NIWA
Taihoro Nukurangi

Effects of land use on streams – Phase 2 modelling studies in the Tukituki River, Hawke's Bay

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Executive summary

The Hawke's Bay Regional Investment Company Limited (HBRIC) requires an assessment to be made of the likely impacts on nutrients and aquatic plants in the Tukituki River arising from land use changes associated with the proposed Ruataniwha Water Storage Scheme (RWSS), land use change elsewhere in the Tukituki catchment, and point source discharges including wastewater treatment plants (WWTP). This report extends the stream nutrient and periphyton model TRIM1_STREAM to the whole of the Tukituki catchment, details model calibration and discusses model uncertainties. The revised model, TRIM2_STREAM, uses water and nutrient inflows predicted by the TRIM2_CATCHMENT model which is described elsewhere (Rutherford 2013). The TRIM2 models are used to assess the likely impacts of the RWSS on nutrient losses, stream nutrient inflows and concentrations, and stream periphyton biomass.

The TRIM2_STREAM model satisfactorily predicts observed stream nitrogen and phosphorus concentrations, and biomass for a representative pre-irrigation year, 2010. However, there are several different combinations of key model coefficients that give a similar match between predicted and observed stream nutrient concentrations and biomass. The strategy adopted to cope with this non-uniqueness problem with model calibration is to identify the processes and model coefficients that have the greatest effect on model predictions, seek alternative calibrations, and determine whether model uncertainty affects the main conclusions and recommended actions. The TRIM2_STREAM model is considered to be sufficiently reliable to assess the impact of the RWSS, bearing in mind areas of uncertainty in its calibration.

The modelling confirms that phosphorus, rather than nitrogen, determines periphyton biomass, except occasionally near the sea during summer low flows. In the middle Tukituki (from above Waipukurau to near Red Bridge), dissolved inorganic nitrogen concentrations are well in excess of the concentrations that limit plant growth. It is only in the lower Tukituki (from near Red Bridge to the sea) that, during prolonged periods of summer low flow, nitrogen concentrations are low (largely as a result of denitrification) and nitrogen becomes limiting to plant growth.

Sensitivity analysis indicates that phosphorus supply, rather than phosphorus concentration, determines periphyton biomass. Phosphorus supply is largely determined by phosphorus inflows determined by OVERSEER and routed through the catchment by TRIM2_CATCHMENT. In an earlier study (Rutherford 2013) a satisfactory match was obtained between observed and predicted annual flow-weighted mean phosphorus concentrations which indicates that phosphorus inflows to streams are predicted satisfactorily.

This report predicts stream phosphorus concentrations and periphyton biomass assuming that the WWTPs at Waipukurau and Waipawa discharge at their current levels. Consents for these discharges, which come into force in 2014, require a reduction in phosphorus discharges. A reduction in phosphorus discharges from the WWTPs will have beneficial effects for the lower Tukituki River (from Waipukurau to the sea) in terms of reduced periphyton growth rates and biomass.

The model predicts, and there are limited observations to support the prediction, that at times biomass is high above the WWTPs as a result of runoff from agricultural land. In order to minimise the adverse impact of the RWSS on periphyton biomass in the middle reaches of the Tukituki and Waipawa Rivers (viz., above Waipukurau and Waipawa) it is desirable to minimise phosphorus inputs resulting from the RWSS.

A key recommendation arising from the modelling is that phosphorus losses from the RWSS should be minimised in order that nuisance periphyton growths should not occur more frequently, or be more severe, than they are currently. In the lower Tukituki River the combination of phosphorus input reductions from the WWTPs and the mitigation of phosphorus losses from agricultural land, while not eliminating problems, is predicted to have benefits by reducing the incidence and severity of nuisance periphyton growths.

One aspect of the Tukituki River that is not well understood is phosphorus exchange between the stream bed and the overlying water, and it is desirable to undertake experimental work on this topic. Since mitigation measures are proposed to ensure that RWSS is ‘phosphorus-neutral’ (viz., phosphorus inflows to streams do not increase as a result of the scheme) it is unlikely that the phosphorus exchange with the bed will change significantly. Consequently, uncertainties in the modelling of phosphorus exchange are considered unlikely to invalidate the recommendation to maintain or reduce phosphorus losses from the catchment.

Assuming current farming practice with no additional on-farm mitigation to reduce nutrient loss, nitrogen and phosphorus losses across the entire catchment are predicted to increase by 32% and 6% respectively as a result of land use intensification associated with the RWSS. Nitrogen and phosphorus losses within the irrigation consent area are predicted to increase by an average of 81% and 41% respectively (Table 3-11). These increases assume current farming practice with no additional on-farm mitigation to reduce nutrient loss.

Fencing to exclude stock from streams and the optimal use of phosphorus fertiliser are predicted to offset the 6% increase in phosphorus losses, and make the RWSS close to phosphorus-neutral overall. Within the irrigation consent area, these measures are predicted to result in increase phosphorus losses by 7% relative to pre-irrigation levels – significantly lower than the predicted 41% predicted without any mitigation, but still not ‘phosphorus-neutral’. OVERSEER probably under-estimates the benefits of stock exclusion from streams, because it only quantifies the consequences of direct deposition of dung and urine, but not trampling of the banks and stream bed. Nevertheless, additional mitigation measures may be required in some irrigated sub-catchments for them to be ‘phosphorus-neutral’. There are a number of additional on-farm mitigation measures that can be undertaken to reduce phosphorus losses (McDowell and Nash 2012).

Note that it will not be possible to completely eliminate nuisance periphyton growths during prolonged summer low flows through phosphorus control alone. Currently, during prolonged summer low flows, periphyton biomass reaches nuisance levels in most parts of the river, including reaches apparently unaffected by nutrient runoff from agriculture. In such reaches, nutrient inflows and growth rates are low, biomass accumulates slowly but, if there is a long period without ‘reset’ flows, often reaches nuisance levels.

In parts of the river where nutrient concentrations are high, periphyton growth rates are high. Periphyton growth is offset by losses (respiration, death, grazing and scour) and biomass accumulates at the net rate (growth minus losses). Consequently, biomass accumulates more quickly, and nuisance levels are reached more quickly, where nutrient inflows are high. In addition, peak biomass is usually higher than where nutrient inflows and concentrations are low.

If phosphorus mitigation is effective, then it is predicted that periphyton biomass in the main stem of the Tukituki River will be similar to current levels. Nuisance biomass levels may still occur during prolonged periods of low flow, but there should be no significant increase in the frequency or magnitude of nuisance growths. This conclusion is robust to uncertainty about phosphorus release from the bed. Earlier modelling using TRIM1 (Rutherford et al. 2012) showed that when phosphorus inflows from the WTTPs decrease, the frequency or magnitude of nuisance growths in the lower Tukituki River are expected to decrease.

Periodically, natural high flows ‘reset’ biomass to low levels and it may be possible to alleviate periphyton biomass problems by releasing flushing flows from the dam. The RWSS proposal now includes the release of up to four flushing flows per irrigation season as discussed by Aquanet (2013). These additional flushing flows have not been incorporated in the TRIM modelling presented in this report, but a preliminary quantitative assessment of the effects of these flushing flows on periphyton biomass could be undertaken using TRIM_STREAM.

No monitoring data exist to compare with model predictions in most of the smaller streams – predictions should therefore be treated with caution. Nevertheless, predictions highlight where potential ‘hot spots’ of high nutrient, and potentially high biomass, are likely to occur. In some sub-catchments, phosphorus inflows are predicted to be higher than pre-irrigation inflows. Additional phosphorus mitigation measures may be required in such sub-catchments to avoid problems associated with high biomass.

Nitrate concentrations are predicted to increase significantly in tributaries draining the irrigation consent areas. Under current conditions, ‘hot spots’ of high nitrate concentration have been identified in some tributaries of the middle Tukituki, which raises concerns about possible nitrate toxicity. Assuming the same denitrification rate in the tributaries as that estimated in the main stem, it is predicted that nitrate concentrations will exceed the limits set in the proposed Tukituki Plan Change in three tributaries – two affected by point source waste discharges and intensive farming, and one only affected by intensive farming. Denitrification has not been studied in the tributaries, but the ‘worst-case’ assumption is that denitrification in the tributaries is zero. Making this assumption, the model predicts only a slight increase in the number of exceedances, compared with predictions assuming the same denitrification rate in the tributaries as that estimated in the main stem. The reason for the increase being small is that the nitrate limits apply to the annual median and 95 percentile concentrations, which are largely determined by winter high flows when denitrification has little effect on nitrate concentrations. Nevertheless, it is recommended that field investigations be undertaken to measure denitrification rates in the tributaries and compare them with rates in the main stem in order to refine nitrate predictions in the tributaries where ‘hot spots’ of high concentration occur.

Additional nitrogen mitigation may be required in some sub-catchments to avoid nitrate toxicity problems. In the earlier TRIM1 study (Rutherford et al. 2012) it was shown that nitrogen mitigation scenarios had the potential to decrease nitrogen losses leaving the Ruataniwha Basin from 1,615 t y^{-1} (Scenario B) to 1,480 t y^{-1} (Scenario C) – a reduction of

8%. Nitrogen reductions of this scale may be sufficient to ensure that toxicity limits are not exceeded in some sub-catchments, although further modelling is required to confirm this. If cost-effective nitrogen mitigation measures are unable to ensure that toxicity limits are not exceeded then it may be necessary to restrict the types of agriculture that will be permitted in some of the more sensitive sub-catchments.

In the scenarios modelled, the land use changes are those determined by Macfarlane Rural Business based on a land use capability and economic analysis. Other mixes of land use are possible. An earlier study (MacKay in Rutherford et al. 2012) investigated an alternative scenario in which dairy and intensive arable were extended by a further 5,450 ha reducing sheep and beef extensive, orchard and vineyard by the corresponding area. This translated to an increase in N losses of 100 t y^{-1} from 3,060 t y^{-1} to 3,160 t y^{-1} which would have a negligibly small impact on the river. Unmitigated P losses would be expected to increase by a similar, very small percentage.

1 Introduction

1.1 Nutrients and periphyton

The Tukituki catchment has been identified as having both high in-stream values (e.g., biodiversity, trout fishing) and out-of-stream values (e.g., abstraction for irrigation, gravel supply). Hawke's Bay Regional Council (HBRC) defines the Tukituki as a 'sensitive catchment' and conducts monitoring to determine the state, and trend over time, of these freshwater resources.

Prolonged summer low flows lead to the accrual of high periphyton biomass which causes problems of poor aesthetics for water users (e.g., anglers, swimmers, kayakers) and possible toxicity if certain species proliferate (e.g., *Phormidium* spp). Most of the problems associated with high summer periphyton biomass occur in the lower Tukituki River in the reach between Waipukurau and the sea. However, there are also 'hot spots' where high periphyton and/or macrophyte biomass occur in the upper and middle Tukituki and Waipawa River catchments, notably where groundwater containing high nutrient concentrations upwells just upstream from the townships of Waipukurau and Waipawa. In combination with high water temperature, high periphyton and macrophyte biomass may lead to low night-time DO concentration and high day-time pH which adversely affect sensitive organisms (e.g., mayflies and trout). High biomass also alters habitat for macroinvertebrates – dense periphyton biofilms tend to favour chironimids and worms over the mayflies and caddisflies. Chironimids and worms are regarded as less valuable food for trout than mayflies and caddisflies.

The hydrological regime exerts strong control on biomass (Biggs 2000). Spates scour periphyton from the river. Nutrients from both point and non-point sources increase the rate at which periphyton and macrophytes re-grow after spates, and thereby contribute to high biomass during summer low flows. In the past HBRC has set a guideline concentration (15 mg m^{-3}) for dissolved reactive phosphorus (DRP) aimed at limiting problems with periphyton (HBRC, 2006) but did not set guidelines for nitrogen or periphyton biomass. HBRC has recently proposed guidelines for the Tukituki River catchment as summarised in Table 7-1.

Currently two projects are underway that have the potential to change nutrient inflows and hence river ecology: (1) the advanced treatment of domestic wastewater from the wastewater treatment plants (WWTP) at the townships of Waipukurau and Waipawa, and (2) the expansion of irrigation on the Ruataniwha Plains associated with a proposed reservoir on the Makaroro River (RWSS). In addition, land use change is occurring elsewhere in the catchment, which has the potential to affect the inflows of water, sediment and nutrient into the river. A method is required to predict the likely impacts of these changes on river nutrient concentrations and river ecology, and for investigating the benefits of various scenarios of land use intensification, on-farm nutrient management and in-river management. The principal focus of this study is an assessment of the likely impacts of the proposed irrigation scheme using the purpose-built conceptual model TRIM (Tukituki RIver Model).

1.2 Previous modelling

An earlier report (Rutherford et al. 2012) presented the results of a multi Crown Research Institute (CRI) approach to modelling the current and expected nutrient loss into the Tukituki River, as a result of land use intensification. The purpose of that study was to determine:

- Current nutrient loss from farms, through the SPASMO model.
- Potential effects of a change to irrigated land use on the Ruataniwha Plain, through
  - economic modelling to estimate the likely land uses under irrigation, and
  - SPASMO modelling to estimate nutrient losses from these land uses.
- The extent of current and potential nutrient inputs to surface water from the Ruataniwha Plain as a result of farm land nutrient losses, and the resulting effects on water quality in the middle and lower Tukituki and Waipawa Rivers, through the conceptual annual land use model TRIM1_CATCH.
- The effects of nutrient inflows and transformations on biomass growth, through the conceptual daily stream model TRIM1_STREAM.
- Mitigation options to avoid or minimise the effects of land use on surface water through the OVERSEER model.

The TRIM1 modelling concluded that:

1. Comparing Scenario B (irrigation and 'top 20%' performance) with Scenario A (current land use and 'average' performance): N losses from the model area (which included not only the irrigation consent area but also farmland lying downstream from the monitoring sites) and increased from 2,440 to 3,060 t y^{-1} (25%) and P losses from 67 to 80 t P y^{-1} (20%).

2. N and P loads leaving the Ruataniwha Basin increased by lower percentages than losses from the irrigation area because of dilution from upstream and attenuation: N loads leaving the Ruataniwha Basin increased from 1,320 t y^{-1} to 1,615 t y^{-1} (22%) and P loads from 57 t y^{-1} to 63 y t^{-1} (10%).

3. Extending dairy and intensive arable by a further 5,450 ha and reducing sheep and beef extensive, orchard and vineyard by the corresponding area translated to an increase in N losses of 100 t y^{-1} compared with Scenario B.

4. Comparing Scenario C (irrigation with N mitigation for arable and dairy) with Scenario A (current land use): N losses from the model area increased from 2,440 to 2,780 t y^{-1} (14%) and N loads leaving the Ruataniwha Basin increased from 1,320 t y^{-1} to 1,480 t y^{-1} (12%).

5. A shift in farming enterprises outside the irrigation zone (to include wintering dairy cows and contract heifer grazing) was predicted to increase N and P losses, but these increases were insignificant relative to the loads leaving the Ruataniwha Basin.

6. The TRIM1_STREAM model was applied between Waipukurau and the sea to assess the effects of the RWSS and WWTP discharges on nutrient concentrations, periphyton biomass and nitrate toxicity in the lower Tukituki River. The majority of problems associated with high periphyton biomass occur in the lower Tukituki River downstream from the townships of Waipukurau and Waipawa. Some 'hot spots' in streams within the Ruataniwha Basin may also occur with high nitrate concentrations and/or high plant biomass.

7. A 2009 review of (mostly overseas) nitrate toxicity studies suggested a nitrate guideline concentration of 1.7 g m^{-3} to protect 95% of species. There were indications that a higher guideline may be acceptable in the Tukituki River. (Work has recently been completed by NIWA to measure the susceptibility to nitrate of keystone New Zealand freshwater organisms, including *Galaxias maculatus* (inanga) and *Deleatidium* spp. (mayfly) and to recommend specific guidelines for the Tukituki River, see Table 7-2).

8. The percentage of days when the 1.7 g m^{-3} guideline was exceeded in the Tukituki River at Waipukurau was predicted to increase from 18% (Scenario A) to 36% (Scenario B) and 29% (Scenario C).

9. TRIM1_STREAM predicted significant beneficial effects (in terms of reduced DRP concentrations, reduced periphyton biomass and associated improvements in ecosystem 'health') from reducing P discharges from the WWTPs at Waipukurau and Waipawa.

10. Irrigation (Scenarios B and C) was predicted to result in higher peak biomasses than for current land use (Scenario A). If P inflows from the WWTPs were reduced, then the highest biomass was predicted to occur at the top of the modelled reach (viz., in the vicinity of Waipukurau). The 10%ile biomass at SH2 currently averaged 49 g C m^{-2}, this was predicted to increase to 57 g C m^{-2} with irrigation because of increased P inflows. These simulations did not consider possible P loss mitigation measures which were then being investigated.

Further work was recommended to:

- model further scenarios including a wider range of modified land uses, and options for mitigating N and P losses
- changing the mix of land uses modelled
- extending the model upstream from Waipukurau and Waipawa in order to assess the impact of irrigation and land use intensification within the Ruataniwha Plain, notably where groundwater upwelling occurs and 'hot spots' of N and P occur.

1.3 Project aims

The aims of this report are to describe how the:

1. TRIM_STREAM model has been extended to the whole catchment, modified and re-calibrated.

2. TRIM2_CATCHMENT and TRIM2_STREAM models have been used to assess the impacts of the RWSS.

1.4 Study area

The Tukituki catchment (Figure 1-1) begins in the Ruahine Ranges in the west and extends to the sea. Near the middle of the catchment, a range of hills runs approximately north-south near the townships of Waipukurau and Waipawa. The Ruataniwha Plain lies between the Ruahine Ranges and these hills and includes the Ruataniwha Basin, an area filled with gravels carried by rivers from the Ruahine Ranges. State Highway 50 (SH50) runs roughly north-south across the Ruataniwha Plain near the western edge of the gravels, and most of the irrigable land occurs on these gravels. The Tukituki and Waipawa Rivers both rise in the Ruahine Ranges, flow across the Ruataniwha Plain and cut through the range of hills just upstream from the townships of Waipukurau and Waipawa. Land upstream from SH50 is termed the ‘upper catchment’ and land between SH50 and the confluence of the Tukituki and Waipawa Rivers, just downstream from Waipukurau and Waipawa, is termed the ‘middle catchment’. The Tukituki River then flows east to the sea along a narrow corridor of land, termed the ‘lower catchment’.

The gravels of the Ruataniwha Basin contain groundwater that flows west to east. The eastern hills near the townships of Waipukurau and Waipawa force groundwater to the surface into the Tukituki and Waipawa Rivers which then flow through gaps in the hills. Three major rivers flow across the Ruataniwha Plain – Makaretu, Tukituki and Waipawa. Seven other major streams – Maharakeke, Porangahau, Mangatewai, Tukipo, Ongaonga, Kahahakuri and Mangaonuku – rise on the plains, as do several smaller streams.

In the Ruahine headwaters, land use includes native land cover, exotic forestry and dry land pasture. The Ruataniwha Basin is intensively farmed although the area has only moderate rainfall, is subject to water shortages in summer, and only a limited supply of water is available for irrigation.

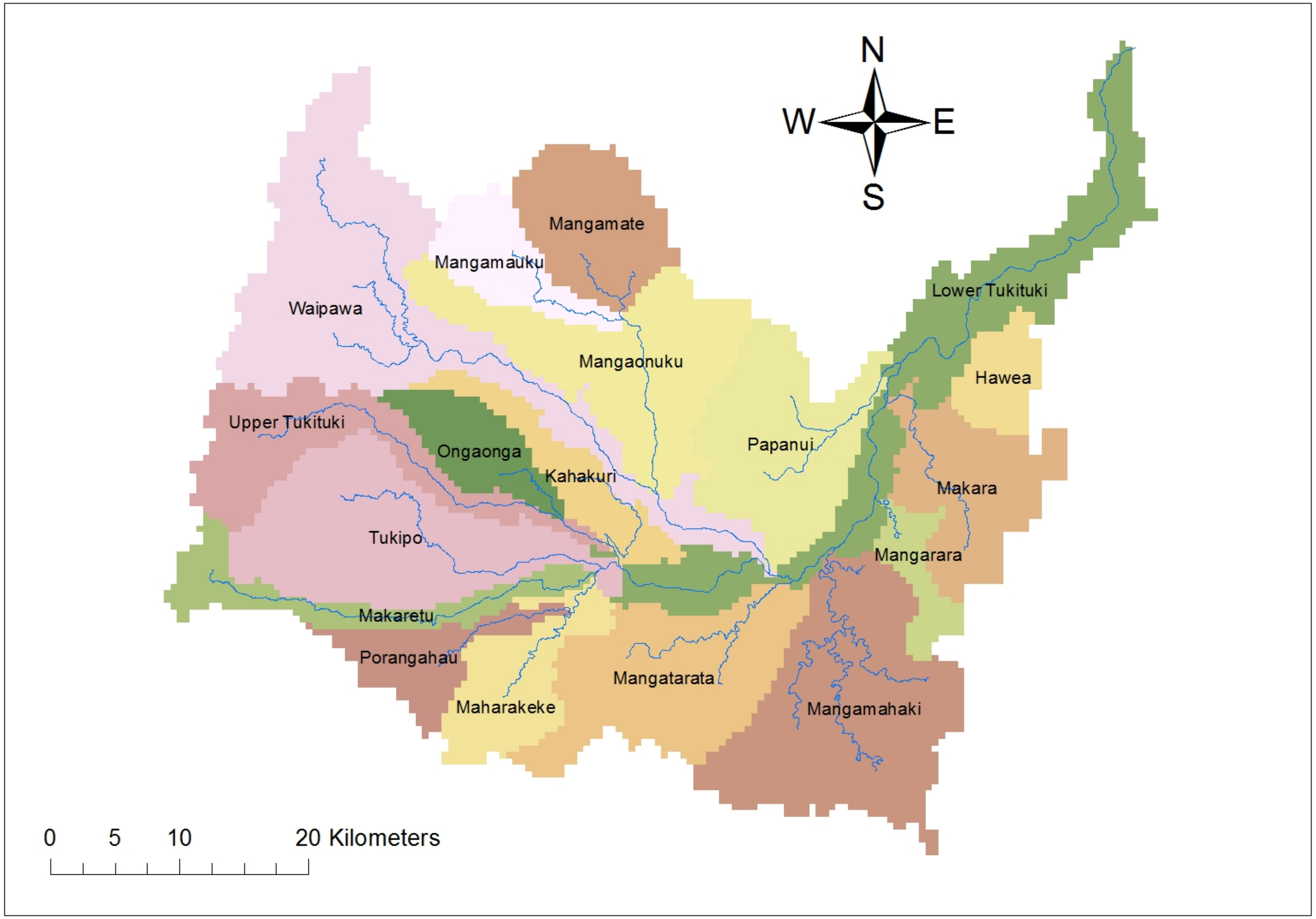

Figure 1-1: Map of the study area showing the major sub-catchments and streams of 4th-order and larger.

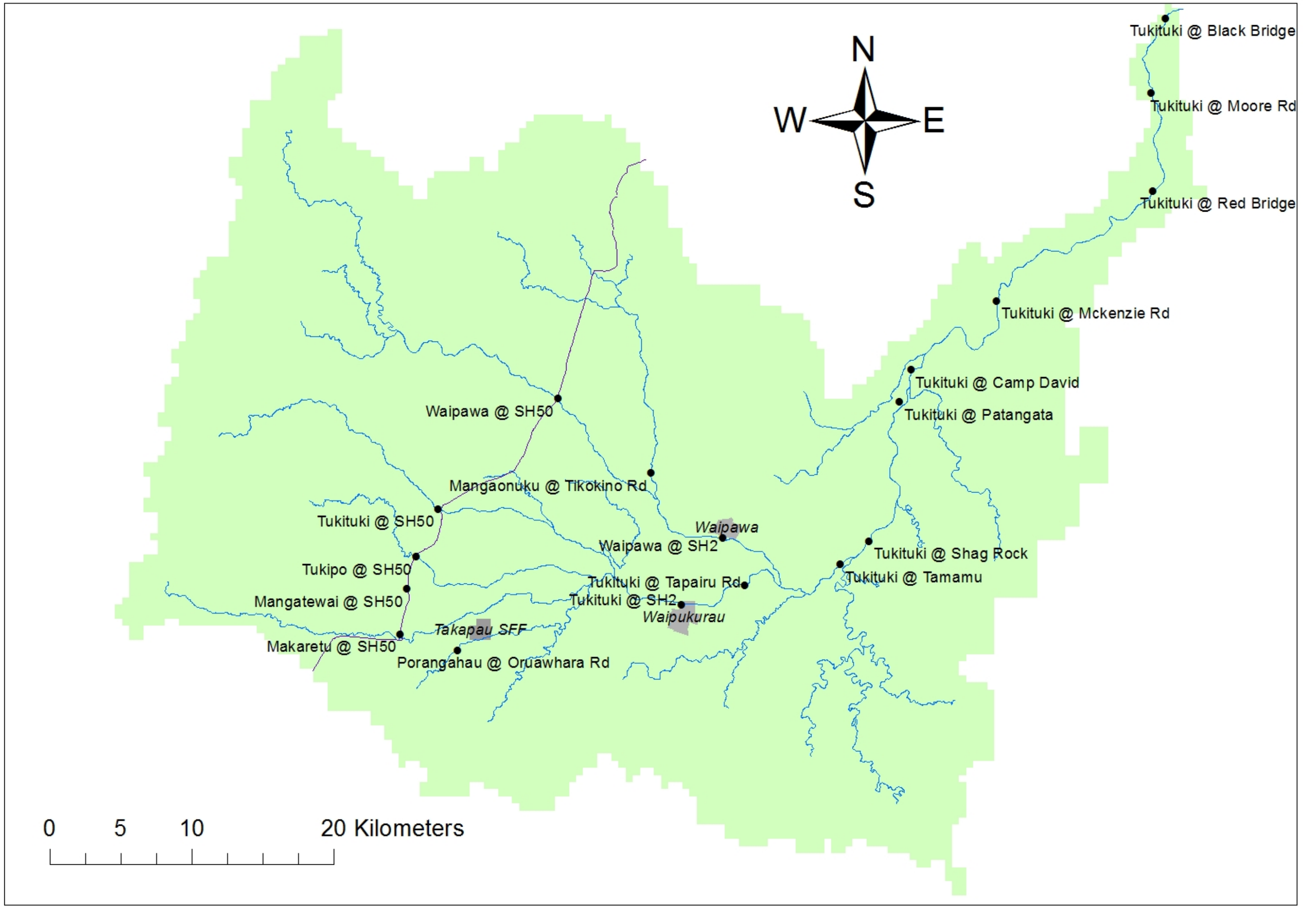

Figure 1-2: Map of the study area showing the main sampling sites. Also shown is SH50, the townships of Waipukurau and Waipawa and the Takapau meat processing facility operated by Silver Fern Farms (SFF).

2 Model framework

The TRIM model framework is detailed in an earlier report (Rutherford 2011) and is summarised briefly here. The three dominant processes in the catchment captured by the model are:

- nutrient losses from land
- delivery from where nutrient leaves land to where it enters streams and rivers, including travel times and attenuation, and
- nutrient/plant interactions in streams, including periphyton growth and nutrient recycling.

The Tukituki catchment is unusual in that the majority of water and nutrients originate in the upper and middle catchment, and the majority of recreational uses and periphyton problems occur in the lower river.

2.1 The TRIM2_CATCHMENT model

In an earlier study the TRIM1_CATCH model was applied to the Ruataniwha Basin, with inflows from other parts of the catchment either specified *a priori* and held constant, or ignored (Rutherford 2011, 2012). For this study, the model was extended to the whole of the Tukituki catchment and renamed TRIM2_CATCHMENT.

The TRIM2_CATCHMENT model estimates annual inflows of N and P into each reach of the stream network comprising streams of 4^{th}-order or larger (Figure 1-2). The TRIM2_CATCHMENT model, and its calibration and testing, are described in detail elsewhere (Rutherford 2013).

