BD), chlorophyll (CHL) and colour (Munsell) with (black line) and without (red line) the point source discharges. Black circles are observed data (mean ± 95percent confidence interval) (Source: NIWA and EW monitoring).

3.4 Changing farming practice and land use

Figures 9 and 10 compare the WCM predictions for the Current State with the farming practice and land use changes in Scenarios 1–3 (described earlier) at base and mean flow respectively.

Water clarity (BD)

The actions of all three scenarios result in improvement to BD water clarity at base flow (Figure 9) and mean flow (Figure 10). Scenarios 2 and 3 result in BD complying with the 1.6 metre guideline immediately below the hydro lakes (190–230 kilometres). However, downstream from the Waipa confluence (240 kilometres) water clarity is still less than one metre at both base flow and mean flow (Figures 9 and 10). At base flow (Figure 9) BD is below the four metre guideline in all the hydro lakes. However at mean flow, the four metre guideline is met in the upper hydro lakes as well as in the headwaters, but not in the lower hydro lakes or further downstream (Figure 10).

Colour (G440 and Munsell)

Dissolved colour (G440) is predicted to decrease significantly downstream from the Waipa confluence (240 kilometres) for Scenarios 2 and 3 at both flows (Figures 9 and 10). None of the scenarios includes additional colour removal at Kinleith (120 kilometres) where there is a step increase in G440.

Munsell colour improves for Scenarios 2 and 3 as a result of lower G440, FSS and CHL (Munsell colour is a function of G440, FSS and CHL). Predicted Munsell colour is well above the guideline (Figures 9 and 10) although the water remains yellow-brown in the lower Waikato.

Chlorophyll (CHL)

At base flow, Scenarios 2 and 3 achieve significant reductions in CHL (Figure 9) – the filters guideline of 20 milligrams per cubic metre is met almost everywhere in the Waikato River. The warning guideline of 10 milligrams per cubic metre is met above the Waipa confluence (240 kilometres) – which means that if a cyanobacteria bloom occurs it is unlikely to pose a health risk to humans or animals except perhaps in the lower Waikato River (Huntly-Tuakau). At mean flow the warning guideline of 10 mg/m^3 is met upstream from the Waipa confluence, and the filters guideline of 20 mg/m^3 continues to be met everywhere.

Nutrients (TP and TN)

The actions of Scenario 1 significantly reduce predicted TP concentrations at base flow (Figure 9) and mean flow (Figure 10). At both flows TP complies with 35 milligrams per cubic metre guideline upstream from Hamilton (220 kilometres) and TP nearly complies with the 20 milligrams per cubic metre guideline in the hydro lakes (50–190 kilometres). Scenarios 2 and 3 result in further reductions in TP concentration at both base flow and mean flow, but compliance remains as for Scenario 1.

There is a slight reduction in predicted TN concentrations under Scenario 1 at base flow (Figure 9) and mean flow (Figure 10). This results in the predicted TN at base flow meeting the 500 mg/m3 guideline everywhere upstream from Rangiriri (265 kilometres) (Figure 9). At mean flow predicted TN concentrations exceed the 500 milligrams per cubic metre guideline below the Waipa confluence (240 kilometres) (Figure 10). There is a significant improvement in predicted TN between Scenarios 1 and 2 at both flows (Figures 9 and 10). This means that the TN targets are met for the entire length of the Waikato River at both base flow and mean flow. The actions of Scenario 3 produce similar results to Scenario 2 (Figures 9 and 10).

