LAKE WAIKARE WATER QUALITY MODELING: USING A NEW MODEL TO INVESTIGATE FLUSHING STRATEGIES

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ABSTRACT

Numerical modeling was used to investigate the potential impacts of a proposed river water flushing scheme on Lake Waikare water quality. The proposed scheme would divert large volumes of Waikato River water into Lake Waikare to provide flushing for lake nutrients and phytoplankton. To investigate the effectiveness of such a scheme, a lake water quality model was constructed and calibrated using the best available data and information. To support this work, and to augment the existing water quality data set, lake sediment and tributary water sampling was undertaken. The model calibration exercise helped better define and understand existing lake water quality dynamics and highlighted the large impact of catchment agriculture on lake water quality. The calibrated model was then used to simulate three predictive scenarios representing proposed flushing options at three different flushing rates (5, 25, and 50 m^3/s). Results indicate the potential for significant reductions in nutrient and phytoplankton concentrations in the lake, and improvements in overall lake trophic status, as a result of the proposed flushing strategies. The caveat to these results, however, is that the quantified mitigation represents only a displacement of pollutant load (to downstream waterways) rather than true mitigation of the problem source (catchment agricultural runoff).

KEYWORDS

water quality model, eutrophication, nutrients, sediment nutrient flux, mitigation, flushing

1 INTRODUCTION

Waikato District Council (WDC) operates the Te Kauwhata Wastewater Treatment Plant (TKWWTP) which discharges treated wastewater to Lake Waikare. As part of the renewal of the discharge consent for treated wastewater, WDC agreed to investigate the potential improvement in Lake Waikare's water quality that could be obtained by flushing the lake with flows from the Waikato River. The study described here investigates the efficacy of river water flushing as an option for improving Lake Waikare water quality using predictive modelling.

Lake Waikare is a shallow (average depth ~1.5 – 2 m), but relatively large (36 km^2) waterbody with a large agricultural drainage area (210 km^2). The catchment drains to the lake via a series of small tributaries, the largest of which is Matahuru Stream. This stream drains approximately half of the entire lake catchment.

Waikare is a hypertrophic lake, which means it is highly enriched with nutrients with large phytoplankton blooms throughout the year. A previous study (Vant, 2008) estimated that the vast majority of the lake nutrient inputs (c. 99% nitrogen, 95% phosphorus) come from the wider catchment landuse (dairy, sheep and beef farming), compared to the TKWWTP contributions. In addition, Vant (2008) was also of the view that the lake sediments are a 'reservoir' of nutrients from the collapse of macrophyte beds, which occurred in the 1970s. Consequently, these sediments would serve as an internal source of nutrients to the lake and would likely remain as such for an unknown period even if catchment loads were reduced.

As Waikato River nutrient concentrations are significantly lower than those observed in the lake, flushing it with large volumes of River water, on a continuous or near-continuous basis would theoretically benefit lake water quality in three ways: 1.) reducing water column nutrient concentrations via dilution, 2.) flushing existing polluted lake sediments and sediment-bound nutrients out of the lake, and 3.) inhibiting phytoplankton growth by reducing lake residence times.

In this paper, we use a simulation model developed by the first author, to predict both long and short term effects on water quality for a suite of potential flushing rate scenarios. Results are intended to provide guidance to WDC in their assessment of this proposed alternative.

2 DATA

2.1 EXISTING DATA

Model construction was supported by existing data from a number of sources. These data include measured historical lake water column nutrient and phytoplankton concentrations, sediment nutrient concentrations, tributary inflow nutrient concentrations, and tributary flows. Additionally, published information on general lake morphology and operations was used to parameterize the model. A summary of existing data used in this analysis, and the sources of these data, is provided in **Table 1**. Monitoring site locations are shown in **Figure 1**. Two sites within the lake have been monitored, along with 5 tributary sites.

Observed total phosphorus concentrations have ranged from 0.03 to 1.1 mg L^{-1}, with an average concentration of 0.22 and a standard deviation of 0.15 mg L^{-1}. Total nitrogen concentrations have ranged from 0.6 to 5.2 mg L^{-1}, with an average concentration of 2.4 and a standard deviation of 1.0 mg L^{-1}. Both nutrient and phytoplankton concentrations are generally highest during the summer months and lowest during the winter. However, short-term concentration spikes for both exist throughout the year. Additionally, based on limited paired data from the two lake monitoring sites (not shown), there is evidence that the lake is well-mixed laterally. Given the shallow depth of the lake, it is also highly likely that it is well-mixed vertically. Lastly, the well-known "Redfield" ratio (c. 7:1 by mass) provides a basis for assessing nutrient limitation to algal growth in the lake. When observed ratios are higher than this, nitrogen is in excess and phosphorus can be assumed to be limiting phytoplankton growth. When ratios are lower than this threshold, phosphorus is in excess and nitrogen can be assumed to be limiting. Based on a cursory look at nitrogen to phosphorus ratios (N:P) in the Lake Waikare historical data, it appears that the lake shifts between N and P limitation through the period of record. However, it does appear to be predominantly P limited in recent years, with a change from predominantly N limitation to predominantly P limitation occurring in c. 2005.

Table 1. Summary of Available Existing Data.

Data Type	Period of Record	Average Values (± std dev)	Source of Data
Lake water quality (nutrients, phytoplankton)	1996 - 2014	TP: 0.22 ± 0.15 mg L^{-1} TKN: 2.4 ± 1.0 mg L^{-1} chl-a: 96 ± 69 µg L^{-1}	Waikato Regional Council
Lake depths	1988 - 2012	1.3 ± 0.1 m	Waikato Regional Council, Wildlands (2011)
Lake volume and surface area	-	43,000 m^3	Wildlands (2011)
Daily tributary inflows (Matahuru and Te Onetea)	1984 – 2014 (Matahuru); 2005 – 2014 (Te Onetea)	1.9 ± 2.8 cms (Matahuru) 1.7 ± 2.3 m^3/s (Te Onetea)	Waikato Regional Council
Tributary water quality (Matahuru only)	2000 - 2014	TP: 0.17 ± 0.14 mg L^{-1} TN: 1.5 ± 0.9 mg L^{-1}	Waikato Regional Council
Waikato River water quality	2010 (monthly)	TP: 0.07 mg L^{-1} TN: 0.8 mg L^{-1}	Waikato Regional Council (2010), average of Huntly and Mercer Bridge sites
Te Kauwhata WWTP effluent inputs	2008 - 2012	flow: 0.004 – 0.013 m^3/s TP load: 1.5 – 2.4 kg d^{-1} TN load: 1.2 – 7.9 kg d^{-1}	Environment Waikato
Lake sediment nutrient data	2004 (TP only), 2011 (TP and TN)	TP: 0.4 mg g^{-1} TN: 3.0 mg g^{-1}	Waikato Regional Council, University of Waikato

To support the modeling of inflow loads to the lake, observed Matahuru tributary data were used to generate (log-log) plots of nutrient load vs. flow rate for this major inflow point (**Figure 2**). Only the most recent data available, were used for this analysis. Linear regression models were fitted to each data set, also shown in the figure. These models were used to estimate daily loads to the lake as a function of tributary flow for use in the water quality modeling described below.

