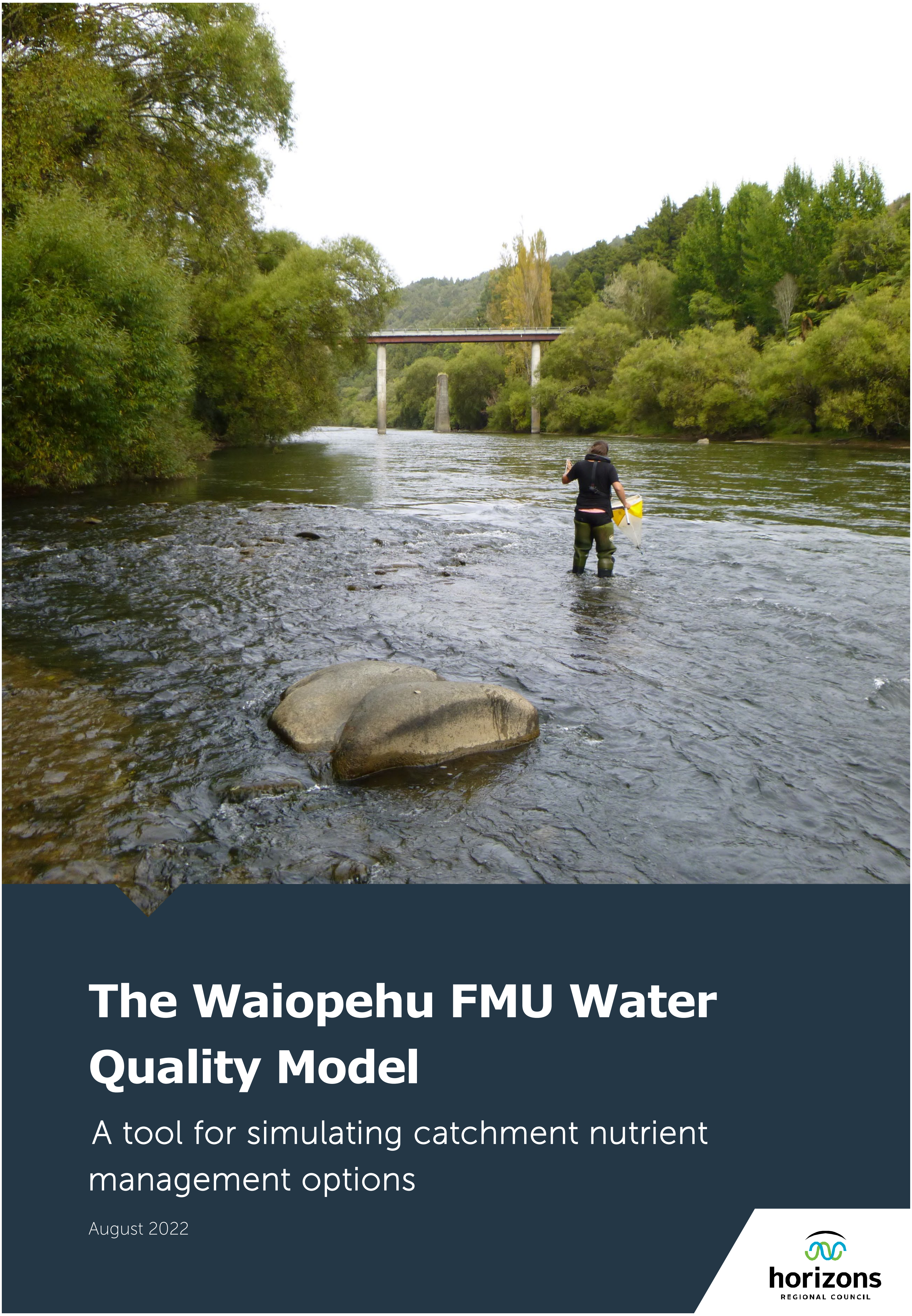

The Waiopehu FMU Water Quality Model

A tool for simulating catchment nutrient management options

August 2022

horizons
REGIONAL COUNCIL

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Executive Summary

A new catchment water quality model of the Waiopehu freshwater management unit (FMU) has been developed using an enhanced version of the Simplified Contaminant Allocation Modelling Platform (SCAMP). In addition to representing catchment nutrient (i.e., nitrogen and phosphorus) generation, transport and transformation, which are fundamental to SCAMP, the model represents several other processes. The load of nitrogen entering Lake Horowhenua via groundwater is a significant portion of the total lake nutrient budget. The model represents the flux of nitrogen discharged into the lake via groundwater. The model represents trophic responses to nutrient loads and/or concentrations in multiple receiving environments including rivers and streams, lakes and estuaries in terms of algal biomass measures. Lake Horowhenua is explicitly represented in the model with in-lake nutrient and phytoplankton concentrations simulated as a function of catchment (including groundwater) supplied nutrient loads to the lake. Trophic responses in streams are represented by estimates of periphyton biomass and in estuaries in terms of the Estuary Trophic Indicator (ETI) which is also an algal biomass measure. The model also represents the uptake of nutrients by wetlands and the subsequent attenuation of catchment loads. The mathematical models, and model parameterisation, associated with these new features in SCAMP have been derived from previous studies.

The model provides a spatially explicit ledger of all nutrient sources and their fates as well as a tool to simulate nutrient management options in the FMU. The ledger provides the basis for a coarse freshwater quality accounting system for nitrogen and phosphorus for the Waiopehu FMU. Under clause 3.29 of the National Policy Statement – Freshwater Management (NPS-FM), every council must operate and maintain a freshwater quality accounting system. The purpose of the accounting system is to provide information that is relevant to limit setting, assess whether an FMU is over-allocated, and to track over time the cumulative effects of activities. We consider that the ledger provided by the catchment water quality model of the Waiopehu FMU can fulfil these functions. However, the spatial resolution is limited to categorical descriptions of land use type within the eight sub-catchments that are represented by the model. This resolution is coarser than individual properties and the question of whether this is adequate can only be answered once HRC have formulated policies for managing land and freshwater under the NPS-FM. In addition, the ledger will need to be periodically updated if it is to be used to track the cumulative effects of activities. Updating would need to include representing within the ledger the effects of changes in land use and management and the implementation of mitigations and other management actions over time.