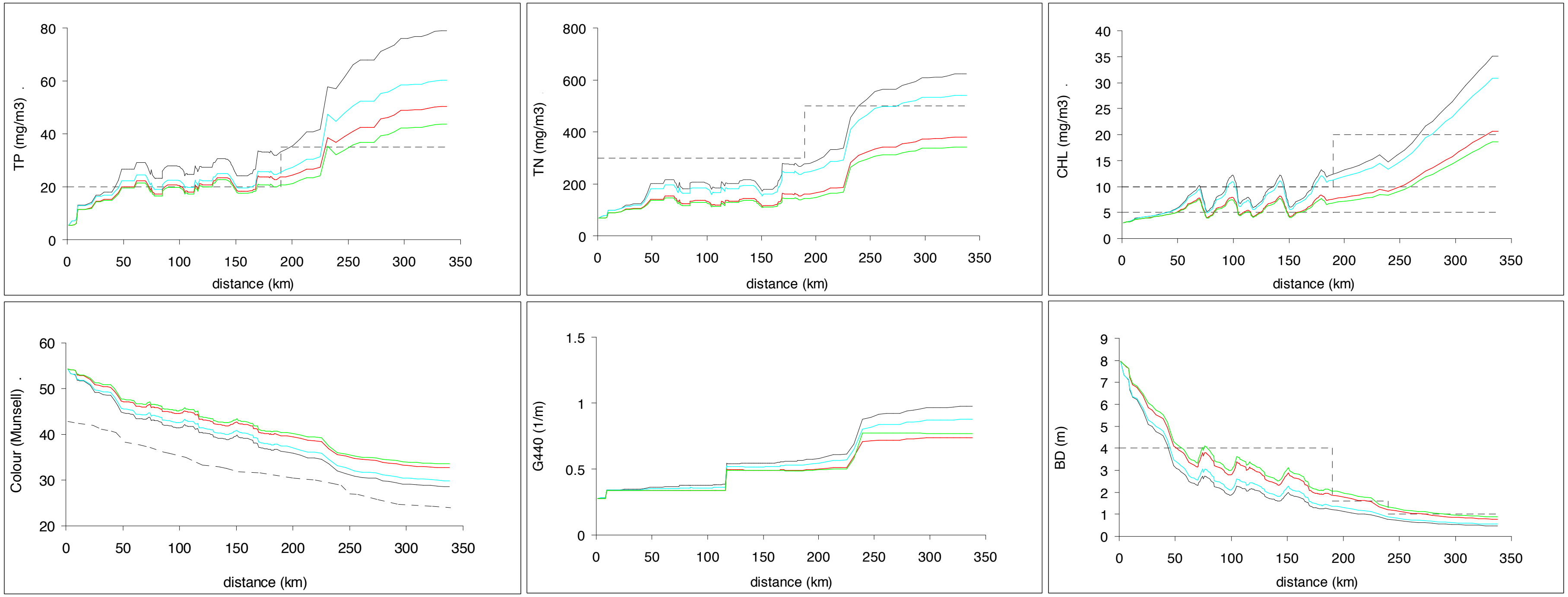

Figure 9: Variation in Waikato River water quality with distance downstream at **base flow** predicted by the WCM : phosphorus (TP), nitrogen (TN), dissolved colour (G440), water clarity (BD), chlorophyll (CHL) and colour (Munsell) for the Current State (black line), Scenario 1 (blue line), Scenario 2 (red line) and Scenario 3 (green line). The dashed lines are targets (Table 1).

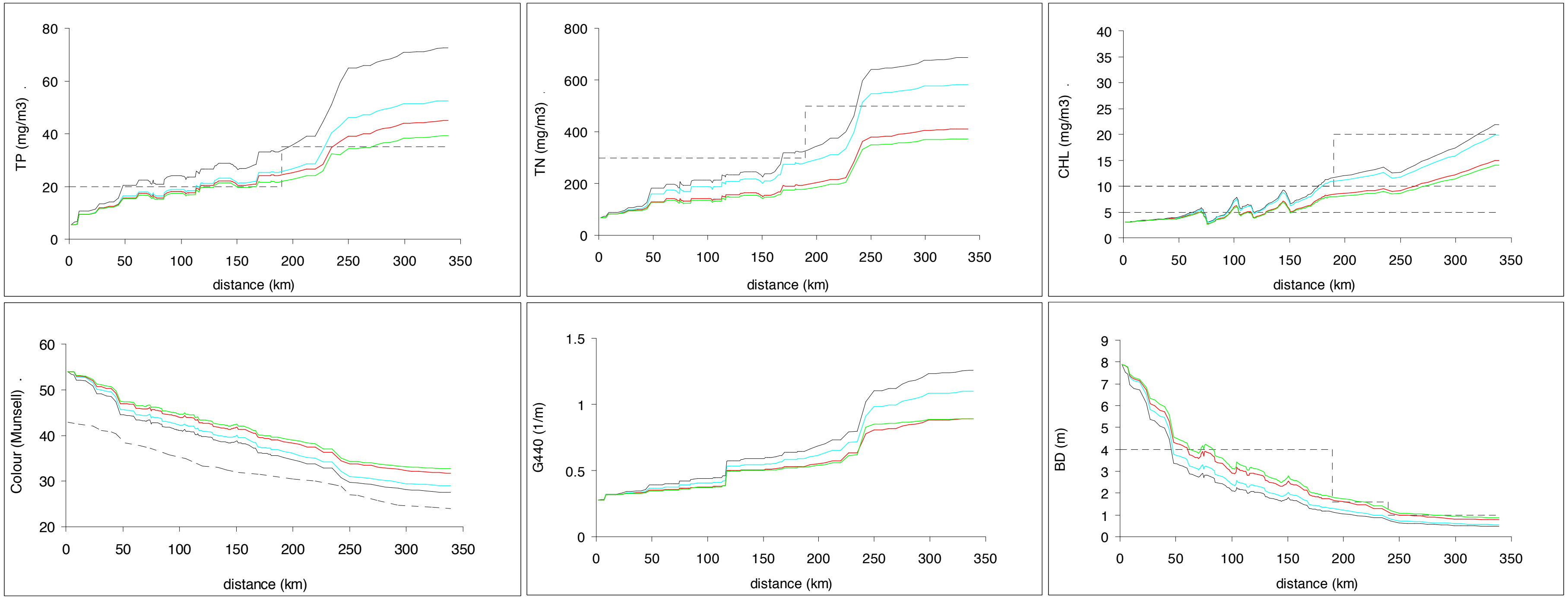

Figure 10: Variation in water quality at **mean flow** in the Waikato River with distance downstream as predicted by the WCM: phosphorus (TP), nitrogen (TN), dissolved colour (G440), water clarity (BD), chlorophyll (CHL) and colour (Munsell) for the Current State (black line), Scenario 1 (blue line), Scenario 2 (red line) and Scenario 3 (green line). The dashed lines are targets (Table 1).

4. Other priority actions to improve water quality

4.1 Revegetating streambanks

The contribution made by streambank erosion to suspended sediment loads and water clarity in streams has not yet been measured in the Waipa or Waikato catchments, although studies are underway that will help to quantify streambank erosion. There is evidence from NIWA and Environment Waikato studies in the Waikato basin that streambanks covered with pasture grasses are more likely to be actively eroding than streambanks covered with woody vegetation (Kotze et al., 2008). This is consistent with overseas studies which show that woody vegetation is more deeply rooted and protects streambanks from the effects of the current (Abernathy and Rutherfurd, 2000). Suspended sediment loads have been measured at a small number of sites in the Waikato, and water clarity has been monitored at a larger number of sites. This Study re-analysed that data but found there was no reliable way to separate the effects of streambank erosion from other sources of sediment.

