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Catchment and lake water quality modelling to assess management options for Lake Tutira

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Executive Summary

Lake Tutira is an important ecological, historical and cultural asset to the Hawke's Bay. It is a highly utilised trout fishery, a popular recreational destination, and is particularly significant to Ngāti Kahungunu, for its historical eel fishery and rongoa (medicinal) harakeke (flax) beds. The lake and its catchment have been substantially altered from their natural condition, including conversion of forested catchment to pasture, invasion by aquatic macrophytes such as *Hydrilla sp.*, the introduction of grass carp (*Ctenopharyngaodon idella*) for weed management, and diversion of the largest stream inflow, Papakiri Stream (Sandy Creek), away from the lake and directly to the outflow (Mahiaruhe Stream) in the early 1980s. Lake Tutira's history of poor water quality dates back decades, with Trophic Level Index (TLI; a metric of overall water quality) values from the 1960s similar to recent years, and blooms of cyanobacteria (blue-green algae) recorded as early as the 1970s. Nevertheless, the years since 2010 have been characterised by very poor water quality and particularly severe blooms, sometimes resulting in near-complete loss of oxygen from surface waters and associated fish kill events. This has attracted media attention and provided impetus from community and stakeholders to assess available management options for restoring more natural conditions and improving water quality in the lake.

This report examines the drivers of poor water quality and algal blooms the lake, and assesses various management options that have either been specifically proposed for Tutira, or have proven effective for other lakes in New Zealand and globally. Here we report on monitoring undertaken by Hawke's Bay Regional Council in the catchment (surface inflows) and lake. We also apply state-of-the-art computer models for simulating physical, chemical, and biological processes in the catchment and lake. These simulations are then used to evaluate a range of management 'scenarios' to provide guidance on the likely effects of management options tested with the model.

Monitoring data for the catchment show that concentrations of nitrogen (N), phosphorus (P) and suspended sediment (SS) in stream inflows (including Papakiri) are very strongly flow-dependent. The highest observed concentrations were in Papakiri, although high concentrations were also observed in the immediate lake catchment (e.g., Kahikanui Stream, maximum of > 5 g m^{-3} total N and > 1 g m^{-3} total P). Therefore, a very large proportion of annual nutrient and sediment loads are delivered to the lake during brief periods of high discharge.

Measurements from the lake, approximately monthly from 2010 to 2016, show a ratio of TN to TP in surface waters (c. 20:1), suggesting a higher probability of P-limitation. However, dissolved inorganic N was frequently below detection limits, and elevated total N associated with high chlorophyll values (particularly during a bloom of cyanobacteria in summer 2015/16) could indicate substantial nitrogen-fixation in order to meet shortfalls in N supply (i.e. when N:P ratio is low). Anoxic bottom waters during temperature-stratification over

warmer months were associated with highly elevated dissolved N and P, indicative of strong but variable internal nutrient loading from lake sediments. Highest concentrations of TN, TP and chlorophyll were observed in summer 2015/2016, associated with widely publicised phytoplankton blooms and fish kills. No evidence of increased internal loading in the preceding year was observed, therefore, it is more likely that this event was driven by increased P supply to the lake from the catchment, possibly associated with a high rainfall event in September 2015. The extremely high TN concentrations could be due to N-fixation by cyanobacteria in the lake and/or similarly elevated catchment N supply. Such interannual variability in stream inflow N and P loads is difficult to model in the absence of detailed information for the catchment and inflows with which to calibrate and validate in-stream models.

The process-based catchment model INCA-N was used to simulate daily time-series of flow and nitrogen concentrations in all surface inflows, and empirical modelling was undertaken to estimate corresponding values for phosphorus and sediment. Modelled annual hydraulic, nutrient and sediment loads were somewhat lower than estimates obtained from the coarse-scale nutrient loss model CLUES (which is calibrated at the national-scale). Modelled flows, nutrient and sediment concentrations provided a satisfactory fit to in-stream observations and were used as daily input to the in-lake model.

A process-based physical-biogeochemical model (DYRESM-CAEDYM) was set up for Lake Tutira for the period July 2010 to June 2016. Because 2015/16 was a year of exceptional lake dynamics (e.g. a major cyanobacteria bloom event), and possibly driven by episodic events in the catchment (for reasons outlined above), the model calibration was optimised for the period 2010 to 2015. The model was able to reproduce physical and chemical dynamics in the lake over this period extremely well. Simulating the precise timing and extent of cyanobacteria proliferation in the lake proved more difficult; however, on an annual average basis the model accurately reproduced Trophic Level Index dynamics for N, P, chlorophyll and Secchi depth (clarity). It can therefore be considered the most advanced tool available with which to assess potential management options for Tutira. Four broad categories of scenarios were undertaken using model simulations, with results as follows:

1. **Nutrient load reduction:** Reduction of nutrient loads from the immediate catchment of Tutira predictably resulted in improved water quality (reduced TLI). However, the magnitude of change was lower than might have been expected. This is likely because of the combined influences of inputs from internal loading (bed sediment N and P fluxes) and overspill from Papakiri. DYRESM-CAEDYM cannot explicitly model changes in internal loading that would be expected to occur in response to changes in external loading, however, a further scenario for which internal loading was (manually) modified in a fixed proportion to reductions in external loading (i.e., a 50% reduction in both), resulted in a larger TLI reductions. If catchment load reductions progressively reduce internal loads of nutrients, as might be expected over long time

scales, then the model, without accounting for this effect, may provide conservative estimates of the effects of catchment load reductions. Time-scales of internal load response are generally of a decade or more.

2. **Hydrological modifications**: As modelled, full rediversion of Papakiri into the lake reduced lake retention time from an estimated 6.4 years to 2.8 years (i.e. increased flushing). However, because Papakiri is an intensively farmed catchment with substantial flows of nutrient and sediment-rich water, the net result of rediversion was a substantial deterioration in simulated water quality. Even a 50% reduction in nutrient loads from both the inner and Papakiri catchments did not sufficiently mitigate the effects of full flow rediversion. Scenarios restricting low flows only into the lake more closely approached a net-neutral effect on water quality (particularly at a threshold discharge < 0.2 $m^3\ s^{-1}$). These results suggest a more detailed analysis may be warranted if some rediversion of Papakiri is desired. Preventing the present overspill of Papakiri into Tutira made only a very slight improvement in lake water quality, however, it should be noted that the modelled 'baseline' assumption of this inflow being diverted to the lake only for discharge > 5 $m^3\ s^{-1}$ is highly uncertain. Indeed, a simulation allowing Papakiri discharge > 4 $m^3\ s^{-1}$ into the lake produced a TLI increase similar to that of the restricted low-flow rediversion scenario. More accurate quantification of the frequency and extent of overspill from Papakiri to Tutira would greatly aid future modelling assessments. However, prevention of any overspill is likely to provide an immediate, if minor, improvement in water quality and may thus be preferable.
3. **Artificial aeration:** DYRESM-CAEDYM allows for the simulation of either aeration by a bubbler plume (bottom-up) or surface mixing by impellers (top-down). A range of simulations of various air and water flow rates provided highly variable impacts on water quality. While high air-flow rates resulted in only a minor improvement in TLI, they also reduced or ablated cyanobacterial blooms, shifting species dominance towards less buoyant species (diatoms and green algae). Conversely, lower rates of airflow and mixing actually increased the modelled occurrence of surface blooms, presumably due to improving access to light and increasing transport of nutrients from bottom to surface waters, while not sufficiently negating the buoyancy capabilities of cyanobacteria. Although CAEDYM includes only a simplistic representation of phytoplankton motility, these results highlight potential pitfalls of aeration, and suggest that any system implemented should have substantial 'headroom' to ensure adequate mixing. The advantage of aeration as a management option is that it can be implemented in an adaptive framework and can be easily and quickly stopped if adverse impacts are encountered. The potential effects of aeration/mixing on aquatic biota (particularly the effects of altered temperature dynamics on the trout population) should be considered in detail and are beyond the scope of the present study.

4. **Geochemical engineering:** The application of flocculation and/or sediment capping agents such as Phoslock^{TM}, Z2G1 (modified zeolite), or aluminium sulphate (alum) is a management approach that has been applied with some success in the Rotorua lakes (Bay of Plenty). Although CAEDYM cannot explicitly simulate the mode of action of these agents, scenarios were undertaken to approximate their effects by adjusting process rate coefficients to simulate an increase in the settling rate of organic matter (flocculation), and the reduction of internal sediment-water nutrient fluxes (sediment capping). Flocculation and capping resulted in substantial reductions in TLI (as has been the experience in Lake Rotorua), although results should be interpreted cautiously due to conceptual simplifications necessary in these simulations. The efficacy of these agents is highly pH-dependent, and the timing and intensity of their application must be considered in detail. Further, ecotoxicological and community/cultural considerations are important considerations when evaluating geochemical engineering as a lake management option.

Summary

The catchment discharge model and lake monitoring record suggest that cyanobacteria blooms tend to follow from earlier high-flow events. The events produce elevated nutrient and sediment loads and concentrations, and N-fixation by cyanobacteria may contribute further to their proliferation and formation of blooms. Lake model results suggest that full reconnection of Papakiri Stream is likely to result in poorer water quality and more frequent phytoplankton blooms. It should be noted that the present extent of intrusion of Papakiri into Lake Tutira during high-flow events is relatively poorly understood. Modelling showed the lake was somewhat sensitive to increased intrusion by high flows from Papakiri, therefore, quantifying the present extent and timing of Papakiri intrusion ('backflow') into Tutira would assist with modelling of future management options. Diversion of low flows only may reduce the negative effects of Papakiri rediversion but is unlikely to result in substantial improvement in lake water quality. Reduction of catchment nutrient loads and improved control of Papakiri flows is likely to improve water quality, however, effects may take some time to be fully realised in the lake due to expected long lag times as internal lake processes adjust to changes in external forcing. An improved understanding of sediment nutrient pools and fluxes is vital to improve future modelling efforts. These 'legacy' nutrient sources result from decades of accumulation, and may provide a source of N and P for decades to come. Geoengineering to increase flocculation and reduce internal loading may be effective but should be evaluated carefully. Aeration and mixing of the water column may achieve water quality aspirations relating to the disruption of cyanobacterial surface blooms, but only if implemented so that water column turbulence would be sufficient to negate their buoyancy regulation.

Modelling results, taken in context, do not reveal a 'silver bullet' for the improvement of Lake Tutira water quality. As is often the case, a multi-faceted approach may yield the best result. Catchment nutrient load reductions, including comprehensive management of catchment erosion and phosphorus transport during high flows, along with better control of Papakiri flows are likely to provide gradual and sustained improvements in water quality. Geochemical dosing could form part of a holistic management program if deemed acceptable by community and stakeholders, and aeration could contribute substantially if implemented at sufficient capacity. Land management practises in the catchment should focus on prevention of 'pulses' of sediment and phosphorus loss, particularly in spring and early summer, to reduce the proliferation of cyanobacteria over warmer months.

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1 Introduction

Lake Tutira is an important ecological, historical and cultural asset to the Hawke's Bay Region. The lake is culturally significant, particularly to Ngāti Kahungunu, for its historical eel fishery and rongoa (medicinal) Harakeke (flax) beds (Walls 1994). Trout were introduced to Tutira in the 1920s and it supports the region's primary rainbow trout (*Onchorynchus mykiss*) fishery. However, Tutira has a history of eutrophication, with sedimentation, proliferation of invasive weeds and blooms of cyanobacteria dating back decades. Settlers began clearing native vegetation from the lake catchment around 1880, most of the catchment comprised pasture by 1930 (Page et al. 1994), and aerial topdressing of fertiliser in the catchment began in the 1950s (Tierney 2012). Catchment land use has been linked to declining water quality in Tutira (McColl 1978). The catchment is particularly sensitive to soil erosion due to steep topography, occurrence of high intensity rainfall and land clearance. Substantial storm–associated sedimentation has occurred in the lake on an approximately annual basis (Page et al. 1994). McColl (1978) described excessive weed growth by 1959, occurrence of blooms of cyanobacteria (*Microcystis aeruginosa*, *Dolichospermum* (formerly *Anabaena*) sp.) by 1972, and a trophic state of 'moderately to highly eutrophic' in 1978. Various water quality indices measured in the mid- to late-1970s by Teirney (1980) also categorised the lake as eutrophic, and observed impacts on the trout fishery due to anoxia in the lower water column during the stratified period (late-Spring to Autumn).

Attempts to restore the water quality of Lake Tutira began as early as the mid-1970s, when aerohydraulic 'guns' (vertical draft tubes with compressed air pumped to the bottom) were installed in the lake for several summers to increase vertical mixing, in order to improve trout habitat during warmer months. Although these devices were successful in increasing mixing during summer, the cost of their continued operation was deemed too high. A more sustainable solution was sought via the diversion of the main stream inflow at the time, Papakiri Stream (Sandy Creek), directly to the lake outlet (Tierney 2012). This prevented much of the drainage from intensively used land in the catchment to the lake, and reduced total nitrogen (N), phosphorus (P) and suspended sediment (SS) loads. However, this diversion also increased hydraulic retention time and did not address a legacy of enriched lake sediments, from which nutrients may be recycled to the water column during bottom water anoxia that recurs when the lake stratifies during warmer months of each year.

The invasive macrophyte *Elodea canadensis* was observed in Tutira as early as the 1920s, and by the 1960s the highly problematic aquatic weed *Hydrilla verticillata* was established (Tierney 2012). *Hydrilla* formed extensive beds over subsequent years, reducing the aesthetic, recreational and ecological value of the lake. Hawke's Bay Regional Council (HBRC) in conjunction with the Ministry of Primary Industries and Biosecurity New Zealand initiated a programme to eradicate *Hydrilla* from Tutira and prevent it spreading to nearby lakes. The principal actions of this project were the introduction of grass carp (*Ctenopharyngodon* *idella*) to the lake following an application of herbicide (endothall) in December 2008. These management actions substantially reduced the extent of *Hydrilla* beds within the lake (Hofstra 2016). As part of this project, HBRC commissioned the University of Waikato to install a high–frequency lake water quality monitoring buoy in early 2009. The buoy was intended to track the response of the lake following *Hydrilla* removal, and it provides comprehensive monitoring data for analysis of lake dynamics at time-scales from sub-daily to inter-annual.

Figure 1. Lake Tutira on 31 October 2012 (Image: A. Uytendaal).

Despite past lake restoration initiatives, poor water quality has persisted in Lake Tutira (Figure 1). As recently as summer 2015/16, severe cyanobacteria blooms, surface water hypoxia, and even fish kills have been observed. The local Health Board has an ongoing recommendation against contact with lake water due to risks associated with potentially toxic cyanobacterial blooms which have been observed between spring and autumn. Because of sustained degraded water quality, Hawke's Bay Regional Council (HBRC) is considering a range of additional and alternative management options for Lake Tutira, aiming to restore water quality to meet the values and expectations of the community and stakeholders. Options include lake flushing (by altering the modifications to Papakiri Stream), reduction of nutrient loads from external (e.g. catchment land use) and internal (e.g. lake sediments) sources and artificial mixing/aeration.

Assessing the relative merits of various potential management options can be complex. Process-based ecosystem models are a valuable decision support tool for assessing land and lake management options (Hamilton et al. 2012, Trolle et al. 2012). In this study, we applied the catchment model INCA-N to model nitrogen, and empirical methods to model phosphorus, and sediment losses from catchment sources. Output data from models for each source of water to the lake were then coupled to the one-dimensional (horizontally integrated) lake water quality model DYRESM-CAEDYM. A schematic representation of the model is shown in Figure 2. All models were calibrated against field measurements, and were then used to simulate various scenarios of catchment and lake management. The primary objective was to provide a comparative assessment of the effects, positive or negative, on water quality for a range of potential water quality restoration actions.

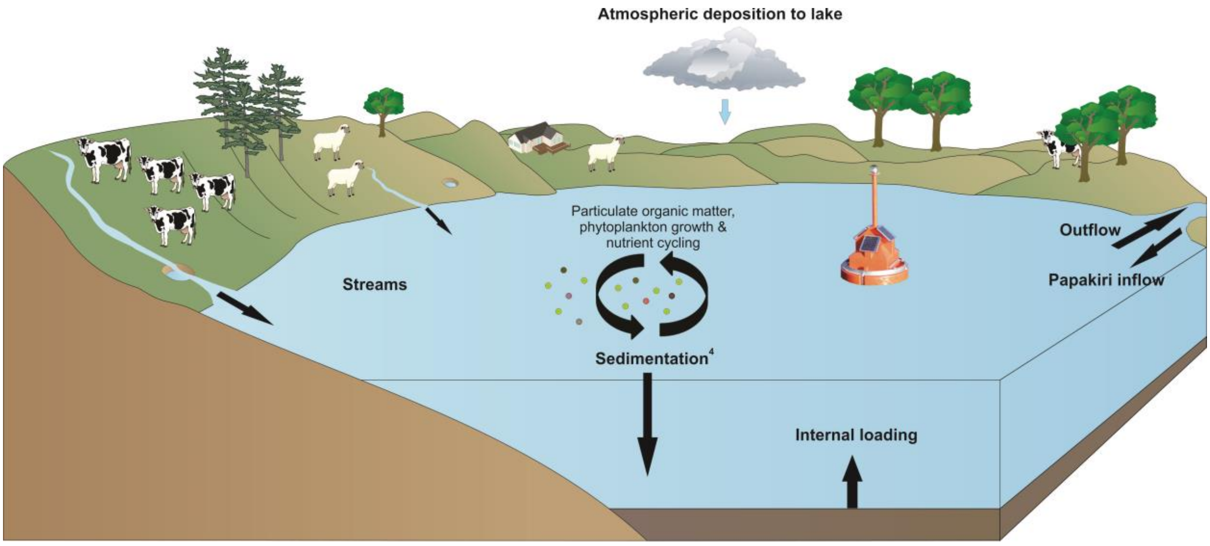

Figure 2. Conceptual drawing of the Lake Tutira water quality model.

2 Methods

2.1 Study site

Lake Tutira (39° 13 30S, 176° 53 30 E; Figure 3) is located 30 km north of Napier and is an important recreational resource for the Hawke's Bay region. The lake has a surface area of approximately 1.74 km^2, mean depth of 21 m and maximum depth of 42 m (Table 1). The lake has several stream inflows and periodically receives water from Lake Waikapiro to the south (Figure 3). The lake's watershed, originally 27.2 km^2, was reduced to 8.4 km^2 when its major inflow, Papakiri Stream, was diverted directly to the outflow at the north of the lake. Tutira is situated c. 155 m above sea level (Irwin 1978) in landslide-prone hill country. This region lies within the forearc of the active convergent Hikurangi Margin (Lewis and Pettinga 1993). The lake was formed by the collapse of a hillside c.7200 years ago, damming the southern valley outlet (Eden and Page 1998). Before Polynesian settlement the catchment was covered with conifer-broadleaved forest. This was replaced by bracken fern/scrub following a succession of fires beginning c. 490 years ago (Wilmshurst et al. 2004). The catchment has been largely transformed into pasture since the arrival of European settlers during the 1870s (Guthrie-Smith 2011). Sedimentation in the lake is substantial, with an estimated total of 1.9 x 10^6 m^3 of sediment estimated to have been deposited in the lake between 1925 and 1963 (equivalent to 5.4 x 10^4 m^3 y^{-1}; Grant 1966). The Lake Tutira catchment periodically experiences major rainstorms, the most recent major sediment deposition event being associated with Cyclone Bola (1988), when c. 750 mm of rainfall occurred over four days.

Table 1. Lake Tutira morphological characteristics

Altitude[1]	150 m
Area[1]	1.74 km^2
Catchment land area prior to Papakiri Creek diversion[1]	27.19 km^2
Catchment land area after diversion of Papakiri Creek[2]	8.44
Catchment to lake area ratio (at present)	4.9 : 1
Mean depth[1]	21 m
Maximum depth[1]	42 m
Shoreline length[3]	8.0 km
Volume[1]	36.1 x 10^6 m^3

1. McColl (1978)
2. Hooper (1989)
3. Teirney (2009)

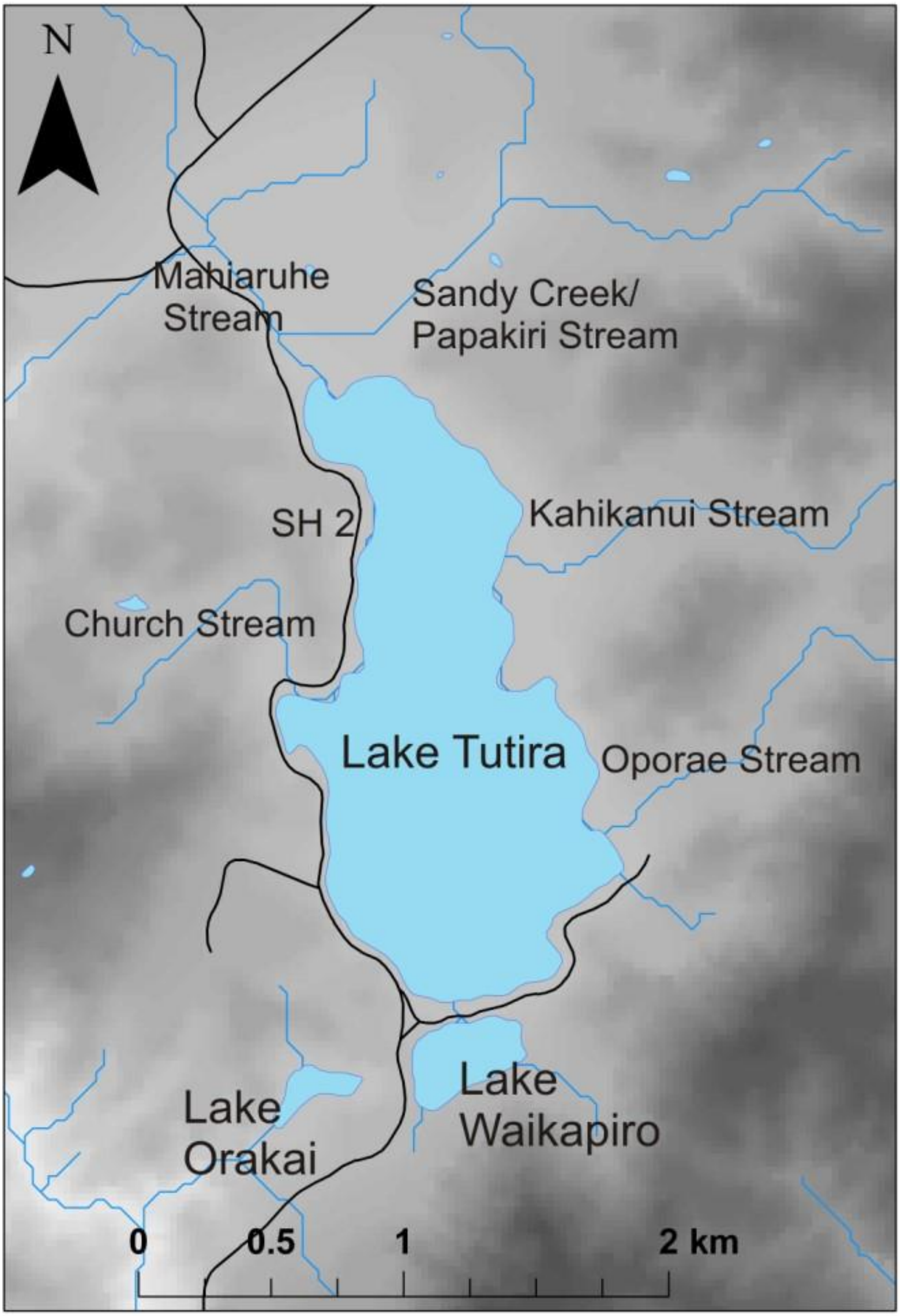

Figure 3. Lake Tutira. Stream names are reproduced from Hooper (1989).

2.2 Catchment

2.2.1 Catchment monitoring

In-stream measurements of water temperature, chemistry, and discharge were collected for calibration and validation of catchment models. HBRC sampled stream inflows between January 2013 and June 2014. Approximately monthly samples were collected from the Kahikanui Stream (the largest stream inflow), as well as sub-daily sampling during several high rainfall events. In addition to these relatively infrequent discharge measurements, a continuous water level recorder was deployed in the stream from which a flow record was derived using a rating curve (HBRC). Papakiri Stream (Sandy Creek) was sampled similarly to Kahikanui Stream, whereas the smaller inflows, Oporae and Church Stream, were sampled much less frequently. A summary of all measurements collected is given in Table 2.

Table 2. Summary of stream inflow samples (HBRC), Jan-2013 to Jun-2014. Baseflow limit was determined from the synthetic flow record. n.g. = not gauged.

	Samples	Days	Baseflow* (days)	Moderate* (days)	High* (days)	Synthetic flow (days)	Baseflow limit ($m^3 s^{-1}$)
Kahikanui	121	27	6	8	13	322	0.016
Oporae	30	11	4	2	5	281	0.006
Church	4	4	0	1	3	0	n.g.
Papakiri	50	27	9	10	4	356	0.129

*The three discharge categories describe discharge conditions during sample collection. Baseflow includes mean daily (spot-measured) discharge below the baseflow limit; moderate includes flows up to 10-fold baseflow; and high includes discharges greater than 10-fold baseflow. Where the total of the three flow categories is less than the number of days sampled, spot-measured discharge was not collected for all days.

2.2.2 Catchment characteristics

The catchment model 'CLUES' (Catchment Land Use for Environmental Sustainability; developed by NIWA) was used to provide broad estimates of discharge, nutrient and sediment loads from the Tutira catchment for comparison with measurements and subsequent, more detailed catchment modelling. CLUES predicts annual average stream discharge and annual loads of total nitrogen, total phosphorus, E. coli and sediment at spatial scales from individual stream reaches to the whole nation using input variables including climate, land use, geology and topography (Elliott et al. 2016). CLUES utilises the River Environment Classification (REC; NIWA) whereby streams and rivers are divided into 'reaches' based on stream order, with each reach associated with an area of land (subcatchment). The CLUES model adopts a GIS-based approach and catchments are associated with national maps of land use, topography, and soil type. These inputs are linked to a simplified version of the nutrient loss model Overseer® to generate estimates of nutrient leaching, *E. coli* and sediment loss at each sub-catchment. These estimates are nationally calibrated, and given as annual loads. Therefore, the present study used CLUES to define sub-catchment and land use areas, and its estimates of nutrient loads were used only as a coarse benchmark against which the more detailed catchment models could be assessed.

2.2.3 Catchment modelling

Detailed modelling of Lake Tutira required daily data for stream inflow discharge, nutrient and sediment concentration. Because available field data were not available at sufficient temporal resolution, we chose the INtegrated CAtchments model for Nitrogen and Phosphorus (INCA-N and INCA-P; versions 1.11.10 and 0.1.31 respectively) to simulate stream discharge and biogeochemistry for the period July 2010 to June 2016. INCA-P and INCA-N are process-based, mass balance models describing water, nitrogen phosphorus and sediment transport in both the land and in-stream environments of river catchments. INCA-P simulates dissolved and particulate phosphorus, as well as several grain size classes of stream-bed and suspended sediment (Wade et al. 2002a). INCA-N simulates only dissolved inorganic nitrogen (DIN; Whitehead et al. 1998, Wade et al. 2002, Wade 2004, Jin et al. 2013). Therefore, total N (TN) was estimated using empirical relationships observed between DIN and TN for each subcatchment. Multiple sources of N and P are considered by the models (Whitehead et al., 2009), including atmospheric deposition, livestock, fertiliser application, leaching from the terrestrial environment and direct discharges. In modelling catchment hydrology, a simple two-box approach is used for residence time in the major stores of water in the reactive zone and deep groundwater zone (Rankinen et al. 2002). Base Flow Index (BI) is used to divide the total volume of water stored between the soil and the groundwater (Wade et al. 2002) and calculation of river flow is based on mass balance of flow and on a multi-reach description of the river system if required (Whitehead et al. 1998). Mass balance equations for nutrient and sediment fluxes in the soil and groundwater zones are solved simultaneously with the flow equations. Hydrologically effective rainfall (HER) is used to drive the dissolved nutrients through the catchment system, entering the river system by lateral flow through the surface soil layers or by the vertical movement and transport through the groundwater zone. The models simulate spatial variation in N and P export using a 'semi-distributed' approach which allows up to six different land use types within a river system. Terrestrial fluxes of N and P are parameterised independently for each land use category, thereby accounting for the impacts of different land management practices on nutrient loss and stream concentrations.