The spatial resolution of the model allows for investigations of nutrient source mitigation (at the scale of land use types within sub-catchments rather than at the property scale), design choices for a proposed wetland complex, and nutrient allocation at the FMU scale. The model has been developed within a user-friendly and easily portable Excel-based platform, that allow for “what if” questions to be asked by a range of potential end users.

A set of example predictive simulations are presented. The results demonstrate the potential for moderate, but significant, improvements in catchment water quality from available on-farm mitigation options and/or the construction of an intercepting wetland. A sizing curve has been generated using the model, equating wetland area with predicted in-lake phytoplankton concentrations, to be used to guide wetland design. Additional simulations can be performed in the future to either demonstrate and verify concepts (“proof of concept”) or to investigate specific proposed catchment management and mitigation scenarios. Model parameterisation will be refined in the future upon conclusion of an in-progress Lake Horowhenua water quality modelling study.

1 Introduction

Horizons Regional Council (HRC) require appropriate scientific information to support objective and limit setting in the Manawatū-Whanganui region as part of its process to develop a new regional water plan that implements the National Policy Statement – Freshwater Management (NPS-FM; NZ Government, 2020). An important component of that information is how loss of contaminants from land in the region can be managed to achieve water quality objectives in freshwater and coastal receiving environments.

There are a wide range of potential management actions and limits that could help achieve water quality objectives. Identifying which set of actions and limits is preferred requires analysis for at least two reasons. First, the impacts of actions and limits will not be evenly distributed across the region because land use and receiving environment sensitivity to contaminants are spatially variable. Second, there is environmentally mediated variation in both potential contaminant losses from land use and the transformation of contaminants (attenuation) as they move through the drainage network. Because these two factors interact, the assessment of options requires iterative simulation modelling of the land-water systems being managed. The basis for such simulation is catchment water quality models. Catchment water quality models attempt to account for the relevant processes such as contaminant loss from land and attenuation as well as spatial variation in factors such as current and potential land use.