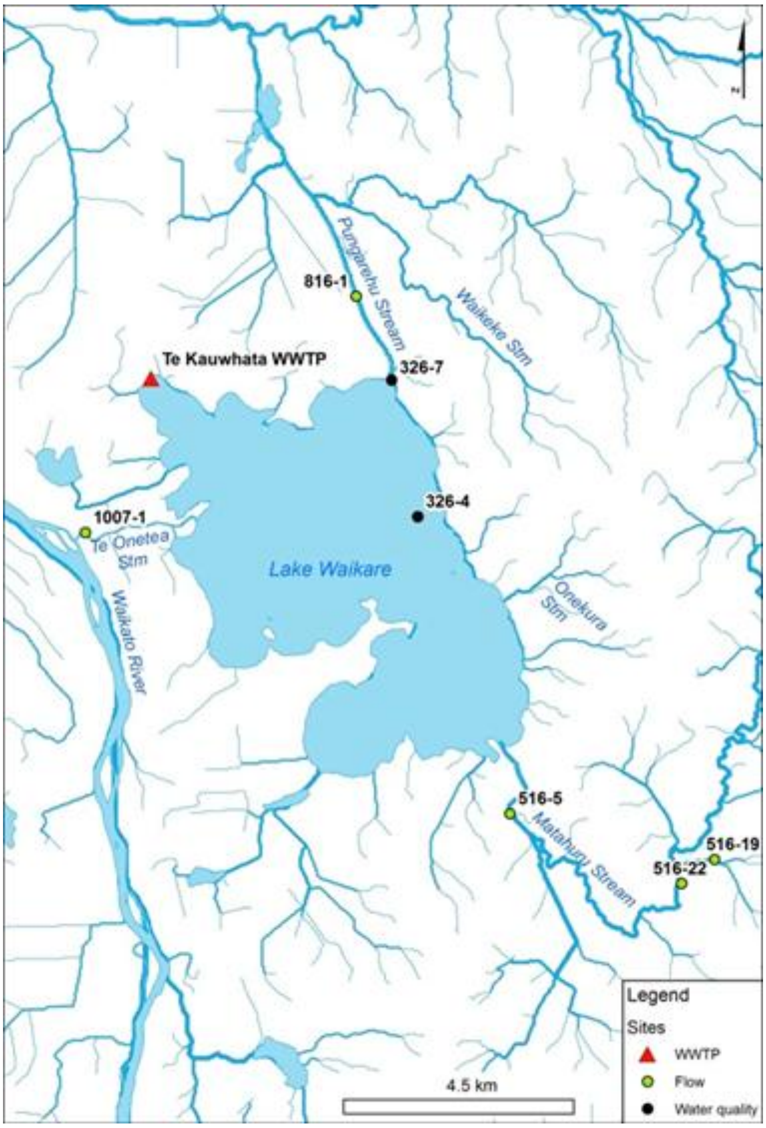

Figure 1. Existing Water Quality and Flow Monitoring Locations[1].

1 = locations based on northing and easting coordinates provided by Waikato District Council

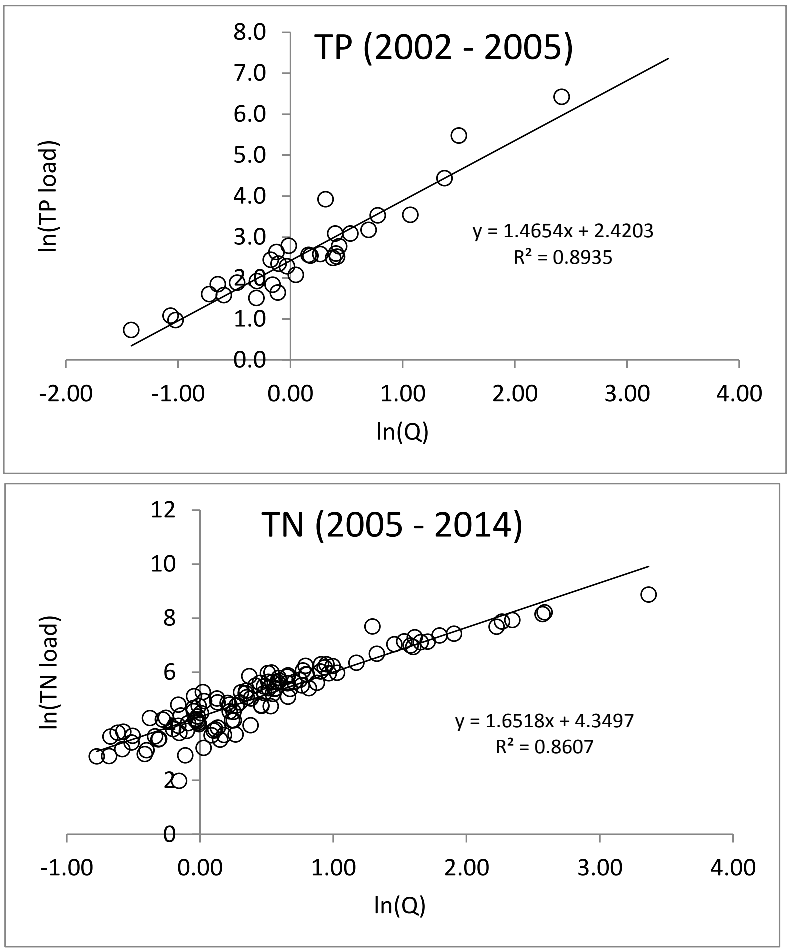

Figure 2. Matahuru Stream Load vs. Flow Relationships.

2.2 NEW DATA

Preliminary modelling and data analyses identified two significant data gaps with respect to Lake Waikare water quality modelling: sediment nutrient data and lake tributary nutrient data. To address this data gap, we undertook additional lake sediment and tributary sampling on 3 November, 2014. Shallow sediment grab samples were collected from seven (7) site locations distributed across the lake (**Figure 3**). GPS was used to locate each sampling site. Samples were collected from a boat using a "petite" Ponar grab sampler (Wildco Inc.). At each site, the sampler was lowered with a rope through the water column to the lake bottom and surface sediment samples were retrieved. A spring-loaded trigger mechanism closes the sampler when the bottom sediments are reached and the rope is relaxed, scooping a shallow sediment sample in the process. Collected samples included approximately the top 15 cm of the lake sediments and were relatively intact upon retrieval (**Figure 4**).