We established and calibrated the INCA models for the Tutira catchment for the period from 1 July 2010 to 30 June 2016 using a daily time step. Meteorological inputs were obtained from the Virtual Climate Network (NIWA; obtained by license for HBRC) and are shown in Appendix Figure 15. Five sub-catchments were delineated using subcatchment definitions from CLUES; Papakiri, Kahikanui, Oporae, and Church Streams, and a sub-catchment representing the residual land area outside surface stream catchments (i.e. overland and ephemeral flows). Papakiri Stream was conceptualised as a single reach because detailed modelling of the relatively complex catchment was outside the scope of the present study. Model parameters were adjusted manually using a trial and error approach with values set to within literature ranges (e.g., Whitehead et al. 2002, Farcas et al. 2013). During the model calibration process model error was quantified using root-mean-square-error (RMSE) and Pearson correlation coefficient (R) for each output variable after the adjustment of model coefficients. Calibration continued until there was negligible improvement in RMSE and R values with repeated model simulations. Satisfactory model performance was achieved for INCA-N, but not for INCA-P. Because documentation available for INCA-P was insufficient to refine the model calibrations, empirical methods using Eureqa statistical modelling software (Nutonian Inc.) were used to estimate phosphorus and sediment concentrations for each subcatchment based on predictive variables including air temperature and antecedent rainfall.

2.3 Lake

2.3.1 Lake monitoring

HBRC collect samples of physical, chemical, biological and optical properties of water from Lake Tutira approximately monthly. The Trophic Level Index (TLI) is commonly used in New Zealand to report on lake water quality and assess the performance of restoration initiatives. The TLI is the average of four individual components on standardised (logarithmic) scales, including (annual averages of total nitrogen (TN), total phosphorus (TP), chlorophyll *a*, and transparency (as measured by Secchi depth). Background information and TLI equations can be found in Burns (1999). Raw monitoring data from surface waters (HBRC) were used to calculate annual TLI for the study period, and monitoring records were assessed for features that can affect the choice of management activities for Tutira (e.g., N:P ratio, evidence of nitrogen-fixation, internal loading). Field measurements were also used for the calibration of the lake model and assessment of its performance.

2.3.2 Lake modelling

The one-dimensional (1D) hydrodynamic model DYRESM (version 3.1.0-03) was coupled with the aquatic ecological model CAEDYM (version 3.1.0-06), both developed at and used under license from the Centre for Water Research, The University of Western Australia. DYRESM resolves the vertical distribution of temperature, salinity, and density in lakes and reservoirs, while CAEDYM simulates time varying fluxes of biogeochemical variables (e.g., nutrient species, phytoplankton biomass). The model includes comprehensive process representations for carbon (C), nitrogen (N), phosphorus (P), and dissolved oxygen (DO) cycles, and several size classes of inorganic suspended solids. Several applications have been made of DYRESM-CAEDYM to different lakes (e.g., Bruce et al., 2006; Burger et al., 2008; Trolle et al., 2008; Gal et al., 2009) and these applications provide detailed descriptions of the model equations.

The interactions between phytoplankton growth and losses, sediment nutrient fluxes, and the mineralisation and decomposition of particulate organic matter influence N and P cycling in the model (Appendix Figure 3). Fluxes of dissolved inorganic and organic nutrients from the bottom sediments are dependent on temperature, NO_3-N and DO concentration in the water layer immediately above the sediment surface. In the present application, CAEDYM was configured with three phytoplankton groups (positively buoyant cyanobacteria, neutrally buoyant green algae and negatively buoyant diatoms) and the effects of higher trophic levels are parameterised through loss terms. Secchi depth is not explicitly simulated by CAEDYM but was estimated from simulated optical properties in order to calculate TLI from model output. Modelled TLI was compared with observed data and calibration of parameters was undertaken in DYRESM-CAEDYM until an optimal match was achieved between daily simulated variables and available field measurements, and between modelled and measured TLI components. We aimed to calibrate model TLI within ± 0.1 TLI units of measured TLI. Auto-calibration software was developed to assist calibration efforts, and thousands of simulations were run until no further improvement in model performance was achieved.

2.3.3 Scenario simulations

Multiple lake management ‘scenarios’ were conceptualised in consultation with HBRC, and modelled using DYRESM-CAEDYM. The management approaches assessed can be broadly considered as belonging to four categories:

1- **External nutrient load reduction:** associated with land use change or nutrient loss mitigation by improved management practices and/or targeted interventions, e.g. erosion mitigation, denitrification beds.
2- **Hydrological modifications:** various options to re-route Papakiri Stream (Sandy Creek) flows back into the lake. Options include full or partial diversion, as well as more complex scenarios using a ‘choked’ inlet to divert high, nutrient-rich flows away from the lake.
3- **Artificial mixing:** by aeration (bubbler) or physical mixing (impeller).
4- **Geochemical engineering:** by sediment capping to reduce internal loading (e.g. Phoslock™) and/or continuous low-dosage alum treatment to reduce dissolved P and increase flocculation in the water column.

A daily water balance model was constructed (predicting lake outflow from inflows and water level) so that water level could be simulated for Papakiri rediversion scenarios. The combination of above management options comprising each simulated management scenario are described in Table 3. TLI values were compared between modelled scenarios to provide an assessment of the predicted effects of each scenario on lake trophic status in the context of water quality objectives.

Table 3. List of lake management scenarios simulated using DYRESM-CAEDYM.

Scenario name	Catchment N & P	Papakiri flow to Tutira	Papakiri N & P	Aeration/ mixing rate	Flocculant	Sediment cap	Description
	(%)	-	(%)	(L or m^3 s^{-1})	?	?	
C100	100	> 5 m^3 s^{-1}	100	-	-	-	Baseline ('business-as-usual')
C100M	100	> 5 m^3 s^{-1}	100	-	-	-	Baseline with modelled outflow rate
C90	90	> 5 m^3 s^{-1}	100	-	-	-	10% reduction in catchment nutrient loads
C75	75	> 5 m^3 s^{-1}	100	-	-	-	25% reduction in catchment nutrient loads
C50	50	> 5 m^3 s^{-1}	100	-	-	*	50% reduction in catchment nutrient loads
C50i50	25	> 5 m^3 s^{-1}	100	-	-	-	50% reduction in catchment, corresponding reduction in internal loads (long-term)
C25	100	> 5 m^3 s^{-1}	100	-	-	-	75% reduction in catchment nutrient loads
C100_Pk100	100	all	100				Diversion of Papakiri Creek (Pk) to lake
C100_Pk75	100	all	75	-	-	-	Pk diversion with 25% reduction in Pk nutrient loads
C75_Pk75	75	all	75	-	-	-	25% catchment load reduction, Pk diversion with 25% load reduction
C50_Pk50	50	all	50	-	-	-	50% catchment load reduction, Pk diversion with 50% load reduction
C100_P.g4000	100	> 4 m^3 s^{-1}	100	-	-	-	Baseline with slightly more intrusion of Pk to lake
C100_P.f0	100	0	by calculation	-	-	-	Prevention of any intrusion from Pk to lake
C100_P.fl200	100	< 0.2 m^3 s^{-1}	by calculation	-	-	-	Choked' inflow of Pk flows less than 0.2 m^3 s^{-1} into lake
C100_P.fl1000	100	< 1 m^3 s^{-1}	by calculation	-	-	-	Choked' inflow of Pk flows less than 1.0 m^3 s^{-1} into lake
C75_P.fl200	75	< 0.2 m^3 s^{-1}	by calculation	-	-	-	Pk flows less than 0.2 m^3 s^{-1} into lake, 25% reduction of catchment loads
C100_bub.d100	100	> 5 m^3 s^{-1}	100	100 L s^{-1}	-	-	Artificial aeration 0.5 m above lake bottom with air flow rate of 100 L s^{-1}
C100_bub.d500	100	> 5 m^3 s^{-1}	100	500 L s^{-1}	-	-	Artificial aeration 0.5 m above lake bottom with air flow rate of 500 L s^{-1}
C100_bub.m100	100	> 5 m^3 s^{-1}	100	100 L s^{-1}	-	-	Artificial aeration 15 m above lake bottom with air flow rate of 100 L s^{-1}
C100_imPk.m10	100	> 5 m^3 s^{-1}	100	10 m^3 s^{-1}	-	-	Artificial mixing with water flow rate of 10 m^3 s^{-1}
C100_Pk100_bub.d500	100	all	100	500 L s^{-1}	-	-	Diversion of Pk to lake, with full aeration
C100_floc	100	> 5 m^3 s^{-1}	100	-	✓	-	Flocculation of water column
C100_cap	100	> 5 m^3 s^{-1}	100	-	-	✓	Sediment capping
C100_floc.cap	100	> 5 m^3 s^{-1}	100	-	✓	✓	Flocculation of water column and sediment capping

*scenario includes internal load reduction in response to external load reduction

3 Results

3.1 Catchment

3.1.1 Catchment characteristics (CLUES model)

According to land use obtained from the CLUES model, Tutira's inner catchment is predominantly exotic forestry, with substantial areas of ungrazed land and scrub, dry stock grazing, and a relatively small amount of native forest (Table 4). A detailed description of REC subcatchments, discharge and nutrient loads is given in Table 5, and these are summarised by sub-catchment in Table 6. CLUES-estimated annual loads for discharge, N, P, and SS were 0.155 m^3 s^{-1}, 2.7 t y^{-1} TN, 1.25 t y^{-1} TP, and 4.7 kt y^{-1} TSS, respectively. It should be noted that CLUES is a coarse-scale nationally calibrated model, and loads are indicative only.

Table 4. Summary of aggregated land used categories used for INCA catchment modelling.

	Area (ha)	Native (%)	Exotic (%)	Drystock (%)	Dairy (%)	Ungrazed (%)	Scrub (%)
Kahikanui Stream	239.22	4.2	37.7	19.0	0.0	14.0	25.1
Oparae Stream	136.62	0.4	25.9	0.0	0.0	33.3	40.4
Church Stream	110.70	2.9	72.7	9.6	0.0	14.1	0.7
Residual catchment	233.28	11.0	14.2	23.5	0.0	33.4	17.9
Sandy Creek	2068.11	0.3	14.2	48.7	36.0	0.0	0.8

3.1.1 Inflow monitoring

Monitoring data within the catchment showed that concentrations of nitrogen (N), phosphorus (P) and suspended sediment (SS) in stream inflows (including Papakiri) were strongly positively related to discharge. Highest observed concentrations were in Papakiri, although high concentrations were also observed in the immediate lake catchment (e.g. Kahikanui Stream; maximum of > 5 g m^{-3} TN and > 1 g m^{-3} TP). Therefore, a large proportion of annual nutrient and sediment loads are delivered to the lake during periods of high flow. Flow relationships for the monitored streams are shown in Appendix Figures 5 – 7.

3.1.1 Inflow modelling

The process-based catchment model INCA-N was used to simulate daily time-series of flow and nitrogen concentrations in all surface inflows. Empirical modelling was undertaken to estimate corresponding values for phosphorus and sediment. Measurements with which to calibrate the inflow models were available only for the period 2013 to mid-2014, therefore any interannual variability in stream contaminant concentration may not be encompassed by the modelled stream values. Nevertheless, a fair fit was obtained for nutrient and sediment concentrations, and relationships between observed and modelled values for Papakiri and Kahikanui are shown in Appendix Figures 10 and 11. Few samples were available for other subcatchments, therefore daily concentrations were derived from the Kahikanui and Oporae Streams using areally-weighted load relationships from CLUES output.

Table 5. Land use and loads of nitrogen and phosphorus from River Environment Classification land blocks within the CLUES model. Flow values given as 'n/a' denotes no availability of estimated discharge from CLUES, because of the absence of a surface stream reach corresponding to the land area.

ID	NZ Reach	Load to lake	Type	REC order	DYRESM inflow number	Description	Land area (ha)	Forest (native)	Forest (plantation)	Dairy	Sheep & Beef (Intensive)	Drystock (Other)	Pasture (ungrazed)	Scrub	N ($t\ y^{-1}$)	P ($t\ y^{-1}$)	TSS ($kt\ y^{-1}$)	Flow ($m^3\ s^{-1}$)
1	8018257	N		1	1	Northeast Kahikanui	**79.20**	8.190	30.330	0.004	0.090	6.691	6.716	27.180	0.2865	0.2199	0.3927	n/a
2	8018368	N		1	1	East Kahikanui	**33.48**	0.000	9.360	0.000	0.000	0.356	1.444	22.320	0.1578	0.0995	0.2582	n/a
3	8018363	Y	Stream	2	1	Lower Kahikanui	**126.54**	1.890	50.580	0.017	7.393	30.917	25.304	10.440	1.0518	0.4587	1.5355	0.0438
4	8018434	Y	Overland	2	5	Eastern shores	**34.11**	6.210	5.130	0.000	0.000	0.000	13.590	9.180	0.1172	0.0562	0.2257	0.0063
5	8018475	Y	Stream	1	2	Oparae Stream	**136.62**	0.540	35.370	0.000	0.000	0.000	45.450	55.260	0.3351	0.1901	1.2190	0.0250
6	8018646	Y	Stream (ephemeral)	1	5	Small southeast stream	**57.06**	2.700	0.090	0.000	0.000	0.713	25.837	27.720	0.1412	0.0899	0.5921	0.0103
7	8018704	N		1	5	Southeast Waikapiro	**69.48**	1.080	7.470	0.000	0.000	18.540	7.920	34.470	0.1508	0.0448	0.0218	n/a
8	8018703	N		1	5	Southwest Waikapiro	**42.93**	0.000	0.090	0.017	0.428	36.092	5.224	1.080	0.1083	0.0320	0.0204	n/a
9	8018409	Y	Lake overflow	2	4	Waikapiro overflow	**0.81**	0.000	0.000	0.000	0.000	0.450	0.360	0.000	0.2685	0.0789	0.0421	0.0227
10	8018264	Y	Lake outflow	3	5	S, NNW & NNE shores	**42.75**	6.480	5.850	0.023	2.516	9.624	17.357	0.900	0.1468	0.0705	0.2829	0.0079
11	8018337	Y	Overland	2	5	SSW shores	**26.01**	1.890	0.270	0.032	0.810	5.597	17.411	0.000	0.0893	0.0429	0.1721	0.0048
12	8018523	Y	Overland	1	5	SW shores	**31.41**	7.830	2.340	0.001	0.023	19.805	0.242	1.170	0.1079	0.0518	0.2078	0.0058
13	8018445	Y	Stream	1	3	Church Stream	**110.70**	3.240	80.460	0.013	0.315	10.319	15.633	0.720	0.3035	0.1443	0.1662	0.0209
14	8018338	Y	Overland	3+	5	Remainder	**41.13**	0.000	19.350	0.008	2.545	13.167	3.180	2.880	0.1413	0.0678	0.2722	0.0076
15	8018410	Y	Overland	3+	5	NW shores	**0.81**	0.450	0.000	0.000	0.017	0.071	0.272	0.000	0.0028	0.0013	0.0054	0.0001
						TOTAL	**833.04**	40.50	246.69	0.11	14.14	152.34	185.94	193.32	2.705	1.252	4.721	0.155

Table 6. Summary of land use and nutrient loads from the sub-catchments of Lake Tutira.

DYRESM inflow number	Description	Land area	Forest (native)	Forest (exotic)	Dairy	Drystock (Intensive)	Drystock (Other)	Pasture (ungrazed)	Scrub	Total N	Total P	TSS	Flow
		(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	(ha)	($t\ y^{-1}$)	($t\ y^{-1}$)	($kt\ y^{-1}$)	($m^3\ s^{-1}$)
1	Kahikanui Stream	239.2	10.1	90.3	0.0	7.5	38.0	33.5	59.9	1.05	0.46	1.54	0.044
2	Oparae Stream	136.6	0.5	35.4	0.0	0.0	0.0	45.5	55.3	0.34	0.19	1.22	0.025
3	Church Stream	110.7	3.2	80.5	0.0	0.3	10.3	15.6	0.7	0.30	0.14	0.17	0.021
4	Residual catchment	233.3	25.6	33.0	0.1	5.9	49.0	77.9	41.9	0.75	0.38	1.76	0.043
5	Waikapiro	113.2	1.1	7.6	0.0	0.4	55.1	13.5	35.6	0.27	0.08	0.04	0.023
	Catchment	**833.0**	**40.5**	**246.7**	**0.1**	**14.1**	**152.3**	**185.9**	**193.3**	**2.71**	**1.25**	**4.72**	**0.155**
8	**Sandy Creek**	**2068.2**	**5.5**	**293.2**	**745.0**	**46.9**	**960.6**	**0.1**	**17.1**	**30.30**	**3.12**	**8.49**	**0.414**

3.1.1.a Papakiri Stream

Waters of Papakiri Stream were very nutrient-rich, particularly during flood flows when daily average values in excess of 1 g P m^{-3} and 4 g N m^{-3} were observed. Soluble reactive phosphorus (SRP) was only moderately flow-related but also showed sinusoidal seasonal variation (Figure 4). Empirical models for TP, SRP and TSS predicted well the observed concentrations, although under predicted concentrations during some flood flow events.

Discharge simulated using INCA-N matched well the observed synthetic discharge record for Papakiri Stream (Figure 5). An additional interception factor (loss of water via evapotranspiration or possibly groundwater transport out of the surface catchment) was required in order to match simulated flows to the synthetic flow record, which over the whole simulation period gave a substantially lower water yield than predicted by CLUES. It should be noted that the gauged and monitored months were a period of relatively low rainfall and flow in the context of the entire study period.

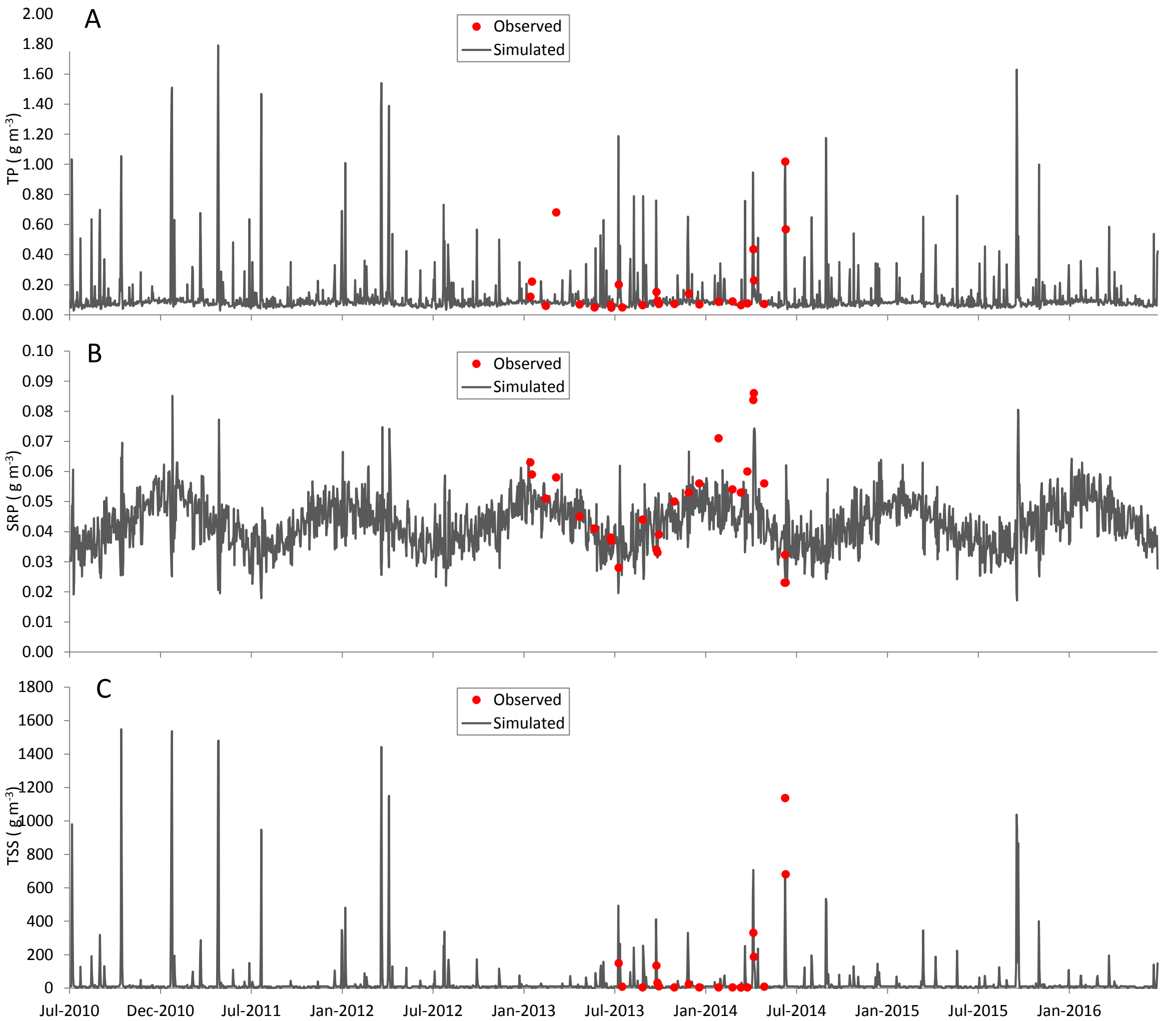

Figure 4. Modelling of phosphorus and suspended sediment in Papakiri Stream for A) total phosphorus, B) soluble reactive phosphorus, and C) suspended sediment.

Nitrogen was strongly flow related for all species and was simulated well by the calibrated INCA-N model (Figure 5).

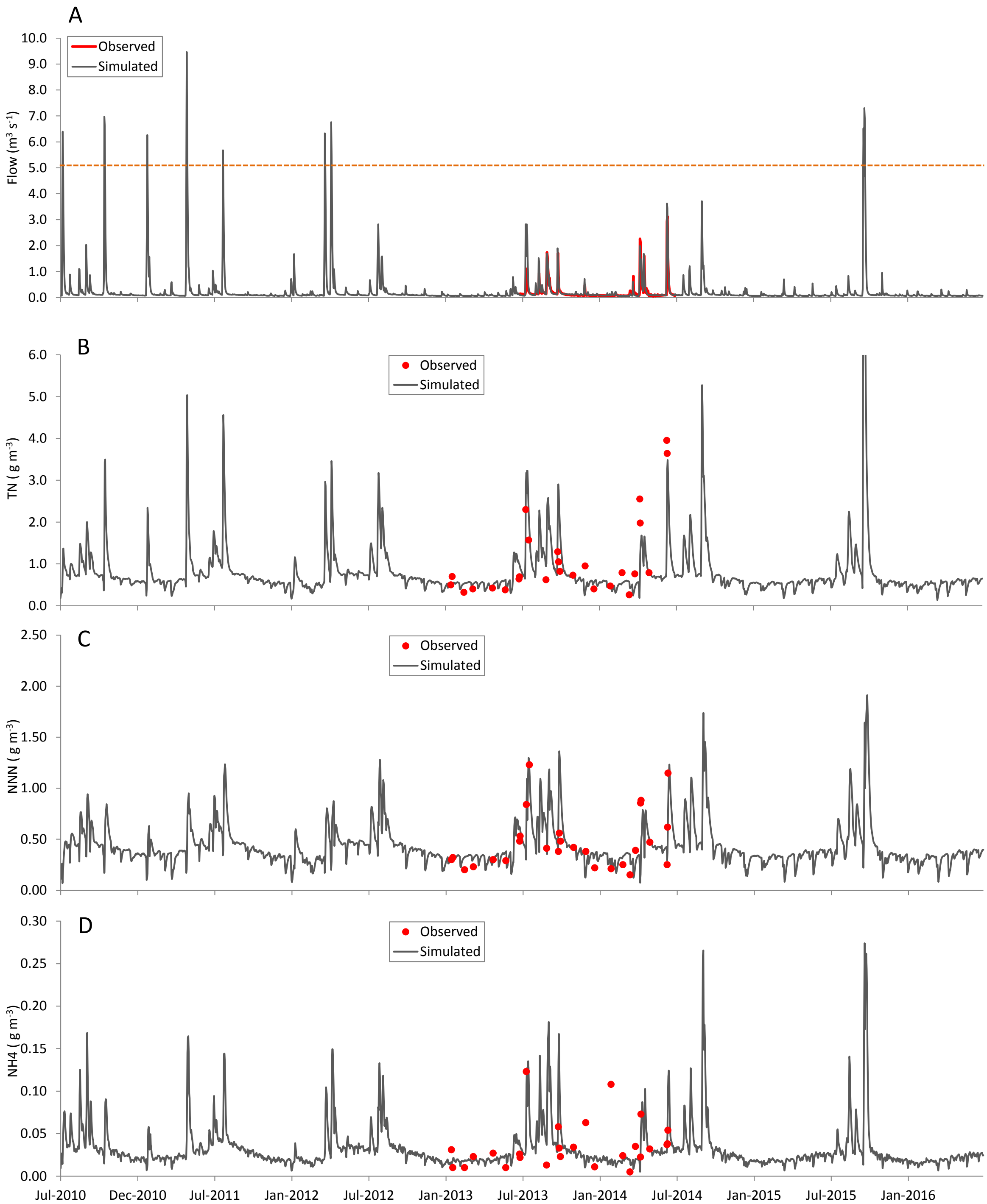

Figure 5. Modelling of nitrogen in Papakiri Stream for A) discharge, B) total nitrogen, C) nitrate and D) ammonium. The dashed orange line represents the flow threshold above which water from Papakiri was input to Lake Tutira for the baseline lake model water balance.

3.1.1.b Kahikanui Stream

Kahikanui was also very nutrient-rich during flood flows, although maximum daily average values were somewhat lower than for Papakiri (>0.6 g P m^{-3} and > 3 g N m^{-3}). Soluble reactive phosphorus (SRP) was not strongly flow-related and did not show the obvious seasonal variation observed at Papakiri, although fewer in-stream measurements were available (Figure 6). Similarly to Papakiri, simulated discharge for Kahikanui matched well the observed synthetic discharge record for Kahikanui Stream (Figure 7). An additional interception factor (loss of water via evapotranspiration or possibly groundwater transport out of the surface catchment) was again required in order to match simulated flows to the synthetic flow record. Empirical models for TP, SRP and TSS predicted well the observed concentrations, although may have again slightly under predicted values for certain flood flow events.

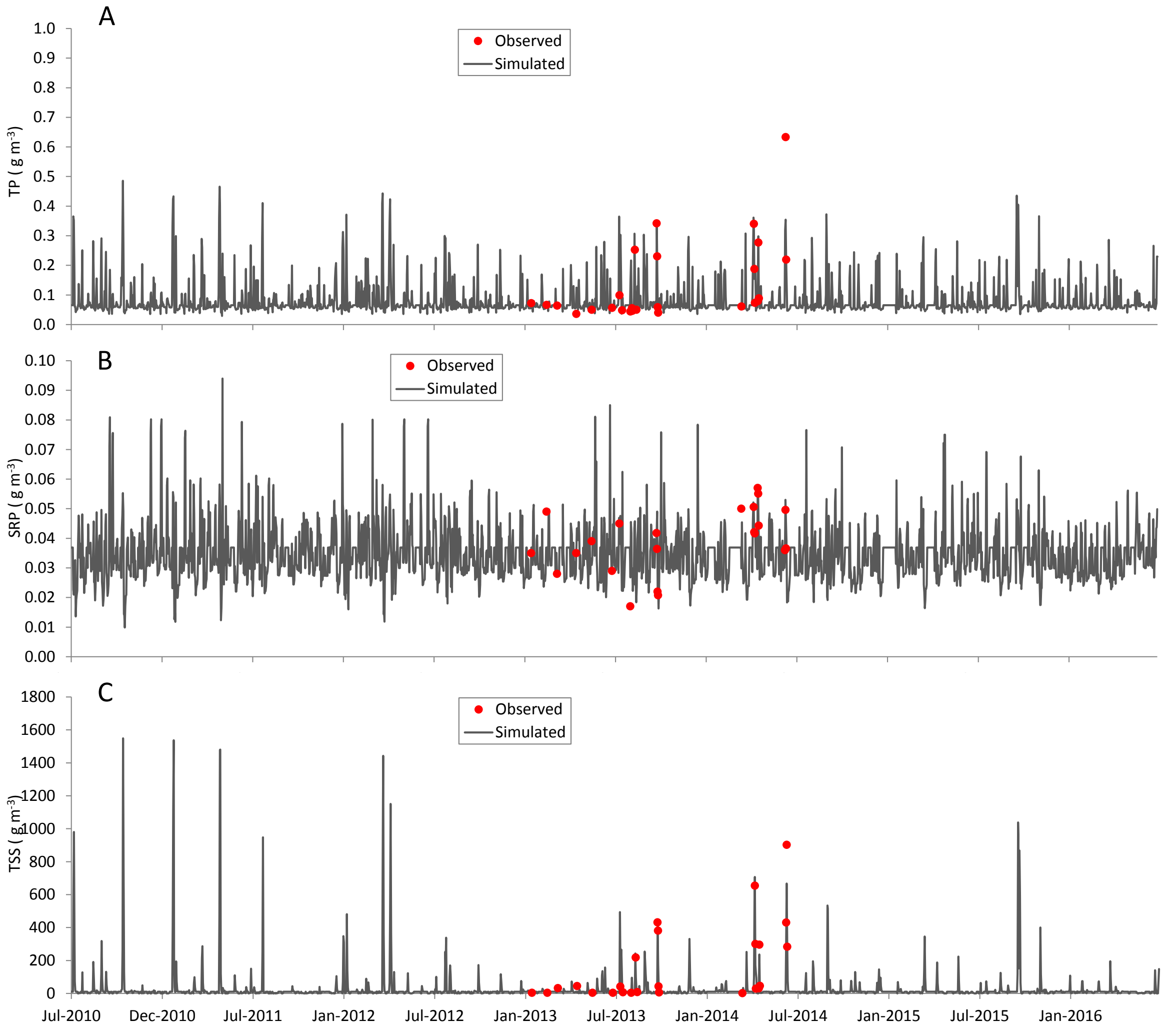

Figure 6. Modelling of phosphorus and suspended sediment in the Kahikanui Stream for A) total phosphorus, B) soluble reactive phosphorus, and C) suspended sediment.