Two studies in the Waikato have measured suspended sediment loads, turbidity and water clarity before and after streambank revegetation and other catchment restoration. McKerchar and Hicks (2001) found that fencing streams and planting erosion-prone areas in the Waitomo catchment reduced suspended sediment loads at a given flow by about 40 percent. They focused on high flow events which delivered the majority of suspended sediment and they did not quantify changes in water clarity. Dr Deborah Ballantine performed a trend analysis on turbidity measurements in the Waitomo Stream (Dr Deborah Ballantine, NIWA, pers. comm.) and found that there had been no significant change over time. This suggests that although riparian restoration had reduced the supply of coarse sediment, it had not reduced the supply of fine sediment – which is the main contributor to turbidity and low water clarity. Dr Ballantine did not examine changes in turbidity at base flow which is when the majority of contact recreation occurs. Quinn et al., (2009) found that stream fencing to exclude cattle and replanting the riparian zone with poplars has resulted in a significant increase in water clarity (roughly a doubling) in the stream PW3 at the Whatawhata study site in the Waipa catchment. However, in the adjacent PW2 catchment, retirement and reforestation with pine trees has not resulted in any significant change in water clarity for reasons that are not fully understood but may include channel widening and the disappearance of small riparian wetlands.

Elsewhere in New Zealand, studies have shown that suspended sediment yields from pasture catchments are significantly higher than yields from forest catchments. Fahey (2003) reports that in the Hawke's Bay pasture yields is two to three times forest yields. Hicks (1988, 1990) analysed data from paired catchment studies at several locations around New Zealand and concluded that for a given rainstorm pasture yield is six to eight times exotic forest yield. Thus, the retirement and reforestation of pasture is likely to reduce sediment loads in streams significantly. Note, however, that Fahey (2003) and Hicks (1988, 1990) quantified the change in mean annual yield of suspended sediment which is dominated by loads during storms, whereas the principal concern for contact recreation is with turbidity and water clarity at base flow. There are good reasons for believing that reducing the annual suspended sediment yield will have benefits in terms of increased base flow water clarity. However, those benefits have not been quantified and may not be as large as the two to three and six to eight fold differences cited above.

4.2 Input reductions

The WCM model estimates the yields of fine sediment and dissolved colour from different land uses from monitoring data gathered in the catchment. For Scenarios 1, 2 and 3 the WCM model reduces these yields by the amounts shown in Tables 2 and 3. These reductions have been estimated from the results of detailed studies in a number of farming catchments throughout New Zealand (Dr Ross Monaghan, AgResearch, pers. comm.). It is important to note that these reductions relate to what leaves the farm. They do not include the reductions in bank erosion that are likely to occur when streambanks are retired and replanted with woody vegetation. The effects of replanting and increasing the strength of streambanks are not modelled in the WCM predictions described earlier. Consequently, additional benefits beyond those predicted for water clarity are likely if streambank erosion can be decreased below that in typical pasture streams by revegetating the streambanks.

At the stakeholders' workshop held on 16th February 2010, anecdotal evidence was presented suggesting that the current low clarity in the Waipa near Otorohanga was the result of injudicious willow removal that had damaged the riverbanks and left them susceptible to erosion. If this is the case then revegetation of the riverbanks should be a priority action. There is clear evidence of active bank erosion in several Waikato tributaries. Erosion occurs in places along straight parts of the channel through undercutting and bank slumping. Revegetating straighter parts of the channel is likely to reduce undercutting and bank slumping. Erosion also occurs on the outside of bends where the current 'attacks' the bank. Efforts to reduce bank erosion in such hot spots including re-vegetation and the placement of protection (e.g., logs or rock) may have benefits, but it may simply move the erosion hot spot further downstream.

In conclusion, revegetation of streambanks with woody vegetation (trees and shrubs) in the Waipa and Waikato catchments will almost certainly have benefits in terms of reduced bank erosion, with ongoing benefits to water clarity. Currently, however, it is not possible to quantify accurately what the benefits will be. The modelling described in this Section does not include the effects that riparian revegetation is expected to have on reducing sediment inputs, and consequently predictions are conservative (viz., under-estimate the likely benefits).

4.3 Legacy sediment

As discussed earlier, material deposited into the Waipa River by the Tunawaea slip in 1991 is thought to be contributing to degraded water clarity. The same may also be true for material deposited elsewhere in the river by major erosion events that have occurred periodically since land clearance commenced. If this is the case, and if remedial actions reduce the supply of new fine sediment into the river, then over time the effects of legacy sediment in the river channel should decline. There is not enough information available to make a reliable estimate of how long this might take, or the contribution legacy sediment is making to current water clarity. Work in East Cape, the Motueka catchment and in Glenbervie Forest (Northland) suggests that the effect of large erosion events decays exponentially over a period of several years (Hicks and Harmsworth, 1989; Hicks and Basher, 2008).

4.4 Land disposal

Land disposal of municipal effluent is listed as one of the priority actions in Section 8 in the main Report. The primary benefits of land disposal are cultural health with co-benefits being reduced human health risk and improved water quality. However, the WCM modelling above shows that, with the exception of phosphorus in Hamilton sewage, the co-benefits of land disposal in terms of reduced nutrient and phytoplankton concentrations, increased water clarity and improved colour are minor.

5. Summary of input data for the WCM model

5.1 Scenarios

Table 4: Scenarios from Monaghan (2010).

	Dairy	Sheep-beef	Forestry (planted forest)	Horticulture
Current State	**Present situation**			
Scenario 1 – Current Best Practice	Full stock exclusion from streams using single-wire fencing. Soil Olsen P levels reduced from 38 to 32 (economic optimum). Effluent areas enlarged appropriate to effluent K (potassium) and N loading rates. Additional 1 month's effluent pond storage; low application depth.	Exclusion of cattle from streams using single-wire electric fencing and provision of stock troughs and water supply.	10 m stream buffer for blocks > 50 ha. 5 m stream buffer for blocks 20 – 50 ha.	Reduced fertiliser inputs. Sediment control measures.
Scenario 2 – Changing farm practice	All Scenario 1 actions adopted. Use of nitrification inhibitors (5% pasture production response assumed). Wetlands installed on 1% of farm area (fencing out of seeps and bogs). Berms on sections of lanes to direct runoff away from	As per Scenario 1. Wetlands installed on 1% of farm area (fencing out of seeps and bogs). Poplar plantings (with sleeves) at 10 m spacings on each side of streams.	As per Scenario 1.	As per Scenario 1.