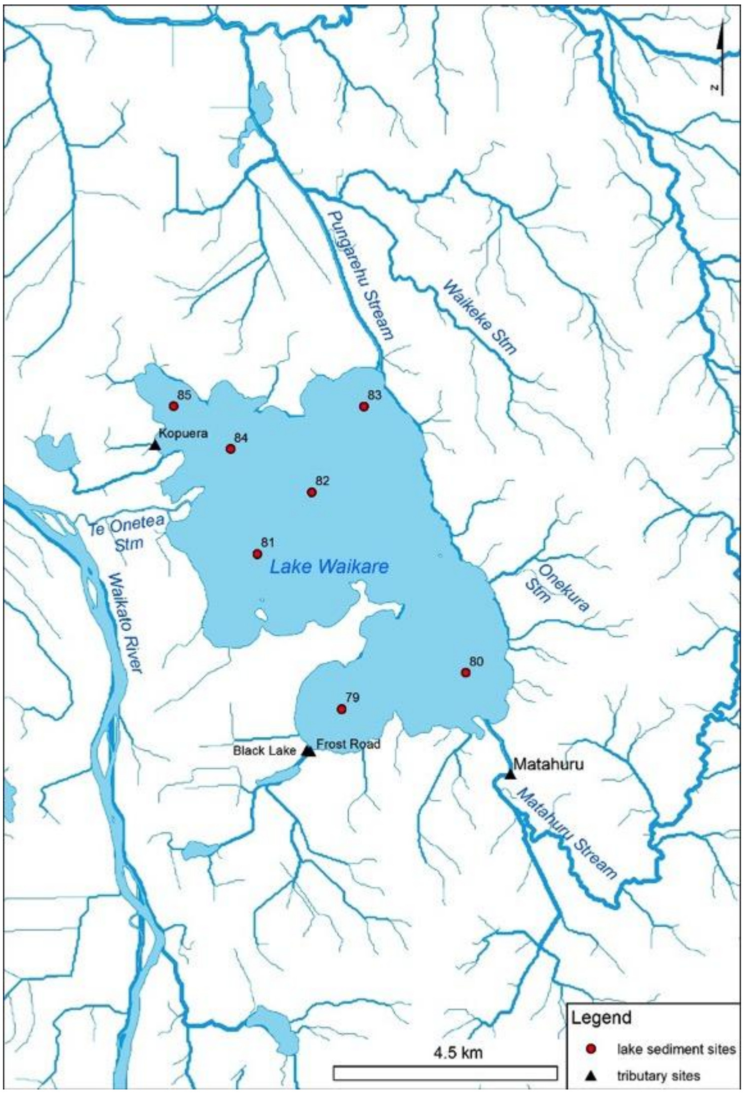

Figure 3. November 2014 Lake Sediment and Tributary Sampling Locations.

After retrieval, any excess lake water was drained from the sampler and the sampler was emptied into a shallow plastic bin (Figure 4). Each sample was mixed in the bin, and a well-mixed sub-sample was placed in a laboratory sampling jar. Replicate samples were collected at each sample site in close proximity to the original location (e.g. opposite side of boat). Both the sampler and the mixing bin were thoroughly rinsed with lake water between sampling locations.

For two of the replicate samples (84B and 85B), only the top 1-2 cm of the samples were collected for laboratory analyses. There was evidence of heterogeneity between this thin upper layer and the rest of the sample (Figure 4). The top layer samples were therefore collected to provide for a comparison to the well-mixed samples. Lastly, a deeper "core" sample was collected at Site 83 using a PVC tube (c. 10 cm diameter). This deeper core extended down approximately 50 cm into the sediments. A sample was collected from the bottom of this core to provide information on vertical nutrient gradients in the sediments. The bottom of the core consisted largely of a dryer, more organic material (Figure 4e) and may be indicative of the collapsed macrophyte beds (1970's) referred to by Vant (2008).

To supplement existing tributary water quality data, four of the major tributaries draining into the lake were sampled for nutrient analysis (Kopuera, Black Lake, Frost Road, and Matahuru Stream). Water column grab samples were collected from each tributary just upstream of the stream mouth. Kopuera, Black Lake, and Frost Road were all accessed with a boat, while Matahuru was accessed from the road. Samples were collected from near centre stream, to the extent possible.

Figure 4. Lake Sediment Sampling, November 2014. a) Lake Waikare, b) ponar sampling, c) sediment sample and mixing bin, d) sediment sample (note thin, less consolidated, light brown top layer), e) sediment core sample.

Sediment sampling results are summarized in **Table 2**. Sediment type was uniform throughout the lake: soft clay (grey) with a thin silt-clay upper layer (light brown). Sediment nutrient concentrations also exhibited uniformity for all sites, with total phosphorus ranging from 0.31 to 0.50 mg g^{-1} and total nitrogen ranging from 2.3 to 3.4 mg g^{-1} for the mixed sediment samples. These values agree well with the limited available data from previous sediment sampling efforts (Table 1). Site 85A had the lowest concentrations of both nutrients. This site is the northwestern-most site and likely less impacted by the agricultural drainage which predominates from the east and southeast. Interestingly, it is also the site closest to the TKWWTP outfall. The thin upper silt layer is shown to have slightly higher concentrations for both phosphorus and nitrogen (84B vs. 84 and 85B vs. 85). We surmise that this may be the microbial "active" layer with concentrated nutrient levels, typically constrained to the top 1 to 10 cm in lake sediments. Lastly the bottom of the extracted sediment core had significantly lower nutrient concentrations compared to the shallow sediment samples. This indicates a fairly sharply decreasing concentration gradient with sediment depth.

Table 2. Lake Sediment Sampling Results. 3 November, 2014.

Site	Site 79 (A, B)	Site 80 (A, B)	Site 81 (A, B)	Site 82 (A, B)	Site 83 (A, B)	Site 84 (A, B[1])	Site 85 (A, B[1])	Site 83 Core
TP (mg g^{-1})	0.46, 0.45	0.45, 0.49	0.45, 0.47	0.43, 0.47	0.44, 0.44	0.42, 0.50	0.31, 0.37	0.15
TN (mg g^{-1})	3.3, 3.2	2.7, 2.9	3.2, 3.4	2.9, 2.9	3.3, 3.0	2.7, 4.2	2.3, 3.1	1.7

[1] = "B" sample targeted upper 2 cm silt layer only

Tributary sampling results (**Table 3**) show higher nutrient concentrations for the smaller tributaries compared to Matahuru Stream, the largest tributary inflow to the lake, by factors of approximately 2 and 4, for nitrogen and phosphorus respectively. This could be attributable to the fact that the Matahuru catchment has a greater proportion of low fertility eroded hill pasture, compared to the catchments of the small tributaries, which include dairy and maize. Measured Matahuru concentrations agree well with those measured previously (Table 1). The smaller tributary concentrations generally exceed both Matahuru Stream concentrations and lake water column concentrations (Table 1).

Table 3. Lake Tributary Sampling Results. 3 November, 2014.