2.2 The TRIM2_STREAM model

2.2.1 Outline

The TRIM2_STREAM model predicts daily average nutrient concentrations and periphyton biomass in selected years. It comprises two sub-models: the hydraulic and the nutrient-biomass sub-models. Both sub-models operate on a sub-daily time step that depends on stream velocity and the segment length.

The network of streams 4^{th}-order and higher is sub-divided into 18 sub-catchments and then into 827 segments. Segments are 600 m long to match the spatial scale of the TRIM2_CATCHMENT model (cell size 500 x 500 m, area 25 ha). The river channel is assumed to be straight and uniform within each segment. Transverse and longitudinal spatial variations in depth, velocity and width are neglected, and the model predicts segment average nutrient concentration and biomass.

The nutrient-biomass sub-model simulates daily average photosynthesis, nutrient uptake and release but neglects sub-daily changes that arise from diurnal variations in photosynthesis. Periphyton biomass (BIO) is modelled as carbon (units: g C m^{-2}). Phytoplankton is not modelled. Four forms of nitrogen in the water column are modelled: ammonium (AMM), oxidised nitrogen (NNN), dissolved organic nitrogen (DON) and particulate organic nitrogen (PN). The nitrogen content of periphyton biomass is calculated from biomass carbon (BIO) using a fixed C/N ratio. Three forms of phosphorus in the water column are modelled: dissolved reactive phosphorus (DRP), dissolved organic phosphorus (DOP) and particulate phosphorus (PP). The phosphorus content of biomass is calculated from biomass carbon (BIO) using a fixed C/P ratio. Suspended solids concentration (SS) is calculated from PN and/or PP using fixed C/P and C/N ratios for comparison with measured SS concentrations. The model calculates total nitrogen (TN) and total phosphorus (TP) for comparison with measured TN and TP concentrations. Details of the process included in TRIM1_STREAM are given in Rutherford (2011).

The TRIM1_STREAM model was modified by allowing the user to include, or exclude, phosphorus exchange between the bed and the overlying water. The rate of exchange is assumed to be proportional to the difference between the stream DRP concentration and the equilibrium bed phosphorus concentration. Lucci et al. (2012) measured equilibrium bed P concentrations in New Zealand rivers and work is underway to measure exchange rates (Richard McDowell, AgResearch, pers. comm.). Neither the equilibrium concentration nor the exchange rate coefficient has been measured in the Tukituki River, and for this study they were estimated by calibration to measured stream DRP concentrations.

Analysis of observed and predicted stream nutrient concentrations and biomass is restricted to periods when flow is below 3 times median, because 3 times median flow is widely recognised as a flow that resets biomass (Biggs 2000). On days when the flow exceeds 5 times median, the full model equations are not solved. Nutrients are assumed to be conservative and periphyton biomass is reset to a prescribed low and uniform value.

2.2.2 Nutrient inflows

OVERSEER, which provides the input data for TRIM2_CATCHMENT, predicts long-term average nutrient losses from farmland expressed as annual TN and TP yields (kg ha^{-1} y^{-1}). The TRIM2_CATCHMENT model routes the annual TN and TP losses through the catchment and predicts annual TN and TP inflows into each stream segment. TRIM2_STREAM converts these annual inflows into daily inflows using a statistical technique, routes the daily inflows downstream, and simulates nutrient transformations and periphyton growth which vary seasonally[1].

HBRC provided monthly stream monitoring data covering the period 1989-2012. Only data from five sites in the middle Tukituki/Waipawa were used to develop the statistical model for daily nutrient inflows. These observations are affected by attenuation but less so that observations at sites further down the river network. Attenuation was accounted for by normalising as detailed below. Data from four sites in the lower Tukituki corridor were used for testing the TRIM2_STREAM model. Daily flows and monthly concentrations of NNN, TN, DRP and TP were collated and obvious outliers removed. Data were examined for time trends but no statistically significant trends were detected over the period 1989-2012. The relatively small number of samples and the high variability mean that trends may exist but are difficult to detect. Data from all years were pooled and occasional missing values filled using the median of all years. Concentrations were normalised by the flow-weighted mean

[1] TRIM2_CATCHMENT calculates annual average TN and TP concentrations in each stream in order to help calibrate key model coefficients (groundwater lag times, quick flow and slow flow attenuation, and stream attenuation). It needs to do this because calibration involves matching model predictions to stream monitoring results. TRIM2_STREAM does not use these predictions of annual average nutrient concentrations but rather repeats the stream calculations using a daily time step.

concentration for the site, and flows on the days samples were collected were normalised by the median flow for the site.

Figure 2-1 shows the relationship between normalised concentration and flow. In most streams there are several unexplained high concentrations at low flows. There is a weak but statistically significant correlation with flow for TN, TP and NNN, but not for DRP. There is no significant difference in normalised concentration between streams, partly because of high variability in concentration at a given flow. A power law equation was fitted to the pooled, normalised data using standard regression methods. An empirical error model was then fitted to the regression residuals. This model mimics the day-to-day changes in nutrient concentration.

Figure 2-2 shows the pooled TN and TP data and the fitted model. The error model contains random variables of which a single realisation was used for model calibration.

The input data for TRIM2_STREAM are estimated as follows:

- Daily stream flows are specified for each stream from adjacent flow sites, and values of Q/Q_{median} calculated.
- Inflow concentrations of NNN, TN, DRP and TP are calculated from Q/Q_{median} using statistical models.
- The majority of measured stream AMM concentrations in the middle Tukituki are close to the limit of detection, and AMM inflows from land are neglected. However, AMM inflows from point source discharges are included.
- There are few stream measurements of DON, PN, DOP and PP. It is assumed that DON = PN = (TN – NNN)/2 and that DOP = PP = (TP – DRP)/2. These approximate the relationships in the few observations that have been made of all the N and P species.

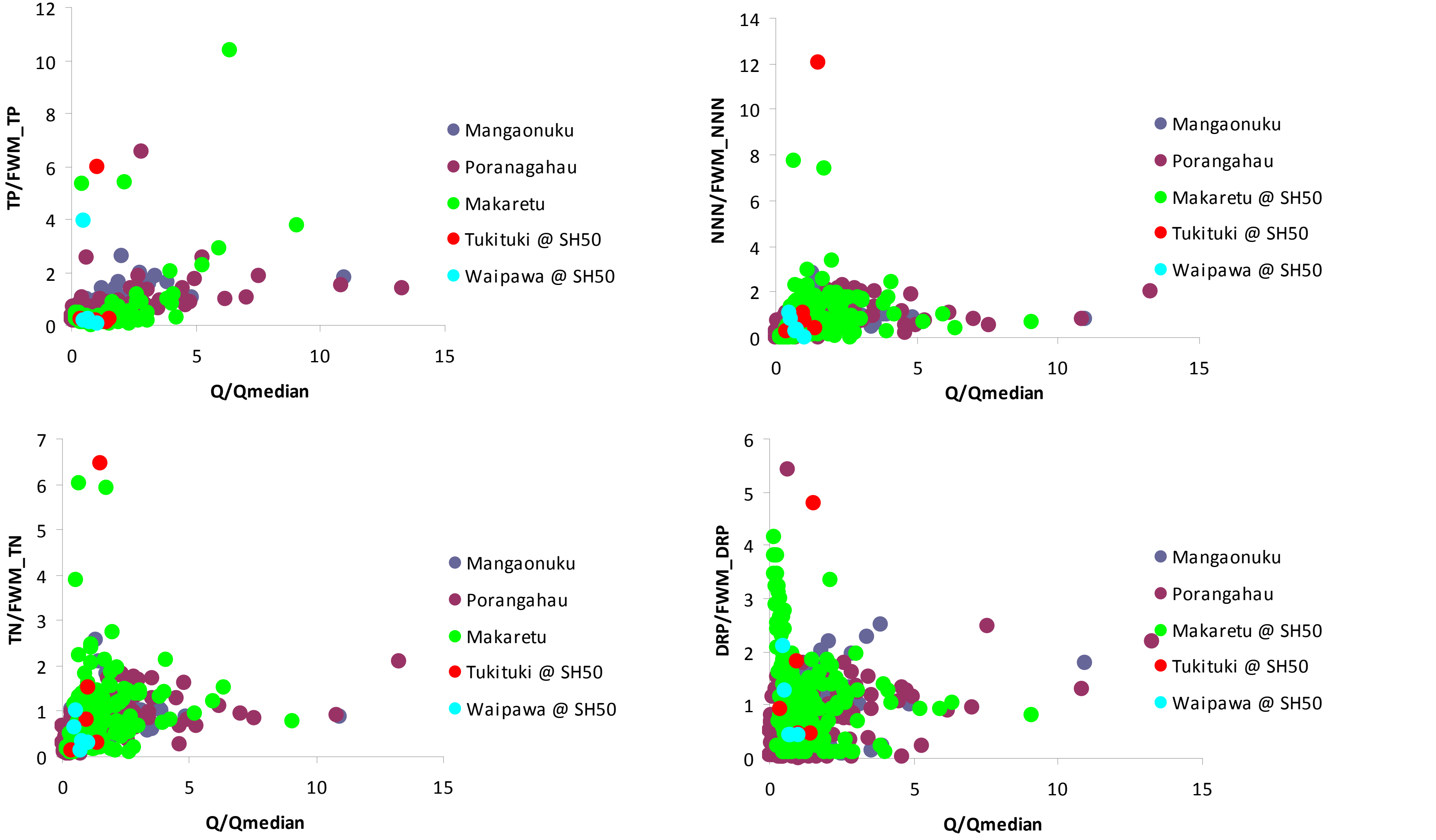

Figure 2-1: Variation of TN, TP, NNN and DRP concentration and flow at five stream sampling sites in the middle Tukituki 1989-2011. Flows are daily mean flow on the date sampled, normalised by the median flow for the site. Concentrations are normalised by the flow-weighted mean for the site.

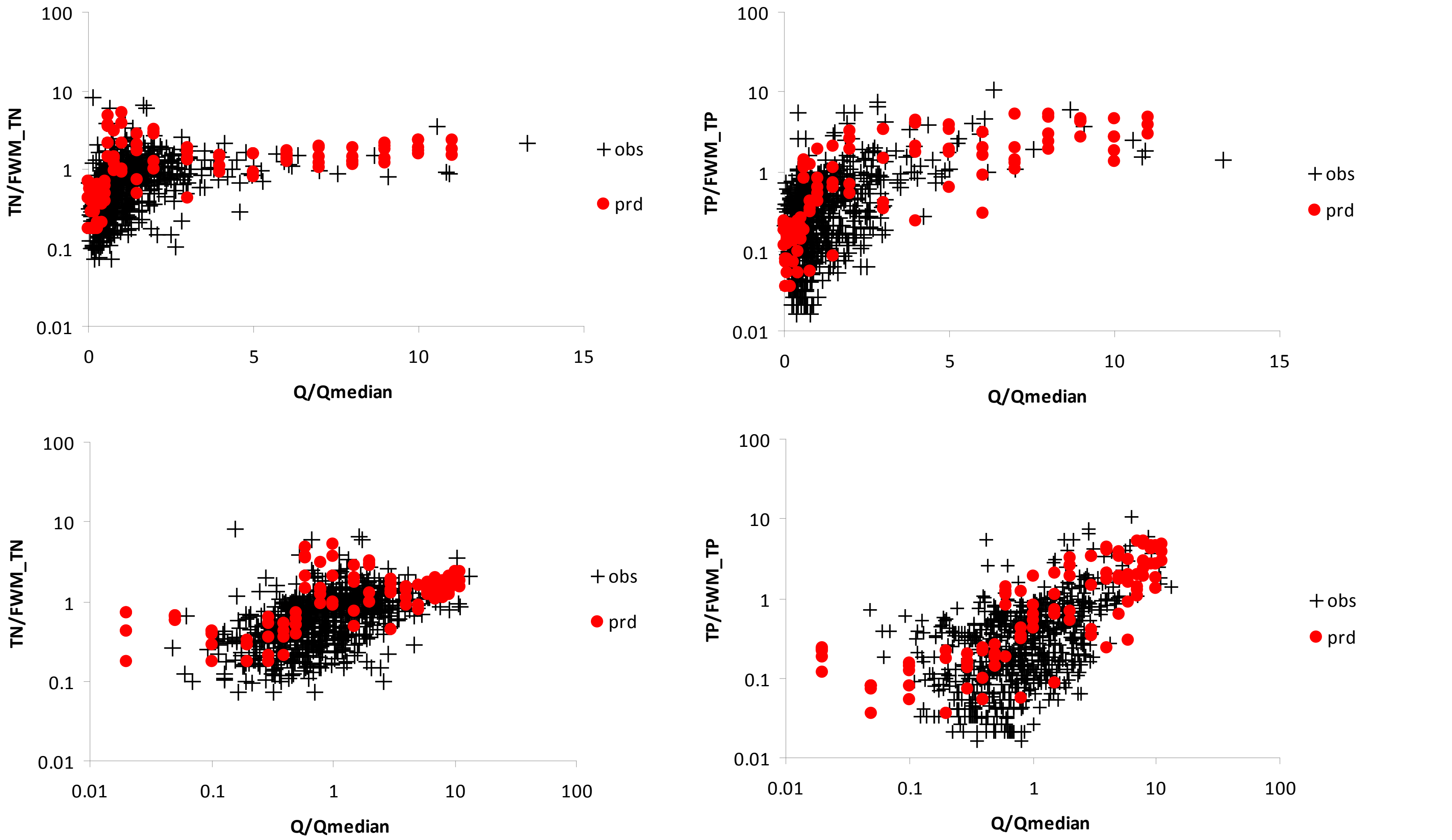

Figure 2-2: Observed variation of pooled TP and TN concentration with flow. Also shown is one realisation of the statistical model used to estimate daily inflow concentrations. The same data are plotted with two combinations of natural (top) and $\log_{10}$ (bottom) scales for flow to illustrate the model fit.

2.2.3 Nutrient concentrations and biomass

The TRIM2_STREAM model was modified by including phosphorus exchange between the stream bed and the overlying water[2], and the model was re-calibrated for 2010. 2010 was chosen because pre-irrigation land use is based on information around 2010 and rainfall in 2010 was close to the long-term average.

Figure 2-3 shows predictions along the Tukituki River from where it first becomes 4th-order to the sea. Distance is the cumulative distance along the nested stream channel network, working clockwise around the catchment from south-west (Maharakeke) to south-east (Hawea) finishing with the Tukituki main stem. In this system the Tukituki first becomes 4th-order at 370 km and then flows for a further 123 km to the sea at 493 km. Predictions are the upper and lower 95% confidence limits of the mean of daily values for 2010 on days when flows were less than three times median. Figure 2-3 also shows the mean and 95% confidence intervals of stream observations at flows less than 3 times median during the period 1989-2011.

Observations only exist for a small number of sites, mostly on the main stem of the Tukituki and Waipawa Rivers, or along SH50 near the middle of the tributaries. Consequently an assessment of model performance is possible in the middle and lower Tukituki River, but not near the bottom of the sub-catchments where the majority of groundwater upwelling occurs and high nutrient concentrations might be anticipated.

The model was calibrated assuming:

- Periphyton remove DRP, AMM and NNN from the water column during growth.
- Shade decreases with increasing stream order and affects periphyton growth rate.
- Growth and respiration rates vary with Julian day number to mimic temperature dependence.
- Periphyton respiration releases AMM and DRP with a recycling efficiency of 75%.
- Oxidation converts AMM to NNN.
- Periphyton scour increases with velocity and adds PN and PP to the water.
- Settling removes PN and PP from the water, with no recycling.
- Hydrolysis of PN and PP releases AMM and DRP respectively, with a recycling efficiency of 75%.
- Denitrification[3] removes NNN from the water.
- DON and DOP are assumed to be conservative.
- Exchange of DRP between the stream bed and the water is neglected[4].

[2] Initially the model is calibrated setting the phosphorus exchange rate to zero.
[3] Denitrification probably occurs in the periphyton mats of the hyporheos (stream bed sediments).
[4] Phosphorus exchange with the bed is modelled when alternative calibrations are considered, as discussed below.

Coefficients were initially those derived by calibration to detailed measurements made during a low flow period in January 2011 (Rutherford 2011, 2012). For this study, key coefficients were varied using a grid search to match predictions for 2010 to observations for 1989-2011. Goodness of fit was assessed visually. Calibrated coefficients after recalibration, discussed below, are summarised in Table 2-1.

Figure 2-3 indicates that with this set of coefficients TRIM2_STREAM predicts tolerably well the magnitude and spatial pattern of average nutrient concentrations and biomass in the main stem of the Tukituki River tolerably well. Predicted TP and DRP concentrations are high in the upper reaches of the Tukituki because of the high P yield in the Ruahine Ranges. Predicted mean TP and DRP concentrations exceed the mean of observations at 390 km (Tukituki River at SH50). However, predicted TP concentrations are high during high river flows and high flow concentrations dominate the means shown. Few measurements are made at high river flows and this makes the comparison of observed and predicted mean TP concentrations tenuous.

Predicted TN and NNN concentrations increase as the Tukituki River flows across the Ruataniwha Plain. Groundwater modelling predicts, and stream gaugings confirm, significant upwelling of groundwater upstream from Waipukurau (410 km). Bore water monitoring and groundwater modelling indicate that upwelling groundwater has high NNN concentrations. In the lower Tukituki, predicted and observed average NNN and TN concentrations do not decrease with distance. However, average predictions are strongly influenced by high flows when inflow nitrogen concentrations are high and there is little in-stream nitrogen removal. As discussed below, during summer low flows denitrification reduces nitrate concentrations to very low levels in the lower Tukituki. AMM concentrations are low except just below the WWTP because ammonium inflows from land are small and AMM is rapidly oxidised to NNN.

There is high spatial variability, and possibly bias, in measured periphyton biomass. The model predicts reach-average biomass but the observations tend to be made at a single cross-section, often on a selection of cobbles, and they may not be representative of reach-average biomass. There are few biomass measurements in the upper Tukituki, but the model appears to over-estimate biomass at 390 km (Tukituki at SH50). The highest observed biomass occurs at 420 km (Tukituki at SH2) in Waipukurau just upstream from the WWTP discharge. This high biomass is the result of diffuse source nutrients from the Ruataniwha Plain and/or as yet unidentified point sources in the township. The model predicts an increase in biomass immediately downstream from the WWTP in Waipukurau but, surprisingly, observed biomass is low immediately downstream from the WWTP. Possible reasons include: the stream is shaded, the bed sediment is fine and easily disturbed, and urban/industrial runoff may affect water clarity. The model predicts a decrease in biomass in the lower Tukituki whereas the observations suggest high biomass is maintained in the lower reaches. There are very few periphyton measurements away from the main stem river sites, which makes model predictions of biomass in the upper catchment and tributaries speculative.

Table 2-1: Coefficients of the TRIM2_STREAM model after re-calibration. * denotes coefficients that strongly influence model predictions for which reliable *a priori* estimates cannot be made from experimental data or the literature.

	Coefficient	Value	Units	Comment
1	NHalfSat	0.02	$g\ N\ m^{-3}$	half-saturation coefficient for DIN
2	PHalfSat	0.002	$g\ P\ m^{-3}$	half-saturation coefficient for DRP
3	BHalfSat	50	$g\ C\ m^{-2}$	half-saturation coefficient for BIO
4	GrowMax	15	$g\ C\ m^{-2}\ d^{-1}$	BIO maximum growth rate
5*	RespRate	0.02	d^{-1}	BIO respiration rate
6*	ScourRate	0.01	d^{-1}	BIO scour rate at the critical shear velocity
7	CritShearVel	0.03	$m\ s^{-1}$	Critical shear velocity for scour
8	ScourExp	2	(-)	Exponent of scour and shear velocity
9*	MaxSettle	20	$m\ d^{-1}$	Settling rate at the crucial velocity
10	CritSettle	0.3	$m\ s^{-1}$	Critical velocity for settling
11	SettleExp	2	(-)	Exponent of settling and velocity
12	N/C periphyton	0.1	(-)	N-C ratio of BIO
13	NNN respired	0	(-)	Fraction of N released as NNN by BIO respiration
14*	AMM respired	0.75	(-)	Fraction of N released as AMM by BIO respiration
15	PN hydrolysis	0	(-)	Fraction of N released as NNN by PN hydrolysis
16*	PN hydrolysis	0.75	(-)	Fraction of N released as AMM by PN hydrolysis
17	P/C periphyton	0.01	(-)	P-C ratio of BIO
18*	DRP respired	0.75	(-)	Fraction of P released as DRP by PER respiration
19*	PP hydrolysis	0.75	(-)	Fraction of P released as DRP by PP hydrolysis
20*	Hydrolysis	1	d^{-1}	Hydrolysis rate of PN and PP - assumed identical
21*	Denitrification	0.1	$g\ N\ m^{-2}\ d^{-1}$	Maximum denitrification rate
22	DNHalfSat	0.02	$g\ N\ m^{-3}$	Half-saturation for denitrification
23	AmmOxRate	10	d^{-1}	Ammonium oxidation rate
24*	PAdsorb	1	$m\ d^{-1}$	Bed P exchange rate
25*	Pequilibrium	0.005	$g\ P\ m^{-3}$	Equilibrium P concentration

Figure 2-4 and Figure 2-5 illustrate the spatial distribution along the Tukituki main stem in late summer (Julian Day 46) and early summer (Julian Day 307). On both days flow was close to the long term average at Red Bridge (20 $m^3\ s^{-1}$). Observed and predicted NNN, TN, DRP and TP concentrations match tolerably well. The model appears to over-estimate periphyton biomass.

Figure 2-6 and Figure 2-7 show time-series of predicted daily nutrient concentrations and biomass at two sites on the Tukituki River: SH2 in Waipukurau and Red Bridge. At SH2, predicted NNN concentrations are low during low flows. This arises from the assumption of a constant benthic denitrification rate (0.1 g $m^{-2}\ d^{-1}$). As the flow drops, depth decreases and the constant benthic denitrification rate causes the rate of removal of NNN from the overlying water to increase significantly. Denitrification rate has been measured in the lower Tukituki on two occasions. However, no measurements have been made in the upper parts of the catchment or the tributaries. The variation of denitrification rate throughout the year is not known.

Predicted DRP concentrations are low during low flows due to uptake by periphyton, despite 75% recycling during respiration. Predicted DRP concentrations drop below 0.001 g m^{-3} in the lower Tukituki. However, low flow studies in January 2011 found that DRP concentrations in the lower river did not drop below 0.003-0.005 g m^{-3}. It is not clear whether this was because:

- nitrogen became limiting to periphyton uptake so that DRP was not being removed from the water column while phosphorus was being recycled, or
- phosphorus was being released from the stream bed.

Note that in this simulation phosphorus exchange between the stream bed and the overlying water is neglected.

During prolonged low flows, periphyton biomass is predicted to reach high levels at SH2 (c. 20 g C m^{-2}). This site is upstream from the WWTP discharges and periphyton growth is controlled by diffuse inflows of N and P.

Low flow biomass at Red Bridge is slightly lower than at SH2 (c. 15 g C m^{-2}). The WWTP discharges increase DRP concentrations between SH2 and Red Bridge, which in turn increase periphyton growth rates and biomass. However, by the time the river reaches Red Bridge, periphyton uptake has reduced DRP concentrations, growth rate and biomass.

During high flows, periphyton biomass is predicted to be low because of scour, while nutrient concentrations are high because inflows are high and there is little nutrient removal in the stream channel.

Figure 2-8 and Figure 2-9 show predicted time-series of NNN and DRP concentration in the 7 major sub-catchments of the middle Tukituki, and 2 sites on the main stem of the Tukituki and Waipawa Rivers. The sub-catchments of these sites include most of the land in Zones A-D of the irrigation consent area (ICA). There are no measured nutrient concentrations in 6 of the sub-catchments to compare with 2010 predictions, although monitoring is now being undertaken. However, the Mangaonuku has been monitored near its confluence with the Waipawa. Average measured NNN concentrations (1.9 ± 0.1 g m^{-3}, mean ± 95% confidence interval) and DRP concentrations (0.010 ± 0.001 g m^{-3}) in 1989-2011 are consistent with those predicted (Figure 2-8 and Figure 2-9). The temporal variability in predicted concentrations is high and the observed ranges (maximum minus minimum) for NNN (4.8 g m^{-3}) and DRP (0.031 g m^{-3}) are consistent with the predictions.

These results indicate that 'hot spots' of high NNN and DRP concentration are likely to occur in several sub-catchments. In the Porangahau Stream, NNN and DRP concentrations are high partly as a result of drainage and runoff from the SFF land disposal site, combined with drainage and runoff from intensive pastoral agriculture. In the Maharakeke and Ongaonga Streams NNN and DRP concentrations are high because of drainage and runoff from intensive agriculture. In the Tukituki and Waipawa Rivers at SH2, NNN and DRP concentrations are lower than in the tributaries because of dilution by low nutrient concentration water draining the Ruahine Ranges.

Nutrient concentration predictions in 6 of the 7 major tributaries are unvalidated because there are no measurements to corroborate them. However, based on the tolerably good match between observed and predicted concentrations in the Mangaonuku, they are considered sufficiently reliable for assessing the likely impacts of the RWSS.

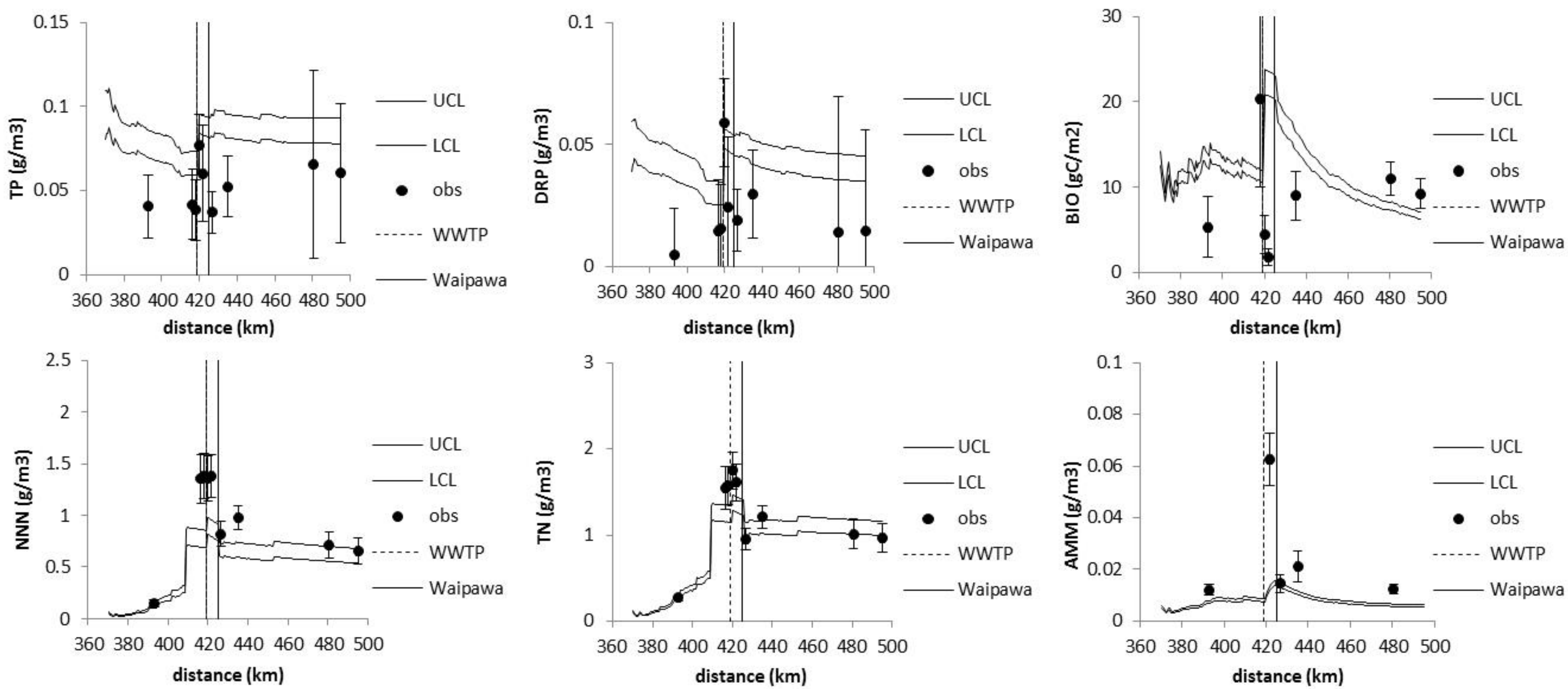

Figure 2-3: Pre-irrigation – observed (obs) and predicted (UCL, LCL) nutrient concentrations and periphyton biomass along the main stem of the Tukituki River in 2010. UCL and LCL denote the upper and lower 95% confidence limits of the mean of daily predictions during 2010 at flows below three times median. Obs denotes the mean and 95% confidence limits of monthly sampling results 1989-2011 at flows below 3 times median. Distance is the cumulative distance along the nested stream channel network (see text for details).