This report describes the development and calibration of a catchment water quality model that simulates the production, transport and attenuation of two important nutrients: nitrogen and phosphorus, in the Waiopehu Freshwater Management Unit (FMU). The model also includes modules (drawn from other focused studies) that describe receiving environment response to the simulated nutrient loads and concentrations, providing an integrated platform for predictive simulation modelling of the land-water system in the FMU. The receiving water environments that are explicitly included in the model include rivers and streams in the FMU, Lake Horowhenua, and the Ōhau and Waikawa estuaries at the mouths of the Ōhau River and Waikawa Stream, respectively.

The model is designed to be used as a predictive tool that can be used to assess the effectiveness and feasibility of various options throughout the FMU including different sets of mitigation measures and land management practices, applying different discharge standards to land and/or point sources, and changing land use. The model also provides a spatially explicit ledger that describes the sources of nitrogen and phosphorus in the FMU and their fates (i.e., the degree to which these are attenuated or transported to the coast). The ledger could be used as a basis for a coarse freshwater quality accounting system for nitrogen and phosphorus for the Waiopehu FMU. freshwater quality accounting systems are a requirement for regional councils under clause 3.29 of the NPS-FM. The model is user-friendly and is housed in the commonly used Microsoft Excel spreadsheet software, which means it is transparent and easily shared.

2 Methods

2.1 Modelling Software

The Waiopehu FMU model was developed using RMA Science's (RMA) Simplified Contaminant Allocation and Modelling Platform (SCAMP) software. SCAMP is designed as a flexible modelling tool for simulating diffuse and point source contamination, and receiving water response, at a catchment scale. Details on the fundamental catchment fate and transport structure and calculations in SCAMP are provided by Cox et al. (2022). New receiving water elements, and a wetlands object, have been added to the software to support the goals of this study. Each of these software enhancements is described below.

2.1.1 Lake Water Quality

Lake trophic response is simulated in SCAMP, for any number of user-defined lake “objects”, using a series of published empirical equations that describe the relationships between nutrient loads and in-lake nutrient and phytoplankton concentrations. The equations were derived by a recent study of more than 1000 New Zealand lakes (Abell *et al.*, 2019). The equations implemented in SCAMP are as follows:

$$log_{10}(TP_{lake}) = \frac{log_{10}(TP_{in})}{1+(k_1+\Delta k_1 d)\tau_w^{k_2}} \qquad \text{Equation 1}$$

$$log_{10}(TN_{lake}) = \beta_0 + \beta_1 log_{10}(TN_{in}) + \beta_2 log_{10}(z_{max}) \qquad \text{Equation 2}$$

$$log_{10}(Chla) = \beta_3 + \beta_4 log_{10}(TP_{lake}) + \beta_5 log_{10}(TN_{lake}) \qquad \text{Equation 3}$$

where TP_{lake} TN_{lake}, and Chla are calculated lake water column mean concentrations of total phosphorus, total nitrogen, and phytoplankton as chlorophyll a (mg m^{-3}), respectively, TP_{in} and TN_{in} are mean inflow concentrations to the lake (mg m^{-3}), k_1, Δk_1, k_2, and all β values are fitted parameters, τ_w is the lake water residence time (years), and z_{max} is the maximum depth of the lake. The variable d is a flag that indicates whether a lake is shallow (d = 0) or deep (d = 1). The authors of the original publication use a threshold of >7.5 m to define deep lakes.

In SCAMP, TP_{in} and TN_{in} are calculated as a function of upstream catchment diffuse export loads, point source loads, and transformation during transport (attenuation), and estimated lake mean annual total inflow (m^3 s^{-1}). Lake maximum depth (z_{max}) and shallow flag (d) are user defined and lake specific. Default lake model fitted parameters, as presented in Abell *et al.* (2019), are summarised in Table 1.

Table 1. SCAMP default lake water quality model parameters. The parameters are shown for each of the three models defined by Equations 1 to 3.