Site	Matahuru	Kopuera	Black Lake	Frost Road
TP (mg L^{-1})	0.10	0.22	0.34	0.76
TN (mg L^{-1})	1.4	4.0	2.7	2.7

3 WATER QUALITY MODELING SOFTWARE

The Simplified Lake Analysis Model (SLAM) (CDM Smith, 2012) was used in this study to simulate nutrient and phytoplankton dynamics in Lake Waikare and to evaluate the impacts of the proposed flushing strategy on lake water quality (**Figure 5**). The SLAM software was originally developed to address an identified need for a practical water quality modeling tool focused on lake eutrophication that could be easily and simply applied in planning studies by a wide range of end-users. SLAM is designed to be intuitive in its use and streamlined in functionality and data requirements, while still providing for a robust simulation of small lake nutrient and phytoplankton dynamics. The model was originally developed as an enhanced version of the U.S. Army Corps of Engineers BATHTUB model (Walker 2004) and retains many of the core algorithms of that model.

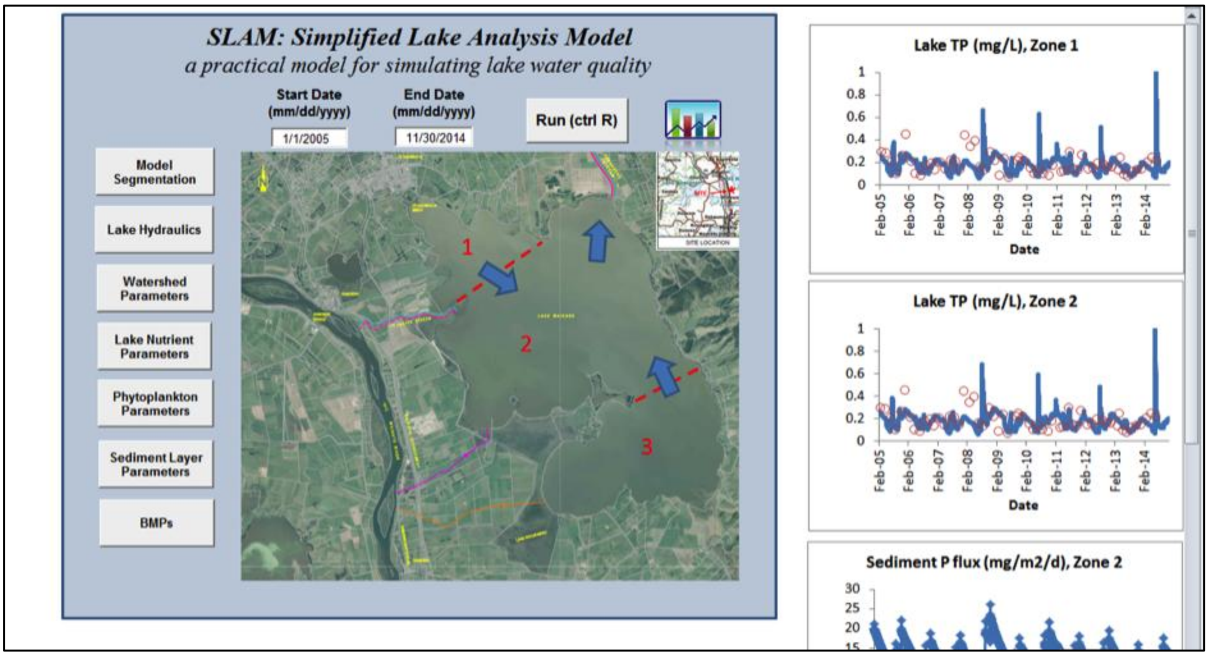

Figure 5. Simplified Lake Analysis Model (SLAM) (CDM Smith, 2012).

SLAM calculates lake mass and flow balances on a daily timestep, assuming one or more well-mixed lake zones. Each zone follows the conceptual model often referred to as a “continuously stirred tank reactor” (CSTR), whereby complete and immediate mixing is assumed for each zone in both the vertical and horizontal directions. This assumption makes the model particularly well suited for lakes that are generally well-mixed and can justifiably be divided into a limited number of small and/or shallow zones. For deeper lakes, SLAM does not explicitly calculate lake stratification but does allow for user-defined seasonal stratification and calculates the resulting impacts on water quality. Seasonal stratification was not included in the model constructed for Lake Waikare described here.

SLAM targets the key parameters important for eutrophic lakes: phytoplankton (as chl-a), phosphorus (P), and nitrogen (N). An established empirical model (Walker 2004) is used to describe the relationship between summer phytoplankton levels and lake nutrient concentrations and hydraulics. Lake catchment hydrology and pollutant loadings can either be explicitly calculated by the model or can be user prescribed. The model allows for quick and easy simulations of a variety of in-lake best management practices (BMPs), including: sediment dredging, hypolimnetic oxygenation, supplemental water inputs, pump and treat systems, alum application, and re-circulating off-channel wetlands treatment. Lastly, the model includes a state-of-the-art dynamic sediment nutrient flux module. This module calculates internal nutrient loads from the sediments to the water column as a function of shallow sediment nutrient dynamics and diffusive exchanges between sediment porewater and the overlying water column. Internal nutrient loads are a key component of many eutrophic lakes.

4 MODEL CONSTRUCTION AND CALIBRATION

The water quality and hydrologic data described above were used to construct and calibrate a Lake Waikare water quality model using the SLAM software. The baseline calibration model was constructed to simulate a continuous period from 1/1/2005 to current day (Nov, 2014) on a daily timestep. The best available information and data were used to support the model construction and calibration. This includes historical data, previous studies, and the recent sediment and tributary sampling event. The lake was divided into three well-mixed zones (**Figure 6**) for modeling, based on a qualitative assessment of the lake geography and bathymetry, existing data suggestive of a well-mixed system, and in recognition of the practical constraints of this modeling study. Individual zone volumes were estimated based on estimates of relative zone surface areas. A uniform depth was assumed in the model throughout the lake. Mixing lengths between zones were similarly estimated from visual inspection of maps and aerial photographs. Lake hydraulics (volumes, depths, areas) were assumed constant in time for the simulation period, based on recorded depths over this period that indicate a relatively steady water level in the lake (the lake is maintained within a tight range of water levels as part of the Lower Waikato and Waipa Flood Control Scheme – RC 101725). In other words, complex lake hydrodynamics were not included in this modeling study.

Daily inflows and loads to the lake were established using Matahuru monitoring data and data from the November 2014 sampling event. Drainage area flow-weighting was used to extend monitored daily Matahuru flow rates (51% of the drainage area) to estimate lake inflows from the rest of the catchment. Matahuru inflows were assigned completely to Zone 3. The majority of the other half of the catchment was assumed to drain to Zone 2, with a small portion assigned to Zone 1. Nutrient loads associated with these inflows were estimated using the load-flow relationships shown in Figure 2. Daily N and P load estimates were calculated for the Matahuru inflow, using the shown regression equations, as a function of daily flow rate. For the rest of the catchment inflows, the equations were modified to include load ratio factors observed during the November 2014 tributary sampling event (average ratios of 2.2 and 4.4 for TN and TP, respectively). In other words, inflow nutrient concentrations from the ungauged portion of the catchment (49% of the total) were assumed to be approximately two and four times higher, for N and P respectively, than those coming in from the Matahuru catchment. In the absence of more complete monitoring data, and given the observations of the November sampling, this assumption appears justified and is an important piece of the model calibration, as described below.