Nitrogen in Kahikanui was again strongly flow related for all species and was simulated well by the calibrated INCA-N model (Figure 7).

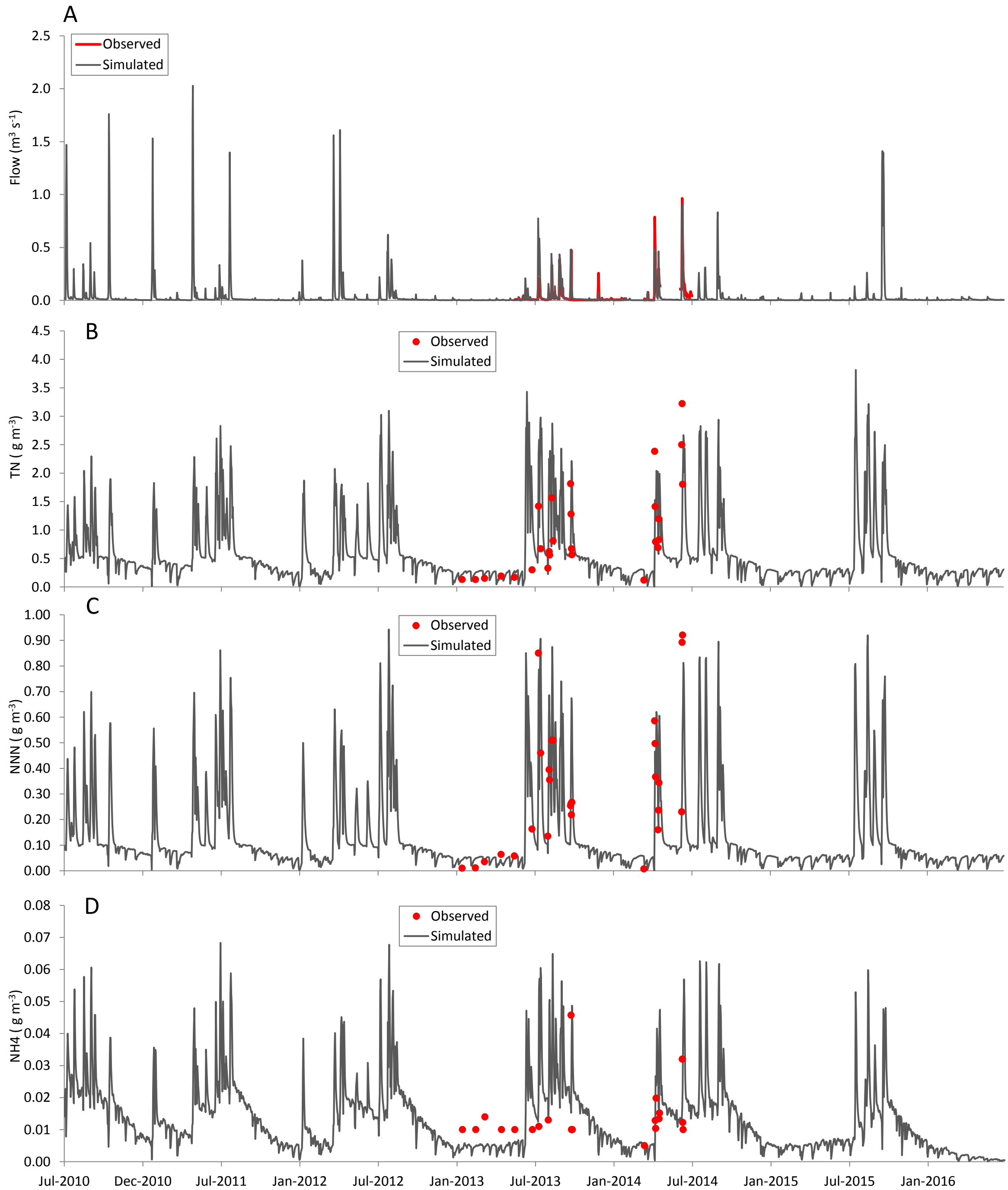

Figure 7. Modelling of nitrogen in the Kahikanui Stream for A) discharge, B) total nitrogen, C) nitrate and D) ammonium.

3.1.1.c Other inflows

Modelled dynamics in Oporae Stream were similar to that of Kahikanui, although fewer data were available against which to calibrate the model (Appendix Figures 12 and 13). For Church Stream and the residual catchment, where minimal data were available, observations were insufficient to establish models for N and P concentrations. Therefore, flow was derived using INCA-N simulations with identical hydrology configurations (pro-rated to catchment size) for Kahikanui and Oporae, and daily nutrient concentrations were derived using load-weighted ratios from CLUES output.

3.1.1.d Summary of modelled inflow loads

Modelled annual hydraulic, nutrient and sediment loads were somewhat lower than estimates obtained from the coarse-scale nutrient loss model CLUES (which is calibrated at the national-scale). Table 7 provides a summary comparison.

Table 7. Summary of modelled loads for Lake Tutira surface inflows, and comparison with outputs from the CLUES catchment model.

Source	**Discharge** (m^3 s^{-1})	**TP load** (t y^{-1})	**SRP** (t y^{-1})	**TN load** (t y^{-1})	**DIN** (t y^{-1})	**TSS load** (t y^{-1})
Kahikanui Stream	0.035	0.390	0.039	1.08	0.37	576
Oporae Stream	0.018	0.215	0.032	0.72	0.18	137
Church Stream	0.016	0.162	0.028	1.59	0.16	487
Residual catchment	0.033	0.366	0.059	1.23	0.44	229
Lake Catchment	**0.102**	**1.133**	**0.159**	**4.63**	**1.15**	**1429**
(CLUES)	(0.155)	(1.252)	-	(2.705)	-	(4721)
Sandy Creek (100%)	0.251	3.787	0.362	15.51	4.99	3912
(CLUES)	(0.414)	(3.122)	-	(30.30)	-	(8490)

3.1.1.e Other flow, nutrient and sediment sources

Nutrient loads from atmospheric deposition were set using available literature (e.g., Parfitt et al. 2006). Backflows from Papakiri and Waikapiro to the Lake Tutira model were derived from water balance calculations. In consultation with HBRC it was estimated that 'backflow' of Papakiri into Tutira occurred on average about once per year and during very high flows. Accordingly, a threshold of 5 m^3 s^{-1} was set, above which water over and above this threshold would flow directly from Papakiri into the lake. Appendix Figure 9 shows the timing and extent of these intrusions, with a total of eight estimated events over the 6-year simulation period. This threshold was defined based on anecdotal evidence, and as such has a high degree of uncertainty.

3.1.1.f Model scenarios and loads

Table 8 summarises the total flow, nutrient and sediment loads under each of the management scenarios concerning changes in nutrient loading or hydrology. Scenarios relating to aeration and flocculation/capping had identical loads to those presented for the baseline case (C100). Lake residence time resulting from these hypothetical hydrological modifications is also given. Simple steady-state mass balance models after Vollenweider (1976) and OECD (1982) were trialled for assessing the balance between nutrient loading and hydraulic retention time, however, were found to give a poor match for observed in-lake concentrations and are not reported.

Table 8. Summary of modelled loads for lake model scenarios relating to nutrient load and hydrology modifications. 'Catch.' Denotes loads from all catchment sources other than Papakiri.

Scenario	Flow ($m^3 s^{-1}$)			Residence time (y)	TP ($t y^{-1}$)		TN ($t y^{-1}$)		TSS ($t y^{-1}$)	
	Catch.	Papakiri	Outflow	Lake	Catch.	Papakiri	Catch.	Papakiri	Catch.	Papakiri
C100	0.12	0.01	0.18	6.42	0.821	0.266	4.33	0.71	943	315
C90	0.12	0.01	0.18	6.42	0.739	0.266	3.94	0.71	849	315
C75	0.12	0.01	0.18	6.42	0.616	0.266	3.34	0.71	707	315
C50	0.12	0.01	0.18	6.42	0.410	0.266	2.35	0.71	472	315
C25	0.12	0.01	0.18	6.42	0.205	0.266	1.35	0.71	236	315
C100_P0	0.12	0.00	0.17	6.82	0.821	0.000	4.33	0.00	943	0
C100_Pg4000	0.12	0.02	0.18	6.13	0.821	0.436	4.33	1.21	943	499
C100_P100	0.12	0.25	0.41	2.79	0.821	2.418	4.33	11.01	943	1788
C100_P75	0.12	0.25	0.41	2.79	0.821	1.814	4.33	8.26	943	1341
C75_P75	0.12	0.25	0.41	2.79	0.616	1.814	3.34	8.26	707	1341
C50_P50	0.12	0.25	0.41	2.79	0.410	1.209	2.35	5.50	472	894
C100_PI200	0.12	0.11	0.27	4.21	0.821	0.413	4.33	2.78	943	126
C75_PI200	0.12	0.11	0.27	4.21	0.616	0.413	3.34	2.78	707	126
C100_PI1000	0.12	0.17	0.32	3.49	0.821	1.030	4.33	5.82	943	485

3.2 Lake

3.2.1 Lake monitoring

Data from monthly manual samples (HBRC) and the Lake Tutira automated high-frequency monitoring buoy provide a background against which to assess more detailed studies of lake processes.

3.2.1.a Lake samples

Measurements from the lake, approximately monthly from 2010 to 2016, show a very high ratio of N to P in surface waters (c. 20:1), which is usually indicative of strong P-limitation. However, dissolved inorganic N was frequently below detection limits, and elevated total N associated with high chlorophyll values (particularly in summer 2015/16) could indicate substantial nitrogen-fixation during blooms in order to meet any shortfall in N supply (i.e. when N:P ratio is low). Observed in-lake chlorophyll was relatively low from 2013 to mid-2014 relative to the entire study period, corresponding to the period of low flow and consequently low catchment nutrient loads when in-stream samples were collected for calibrating catchment models. Anoxic bottom waters associated with temperature stratification during spring to autumn were associated with highly elevated dissolved N and P, indicative of strong but variable internal nutrient loading from lake sediments (Figure 8). Erratic sample depths pre-2014, and a lack of bottom water (> 35 m) samples post-2014 made assessment of interannual variability in internal loading difficult. Highest concentrations of TN, TP and chlorophyll in surface waters were observed in summer 2015/2016, associated with widely publicised phytoplankton blooms and fish kills. No evidence of increased internal loading in the preceding year was observed, therefore, it is likely that this event was driven by increased P supply to the lake from the catchment, possibly associated with a high rainfall event in September 2015. The extremely high TN concentrations could be due to N-fixation by cyanobacteria in the lake and/or similarly elevated catchment N supply. Such interannual variability in stream inflow N and P loads is difficult to model in the absence of detailed information form the catchment and inflows with which to calibrate and validate models.

3.2.1.b Monitoring buoy

Data from the monitoring buoy provided a record of water level against which to construct the model water balance, as well as highly resolved measurements to assist with model calibration. Bottom water oxygen measurements show very rapid descent to anoxia following the onset of stratification (Figure 9). Following winter mixing, oxygen levels in surface waters remain very low (< 70 % saturation) for a number of days, likely placing stress on sensitive aquatic species, particularly rainbow trout (*Onchorynchus mykiss*). The relative strength of chlorophyll and phycocyanin fluorescence signals gives a broad indication of cyanobacterial blooms, with the strongest events observed in 2012 and 2015-16 (Figure 10).

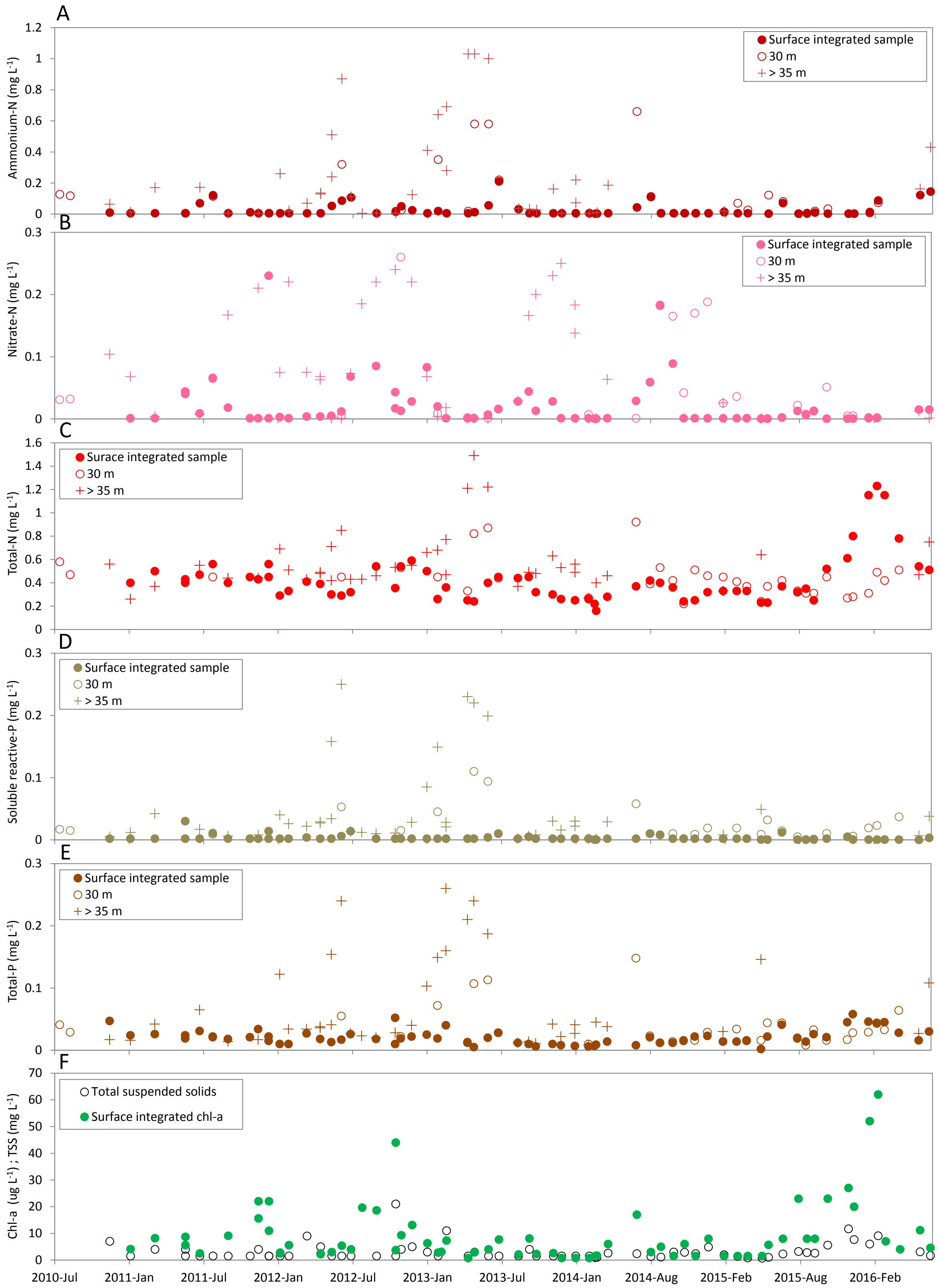

Figure 8. Monitoring results for samples collected by HBRC July 2010 to June 2015, for A) ammonium, B) nitrate, C) total nitrogen, D) soluble reactive phosphorus, E) total phosphorus and E) chlorophyll-*a* and total suspended solids.

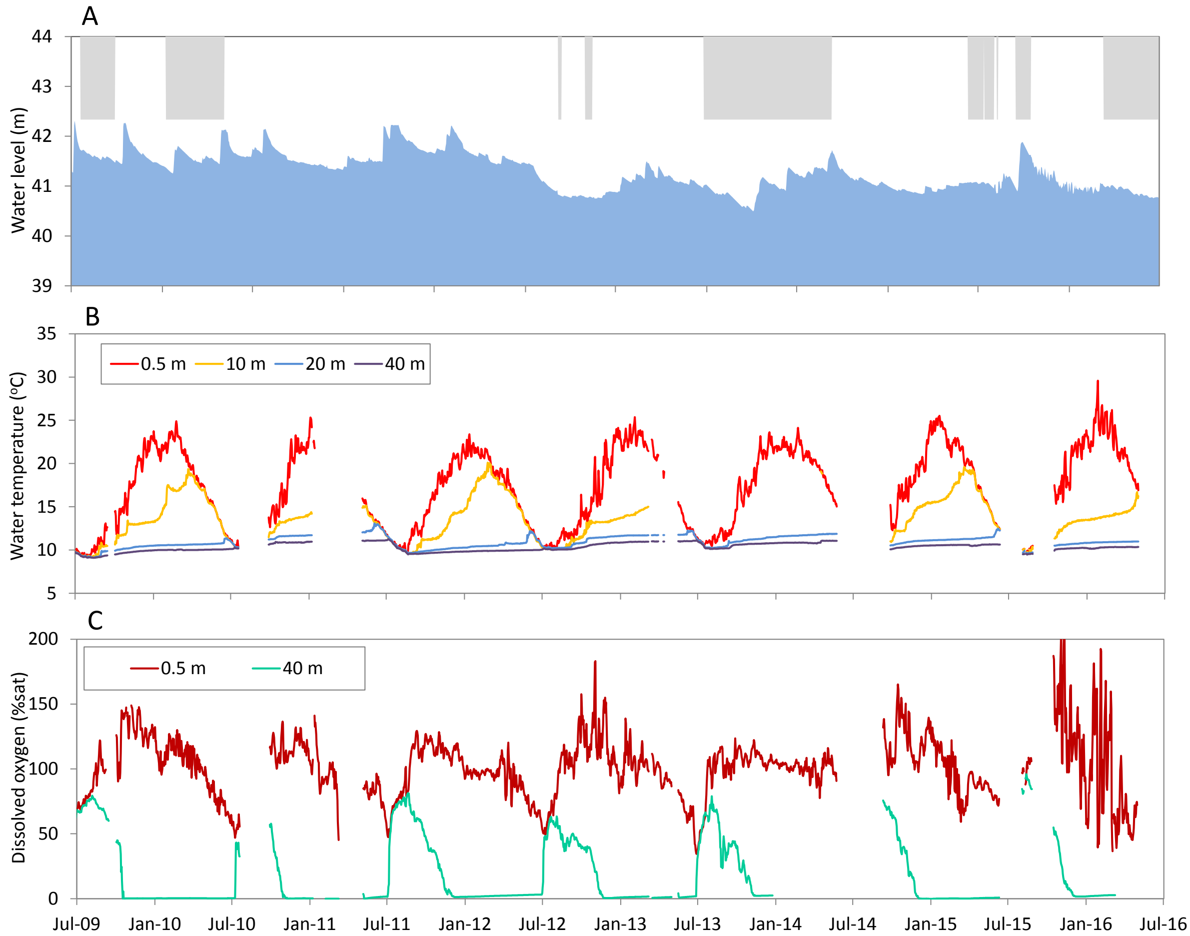

Figure 9. Measurements from the Lake Tutira monitoring buoy maintained by HBRC and Limnotrack, for A) water level (grey bars denote periods where synthetic water level change was estimated form rainfall data, due to gaps in the monitoring buoy record, B) water temperature at four depths, and C) surface and bottom water dissolved oxygen.

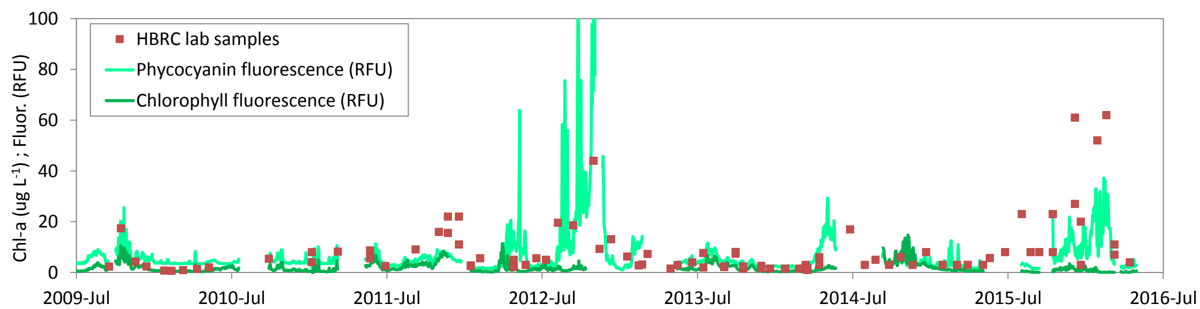

Figure 10. Sensor measurements from the Lake Tutira monitoring buoy for chlorophyll fluorescence and phycocyanin (cyanobacteria) fluorescence, shown in relative units, alongside laboratory measurements of extracted chlorophyll from lake water samples (HBRC).

3.2.2 DYRESM-CAEDYM lake modelling

A process-based DYRESM-CAEDYM physical-biogeochemical model was established for Lake Tutira for the period July 2010 to June 2016. Because 2015-16 was a year of unusual and extreme lake dynamics, and possibly driven by episodic events in the catchment (see Section 3.2.1a), the model calibration was optimised for the period 2010 to 2015. The model was able to reproduce physical and chemical dynamics in the lake over this period well. A summary of model performance metrics over this period is presented in Appendix Table 5.

3.2.2.a Model calibration

Temperature and oxygen dynamics were simulated well by the calibrated model (Figure 11), including hypolimnetic oxygen demand (slope of oxygen decline over time in bottom waters). The modelled bottom water temperature was very cold in summer 2011/12 and hence simulated time of lake turnover (mixing) was delayed somewhat relative to measurements. For all other years the timing of stratification onset and mixis was well simulated, as evidenced by comparison of modelled temperature and oxygen with measurements from the monitoring buoy (Appendix Figure 16).

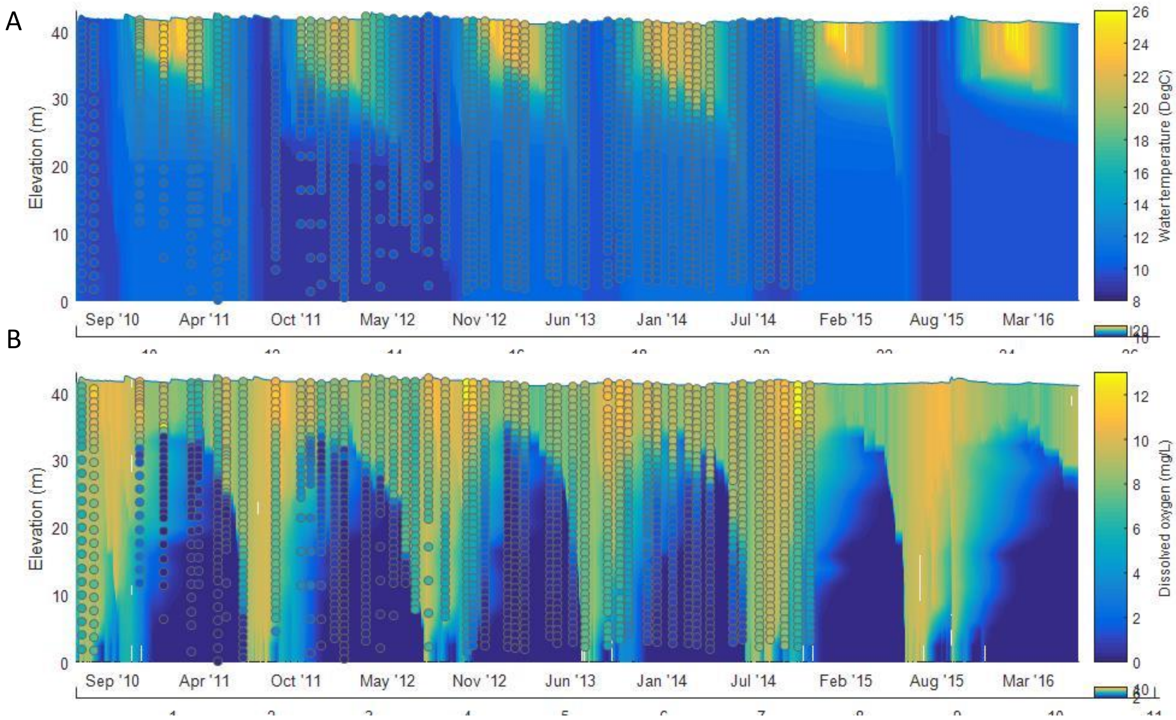

Figure 11. Comparison of model simulations (background colour) with field observations (coloured circles) for all depths (y-axis) through time (x-axis), over model the calibration period. For A) water temperature, and B) dissolved oxygen.

Modelled nutrient concentrations fit observations well, including those at depth (Figure 12, Appendix Table 5), suggesting that the internal loading dynamics appeared to be well represented (R ≈ 0.6 for NH_4 and SRP, all depths), although inconsistent sampling depths confounded interpretation of interannual dynamics. Detailed comparison of simulated and observed nutrient dynamics in surface waters is given in Appendix Figure 17.

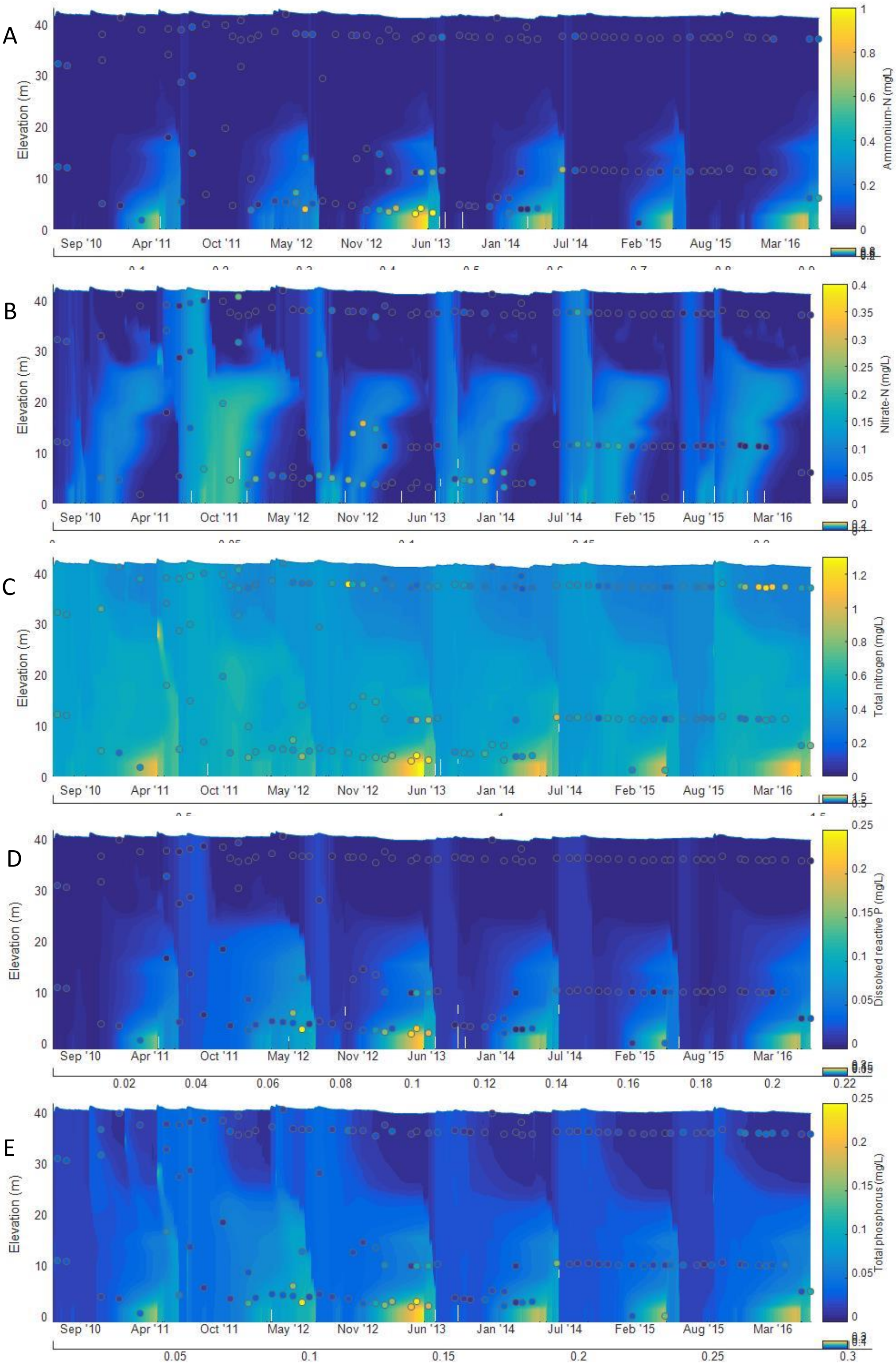

Figure 12. Comparison of model simulations (background colour) and field observations (coloured circles) for all depths (y-axis) through time (x-axis), over the calibration period. For A) ammonium, B) nitrate, C) total nitrogen, D) soluble reactive phosphorus (phosphate), and E) total phosphorus.