Table 4: (cont.)

	Dairy	Sheep-beef	Forestry (planted forest)	Horticulture
Current State	**Present situation**			
	streams. 5 m buffer on each side of streams, planted with natives. Existing fences relocated to protect the natives. Farm inputs of purchased feed and fertiliser N reduced to nil.			
Scenario 3	All Scenario 2 actions adopted.	15 m fenced and planted buffers on all streams. 60% of steep sheep-beef farms retired and planted in pines 25% of easy sheep-beef farms retired and planted in pines.	As per scenario 1. 60% of steep sheep-beef farms retired and planted in pines 25% of easy sheep-beef farms retired and planted in pines.	As per scenario 1.

5.2 Point sources

Table 5: Point source discharges of TP (total phosphorus), TN (total nitrogen), SS (suspended sediment), G440 (dissolved colour), CHL (chlorophyll), and FSS (fine suspended sediment) into the Waipa River. The bold values are from AEE (Assessment of Environmental Effects) documents and the rest from Environment Waikato consents

	Km from source	Average dry weather flow (m³/d)	TP			TN			SS		G440 (1/m)	CHL (mg/m³)	FSS (1/m)
			Load (kg/d)	Concentration (mg/m³)	% of pt source load	Load (kg/d)	Concentration (mg/m³)	% of Pt source load	Load (kg/d)	Concentration (mg/m³)			
Te Kuuiti sewage*	55	**4,200**	**34**	**8,000**	**43.6**	**92**	**22,000**	**25.5**	**55**	**13,000**	15	0	20
Otorohanga sewage	65	600	12	20,000	**15.4**	50	83,333	**13.9**	55	91,667	15	0	20
Te Awamutu Dairy factory	94	5,128	14	2,691	**17.9**	154	30,031	**42.7**	154	30,000	15	0	20
Te Awamutu sewage	96	600	12	20,000	**15.4**	50	83,333	**13.9**	55	91,667	15	0	20
Roto-o-Rangi Piggery	97	330	1	3,939	**1.3**	7	19,697	**1.9**	10	30,000	15	0	20
Templeview	100	**750**	5	6,000	**6.4**	**8**	**10,000**	**2.2**	**23**	**30,000**	15	0	20

* Consents currently under application. Actual discharge limits may differ from those tabulated.

Table 6: Point source discharges of TP (total phosphorus), TN (total nitrogen), SS (suspended sediment), G440 (dissolved colour), CHL (chlorophyll), and FSS (fine suspended sediment) into the Waikato River. The flow, TP load, TN load, SS load and G440 values for Kinleith are measured; the bold values are from AEE documents, and the rest are from EW consents. Figures in italics are discharged to land.

	Km from Taupoo	Average dry weather flow (m^3/d)	TP			TN			SS		G440 (1/m)	CHL (mg/m^3)	FSS (g/m^3)
			Load (kg/d)	Concentration (mg/m^3)	% of pt source load	Load (kg/d)	Concentration (mg/m^3)	% of pt source load	Load (kg/d)	Concentration (mg/m^3)			
Taupoo sewage	*4*	*8,640*	*12*	*1,389*	*2.6*	*60*	*6,944*	*2*	*259*	*30,000*	*5*	*5*	*30*
Timber Mill	*8*	*ND*	*0*	*0*	*0.0*	*0*	*0*	*0.0*	*0*	*0*	*5*	*0*	*0*
Prawn Farm Wairaakei	8	864	4	4,051	0.9	4	4,051	0.1	26	30,000	5	0	0
Wairaakei Power Station	10	95,040	36	378	8.1	131	1,373	4.5	0	0	5	0	0
Oohaakii Power Station	48	86	0	0	0.0	0	0	0.0	0	0	5	0	0
Reporoa Dairy factory	*48*	*0*	*0*	*0*	*0.0*	*0*	*0*	*0.0*	*0*	*0*	*5*	*0*	*10*
Kinleith pulp mill	117	87,600	52	594	11.8	431	4,920	14.9	5,900	67,352	**40**	0	10
Litchfield Dairy factory	*167*	*2,200*	*4*	*1,773*	*0.9*	*115*	*52,273*	*4.0*	*22*	*10,000*	*5*	*0*	*10*
Tokoroa sewage	168	**4,000**	38	9,500	8.6	**160**	**40,000**	5.5	**48**	**12,000**	5	5	30
Cambridge sewage	*196*	*2,000*	*11*	*5,600*	*2.4*	*20*	*9,850*	*0.7*	*60*	*30,000*	*5*	*5*	*30*
Hautapu Dairy factory	*214*	*2,200*	*4*	*1,773*	*0.9*	*115*	*52,273*	*4.0*	*22*	*10,000*	*5*	*0*	*10*
Hamilton sewage (summer)	228	**224,000**	**100**	446	22.6	**450**	2,009	15.5	**700**	**15,000**	5	5	30

Table 6: (cont.)