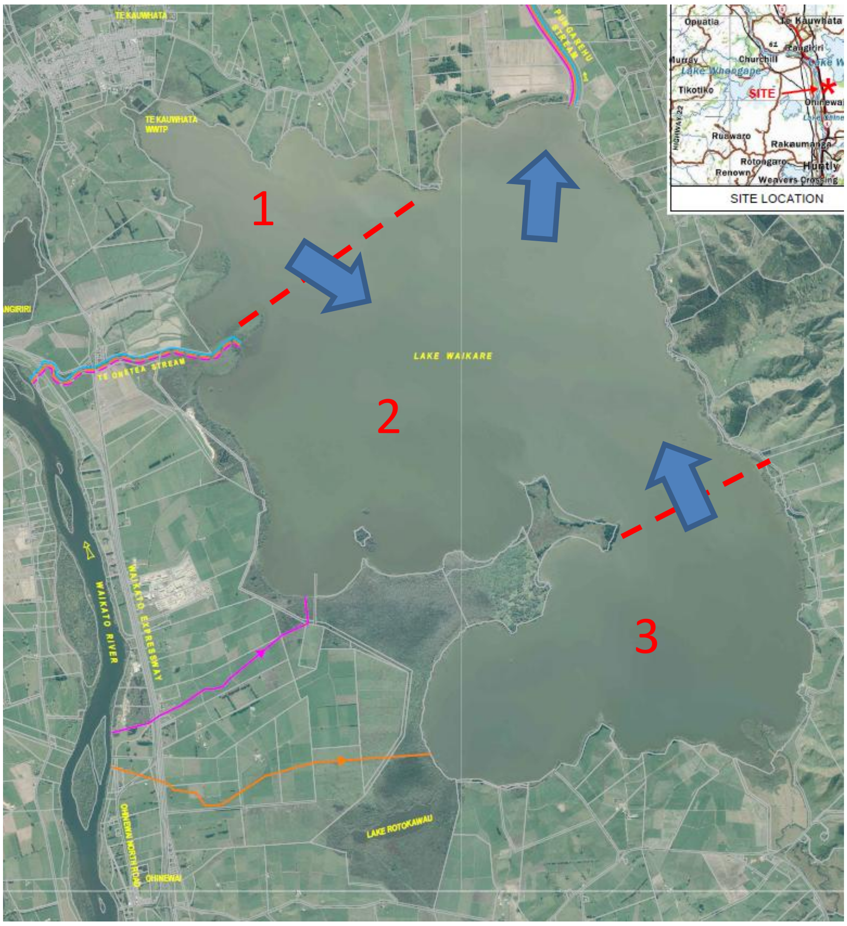

Figure 6. Lake Waikare Model Calculation Zones.

In addition to catchment drainage, two other lake inflows were included in the model. Firstly, a daily varying inflow from the Waikato River via the Te Onetea canal was included into Zone 2 based on available daily monitoring data (Table 1). Constant nutrient concentrations were assumed for this inflow, set equal to the average Waikato River values listed in Table 1 (Huntly and Mercer Bridge stations). Secondly, wastewater treatment plant effluent from the Te Kowhai WWTP was included as monthly variable flow and nutrient loads into Zone 1. Reported monthly average flows, total phosphorus concentrations, and total nitrogen concentrations (2008 – 2012) (Environment Waikato) from the plant to the lake were used to quantify these inflows in the model (Table 1).

Model internal kinetic rates and coefficients were set based on a model calibration exercise whereby adjustments were made to selected model parameters, within plausible ranges, to achieve an acceptable agreement between modelled and measured lake water and sediment quality data. Root mean squared errors (RMSE) associated with long term average modelled vs. measured lake nutrient and phytoplankton concentrations were used as guides in this process. Simultaneous to this, the calibration also focused on achieving realistic sediment nutrient flux rates within model recommended ranges. Key calibration parameters included: particulate nutrient settling rates (with seasonal variation), dissolved nutrient first order uptake rate constants, settled nutrient burial fractions, sediment anoxic fractions, and sediment nutrient mineralization rates. Other model parameters were maintained at model default values or were estimated based on recommended ranges.

Final model parameterization is summarized in **Appendix 1**. Calibration results are shown graphically in **Figure 7** and summarized in **Table 4**. A strong agreement between modelled and measured nutrient data was achieved in terms of both average annual values and general patterns of variability. A similar range of concentration values is predicted by the model time series calculations compared to the measured data. While an exact match of daily concentration fluctuations has not been achieved, this is expected given the high uncertainty associated with modelled inflow concentrations and is typical of lake water quality modeling. The agreement in particulate fractions lends confidence to the general nutrient speciation predicted in the model – with the vast majority of water column nutrients in organic form (phytoplankton biomass). Sediment nutrient concentrations agree very well with the limited data available. Sediment nutrient flux rates agree well with known published rates for similarly impacted lakes. Lastly, predicted seasonal average phytoplankton concentrations (as chlorophyll a) agree well with measured values.

Table 4. Summary of Model Calibration Results (2005 – 2014).

Output Parameter	Measured Value	Modelled Value	% Difference
Average annual TP (mg L^{-1})	0.19	0.19	0%
Average annual TN (mg L^{-1})	2.7	2.6	-4%
Average growing season chl-a (ug L^{-1})	125	127	2%
Average sediment P (mg g^{-1})	0.4	0.4	0%
Average sediment N (mg g^{-1})	3.1	2.6	-16%
Water column P fp	0.98	0.92	-6%
Water column N fp	0.98	0.92	-6%
Sediment P flux (mg m^{-2} d^{-1})	NA	4 - 17	NA
Sediment N flux (mg m^{-2} d^{-1})	NA	65 - 247	NA

NA = not available

It should be noted that without the load ratios applied to the smaller tributary inflow loads (non-Matahuru), described above, a reasonable model calibration could not be achieved. Specifically, it was clear that a significant source of nitrogen to the model was missing from the model construct if we assumed that inflow concentrations from the smaller tributaries were similar to those measured historically for Matahuru. It was only when the ratios quantified during the November sampling event (2.2 for TN, 4.4 for TP) were applied in the model that reasonable calibration could be achieved. This appears to lend confidence to our modeling assumption that nutrient concentrations in the smaller tributaries are significantly higher than those associated with the Matahuru Stream.