Equation 1 (TP_{lake})			**Equation 2 (TN_{lake})**			**Equation 3 ($Chla_{lake}$)**		
k_1	**k_2**	**k_3**	**ß$_0$**	**ß$_1$**	**ß$_2$**	**ß$_3$**	**ß$_4$**	**ß$_5$**
0	0.44	0.13	1.6	0.54	-0.41	-1.8	0.55	0.7

2.1.2 Stream Periphyton

The SCAMP periphyton module is based on nutrient criteria to achieve periphyton biomass objectives described by Snelder *et al.* (2021). The criteria are presented as look-up tables for stream nutrient (TN and TP) concentrations thresholds, defined as median concentrations, to achieve National Objective Framework (NOF) periphyton attribute bands. The criteria are defined for each of 21 River Environment Classification (REC) Source-of-Flow (SOF) classes (Snelder and Biggs, 2002) and for designated stream shade status (shaded or unshaded). The look-up tables are based on statistical analysis of data collected at 251 monitoring sites across New Zealand. SOF class designations are available for all New Zealand rivers based on the REC. SOF classes account for differences between rivers in the drivers of periphyton biomass to nutrient concentration that are attributable to differences in factors such as flow regime, temperature and light. Snelder *et al.* (2021) recommend that the criteria are applied to third order rivers or higher because few of the 251 sites in the dataset were located on streams of order less than three.

Each NOF attribute band is associated with thresholds defined by periphyton biomass concentration (g m^{-2}) (Table 2). These thresholds are applied to the 92nd percentile of observed periphyton concentrations for assigning NOF bands. Snelder *et al.* (2021) provide nutrient concentration criteria for a range of levels of "under-protection risk". The under-protection risk can be interpreted as the probability of exceeding a given periphyton band threshold despite being compliant with the nutrient concentration criteria. These risks were derived by Snelder *et al.* (2021) and reflect the quantified uncertainty associated with the underlying statistical models.

In SCAMP, the Snelder *et al.* (2021) criteria are implemented with separate look up tables for modelled TN and TP concentrations, as shown by the example in Table 3. For each location of interest, defined by the user, the modelled instream median nutrient concentration is translated into an estimated probability of membership of each of the NOF periphyton attribute states (i.e., probability the state is A, B, C or D band. Linear interpolation of the lookup tables is used to calculate the probability that each of the NOF band's upper thresholds are exceeded, given the modelled nutrient concentration). Model output is expressed as exceedance percentages for each NOF periphyton attribute band. In other words, the model estimates the likelihood (as a percentage) that the 92nd percentile periphyton concentration will exceed each upper threshold for each NOF periphyton band based on the modelled nutrient concentration. These model outputs are provided for each assessment point under the assumptions that these locations are shaded and unshaded (i.e., two sets of probabilities).

Note that stream periphyton calculations in SCAMP are performed for TN and TP separately. The utilised look up tables are specific to TN and TP independently. Dual nutrient periphyton models are not available in SCAMP currently. Consequently, periphyton output can be generated for one, or both (separately), of the modelled nutrients. No interpretation is provided for inconsistent results (TN-based vs. TP-based). However, it is recommended that the higher of the two periphyton output sets (worst case) be used to support decision making (i.e., a conservative approach).

Table 2. NOF periphyton attribute band thresholds (mg m^{-2}). The thresholds are applied to the 92nd percentile of monthly periphyton (represented by x).

Band A	**Band B**	**Band C**	**Band D**
$x \le 50$	$50 < x \le 120$	$120 < x \le 200$	$x > 200$

Table 3. Example SCAMP periphyton – TN look up table (partial).

SOF Class	Exceedance Probability	Median TN Threshold (mg L^{-1})					
		Unshaded Band A	Unshaded Band B	Unshaded Band C	Shaded Band A	Shaded Band B	Shaded Band C
CD/H	5	0.001	0.057	0.91	0.003	0.258	2.32
CD/H	10	0.003	0.223	2.16	0.012	0.787	3.58
CD/H	15	0.006	0.497	3.05	0.030	1.49	4.13
CD/H	20	0.013	0.858	3.67	0.063	2.24	4.37
CD/H	30	0.045	1.88	4.28	0.206	3.36	4.48
CD/H	50	0.305	3.69	4.50	0.998	4.37	4.50
CD/H	70	1.33	4.43	4.50	2.87	4.50	4.50
CD/H	80	2.52	4.50	4.50	3.83	4.50	4.50
CD/H	90	3.88	4.50	4.50	4.42	4.50	4.50
CD/H	95	4.39	4.50	4.50	4.50	4.50	4.50
CD/L	5	0.001	0.007	0.182	0.001	0.036	0.806
CD/L	10	0.001	0.031	0.694	0.002	0.147	2.14
CD/L	15	0.001	0.079	1.48	0.004	0.368	2.96
CD/L	20	0.002	0.164	2.25	0.008	0.744	3.53
CD/L	30	0.006	0.533	3.27	0.028	1.85	4.16
CD/L	50	0.042	2.28	4.30	0.200	3.56	4.49
CD/L	70	0.3	3.81	4.50	1.26	4.38	4.50
CD/L	80	0.929	4.31	4.50	2.48	4.49	4.50
CD/L	90	2.55	4.50	4.50	3.76	4.50	4.50
CD/L	95	3.62	4.50	4.50	4.33	4.50	4.50