	Km from Taupoo	Average dry weather flow (m^3/d)	TP			TN			SS		G440 (1/m)	CHL (mg/m^3)	FSS (g/m^3)
			Load (kg/d)	Concentration (mg/m^3)	% of pt source load	Load (kg/d)	Concentration (mg/m^3)	% of pt source load	Load (kg/d)	Concentration (mg/m^3)			
Te Raapa Dairy factory	232	10,000	25	2,500	5.7	400	40,000	13.8	100	10,000	5	0	10
AFFCo Horotiu	233	**4,838**	100	20,670	22.6	800	165,358	27.6	**97**	**20,000**	5	0	10
Ngaaruawaahia sewage* (summer)	245	**2,000**	**16**	**8,000**	3.6	**50**	20,000	1.7	**60**	**30,000**	5	5	30
Huntly Power Station	258	0	0	0		0	0		0	0	5	0	0
Huntly Sewage* (summer)	262	**1,500**	**12**	**8,000**	0.0	**38**	**17,600**	0.0	**45**	**30,000**	5	5	30
Johnson Piggery	292	104	4	40,385	**5.7**	21	200,000	**1.3**	3	30,000	5	0	50
PIC Maramarua Piggery	294	88	4	39,773		18	198,864		3	30,000	5	0	50
Tuakau Sewage	314	4,500	18	3,978	0.9	33	7,400	0.7	62	13,778	5	5	30
Waikato By-Products	316	**1,000**	10	10,000	0.9	**100**	100,000	0.6	**62**	62,000	5	0	5
Te Kauwhata sewage*	275	**1,100**	**3**	**2,800**	4.1	**9**	**8,000**	1.1	**17**	**15,000**	5	5	30
Meremere sewage	292	**160**	**1**	**5,400**	2.3	4	25,000	3.4	**8**	**48,000**	5	5	30

* Consents currently under application. Actual limits once consent granted may differ from those tabulated.

5.3 The catchment water quality model

Background

The Waikato Catchment Model (WCM, Rutherford et al., 2001) was originally developed under contract to Mighty River Power in connection with consents for the hydro dams. It has subsequently been used by Environment Waikato to examine the effects of land use change and to model blue-green algal blooms. The model has several unique features, including its ability to model not only nutrients and suspended sediment but also phytoplankton growth, water clarity and colour. The model assumes steady flow but can be run at a number of different flow regimes. It divides the river into segments c. 100–200 metres long and predicts the changes in concentration that occur from Taupoo (headwaters) to Te Puuaha (near the mouth). For this study, the WCM was modified so that it also models changes along the Waipa River from its headwaters to Ngaaruawaahia (confluence with the Waikato River) and the effects that the Waipa has on the lower Waikato River. Other tributaries are not modelled in detail but their inputs into the Waikato or Waipa are estimated using information about landuse and point source discharges in their sub-catchment.

The river is sub-divided into a number of segments each of which is assumed to be well mixed vertically, transversely and longitudinally. The number of segments varies depending on the flow and the specified time step and is calculated within the model. Where the channel is riverine, segments are long, narrow, shallow and the velocity is swift. In the hydro lakes, segments are short, wide, deep and the velocity is slow. Longitudinal dispersion is neglected.

The river water quality sub-model calculates the concentration profiles along the Waikato and Waipa River systems of total phosphorus (TP), total nitrogen (TN), phytoplankton chlorophyll (CHL), fine inorganic suspensoids (FSS), suspended sediment (SS), dissolved colour (G440), black disc clarity (BD) and colour (Munsell). Flow is assumed steady, the phytoplankton growth equations are averaged over 24 hours, and steady-state solutions are sought.

Mass balance equations are used to predict the concentration of total phosphorus and total nitrogen in each segment. Both TP and TN are both assumed to be biologically inactive, with settling the only removal process. The inflow or initial concentration is set equal to the average concentration measured in the outflow from Lake Taupoo. The model determines whether nitrogen or phosphorus limits maximum phytoplankton biomass in the hydro lakes and river based on published information on the nitrogen:phosphorus ratio in phytoplankton.

Assuming a linear relationship between G440 (light absorbance at 440 nm) and yellow substance (dissolved colour) mass concentration, a mass balance equation is used for the prediction of G440. Dissolved colour is assumed to be biologically inactive and, because it is a dissolved constituent, to have a negligibly small settling velocity.

A mass balance equation is used to predict the concentration of SS in each segment. Assuming a linear relationship between FSS and SS mass concentration, a mass balance equation is also used for the prediction of FSS. Settling is included in the model although the majority of beam attenuation is caused by very small particles which have a very low settling velocity.

The WCM incorporates the model of Pridmore and McBride (1983) for phytoplankton chlorophyll (CHL), which accounts for the effects of nutrient concentration and flushing. This model is modified to include the effects of settling and by making the growth rate a function of temperature and light.

Water clarity varies with changes in the concentrations of phytoplankton, yellow substance and other fine suspensoids (e.g., clay, silica, detritus etc.). Water clarity is taken to be the horizontal visibility of a black disc (termed black disc clarity, BD). Black disc clarity (in segment i) is inversely related to the beam attenuation coefficient (c):

$$BD_i = \frac{4.8}{c_i} \quad (1)$$

The beam attenuation coefficient varies with the concentrations of phytoplankton, yellow substance and other suspensoids and the following relationship is assumed:

$$c_i = c_o + \alpha_1 CHL_i^{\beta_1} + \alpha_2 G440_i^{\beta_2} + \alpha_3 FSS_i^{\beta_3} \quad (2)$$

where co = background beam attenuation coefficient of pure water (m-1) = 0.064, and β and α are empirical coefficients.

$$\beta_1 = \beta_2 = \beta_3 = 1, \alpha_1 = 0.10, \alpha_2 = 0.17, \alpha_3 = 1.00.$$

Colour is quantified in the model by Munsell hue which changes as a result of increases of yellow substance, chlorophyll and inert suspensoid concentrations. A regression model is used (derived using monitoring data)

$$Munsell = m_o + m_1 \ln(FSS) + m_2 \ln(G440) + m_3 \ln(CHL) \quad (3)$$

where m are constants estimated during calibration.

This Study

The model was firstly calibrated to the measured data (Figures 1, 2, 6 and 7) using the Current State yields (Table 7). Two flow regimes were considered, namely mean and base flow and the measured data were categorised using these two flows. A flow scaling factor depending on these two flows along with attenuation or amplification of the Current State yields at various reaches of the rivers were included in the calibration. For the calibration to the chlorophyll concentrations, the settling velocity and maximum growth rate of the phytoplankton chlorophyll were adjusted. For Scenarios 1–3, the yields varied (Table 7) but the scaling factors, the attenuations or amplifications, the settling velocity and growth rate remained unchanged.