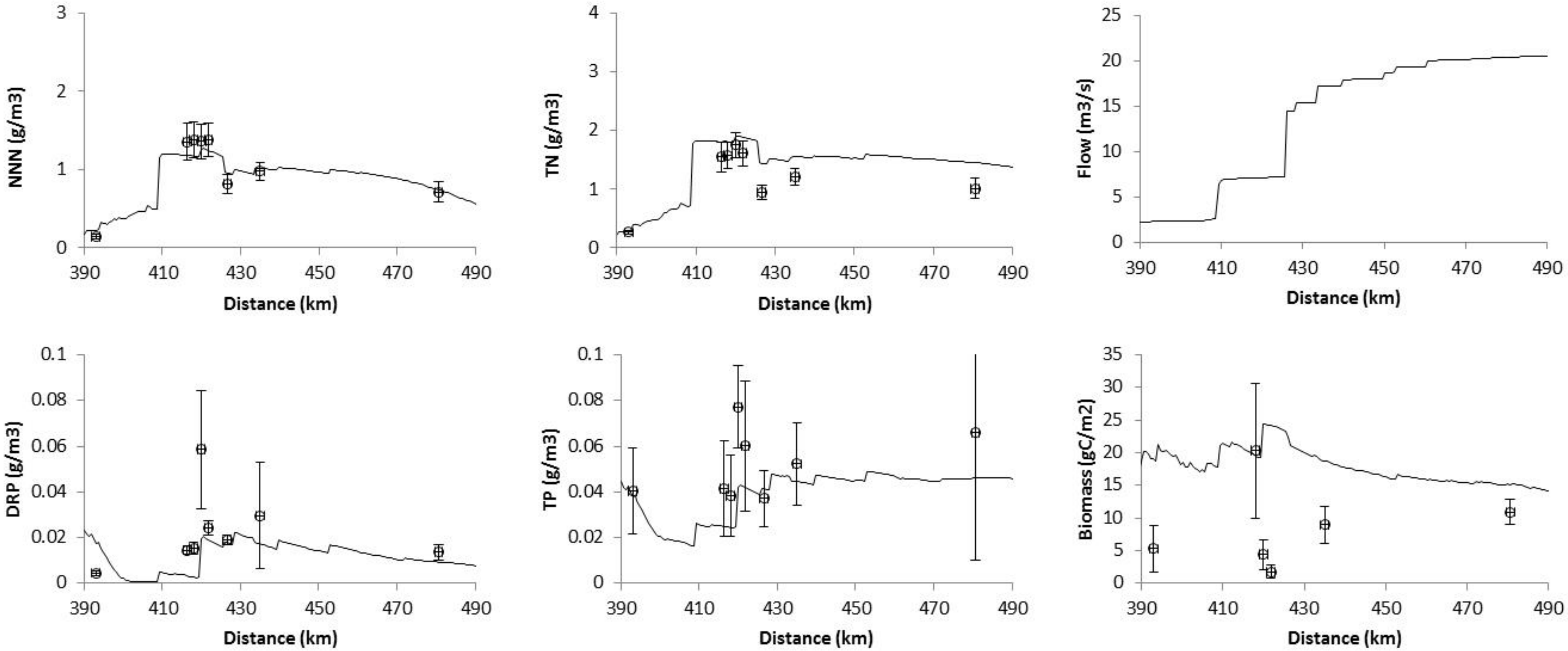

Figure 2-4: Pre-irrigation – predicted flows, nutrient concentrations and periphyton biomass (lines) along the Tukituki River on Julian Day 46 in 2010. Predictions above 3 times median are omitted. Also shown (circles) are the mean and 95% confidence intervals of observations in 1989-2011 at flows below 3 times median.

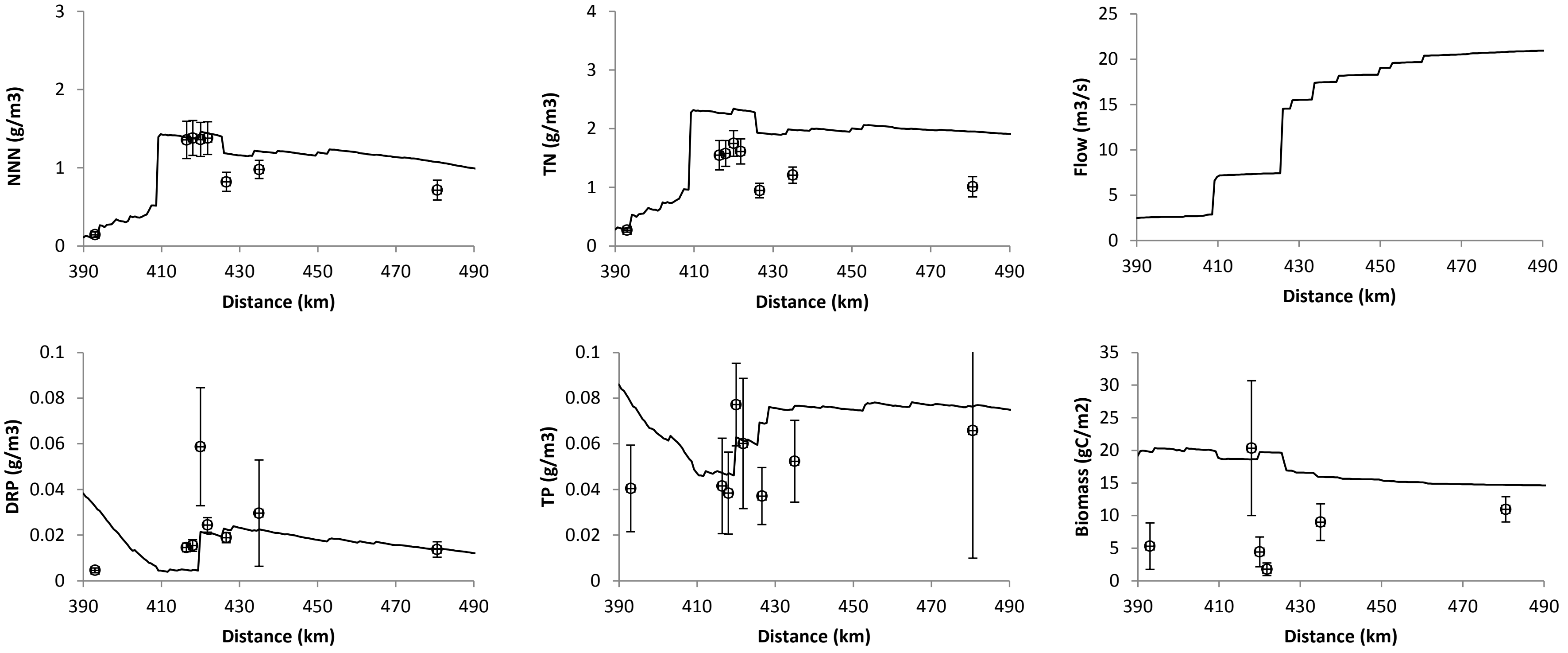

Figure 2-5: Pre-irrigation – predicted flow, nutrient concentrations and periphyton biomass (lines) along the Tukituki River on Julian Day 307 in 2010. Predictions above 3 times median flow are omitted. Also shown (circles) are the mean and 95% confidence intervals of observations in 1989-2011 at flows below 3 times median.

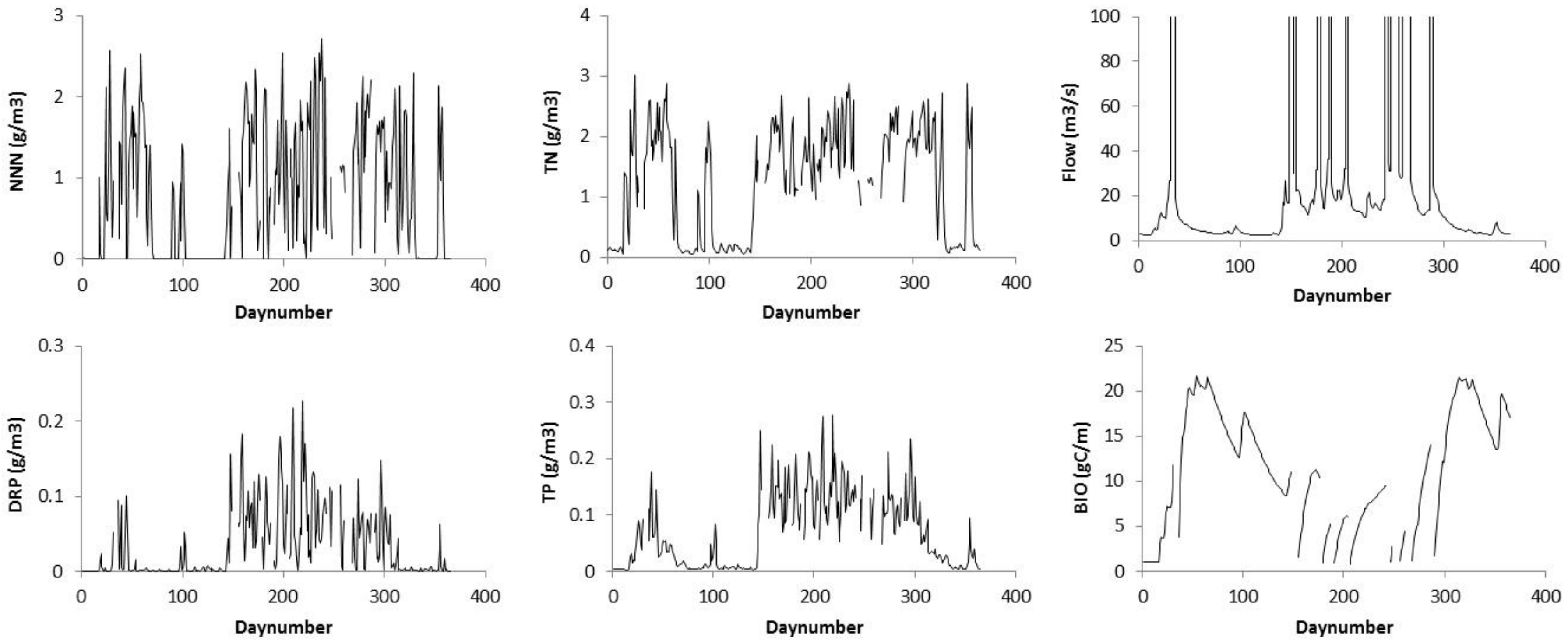

Figure 2-6: Pre-irrigation – predicted time-series of nutrients and biomass in the Tukituki River at SH2 during 2010. Predictions above 3 times median flow are omitted.

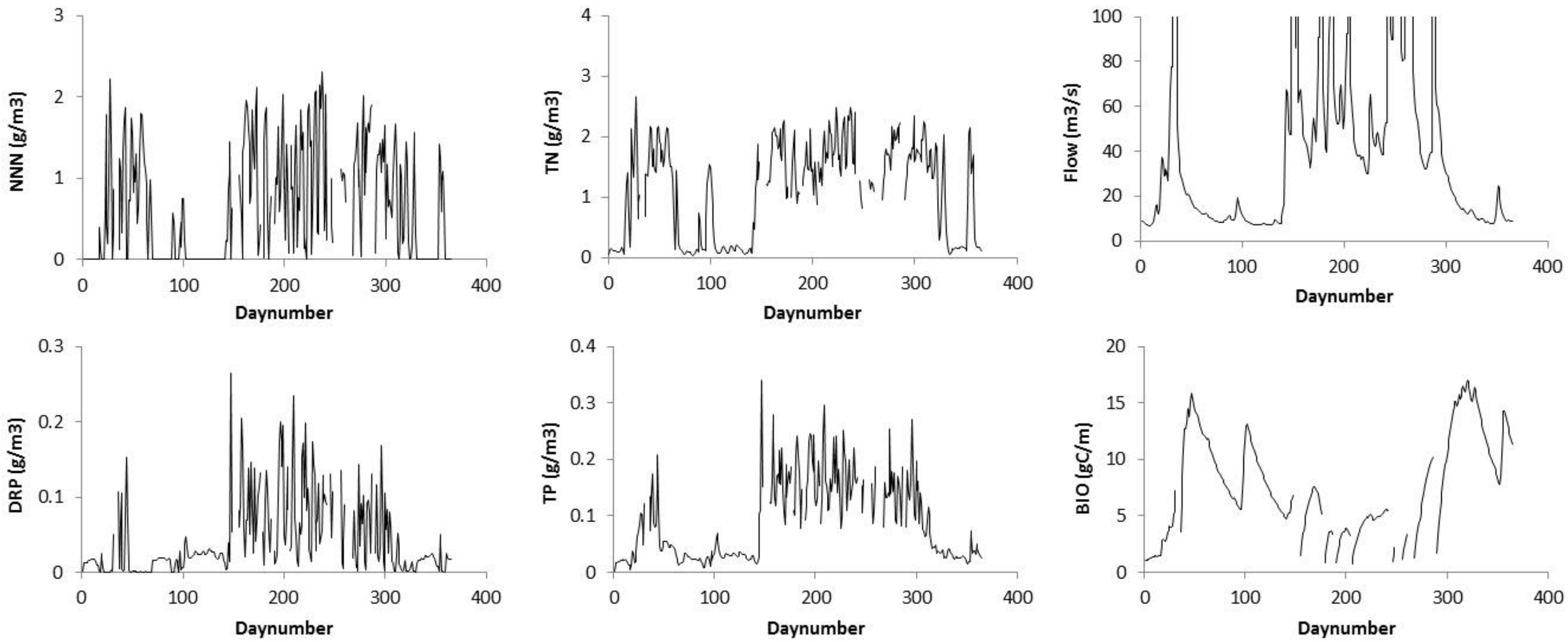

Figure 2-7: Pre-irrigation – predicted time-series of nutrients and biomass in the Tukituki River at Red Bridge during 2010. Predictions above 3 times median flow are omitted.

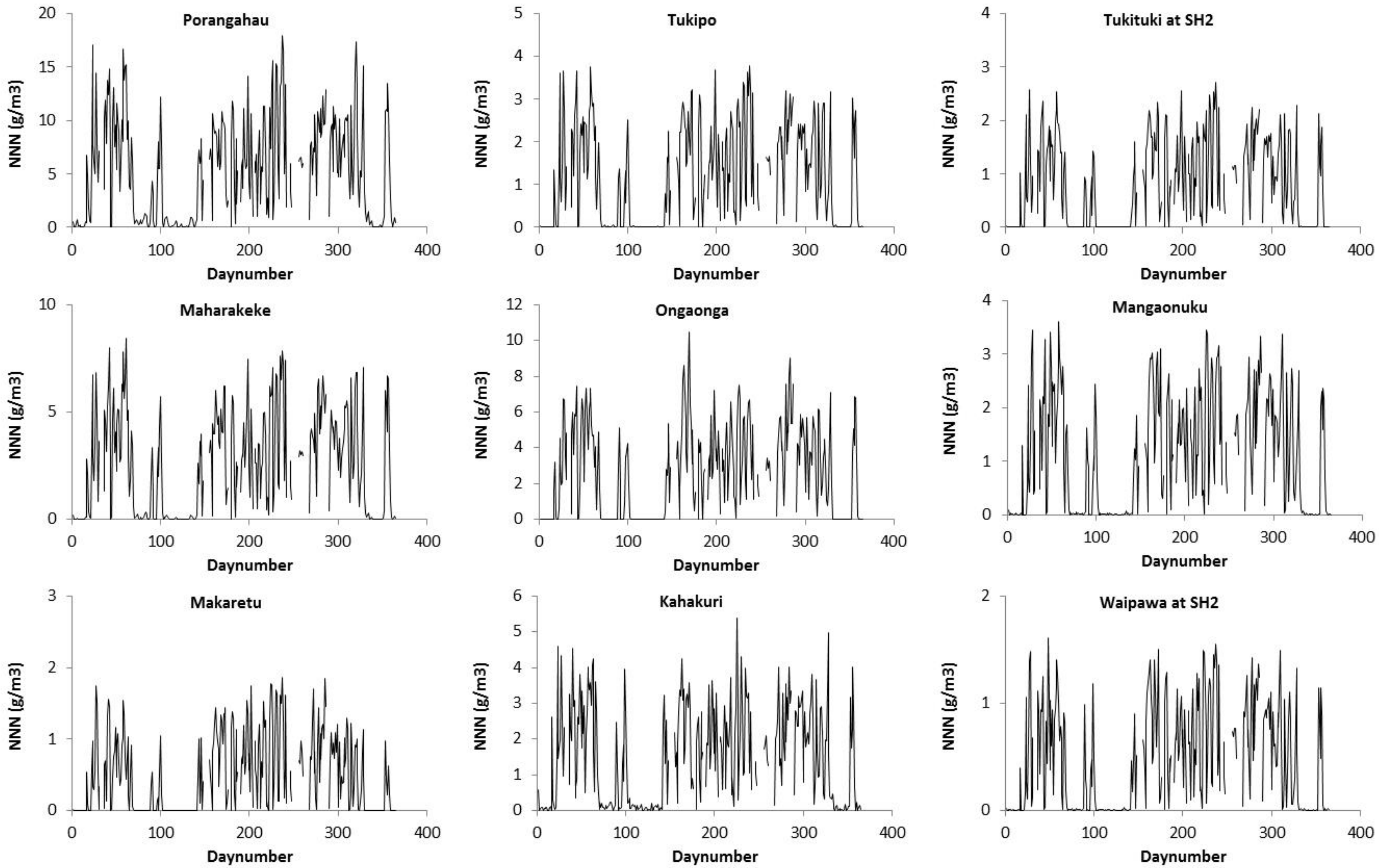

Figure 2-8: Pre-irrigation – predicted time-series of NNN concentration in the middle Tukituki and tributaries in 2010. Except for the Tukituki and Waipawa at SH2, concentrations are shown just above the confluence (viz., at the bottom of the sub-catchment).

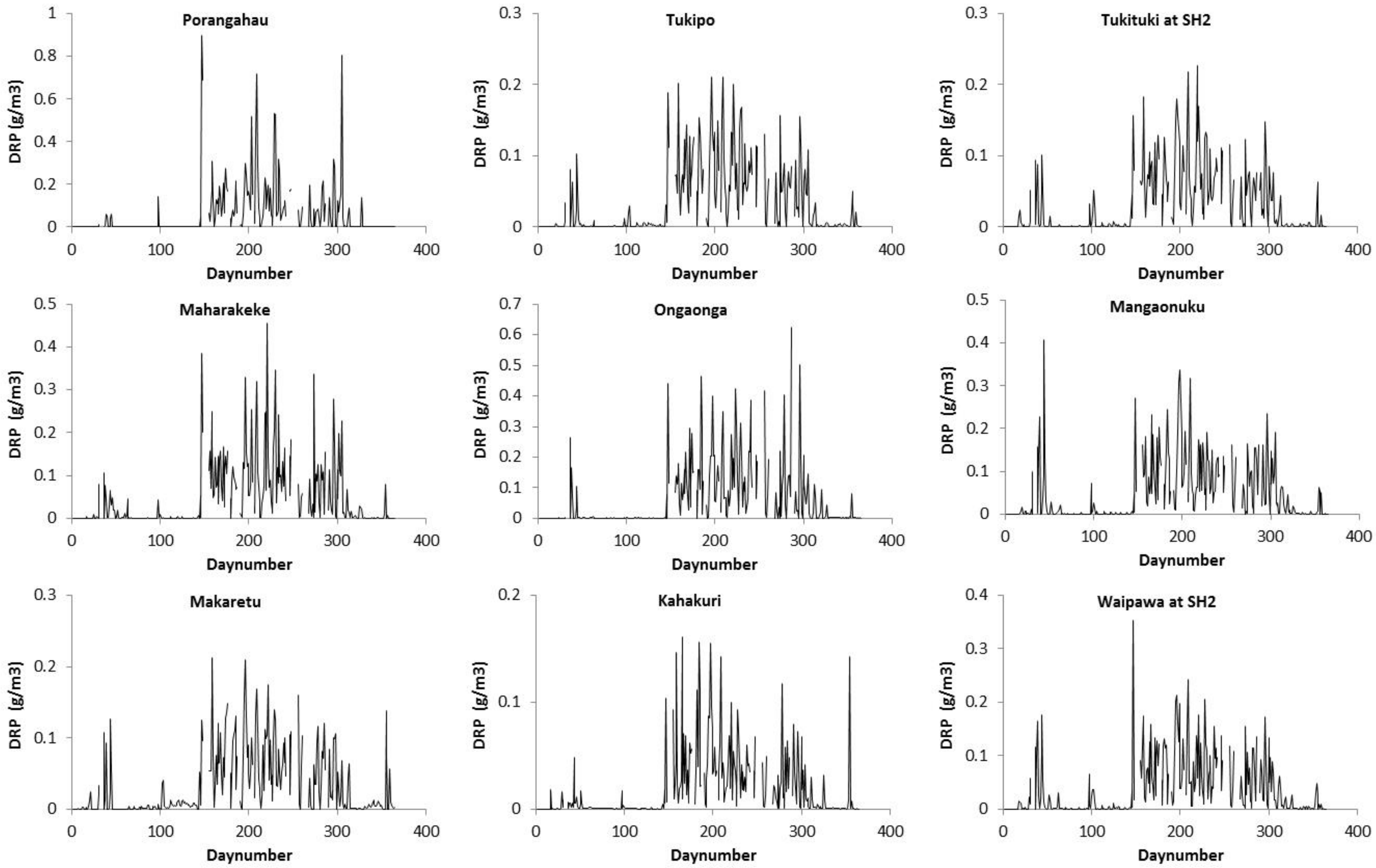

Figure 2-9: Pre-irrigation – predicted time-series of DRP concentration in the middle Tukituki and tributaries. Except for the Tukituki and Waipawa at SH2, concentrations are shown just above the confluence (viz., at the bottom of the sub-catchment).

2.2.4 Discussion of model calibration

These simulations indicate that the TRIM2_STREAM model simulates nutrient concentration and periphyton biomass under pre-irrigation conditions tolerably well. There are some mismatches between observations and predictions. These arise from uncertainty in:

1. Model input data.
2. Monitoring results, notably of periphyton biomass.
3. Calibration.

Uncertainties in model input data arise from the farming systems data provided as input to OVERSEER, the OVERSEER predictions of nutrient loss, information on point source nutrient inflows, and possible inflows from unrecorded sources. Uncertainties in monitoring results arise from the fact that sampling is monthly and may not occur across a representative range of flows and conditions within the catchment. Uncertainties in model calibration arise from the possibility that different combinations of coefficients might give equally good matches between observations and predictions.

The TRIM2_STREAM model contains 25 coefficients (Table 2-1). For 14 of these, either reliable estimates can be made from the literature and field measurements, or predictions are not very sensitive to variations within a sensible range of values. This leaves 11 coefficients that have a strong influence on model predictions but cannot be estimated reliably from experimental data or the literature (marked in Table 2-1).

Maximum periphyton growth rate is a key coefficient. It was estimated from gross primary productivity (GPP) rates calculated from diurnal dissolved oxygen data measured during the low flow survey in January 2011 (Roger Young, Cawthron Institute, pers. comm.). In the model actual growth rate is lower than the maximum growth rate because of the effects of shade, seasonally varying temperature and sub-optimal nutrient concentrations. The maximum growth rate used (15 g C m^{-2} d^{-1}) lies at the upper end of published growth rates measured in laboratory and chamber studies (Rutherford et al. 1997).

The diurnal dissolved oxygen data from January 2011 also furnished estimates of community respiration rate. However, community respiration rate includes contributions from both autotrophic (periphyton) and heterotrophic (bacteria, fungi) organisms. The latter are not explicitly modelled in TRIM2_STREAM and so periphyton respiration was set lower than community respiration, and adjusted so that observed and predicted biomass matched.

Nutrient recycling affects the distance over which nutrient inflows cause elevated periphyton growth rates and biomass. A parsimonious model of recycling is used in TRIM2_STREAM which assumes:

1. Fixed C:N:P ratios.
2. Recycling of AMM and DRP by periphyton respiration.
3. Scour of periphyton to suspended detritus.
4. Recycling of AMM and DRP by hydrolysis of suspended detritus.
5. Settling of suspended detritus.

6. No recycling of AMM and DRP by hydrolysis of settled detritus.

The efficiency of recycling (viz., the proportions of N and P recycled) was adjusted so that observed and predicted AMM, TN, DRP and TP concentrations matched.

Periphyton biomass is determined by maximum growth rate, AMM and DRP concentrations, shade, temperature, respiration rate and scour rate. Concentrations of particulate nutrient were measured during the low flow survey in January 2011 from which an estimate of scour rate was made. Particulate nutrient concentrations were similar along the channel which indicates that scour and settling rates were similar. The rate of nutrient recycling from scoured material has not been measured and model calibration assumes that PN and PP are hydrolysed to AMM and DRP while suspended, but that once settled there is no further recycling. During the 2011 survey, dry settled material was abundant along the water's edge – presumably stranded as flow decreased and water level declined. When the water level is constant or rising, scoured material settles in shallow water along the edges of the channel where decomposition and recycling are likely to occur. If so, then the calibrated rate of hydrolysis of suspended PN and PP includes recycling from both suspended and settled particulates.

The major loss mechanism of NNN in the middle Tukituki River during summer low flows has recently (February 2013) been confirmed as denitrification (Bob Wilcock, NIWA, pers. comm.). Denitrification rates have not yet been calculated from the observed nitrous oxide and di-nitrogen gas measurements. The model has been calibrated assuming a spatially uniform, and time invariant, benthic denitrification rate (units g m^{-2} d^{-1}). It is conceivable that denitrification occurs within the periphyton mat, in which case it may be low when periphyton biomass is low. On the other hand, denitrification may occur within the hyporheic zone (viz., within the top layer of porous gravels on the stream bed), in which case it may not vary much during the year. There is evidence from flow gaugings in the Tukituki River and water temperature studies in the adjacent Ngaruroro River of flow through the top layer of gravels – which suggests an active hyporheos. Overseas studies have shown that denitrification occurs in the hyporheos where streambed sediments are porous.

Observed BIO is highest just upstream from the WWTP and is low immediately downstream from the WWTP. There may be a source of phosphorus in Waipukurau that gives rise to locally elevated nutrient concentrations and periphyton biomass, although this possibility has yet to be investigated. The channel immediately downstream from the WWTP is heavily shaded and comprises small gravels that are mobile under moderate flows. Industrial activity including gravel extraction and processing may release fine sediment that affects periphyton biomass, although this possibility has yet to be investigated. It is conceivable that these three factors contribute to low biomass immediately below the WWTP, even though observed DRP concentrations are high.

It is difficult to measure reach-average periphyton biomass accurately for comparison with model predictions. Periphyton biomass varies spatially in response to variations in substrate stability, water depth and velocity, shade, grazing pressure and disturbance. The model predicts reach-average biomass, whereas most sampling involves measuring biomass on a few selected stones or making a visual assessment of percentage cover across one or more cross sections of the river. Observations of periphyton biomass provide a useful indication of abundance and spatial changes, but are less amenable to a quantitative comparison with predictions than are nutrient concentrations.

2.2.5 Sensitivity analysis

Two key questions are:

1. Do alternative combinations of coefficients exist that give an equally good match between observations and predictions?
2. If so, do the alternative coefficients result in significantly different predictions of the impact of the RWSS?