2.1.3 Estuary Water Quality

The SCAMP estuary object provides for the calculation of total modelled nutrient load (tonnes year^{-1}) for a specified catchment or basin coastal terminus. If NOF band (A – C) nutrient load thresholds are provided by the user, the software also translates modelled loads into NOF bands for each estuary object. Such thresholds are site specific and require external analyses, such as those provided by the Estuary Trophic Indicator (ETI) tool (https://shiny.niwa.co.nz/Estuaries-Screening-Tool-1/). SCAMP simulations are performed separately for TN and TP. Consequently, estuary NOF band designations can be calculated based on TN only, TP only, or both independently.

2.1.4 Wetlands

The SCAMP wetland object simulates the removal of nutrients by a wetland, via a combination of biochemical and physical processes, based on lumped attenuation parameters. The calculation utilises site specific wetland characteristics (size, location, and climate) and a literature-based attenuation algorithm. The object requires the following user inputs:

- name of the SCAMP model sub-catchment within which the wetland is located
- size (area) of wetland (ha)
- size (area) of drainage area upstream of the wetland (ha)
- land use distribution of the upstream drainage area (%)
- name of any downstream, in-series, modelled wetland (if applicable)
- annual average precipitation for the upstream drainage area (m yr^{-1})
- lumped contaminant removal rate constant (k, m yr^{-1}).

For each wetland, a biokinetic model, following Kadlec and Wallace (2008), is used to calculate the nutrient load reduction (attenuation) associated with flow through the wetland:

$$attenuation = 1 - \left[1 + \frac{k}{Precip} * R_W\right]^{-1},$$

where k = first order removal rate constant (m yr^{-1}); *Precip* = annual average precipitation (m yr^{-1}); R_W = the ratio of wetland area to upstream drainage area (unitless); and attenuation = effective wetland attenuation coefficient, represented as a fraction of the total inflow load to the wetland. The total inflow load to the wetland is calculated in the model as a function of the upstream drainage area, land use distribution associated with the upstream drainage area, and associated export coefficients.

SCAMP enables the accurate representation of in-series wetlands, within the same catchment, based on specifying a “downstream wetland”. If no downstream wetland is specified for a given wetland object, the model represents the wetland as being in parallel to any other wetland objects in the catchment. If a downstream wetland is specified, then the model performs an in-series calculation of wetland load removal, to avoid double counting of removed loads. In other words, wetland attenuated loads are calculated, and applied, in the models in correct sequential order (upstream to downstream).

In this study, default biokinetic first order rate constants (k) were used for the wetland simulations: 15 m yr^{-1} for nitrogen and 22 m yr^{-1} for phosphorus. The values were originally derived from an analysis of data presented by Tanner *et al.* (2020). These authors present removal curves that express expected nutrient removal rates as a function of R_W. While not directly useable in SCAMP, the curves served as calibration targets, within a separate analysis, to derive the stated equivalent first order rate constants. In other words, the wetland biokinetic rates used for the scenario simulations described here were approximately equivalent to the rates presented in Tanner *et al.* (2020).

2.2 Waiopehu FMU Model

The Waiopehu FMU model (Figure 1) includes five tributary objects, nine catchment objects, one point source object, two estuary objects, and one lake object. These model objects and their associated spatial entities are listed in Table 4. All catchment object parameters (land use, export coefficients, attenuation coefficients) were extracted directly from the larger Manawatū River basin model (Cox *et al.*, 2022), which includes all of the Waiopehu FMU. The exception to this (Hoki_1a TN attenuation) is described below.