The following describes how the concentrations of TP, TN, SS, G440 and FSS are predicted in each sub-catchment which are then used in the mass balance equations for each segment.

There are a number of sites along the Waikato and Waipa Rivers and each one is associated with a sub-catchment or a point source discharge. There are various land use types in each sub-catchment and these include forestry or planted forest (PF), sheep-beef on steep hill country (Class 3) (SB3), sheep-beef on easy hill country (Class 4) (SB4), sheep-beef on easy rolling country (Class 5) (SB5), dairy on peat soils (DPe), dairy on well-drained soils (DW), dairy on poorly-drained soils (DPo), cropping and horticulture (CH), native forest (NF) and urban (U) (see Appendix 9: Farms).

Firstly the yield of TP, TN, SS, G440 or FSS from a land use in a sub-catchment is calculated by multiplying the yield from that land use by the fraction of area that it occupies in the sub-catchment. These yields are then summed across the land use types (PF, SB3, SB4, SB5, DPe, DW, DPo, CH, NF, U) to give a total yield of TP, TN, SS, G440 or FSS for the sub-catchment.

For TP, TN and SS, the yield has units of kg/ha/yr. Concentrations of TP (mg/m^3), TN (mg/m^3) and SS (g/m^3) are calculated from their yields using the sub-catchment area and flow rate. For G440 and FSS the yield units are m^2/m^3 = 1/m, and these are also used for their concentrations.

The yield from the land use is scaled according to the flow so that

Yield from land use$_j$ of substance$_v$ from sub-catchment$_k$ =

Yield from land use$_j$ of substance$_v$ x Flow scaling factor

x Area of land use$_j$ in sub-catchment$_k$/Area of sub-catchment$_k$;

where j = PF, SB3, SB4, SB5, DPe, DW, DPo, CH, NF or U;

v = TP, TN, SS, G440 or FSS and k = a sub-catchment

Or if Y = yield;

SF = (flow) scaling factor;

A = area;

r = Waikato River (Wk) or Waipa River (Wp);

s = Pasture (P) or Forest (F); and

t = Mean flow (M) or Base flow (B) then

$$Y_{j,v,k} = Y_{j,v} \times SF_{r,s,t,v} \times \frac{A_{j,k}}{A_k} \qquad (4)$$

and for the total yield of substance$_v$ from sub-catchment$_k$

$$= \sum_j Y_{j,v} \times SF_{r,s,t,v} \times \frac{A_{j,k}}{A_k} \qquad (5)$$

If j = PF, NF or U then $SF_{r,s,t,v} = SF_{r,s=F,t,v}$ else if j = SB3, SB4, SB5, DPe, DW, DPo, or CH then $SF_{r,s,t,v} = SF_{r,s=P,t,v}$. "Yields", $Y_{j,v}$ for v = TP, TN and SS were obtained from Dr Ross Monaghan (AgResearch, pers. comm.) for Current State and Scenarios 1, 2 and 3 for TN, TP and SS (Table 7). $Y_{j,v=TP}$ for the Waipa needed to be different to that for the Waikato in order to calibrate the model for the Current State (Table 7).

$Y_{j,v}$ for v = FSS and G440 for the Current State were estimated in order to calibrate the model to the measured data. for FSS and G440. For Scenarios 1–3, the yields for FSS and G440 were obtained by applying the same reductions in SS yields between the Current State and Scenarios 1–3.

These estimations included looking at plots of forest (both planted and native) and total pasture versus FSS and G440 (Figure 11) in order to estimate the yields of FSS and G440 in mainly forested sub-catchments compared with mainly pastured sub-catchments. If it is assumed that mainly pastured sub-catchments are dairy farms and sheep-beef farms are a mixture of pasture and forest, then from Figure 11 (a) and (b), the FSS yield for the dairy farms is about 10, for sheep-beef farms is about five, and for forested sub-catchments is about 1(Table 7). Similarly, from Figure 11 (c) and (d), the G440 yield for the dairy farms is about four, for sheep-beef farms is about three, and for forested sub-catchments is about two (Table 7).

(a) (b)

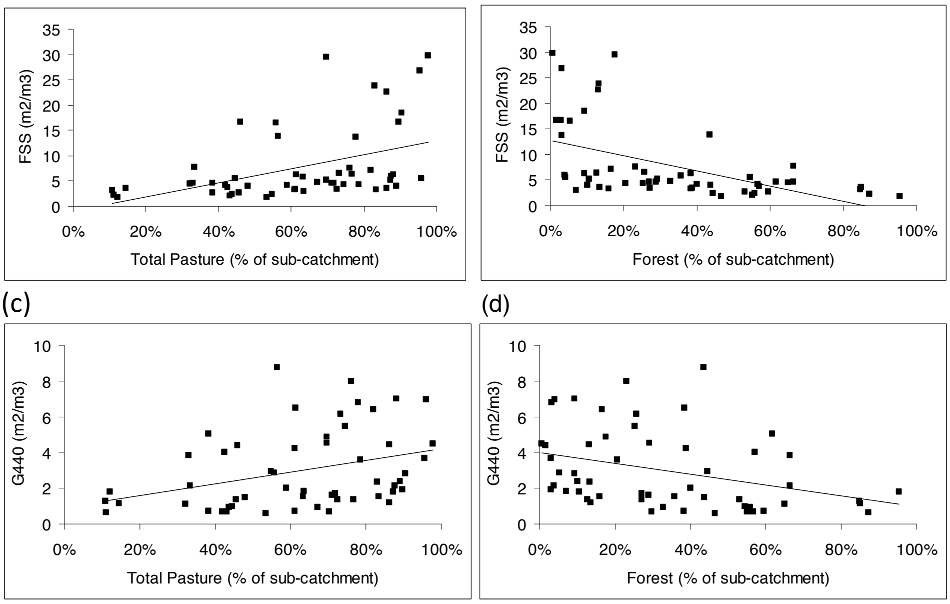

Figure 11: Variation with percentage of forest (planted and native) and total pasture in various sub-catchments of the Waikato and Waipa Rivers versus observed FSS and G440 with trendlines.