The first is a difficult question to address for three reasons. First, the model contains a lot of coefficients and a formal sensitivity analysis would be very time consuming. Second, there are uncertainties in the model input data and so not only would the sensitivity analysis need to vary the model coefficients, but it would also need to vary the input data. This would make sensitivity analysis even more time consuming. Thirdly, there are uncertainties in the observations against which the model fit is assessed. This means that it may not be possible to identify model coefficients through a formal sensitivity analysis.

The approach taken in this study is to:

1. Identify the processes and hence model coefficients most likely to affect predictions of the impact of the RWSS.
2. Seek possible alternative calibration(s).
3. Make predictions using the alternative model(s).

In the upper and middle catchment there is clear evidence that periphyton growth rate and biomass are controlled by the availability of phosphorus. Nitrogen is present in excess of the concentrations that limit periphyton growth rate, with two exceptions: in the headwater streams where they emerge from the Ruahine Ranges, and in the lower reaches of the Tukituki River (from near Red Bridge to the sea) during summer low flows as a result of denitrification. Consequently, controlling phosphorus inflows is the key to controlling periphyton biomass in the majority of the Tukituki River.

In the model the key processes that affect total phosphorus within the river channel are:

1. Adsorption/desorption on bed sediments.
2. Settling of scoured biomass (detritus).
3. Recycling by respiration, hydrolysis of suspended detritus, and hydrolysis of settled detritus.

Ideally, experimental measurements would indicate which of these processes dominates and furnish direct estimates of key model coefficients. However, no direct measurements of phosphorus exchange with bed or recycling from suspended and settled detritus have yet been made in the Tukituki River.

Periphyton biomass is largely determined by phosphorus supply, and any increases in AMM and NNN concentration resulting from the RWSS are unlikely to affect periphyton. However, concerns have been raised about the risks of nitrate toxicity. Given the expected increases in TN losses from land use intensification, it is important to determine the sensitivity of predicted NNN concentrations to uncertainty in model calibration.

In the model the key processes that affect nitrogen are:

1. Denitrification.
2. Recycling by respiration, hydrolysis of suspended detritus and hydrolysis of settled detritus.

2.2.6 Alternative model calibration – phosphorus exchange with the bed

There is evidence from the 2011 survey that phosphorus release from the bed may have maintained DRP concentrations at 0.003-0.005 g m^{-3} in the lower reaches of the Tukituki River (from near Red Bridge to the sea) at a time when periphyton growth rate and biomass were high. However, an alternative explanation is that DRP concentrations remained high because NNN concentrations were low, periphyton were nitrogen limited, and DRP uptake was low. To help explore these two alternatives, phosphorus exchange between the stream bed and the overlying water was added to the TRIM2_STREAM model.

Figure 2-10 compares predicted DRP concentrations and periphyton biomass with and without phosphorus exchange. The equilibrium concentration of bed sediment was set to 0.005 g m^{-3} being close to the minimum DRP concentrations measured during the January 2011 survey. The exchange rate was estimated to be 1 m d^{-1} by matching observed and predicted DRP and TP concentrations. Phosphorus exchange reduces the previously high average DRP concentration in the upper Tukituki River because DRP is absorbed by sediment particles in the stream bed. The same occurs in the lower Tukituki River, but average concentrations are similar just below the WWTP. Despite the differences in average DRP concentration, maximum biomass near Waipukurau remains much the same. Phosphorus exchange increases average biomass in the lower Tukituki River from 460-500 km. The reason is that, during low flows, phosphorus is released from the bed which offsets uptake by periphyton, and helps maintain high biomass.

Figure 2-11 compares time-series of predicted concentrations at Red Bridge during 2010. Phosphorus exchange reduces DRP concentrations by an order of magnitude, and TP concentrations by about 50%. TP concentrations do not change as much as DRP concentrations because PP contributes to TP concentrations and is determined by periphyton biomass, scour and settling – none of which changes significantly. However, the reductions in DRP concentration have only a minor impact on predicted biomass. The reason is that phosphorus supply, rather than phosphorus concentration, determines periphyton growth rate and biomass. With phosphorus exchange included in the model, when concentrations are above the equilibrium concentration (0.005 g m^{-3}) phosphorus is absorbed by the bed. Conversely, there is a steady resupply of phosphorus from the bed when concentrations drop below 0.005 g m^{-3}. The phosphorus released is immediately taken up by periphyton, and does not show up as elevated DRP concentrations, but is sufficient to maintain high biomass.

Decreasing the exchange rate from 1 to 0.1 m day^{-1} while holding the equilibrium concentration at 0.005 g m^{-3} increases predicted DRP and TP concentrations but does not significantly change predicted biomass (Figure 2-12).

Increasing the equilibrium concentration from 0.005 to 0.050 g m^{-3} while holding the exchange rate at 1 m day^{-1} increases DRP and TP concentrations and doubles periphyton biomass (Figure 2-12). In this simulation there is no coupling between phosphorus inflows and equilibrium concentration. One might expect the equilibrium concentration to be low in forested catchments where phosphorus inflows are low, and high in agricultural catchments where phosphorus inflows are high, although this relationship has not been quantified in the Tukituki. As detailed below, the anticipated changes in phosphorus inflows from the RWSS are small (6% in the absence of any mitigation), and one would not expect the equilibrium concentration to change significantly.

The current values of the equilibrium concentration and the exchange rate are unknown, as are the likely changes as a result of the RWSS. It is desirable to investigate the mechanisms and rates of phosphorus exchange with the bed in the Tukituki. However, the forgoing simulations suggest that phosphorus exchange does not have a strong influence on periphyton biomass provided the equilibrium phosphorus concentration does not change significantly. Given that the anticipated changes in phosphorus inflows from the RWSS are small, it seems unlikely that the RWSS will significantly alter the equilibrium phosphorus concentration.

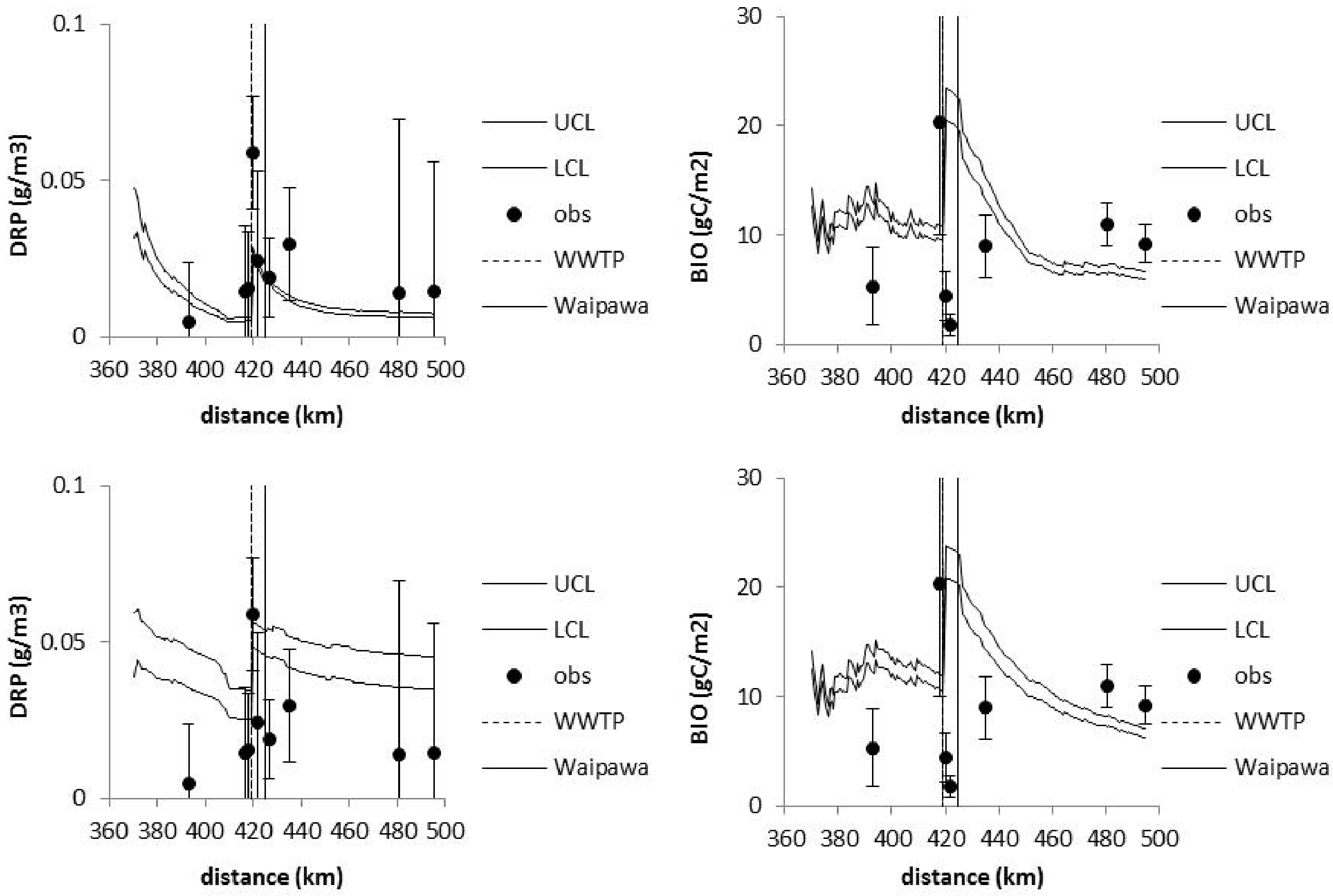

Figure 2-10: Comparison of predicted mean DRP concentrations and periphyton biomass with (top) and without (bottom) phosphorus exchange between the bed and the overlying water. UCL and LCL are the 95% confidence limits of the mean of daily predictions in 2010. Obs are the mean and 95% confidence limits of monthly observations in 1989-2011. Predictions and observations at flows above 3 times median are omitted. Phosphorus exchange is modelled assuming an equilibrium concentration of 0.005 g m^{-3} and an exchange rate of 1 m d^{-1}.

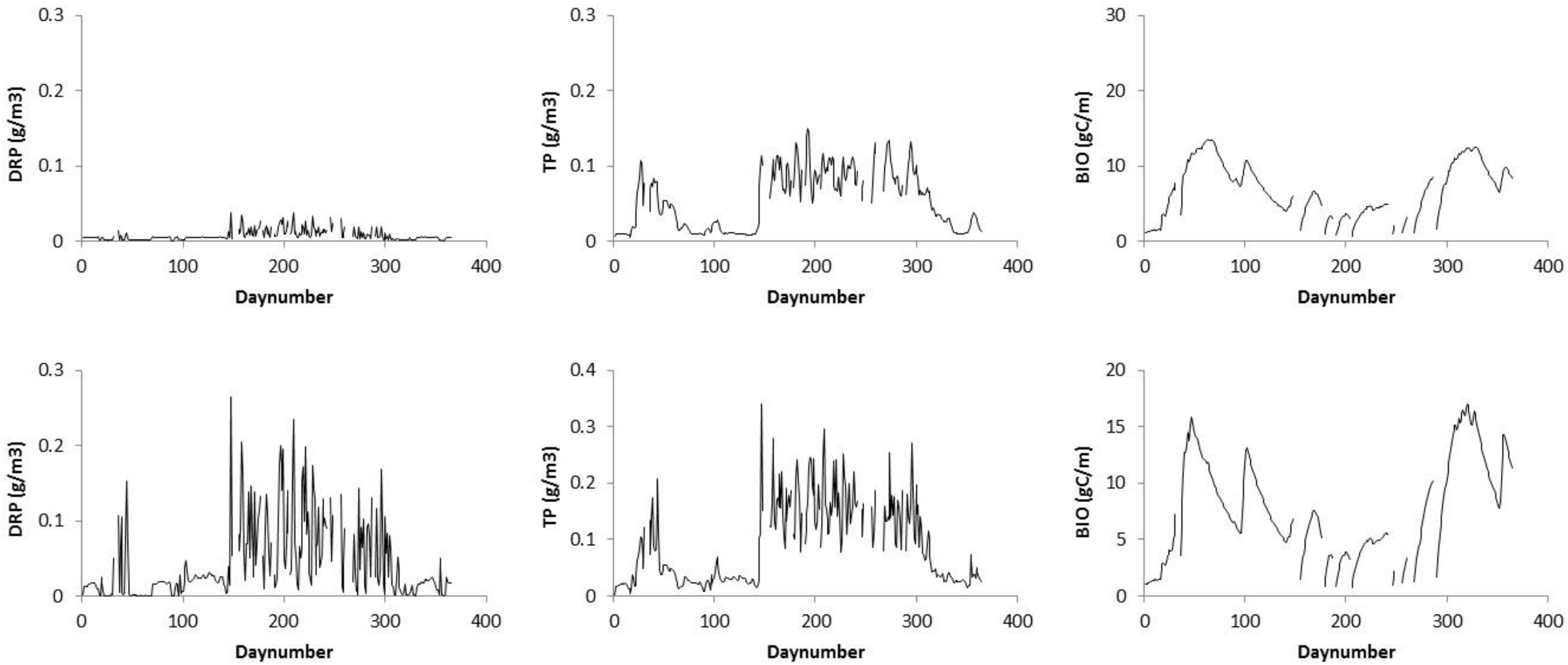

Figure 2-11: Comparison of predicted DRP, TP and BIO at Red Bridge with (top) and without (bottom) phosphorus exchange between the bed and the overlying water. Phosphorus exchange is modelled assuming an equilibrium concentration of 0.005 g m^{-3} and an exchange rate of 1 m d^{-1}.

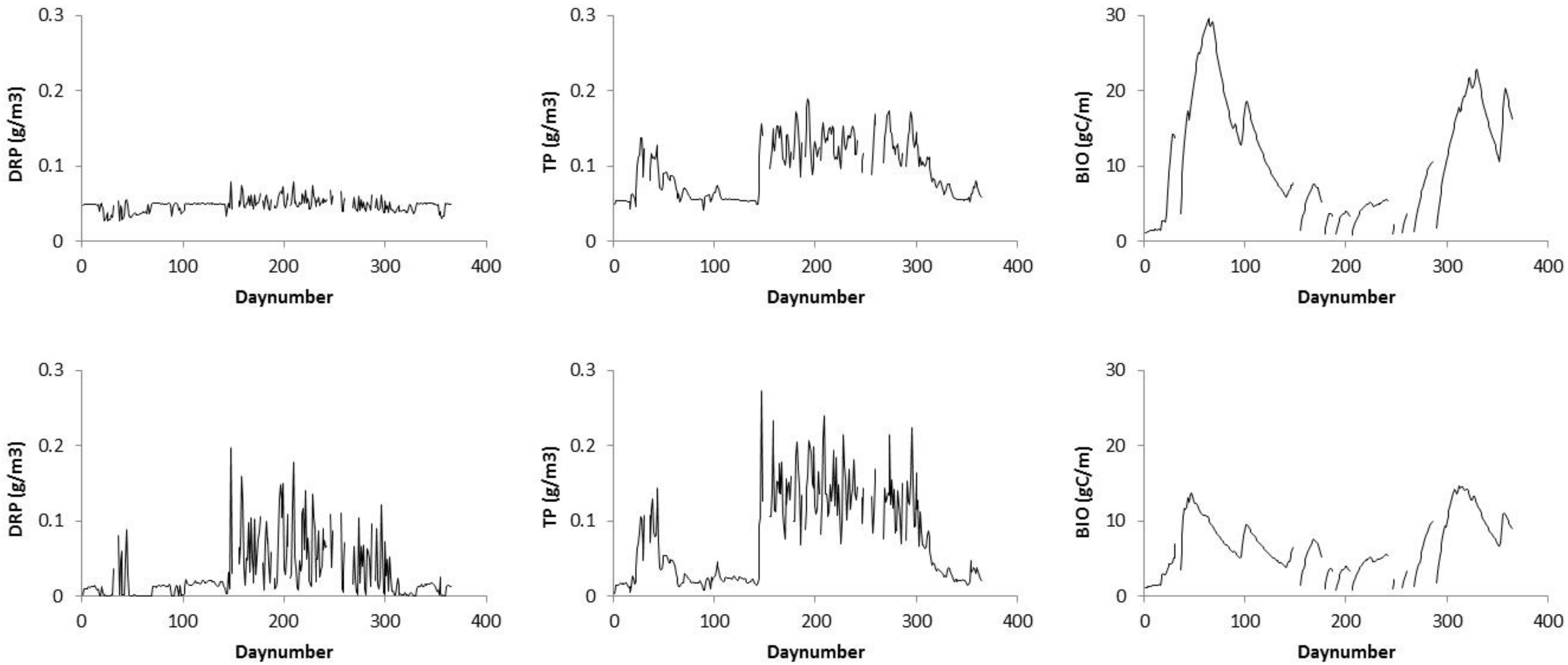

Figure 2-12: Sensitivity of predicted DRP, TP and BIO at Red Bridge to equilibrium P concentration and exchange rate. Equilibrium P concentration – 0.050 g m^{-3} (top) and 0.005 g m^{-3} (bottom). Exchange rate – 1.0 m d^{-1} (top) and 0.1 m d^{-1} (bottom).

2.2.7 Alternative model calibration – phosphorus recycling

As detailed above, a satisfactory match between observed and predicted phosphorus concentrations and periphyton biomass can be achieved assuming:

1. A periphyton respiration rate of 0.02 d^{-1} with 75% recycling.
2. A hydrolysis rate for suspended detritus of 1.0 d^{-1} with 75% recycling.
3. A detritus settling rate of 20 m d^{-1} with no recycling.

Phosphorus is unlikely to be recycled from detritus that becomes stranded above the water line. However, phosphorus recycling is likely from detritus that settles in shallow water or becomes trapped in the hyporheos. An alternative calibration was sought assuming a detritus settling rate of zero, by varying recycling during hydrolysis. This mimics bulk recycling of phosphorus from scoured periphyton without separating the contributions from suspended and settled detritus.

Figure 2-13 shows that similar time-series of DRP, TP and BIO at Red Bridge are predicted with:

1. No settling and 25% recycling from suspended detritus.
2. Settling, no recycling from settled detritus and 75% recycling from suspended detritus.

In the first scenario, there is no removal of detritus from the system and observed phosphorus concentrations and biomass can be matched with low recycling from suspended detritus. In the second scenario, settling removes detritus from the water column. In this scenario, because there is no recycling from settled detritus, it is necessary to specify high recycling from suspended detritus to match observed phosphorus concentrations and biomass.

In reality, recycling is likely to occur from both settled and suspended detritus. Currently, insufficient experimental data exist to separately quantify the contributions made to recycling from settled and suspended detritus. What is important, however, is the total amount of recycling rather than its separate components, and this has been inferred through model calibration. It is unlikely that the RWSS will significantly change the types of periphyton growing in the Tukituki River or the nature of detritus derived from scour. At most it will increase growth rates, biomass and detritus supply. It seems unlikely, therefore, that the predicted effects of the RWSS will be sensitive to different combinations of settling and recycling coefficients.

2.2.8 Alternative model calibration – denitrification

High nitrate concentrations can be toxic to sensitive stream organisms. HBRC has recently proposed guidelines for nitrate concentration to protect stream ecosystems. These vary within the catchment, with limits on annual mean and 95%ile nitrate concentrations in farmed parts of the catchment ranging from 2.4-3.8 and 3.5-5.6 g N m^{-3} respectively.

The model assumes a denitrification rate that is uniform in space and time. A satisfactory match between observed and predicted average NNN concentrations in 2010 was achieved with a spatially and temporally uniform denitrification rate of 0.1 g m^{-2} d^{-1}. This is a similar to the rate of 0.15 g m^{-2} d^{-1} in the lower Tukituki River derived by calibrating the TRIM model to low flow measurements of NNN made in January 2011 (Rutherford 2011). Although measurements of nitrous oxide and nitrogen gas have recently been made during summer low flows, these data have not yet been analysed to determine the denitrification. When this is done, it will enable a comparison with the denitrification inferred during model calibration, although it will not furnish information about denitrification in the tributaries, or the variation of denitrification rate with flow, season or biomass.

NNN concentrations are currently high in some of the tributaries, giving rise to 'hot spots'. As discussed below, the RWSS is likely to increase nitrogen inflows (by up to 60% in some tributaries assuming no mitigation). There are no measurements of denitrification rate in the tributaries, and the model assumes the same rate as in the main stem of the Tukituki River. Information about how denitrification rate varies with flow and season does not exist either, and the model assumes the same rate through the year and at all flows. If denitrification rates in the tributaries are high, this will help offset the effects of increased inflows. On the other hand, if denitrification rates in the tributaries are low, then the impacts of the RWSS will have a greater effect on NNN concentrations.

Many of the tributaries considered in the model appear to have similar cobble/gravel streambeds to the main stem of the Tukituki, although the tributaries are narrower, more highly shaded and slightly cooler. High periphyton and/or macrophyte biomass occurs in many places along the tributaries during summer low flows and these generate detritus through scour and senescence, as in the main channel. Where the channels are similar, the conditions that favour denitrification (high nitrate concentrations, a supply of organic carbon from detritus, low redox and high water temperature) are likely to occur in the hyporheos and/or in periphyton mats in both the main stem and the tributaries.

During summer, the denitrification rate is likely to be high because periphyton biomass, the supply of detritus, and water temperatures are all high. The model assumes a constant benthic denitrification rate (units g m^{-2} d^{-1}). If the denitrification rate is constant, the rate of change of concentration increases with decreasing depth and velocity (viz., decreasing flow). Consequently, denitrification is predicted to cause rapid nitrate removal from the water column during summer low flows. During winter high flows, NNN inflows are high, the conditions that favour denitrification are less likely to occur, and water depth and velocity are high. As a result, the rate of removal from the water column is expected to be low during winter high flows. Model predictions of NNN are insensitive to denitrification rate during winter high flows, even assuming a constant denitrification rate because of the effects of higher water depth and velocity, and higher inflows. A 'worst case' assumption is that denitrification rates in the tributaries are zero during summer low flows. An alternative calibration was sought assuming zero denitrification in both the tributaries and the main stem throughout the year, and adjusting the recycling efficiency during respiration and hydrolysis. Figure 2-14 compares predicted NNN, TN and BIO in the Tukituki River at Red Bridge with:

1. Denitrification = 0.1 g m^{-2} d^{-1} and 75% recycling.
2. Denitrification = 0.0 g m^{-2} d^{-1} and 25% recycling.

During low flows (Days 100-140 and 340-350), predicted NNN concentrations are low in both cases, because nitrogen inflows are low and uptake by periphyton is high. Predicted BIO are similar regardless of denitrification rate and recycling efficiency, because periphyton at Red Bridge are controlled by phosphorus rather than nitrogen. Setting denitrification to zero in all streams removes a significant nitrogen sink from the model. In order for predicted NNN and TN concentrations to remain similar, nitrogen recycling during respiration and hydrolysis must be reduced from 75% to 25%. Phosphorus recycling remains at 75%. It seems unlikely that nitrogen recycling would be significantly lower than phosphorus recycling – indeed the literature indicates that phosphorus is more likely than nitrogen to remain bound within the benthic communities. The inference from these simulations is that denitrification is a significant sink for nitrogen at least in the main stem of the Tukituki River, and this has been confirmed by recent measurements.

Figure 2-15 compares predicted NNN concentrations in the Tukituki at Red Bridge with:

1. Denitrification = 0.1 g m^{-2} d^{-1} in the main stem of the Tukituki and Waipawa Rivers and 0 g m^{-2} d^{-1} in the tributaries.
2. Denitrification = 0.1 g m^{-2} d^{-1} in all streams.

Both scenarios assume phosphorus exchange with the bed. Predicted NNN and TN concentrations at Red Bridge during low flows are significantly higher for the first scenario in which denitrification in the tributaries is zero. In the second scenario the denitrification rate of 0.1 g m^{-2} d^{-1} significantly reduces NNN concentrations in the tributaries, where depth and velocity are lower than in the main stem. This is the expected response. It indicates that NNN concentrations in the main stem are affected not only by nitrogen removal in the main stem, but also by nitrogen removal in the tributaries. Predicted periphyton biomass is higher for the first scenario. This may seem surprising given that phosphorus, rather than nitrogen, controls biomass in most parts of the Tukituki River most of the time. Biomass is higher only at the end of a prolonged period of low flow and only in the lower Tukituki from near Red Bridge to the sea. It is in this part of the river that, after prolonged low flows, there is experimental evidence of a switch from phosphorus to nitrogen limitation. These simulations indicate that during summer low flows periphyton biomass in the lower Tukituki River is sensitive to nitrogen removal in the tributaries.

Figure 2-16 and Figure 2-17 compare predicted NNN concentrations in the 7 major tributaries with and without denitrification in those tributaries. Denitrification in the main stem of the Tukituki and Waipawa Rivers remains at the calibrated value. Not surprisingly, predicted NNN concentrations in the tributaries are significantly higher when tributary denitrification is assumed to be zero. Although denitrification has been confirmed in the main stem of the Tukituki River, the denitrification rate there has not yet been determined for comparison with the model value (0.01 g m^{-2} d^{-1}) estimated by matching observed and predicted NNN concentrations during a summer low flow period in 2011. Denitrification has not been studied in any of the tributaries, nor has the variation of denitrification rate with flow, season or periphyton biomass.

1. These simulations indicate that predicted NNN concentrations in the major tributaries are sensitive to the denitrification rate. Denitrification has not been studied in the tributaries, and it is recommended that further work be done on denitrification.
2. Predicted NNN concentrations in the main stem are also sensitive to denitrification rate. To date an estimate of 0.15 g m^{-2} d^{-1} has been made by calibrating the TRIM

model to summer low flow NNN concentrations in 2011. Gas measurements have been made during a summer low flow period in 2013, but the denitrification rate has not yet been calculated from these data.

3. There is no information available about how denitrification rate in the main stem or the tributaries varies with flow, season or biomass. Further work is recommended to study this variation. The sensitivity of model predictions and management recommendations to uncertainty in denitrification are detailed below.

2.2.9 Predicting the likely effects of the RWSS

The key questions associated with an assessment of effects are:

1. To what extent will the RWSS increase nutrient losses?
2. What effect will any increase in losses have on stream nutrient concentrations and biomass?
3. Will any increases have adverse effects on stream ecology or recreational use?
4. What mitigation measures can be put in place to avoid or remedy any adverse effects?

The TRIM model is used to help answer these questions. Like all models, the TRIM model has inherent uncertainties. This means that there is uncertainty about the accuracy of the numbers that the TRIM model predicts. For example, there is uncertainty about the absolute values of NNN concentration and periphyton biomass predicted by the model. However, a key question is whether these uncertainties affect the robustness of the main conclusions drawn from the modelling, and hence affect the management decisions that are made. For example, the predicted NNN concentrations identify the possibility of ‘hot spots’ in some of the tributaries where nitrate concentrations approach limits set for the protection of sensitive species. The management action is to investigate further and, if this risk is confirmed, to put in place additional mitigation to avoid adverse effects. Bearing this in mind, the next sections use the re-calibrated TRIM model to examine various scenarios of land use change associated with the RWSS with the objective of identifying potential adverse effects and suggesting appropriate actions.