The lone point source in the model (POT Levin STP) is parameterised with mean annual TN and TP discharge loads. Data based on facility monitoring data describing discharge concentration of TN and TP for this point source discharges were provided by HRC. The point source loads were estimated based on compliance monitoring data collected over the period from the start of 2014 to the end of 2018. Discharge volume estimates were provided by HRC (mean daily flows, based on consented volumes, observed discharge rates and/or spot observations).

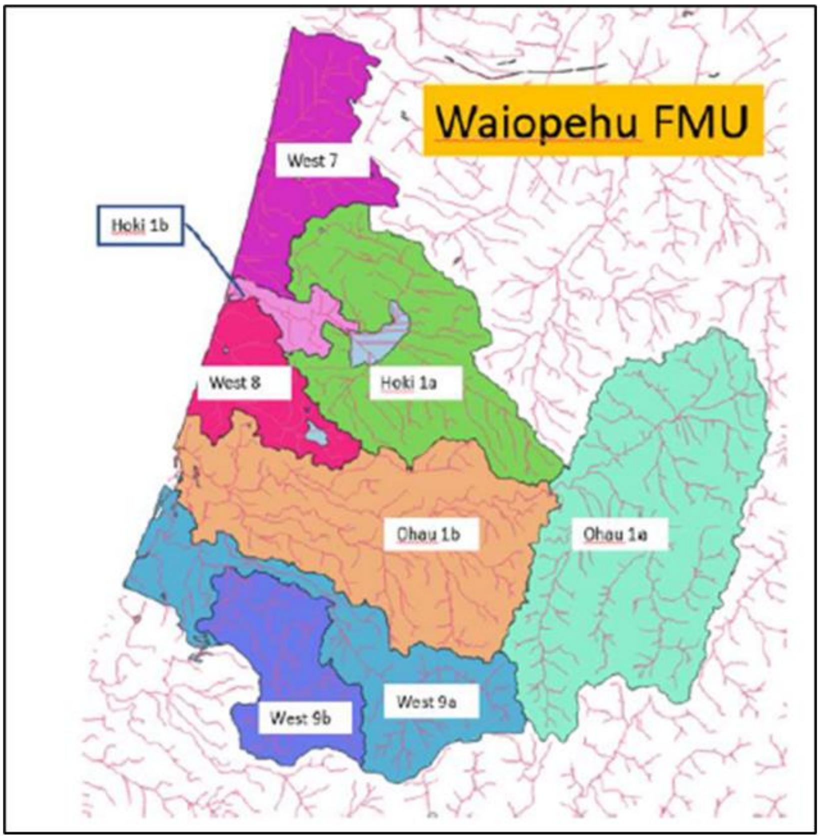
Lake Horowhenua is explicitly included in the model as a lake object. Inflow loads to the lake are calculated in the model as the sum of surface catchment (Hoki_1a) diffuse load and groundwater loads (described below). The surface catchment diffuse pathway TN attenuation coefficient was adjusted slightly, from the original larger basin parameterisation, to achieve a satisfactory agreement between modelled lake surface inflow concentration (Arawhata Stream) and published data (Gibbs, 2011). The Hoki_1a TP attenuation coefficient was maintained at the original value that was assigned by calibration of the Manawatū River basin model (Cox *et al.*, 2022).

Groundwater nutrient loads are known to comprise a significant portion of the total lake external loads (Gibbs 2011). These loads are simulated in the Waiopehu FMU model using a discrete catchment object representing the groundwater recharge zone. Currently, the groundwater recharge zone, and associated export load, is parameterised based on information provided by a groundwater model developed by Pattle Delamore Partners (PDP, personal communication). Land use class delineation within the recharge zone was performed following the methods described in Cox *et al.* (2022). Export coefficients for each land use class were set equal to those associated with the lake's surface water catchment (Hoki_1a). Groundwater catchment attenuation coefficients were adjusted to achieve agreement between modelled and reported lake groundwater inflow loads and concentrations, as estimated by Gibbs (2011). The parameterisation and model structure representing groundwater nutrient loads delivered to Lake Horowhenua can be refined in future as the groundwater modelling study, which is currently in-progress, is completed.