An overall lake nutrient mass balance (**Table 5**), derived from the calibrated model, indicates that the predominant source of nutrient to the lake is catchment runoff. More specifically, loads from the non-Matahuru portion of the catchment comprise approximately 77% and 63% of the total annual load to the lake for P and N, respectively. The Matahuru catchment contributes approximately 19% and 30% of the total load for the two nutrients, respectively. External loads are the highest during the winter months (high flow) and lowest during the summer and autumn months (drier hydrology). The Te Kauwhata WWTP contributes only approximately 0.8% and 0.2% of the total loads of P and N, respectively. These relative percentages are lower than those previously estimated by Vant (2008) for the WWTP, especially for nitrogen. This is likely attributable to our larger estimate of loads from the non-Matahuru portion of the catchment.

A large portion of these external loads settle to the lake active sediment layer, as particulates, and re-emerge as dissolved, biologically available internal loads later in the year. In other words, the lake sediments recycle a large portion of the lake external loads in the form of sediment nutrient fluxes. Internal loads from the sediments are highest during the summer months and lowest during the winter. The opposite is true of the settled loads – with the largest amount of settling occurring during the winter. The sediments serve as a net source of nutrients (releases >> sedimentation) during the summer and a net sink for nutrients during the winter.

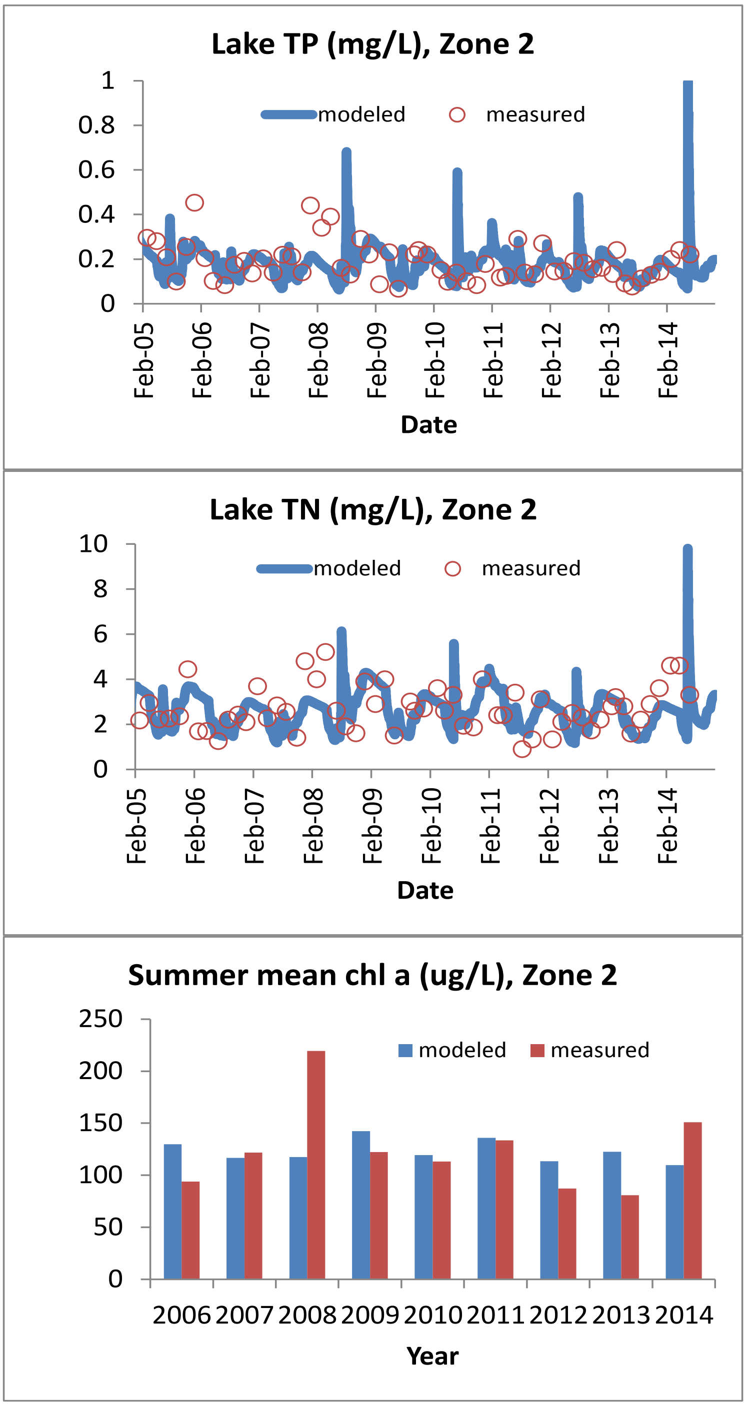

Figure 7. Lake Waikare Model Calibration Results.