Simulating the precise timing and extent of cyanobacteria proliferation in the lake proved difficult. Seasonal succession from diatoms in cooler months to cyanobacteria in warmer months was generally reproduced, as were average phytoplankton abundance and the sporadic and variable occurrence of surface cyanobacteria proliferation.

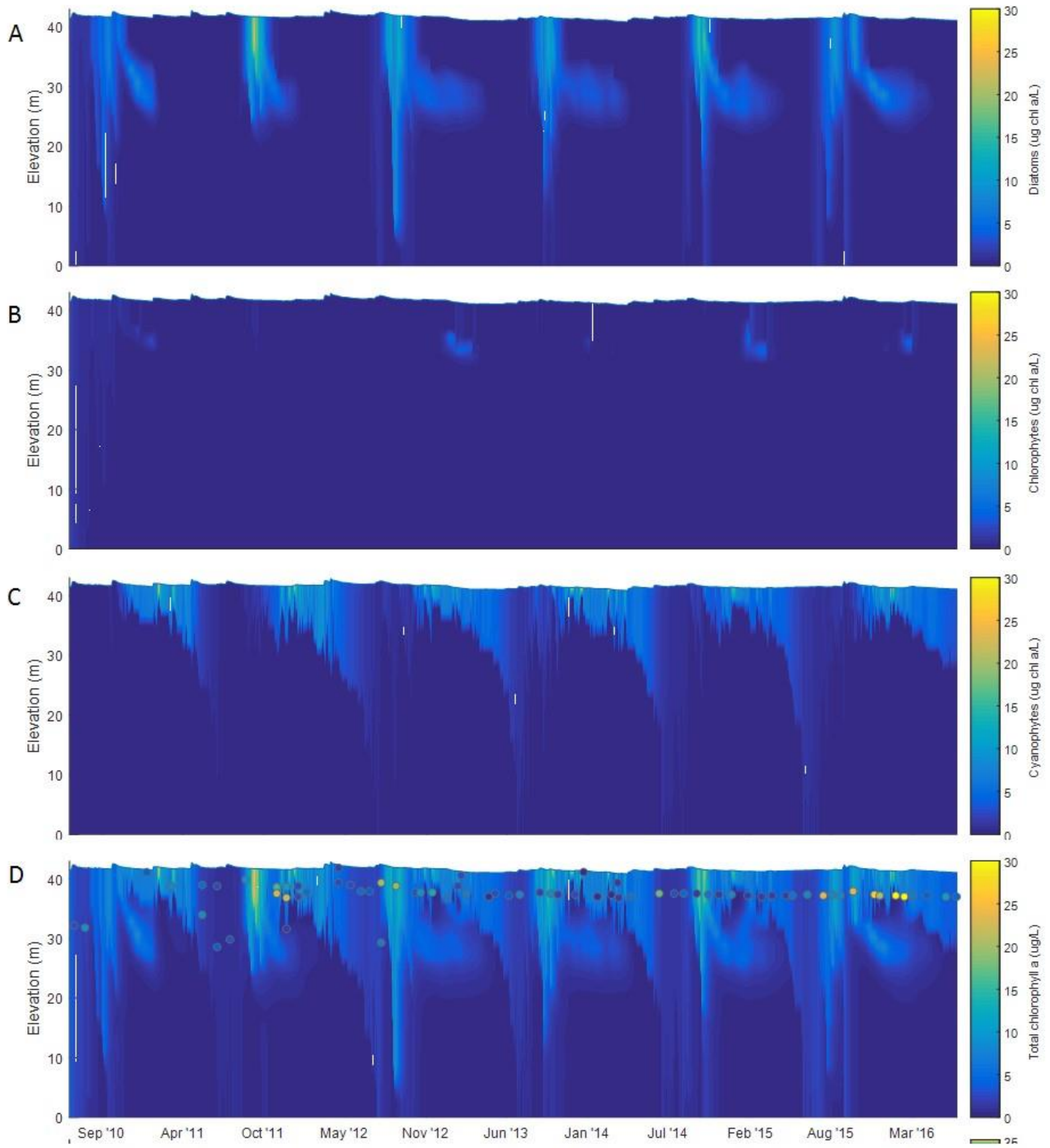

Figure 13. Comparison of model simulations (background colour) and field observations (coloured circles) for all depths (y-axis) through time (x-axis), over the calibration period. For A) diatoms, B) green algae (chlorophytes), C) blue-green algae (cyanobacteria), and D) total chlorophyll *a*. Note that field measurements of chlorophyll presented at depths of 3 to 4 meters are generally integrated tube samples representing the average over a depth range, typically 0 – 8 m.

On an annual average basis the model accurately reproduced the Trophic Level Index and its four component indices over the period 2010 – 2015 (±0.1 TLI unit, Figure 14). Over the entire simulation period (2010 to 2016) all indices were on average slightly under-predicted, due to the strong bloom in 2015/16 which was possibly exacerbated by N-fixation (the version of CAEDYM used cannot accurately simulate N-fixation).

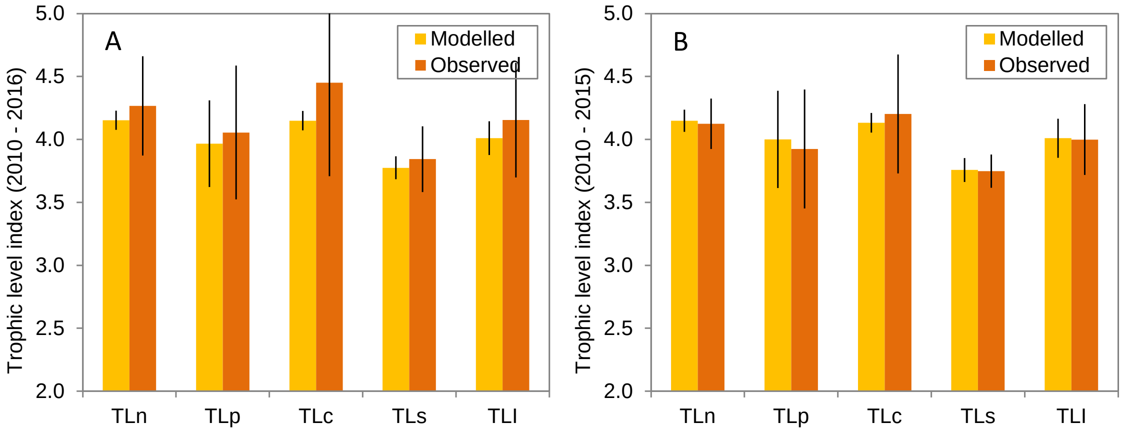

Figure 14. Comparison of modelled and measured composite Trophic Level Index. A) for all years of the simulation period, and B) for the period July 2010 to June 2015. Vertical bars represent the standard deviation of annual trophic level index for the given period.

Modelled and observed interannual variation in TLI components showed that dynamics were generally captured although observed modelled Trophic Level phosphorus (TLp) and chlorophyll (TLc) showed substantially narrower ranges 2010 to 2015 (Figure 15).

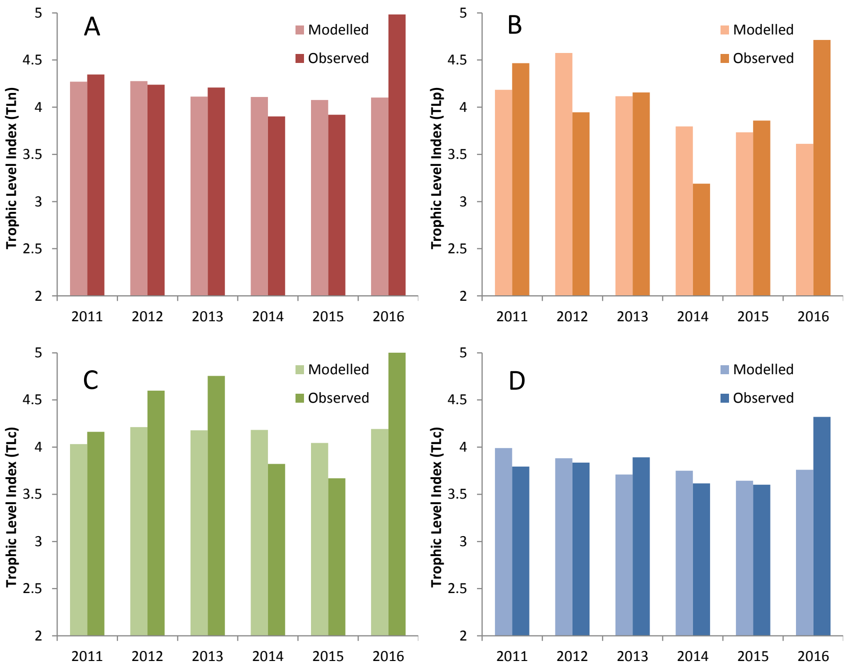

Figure 15. Comparison of modelled and measured annual Trophic Level Index components, A) trophic level nitrogen (TLn), B) trophic level phosphorus (TLp), C) trophic level chlorophyll (TLc) and D) trophic level Secchi disk depth (TLs), for the entire simulation period. A higher trophic level index value is indicative of poorer water quality.

3.2.2.b Scenario modelling

A summary of TLI for all scenarios is shown in Figure 16, and a detailed breakdown of the effects of each scenario on the four Trophic Level components is given in Appendix Figure 27. Scenarios were run for the period July 2010 to June 2015, however, output was assessed for the period July 2011 to June 2015, excluding the first year as a 'spin-up' period in order to minimise the influence of initial conditions on the output TLI. Among all scenarios, TLI ranged from 3.3 (mesotrophic) to 4.5 (eutrophic) (Figure 16). When considering the magnitude of TLI change it should be remembered that the TLI scale is logarithmic for N, P and chlorophyll, meaning that a small change in TLI usually indicates a relatively larger change in annual average TN, TP, chlorophyll and/or Secchi depth.

Scenarios C100, C75, C50 and C25

These scenarios reduced the nutrient load from the inner lake catchment, but made no modification to internal (sediment) nutrient loading, or to discharge intrusion from Papakiri to the lake. Reduction of nutrient loads from the immediate catchment of Tutira predictably resulted in improved water quality (Figure 16), however, the magnitude of change was small (reduction of <0.2 TLI units).

Scenario C50i50

This scenario was established to simulate a 50% reduction in catchment nutrient and sediment loads, with a corresponding internal load reduction. There was no modification of Papakiri input. These reductions resulted in substantially larger TLI reduction (c. 0.35 TLI units) than for external loading alone (Figure 16). This scenario also eliminated the modelled occurrence of surface cyanobacteria blooms (defined here as cyanobacteria > 12 mg m^{-3} at the lake surface).

Scenarios C100_Pk100, C100_Pk75, C75_Pk75, and C50_Pk50

These scenarios assessed a rediversion of all discharge from Papakiri into the lake (as per pre-1980s), along with reduced Papakiri nutrient concentrations to potentially mitigate the additional loading from Papakiri. Full rediversion of Papakiri into the lake reduced lake retention time from an estimated 6.4 years to 2.8 years (i.e. increased flushing), however, because Papakiri is an intensively farmed catchment with substantial flows of nutrient and sediment-rich water, the net result of rediversion was a substantial deterioration in simulated water quality. C100_Pk100, which had no nutrient reduction, yielded the highest TLI of all scenarios (TLI = 4.5), and even a 50% reduction in nutrient loads from both catchments did not sufficiently mitigate the effects of full flow rediversion (Figure 16).

Scenario C100_Pk.g4000

This scenario was configured as for C100 but allowed Papakiri discharge > 4000 L s^{-1} into Tutira (C100 = > 5000 L s^{-1}), i.e. a greater degree of backflow from Papakiri into Tutira. This yielded a TLI increase of 0.1 units (figure 16), showing some sensitivity of the lake to small changes in the (highly uncertain) conceptualisation of Papakiri intrusion into Tutira.

Scenarios C100_Pk.fl0, C100_Pk.fl200, C100_Pk.fl1000, and C75_Pk.fl200

Scenarios restricting low Papakiri flows only into the lake more closely approached a net-neutral effect on lake water quality (i.e. balance between the positive effects of flushing and the negative effects of nutrient-rich Papakiri water), although even a scenario with a 25% reduction in inner catchment nutrient loads and Papakiri intrusion restricted to discharge < 0.2 $m^3 s^{-1}$ (C75_Pk.fl200) resulted in a very slight TLI increase (< 0.05 TLI units) relative to C100 (Figure 16). These results suggest a more detailed analysis may be warranted if some rediversion of Papakiri is desired. Preventing the present overspill of Papakiri into Tutira entirely (C100_Pk.f0) made only a very slight improvement in lake water quality, however, it should be noted that the modelled 'baseline' assumption of this inflow being diverted to the lake only for discharge > 5 $m^3 s^{-1}$ is highly uncertain.

Scenarios C100_bub.d100 and C100_bub.d500

Scenarios simulating aeration by a bottom-mounted bubble plume of either 100 L s^{-1} (C100_bub.d100) or 500 L s^{-1} (C100_bub.d500) yielded contrasting results. The simulation with a moderate airflow rate (100 L s^{-1}) actually increased the occurrence of cyanobacteria blooms and TLI (Figure 16). However, the scenario with a high airflow rate (C100_bub_d500) had positive effects on water quality, eliminating bloom formation and slightly reducing TLI.

Scenarios C100_bub.m100 and C100_imp.d500

Simulations using a bubbler (100 L s^{-1}) or impeller (downward flow of 10 $m^3 s^{-1}$) yielded the highest presence of cyanobacteria blooms of all simulations (Figure 16).

Scenario C100_Pk100_bub.d500

A scenario of high air flow, bottom-mounted aeration including the full diversion of Papakiri into Tutira suggested that aeration was unlikely to compensate for the negative water quality impacts of rediversion of Papakiri.

Scenarios C100_floc, C100_cap and C100_floc.cap

Although CAEDYM cannot explicitly simulate the mode of action of flocculation and sediment capping agents, scenarios were undertaken to approximate their effects by adjusting process rate coefficients to simulate an increase in the settling rate of organic matter (flocculation), and the reduction of internal sediment-water nutrient fluxes (sediment capping). Flocculation and capping resulted in strong reductions in TLI particularly when applied simultaneously, although results should be interpreted cautiously due to necessary conceptual simplifications.

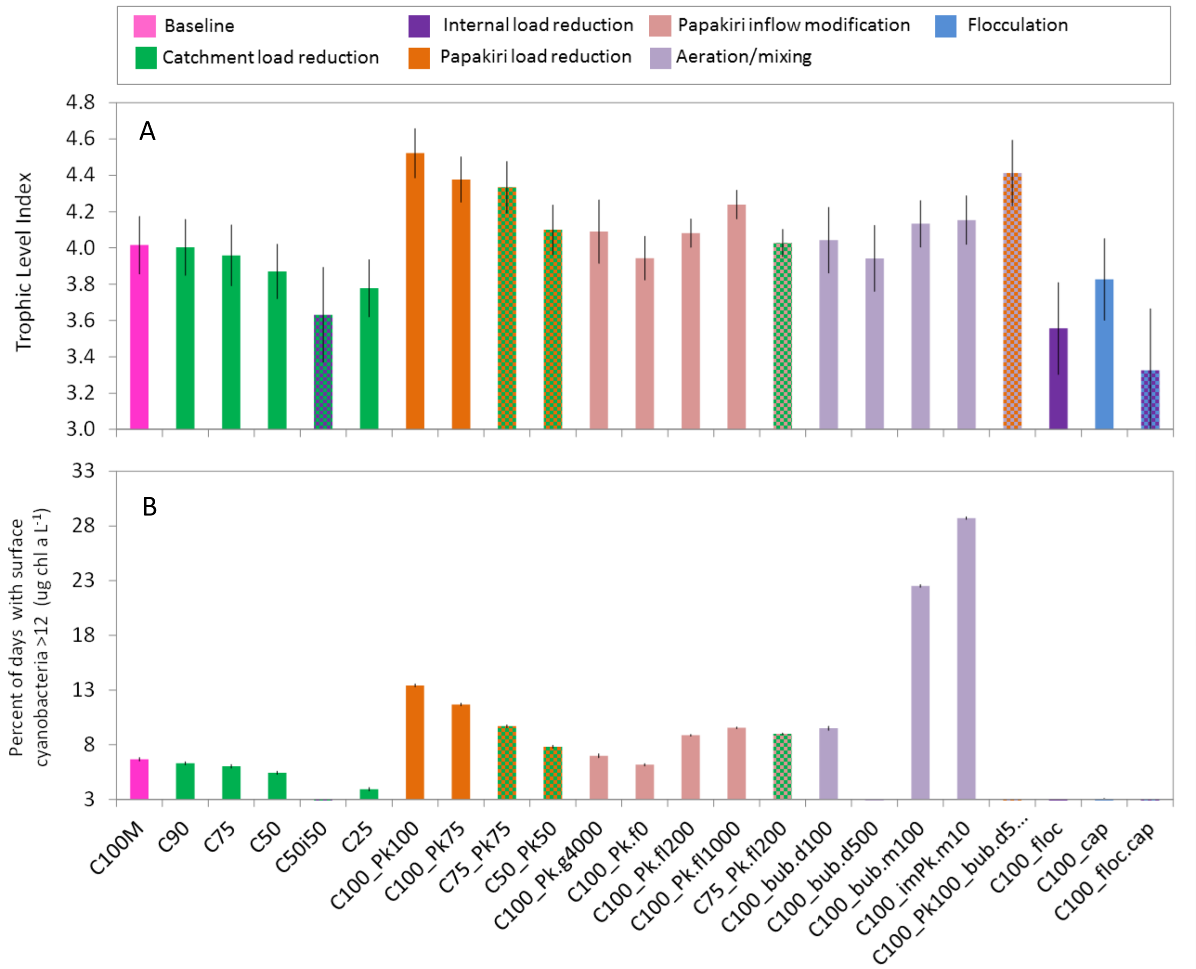

Figure 16. Summary of results for all scenario simulations, for A) Trophic Level Index for the period July 2011 to June 2015, and B) percentage of days with surface cyanobacteria bloom (defined as surface concentration of cyanobacteria > 12 mg m^{-3}). Error bars represent one standard deviation. Bars with 'checkerboard' colour scheme denote scenarios which utilise a combination of management approaches.

4 Discussion

This study leveraged substantial monitoring data as well as process-based catchment and lake models to examine the drivers of poor water quality and algal blooms in Lake Tutira, and to assess various management options that have either been specifically proposed for Lake Tutira, or have proven effective for other lakes in New Zealand and globally.

Monitoring data for the Tutira catchment show that concentrations of nitrogen (N), phosphorus (P) and suspended sediment (SS) in stream inflows (including Papakiri) are generally strongly positively related to discharge. Therefore, a very large proportion of annual dissolved and particulate nutrient and suspended material loads are delivered to the lake during brief periods of high discharge. Tutira appears to be sensitive to these storm flow loads although the relative contribution of particulate and dissolved nutrient inputs to poor lake water quality remains unclear, because the effects of particulate nutrient loads may manifest in the medium- to long-term via remineralisation from bottom sediments during anoxia in bottom waters. Observed TN to TP ratios in surface waters (c. 20:1) suggest a higher probability of P-limitation. However, dissolved inorganic N was frequently below detection limits, and elevated total N associated with high chlorophyll values (particularly during a bloom of cyanobacteria in summer 2015/16) could indicate substantial nitrogen-fixation in order to meet shortfalls in N supply (i.e. when N:P ratio is low). This is consistent with observations of the N-fixing cyanobacterium *Dolichospermum sp.* in the lake over recent years (HBRC; unpubl. data). Anoxic bottom waters during temperature stratification over warmer months were associated with highly elevated dissolved N and P for some years, indicative of strong but interannually variable internal nutrient loading from lake sediments. More regular bottom water samples at consistent depths would help with quantifying the extent and variability in internal loading, as would analysis of the chemical composition of bottom sediment profiles.

The process-based catchment model INCA-N was used to simulate daily time-series of flow and nitrogen concentrations in all surface inflows, including Papakiri Stream. Empirical modelling was undertaken to estimate corresponding values for phosphorus and sediment. Modelled annual hydraulic, nutrient and sediment loads were somewhat lower than estimates obtained from the coarse-scale nutrient loss model CLUES (which is calibrated at the national scale). Additional gauging data from streams within the catchment could help to increase confidence in modelled discharge and loads, given the discrepancy between modelled water yield and that estimated form other sources (CLUES). Modelled flows and nutrient and sediment concentrations provided a satisfactory fit to available in-stream observations and were used as daily input to the in-lake model.

A process-based physical-biogeochemical model (DYRESM-CAEDYM) was set up for Lake Tutira for the period July 2010 to June 2016. The calibrated model was able to reproduce physical and chemical dynamics in the lake over this period very well. Simulating the precise timing and extent of cyanobacteria proliferation in the lake proved more difficult. Several factors could have contributed to the relatively poorer model performance with regard to phytoplankton bloom timing and magnitude. If blooms are driven primarily by P supply (whereby excess P supply will stimulate N-fixation by certain cyanobacteria to meet shortfalls in N supply), then the occurrence of blooms may depend on seasonal or interannual variability in P loads. Such variability may not have been captured by the empirical methods for P and TSS prediction used to drive the stream inputs to the lake model, particularly where variability in loading was due to intermittent catchment processes (major land slips, erosion events, or fertiliser applications). Further, the version of CAEDYM used was not able to simulate N-fixation and as such may under-represent the capacity of the cyanobacteria population to bloom.

Nevertheless, on an annual average basis the model accurately reproduced Trophic Level Index dynamics for N, P, chlorophyll and Secchi depth (clarity). It can therefore be considered as the most advanced tool available with which to assess potential management options for Tutira both for the catchment and for the lake. Four broad categories of scenarios were undertaken using model simulations, with results as follows:

1. **Nutrient load reduction:** Reduction of nutrient loads from the immediate catchment of Tutira predictably resulted in improved water quality (lower TLI). However, the magnitude of change was lower than might have been expected. This is likely because of the combined influences of inputs from internal loading (bed sediment N and P fluxes) and overspill from Papakiri. DYRESM-CAEDYM cannot explicitly model changes in internal loading that would be a response expected to occur with changes in external loading, however, a further scenario for which internal loading was (manually) modified in a fixed proportion to reductions in external loading (i.e., a 50% reduction in both), resulted in a larger TLI reductions. If catchment load reductions progressively reduce internal loads of nutrients, as might be expected over long time scales, then the model, without accounting for this effect, may provide a conservative value of the effects of catchment load reductions. Time-scales of internal load response are generally of a decade or more.
2. **Hydrological modifications**: As modelled, full rediversion of Papakiri into the lake reduced lake retention time from an estimated 6.4 years to 2.8 years (i.e. increased flushing). However, because Papakiri is an intensively farmed catchment with substantial flows of nutrient and sediment-rich water, the net result of rediversion was a substantial deterioration in simulated water quality. Even a 50% reduction in nutrient loads from both the inner and Papakiri catchments did not sufficiently mitigate the effects of full flow rediversion. Scenarios restricting low flows only into the lake more closely approached a net-neutral effect on water quality (particularly at a threshold discharge < 0.2 $m^3\ s^{-1}$). These results suggest a more detailed analysis may be warranted if some rediversion of Papakiri is desired. Preventing the present overspill of Papakiri into Tutira

made only a very slight improvement in lake water quality, however, it should be noted that the modelled 'baseline' assumption of this inflow being diverted to the lake only for discharge > 5 $m^3 s^{-1}$ is highly uncertain. Indeed a simulation allowing Papakiri discharge > 4 $m^3 s^{-1}$ into the lake produced a TLI increase similar to that of the restricted low-flow rediversion scenario. More accurate quantification of the frequency and extent of overspill from Papakiri to Tutira would greatly aid future modelling assessments. However, prevention of any overspill is likely to provide an immediate, if minor, improvement in water quality and may thus be preferable.

3. **Artificial aeration:** DYRESM-CAEDYM allows for the simulation of either aeration by a bubbler plume (bottom-up) or surface mixing by impellers (top-down). A range of simulations of various air and water flow rates provided highly variable impacts on water quality. High air-flow rates resulted in only a minor improvement in TLI, but they reduced or ablated cyanobacterial blooms, shifting species dominance towards less buoyant species (diatoms and green algae). Conversely, lower rates of airflow and mixing actually increased the occurrence of surface blooms, presumably due to improved access to light and increased transport of nutrients from bottom to surface waters, while not sufficiently negating the buoyancy capabilities of cyanobacteria. Although CAEDYM includes only a simplistic representation of phytoplankton motility, these results highlight potential pitfalls of aeration, and suggest that any system implemented should have substantial 'headroom' to ensure adequate mixing. The advantage of aeration as a management option is that it can be implemented in an adaptive framework and can be easily and quickly stopped if adverse impacts are encountered. The potential effects of aeration/mixing on aquatic biota (particularly the effects of altered temperature dynamics on the trout population) should be considered in detail and are beyond the scope of the present study.
4. **Geochemical engineering:** The application of flocculation and/or sediment capping agents such as Phoslock™ or aluminium sulphate (alum) is a management approach that has been applied with some success in the Rotorua lakes (Bay of Plenty). Although CAEDYM cannot explicitly simulate the mode of action of these agents, scenarios were undertaken to approximate their effects by adjusting process rate coefficients to simulate an increase in the settling rate of organic matter (flocculation), and the reduction of internal sediment-water nutrient fluxes (sediment capping). Flocculation and capping resulted in strong reductions in TLI (as has been the experience in Lake Rotorua), although results should be interpreted cautiously due to conceptual simplifications necessary in these simulations. The efficacy of these agents is highly pH-dependent, and the timing and intensity of their application must be considered in detail. Further, ecotoxicological and community/cultural considerations are important considerations when evaluating geochemical engineering as a lake management option.

A summary of available management and restoration methods and their relevance to Lake Tutira is given in Tables 9 and 10.

Table 9. Catchment–based actions designed to improve water quality in eutrophied lakes. Adapted from Abell et al. (2013).