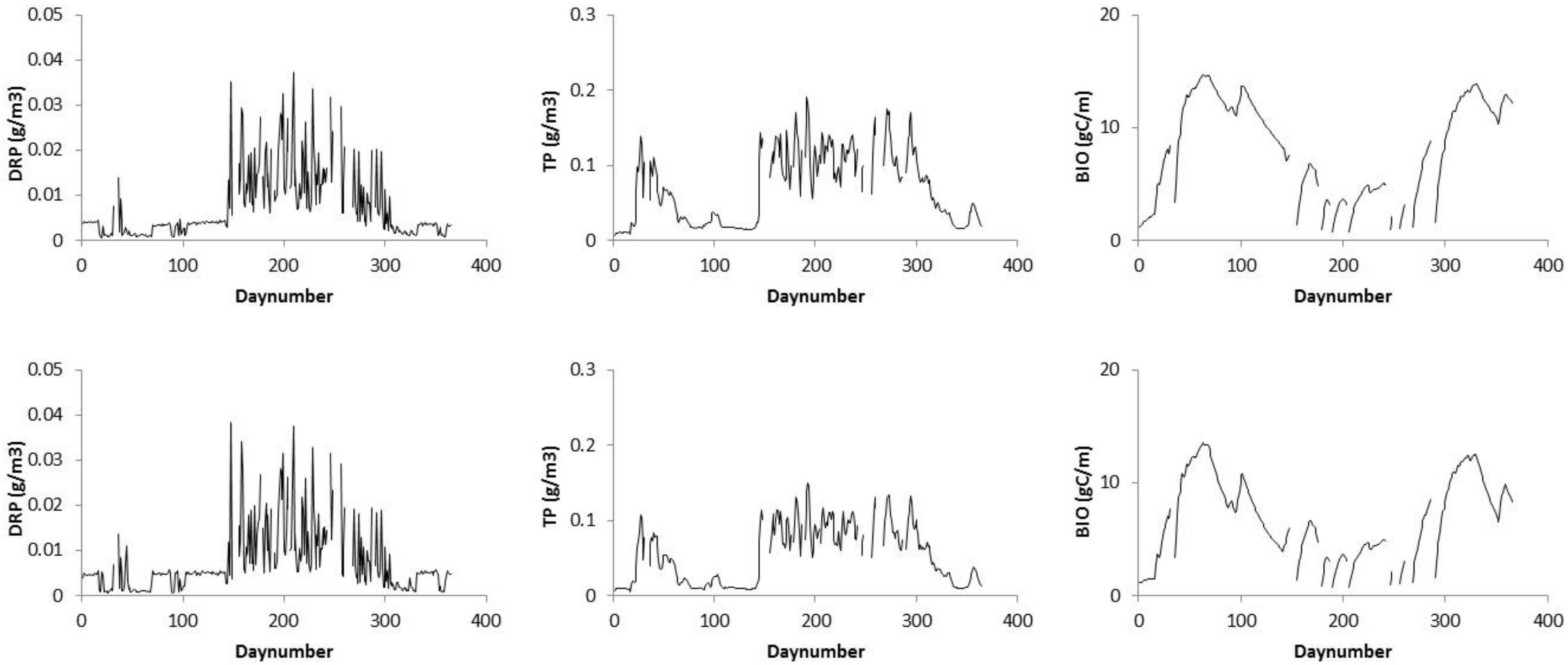

Figure 2-13: Sensitivity of predicted DRP, TP and BIO at Red Bridge to P recycling. Detritus settling – 0 m d^{-1} (top) and 20 m d^{-1} (bottom). Recycling during hydrolysis – 25% (top) and 75% (bottom).

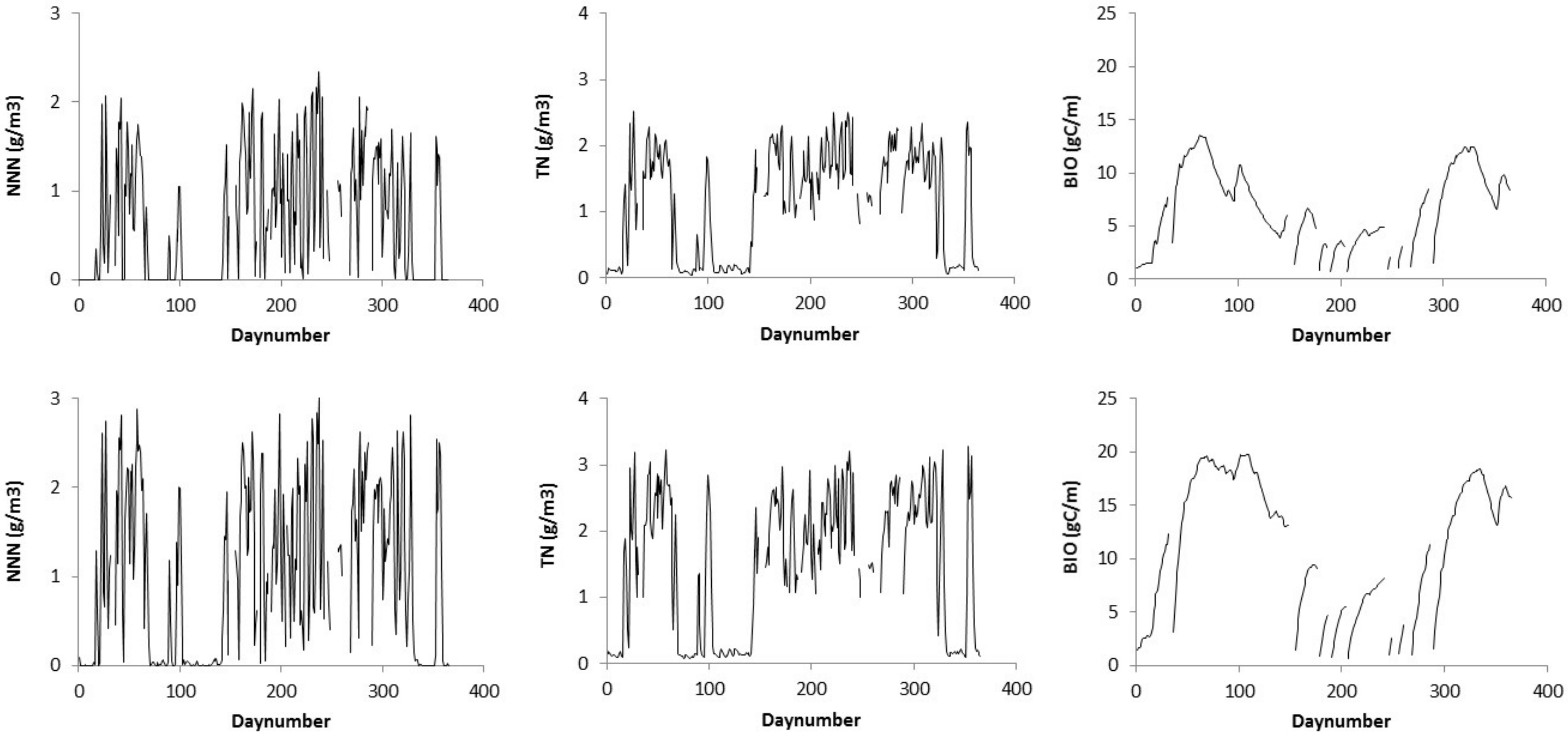

Figure 2-14: Sensitivity of predicted NNN, TN and BIO at Red Bridge to denitrification. Denitrification – 0.1 g m^{-2} d^{-1} (top) and 0.0 g m^{-2} d^{-1} (bottom).

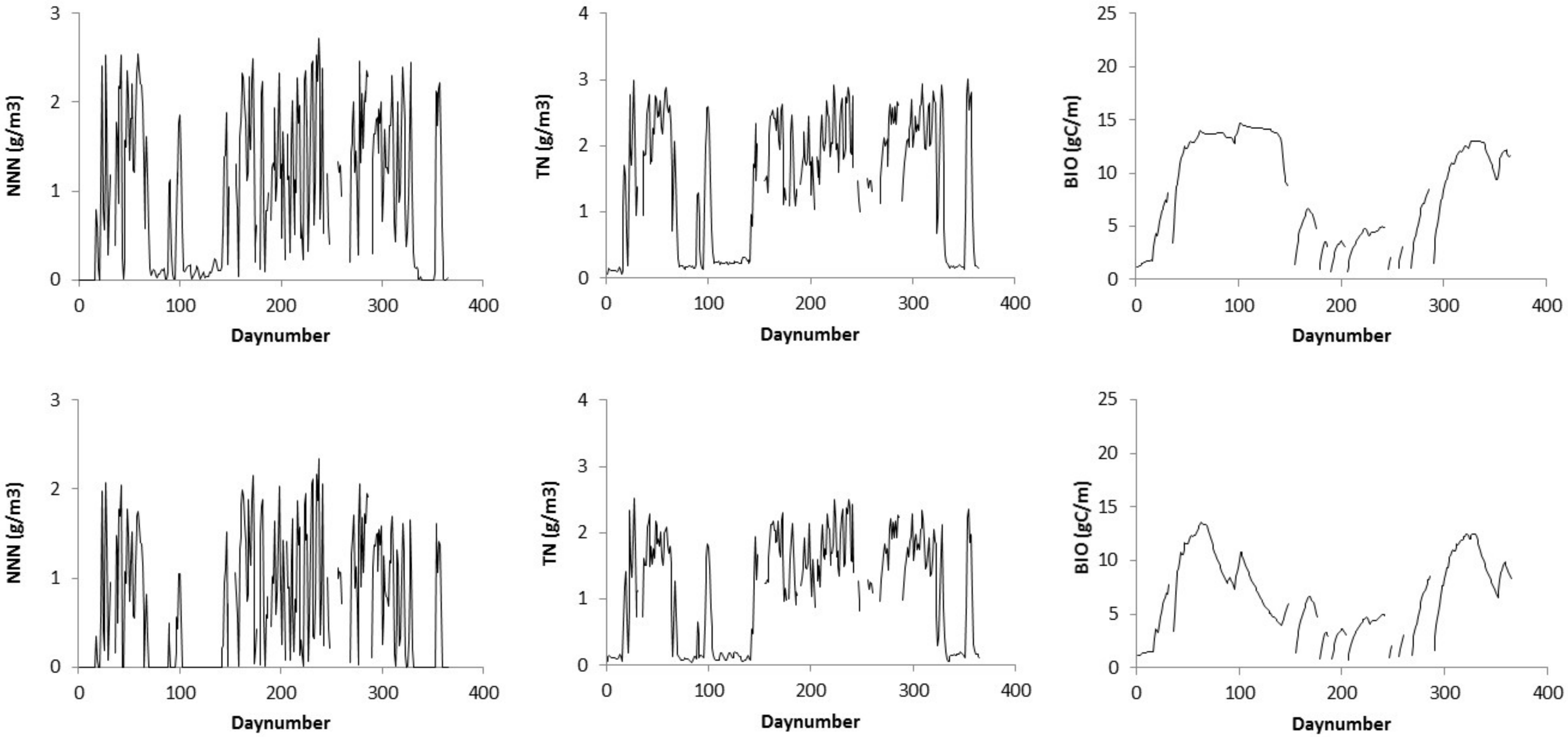

Figure 2-15: Sensitivity of predicted NNN, TN and BIO at Red Bridge to denitrification. Denitrification in the tributaries – 0.0 g m^{-2} d^{-1} (top) and 0.1 g m^{-2} d^{-1} (bottom). Denitrification in the main stem of the Tukituki and Waipawa Rivers – 0.1 g m^{-2} d^{-1} (top and bottom).

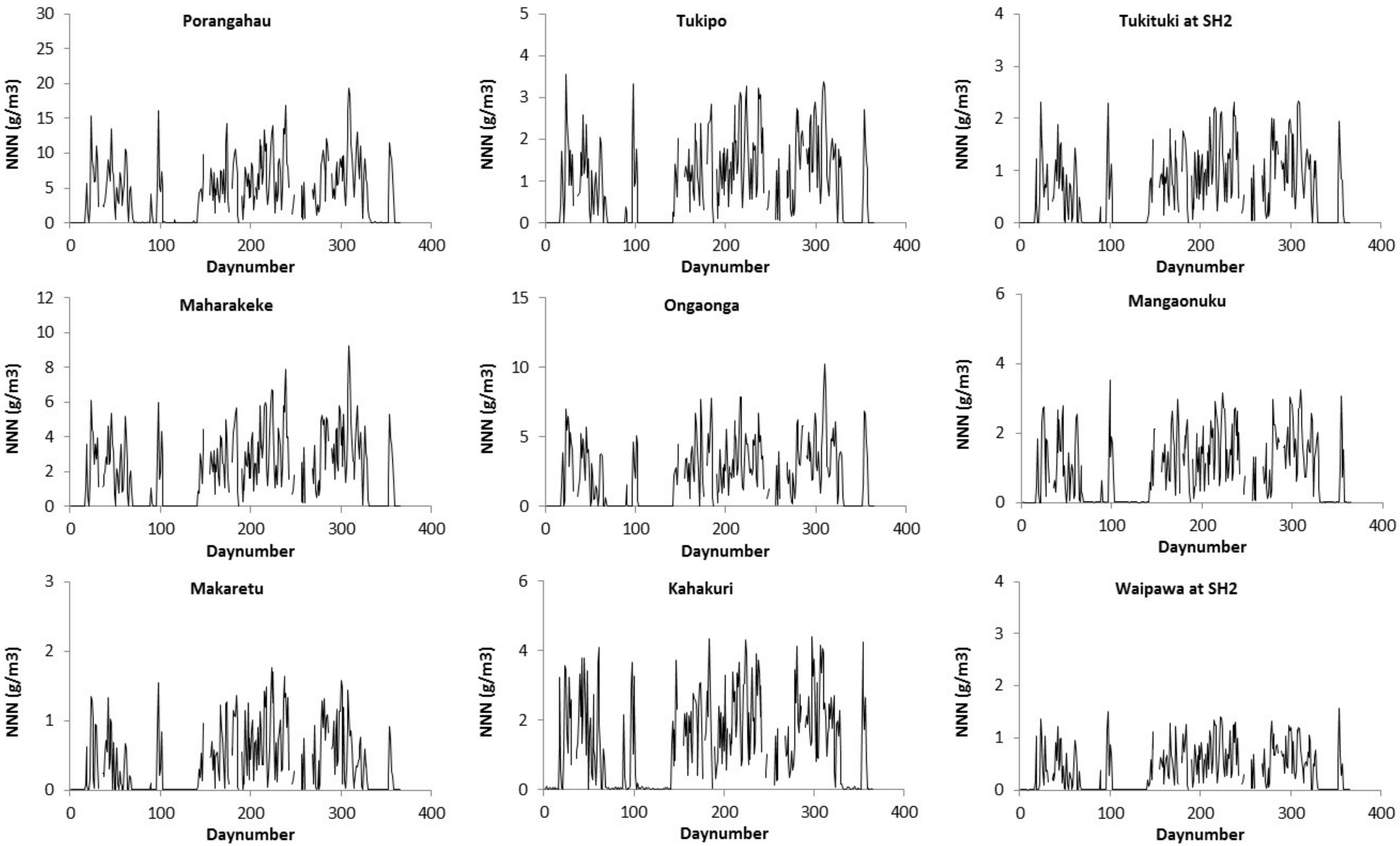

Figure 2-16: Sensitivity of NNN in the tributaries to denitrification – predicted NNN concentrations in the 7 major tributaries and the main stem of the Tukituki and Waipawa Rivers near Waipukurau. Denitrification in the tributaries and the main stem – 0.1 g m^{-2} d^{-1}.

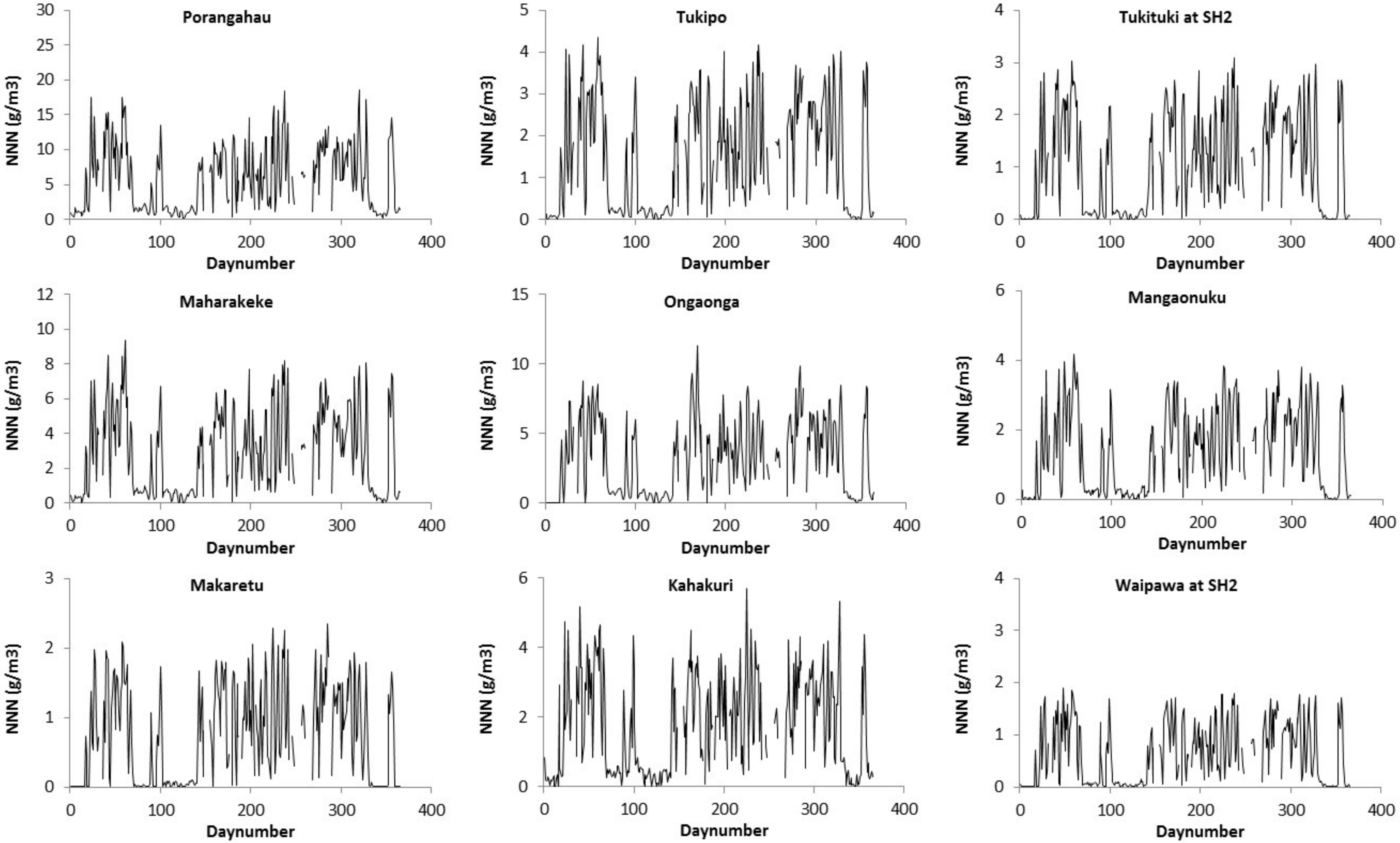

Figure 2-17: Sensitivity of NNN in the tributaries to denitrification – predicted NNN concentrations in the 7 major tributaries and the main stem of the Tukituki and Waipawa Rivers near Waipukurau. Denitrification in the tributaries – 0.0 g m^{-2} d^{-1} and the main stem – 0.1 g m^{-2} d^{-1}.

3 Scenario modelling

3.1 Pre-irrigation nutrient losses

The TRIM2_CATCHMENT model requires TN and TP losses from each land parcel to be specified, based on OVERSEER simulations.

Figure 3-1 shows the spatial distribution of pre-irrigation (current) land use. Farm system codes are described in Table 3-1. Some dairy farms in the west and south-west of the catchment are currently dryland (Code 7) but many in middle of the catchment are currently partly irrigated (Code 7a). Mixed arable (5a) is partly irrigated, as are orchards and vineyards (Ox).

Figure 3-2 and Figure 3-3 show the TN and TP losses predicted by OVERSEER for current land use, taking account of spatial variations in soils, rainfall and current irrigation. Note that OVERSEER predicts long-term average losses for each farming enterprise, but not year-to-year variations which result from variations in climate and farm management. TN losses are highest on irrigated dairy farms, but are also high on dryland dairy and mixed arable farms. TP losses are high in steep, high rainfall forested land in the Ruahine Ranges in the west of the catchment. High TP and TN losses do not always coincide. On the Ruataniwha Plains TP losses are high on some sheep/beef farms where TN losses are moderately low (Codes 1a, 2a and 3a) notably where rainfall is high and soils are erodible. TP losses are low on much of the flat farmland in the lower Ruataniwha Plain, but are moderately high on steep farmland and forest along the lower Tukituki corridor.

Table 3-2 summarises pre-irrigation TN and TP losses by zone and farm system and Table 3-3 summarises losses by zone and catchment. For a given farm system, losses vary with soli type and rainfall – averages are shown. Nitrogen yields for dairy farms range from 19-27 kg ha^{-1} y^{-1} (code 7, dryland) and 47-67 kg ha^{-1} y^{-1} (code 7a, irrigated) respectively. Nitrogen yields for finishing (3a) and mixed arable (5a) are comparable with dryland dairy, while yields for sheep/beef (1a) and mixed livestock (2a) are significantly lower. TP yields are high on dairy (7 and 7a) and mixed livestock (2a). Slopes are generally higher outside the ICA and soils are more erodible. Consequently for most farm systems TP yields are higher outside the ICA than inside. TP yields from forest (Fx) are high because of the influence of steep, high rainfall and often erodible country in the Ruahine Ranges and in the hills along the lower Tukituki corridor. These yields are consistent with published values (Menneer et al. 2004).

Table 3-1: Land use categories modelled using OVERSEER. Source: Macfarlane Rural Business (2012).

Code	Description	Comment
Fx	Forest	
NPL	Non-productive land	Towns, roads, stream beds etc.,
	Pre-irrigation	
Ox	Orchard/Vineyard	Part irrigated
1a	Sheep/Beef breeding	Dryland
2a	Mixed livestock	Dryland
3a	Finishing	Dryland
5a	Mixed arable	Part irrigated
7	Dairy – dryland	Dryland
7a	Dairy – irrigated	Part irrigated
	Post-irrigation	
Ox	Orchard/Vineyard	Part irrigated
1b	Sheep/Beef breeding	Part irrigated
2b	Dairy support	Dryland
3b	Finishing	Irrigated
5b	Intensive arable	Irrigated
7b	Dairy – irrigated	Irrigated

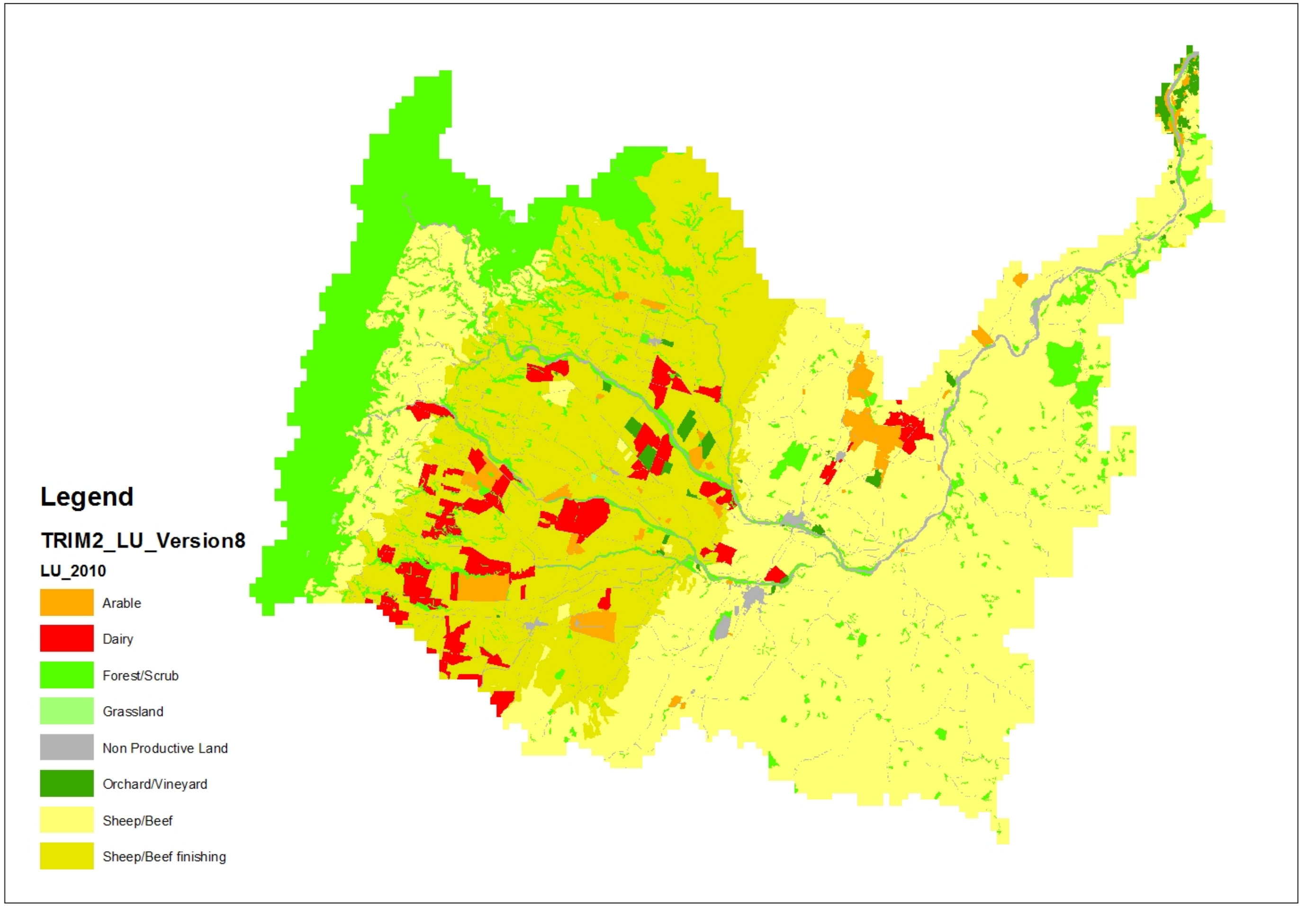
Legend
TRIM2_LU_Version8
LU_2010
Arable
Dairy
Forest/Scrub
Grassland
Non Productive Land
Orchard/Vineyard
Sheep/Beef
Sheep/Beef finishing

Figure 3-1: Pre-irrigation land use.

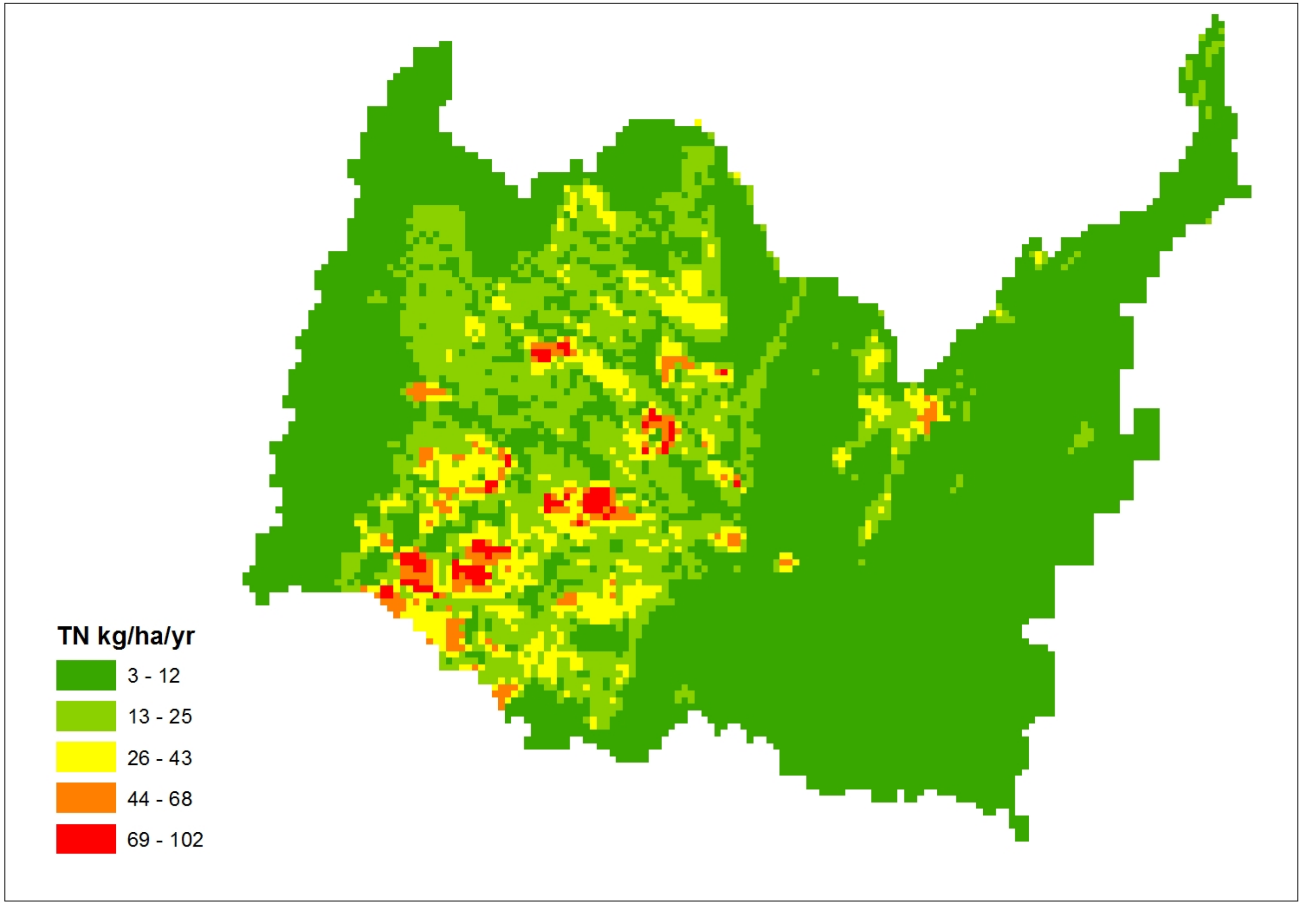

Figure 3-2: Current TN yields. Yields were estimated by AgResearch using OVERSEER for various combinations of farming enterprise, soils and rainfall.