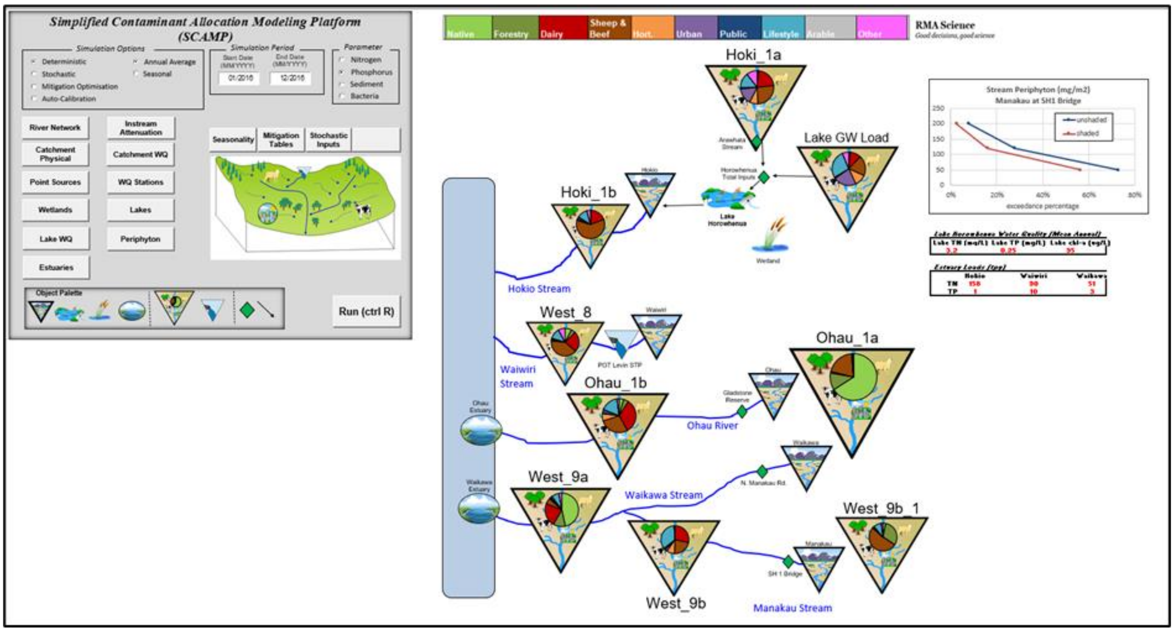
The lake object water quality parameterisation was initially set using model default coefficients, shown in Table 1. However, to achieve better agreement with a limited set of available in-lake nutrient and phytoplankton data, the TP k_1 parameter was adjusted (see results presented in Section 3). The parameterisation and model structure representing Lake Horowhenua can be refined in future as the Lake Horowhenua water quality modelling study by HRC and Otago University, which is currently in-progress, is completed. The current representation of Lake Horowhenua in the Waiopehu FMU model should, therefore, be viewed as a placeholder only. It is expected that the new lake modelling study will provide updated information to allow for the refinement of the parameters, with respect to surface and groundwater loads and the lake trophic response to nutrient loads.

In the Waiopehu FMU, only two streams (Ōhau River and Waikawa Stream) have estuaries that are recognised by the ETI tool. This tool was used to provide a preliminary estimate of NOF band TN load thresholds for the Waikawa Stream. This is provided in the tool as an example only and is subject to future refinement. We understand that HRC have work underway that is investigating the estuaries at the mouths of the Waikawa Stream and Ōhau River. If these studies produce relationships between TN and TP loads and estuary state, these can be easily added to the Waiopehu FMU model.

Waiopehu model domain showing the eight sub-catchments



Architecture of the SCAMP Waiopehu FMU model


Simplified Contaminant Allocation Modeling Platform (SCAMP)

Simulation Options
- ● Deterministic
- ○ Stochastic
- ○ Mitigation Optimisation
- ○ Auto-Calibration
- ● Annual Average
- ○ Seasonal

Simulation Period
Start Date (MM/YYYY) 01/2016
End Date (MM/YYYY) 12/2016

Parameter
- ○ Nitrogen
- ● Phosphorus
- ○ Sediment
- ○ Bacteria

Lake Horowhenua Water Quality (Mean Annual)

Lake TN (mg/L)	Lake TP (mg/L)	Lake chl-a (ug/L)
3.2	0.25	35

Estuary Loads (tpy)

	Hokio	Waiwiri	Waikaw
TN	158	90	51
TP	1	10	3

Figure 1. Waiopehu FMU model domain and architecture.