Action	Details	Specific relevance to Tutira	Relevant scenarios	Indicative costs
Land use change	Nutrient export varies with land use hence the redesign of catchment land use can greatly reduce external loads.	Nutrient export from hill pasture is high, particularly for phosphorus (P); e.g. mean P export from hill pasture (1.98 kg P ha^{-1}) is twice that of dairy (1.0 kg P ha^{-1}) (Elliott & Sorrell, 2002). P losses from forestry may be substantial prior to canopy closure.	C75, C50, C25, C50i50, C100_Pk75, C75_Pk75, C50_Pk50, C75_Pk.fl200.	Highly variable depending on extent and type of conversion.
Adoption of Best Management Practices (BMPs) by farmers	Examples include: • Detailed soil testing (e.g. of Olsen P) to inform paddock–scale fertiliser requirements. • Use of nitrification inhibitors to reduce nitrogen leaching. The nitrification inhibitor dicyandiamide (DCD) has been withdrawn from the NZ market until standards have been introduced with regards to levels of DCD in milk. • Use of low–solubility P fertiliser.	Current farm management practices were not considered during this study. Applicability of individual BMPs will vary and can be identified during development of individual Environmental Farm Plans in consultation with agri–environment specialists. Estimates of nutrient loss using the Overseer™ model already assume best management practice.	C75, C100_Pk75, C75_Pk75, C75_Pk.fl200	Highly variable depending on mitigation/ management type.
Soil conservation	Actions to minimise soil erosion will reduce sediment and particulate phosphorus loads. Examples include: • Stabilising steep slopes with planting or engineering interventions. • Incorporation of vegetative buffer strips alongside raceways or in ephemeral flow paths. • Agricultural detention bunds.	Particularly relevant to the catchment due to known problems of erosion and subsequent excess sediment and particulate nutrient loading during storms. Recommendations to retire erosion prone areas from farming and promote forestry at such sites were made in the 1970s (Hooper, 1989). This study has not reviewed the status of these recommendations.	C75, C100_Pk75, C75_Pk75, C75_Pk.fl200	Variable

Creation of riparian buffers	Excluding stock access and planting in riparian margins reduces stream bank erosion and attenuates nutrient export.	A recommendation to "fence the lake reserve and streams to exclude stock" was made in the 1970s (Hooper, 1989). This study has not reviewed the current status of fencing.	C75, C100_Pk75, C75_Pk75, C75_Pk.fl200	Variable
Wetland construction	Constructed wetlands trap sediments and particulate nutrients, in addition to attenuating dissolved nutrients via processes such as plant uptake and denitrification. A wetland comprising 2.5–5% of the area of the upstream catchment may be expected to remove 40–50% of influent nitrate (Tanner et al., 2010).	The treatment performance of constructed wetlands is greatly reduced during periods of overland flow due to reduced water residence time. The demonstrated high relative importance of overland flow processes for sediment and nutrient transport in the catchment of Lake Tutira may therefore limit the potential value of this action.	C75, C50, C25, C50i50, C100_Pk75, C75_Pk75, C50_Pk50, C75_Pk.fl200.	Wetland construction cost approx. $300K/ha
Drainage network manipulation	'Soft–engineered' structures can be incorporated into agricultural landscapes to promote nutrient and sediment attenuation primarily by enhancing sediment settling rates. Such methods are established in Australia but are currently being developed for use in New Zealand (McDowell & Nash, 2012). Examples include sediment traps incorporated into agricultural drains and detainment dams designed to treat ephemeral streams.	The demonstrated high relative importance of overland flow processes for sediment and nutrient transport in the catchment of Lake Tutira suggests that detainment dams could be beneficial. Such structures have been implemented in high–rainfall areas west of Lake Rotorua. They are designed to temporarily pond ephemeral streams to attenuate sediment transport and storm flow discharge with minimal detriment to pasture quality.	C75, C50, C25, C50i50, C100_Pk75, C75_Pk75, C50_Pk50, C75_Pk.fl200.	Bund cost approx.. $10-100K per bund
Denitrification beds	Containers or excavated areas filled with a carbon source such as woodchips. They promote the conversion of nitrate to di–nitrogen gas by microbes. Trials in NZ have shown denitrification beds can provide a low–cost solution for near complete removal of nitrate from dairy shed effluent (Schipper et al. 2010). Results will depend on local soil type and topography.	The small size of stream inflows to Lake Tutira (Table 6) suggests that this action may be suitable for base–flow treatment but further scoping is necessary to assess potential for application.	C75, C50, C25, C50i50, C100_Pk75, C75_Pk75, C50_Pk50, C75_Pk.fl200.	Unknown

Table 10. Lake–based actions designed to improve water quality in eutrophied lakes. Adapted from Abell et al. (2013).

Action	Details	Specific relevance to Tutira	Relevant scenarios	Likely costs
Sediment capping / phosphorus inactivation	Addition of certain materials such as potassium aluminium sulphate ('alum') and proprietary products made by modification of clays (e.g., Phoslock^{TM}, Z2G1) can render nutrients unavailable for plant growth and reduce nutrient remineralisation from lake bed sediments. Bay of Plenty Regional Council has trialled a range of products to both reduce sediment nutrient release over annual time scales and pre-emptively control seasonal algal blooms (Özkundakci et al., 2010).	Further work would be necessary to assess potential for this action to be applied to Lake Tutira. Alum application would require consideration of buffering to prevent pH related toxicity issues. Consultation with the community would be necessary as the issue of adding chemicals to waterways is a potentially sensitive issue for many stakeholders.	C100_floc, C100_cap, C100_floc.cap	Alum cost approx. $360 per tonne alum (4% aluminium).
Oxygenation/ destratification	Delivering oxygen directly to the bottom waters of a lake can prevent oxygen depletion and associated nutrient release from bottom sediments. Aeration can also be used to disrupt lake stratification or surface blooms/scums, and prevent the occurrence of oxygen–depleted bottom waters.	Six 'aerohydraulic guns' were previously deployed in 1975–1977 with the aim to prevent or disrupt the formation of vertical thermal stratification and thus prevent oxygen depletion in the bottom waters. The exercise was only partly successful (Teirney, 2009) but information gained could inform improved application of this technique. The bottom waters of Lake Tutira have a very high oxygen consumption rate which could make application of this technique challenging. Modern aeration is most commonly applied by linear bubbler tube with tens or hundreds of 'ports' laid across the lake or reservoir bottom.	C100_bub.d100, C100_bub.d500, C100_bub.m100, C100_imPk.m10, C100_Pk100_bub.d500.	Typically $100K+

Dredging	Removes nutrients from the lake bed, reducing cycling through and from the sediments. A recognised method worldwide although expensive and a major logistical undertaking. Identifying a receiving site for dredged material can be difficult.	Sedimentation and consequent accumulation of nutrients in the bottom sediments are a known problem for Lake Tutira (Page et al. 2004). A difficult approach logistically, in such a deep lake.	C100_cap (internal load reduction)	High
Diversion of inflows	Reduces nutrient inputs to the lake. May adversely affect water bodies downstream.	Sandy Creek has been diverted. Improved control of all flows would be ideal. Allowing for some low flows to enter Tutira may enhance flushing without dramatically impacting water quality. Further investigation needed.	C100_Pk100/75, C75_Pk75, C50_Pk50, C100_Pk.fl200, /1000, C100_Pk.fl1000.	Subject to detailed investigation/ scope of engineering required.
Hypolimnetic discharge	Removal of nutrient–rich water from bottom layers while a lake is stratified and oxygen near the lake bed is depleted. Withdrawn water is then transported downstream of the withdrawal location.	Anoxic conditions and elevated dissolved nutrient concentrations are known features of the bottom waters of Lake Tutira during summer (Verberg, 2012). Hypolimnetic siphoning may be used to reduce pumping costs but would require feasibility study.	Not modelled	Unknown
Bio-manipulation	Organisms such as the kakahi/freshwater mussel (*Hyridella menziesii*) can assimilate nutrients or consume algae. The efficacy and the potential for adverse ecological impacts are uncertain.	Grass carp have previously been introduced to Lake Tutira to graze on invasive macrophytes.	Not modelled	Variable
Floating wetlands	Floating wetlands are being trialled in lakes Rotoehu and Rotorua in the Bay of Plenty. Aquatic plants remove dissolved nutrients from the water column.	In isolation, such an action is unlikely to result in attainment of ambitious restoration objectives for Lake Tutira. Such an action may, however, provide a focal point to help engage lake stakeholders in water quality issues.	Not modelled	Typically \$200 - 250 / m^2.

5 Conclusion and recommendations

Catchment inputs of nutrients and sediment to Lake Tutira are strongly flow-dependent, and the lake monitoring record suggests that years with strong cyanobacteria blooms tend to follow from earlier high flow events. Modelling showed the lake was sensitive to increased intrusion by high flows from Papakiri, therefore, quantifying the present extent and timing of Papakiri intrusion ('backflow') into Tutira would assist greatly with future management evaluations. N-fixation by cyanobacteria may contribute further to the proliferation and formation of cyanobacteria blooms. Maintaining regular monitoring of species composition of the phytoplankton assemblage complementary to the monitoring buoy data would assist in tracking the response of the lake to restoration initiatives. Based on modelling results, and conceptual simplifications, full reconnection of Papakiri Stream is likely to result in poorer water quality and more frequent phytoplankton blooms. Diversion of low flows only may reduce the negative effects of Papakiri rediversion, and although unlikely to result in substantial improvement in lake water quality, may warrant further investigation if some degree of reconnection of Papakiri to Tutira is desired. Reduction of catchment nutrient loads and improved control of Papakiri flows is likely to improve water quality, however, effects may take some time to be fully realised in the lake due to expected lag times of up to a decade or more as internal lake processes adjust to changes in external forcing. An improved understanding of sediment nutrient pools and fluxes would be vital to improve future modelling efforts. These 'legacy' nutrient sources result from decades of accumulation, and may provide a source of N and P for decades to come. Geoengineering to increase flocculation and reduce internal loading may be effective but should be evaluated carefully. Aeration and mixing of the water column may achieve water quality aspirations relating to the disruption of cyanobacterial surface blooms, but only if implemented so that water column turbulence would be sufficient to negate their buoyancy regulation.

Modelling results do not reveal a 'silver bullet' for the improvement of Lake Tutira water quality. As is often the case, a multi-faceted approach may yield the best results. Catchment nutrient load reductions, including comprehensive management of catchment erosion and phosphorus transport during high flows, along with better control of Papakiri flows are likely to provide gradual and sustained improvements in water quality. Geochemical dosing could form part of a holistic management program if deemed acceptable by community and stakeholders, and aeration could contribute substantially if implemented at sufficient capacity. Land management practises in the catchment should focus on prevention of 'pulses' of sediment and phosphorus loss, particularly in spring and early summer, to reduce the proliferation of cyanobacteria over warmer months.

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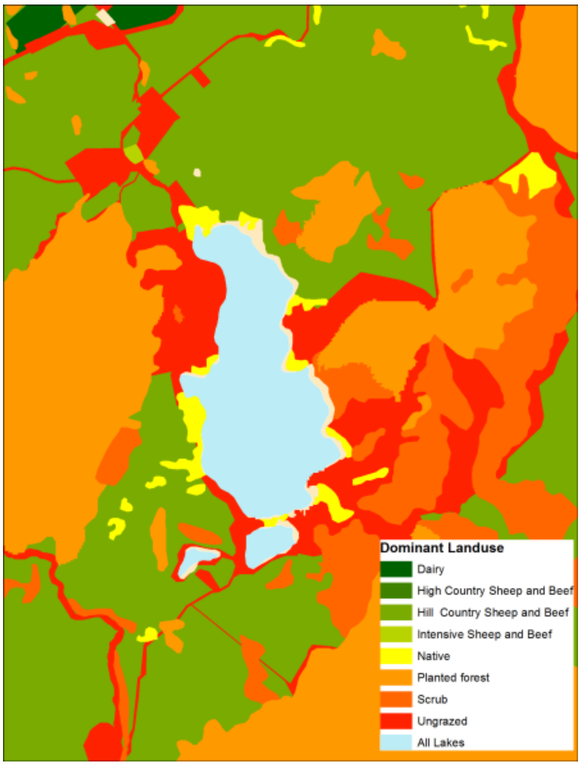
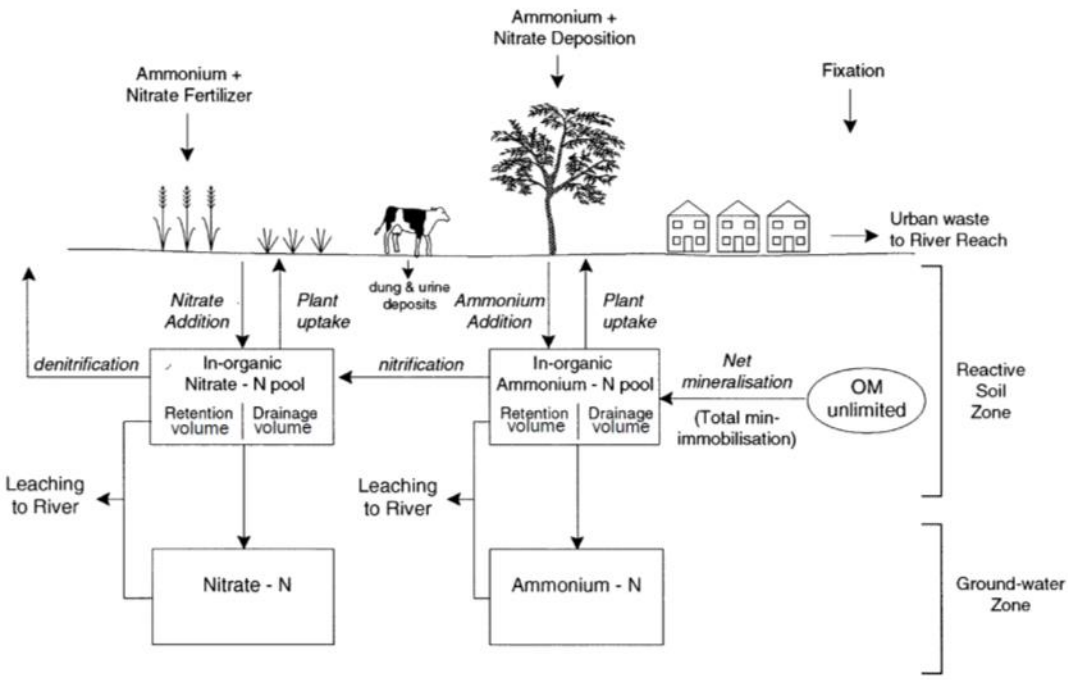
7 Appendices

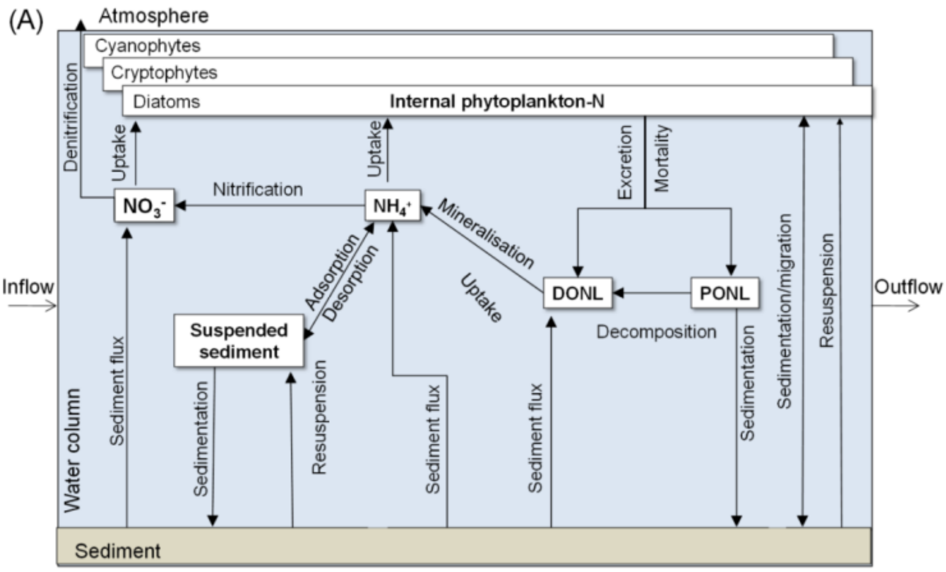
Methods

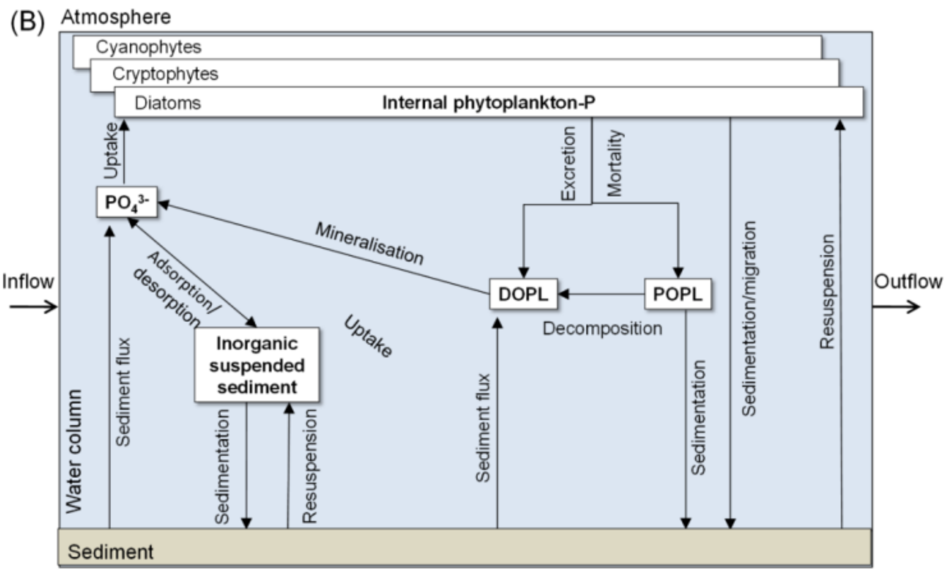


Appendix Figure 1. Land use maps for the Tutira catchment. Obtained from the 'CLUES' model (NIWA; Elliott et al. 2016).



Appendix Figure 2. Conceptual diagram of land phase structure of the INCA-N model (from Wade et al. 2002).

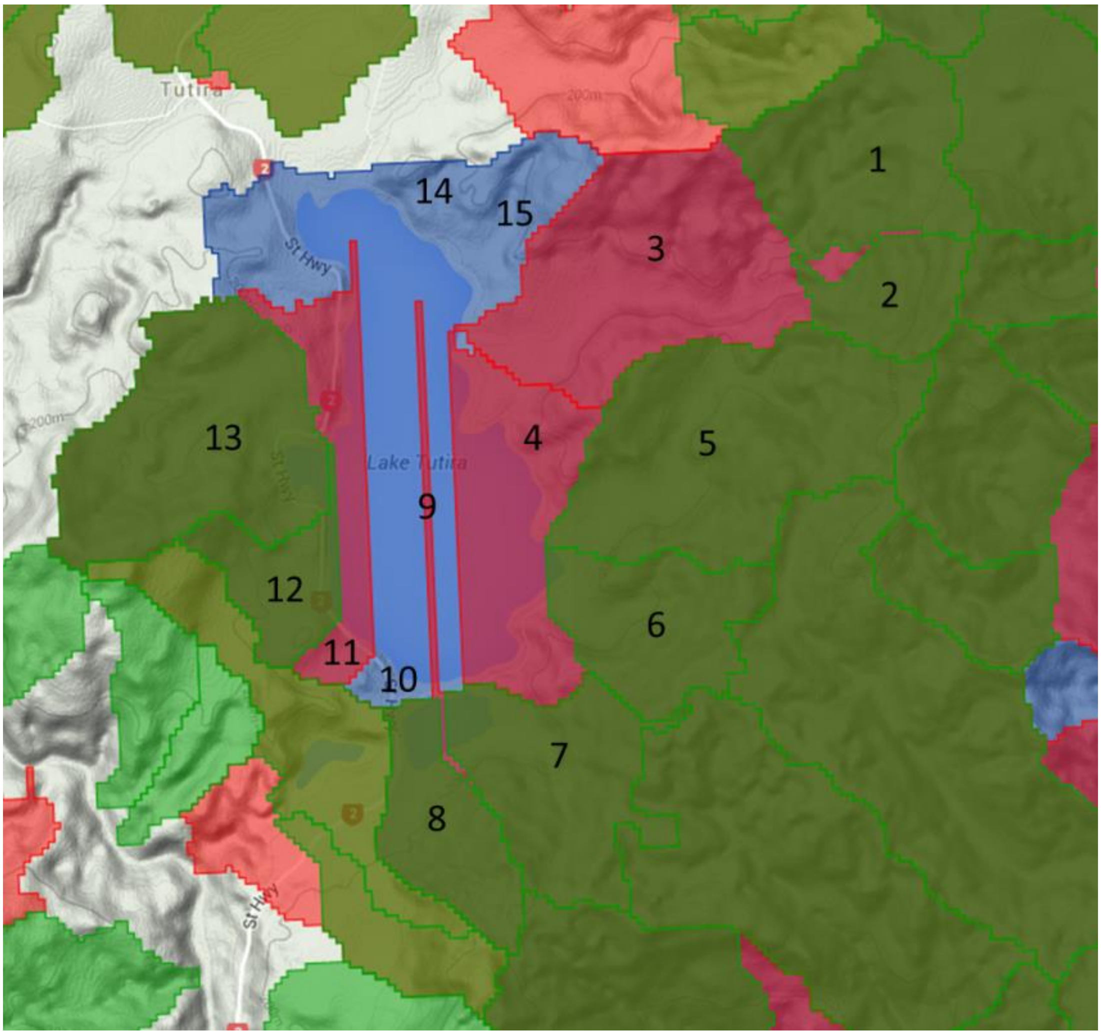




Appendix Figure 3. Conceptual model of the (A) phosphorus and (B) nitrogen cycles represented in DYRESM-CAEDYM for the present study. POPL, PONL, DOPL and DONL represent particulate labile organic phosphorus and nitrogen, and dissolved labile organic phosphorus and nitrogen, respectively. Adapted from Hamilton et al. (2012)

Appendix Table 1. Model performance statistics

Abbreviation	Statistic	Details	Equation
r	Pearson product moment correlation	Measures the strength of the correlation between modelled and measured data, i.e. how 'in phase' the two signals are. Vales range from -1 (perfect negative correlation) to 1 (perfect positive correlation).	$\frac{\sum_{i=1}^{n}(o_i-\bar{o})\times(m_i-\bar{m})}{\sqrt{\sum_{i=1}^{n}(o_i-\bar{o})}\times\sqrt{\sum_{i=1}^{n}(m_i-\bar{m})}}$
RMSE	Root mean square error	A measure of the magnitude of the error between modelled and measured data which is disproportionately affected by large errors.	$\sqrt{\frac{\sum_{i=1}^{n}(m_i-o_i)^2}{n}}$
MAE	Mean absolute error	Measures the average error, irrespective of whether the model under– or over–predicts measurements.	$\frac{\sum_{i=1}^{n}\lvert(m_i-o_i)\rvert}{n}$

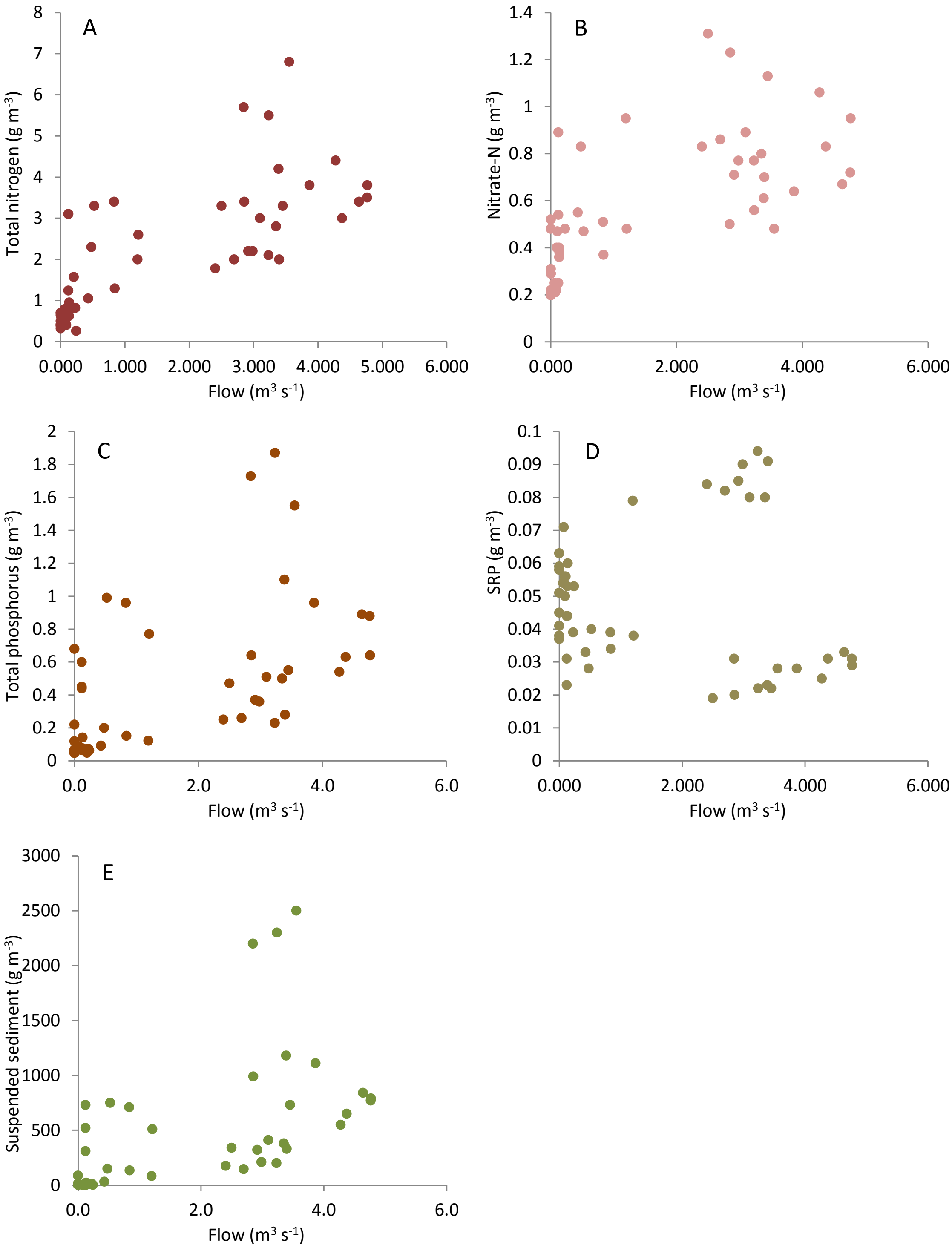


Appendix Figure 4 Lake Tutira sub-catchment used by the CLUES model. Image from Koordinates.com, River Environment Classification layers.

Results

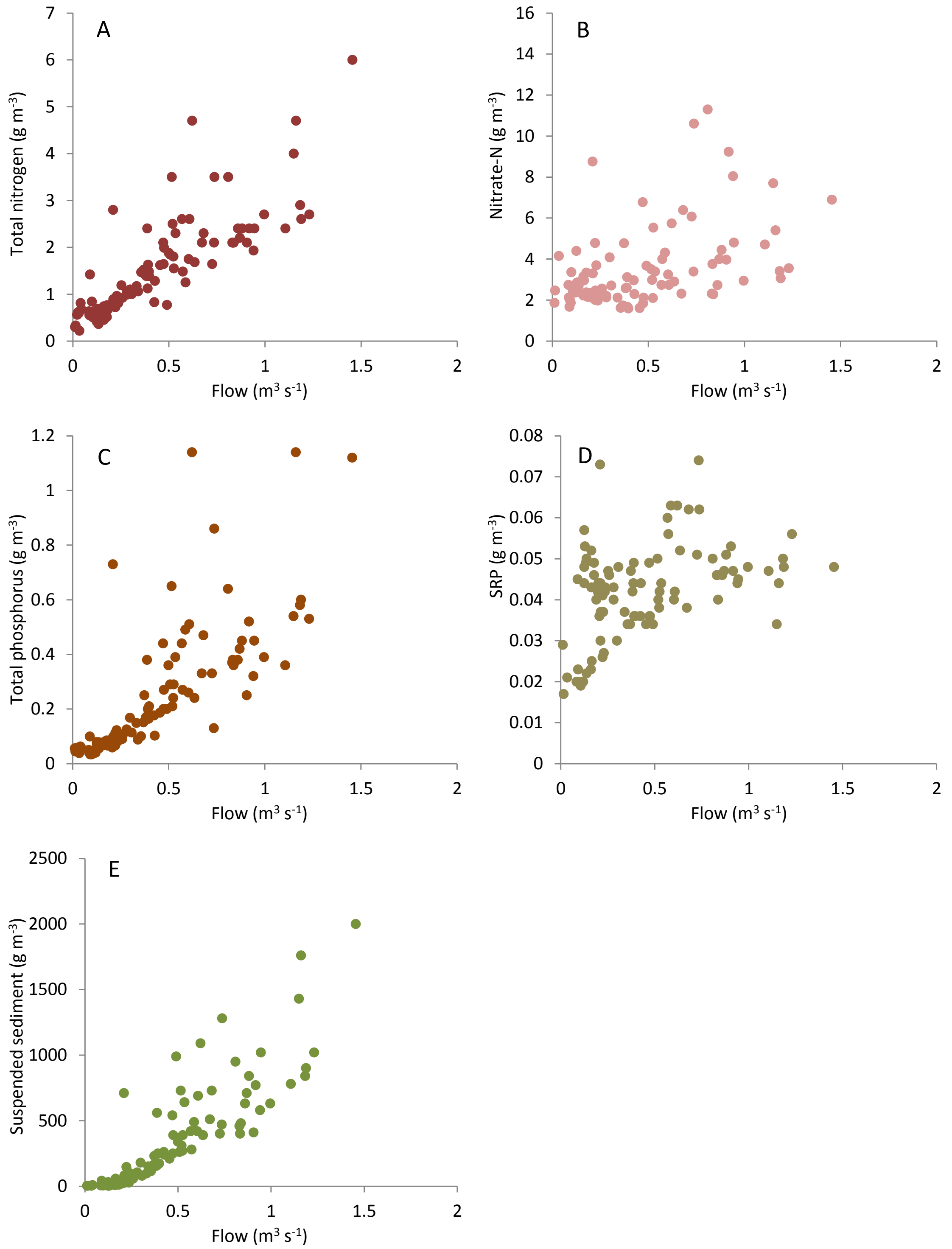
Catchment monitoring

Papakiri Stream (Sandy Creek)



Appendix Figure 5. Summary of all instantaneous samples of water quality plotted against synthetic discharge at Sandy Creek for A) total nitrogen, B) nitrate, C) total phosphorus, D) soluble reactive phosphorus and E) total suspended sediment.