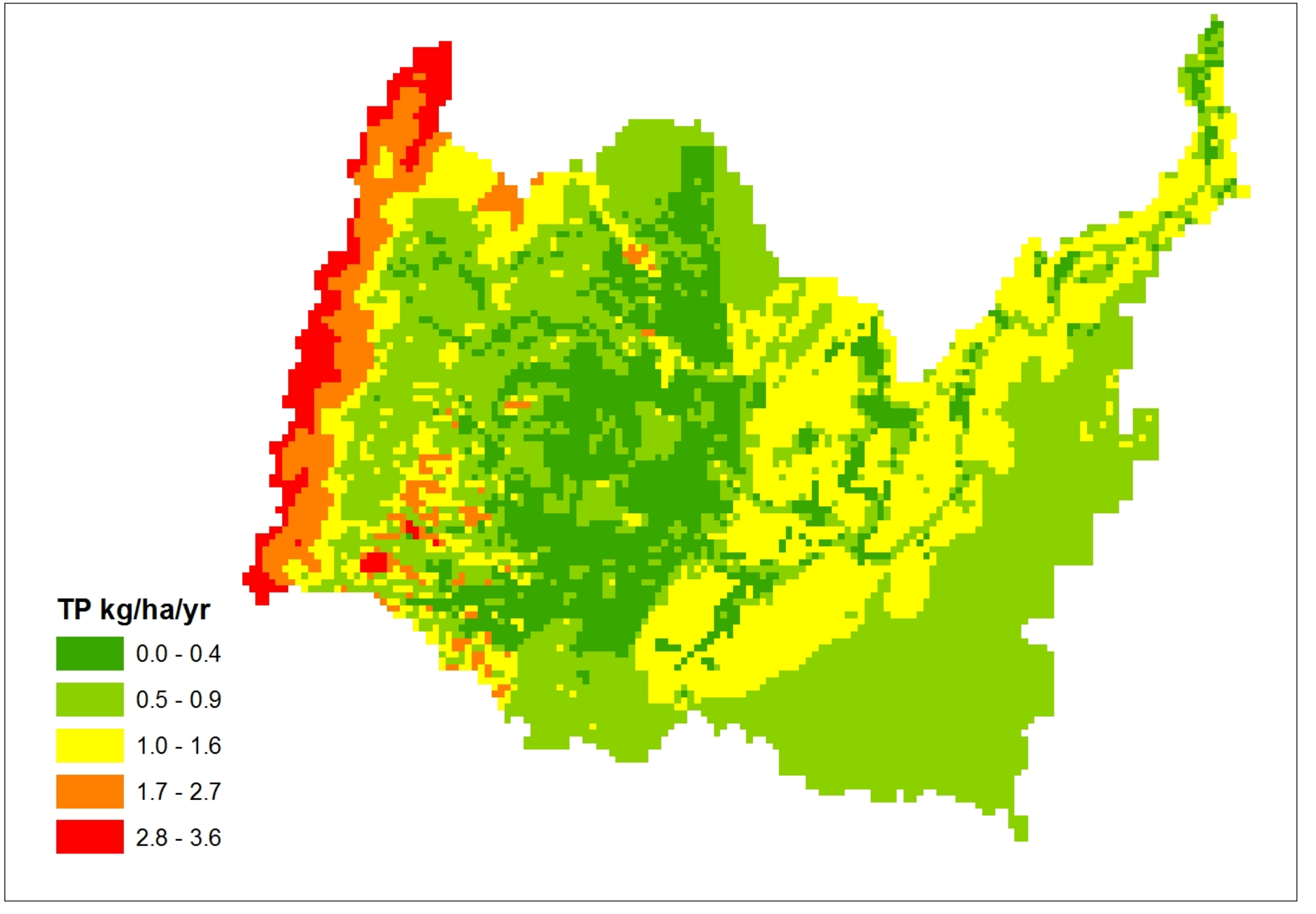

Figure 3-3: Current TP yields. Yields were estimated by AgResearch using OVERSEER for various combinations of farming enterprise, soils and rainfall.

Table 3-2: Pre-irrigation TN and TP losses predicted by OVERSEER. Land use codes (1a, 2a etc.,) are described in Table 3-1. The irrigation consent area (ICA) denotes land within the proposed irrigation areas including Zones A-D on the Ruataniwha Plain, and Zone M in the Papanui catchment. Outside refers to all land in the Tukituki catchment not within the ICA.

LU code	ICA			Outside			Total		
	Area ha	N yield kg ha^{-1} y^{-1}	N yield kg ha^{-1} y^{-1}	Area ha	N yield kg ha^{-1} y^{-1}	N yield kg ha^{-1} y^{-1}	Area ha	N yield kg ha^{-1} y^{-1}	N yield kg ha^{-1} y^{-1}
1a	27704	11.7	0.57	124350	10.8	0.77	152053	11.1	0.72
2a	2291	11.3	1.23	3760	12.3	1.73	6051	11.9	1.56
3a	9756	27.4	0.59	6030	30.2	0.93	15785	28.6	0.73
5a	7864	28.9	0.33	2738	29.6	0.55	10602	29.1	0.41
7	1945	22.8	0.80	4124	25.2	1.01	6069	24.5	0.95
7a	3724	59.4	1.07	100	65.4	1.07	3824	59.6	1.07
Fx	6418	3.0	0.42	40607	3.0	1.26	47025	3.0	1.07
NPL	4661	3.0	0.04	3724	3.0	0.04	8385	3.0	0.04
Ox	787	11.0	0.60	892	11.0	0.60	1679	11.0	0.60
Total	**65150**	**15.3**	**0.50**	**186324**	**9.8**	**0.86**	**251474**	**11.6**	**0.74**

Table 3-3: Pre-irrigation TN and TP losses predicted by OVERSEER. ICA (Irrigation Consent Area) denotes land within Zones A-M where irrigation is proposed. Outside denotes land within the Tukituki catchment not within the ICA. Point source discharges are included.

	ICA			Outside			Total		
	Area ha	kg P ha^{-1} y^{-1}	kg N ha^{-1} y^{-1}	Area ha	kg P ha^{-1} y^{-1}	kg N ha^{-1} y^{-1}	Area ha	kg P ha^{-1} y^{-1}	kg N ha^{-1} y^{-1}
Hawea	0	NA	NA	4700	0.75	7.1	4700	0.75	7.1
Kahahakuri	6100	0.43	18.3	625	0.73	19.3	6725	0.46	18.4
Lower Tukituki	2650	0.74	6.6	18900	0.94	8.0	21550	0.92	7.9
Maharakeke	7475	0.61	15.7	1775	0.73	9.1	9250	0.63	14.4
Makara	0	NA	NA	12475	0.68	8.7	12475	0.68	8.7
Makaretu	2925	0.33	16.7	4825	1.74	10.9	7750	1.21	13.1
Mangamahaki	0	NA	NA	26150	0.63	8.8	26150	0.63	8.8
Mangamate	2775	0.64	14.4	8450	0.65	9.2	11225	0.65	10.5
Mangamauku	1500	0.55	17.4	5575	0.91	13.9	7075	0.83	14.7
Mangaonuku	8950	0.50	16.2	10450	0.89	10.9	19400	0.71	13.4
Mangarara	0	NA	NA	3850	0.65	8.7	3850	0.65	8.7
Mangatarata	450	0.89	8.5	18275	0.89	8.4	18725	0.89	8.4
Middle Tukituki	2550	0.51	25.8	13800	1.43	7.9	16350	1.29	10.7
Ongaonga	4700	0.40	13.6	1775	0.77	14.7	6475	0.50	13.9
Papanui	7400	0.78	12.1	9225	0.98	8.9	16625	0.89	10.4
Porangahau	4250	0.60	21.0	2300	0.94	19.9	6550	0.72	20.6
Tukipo	8675	0.47	24.3	13375	1.17	16.3	22050	0.90	19.4
Waipawa	4750	0.53	24.3	29800	1.58	8.3	34550	1.44	10.5
Total	**65150**	**0.55**	**17.6**	**186325**	**1.02**	**9.6**	**251475**	**0.90**	**11.7**

3.2 Post-irrigation nutrient losses

3.2.1 Effects of irrigation

Irrigation enables increased stocking rates on dairy and sheep/beef farms with subsequent increases in nutrient loss. Irrigation also enables more intensive arable farming. Table 3-4 and Table 3-5 compare nutrient losses for pre-irrigation (a) and post-irrigation (b) farm systems, as predicted by OVERSEER. Losses vary between soil types and the averages are shown. Losses increase with increasing rainfall, and are higher where stock have access to streams than where streams are fenced. Yields at 200 mm rainfall intervals are interpolated between OVERSEER predictions supplied by AgResearch at rainfalls of 900, 1036 and 1250 mm.

3.2.2 Effects of fencing

OVERSEER predicts higher TN and TP losses where stock have access to streams than where streams are fenced. OVERSEER quantifies the impacts of the direct deposition of dung and urine but not the impacts of trampling damage to stream banks and bed (David Wheeler, AgResearch, pers. comm.). As a result, OVERSEER probably under-estimates the benefits of fencing streams to exclude stock, and hence TRIM probably under-estimates the benefits of stock exclusion. For TN the difference between stock access and no access is small, but for TP where cattle are farmed the difference is significant.

It is proposed that on pasture receiving water for irrigation, all streams of 2nd-order or larger will be fenced to exclude stock. It is estimated that stock are currently excluded from 40% of 2nd-4th order streams in the ICA. In addition, the proposed Tukituki Plan Change will require that, on all other farmland in the Tukituki catchment where slope is less than 15 degrees, streams will be fenced to exclude stock. Currently, it is estimated that cattle are excluded from 50% of streams of 2nd-4th order outside the ICA and from 61% of streams on land whose slope is greater than 15 degrees. Note that land outside the ICA includes significant areas of steep, forested land with no stock – this contributes to the high proportion of streams outside the ICA with no stock access (Barry Lynch, HBRC, pers. comm.).

3.2.3 Current fencing

A 'worst-case' scenario assumes no additional fencing post-irrigation. Table 3-6 compares pre-and post-irrigation losses assuming current stock access on a catchment basis. There are no changes where a catchment lies outside the ICA. Where a large proportion of the catchment lies within the ICA, TN and TP yields are predicted to increase significantly. The biggest increases are 67% for TN in the Papanui, and 48% for TP in the Kahahakuri. For the whole catchment, TN and TP losses are predicted to increase by 32% and 6% respectively.

Table 3-4: Comparison of pre-irrigation (suffix a) and post-irrigation (suffix b) TN yields predicted by OVERSEER. Units are kg ha^{-1} y^{-1}. Yields at 200 mm rainfall intervals were interpolated between OVERSEER predictions at rainfalls of 900, 1036 and 1250 mm supplied by AgResearch.

Annual rainfall mm	700	900	1100	1300	1500	1700	1900
Farm system				**No stock access**			
1a	11.4	11.8	14.2	16.4	18.5	20.4	22.2
1b	14.7	15.3	18.5	21.4	24.1	26.6	29.0
2a	9.8	10.1	11.4	12.7	13.8	14.8	15.8
2b	31.0	31.9	38.8	45.0	50.8	56.2	61.3
3a	23.4	24.3	28.8	33.0	36.9	40.6	44.0
3b	28.0	29.5	35.6	41.3	46.5	51.4	56.0
5a	25.4	25.8	32.7	39.0	44.9	50.4	55.5
5b	53.6	55.9	72.7	88.1	102.3	115.6	128.2
7	17.1	18.3	22.4	26.3	29.9	33.2	36.4
7a	46.9	49.5	58.8	67.4	75.3	82.7	89.7
7b	55.3	59.1	70.6	81.2	91.1	100.3	109.0
				Stock access			
1a	11.5	11.8	14.3	16.5	18.6	20.5	22.3
1b	14.8	15.4	18.6	21.5	24.2	26.7	29.1
2a	9.9	10.2	11.5	12.8	13.9	14.9	15.9
2b	31.2	32.1	38.9	45.2	51.0	56.4	61.5
3a	24.4	25.4	30.1	34.4	38.4	42.1	45.6
3b	28.8	30.3	36.6	42.3	47.6	52.5	57.2
5a	25.4	25.9	32.8	39.2	45.1	50.7	55.9
5b	53.8	56.2	73.1	88.5	102.8	116.2	128.8
7	18.2	19.4	23.7	27.6	31.3	34.8	38.0
7a	48.7	51.4	60.8	69.5	77.5	85.1	92.2
7b	57.6	61.5	73.1	83.9	93.9	103.2	112.0

Table 3-5: Comparison of pre-irrigation (suffix a) and post-irrigation (suffix b) TP yields predicted by OVERSEER. Units are kg ha^{-1} y^{-1}. Yields at 200 mm rainfall intervals were interpolated between OVERSEER predictions at rainfalls of 900, 1036 and 1250 mm supplied by AgResearch.

Annual rainfall mm	700	900	1100	1300	1500	1700	1900
Farm system				**No stock access**			
1a	0.36	0.37	0.50	0.64	0.77	0.90	1.01
1b	0.41	0.41	0.66	0.91	1.14	1.36	1.56
2a	0.79	0.79	1.59	2.35	3.05	3.71	4.34
2b	0.77	0.77	1.48	2.17	2.80	3.39	3.95
3a	0.38	0.38	0.59	0.85	1.08	1.30	1.50
3b	0.67	0.67	0.92	1.19	1.44	1.67	1.89
5a	0.33	0.38	0.70	1.03	1.34	1.62	1.89
5b	0.58	0.59	0.97	1.35	1.69	2.02	2.33
7	0.41	0.46	0.79	1.10	1.38	1.64	1.89
7a	1.01	1.01	1.24	1.49	1.72	1.93	2.14
7b	1.21	1.22	1.43	1.67	1.89	2.10	2.30
				Stock access			
1a	0.36	0.37	0.50	0.64	0.77	0.90	1.01
1b	0.41	0.41	0.66	0.91	1.14	1.36	1.56
2a	0.79	0.79	1.59	2.35	3.05	3.71	4.34
2b	0.77	0.77	1.48	2.17	2.80	3.39	3.95
3a	0.58	0.59	0.91	1.23	1.52	1.79	2.05
3b	0.87	0.87	1.12	1.39	1.64	1.87	2.09
5a	0.33	0.38	0.70	1.03	1.34	1.62	1.89
5b	0.68	0.69	1.07	1.45	1.79	2.12	2.43
7	0.61	0.71	1.11	1.48	1.82	2.14	2.44
7a	1.41	1.41	1.64	1.89	2.12	2.33	2.54
7b	1.71	1.72	1.93	2.17	2.39	2.60	2.80

3.2.4 Fencing within the ICA

Table 3-7 compares pre- and post-irrigation losses assuming that post-irrigation no stock have access to streams within the ICA but that pre-irrigation stock access is at current levels. Outside the ICA the current level of stock access is assumed. Compared with the previous scenario, there is very little change in TN losses. This is because OVERSEER predicts that TN losses are dominated by pasture drainage and runoff, while the direct deposition of urine in streams makes only a minor contribution to nitrogen loss.

Excluding stock from streams in the ICA significantly reduces TP losses. For example, in the Kahahakuri, where the largest increase in TP loss occurs, the ratio of pre- to post-irrigation TP losses decreases from 148% to 130% as a result of stock exclusion. In the whole of the catchment the ratio decreases from 106% to 104%. Thus fencing stock out of streams within the ICA has significant benefits in terms of reducing TP losses from grazed pasture.

3.2.5 Fencing outside the ICA

Table 3-8 compares pre- and post-irrigation losses assuming stock exclusion not only from all streams within the ICA, but also from streams outside the ICA where slopes are less than 15 degrees. Within the ICA there is no change from the previous scenario. Outside the ICA there is only a small decrease in TP losses and an insignificant change in TN losses. The reason is that the predominant land uses outside the ICA are sheep/beef farming (Codes 1a, 2a and 3a). OVERSEER predicts that excluding stock from waterways has no significant effect on TN and TP losses for these land uses. If more cattle were to be farmed outside the ICA, then the benefits of additional fencing to exclude stock from streams would be greater.

3.2.6 Optimising P fertiliser use within the ICA

There are a number of on-farm measures whereby P loss may be reduced. OVERSEER was run on pre- and post-irrigation land uses assuming not only that stock are fenced out of waterways, but also that P fertiliser application and type are optimised. Table 3-10 describes a number of on-farm practices relating to fertiliser use that reduce phosphorus losses. These measures reduce soil Olsen P below levels commonly found in pasture by applying phosphorus at the optimal time of the year using a slow release fertiliser.

Table 3-9 compares pre- and post-irrigation losses, assuming that these mitigation measures are fully implemented within the ICA in addition to fencing stock out of streams. Table 3-10 gives two mitigation options for dairy farms and it is assumed that 50% of farms adopt each option. The mitigation measures target phosphorus and have no effect on TN losses.

Considering the catchment as a whole, TP losses are reduced to within 1% of pre-irrigation levels. In four catchments with significant areas of land within the ICA, TP losses are below pre-irrigation levels by 1-4%. In two catchments TP losses are the same as pre-irrigation levels. In the remaining six catchments TP losses are above pre-irrigation levels by 1-13%.

Table 3-6: Post-irrigation TN and TP losses – current stock access. % pre-irrigation denotes the ratio of post- to pre-irrigation losses. Post-irrigation losses assume current stock access.

Catchment	Area %ICA	N yield kg ha^{-1} y^{-1}				P yield kg ha^{-1} y^{-1}			
		ICA	Outside	Catchment	% pre-irrigation	ICA	Outside	Catchment	% pre-irrigation
Hawea	0%		7.1	7.1	100%		0.75	0.75	100%
Kahahakuri	91%	31.6	19.3	30.5	166%	0.67	0.73	0.67	148%
Lower Tukituki	12%	11.6	8.0	8.5	108%	0.84	0.94	0.93	101%
Maharakeke	81%	24.9	9.1	21.9	151%	0.80	0.73	0.78	125%
Makara	0%		8.7	8.7	100%		0.68	0.68	100%
Makaretu	38%	32.4	10.9	19.0	145%	0.59	1.74	1.31	108%
Mangamahaki	0%		8.8	8.8	100%		0.63	0.63	100%
Mangamate	25%	25.6	9.2	13.2	126%	0.70	0.65	0.66	102%
Mangamauku	21%	50.2	13.9	21.6	147%	0.83	0.91	0.89	107%
Mangaonuku	46%	27.8	10.9	18.7	140%	0.69	0.89	0.80	113%
Mangarara	0%		8.7	8.7	100%		0.65	0.65	100%
Mangatarata	2%	11.0	8.4	8.4	101%	0.81	0.89	0.89	100%
Middle Tukituki	16%	38.5	7.9	12.7	118%	0.73	1.43	1.32	103%
Ongaonga	73%	25.6	14.7	22.6	162%	0.66	0.77	0.69	137%
Papanui	45%	27.7	8.9	17.3	167%	0.94	0.98	0.96	108%
Porangahau	65%	40.5	19.9	33.3	161%	0.96	0.94	0.96	133%
Tukipo	39%	46.4	16.3	28.1	145%	0.81	1.17	1.03	115%
Waipawa	14%	35.7	8.3	12.1	115%	0.70	1.58	1.46	102%
Total	**26%**	**31.8**	**9.6**	**15.4**	**132%**	**0.77**	**1.02**	**0.96**	**106%**

Table 3-7: Post-irrigation TN and TP losses – no stock access within the ICA. % pre-irrigation denotes the ratio of post- to pre-irrigation losses. Post-irrigation losses assume no stock access within the ICA and current stock access outside the ICA. Pre-irrigation assumes current stock access throughout the catchment.

Catchment	Area %ICA	N yield kg ha^{-1} y^{-1}				P yield kg ha^{-1} y^{-1}			
		ICA	Outside	Catchment	% pre-irrigation	ICA	Outside	Catchment	% pre-irrigation
Hawea	0%		7.1	7.1	99%		0.75	0.75	100%
Kahahakuri	91%	31.3	19.3	30.1	164%	0.58	0.73	0.60	130%
Lower Tukituki	12%	11.5	8.0	8.5	107%	0.82	0.94	0.93	101%
Maharakeke	81%	24.6	9.1	21.6	150%	0.73	0.73	0.73	116%
Makara	0%		8.7	8.7	100%		0.68	0.68	100%
Makaretu	38%	32.1	11.0	19.0	145%	0.52	1.74	1.28	106%
Mangamahaki	0%		8.8	8.8	100%		0.63	0.63	100%
Mangamate	25%	25.3	9.2	13.2	125%	0.64	0.65	0.65	100%
Mangamauku	21%	49.5	13.9	21.5	146%	0.68	0.91	0.86	104%
Mangaonuku	46%	27.4	10.9	18.5	138%	0.62	0.89	0.77	108%
Mangarara	0%		8.7	8.7	100%		0.65	0.65	100%
Mangatarata	2%	11.0	8.4	8.4	100%	0.81	0.89	0.89	100%
Middle Tukituki	16%	38.0	8.6	13.2	123%	0.62	1.44	1.31	102%
Ongaonga	73%	25.3	14.7	22.4	161%	0.61	0.77	0.65	130%
Papanui	45%	27.4	9.4	17.4	167%	0.88	1.00	0.94	106%
Porangahau	65%	39.9	23.8	34.3	166%	0.85	1.02	0.91	126%
Tukipo	39%	45.8	16.4	28.0	144%	0.68	1.18	0.98	109%
Waipawa	14%	35.2	8.4	12.0	115%	0.59	1.58	1.45	100%
Total	**26%**	**31.4**	**9.7**	**15.4**	**131%**	**0.69**	**1.02**	**0.94**	**104%**

Table 3-8: Post-irrigation TN and TP losses – restricted stock access outside the ICA. % pre-irrigation denotes the ratio of post- to pre-irrigation losses. Post-irrigation losses assume no stock access within the ICA and outside the ICA, no stock access to streams with slopes less than 15 degrees.

Catchment	Area %ICA	N yield kg ha^{-1} y^{-1}				P yield kg ha^{-1} y^{-1}			
		ICA	Outside	Catchment	% pre-irrigation	ICA	Outside	Catchment	% pre-irrigation
Hawea	0%		7.1	7.1	100%		0.75	0.75	100%
Kahahakuri	91%	31.2	19.2	30.1	164%	0.58	0.69	0.59	130%
Lower Tukituki	12%	11.5	8.0	8.5	108%	0.82	0.94	0.93	101%
Maharakeke	81%	24.6	9.1	21.6	150%	0.73	0.73	0.73	117%
Makara	0%		8.7	8.7	100%		0.68	0.68	100%
Makaretu	38%	32.1	10.9	18.9	144%	0.52	1.73	1.27	105%
Mangamahaki	0%		8.8	8.8	100%		0.63	0.63	100%
Mangamate	25%	25.3	9.1	13.1	126%	0.64	0.65	0.65	99%
Mangamauku	21%	49.5	13.9	21.4	146%	0.68	0.89	0.85	102%
Mangaonuku	46%	27.4	10.9	18.5	139%	0.62	0.89	0.76	108%
Mangarara	0%		8.7	8.7	100%		0.65	0.65	100%
Mangatarata	2%	11.0	8.4	8.4	101%	0.81	0.89	0.89	100%
Middle Tukituki	16%	38.0	7.9	12.6	117%	0.62	1.43	1.30	101%
Ongaonga	73%	25.3	14.7	22.4	161%	0.61	0.76	0.65	129%
Papanui	45%	27.4	8.9	17.2	165%	0.88	0.98	0.94	105%
Porangahau	65%	39.9	19.7	32.8	159%	0.85	0.89	0.86	121%
Tukipo	39%	45.8	16.1	27.8	143%	0.68	1.15	0.96	107%
Waipawa	14%	35.2	8.3	12.0	114%	0.59	1.58	1.44	100%
Total	**26%**	**31.4**	**9.6**	**15.2**	**131%**	**0.69**	**1.02**	**0.93**	**104%**

Table 3-9: Post-irrigation TN and TP losses – restricted stock access and fertiliser mitigation. Ratio denotes the ratio of post- to pre-irrigation losses. Post-irrigation losses assume no stock access to streams within the ICA or to streams outside the ICA where slopes are less than 15 degrees, and the fertiliser mitigation measures listed Table 3-10.

Catchment	Area %ICA	N yield kg ha^{-1} y^{-1}				P yield kg ha^{-1} y^{-1}			
		ICA	Outside	Catchment	Ratio	ICA	Outside	Catchment	Ratio
Hawea	0%		7.1	7.1	100%		0.75	0.75	100%
Kahahakuri	91%	31.2	19.2	30.1	164%	0.49	0.69	0.51	113%
Lower Tukituki	12%	11.5	8.0	8.5	108%	0.70	0.94	0.91	99%
Maharakeke	81%	24.6	9.1	21.6	150%	0.61	0.73	0.63	100%
Makara	0%		8.7	8.7	100%		0.68	0.68	100%
Makaretu	38%	32.1	10.9	18.9	144%	0.44	1.73	1.24	103%
Mangamahaki	0%		8.8	8.8	100%		0.63	0.63	100%
Mangamate	25%	25.3	9.1	13.1	126%	0.54	0.65	0.62	96%
Mangamauku	21%	49.5	13.9	21.4	146%	0.58	0.89	0.83	99%
Mangaonuku	46%	27.4	10.9	18.5	139%	0.52	0.89	0.72	101%
Mangarara	0%		8.7	8.7	100%		0.65	0.65	100%
Mangatarata	2%	11.0	8.4	8.4	101%	0.68	0.89	0.89	99%
Middle Tukituki	16%	38.0	7.9	12.6	117%	0.55	1.43	1.29	100%
Ongaonga	73%	25.3	14.7	22.4	161%	0.51	0.76	0.58	115%
Papanui	45%	27.4	8.9	17.2	165%	0.75	0.98	0.88	98%
Porangahau	65%	39.9	19.7	32.8	159%	0.71	0.89	0.78	108%
Tukipo	39%	45.8	16.1	27.8	143%	0.60	1.15	0.93	104%
Waipawa	14%	35.2	8.3	12.0	114%	0.53	1.58	1.43	100%
Total	**26%**	**31.4**	**9.6**	**15.2**	**131%**	**0.59**	**1.02**	**0.91**	**101%**

Table 3-10: On-farm mitigation measures to reduce phosphorus loss.