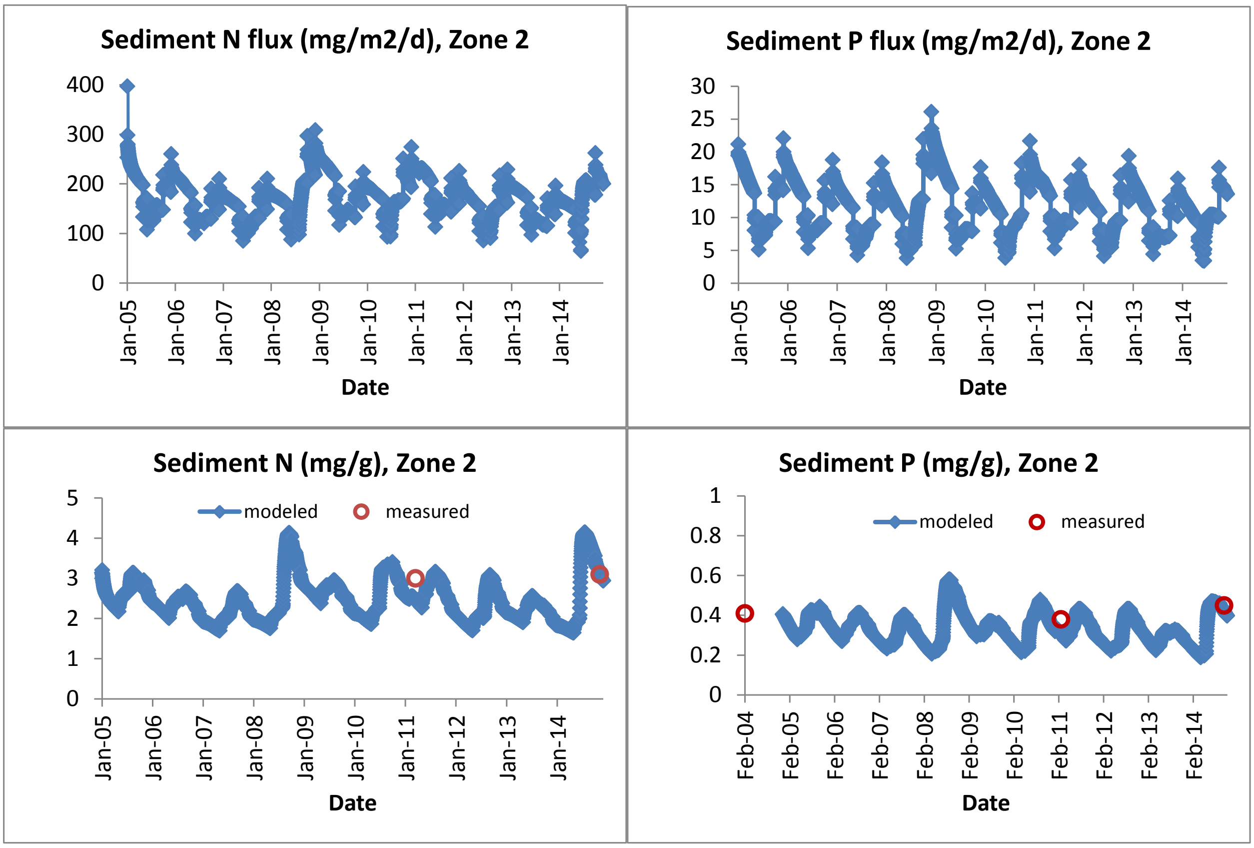

Figure 7. Lake Waikare Model Calibration Results cont.

Table 5. Lake Waikare Nutrient Mass Balance: Modelled Average Seasonal Loads (tonnes).

Season	Summer (Dec – Feb)		Autumn (Mar – May)		Winter (Jun – Aug)		Spring (Sep – Nov)		Annual Total	
Nutrient	P	N	P	N	P	N	P	N	P	N
Overall lake mass balance:										
Matahuru catchment	2	17	2	15	10	109	4	30	18	171
Rest of catchment	10	40	8	32	41	229	15	62	74	363
Te Onetea canal	0.3	4	0.3	4	1.5	18	1.4	17	3.5	43
Te Kauwhata WWTP	0.2	0.2	0.2	0.1	0.2	0.7	0.2	0.3	0.8	1.3
Totals	13	61	11	51	53	357	21	109	96	578
Internal dynamics:										
Sediment release load	49	607	36	509	23	424	38	565	146	2105
Settled active load	38	540	32	517	42	549	34	503	146	2109

5 MODELLED FLUSHING SCENARIOS

The calibrated model was used to simulate a series of future "what if" scenarios associated with the proposed Waikato River flushing strategy. All modelled scenarios assume a new steady inflow of river water to the lake, entering at Zone 2 (e.g. via Te Onetea canal which was the cheapest option in PDP (2014)). River water concentrations were assumed steady in the model set at historical measured mean values of 0.07 mg L^{-1} TP and 0.8 mg L^{-1} TN (Table 1). Particulate fractions associated with the nutrient inflow loads were set at measured mean values (Waikato River). To simplify comparisons, a repeating hydrologic year (2013) was used in the model to simulate a continuous 10-year future period. Lake catchment and WWTP loads and inflows were maintained at the values assumed for the 2013 period in the calibration model. Three different flushing scenarios were simulated, based on PDP, (2014), with river water inflow rates of 5, 25, and 50 m^3/s. All other model parameters were held at previously described values.

Results (**Table 6**) indicate the potential for significant improvements in water quality as a result of the proposed flushing strategies. This table shows future predicted annual average concentrations after a new equilibrium is reached in the lake, as a result of steady flushing over an extended period. The 2013 historical baseline conditions are also included for reference and can be considered representative of the "no action" alternative. Lastly, trophic level index (TLI) values, calculated as a function of the average nutrient and chlorophyll-a values shown, are presented. TLI is a common measure of lake water quality used throughout New Zealand (Burns et al. 1999) and usually also includes secchi depth in its calculation. We exclude secchi depth from the calculation here since it is not an output of our model. For the lowest flow scenario (5 m^3/s), reductions of 33%, 39%, and 42% are projected for mean annual TP, TN, and phytoplankton concentrations, respectively, compared to baseline. For the high flow scenario (50 m^3/s), reductions of 56%, 60%, and 79% were projected for the three water quality parameters, respectively. These improvements are predicted as a result of the combination of: mass dilution (lower concentration river water), flushing of nutrient rich lake sediments and suspended particulates, and inhibition of phytoplankton growth due to reduced lake residence times.

Whilst these projected reductions in TP, TN and chlorophyll-a are impressive, there may be no discernible difference in the quality of the lake to the general public. The lake trophic status would shift from "hypertrophic" to "supertrophic", with trophic level indices (TLI) improving from approximately 7 (current) to below 6 for the higher flushing rate alternatives. Thus the lake would still be turbid and highly enriched with algae. However the incidence of toxic blue-green algal blooms should be reduced.

While significant lake improvement is predicted as a result of the proposed flushing strategies, it should be noted that these strategies do not address the true source of the problem: runoff from agricultural portions of the catchment. In fact, flushing will simply relocate at least a portion of the problematic nutrient load from the lake to the river, which ultimately receives outflow from the lake. Whilst it can be argued that the assimilative capacity of the river, with respect to nutrient loads, is higher than that of the lake, there would be consenting issues associated with additional nutrient loads to the Waikato River because it is contrary to the Vision and Strategy that Waikato Tainui have for the River. Additionally, whilst the Whangamarino wetlands downstream of the lake could provide significant filtration of the lake discharge load prior to entering the river, the bog and fen components of these wetlands are particularly sensitive to nutrients (Bev Clarkson, Landcare Research, pers. comm)_and thus further nutrient additions to the wetland would be unacceptable to Department of Conservation. Whilst neither of these issues are insurmountable and could be mitigated through variable flushing rates, they do represent a significant barrier to the proposal.

As described above, Table 6 summarizes projected water quality after an initial equilibrating period where the lake sediment nutrient pool is flushed and a new steady state equilibrium is achieved in the model between the water column and the shallow sediments. The current model predicts that this new equilibrium will be achieved within approximately 1 to 3 years after initiation of the flushing scenarios. However, it should be noted that the uncertainty associated with this aspect of the model is high. A lack of supporting historical sediment quality data, uncertainty associated with the assumed active sediment layer depth in the model, and limitations in the model's representation of sediment nutrient dynamics all contribute to this uncertainty. Additional sediment nutrient data over an extended monitoring period would help refine the model calibration and representation of sediment-water column interactions. The depth of the microbially active surface sediment layer is unknown and important to this part of the model predictions. While there is some visual evidence from the November sampling to support the 2 cm depth assumed here, other authors have surmised an active layer depth of up to 10 cm (Chapra 2008; Hamilton et al. 2004). Sensitivity analyses with our model indicate that the equilibrium times would be on the order of 5 to 10 years assuming an active sediment layer of 10 cm rather than 2 cm. Lastly, the model neglects potential interactions between the shallow biologically active surface layer and underlying sediments. As evidenced by the single deeper core sample collected in November 2014, significant nutrient pools likely exist to some depth in the lake sediments, although seemingly following a decreasing gradient. Therefore, the potential exists for a certain degree of vertical migration of nutrients from the deeper sediments up to the surface sediments as the surface sediments are flushed. This dynamic is neglected in the model constructed here and thus equilibration times may be under-predicted by the model.