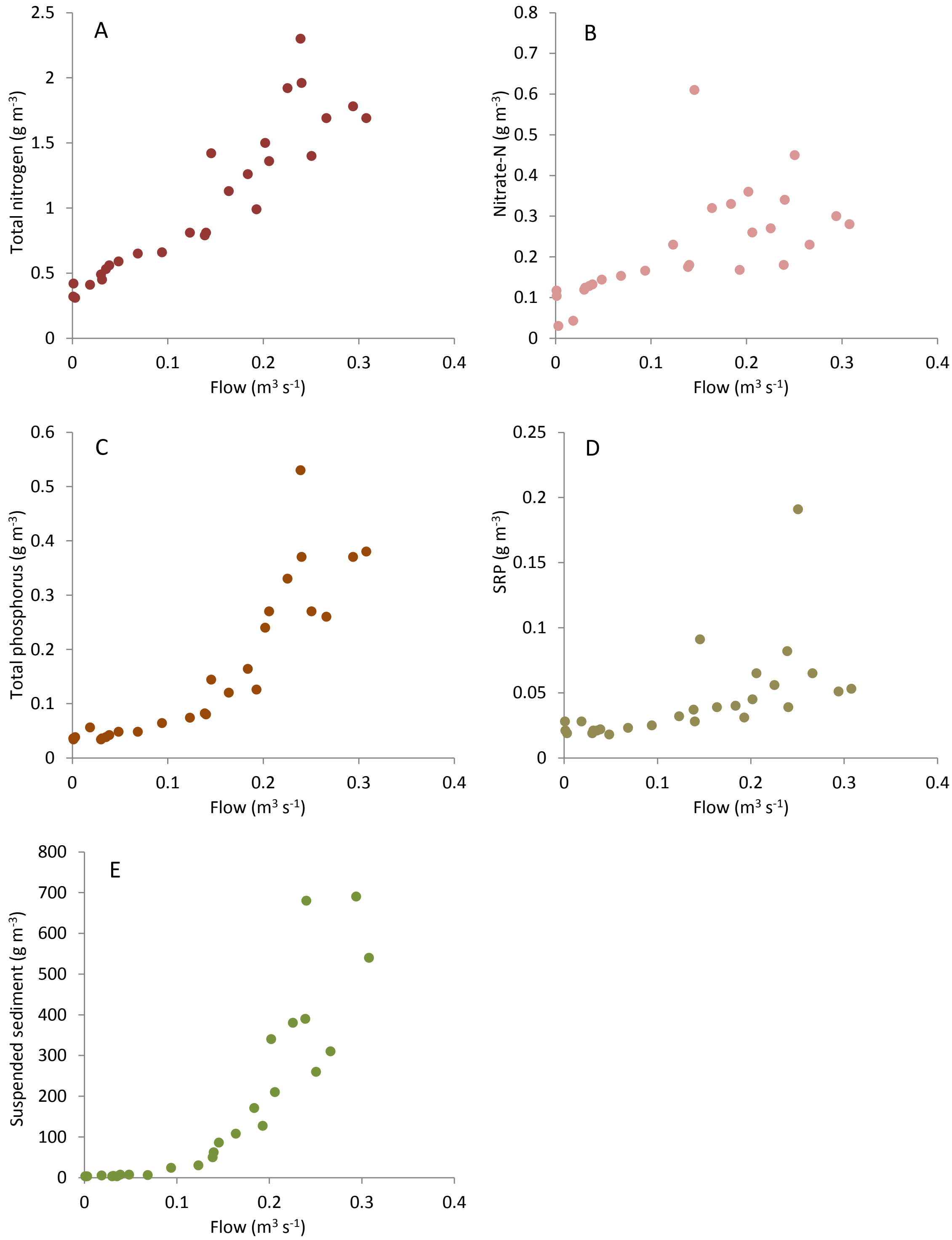
Kahikanui Stream



Appendix Figure 6. Summary of all instantaneous samples of water quality plotted against synthetic discharge at the Kahikanui Stream for A) total nitrogen, B) nitrate, C) total phosphorus, D) soluble reactive phosphorus and E) total suspended sediment.

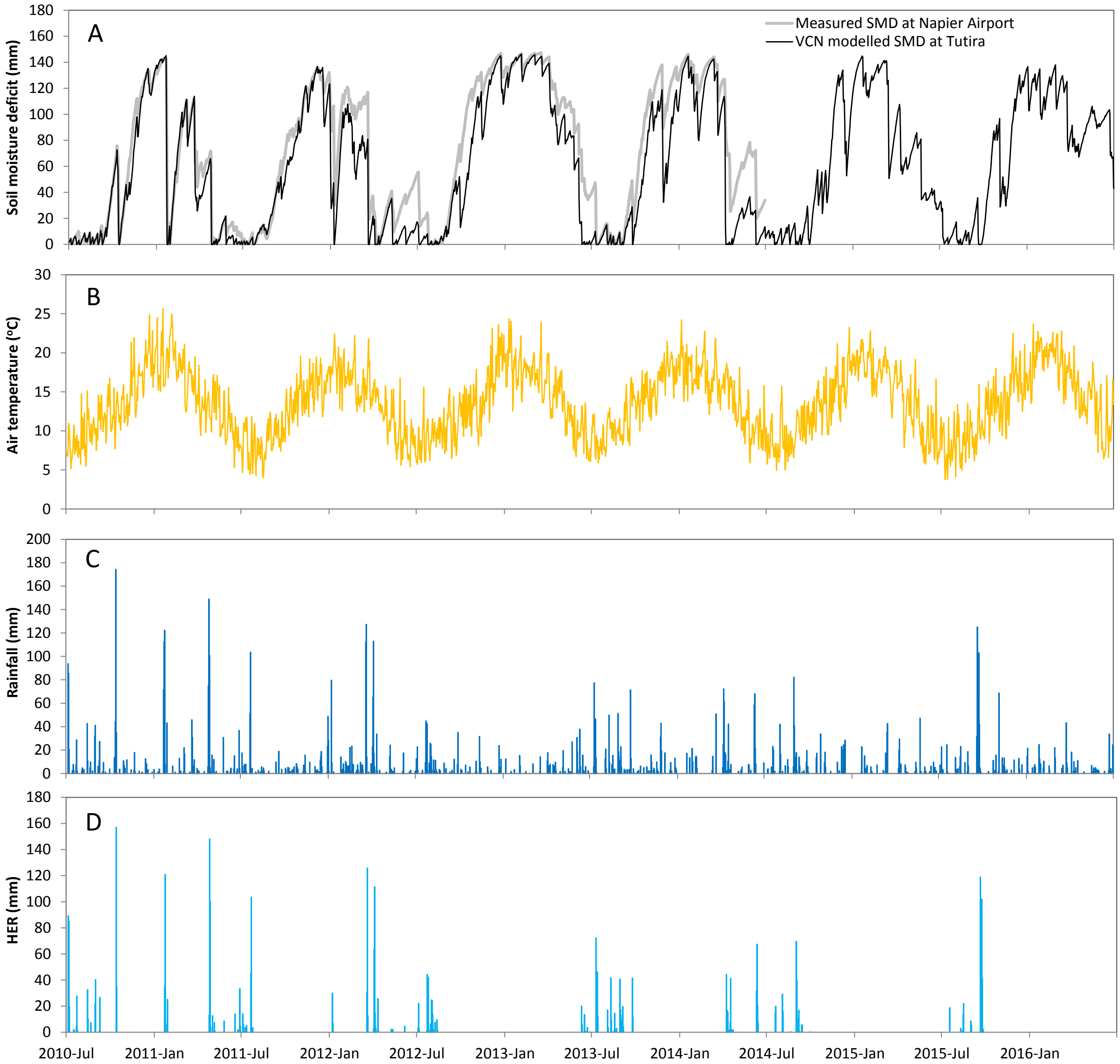
Oporae Stream

Text

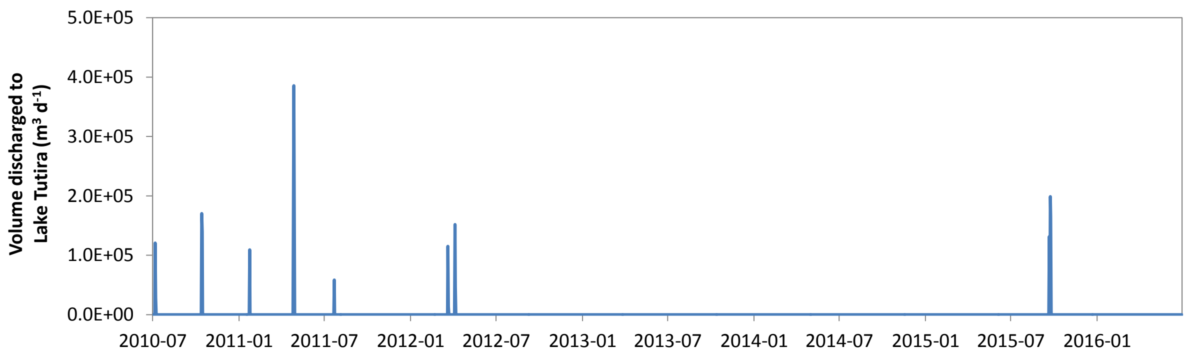


Appendix Figure 7. Summary of all instantaneous samples of water quality regressed against synthetic discharge at the Kahikanui Stream for A) total nitrogen, B) nitrate, C) total phosphorus, D) soluble reactive phosphorus and E) total suspended sediment.

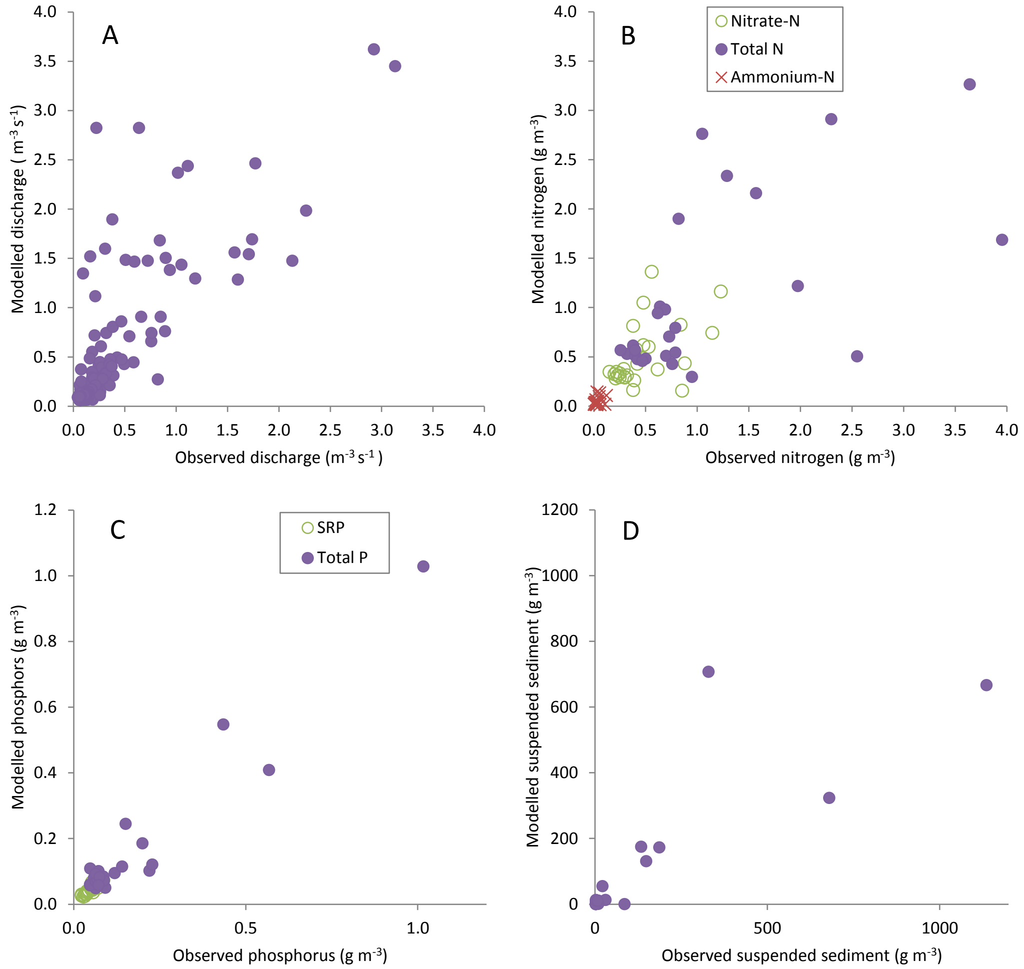
Catchment modelling



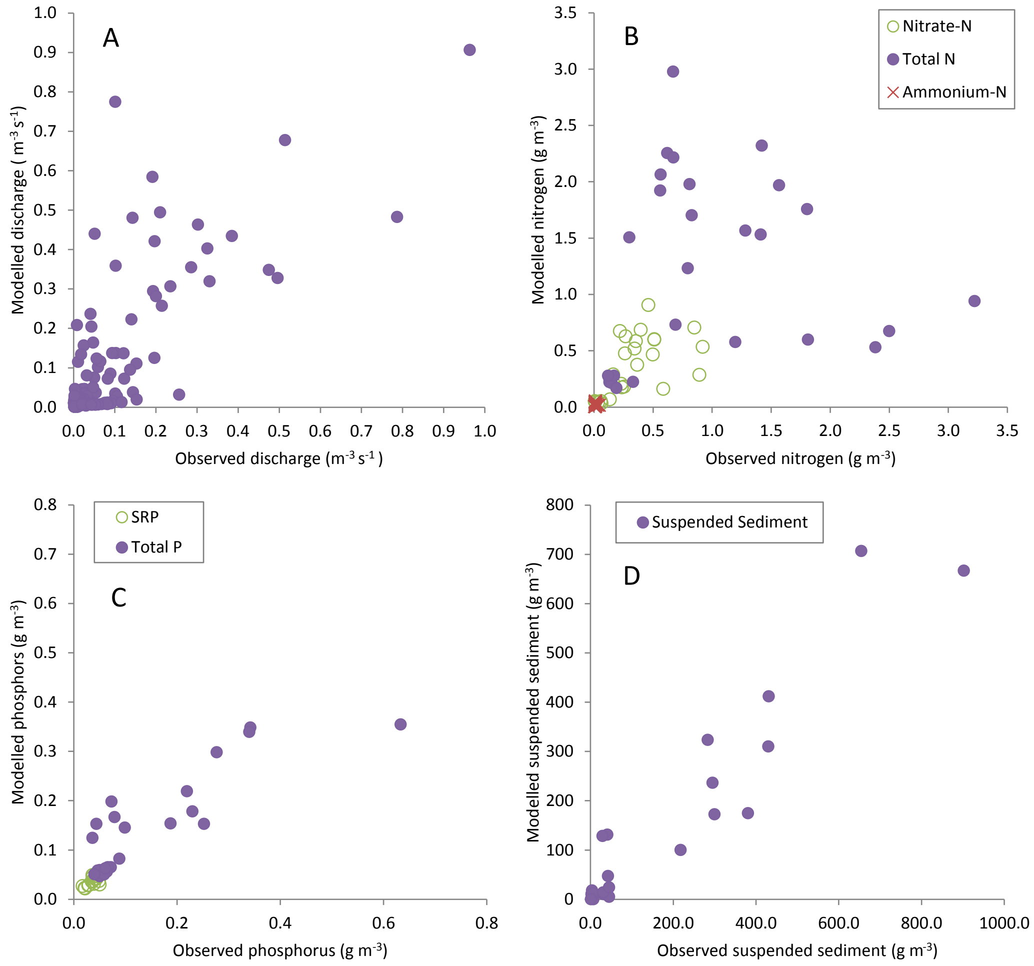
Appendix Figure 8. Meteorological inputs to the INCA-N catchment model.



Appendix Figure 9. Modelled daily discharge from Papakiri Stream directly into Lake Tutira under the baseline (C100) scenario, based on the assumption that flows over 5 m^3 s^{-1} flow back to the lake.

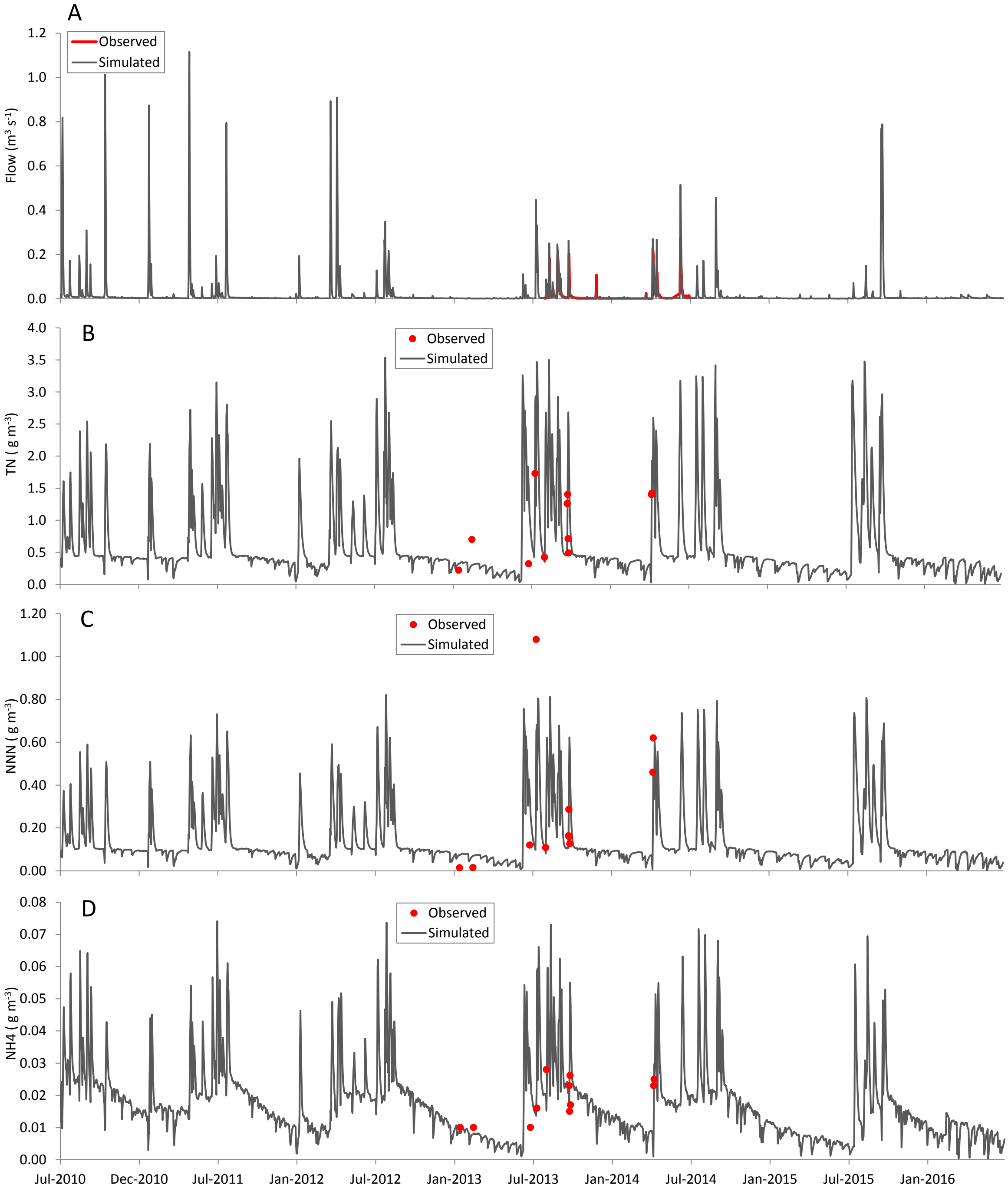


Appendix Figure 10. Modelled versus observed values for A) discharge, B) nitrogen, C) phosphorus and D) suspended sediment at Papakiri Stream.

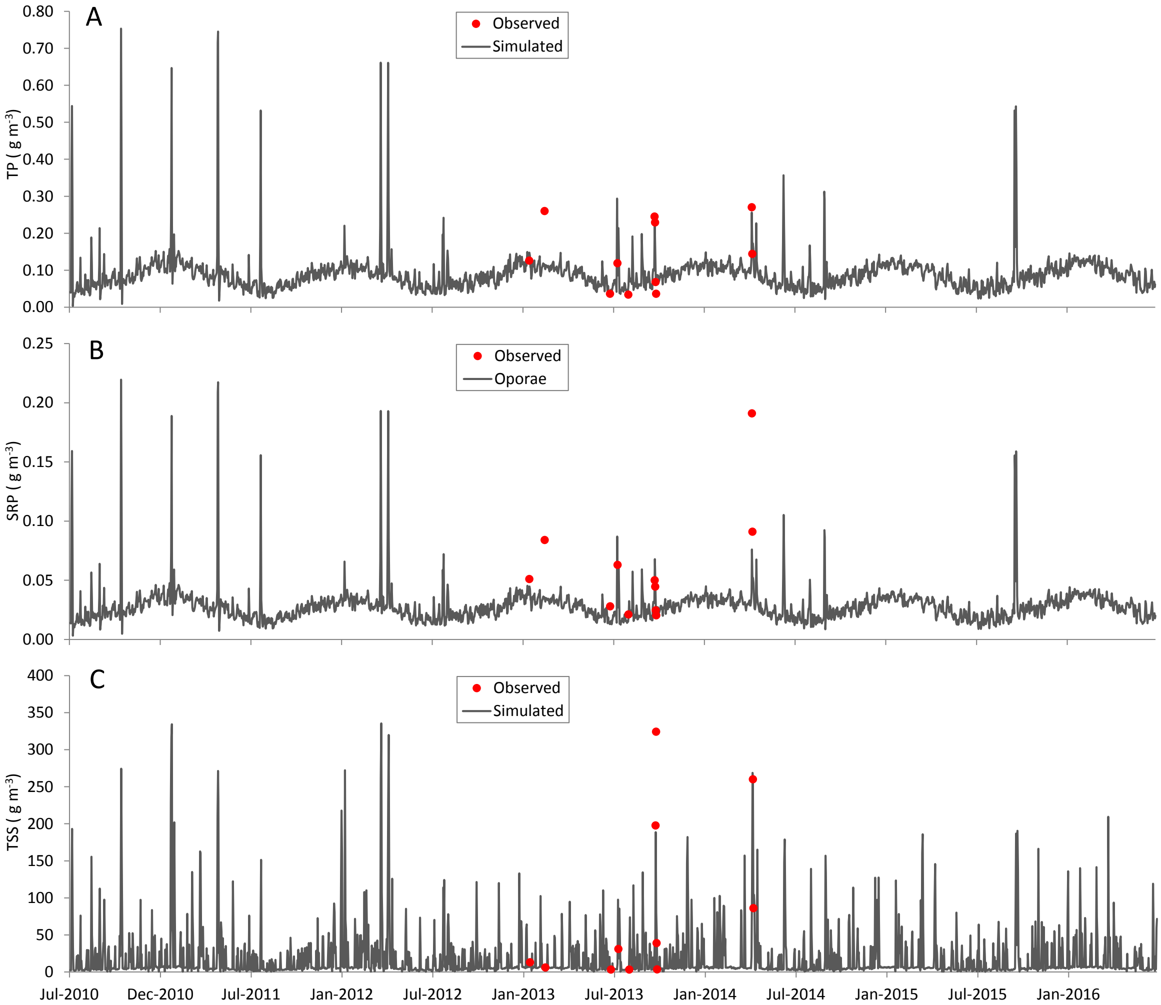


Appendix Figure 11. Modelled versus observed values for A) discharge, B) nitrogen, C) phosphorus and D) suspended sediment at Kahikanui Stream.

Oporae Stream



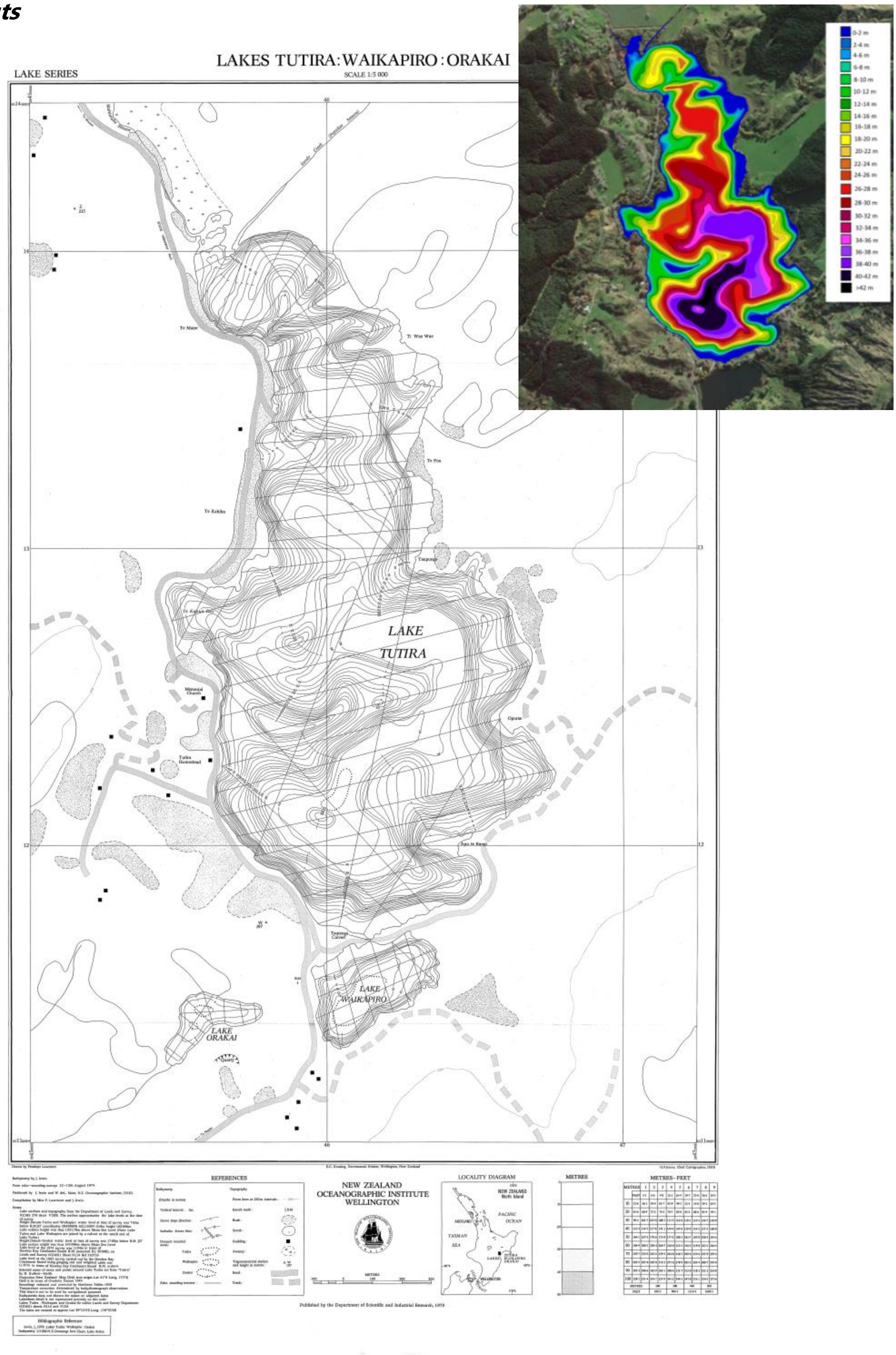
Appendix Figure 12. Modelling of the Oporae Stream for A) discharge, B) total nitrogen, C) nitrate and D) ammonium.