Farm System	Description	P Mitigations
Sheep and Beef Breeding Farm	1B: Sheep breeding and bull beef finishing operation with 22% irrigation.	Apply all P fertiliser as RPR in November; reduce soil P status from 30 to 25.
Mixed Livestock Farm	2B: Mixed livestock sheep breeding and dairy support operation. 300 ha non-irrigated, cropping rape and barley.	Apply all P fertiliser as RPR in November; reduce soil P status from 30 to 25.
Dryland Finishing Farm	3B: Dryland lamb and bull beef finishing operation. 300 ha irrigated, cropping rape (winter) and barley.	Apply all P fertiliser as RPR in November; reduce soil P status from 30 to 25.
Mixed Arable Farm	4B: 300 ha 80% irrigated dairy support block, cropping rape, lucerne, peas, maize and barley.	Apply all P fertiliser as RPR in November; reduce soil P status from 30 to 25.
Arable Farm	5B: Arable high intensity farm – 300 ha lamb finishing and dairy grazing operation, with 90% irrigation, cropping lucerne, rape, peas, maize, potatoes and wheat.	Apply all P fertiliser as RPR in November; reduce soil P status from 30 to 25.
Dairy Farm	7B: Dairy farm milking 1110 cows (3.7 cows/ha) with 100% irrigation.	1. Apply maintenance P fertiliser as RPR in November; ensure P status does not exceed 30; apply farm dairy effluent at a rate less than 12 mm/hr. 2. Apply maintenance P fertiliser as soluble P in November; ensure P status does not exceed 30; apply farm dairy effluent at rate less than 12 mm/hr.

3.2.7 Summary and discussion of nutrient losses

If no mitigation measures are taken, it is estimated that irrigation will increase TN and TP losses across the whole catchment by 32% and 6% respectively. Within the ICA, the percentage increases are higher: 81% and 41% for TN and TP respectively (Table 3-11). Post-irrigation losses are not expected to be as large as this because of mitigation.

Fencing stock out of streams significantly reduces TP losses but has only a minor effect on TN losses. If stock are excluded from streams within the ICA then irrigation increases TN losses from the ICA by 79% compared with 81% assuming current stock access. However, if stock are excluded from streams within the ICA then irrigation increases TP losses from the ICA by 26% compared with 41% assuming current stock access (Table 3-11). For the catchment as a whole, irrigation increases TP losses by 4% if stock are excluded from streams within the ICA, compared with an increase of 6% with current stock access.

The proposed Plan Change for the Tukituki includes a provision to exclude stock from all streams on land outside the ICA with slopes below 15 degrees. Surprisingly, modelling indicates that this has little effect on TP losses. The reason is that the predominant farm systems outside the ICA (1a, 2a and 3a) are dominated by sheep, and OVERSEER predicts that stock access has little effect on TP losses (Table 3-4 and Table 3-5). If stock are excluded from streams both within and outside the ICA, it is predicted that irrigation results in an increase in TP losses from the whole catchment of 4%. If cattle numbers outside the ICA are higher than estimated, or if OVERSEER under-estimates the effects of cattle in the beef/cattle farming systems modelled, then TRIM will have under-estimated the benefits of stock exclusion outside the ICA.

It is intended that the RWSS be phosphorus-neutral meaning that phosphorus concentrations will not increase in any of the streams in the Tukituki catchment as a result of the RWSS. This requires that phosphorus losses within each catchment be no greater than at present.

Fencing to exclude stock from streams within the ICA significantly reduces post-irrigation TP losses but not back to pre-irrigation levels. However, as discussed above, OVERSEER probably under-estimates the benefits of fencing because it only quantifies the direct deposition of dung and urine, but not trampling damage to banks and the bed. Additional mitigation measures may be required if the RWSS is to be phosphorus-neutral.

OVERSEER predicts that reducing soil Olsen phosphorus levels from 30 to 25 significantly reduces TP losses. Olsen P can be maintained at 25 by optimising the timing of phosphorus application and by using slow release fertilisers.

If streams are fenced and optimal soil phosphorus levels are maintained throughout the ICA, then it is predicted that the RWSS will be within 1% of phosphorus-neutral for the catchment as a whole. However, the combined phosphorus losses from the ICA are estimated to be 7% above pre-irrigation levels (Table 3-11), with five sub-catchments being above, and others at or below, pre-irrigation phosphorus inflows. Additional mitigation measures may need to be put in place within these five sub-catchments if the RWSS is to be uniformly phosphorus-neutral. There are a number of options available to reduce phosphorus loss from farms, some of which are not are captured within OVERSEER (Mackay 2012; McDowell and Nash 2012).

Table 3-11: Summary of predicted TN and TP losses within and outside the ICA.

	ICA		OUTSIDE		Total	
	N yield kg ha^{-1} y^{-1}	**% pre**	**N yield kg ha^{-1} y^{-1}**	**% pre**	**N yield kg ha^{-1} y^{-1}**	**% pre**
Pre-irrigation						
	17.59	100%	9.61	100%	11.67	100%
Post-irrigation						
Current fencing	31.81	181%	9.61	100%	15.36	132%
Fence ICA	31.42	179%	9.61	100%	15.26	131%
+ Fence outside	31.42	179%	9.58	100%	15.24	131%
+ Optimal P fertiliser	31.42	179%	9.58	100%	15.24	131%
	P yield kg ha^{-1} y^{-1}	**% pre**	**P yield kg ha^{-1} y^{-1}**	**% pre**	**P yield kg ha^{-1} y^{-1}**	**% pre**
Pre-irrigation						
	0.55	100%	1.02	100%	0.90	100%
Post-irrigation						
Current fencing	0.77	141%	1.02	100%	0.96	106%
Fence ICA	0.69	126%	1.02	100%	0.93	104%
+ Fence outside	0.69	126%	1.02	100%	0.93	104%
+ Optimal P fertiliser	0.59	107%	1.02	100%	0.91	101%

3.3 Flow changes

The water storage scheme will alter flow regimes in the Tukituki and Waipawa Rivers. Land use intensification associated with irrigation is predicted to increase N and P losses from the irrigation area. Flow decreases are likely to increase N and P concentrations for given N and P losses by reducing dilution, and *vice versa*.

The RWSS will alter flows in four ways. First, the Makaroro dam will be filled during high flows. As a result, storage is predicted to reduce peak flows and reduce mean and median flow in the Makaroro, Waipawa and lower Tukituki Rivers. Note that the dam will not affect flows in the Tukituki River above the Waipawa confluence, or its tributaries. Second, the proposed minimum flow released from the dam is equivalent to 90% of MALF at that point. Because this is higher than the lowest flows that occur naturally, the dam will result in higher minimum during periods of very low dry spells – but only the Makaroro, Waipawa and lower Tukituki Rivers. Third, current surface and groundwater abstractions may be reduced once the water storage scheme becomes operative. Reducing surface water abstractions will have an immediate impact on river flow, with increases in summer low flow likely. Reducing groundwater abstractions will, eventually, restore groundwater levels to their natural state. This in turn will increase spring flow returns to streams on the Ruataniwha, and thereby also increase summer low flows. These benefits will accrue throughout the irrigation area. Fourth, irrigation may increase drainage to groundwater in summer because it increases soil moisture levels, and as a result summer low flows may increase (Aquanet, May 2013). Irrigation seeks to maintain soil moisture in summer at the optimal for plant growth, but below field capacity (viz., below the point at which drainage occurs). However, rainfall events during summer, combined with higher antecedent soil moisture, may result in soil moisture exceeding field capacity and drainage occurring. Again, these benefits will accrue throughout the irrigation area.

Predictions presented in this report assume that flow remains at current levels. This is a ‘worst-case’ assumption for phosphorus and periphyton growth, for the following reasons:

- Summer low flows in the Makaroro, Waipawa and lower Tukituki Rivers will be higher than at present.
- Base flows everywhere in the irrigation area will be higher than at present because drainage is expected to increase, and abstraction is expected to decrease.

Both these mechanisms will dilute phosphorus inflows more than is modelled at critical times for periphyton growth.

There will be decreases in median and maximum flows, and this raises the possibility that in winter when nitrate concentrations are highest, there will be lower dilution and a greater risk of nitrate toxicity. Typically the winter peaks in nitrate concentration occur under stable winter base flow conditions, and appear to be driven by groundwater inflows. Detailed modelling of surface-groundwater interactions, and their effects on nitrate concentration, has not been undertaken. However, given the likely increase in groundwater flow, the dilution of nitrate drainage into groundwater is likely to be more, and nitrate concentrations in the groundwater are likely to be less, than has been modelled. It seems likely, therefore, that the assumption flow remains at current levels gives ‘worst-case’ predictions of both nitrate toxicity and periphyton growth.

3.4 WWTP discharges

Currently effluent is discharged into the Tukituki and Waipawa rivers from four wastewater treatment plants (WWTP) near the townships of Waipukurau, Waipawa, Takapau and Otane. There are proposals to reduce nutrient concentrations prior to discharge at Waipukurau and Waipawa through the use of floating wetlands and chemical dosing. Two scenarios of WWTP discharge are modelled:

- Current discharges (CD).
- Phosphorus stripping (PS).

Phosphorus stripping (PS) refers to advanced treatment that results in effluent meeting the conditions on phosphorus concentration specified in consents granted to Central Hawke’s Bay District Council (CHBDC) which are due to come into effect in 2014. Land irrigation was modelled as part of an earlier investigation but is not being implemented.

Predictions are presented in this report assuming the current WWTP discharges.

4 Scenario predictions

4.1 Pre-irrigation stream inflows

4.1.1 Transient and steady state inflows

Table 4-1 shows stream nutrient inflows as predicted in 2010 given the history of generally increasing N and P losses in the catchment from 1900-2010 (transient). Table 4-2 shows inflows predicted assuming N and P losses remain constant at 2010 levels (steady-state). In sub-catchments where there is no groundwater, transient and steady-state inflows are identical.

For TN and TP carried in quick flow, transient and steady-state inflows are identical. In sub-catchments with groundwater, slow flow transient inflows are on average 73% of steady-state. Groundwater lags have only been quantified for the Ruataniwha Plain and in this study are assumed to be negligible elsewhere (e.g., in the Papanui). Groundwater makes a significant contribution to inflows in these catchments and, as a result, total TN inflows are currently 91% of steady state.

Only a small proportion of the TP inflows are carried by slow flow (groundwater). In the Kahahakuri, where a substantial proportion of water inflow is old groundwater, the transient TP inflow is 85% of steady state. In other sub-catchments within the ICA, TP inflows are much closer to steady-state For the whole catchment, however, transient total TP inflows are 99% of steady state TP inflows. Thus groundwater lags have only a second-order effect on TP inflows to streams.

For TN, groundwater lags have a larger effect. In sub-catchments where a large proportion of stream inflow derives from groundwater, slow flow inflows are typically 70-80% of steady-state. In the catchment as a whole, TN inflows currently average 92% of steady-state. Thus, TN inflows are predicted to increase by 8% over the next few decades if land use remains unchanged at current levels.

Table 4-1: Pre-irrigation transient – predicted TN and TP inflows to sub-catchments of the Tukituki River. Predictions are of inflows to streams in 2010 given the history of land use 1900-2010. Quick denotes surface and shallow sub-surface inflows. Slow denotes groundwater inflows. Where Slow is missing, there is no groundwater in the sub-catchment. % denotes the percentage of the total inflow. Stock exclusion is set at current levels.

Catchment	Reaches	TN Quick $t\ y^{-1}$	TN Slow $t\ y^{-1}$	TN Total $t\ y^{-1}$	TN % of SS	TP Quick $t\ y^{-1}$	TP Slow $t\ y^{-1}$	TP Total $t\ y^{-1}$	TP % of SS
Hawea	21	52.3	0.0	52.3	100%	4.9	0.0	4.9	100%
Kahahakuri	20	21.4	67.2	88.6	71%	1.1	0.4	1.5	85%
Lower Tukituki	116	157.9	0.0	157.9	100%	17.7	0.0	17.7	100%
Lower Waipawa	39	64.8	93.6	158.5	71%	7.6	0.9	8.4	95%
Maharakeke	28	95.4	12.7	108.2	97%	6.1	0.1	6.2	99%
Makara	34	79.5	0.0	79.5	100%	6.3	0.0	6.3	100%
Makaretu	64	68.1	70.4	138.5	98%	13.7	0.7	14.4	99%
Mangamahake	45	172.1	0.0	172.1	100%	11.9	0.0	11.9	100%
Mangamate	13	17.5	12.0	29.5	89%	2.8	0.1	2.9	99%
Mangamauku	5	7.7	4.1	11.8	93%	1.6	0.1	1.7	100%
Mangaonuku	52	143.3	94.0	237.2	90%	13.2	0.8	14.0	99%
Mangarara	23	64.9	0.0	64.9	100%	4.5	0.0	4.5	100%
Mangatarata	34	117.0	0.0	117.0	100%	12.3	0.0	12.3	100%
Mangatewai	27	52.6	14.8	67.4	100%	5.4	0.4	5.9	100%
Middle Tukituki	55	100.5	62.0	162.5	83%	9.0	0.4	9.4	98%
OngaOnga	12	14.5	0.4	15.0	100%	0.8	0.0	0.8	100%
Papanui	35	133.5	0.0	133.5	100%	10.3	0.0	10.3	100%
Porangahau	24	103.2	8.8	112.0	99%	3.1	0.0	3.1	100%
Tukipo	48	60.7	83.9	144.7	89%	5.9	0.9	6.8	95%
Upper Tukituki	40	47.4	22.6	70.0	96%	21.4	0.3	21.6	100%
Upper Waipawa	92	118.7	33.0	151.7	96%	38.4	0.2	38.7	100%
Total	**827**	**1693.2**	**579.6**	**2272.8**	**92%**	**197.9**	**5.2**	**203.1**	**99%**

Table 4-2: Pre-irrigation steady state – predicted TN and TP inflows to sub-catchments of the Tukituki River. Predictions are of steady state stream inflows given 2010 land use. Stock exclusion is set at current levels.

Catchment	Reaches	TN Quick $t\ y^{-1}$	TN Slow $t\ y^{-1}$	TN Total $t\ y^{-1}$	TN % total	TP Quick $t\ y^{-1}$	TP Slow $t\ y^{-1}$	TP Total $t\ y^{-1}$	TP % total
Hawea	21	52.3	0.0	52.3	2%	4.9	0.0	4.9	2%
Kahahakuri	20	21.4	103.5	124.9	5%	1.1	0.7	1.8	1%
Lower Tukituki	116	157.9	0.0	157.9	6%	17.7	0.0	17.7	9%
Lower Waipawa	39	64.8	157.3	222.2	9%	7.6	1.3	8.8	4%
Maharakeke	28	95.4	16.3	111.7	5%	6.1	0.1	6.2	3%
Makara	34	79.5	0.0	79.5	3%	6.3	0.0	6.3	3%
Makaretu	64	68.1	72.5	140.6	6%	13.7	0.8	14.5	7%
Mangamahake	45	172.1	0.0	172.1	7%	11.9	0.0	11.9	6%
Mangamate	13	17.5	15.5	32.9	1%	2.8	0.1	2.9	1%
Mangamauku	5	7.7	5.0	12.7	1%	1.6	0.1	1.7	1%
Mangaonuku	52	143.3	119.3	262.5	11%	13.2	1.0	14.2	7%
Mangarara	23	64.9	0.0	64.9	3%	4.5	0.0	4.5	2%
Mangatarata	34	117.0	0.0	117.0	5%	12.3	0.0	12.3	6%
Mangatewai	27	52.6	14.8	67.4	3%	5.4	0.4	5.9	3%
Middle Tukituki	55	100.5	94.3	194.8	8%	9.0	0.6	9.6	5%
OngaOnga	12	14.5	0.4	15.0	1%	0.8	0.0	0.8	0%
Papanui	35	133.5	0.0	133.5	5%	10.3	0.0	10.3	5%
Porangahau	24	103.2	9.6	112.8	5%	3.1	0.0	3.1	2%
Tukipo	48	60.7	101.8	162.5	7%	5.9	1.3	7.2	4%
Upper Tukituki	40	47.4	25.9	73.2	3%	21.4	0.3	21.7	11%
Upper Waipawa	92	118.7	39.7	158.4	6%	38.4	0.3	38.7	19%
Total	**827**	**1693.2**	**775.8**	**2468.9**	**100%**	**197.9**	**7.0**	**204.9**	**100%**

4.2 Post-irrigation stream inflows

It is proposed that, on pasture receiving water for irrigation, all streams of 2nd-order and larger will be fenced to exclude stock. Currently, it is estimated that cattle are excluded from 40% of 2nd to 4th-order streams. In addition, the proposed Tukituki Plan Change will require that, on all other farmland in the Tukituki catchment where slope is less than 15 degrees, streams of 2nd-order or larger will be fenced to exclude stock. Currently, it is estimated that outside the ICA stock are excluded from 50% of 2nd to 4th-order streams and from 32% of 2nd to 4th-order streams on land where slope is less than 15 degrees.

4.2.1 Current fencing

A 'worst-case' scenario assumes that no additional fencing is undertaken post-irrigation (Table 4-3). In the catchment as a whole, land use intensification within the ICA is predicted to increase TN inflows by 32% and TP inflows by 7%. Two sub-catchments within the ICA (Kahahakuri and OngaOnga) experience increases in TN and TP inflows of 59-60% and 59-87% respectively. These increases are consistent with the increases in TN and TP losses discussed earlier. Inflows are not expected to increase as much as this because of proposed mitigation measures.

4.2.2 Excluding cattle from streams in the ICA

It is proposed that, on pasture receiving water for irrigation, all streams of 2nd-order or larger will be fenced to exclude stock. Currently, it is estimated that cattle are excluded from 40% of streams of 2nd-4th order within the ICA.

Table 4-4 shows steady state TN and TP inflows to streams predicted assuming post-irrigation land use and stock exclusion from all streams within the ICA. TN inflows to streams across the whole catchment are 27% higher than pre-irrigation inflows. In catchments where there is a lot of irrigable land, TN inflows are 13-48% higher. TN inflows are reduced by fencing streams within the ICA but the reduction is small. The reason is that the majority of nitrogen is transported to streams by drainage, interflow and groundwater flow and fencing to exclude stock from streams has no effect on nitrogen attenuation along these delivery pathways.

When streams within the ICA are fenced to exclude stock, it is predicted that TP inflows to streams across the whole catchment are 3% higher than pre-irrigation inflows, compared with 6% with current stock access. Within the ICA there are significant reductions in all catchments. Nevertheless, in the OngaOnga and Kahahakuri, total TP losses are predicted to be 36-48% higher than pre-irrigation losses.

4.2.3 Excluding cattle from streams outside the ICA

The proposed Tukituki Plan Change requires streams to be fenced to exclude stock on all farmland in the Tukituki catchment where slope is less than 15 degrees. Currently, it is estimated that stock are excluded from 50% of streams of 2nd-4th order outside the ICA, and from 32% of streams on land where slope is less than 15 degrees. As discussed earlier, TN and TP losses predicted by OVERSEER for post-irrigation land uses outside the ICA were the same regardless of whether streams were fenced to exclude stock or unfenced. Consequently, predicted stream inflows were the same as in Table 4-4 and are omitted for brevity.

4.2.4 On-farm mitigation of phosphorus loss

Table 3-10 details TP losses estimated using OVERSEER, assuming not only that stock are fenced out of waterways, but also and that P fertiliser application and type are optimised.

Table 4-5 shows the stream inflows estimated for these losses.TN losses are unchanged because the on-farm mitigation measures modelled only affect phosphorus losses. In the catchment as a whole, post-irrigation TP inflows are not significantly different from pre-irrigation inflows. Outside the ICA there are no differences. Within the ICA there are some sub-catchments in which post-irrigation inflows are less than pre-irrigation inflows, some in which they are the same, and some in which they are larger. TP inflows to streams show the same pattern as the TP losses from the land (Table 3-9).

Table 4-3: Post-irrigation current stock access – predicted TN and TP inflows to streams in sub-catchments of the Tukituki River. Predictions are of steady state inflows for the Macfarlane scenario of post-irrigation land use. Stock exclusion is at current levels. * denotes significant irrigation within the sub-catchment. Also shown are the %increases compared with steady-state pre-irrigation inflows.

Catchment	Reaches	TN				TP			
		Quick t/y	Slow t/y	Total t/y	% of pre-irrigation	Quick t/y	Slow t/y	Total t/y	% of pre-irrigation
Hawea	21	52.3	0.0	52.3	100%	4.9	0.0	4.9	100%
Kahahakuri**	20	44.1	154.9	199.0	159%	1.9	0.0	2.9	159%
Lower Tukituki*	116	196.6	0.0	196.6	125%	17.9	0.1	17.9	101%
Lower Waipawa*	39	96.0	223.0	319.1	144%	8.5	0.0	10.2	116%
Maharakeke**	28	128.8	27.8	156.6	140%	6.9	0.0	7.2	116%
Makara	34	79.5	0.0	79.5	100%	6.3	0.0	6.3	100%
Makaretu*	64	88.8	101.1	189.9	135%	14.8	0.1	15.9	110%
Mangamahake	45	172.1	0.0	172.1	100%	11.9	0.0	11.9	100%
Mangamate*	13	24.9	21.2	46.1	140%	2.9	0.0	3.0	103%
Mangamauku*	5	8.5	6.2	14.6	115%	1.6	0.0	1.7	99%
Mangaonuku*	52	188.0	188.3	376.3	143%	14.1	0.1	15.5	109%
Mangarara	23	64.9	0.0	64.9	100%	4.5	0.0	4.5	100%
Mangatarata	34	117.0	0.0	117.0	100%	12.3	0.0	12.3	100%
Mangatewai*	27	68.3	25.1	93.4	139%	5.9	0.0	6.4	109%
Middle Tukituki*	55	112.2	152.7	264.9	136%	9.7	0.1	10.6	110%
OngaOnga*	12	23.2	0.8	24.0	160%	1.5	0.0	1.5	187%
Papanui*	35	203.3	0.0	203.3	152%	11.2	0.0	11.2	109%
Porangahau*	24	141.1	22.1	163.2	145%	4.2	0.0	4.4	142%
Tukipo*	48	91.6	166.8	258.4	159%	7.2	0.0	9.2	128%
Upper Tukituki*	40	62.1	34.3	96.4	132%	21.8	0.0	22.1	102%
Upper Waipawa	92	132.4	41.5	173.9	110%	38.8	0.1	39.1	101%
Total	**827**	**2095.7**	**1165.8**	**3261.5**	**132%**	**208.9**	**0.8**	**218.6**	**107%**

Table 4-4: Post-irrigation stock exclusion within the ICA – predicted TN and TP inflows to streams in sub-catchments of the Tukituki River. Predictions are of steady state inflows for the Macfarlane scenario of post-irrigation land use. Stock exclusion is 100% within the ICA and current levels in the rest of the catchment. * denotes significant irrigation within the sub-catchment.

Catchment	Reaches	TN				TP			
		Quick t/y	Slow t/y	Total t/y	% of pre-irrigation	Quick t/y	Slow t/y	Total t/y	% of pre-irrigation
Hawea	21	52.3	0.0	52.3	100%	4.9	0.0	4.9	100%
Kahahakuri*	20	42.7	155.0	197.7	158%	1.6	1.0	2.6	144%
Lower Tukituki	116	196.2	0.0	196.2	124%	17.8	0.0	17.8	101%
Lower Waipawa*	39	93.5	223.2	316.7	143%	8.0	1.7	9.7	110%
Maharakeke*	28	127.3	27.8	155.1	139%	6.6	0.2	6.9	111%
Makara	34	79.5	0.0	79.5	100%	6.3	0.0	6.3	100%
Makaretu*	64	86.9	101.1	188.0	134%	14.4	1.1	15.6	107%
Mangamahake	45	172.1	0.0	172.1	100%	11.9	0.0	11.9	100%
Mangamate*	13	24.3	21.2	45.5	138%	2.8	0.1	2.9	99%
Mangamauku*	5	8.4	6.2	14.6	115%	1.6	0.1	1.7	98%
Mangaonuku*	52	185.2	188.4	373.7	142%	13.6	1.4	15.0	106%
Mangarara	23	64.9	0.0	64.9	100%	4.5	0.0	4.5	100%
Mangatarata	34	117.0	0.0	117.0	100%	12.3	0.0	12.3	100%
Mangatewai*	27	67.6	25.1	92.7	137%	5.8	0.5	6.3	106%
Middle Tukituki*	55	109.8	152.8	262.6	135%	9.3	0.8	10.1	105%
OngaOnga*	12	22.3	0.8	23.1	154%	1.3	0.0	1.3	166%
Papanui*	35	201.7	0.0	201.7	151%	10.9	0.0	10.9	105%
Porangahau*	24	138.4	22.1	160.6	142%	3.7	0.2	3.9	125%
Tukipo*	48	88.4	167.0	255.4	157%	6.6	2.0	8.6	119%
Upper Tukituki*	40	61.6	34.3	95.9	131%	21.7	0.3	22.0	102%
Upper Waipawa	92	130.8	41.5	172.3	109%	38.5	0.3	38.7	100%
Total	**827**	**2070.9**	**1166.6**	**3237.5**	**131%**	**204.0**	**9.7**	**213.7**	**104%**

Table 4-5: Post-irrigation stock exclusion and optimal phosphorus – predicted TN and TP inflows to streams in sub-catchments of the Tukituki River. Predictions are of steady state inflows for the Macfarlane scenario of post-irrigation land use with (a) stock exclusion of 100% within the ICA and on streams in the rest of the catchment where slope is less than 15 degrees, and (b) on-farm phosphorus mitigation measures (see Table 3-10).* denotes significant irrigation within the sub-catchment.

Catchment	Reaches	TN				TP			
		Quick t/y	Slow t/y	Total t/y	% of pre-irrigation	Quick t/y	Slow t/y	Total t/y	% of pre-irrigation
Hawea	21	52.3		52.3	100%	4.9		4.9	100%
Kahahakuri*	20	42.7	146.3	188.9	151%	1.3	0.9	2.2	80%
Lower Tukituki	116	196.2		196.2	124%	17.4		17.4	102%
Lower Waipawa*	39	93.5	213.2	306.7	138%	7.6	1.7	9.2	95%
Maharakeke*	28	127.3	16.4	143.7	129%	5.9	0.2	6.0	103%
Makara	34	79.5		79.5	100%	6.3		6.3	100%
Makaretu*	64	86.3	71.0	157.3	112%	13.9	1.0	14.9	97%
Mangamahake	45	172.1		172.1	100%	11.9		11.9	100%
Mangamate*	13	24.2	19.5	43.7	133%	2.6	0.1	2.7	106%
Mangamauku*	5	8.4	6.2	14.5	114%	1.5	0.1	1.5	110%
Mangaonuku*	52	184.6	165.4	350.0	133%	12.9	1.2	14.1	101%
Mangarara	23	64.9		64.9	100%	4.5		4.5	100%
Mangatarata	34	117.0		117.0	100%	12.3		12.3	100%
Mangatewai*	27	67.0	19.5	86.4	128%	5.5	0.5	6.0	99%
Middle Tukituki*	55	109.7	138.4	248.1	127%	9.0	0.7	9.7	99%
OngaOnga*	12	22.3		22.3	148%	1.1		1.1	75%
Papanui*	35	201.6		201.6	151%	10.2		10.2	101%
Porangahau*	24	138.3	9.3	147.6	131%	3.1	0.1	3.2	96%
Tukipo*	48	87.9	132.2	220.0	135%	6.0	1.8	7.8	92%
Upper Tukituki*	40	61.4	25.4	86.8	119%	21.5	0.2	21.7	100%
Upper Waipawa	92	130.3	33.5	163.8	103%	37.9	0.2	38.1	102%
Total	**827**	**2067.3**	**996.1**	**3063.4**	**124%**	**197.1**	**8.7**	**205.8**	**100%**

4.3 Stream nutrient concentrations and plant biomass

4.3.1 Tukituki River

Figure 4-1 and Figure 4-2 compare pre- and post-irrigation time-series of predicted biomass (BIO) and oxidised nitrogen (NNN) at SH2 and Red Bridge. Post-irrigation predictions assume no stock access within the ICA, restricted stock access outside the ICA and on-farm mitigation of phosphorus loss.