$Y_{j,v=FSS}$ and $Y_{j,v=G440}$ for the Waipa needed to be different to those for the Waikato in order to calibrate the model for the Current State (Table 7).

Flow scaling factor, $SF_{r,s,t,v}$

In this Study, two flow regimes are modelled: the mean and base flows. The flow scaling factor is given by

$$SF_{r,s,t,v} = \alpha_{r,s,v} \times Q_t^{\beta_{r,s,v}} \qquad (6)$$

where α and β (Table 8) are coefficients estimated during calibration.

Since $\alpha_{r,s,v} = 1$ for all r, s, v Equation 6 becomes

$$SF_{r,s,t,v} = Q_t^{\beta_{r,s,v}} \qquad (7)$$

For “mean” flow, the minimum and maximum are set at 75 percent and 125 percent respectively of the measured mean flow (at Rangiriri in the Waikato River, at Whatawhata in the Waikato River) giving an average of 100 percent of the flow, viz. the mean flow ($Q_{t=M}$) in Equation 7 = 1. For base flow, the minimum and maximum are set at 25 percent and 75 percent respectively of the measured mean flow giving an average of 50 percent of the flow, viz. the base flow ($Q_{t=B}$) in Equation 7 = 0.5.

Therefore for mean flow $SF_{r,s,t=M,v} = 1$ (8)

and for base flow $SF_{r,s,t=B,v} = 0.5^{\beta_{r,s,v}}$ (9)

≤ 1 since $\beta_{r,s,v} \geq 0$ for all r, s, v (Table 8).

For mean flow then, Equation 5 becomes

$$\sum_j Y_{j,v} \times \frac{A_{j,k}}{A_k} \tag{10}$$

and for base flow, the flow scaling factor attenuates the yield when $\beta_{r,s,v} > 0$, and when $\beta_{r,s,v} = 0$ then Equation 10 applies.

Table 7: The yields, $Y_{j,v}$ j = PF, SB3, SB4, SB5, DPe, DW, DPo, CH, NF or U; v = TP, TN, SS, G440 or FSS. If the Waipa values are different to the Waikato ones then the Waipa values are given in the brackets; for the Current State (CS), $Y_{j=NF,v}$ and $Y_{j=U,v}$ were set equal to $Y_{j=PF,v}$. The reduction in $Y_{j,v}$ resulting from the actions of Scenarios 1–3 (S1 – 3) did not apply to $Y_{j=NF,v}$ or $Y_{j=U,v}$. The Current State yields were used for calibrating the model

		j = PF	j = SB3	j = SB4	j = SB5	j = DPe	j = DW	j = DPo	j = CH
v = TN	CS	$Y_{PF,TN}$ = 4.00	$Y_{SB3,TN}$ = 9.20	$Y_{SB4,TN}$ = 12.40	$Y_{SB5,TN}$ = 15.50	$Y_{DPe,TN}$ = 30.40	$Y_{DW,TN}$ = 44.30	$Y_{DPo,TN}$ = 40.40	$Y_{CH,TN}$ = 70.50
	S1	$Y_{PF,TN}$ = 3.60	$Y_{SB3,TN}$ = 8.81	$Y_{SB4,TN}$ = 11.87	$Y_{SB5,TN}$ = 14.84	$Y_{DPe,TN}$ = 22.36	$Y_{DW,TN}$ = 37.26	$Y_{DPo,TN}$ = 33.36	$Y_{CH,TN}$ = 22.35
	S2, S3	$Y_{PF,TN}$ = 3.60	$Y_{SB3,TN}$ = 8.64	$Y_{SB4,TN}$ = 11.64	$Y_{SB5,TN}$ = 14.55	$Y_{DPe,TN}$ = 11.03	$Y_{DW,TN}$ = 17.03	$Y_{DPo,TN}$ = 22.53	$Y_{CH,TN}$ = 22.35
v = TP	CS	$Y_{PF,TP}$ = 1.00 (0.25)	$Y_{SB3,TP}$ = 1.30 (1.00)	$Y_{SB4,TP}$ = 1.30 (1.00)	$Y_{SB5,TP}$ = 1.10 (1.00)	$Y_{DPe,TP}$ = 3.70 (3.00)	$Y_{DW,TP}$ = 1.10 (3.00)	$Y_{DPo,TP}$ = 1.80 (3.00)	$Y_{CH,TP}$ = 4.60 (3.00)
	S1	$Y_{PF,TP}$ = 0.85 (0.21)	$Y_{SB3,TP}$ = 1.22 (0.94)	$Y_{SB4,TP}$ = 1.22 (0.94)	$Y_{SB5,TP}$ = 1.03 (0.94)	$Y_{DPe,TP}$ = 2.39 (1.94)	$Y_{DW,TP}$ = 0.27 (0.74)	$Y_{DPo,TP}$ = 0.70 (1.17)	$Y_{CH,TP}$ = 0.96 (0.62)
	S2, S3	$Y_{PF,TP}$ = 0.85 (0.21)	$Y_{SB3,TP}$ = 1.18 (0.91)	$Y_{SB4,TP}$ = 1.19 (0.91)	$Y_{SB5,TP}$ = 1.01 (0.91)	$Y_{DPe,TP}$ = 1.37 (1.11)	$Y_{DW,TP}$ = 0.13 (0.34)	$Y_{DPo,TP}$ = 0.47 (0.79)	$Y_{CH,TP}$ = 0.96 (0.62)
v = SS	CS	$Y_{PF,SS}$ = 457.00	$Y_{SB3,SS}$ = 989.30	$Y_{SB4,SS}$ = 436.80	$Y_{SB5,SS}$ = 174.70	$Y_{DPe,SS}$ = 18.20	$Y_{DW,SS}$ = 55.40	$Y_{DPo,SS}$ = 95.80	$Y_{CH,SS}$ = 405.30
	S1	$Y_{PF,SS}$ = 365.60	$Y_{SB3,SS}$ = 808.26	$Y_{SB4,SS}$ = 356.87	$Y_{SB5,SS}$ = 142.73	$Y_{DPe,SS}$ = 16.92	$Y_{DW,SS}$ = 46.98	$Y_{DPo,SS}$ = 81.48	$Y_{CH,SS}$ = 202.65
	S2, S3	$Y_{PF,SS}$ = 365.60	$Y_{SB3,SS}$ = 657.39	$Y_{SB4,SS}$ = 290.25	$Y_{SB5,SS}$ = 116.09	$Y_{DPe,SS}$ = 4.85	$Y_{DW,SS}$ = 31.88	$Y_{DPo,SS}$ = 54.22	$Y_{CH,SS}$ = 202.65
v = FSS	CS	$Y_{PF,FSS}$ = 1.00 (1.50)	$Y_{SB3,FSS}$ = 5.00	$Y_{SB4,FSS}$ = 5.00	$Y_{SB5,FSS}$ = 5.00	$Y_{DPe,FSS}$ = 10.00 (17.50)	$Y_{DW,FSS}$ = 10.00 (5.00)	$Y_{DPo,FSS}$ = 10.00 (5.00)	$Y_{CH,FSS}$ = 10.00 (5.00)