Appendix Figure 13. Modelling of Kahikanui Stream for A) total phosphorus, B) soluble reactive phosphorus, and C) suspended sediment.

Lake modelling

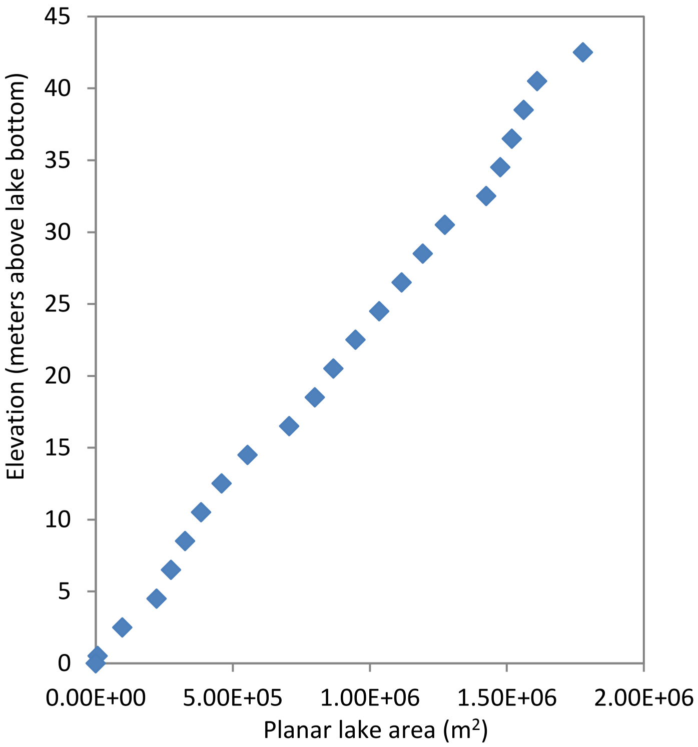
Model inputs

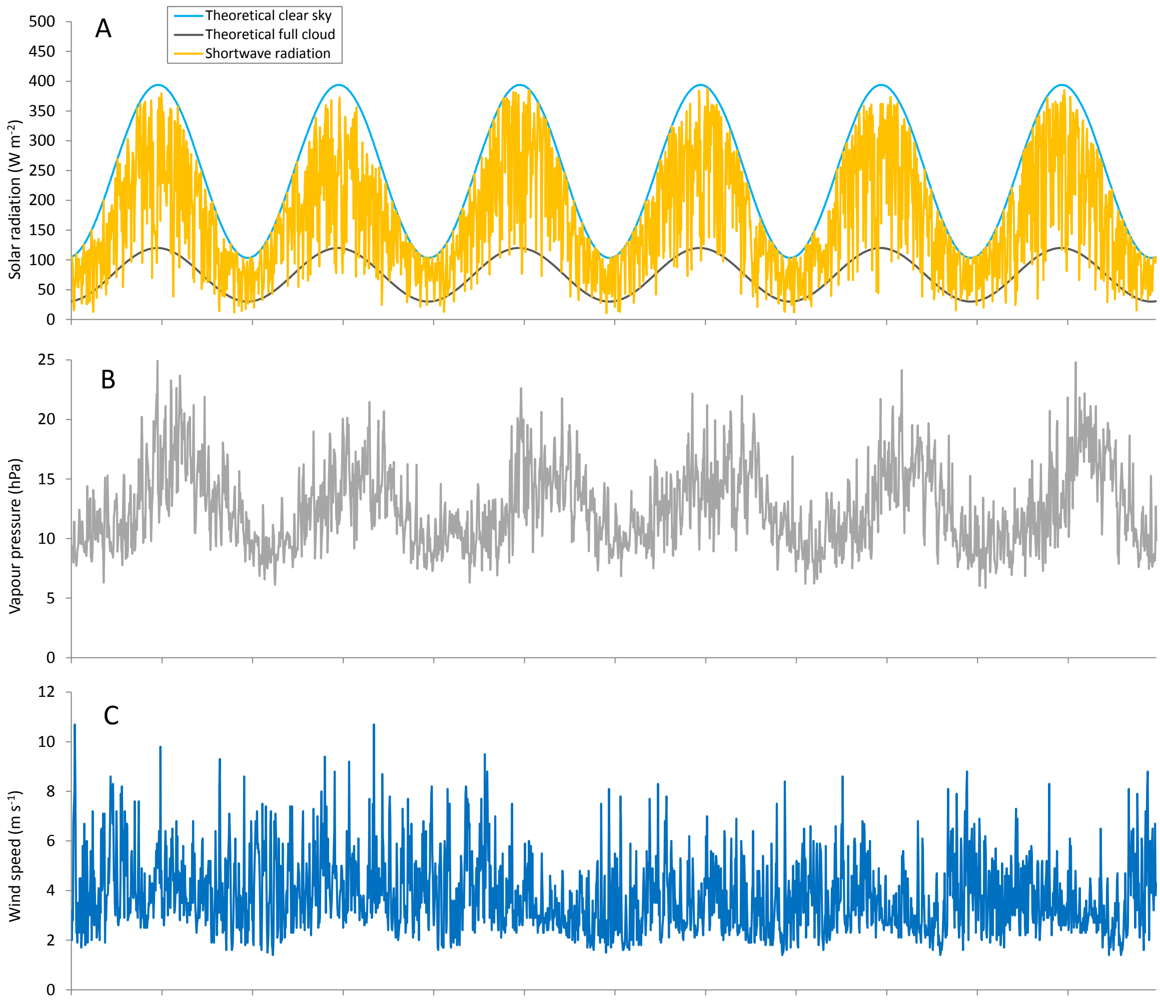


Appendix Figure 14. Bathymetry of Lake Tutira (reproduced from Irwin 1977). Inset: digitised bathymetry used in the present study.

Appendix Table 2. Bathymetric planar area and volume by depth from surface. Calculated by digitisation of bathymetry presented by Irwin 1978.

Depth (m)	Planar area (m^2)	Volume at contour (m^3)
42.5	1.7782E+06	3.7480E+07
40.5	1.6113E+06	3.4090E+07
38.5	1.5617E+06	3.0917E+07
36.5	1.5184E+06	2.7837E+07
34.5	1.4760E+06	2.4843E+07
32.5	1.4243E+06	2.1943E+07
30.5	1.2742E+06	1.9244E+07
28.5	1.1939E+06	1.6776E+07
26.5	1.1164E+06	1.4466E+07
24.5	1.0344E+06	1.2315E+07
22.5	9.4794E+05	1.0333E+07
20.5	8.6703E+05	8.5177E+06
18.5	7.9901E+05	6.8516E+06
16.5	7.0598E+05	5.3466E+06
14.5	5.5378E+05	4.0869E+06
12.5	4.5905E+05	3.0740E+06
10.5	3.8439E+05	2.2306E+06
8.5	3.2643E+05	1.5198E+06
6.5	2.7413E+05	9.1923E+05
4.5	2.2181E+05	4.2329E+05
2.5	9.6913E+04	1.0456E+05
0.5	6.9132E+03	7.3831E+02
0	0.0000E+00	0.0000E+00





Appendix Figure 15. Meteorological inputs to the lake models. Data obtained with permission, by HBRC from NIWA's Virtual Climate Network. For air temperature and rainfall data refer to Appendix figure 8.

Model calibration

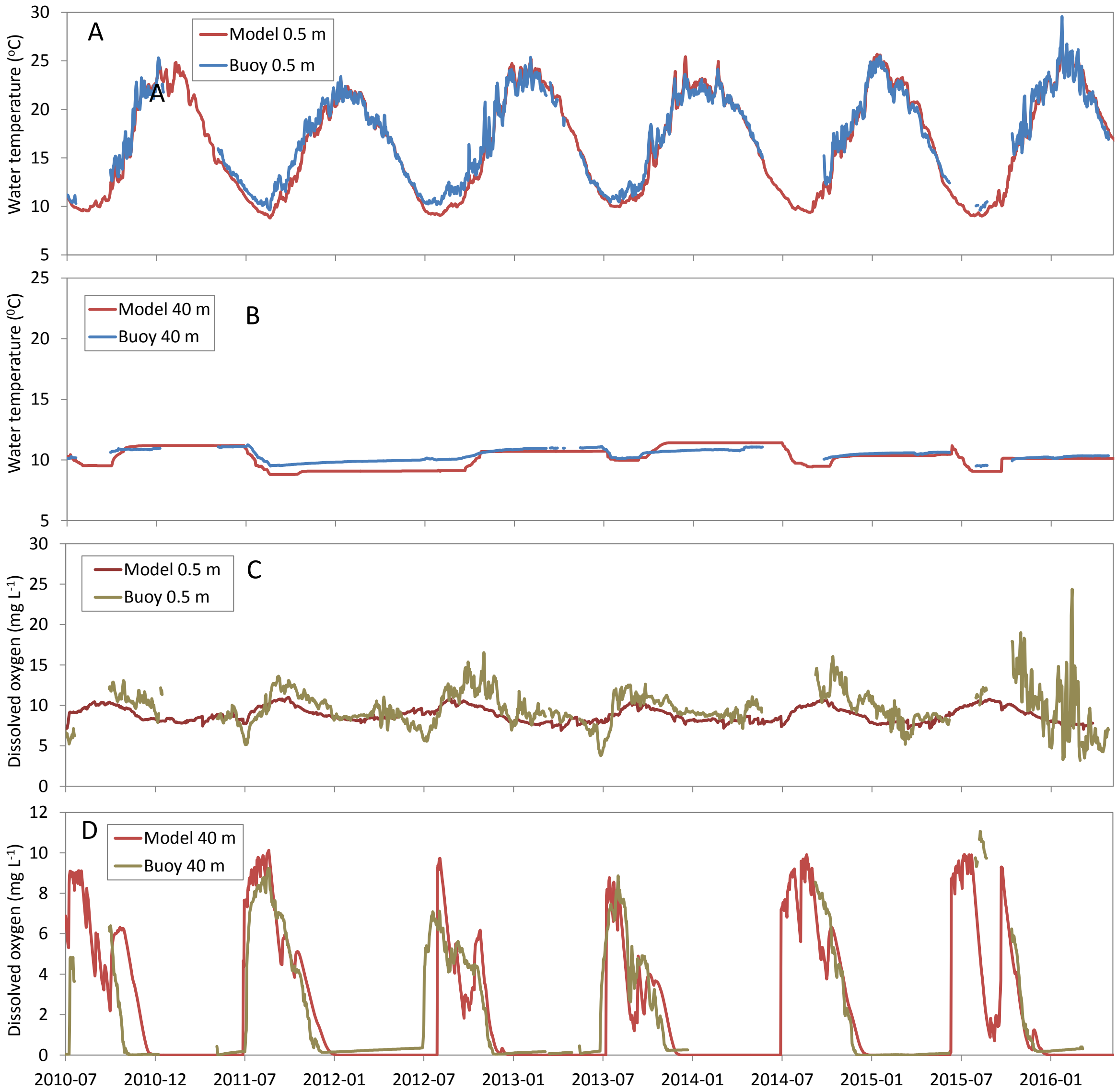
Appendix Table 3. Assigned values for parameters used in DYRESM.

Parameter	Unit	Calibrated value	Reference
Critical wind speed	m s^{-1}	3.0	Best fit to data
Emissivity of water surface	-	0.95	Imberger & Patterson (1981)
Mean albedo of water	-	0.08	Patten et al. (1975)
Potential energy mixing efficiency	-	0.15	Spigel et al. (1986)
Shear production efficiency	-	0.2	Best fit to data
Wind stirring efficiency	-	0.4	Best fit to data
Vertical mixing coefficient	-	200	Best fit to data
Effective surface area coefficient	m^2	1.8×10^6	Best fit to data

Appendix Table 4. Assigned values used in CAEDYM for Lake Tikitapu; DOPL and DONL are dissolved organic phosphorus and nitrogen, respectively.

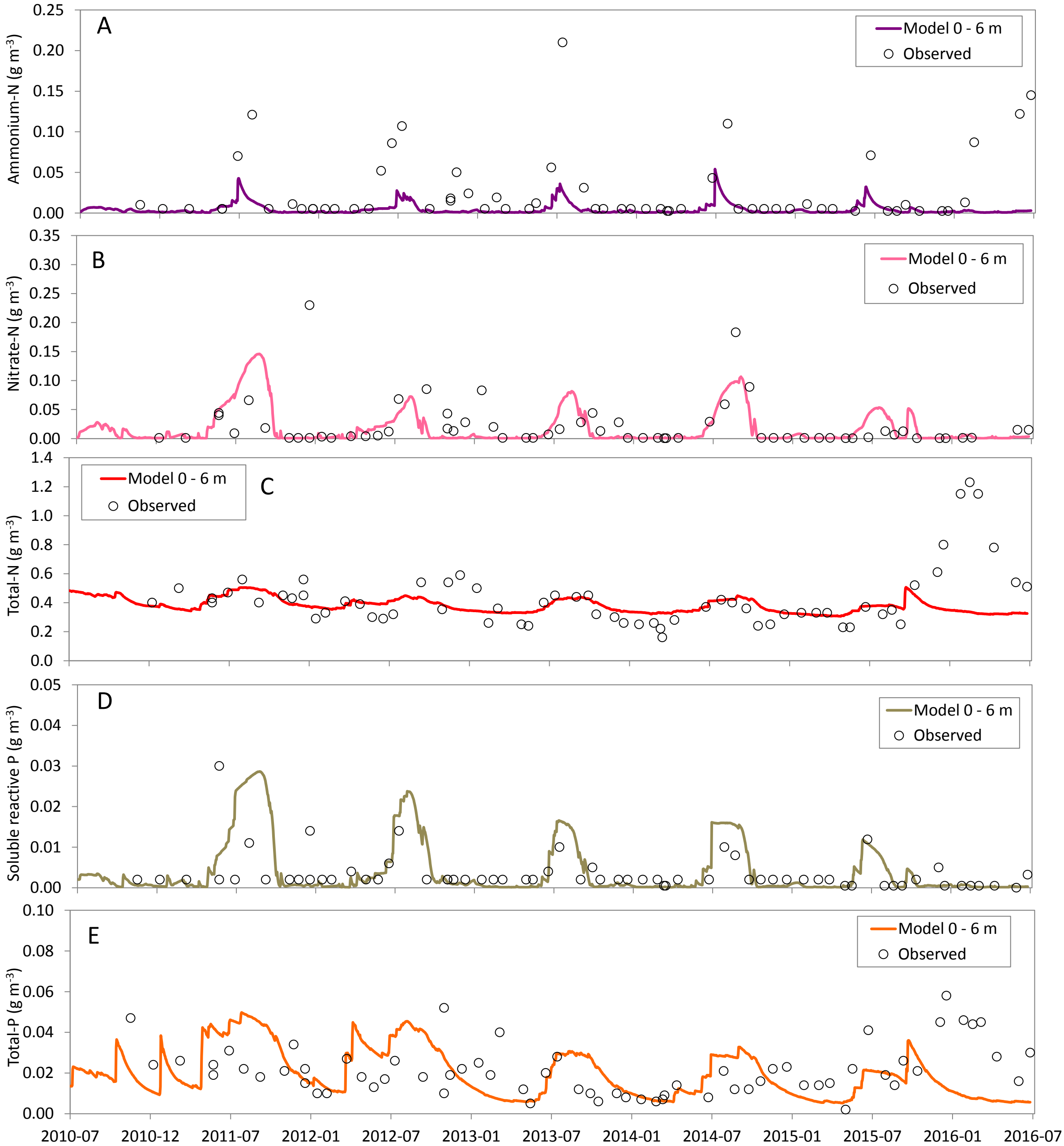
Parameter	Unit	Calibrated value	Reference source
Sediment parameters			
Sediment oxygen demand	g m^{-2} d^{-1}	0.5	Schladow & Hamilton (1997)
Half-saturation coefficient for sediment oxygen demand	mg L^{-1}	0.5	Schladow & Hamilton (1997)
Maximum potential PO_4 release rate	g m^{-2} d^{-1}	0.0003	Best fit to data
Oxygen and nitrate half-saturation for release of phosphate from bottom sediments	g m^{-3}	0.5	Best fit to data
Maximum potential NH_4 release rate	g m^{-2} d^{-1}	0.002	Best fit to data
Oxygen half-saturation constant for release of ammonium from bottom sediments	g m^{-3}	0.2	Best fit to data
Maximum potential NO_3 release rate	g m^{-2} d^{-1}	-0.01	Best fit to data
Oxygen half-saturation constant for release of nitrate from bottom sediments	g m^{-3}	0.9	Best fit to data
Maximum potential Si release rate	g m^{-2} d^{-1}	0.018	Best fit to data
Oxygen half-saturation constant for release of silica from bottom sediments	g m^{-3}	8.0	Best fit to data
Temperature multiplier for nutrient release	-	1.05	Robson & Hamilton (2004)
Nutrient parameters			
Decomposition rate of POPL to DOPL	d^{-1}	0.001	Best fit to data
Mineralisation rate of DOPL to PO_4	d^{-1}	0.008	Best fit to data
Decomposition rate of PONL to DONL	d^{-1}	0.001	Best fit to data
Mineralisation rate of DONL to NH_4	d^{-1}	0.002	Best fit to data
Denitrification rate coefficient	d^{-1}	0.03	Best fit to data
Oxygen half-saturation constant for denitrification	mg L^{-1}	1.5	Best fit to data
Temperature multiplier for denitrification	-	1.07	Best fit to data
Nitrification rate coefficient	d^{-1}	0.07	Schladow & Hamilton (1997)
Nitrification half-saturation constant for oxygen	mg L^{-1}	5.0	Schladow & Hamilton (1997)
Temperature multiplier for nitrification	-	1.08	Best fit to data
Phytoplankton parameters		**Diatoms, chlorophytes**	
Maximum potential growth rate at 20°C	d^{-1}	1.11, 1.15	Best fit to data
Irradiance parameter non-photoinhibited growth	µmol m^{-2} s^{-1}	15, 100	Schladow & Hamilton (1997)
Half saturation constant for phosphorus uptake	mg L^{-1}	0.003, 0.003	Best fit to data
Half saturation constant for nitrogen uptake	mg L^{-1}	0.01, 0.01	Best fit to data
Minimum internal nitrogen concentration	mg N (mg chl *a*)$^{-1}$	1.0, 3.0	Schladow & Hamilton (1997)
Maximum internal nitrogen concentration	mg N (mg chl *a*)$^{-1}$	9.0, 10.0	Schladow & Hamilton (1997)
Maximum rate of nitrogen uptake	mg N (mg chl *a*)$^{-1}$ d^{-1}	0.8, 1.5	Schladow & Hamilton (1997)
Minimum internal phosphorus concentration	mg P (mg chl *a*)$^{-1}$	0.1, 0.1	Schladow & Hamilton (1997)
Maximum internal phosphorus concentration	mg P (mg chl *a*)$^{-1}$	2.0, 2.0	Schladow & Hamilton (1997)
Maximum rate of phosphorus uptake	mg P (mg chl *a*)$^{-1}$ d^{-1}	0.25, 0.15	Schladow & Hamilton (1997)
Constant internal silica concentration	mg Si (mg chl *a*)$^{-1}$	180.0, 0.0	
Half saturation constant for silica uptake	mg L^{-1}	0.2, 0.0	Martin-Jezequel et al (2000)
Temperature multiplier for growth limitation	-	1.04, 1.06	Schladow & Hamilton (1997)
Standard temperature for growth	°C	14.0, 18.0	Coles & Jones (2000)
Optimum temperature for growth	°C	22.0, 25.0	Coles & Jones (2000)
Maximum temperature for growth	°C	31.0, 38.0	Coles & Jones (2000)
Respiration rate coefficient	d^{-1}	0.08, 0.1	Schladow & Hamilton (1997)
Temperature multiplier for respiration	-	1.06, 1.06	Schladow & Hamilton (1997)
Fraction of respiration relative to total metabolic loss rate	-	0.7, 0.7	
Fraction of metabolic loss rate that goes to DOM	-	0.7, 0.7	
Constant settling velocity	m s^{-1}	-1.0×10^{-5}, -2.3×10^{-6}	Modified from: Burger et al. (2007a)

Temperature and oxygen



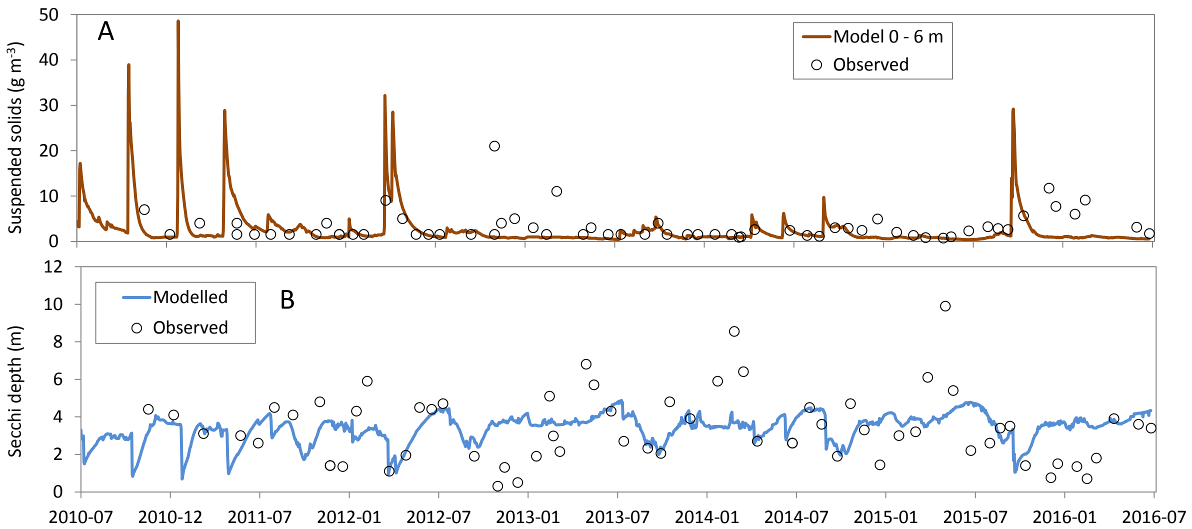
Appendix Figure 16. Comparison of model simulations at fixed depths with corresponding measurements from the Lake Tutira monitoring buoy, for A) surface water temperature, B) bottom water temperature, C) surface dissolved oxygen and D) bottom dissolved oxygen.

Nutrients



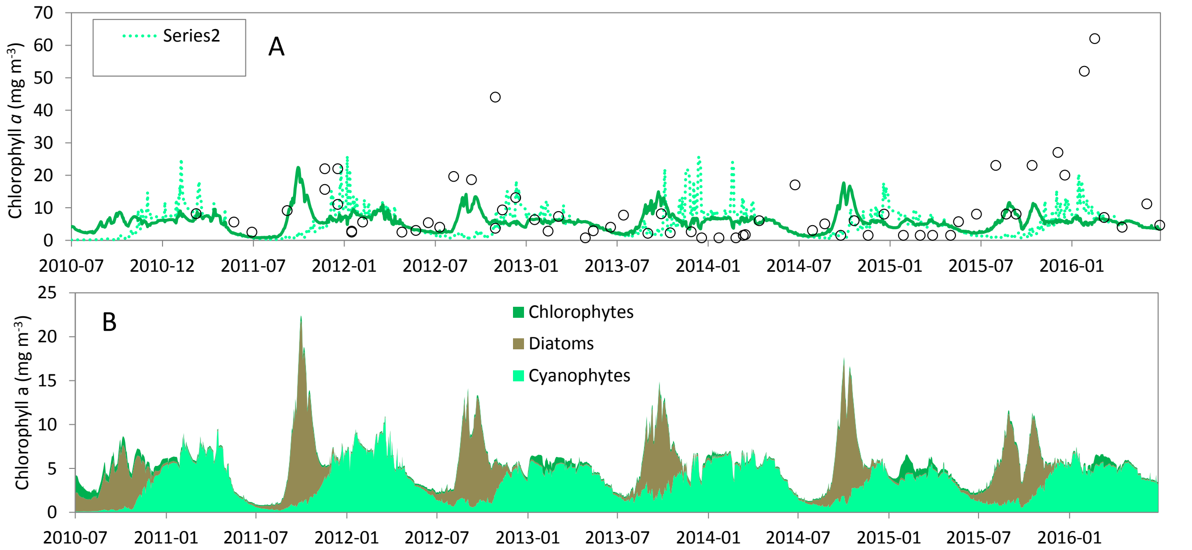
Appendix Figure 17. Comparison of model simulations (lines) and field observations (dots) over an integrated depth range of c. 0 – 6 m, for A) ammonium, B) nitrate, C) total nitrogen, D) soluble reactive phosphorus and E) total phosphorus.

Suspended solids and clarity



Appendix Figure 18. Comparison of model simulations (lines) and field observations (dots) over an integrated depth range of c. 0 – 7 m, for A) total suspended solids, and B) Secchi depth. Modelled Secchi depth was estimated from light attenuation derived from multiple model outputs.

Phytoplankton



Appendix Figure 19. A) Comparison of model simulations (lines) and field observations (dots) over an integrated depth range of c. 0 – 6 m for total chlorophyll *a*. The dashed line is the modelled surface water concentration of cyanobacteria. B) Modelled species composition of phytoplankton over integrated surface depths.

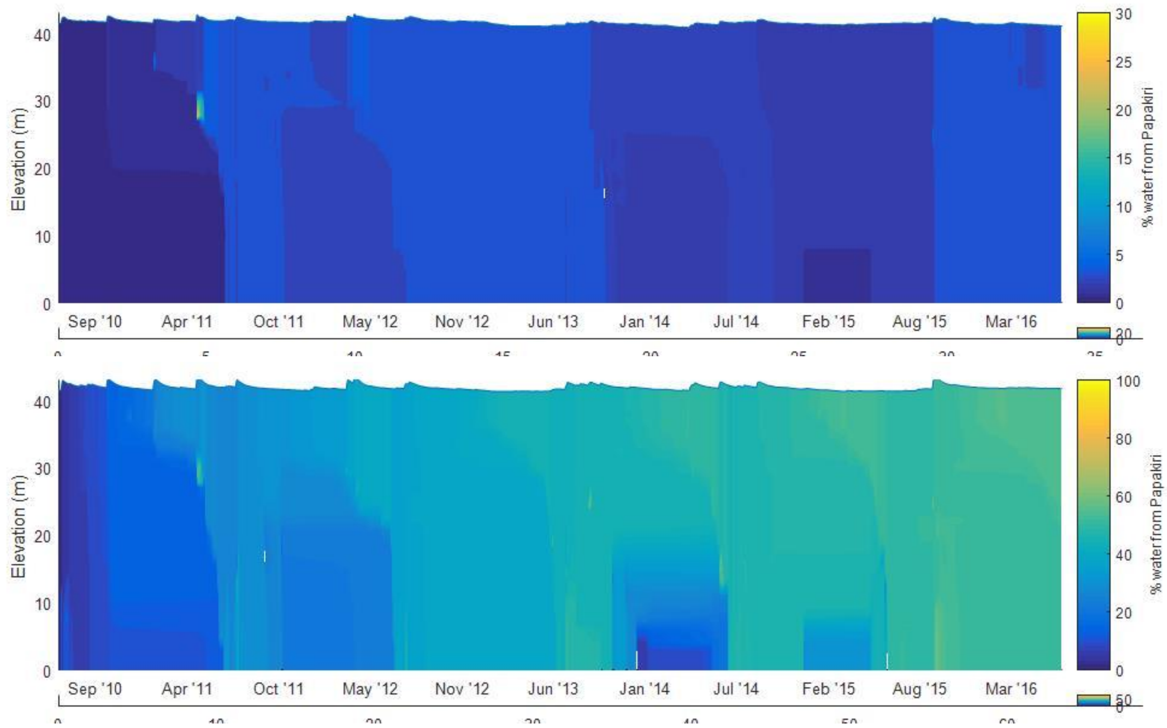
Model performance

Appendix Table 5. Statistical comparison between model simulations and field data (monthly measurements) for samples from all depths in Lake Tutira using Pearson correlation coefficient (R), mean absolute error (MAE), and root mean squared error (RMSE), for the period July 2010 to June 2015.