Periphyton biomass reaches a maximum of 15-20 g C m^{-2} at both sites during periods of prolonged low flow. As flows decrease, so also does scour loss and biomass accumulation. Growth rate increases with nutrient concentration when nutrient concentrations are below those that saturate growth. In the Tukituki nitrogen concentrations are well above saturation concentrations at SH2, and in all except prolonged low flows at Red Bridge. Phosphorus concentrations are below saturation at both sites, and control periphyton growth rate.

Land use intensification associated with the RWSS has the potential to increase phosphorus inflows. However, in the scenario modelled, mitigation measures are in place (stock exclusion and optimal P fertiliser), which ensure that P inflows for the catchment as a whole are similar pre- and post-irrigation. The sum of post-irrigation TP inflows from Zones A-D are not significantly different from pre-irrigation inflows. As a result, predicted periphyton biomass at SH2 is similar pre- and post-irrigation. Post-irrigation TP inflows from Zone M (Papanui) are 4% higher than pre-irrigation inflows (Table 4-5). As a result, predicted periphyton biomass at Red Bridge is slightly higher post-irrigation.

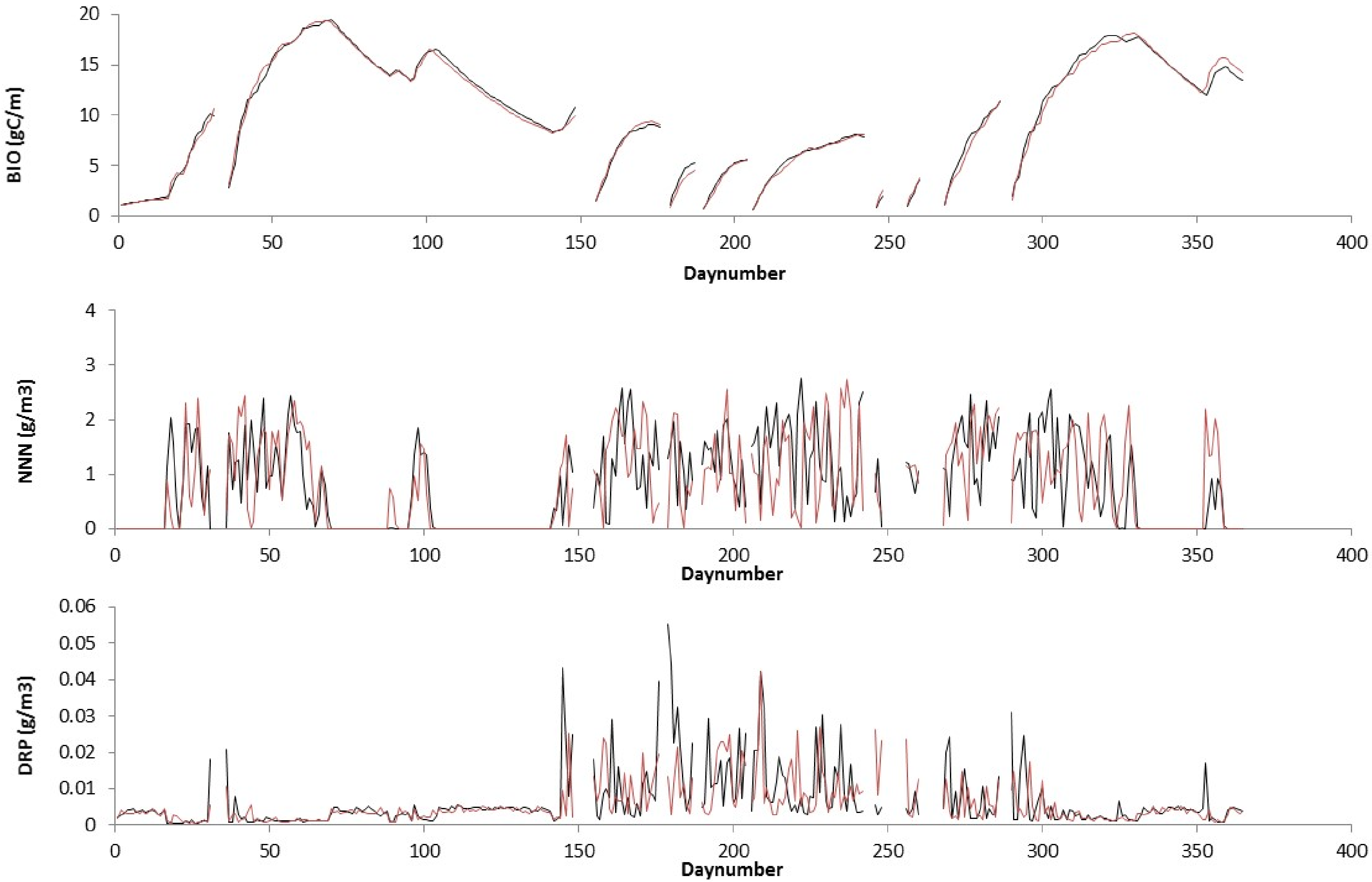

Figure 4-1: Comparison of pre- (red) and post- (black) irrigation time series of biomass (BIO) and oxidised nitrogen (NNN) at SH2. Predictions at flows below three times median are omitted.

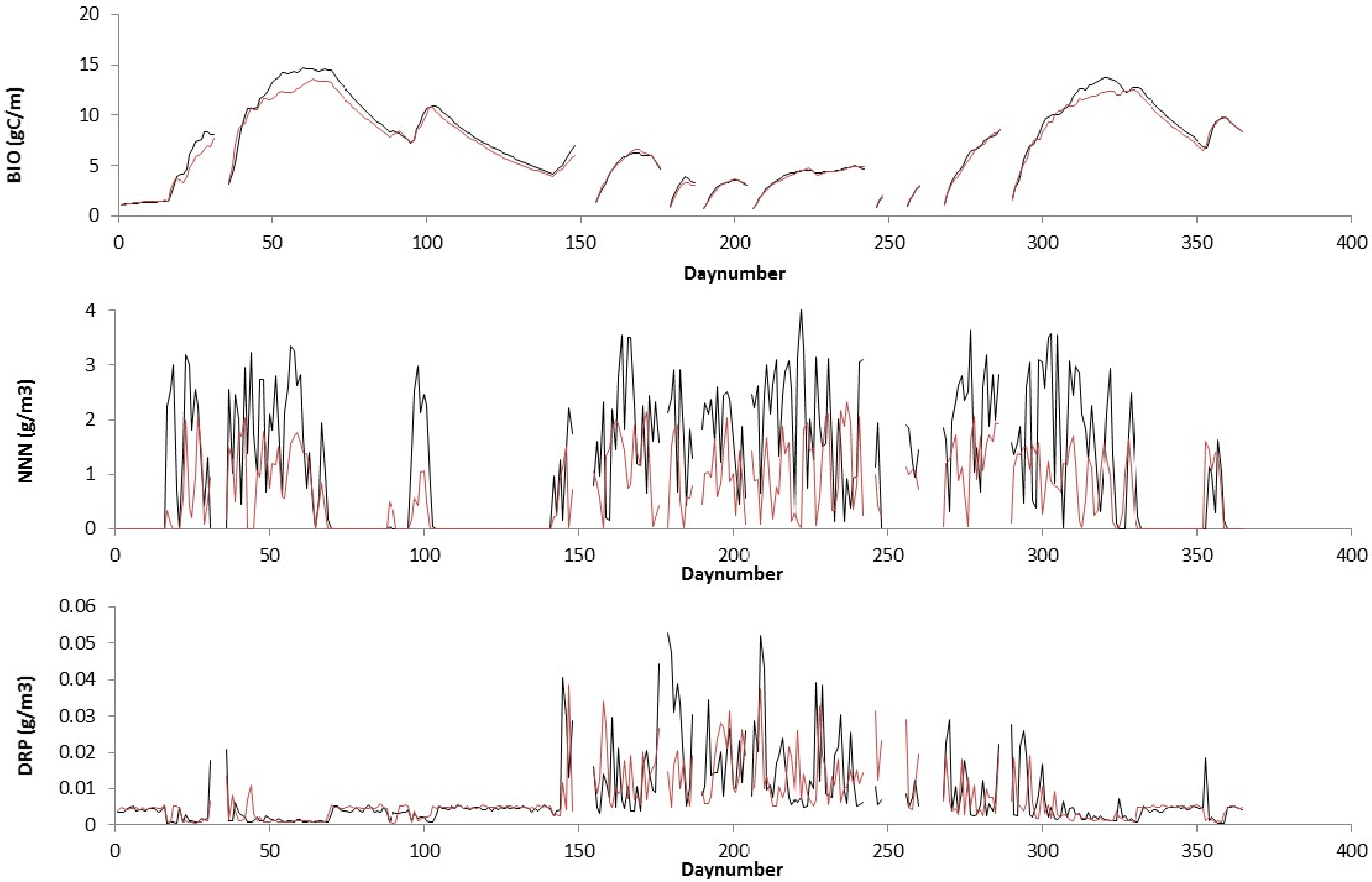

Figure 4-2: Comparison of pre- (red) and post- (black) irrigation time series of biomass (BIO) and oxidised nitrogen (NNN) at Red Bridge. Predictions at flows below three times median are omitted.

4.3.2 Tributaries

Nitrogen

As a result of increased nitrogen inflows from the RWSS, significant increases in NNN and TN concentrations are predicted in streams on the Ruataniwha Plain.

Figure 4-3 shows predicted NNN concentrations in the main tributaries assuming a constant denitrification rate (0.1 g m^{-2} d^{-1}) in both the tributaries and the main stem of the Tukituki and Waipawa Rivers. During summer low flow periods, predicted NNN concentrations are low. However, during high flow periods and during winter predicted NNN concentrations are significantly higher post-irrigation than pre-irrigation (see Figure 2-8).

In the draft Plan Change for the Tukituki, HBRC proposes limits on stream nitrate concentration to avoid problems with nitrate toxicity. The limits vary across the catchment as shown in Table 4-7. For the year simulated (2010), in the 827 stream segments modelled, it is predicted that there are 50 breaches of the nitrate toxicity limit on annual median NNN concentration (Table 4-7), and 52 breaches of the 95%ile limit. These mostly occur in the Kahahakuri, Porangahau and Papanui catchments. The Porangahau Stream is affected by the land disposal of effluent from the Silver Fern Farms meat works and intensive agriculture. The Papanui Stream is affected by the WWTP discharge from Otane and intensive agriculture. The Kahahakuri Stream is only affected by intensive agriculture.

Making the worst-case assumption that denitrification in the tributaries is negligibly small, the number of stream segments in which the nitrate limit is exceeded increases to 51 (median) and 55 (95%ile). The reason the numbers of exceedances are similar with and without denitrification is that the limits apply to the annual median and 95%ile concentrations. These are dominated by winter high flow concentrations which, in the model, are not sensitive to the denitrification rate. The reason is that the denitrification rate (units g m^{-2} d^{-1}) is assumed to be constant, and as the flow increases so does the depth and velocity, with the result that the rate of change of concentration decreases. In addition, the inflow rate of nitrate during winter high flows is much larger than during summer low flows. Thus, although summer low flow NNN concentrations in the tributaries increase significantly when tributary denitrification is set to zero, the annual median and 95%ile concentrations increase only slightly.

The TRIM modelling confirms the existence of nitrate hot spots in the stream segments, and helps understand their origin. However, it would be prudent to conduct detailed sampling in those regions before deciding whether the nitrate toxicity limits are currently being approached and to compare measurements with TRIM predictions for the pre-irrigation scenario.

Table 4-6: Number of stream segments in which annual median or 95%ile nitrate concentration exceeds the limits set in Table 4-7. There are 827 stream segments in the model, all of 4th-order of higher. Columns 3 and 4 assume tributary and main stem denitrification are the same (0.1 g m^{-2} d^{-1}). Columns 5 and 6 assume tributary denitrification is zero. Predictions are for 2010.

		Tributary denitrification		No tributary denitrification	
Stream	**Total segments**	**Exceed median**	**Exceed 95%ile**	**Exceed median**	**Exceed 95%ile**
Hawea	21	0	0	0	0
Kahahakuri	20	18	18	18	19
Maharakeke	28	0	0	0	0
Makara	34	0	0	0	0
Makaretu	64	0	0	0	0
Makaroro	35	0	0	0	0
Mangamahake	45	0	0	0	0
Mangamate	13	0	0	0	0
Mangamauku	5	0	0	0	0
Mangaonuku	52	0	0	0	0
Mangarara	23	0	0	0	0
Mangatarata	34	0	0	0	0
Mangataura	14	0	0	0	0
Mangatewai	27	0	0	0	0
OngaOnga	12	0	1	0	1
Papanui	26	20	21	21	22
Porangahau	24	12	12	12	12
Pukehou	9	0	0	0	1
Tukipo	48	0	0	0	0
Tukituki	211	0	0	0	0
Waipawa	82	0	0	0	0
Total	**827**	**50**	**52**	**51**	**55**

Table 4-7: Surface water quality limits and targets for the Tukituki River Catchment.

Water Management Zone	Mainstems/ Tributaries	Periphyton Limits and Targets			DRP Limits and Targets	Nitrate-nitrogen Limits and Targets		DIN Limits and Targets
		(a)	(b)	(c)		(a)	(b)	
Zone 1 Lower Tukituki and Waipawa Rivers and Tributaries (excluding Papanui Stream catchment)	Mainstems	120	30	60	0.010	2.4	3.5	n/a
	Tributaries				0.015			
Zone 2 Middle Waipawa River and Tributaries above SH2	Mainstems	120	30	60	0.010	3.8	5.6	n/a
	Tributaries				0.015			
Zone 3 Middle Tukituki River and Tributaries above Tapairu Road	Mainstems	120	30	60	0.010	3.8	5.6	n/a
	Tributaries				0.015			
Zone 4 Upper Tukituki and Waipawa Rivers	All	50	30	60	0.004	n/a	1.5	0.150
Zone 5 Papanui Stream	All	120	30	60	0.015	2.4	3.5	n/a

Nitrogen:

(a) Maximum annual median concentration of nitrate-nitrogen (mg NO_3-N /L). The annual average concentration of nitrate-nitrogen shall be calculated as the average of monthly monitoring results obtained over a period of 5 consecutive years.

(b) Maximum 95th percentile concentration of nitrate-nitrogen (mg NO_3-N /L). The 95^{th} percentile concentration of nitrate-nitrogen shall be calculated as the 95^{th} percentile of monthly monitoring results obtained over a period of 5 consecutive years.

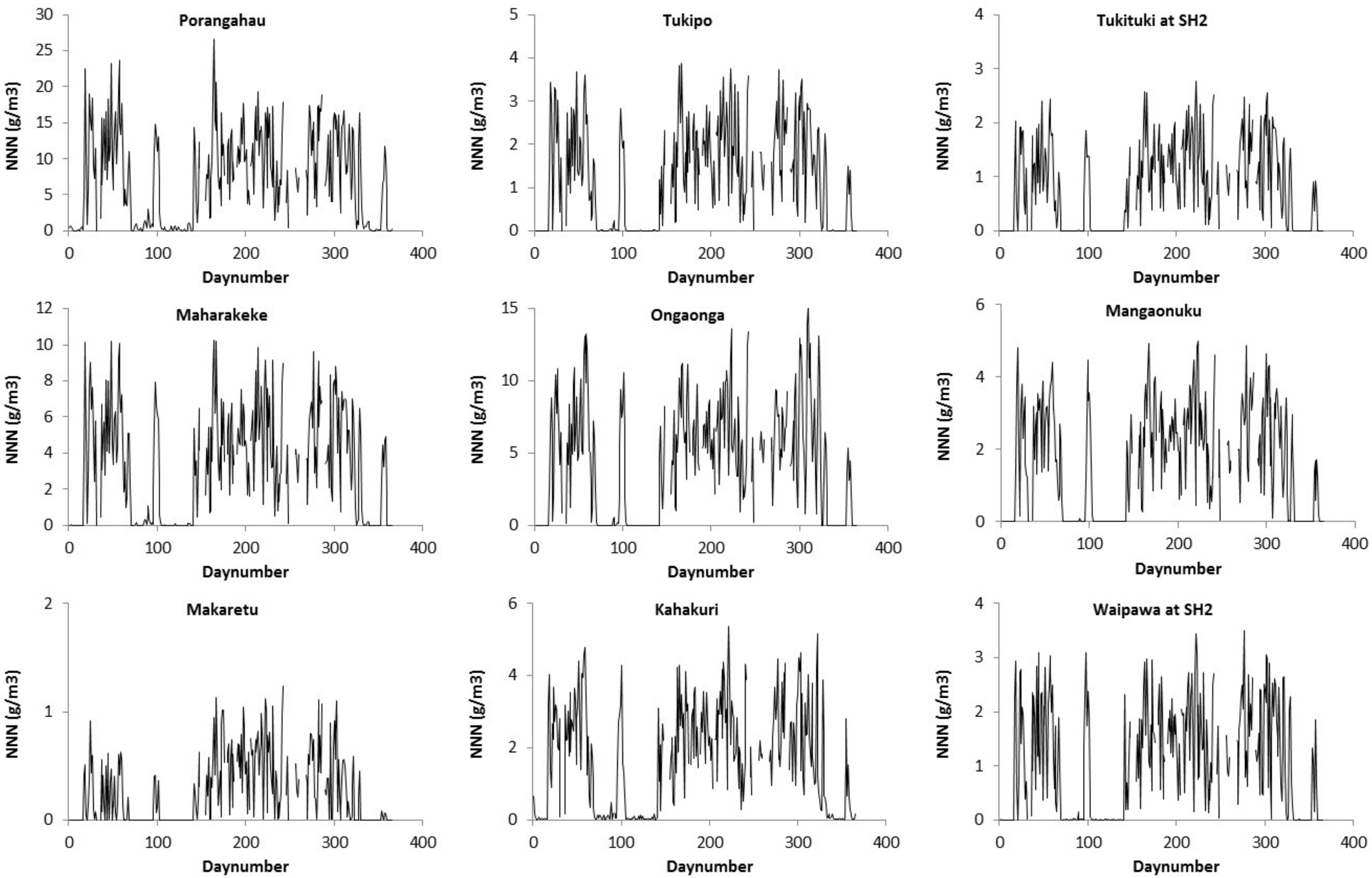

Figure 4-3: Post- irrigation - time-series of predicted NNN concentrations in streams. Results for flows above three times median are omitted. Denitrification is assumed identical (0.1 g m^{-2} d^{-1}) in the tributaries and the main stem of the Tukituki River.

5 Summary and conclusions

The stream nutrient and periphyton model TRIM1_STREAM has been extended to the whole of the Tukituki catchment, re-calibrated, a limited sensitivity analysis conducted, and model uncertainties identified. The revised model, TRIM2_STREAM, uses water and nutrient inflows predicted by the TRIM2_CATCHMENT model which is described elsewhere (Rutherford 2013).

TRIM2_STREAM satisfactorily predicts observed stream nitrogen and phosphorus concentrations, and biomass for a representative pre-irrigation year, 2010. However, there are several different combinations of key model coefficients that give a similar match between predicted and observed stream nutrient concentrations and biomass. Ideally, key coefficients would be estimated directly from experimental data. While this is possible for some coefficients (e.g., plant growth rate and detritus settling rate), experimental data are not available from which to estimate others (e.g., tributary denitrification, phosphorus bed exchange, phosphorus and nitrogen recycling from detritus). The strategy adopted to cope with this non-uniqueness problem with model calibration is to identify the processes and model coefficients that have the greatest effect on model predictions, seek alternative calibrations, and determine whether model uncertainty affects the main conclusions and recommended actions. The TRIM2_STREAM model is considered to be sufficiently reliable to assess the impact of the RWSS, bearing in mind areas of uncertainty in its calibration.

Modelling confirms that phosphorus, rather than nitrogen, determines periphyton growth rates and biomass, except occasionally near the sea during summer low flows. In the middle Tukituki (from above Waipukurau to near Red Bridge), dissolved inorganic nitrogen concentrations are well in excess of the concentrations that limit plant growth. It is only in the lower Tukituki (from near Red Bridge to the sea) that, during prolonged periods of summer low flow, nitrogen concentrations are low (largely as a result of denitrification) and nitrogen becomes limiting to plant growth.

Sensitivity analysis indicates that phosphorus supply, rather than phosphorus concentration, determines periphyton biomass. Phosphorus supply is largely determined by phosphorus inflows, which are initially determined by OVERSEER and then routed through the catchment by TRIM2_CATCHMENT which quantifies phosphorus attenuation. In an earlier study (Rutherford 2013), a satisfactory match was obtained between observed annual flow-weighted mean phosphorus concentrations in the major tributaries, and predictions made by OVERSEER and the TRIM2_CATCHMENT model. This indicates that attenuated phosphorus inflows to streams from the catchment are predicted satisfactorily.

A key recommendation arising from the modelling is that phosphorus losses from the RWSS should be minimised in order that nuisance periphyton growths should not occur more frequently, or be more severe, than they are currently. One aspect of the Tukituki River that is not well understood is phosphorus exchange between the stream bed and the overlying water. There is evidence that, during summer low flows in the lower Tukituki (from near Red ridge to the sea), phosphorus concentrations remain high because phosphorus is released from the bed, although there are alternative explanations. Thus, an aspect of the TRIM2_STREAM model that is uncertain is phosphorus exchange with the stream bed. It is desirable to undertake experimental work on phosphorus release from the bed and also on recycling from detritus, and then to re-calibrate aspects of the TRIM2_STREAM model.

Phosphorus release from the bed depends on the equilibrium concentration in the bed (which depends on the amount of phosphorus adsorbed onto sediment particles and its partitioning into mobile phases) and the rate at which phosphorus is exchanged with the water when concentrations are either higher or lower than the equilibrium concentration. If phosphorus losses from the RWSS do not increase (viz., the RWSS is phosphorus-neutral) then it seems unlikely that the equilibrium concentration will change significantly. However, if the phosphorus inflows from outside the irrigation consent area decrease (e.g., as a result of stock exclusion from streams), the equilibrium concentration may decrease. On the other hand, if phosphorus inflows from outside the irrigation consent area increase (e.g., as a result of intensification), the equilibrium concentration may increase. Since the phosphorus inflows will remain approximately neutral, it seems unlikely that uncertainties in the modelling of phosphorus exchange are sufficient to invalidate the recommendation to maintain or reduce phosphorus losses from the catchment.

In sub-catchments where groundwater provides a substantial component of stream flow, the model indicates that nitrogen inflows will increase over the next century by an average of approximately 30% even if land use remains unchanged. Most of this increase will occur within the next 50 years. For the catchment as a whole, TN inflows are predicted to increase by approximately 9% over the next few decades if land use remains unchanged at current levels.

Two objectives have been set for the RWSS:

- To make the scheme 'phosphorus-neutral' (viz., for there to be no increase in phosphorus concentrations in the streams as a result of the RWSS).
- To minimise the risk of nitrate toxicity to sensitive stream organisms.

Nitrogen and phosphorus losses across the entire catchment are predicted to increase by 32% and 6% respectively as a result of land use intensification associated with the RWSS (Table 3-11). Nitrogen and phosphorus inflows to streams[5] increase by similar percentages, although attenuation varies between sub-catchments.

Nitrogen and phosphorus losses within the irrigation consent area are predicted to increase by an average of 81% and 41% respectively (Table 3-11). These increases assume current farming practice with no additional on-farm mitigation to reduce nutrient loss.

Fencing to exclude stock from streams and the optimal use of phosphorus fertiliser are predicted to offset the 6% increase in phosphorus losses and make the RWSS close to phosphorus-neutral overall.

Within the irrigation consent area these measures are predicted to result in a 7% increase in phosphorus losses compared with pre-irrigation levels – significantly lower than the predicted 41% without any mitigation, but still not 'phosphorus-neutral'. OVERSEER probably under-estimates the benefits of stock exclusion from streams, because it only quantifies the direct deposition of dung and urine, but not trampling of the banks and stream bed. Nevertheless,

[5] When comparing stream inflows, steady-state values are used.

additional mitigation measures may be required in some irrigated sub-catchments for them to be ‘phosphorus-neutral’. There are a number of additional on-farm mitigation measures that can be undertaken to reduce phosphorus losses (McDowell and Nash 2012).

Note that it will not be possible to completely eliminate nuisance periphyton growths during prolonged summer low flows through nutrient control although it may be possible to alleviate problems by releasing flushing flows from the dam.

Phosphorus supply affects the rate of periphyton growth, and any increase in phosphorus inflows will increase the rate at which periphyton biomass accumulates in the river. However, flow also exerts a strong control on biomass. Periodically, high flows ‘reset’ biomass to low levels. Currently, during prolonged summer low flows, periphyton biomass reaches nuisance levels in many parts of the river, including reaches apparently unaffected by nutrient runoff from agriculture. In such reaches, nutrient inflows and growth rates are low. Biomass accumulates slowly but, if there is a very long dry period without any ‘reset’ flows, may reach nuisance values. In parts of the river where nutrient inflows are high, growth rates are high, and biomass accumulates quickly. Consequently, nuisance levels are reached more quickly and peak biomass may be higher.

If phosphorus mitigation is effective, and the flow regime does not change, then it is predicted that periphyton biomass in the main stem of the Tukituki River will be similar to current levels. Note that nuisance biomass levels may still occur during prolonged periods of low flow, but there should be no significant increase in the frequency or magnitude of nuisance growths as a result of the RWSS. This conclusion is robust to uncertainty about phosphorus release from the bed.

One mitigation option to reduce ‘nuisance growths’ is to release water from the dam at critical times and create a flushing flow which scours periphyton from the river and removes deposited biomass. The RWSS proposal now includes the release of up to four flushing flows per irrigation season as discussed by Aquanet (2013). These additional flushing flows have not been incorporated in the TRIM modelling presented in this report, but a preliminary quantitative assessment of the effects of these flushing flows on periphyton biomass could be undertaken using TRIM-STREAM.

No monitoring data exist to compare with model predictions in most of the smaller streams – predictions should therefore be treated with caution. Nevertheless, predictions highlight that potential ‘hot spots’ of high nutrient, and potentially high biomass, are likely to occur in some tributaries.

In some sub-catchments phosphorus inflows are predicted to be higher than pre-irrigation inflows. Additional phosphorus mitigation measures may be required in such sub-catchments to avoid problems associated with high biomass.

Nitrate concentrations are predicted to increase significantly in tributaries draining the irrigation consent areas. Under current conditions, ‘hot spots’ of high nitrate concentration have been identified in some tributaries of the middle Tukituki, which raises concerns about possible nitrate toxicity.

The TRIM model currently assumes a constant denitrification rate, whose value has been estimated by calibration to measured nitrate concentrations in the main stem of the Tukituki

River during summer low flows in 2011. Assuming the same denitrification rate in the tributaries as that in the main stem, it is predicted that nitrate concentrations will exceed the limits set in the proposed Tukituki Plan Change in the Kahahakuri, Porangahau, Pukehou and Papanui. The Porangahau, Pukehou and Papanui are affected by point source waste discharges and intensive farming. The Kahahakuri is only affected by intensive farming. Assuming zero denitrification in the tributaries, there is only a slight increase in the number of stream segments where nitrate concentrations exceed the limits. The reason for the muted response is that the nitrate limits apply to the annual median and 95 percentile concentrations. Although summer low flow nitrate concentrations increase markedly when denitrification is set to zero, the annual median and 95 percentile concentrations only increase by a small amount. Nevertheless, it is recommended that field investigations be undertaken to measure denitrification rates in the tributaries, which should be compared with rates observed in the main stem. Additional nitrogen mitigation may need to be implemented in some sub-catchments to avoid nitrate toxicity problems.

In the scenarios modelled, the land use changes are those determined by Macfarlane Rural Business based on a land use capability and economic analysis. Other mixes of land use are possible. In an earlier study MacKay (in Rutherford et al. 2012) investigated an alternative scenario in which dairy and intensive arable were extended by a further 5,450 ha reducing sheep and beef extensive, orchard and vineyard by the corresponding area. This translated to an increase in N losses of 100 t y^{-1} from 3,060 t y^{-1} to 3,160 t y^{-1}, which would have a negligibly small impact on the river. Unmitigated P losses would be expected to increase by a similar, very small percentage.

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