In addition to time-varying sediment nutrient concentration data, water quality and flow data associated with the lake's smaller tributaries (non-Matahuru) are lacking. Both types are data are recommended for future data collection efforts.

Table 6. Model Flushing Scenario Results.

Parameter	**2013 Baseline**	**Scenario 1, 5 cms**	**Scenario 2, 25 cms**	**Scenario 3, 50 cms**
Average annual TP (mg L^{-1})	0.18	0.12	0.09	0.08
Average annual TN (mg L^{-1})	2.3	1.4	1.0	0.92
Average chl-a (ug L^{-1})	130	76	41	27
Average sediment P (mg g^{-1})	0.34	0.25	0.19	0.17
Average sediment N (mg g^{-1})	2.3	1.4	0.98	0.87
Sediment P flux (mg m^{-2} d^{-1})	12	9	7	6
Sediment N flux (mg m^{-2} d^{-1})	160	93	66	58
Trophic status (TLI)	hyper-trophic (7.0)	hyper-trophic (6.4)	super-trophic (5.9)	super-trophic (5.7)

6 CONCLUSIONS

A new lake water quality model was used to assess the efficacy of a proposed river water flushing strategy with respect to potential water quality improvements in Lake Waikare. The calibrated model provided insight on both current lake nutrient and eutrophication dynamics and the sensitivity of lake water quality to flushing with Waikato River water. The modeling was supported by a fairly comprehensive historical data set and by newly collected lake bottom sediment and tributary nutrient data. Modeling of current conditions indicates that annual nutrient loads to the lake are dominated by diffuse sources (agriculture) in the catchment delivered via a number of small tributaries to the lake. These loads are highest during the wet winter season. However, modeling also shows that a large portion of these loads re-emerage as dissolved, biologically available internal loads during the summer and autumn months. In other words, the lake sediments recycle a large portion of the lake external loads in the form of sediment nutrient fluxes.

Predictive modeling of proposed river water flushing strategies incidate the potential for significant improvements in lake water quality, with predicted reductions in lake phytoplankton concentrations ranging from c. 40% (5 m^3/s flushing rate) to c. 80% (50 m^3/s flushing rate). These improvements are predicted as a result of the combination of: mass dilution (lower concentration river water), flushing of nutrient rich lake sediments and suspended particulates, and inhibition of phytoplankton growth due to reduced lake residence times. It should be noted, however, that these strategies do not address the true source of the problem: runoff from agricultural portions of the catchment. In fact, flushing will simply relocate at least a portion of the problematic nutrient load from the lake to the river, which ultimately receives outflow from the lake. Consequently, differences in assimilative capacities between the lake, river, and intermediary wetlands (Whangamarino) should be considered in a broader modelling analysis in any future studies associated with the proposed flushing strategy.

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APPENDIX 1: MODEL PARAMETERIZATION

Parameter	Value	Units	Source
Catchment:			
Drainage area	211	km^2	Wildlands (2011)
Daily lake inflow, Matahuru Stream	average = 2.1	m^3/s	Waikato Regional Council monitoring data
Daily lake inflow, Te Onetea	average = 1.7	m^3/s	Waikato Regional Council monitoring data
Daily lake inflow, rest of catchment	average = 2.1	m^3/s	Estimated using Matahuru data and drainage area weighting
Te Kauwhata WWTP inflow	average = 0.008	m^3/s	Environment Waikato Data Reports (2008 – 2012)
Daily lake nutrient loads, Matahuru Stream	TP = 47, TN = 471	kg d^{-1}	Estimated using load-flow curves and daily flow data
Daily lake nutrient loads, Te Onetea	TP = 10, TN = 120	kg d^{-1}	Estimated using daily flow records and Waikato River water quality data
Daily lake nutrient loads, rest of catchment	TP = 200, TN = 991	kg d^{-1}	Estimated using load-flow curves (Matahurua), area weighting flow estimation, and Nov. 2014 observed concentration ratios
Te Kauwhata WWTP nutrient loads	TP = 1.9, TN = 3.6	kg d^{-1}	Estimated using Environment Waikato Data Reports (2008 – 2012)
Lake:			
Total volume	43,100,000	m^3	Wildlands (2011)
Zone volume distribution	Zone 1 = 15%, Zone 2 = 60%, Zone 3 = 25%	%	Visual assessment of maps and aerial photographs
Surface area	3442	ha	Wildlands (2011)
Phosphorus:			

Parameter	Value	Units	Source
Fraction particulate (f_p) of inflow	0.81	unitless	Waikato Regional Council monitoring
Settling velocity (v_s) (particle-bound and phytoplankton)	0.12	m d^{-1}	Calibrated
First order removal rate constant (k_d)	0.8	d^{-1}	Calibrated
Burial fraction (f_b)	0.25	unitless	Calibrated
Nitrogen:			
Fraction particulate (f_p) of inflow	0.44	unitless	Waikato Regional Council monitoring
Settling velocity (v_s) (particle-bound and phytoplankton)	0.1	m d^{-1}	Calibrated
First order removal rate constant (k_d)	0.8	d^{-1}	Calibrated
Burial fraction (f_b)	0.04	unitless	Calibrated
Sediment Nutrient Dynamics:			
Vertical diffusion coefficient (D)	100	cm^2 d^{-1}	Model default
Surface sediment porosity (ρ)	0.9	unitless	Model default
Vertical mixing length (z)	0.6	m	Set to ½ of mean lake depth
Depth of active layer (d_2)	0.02	m	Model default (typical: 1 – 10 cm)
N mineralization rate (kd_2) (oxic, anoxic)	0.09, 0.13	d^{-1}	Calibrated
P mineralization rate (kd_2) (oxic, anoxic)	0.04, 0.07	d^{-1}	Calibrated
N adsorption rate (kd_3) (oxic, anoxic)	4, 3	d^{-1}	Calibrated
P adsorption rate (kd_3) (oxic, anoxic)	4, 3	d^{-1}	Calibrated
N monthly anoxia weighting factors (Jan, Feb, Mar, etc.)	1, 1, 1, 1, 0.5, 0, 0, 0, 0, 0.5, 0.5, 1	unitless	Calibrated
P monthly anoxia weighting factors (Jan, Feb, Mar, etc.)	1, 1, 1, 1, 0.5, 0, 0, 0, 0, 0.5, 0.5, 1	unitless	Calibrated
Phytoplankton:			

Parameter	Value	Units	Source
Calibration factor (K)	1.8	unitless	Calibrated (recommended range = 0 – 2)
Algal light extinction coefficient (b)	0.025	m^{-1}	Model default (Walker, 2004)
Secchi disk depth (S)	0.24	m	Measured average
Non-algal light extinction coefficient (a)	1.7	m^{-1}	Calculated (a = 1/S – b * chl a) (Walker, 2004)