Variable	Temp (s)	Temp (b)	DO (s)	DO (b)	NH4	NNN	TN	SRP	TP	TSS	chl a	Secchi
Summary statistics												
Mean observation	17.101	10.460	9.607	2.039	0.025	0.025	0.360	0.003	0.018	2.872	6.390	3.566
Mean model	16.756	10.212	8.799	2.175	0.018	0.005	0.374	0.004	0.020	2.164	5.531	3.480
St. Dev. obs.	4.369	0.449	1.949	2.727	0.041	0.045	0.103	0.003	0.011	3.315	6.249	1.997
St. Dev. mod.	4.902	0.866	0.898	2.892	0.029	0.008	0.044	0.006	0.012	3.413	2.571	0.682
Model error statistics												
Pearson R	0.988	0.922	0.632	0.802	0.614	0.069	0.555	0.627	0.276	0.228	-0.009	0.253
Mean Absolute Error	0.767	0.456	1.417	1.013	0.018	0.023	0.069	0.003	0.011	2.109	5.144	1.486
Mean Bias Error	-0.345	-0.248	-0.807	0.136	-0.008	-0.020	0.014	0.001	0.001	-0.708	-0.859	-0.086
Root-Mean-Square Error	0.930	0.297	3.043	3.165	0.001	0.002	0.008	0.000	0.000	17.622	45.762	3.696
Normalised errors												
NMAE	0.045	0.044	0.148	0.497	0.724	0.925	0.190	0.912	0.594	0.734	0.805	0.417
NMBE	-0.020	-0.024	-0.084	0.067	-0.303	-0.812	0.038	0.158	0.071	-0.246	-0.134	-0.024
NRMSE	0.054	0.028	0.317	1.553	0.043	0.096	0.021	0.008	0.010	6.136	7.162	1.036

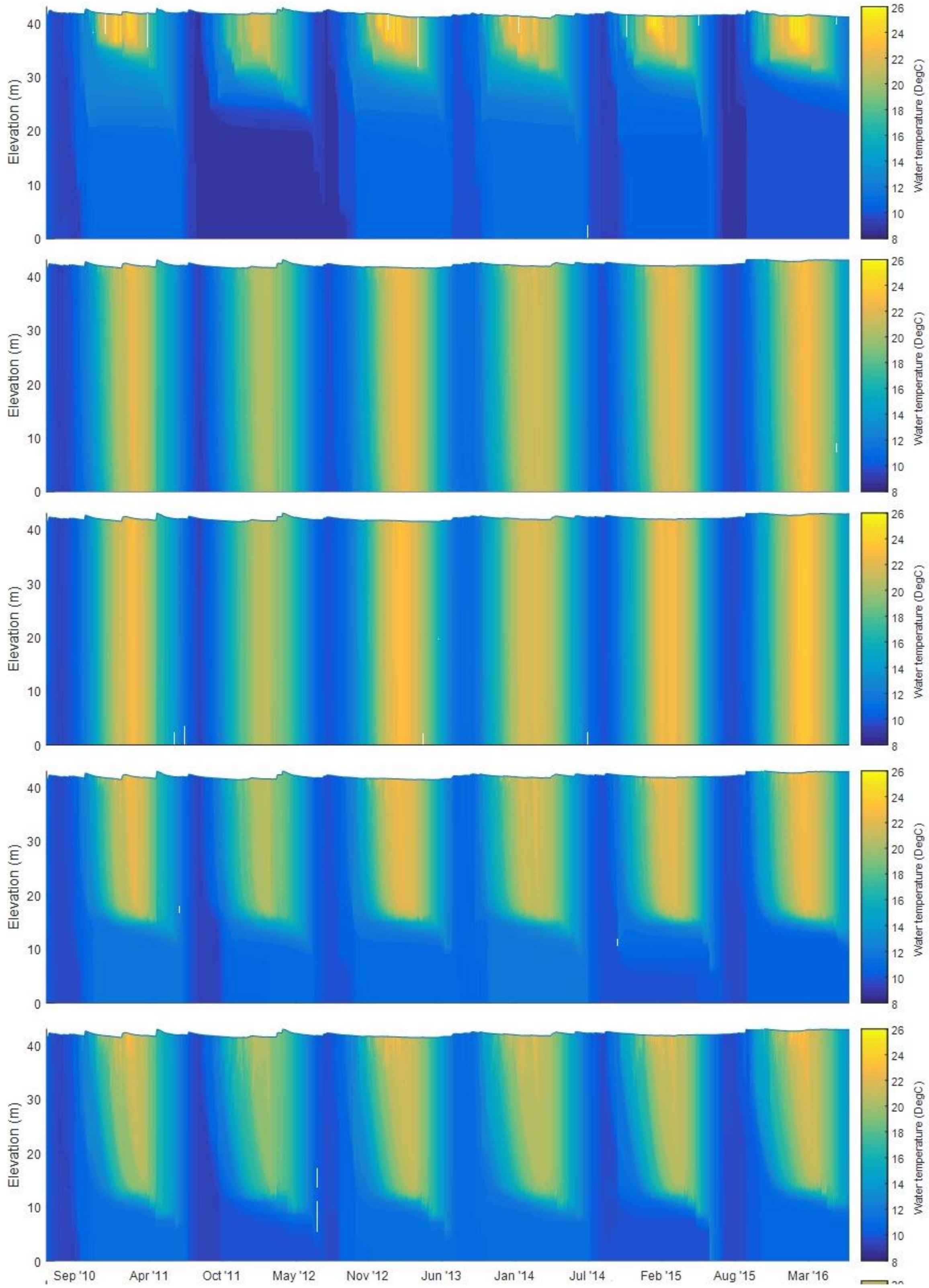
Scenario modelling

Sandy Creek diversion

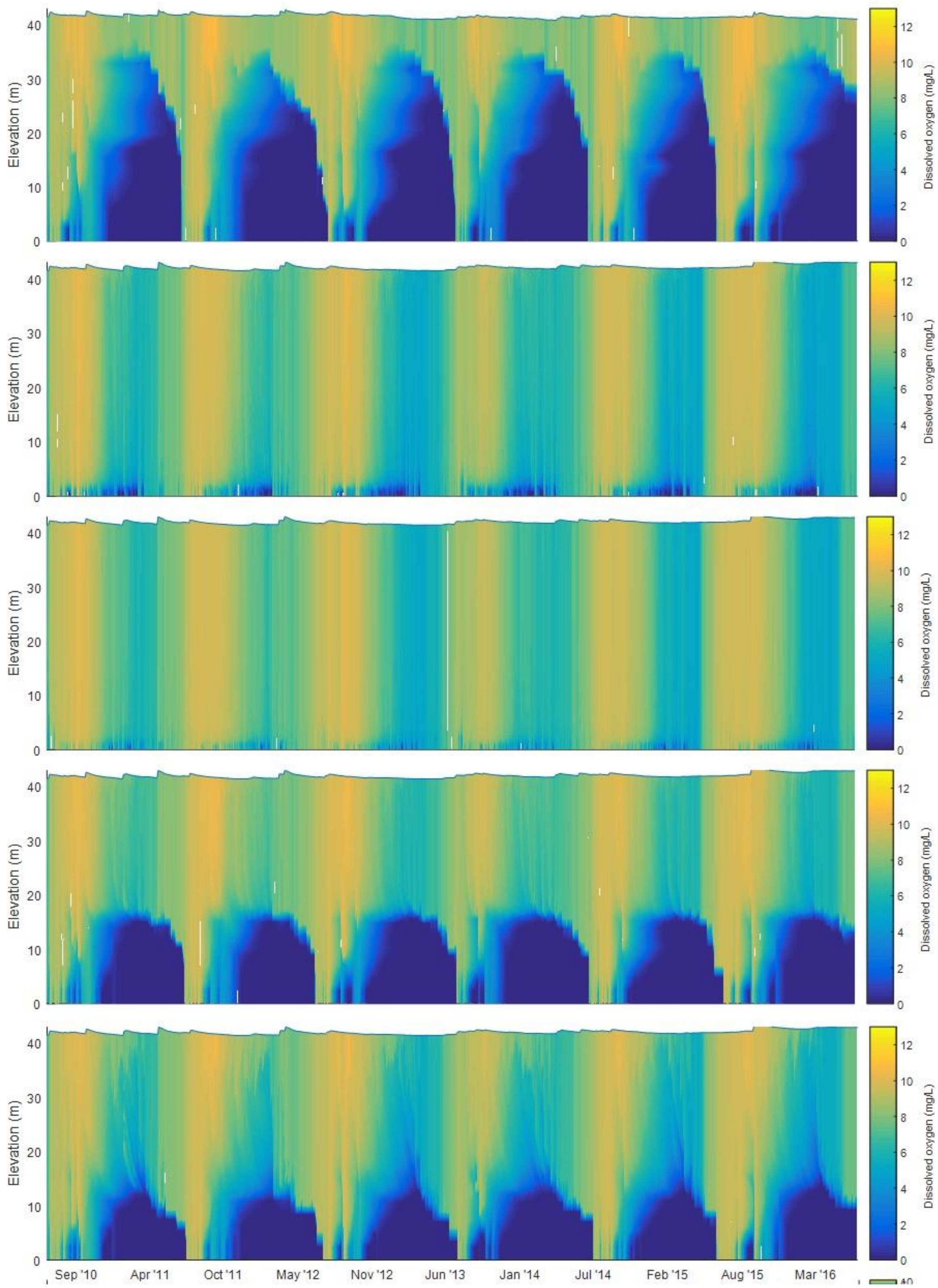


Appendix Figure 20.. Comparison of inflow Papakiri Creek water tracer concentration with and without rediversion of water to the lake. A) scenario C100 (baseline) and B) C100_P100 (full rediversion). NOTE: different colour scale between scenarios.

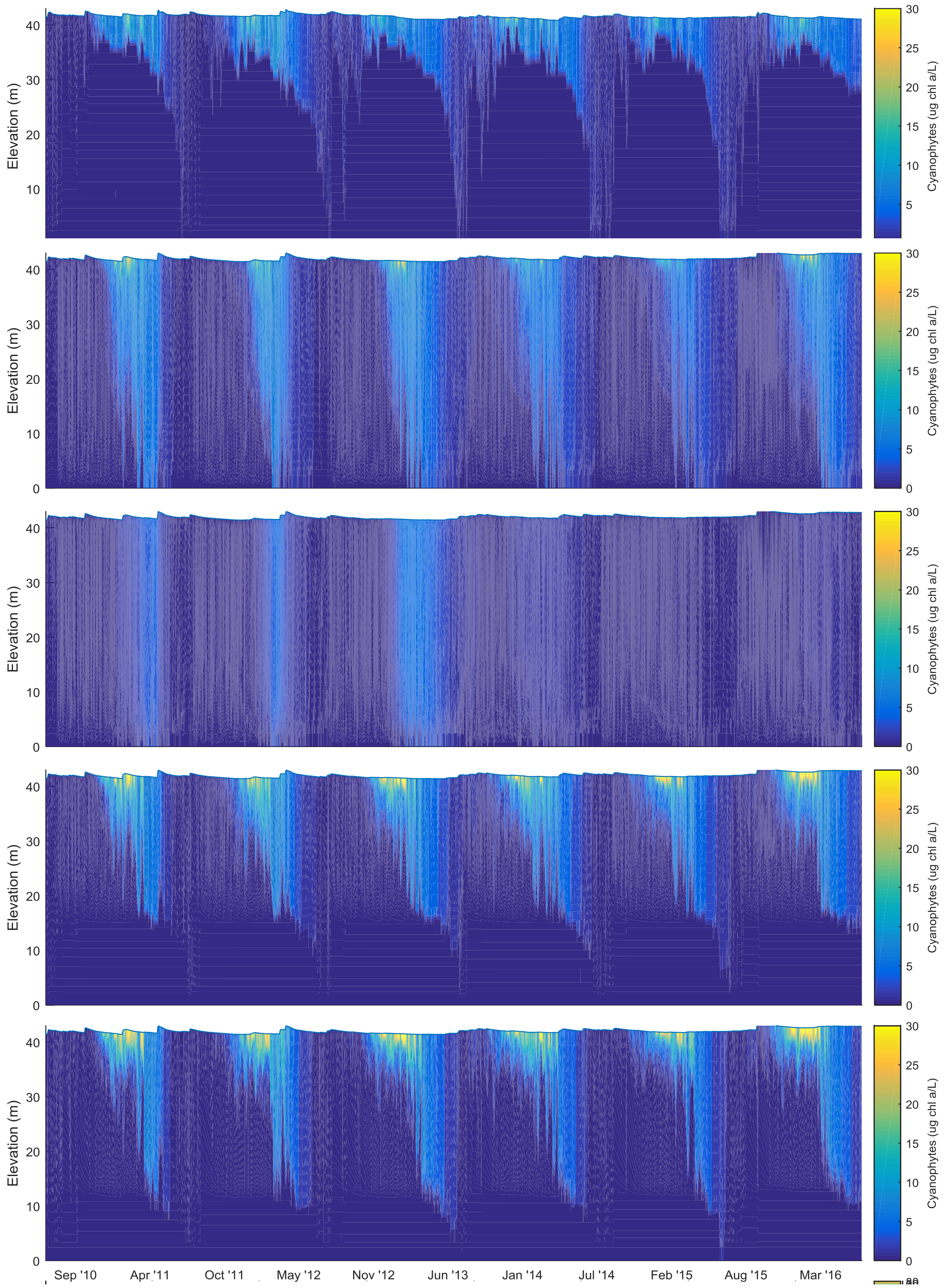
Aeration and artificial mixing



Appendix Figure 21. Colour contour plots of temperature for aeration and mixing scenarios A) C100 (baseline), B) C100_bub.d100, C) C100_bub.d500, D) C100_bub.m100, and E) C100_imp.m10.

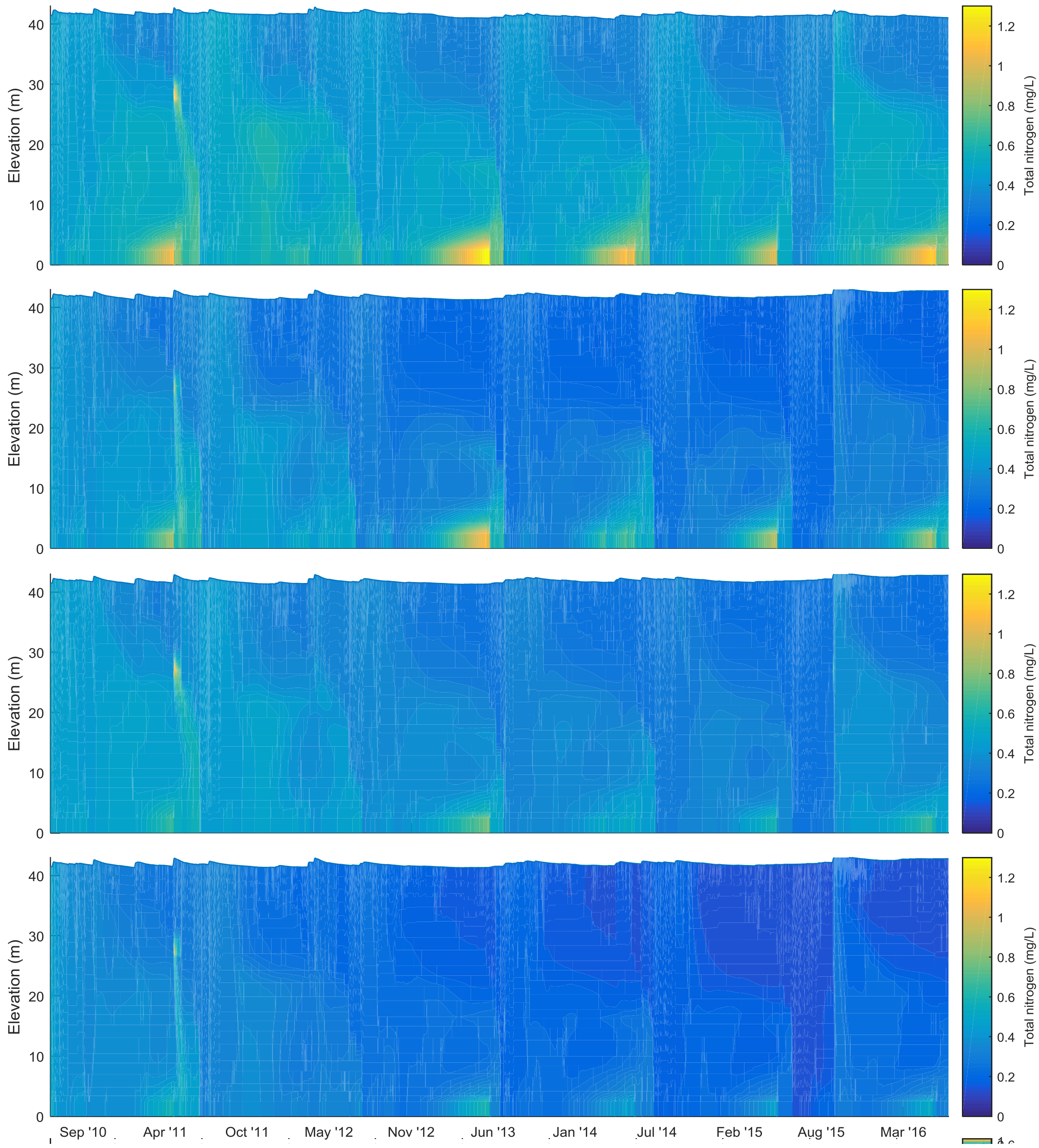


Appendix Figure 22. Colour contour plots of dissolved oxygen for aeration and mixing scenarios A) C100 (baseline), B) C100_bub.d100, C) C100_bub.d500, D) C100_bub.m100, and E) C100_imp.m10.

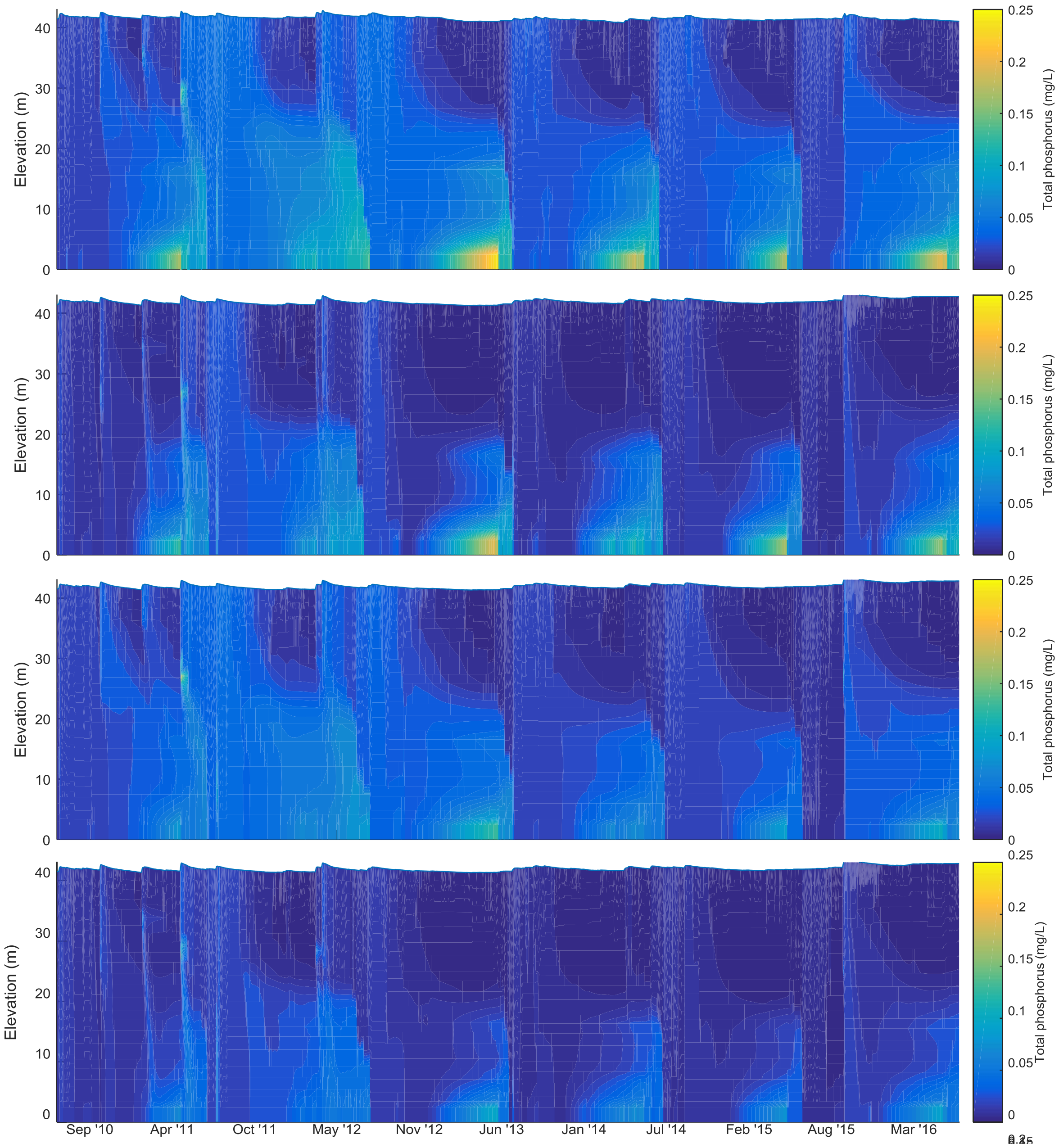


Appendix Figure 23. Colour contour plots of cyanobacteria concentration for aeration and mixing scenarios A) C100 (baseline), B) C100_bub.d100, C) C100_bub.d500, D) C100_bub.m100, and E) C100_imp.m10.

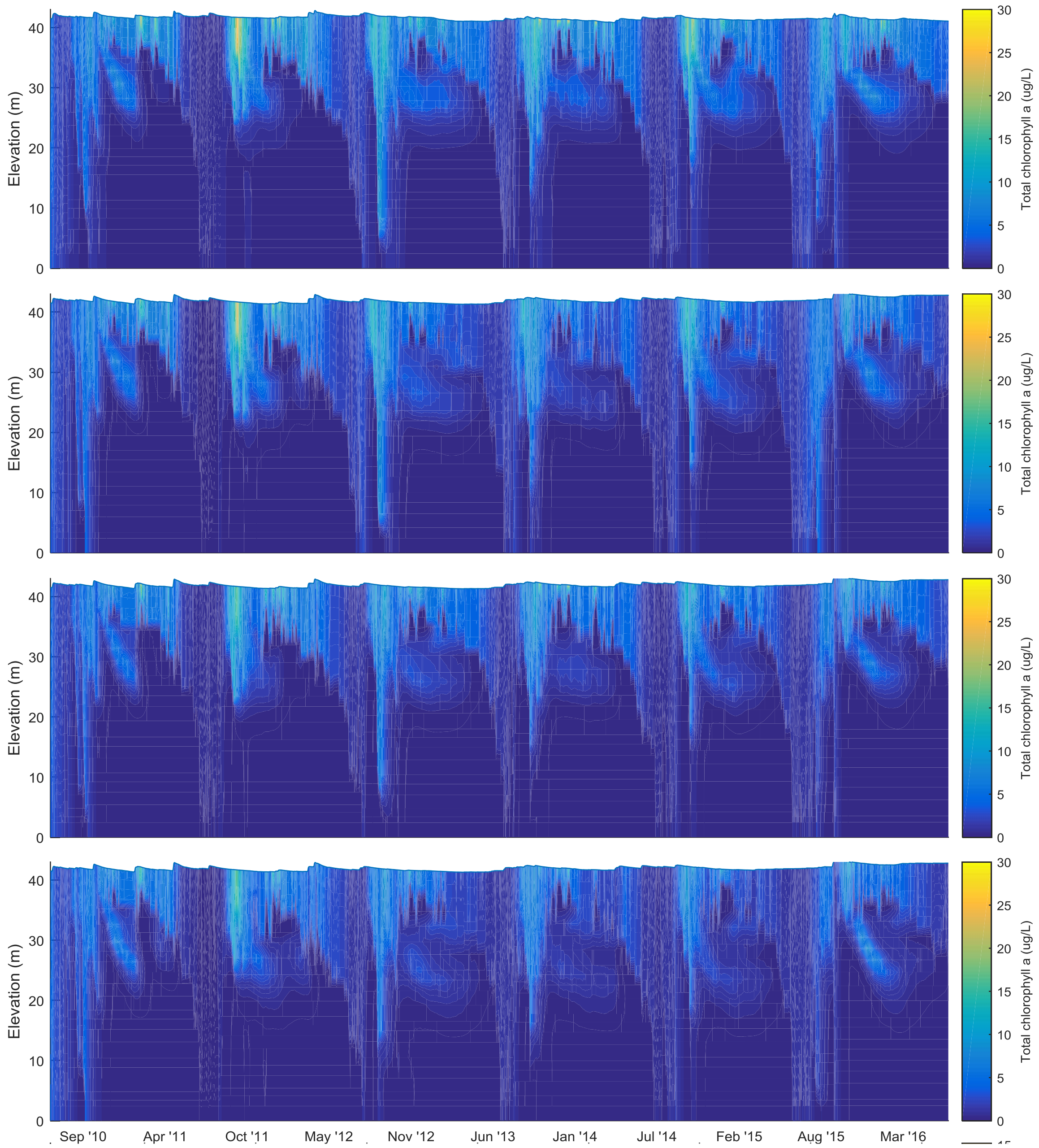
Flocculation and sediment capping



Appendix Figure 24. Colour contour plots of total nitrogen, for scenarios A) C100 (baseline), B) C100_floc, C) C100_cap, and D) C100_floc.cap.

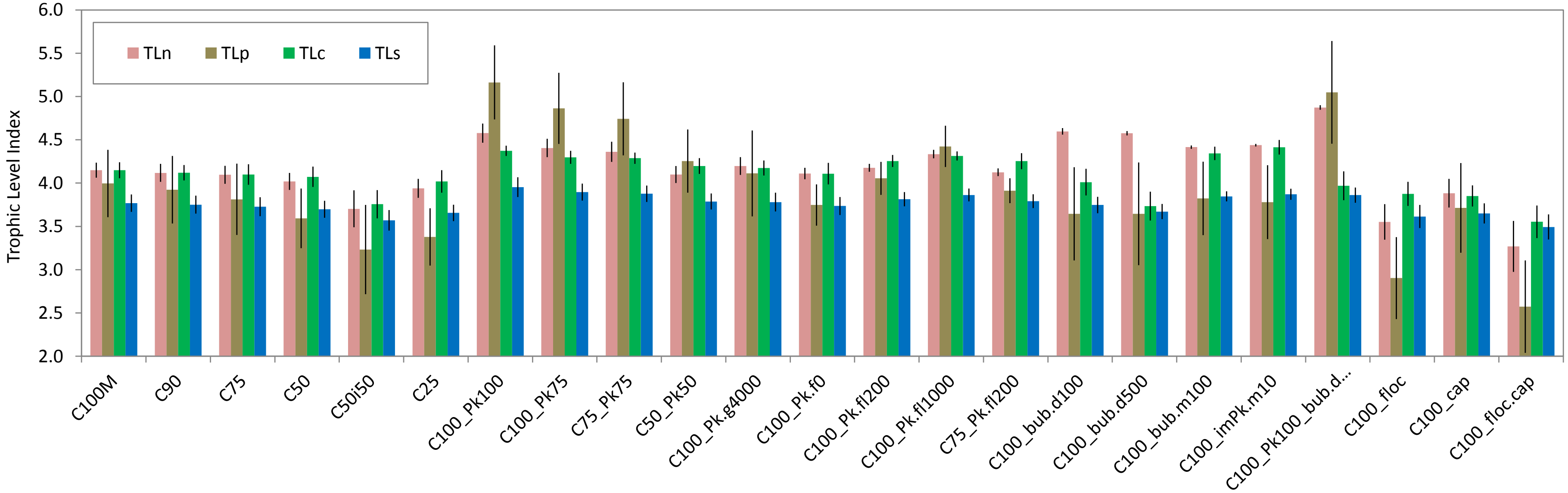


Appendix Figure 25. Colour contour plots of total phosphorus, for scenarios A) C100 (baseline), B) C100_floc, C) C100_cap, and D) C100_floc.cap.



Appendix Figure 26. Colour contour plots of total chlorophyll, for scenarios A) C100 (baseline), B) C100_floc, C) C100_cap, and D) C100_floc.cap.

Scenario summary



Appendix Figure 27. Summary of results for individual trophic level component (nitrogen (TLn), phosphorus (TLp), chlorophyll (TLc) and Secchi depth (TLs)) for all scenario simulations over the period July 2011 to June 2015.

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