Table 7: (cont.)

		j = PF	j = SB3	j = SB4	j = SB5	j = DPe	j = DW	j = DPo	j = CH
	S1	$Y_{PF,FSS}$ = 0.80 (1.20)	$Y_{SB3,FSS}$ = 4.09	$Y_{SB4,FSS}$ = 4.09	$Y_{SB5,FSS}$ = 4.09	$Y_{DPe,FSS}$ = 9.30 (16.27)	$Y_{DW,FSS}$ = 8.48 (4.24)	$Y_{DPo,FSS}$ = 8.50 (4.25)	$Y_{CH,FSS}$ = 5.00 (2.50)
	S2, S3	$Y_{PF,FSS}$ = 0.80 (1.20)	$Y_{SB3,FSS}$ = 3.32	$Y_{SB4,FSS}$ = 3.32	$Y_{SB5,FSS}$ = 3.32	$Y_{DPe,FSS}$ = 2.66 (4.66)	$Y_{DW,FSS}$ = 5.75 (2.88)	$Y_{DPo,FSS}$ = 5.66 (2.83)	$Y_{CH,FSS}$ = 5.00 (2.50)
v = G440	CS	$Y_{PF,G440}$ = 2.00 (4.00)	$Y_{SB3,G440}$ = 3.00 (1.50)	$Y_{SB4,G440}$ = 3.00 (1.50)	$Y_{SB5,G440}$ = 3.00 (1.50)	$Y_{DPe,G440}$ = 4.00 (3.00)	$Y_{DW,G440}$ = 4.00 (3.00)	$Y_{DPo,G440}$ = 4.00 (3.00)	$Y_{CH,G440}$ = 4.00 (3.00)
	S1	$Y_{PF,G440}$ = 1.60 (3.20)	$Y_{SB3,G440}$ = 2.45 (1.23)	$Y_{SB4,G440}$ = 2.45 (1.23)	$Y_{SB5,G440}$ = 2.45 (1.23)	$Y_{DPe,G440}$ = 3.72 (2.79)	$Y_{DW,G440}$ = 3.39 (2.54)	$Y_{DPo,G440}$ = 3.40 (2.55)	$Y_{CH,G440}$ = 2.00 (1.50)
	S2, S3	$Y_{PF,G440}$ = 1.60 (3.20)	$Y_{SB3,G440}$ = 1.99 (1.00)	$Y_{SB4,G440}$ = 1.99 (1.00)	$Y_{SB5,G440}$ = 1.99 (1.00)	$Y_{DPe,G440}$ = 1.07 (0.80)	$Y_{DW,G440}$ = 2.30 (1.73)	$Y_{DPo,G440}$ = 2.26 (1.70)	$Y_{CH,G440}$ =2.00 (1.50)

Table 8: The values of $\beta_{r,s,v}$, r = Waikato River (Wk) or Waipa River (Wp); s = Pasture (P) or Forest (F) and v = TP, TN, SS, G440 or FSS. These were obtained during the calibration of the model to the Current State.

		s = P	s = F
v = TN	r = Wk	$\beta_{Wk,P,TN}$ = 0.40	$\beta_{Wk,F,TN}$ = 0.40
	r = Wp	$\beta_{Wp,P,TN}$ = 1.35	$\beta_{Wp,F,TN}$ = 1.35
v = TP	r = Wk	$\beta_{Wk,P,TP}$ = 0.10	$\beta_{Wk,F,TP}$ = 0.10
	r = Wp	$\beta_{Wp,P,TP}$ = 1.50	$\beta_{Wp,F,TP}$ = 1.50
v = SS	r = Wk	$\beta_{Wk,P,SS}$ = 2.50	$\beta_{Wk,F,SS}$ = 1.00
	r = Wp	$\beta_{Wp,P,SS}$ = 2.50	$\beta_{Wp,F,SS}$ = 1.00
v = FSS	r = Wk	$\beta_{Wk,P,FSS}$ = 0.25	$\beta_{Wk,F,FSS}$ = 0.00
	r = Wp	$\beta_{Wp,P,FSS}$ = 0.50	$\beta_{Wp,F,FSS}$ = 0.50
v = G440	r = Wk	$\beta_{Wk,P,G440}$ = 0.75	$\beta_{Wk,F,G440}$ = 0.75
	r = Wp	$\beta_{Wp,P,G440}$ = 0.40	$\beta_{Wp,F,G440}$ = 0.00

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