Table 4. Waiopehu FMU model objects and associated spatial entities.

Model object type	Spatial entities
Tributaries	Hōkio Stream, Manakau Stream, Ōhau River, Waikawa Stream, Waiwiri Stream
Sub-catchments	Hoki_1a, Hoki_1b, Ohau_1a, Ohau_1b, West_8, West_9a, West_9b, West_9b_1, Lake Groundwater Load
Point Sources	POT Levin STP
Lakes	Lake Horowhenua
Estuaries	Ōhau Estuary, Waikawa Estuary
Water Quality Stations	Manakau at S.H.1 Bridge, Ōhau at Gladstone Reserve, Waikawa at North Manakau Road, Arawhata Stream, Horowhenua Total Inputs

2.3 Predictive Simulations

Six potential future scenarios were simulated using the Waiopehu FMU model. Each scenario represents a different level and type of catchment mitigation action. The scenarios are listed in Table 5 and described below.

Table 5. Summary of modelled scenarios.

Scenario	Description
Scenario 1	Full implementation of established dairy and sheep/beef farm mitigations
Scenario 2	Full implementation of established + developing dairy and sheep/beef farm mitigations
Scenario 3	Constructed wetland upstream of Lake Horowhenua, minimum size
Scenario 4	Constructed wetland upstream of Lake Horowhenua, maximum size
Scenario 5	Scenario 1 + Scenario 4
Scenario 6	Scenario 2 + Scenario 4

The first two scenarios (Scenarios 1 and 2) incorporate two sets of pastoral (dairy and sheep/beef) farm mitigation actions, as described by McDowell *et al.* (2021). Scenario 1 represents full implementation of "established" mitigation options, as of 2015. Scenario 2 represents full implementation of both established and "developing" options, anticipated for 2035. The published paper presents projected reductions in farm nutrient loss rates ("exports") assuming that specific mitigations have been implemented, as a function of both farm type and an environmental typology. The typology classifies farms based on three environmental characteristics: climate, topography, and soil type. For our analysis, for simplicity, we neglected differences associated with environmental typology. Instead, we applied national area-weighted mean reduction values, provided by McDowell et al. (2021), for the two farm types. All load reductions were applied as a percent reduction from baseline values for the dairy and sheep/beef land use categories. No other diffuse source export coefficients, or point source loads, were modified. The calibrated attenuation coefficients were retained in the models for all simulations.

Scenarios 3 and 4 simulate the impacts of a proposed constructed wetland, assuming two different sizes, located upstream of Lake Horowhenua and capturing 90% of the diffuse surface nutrient loads from catchment Hoki_1a. For Scenario 3, the wetland is sized at 15 ha, which is the minimum design size under consideration by HRC (Maree Patterson, HRC, personal communication). For Scenario 4, the wetland is sized at 70 ha, the maximum design size. Wetland kinetics were maintained at model default values (see Section 2.1) for both scenarios.

Scenarios 5 and 6 combine Scenario 4 (maximum wetland size) with Scenarios 1 and 2 (2015 and 2035 farm mitigations), respectively. These scenarios, therefore, simulate the combined effects of on-farm mitigation and the proposed constructed wetland.

Outputs for each scenario, which serve as performance metrics, are the following: Lake Horowhenua mean TN, TP, and Chl-*a* concentrations, Manakau Stream periphyton biomass, and terminal (coastal) loads of TN and TP for each of the four major streams included in the model (Hōkio Stream, Waiwiri Stream, Ōhau River, and Waikawa Stream).

As a supplemental set of simulations, the model was used to develop a wetland sizing curve, providing predicted lake water quality impacts, in the form of mean phytoplankton concentrations, as a function of upstream wetland size.

3 Results

3.1 Baseline model parameterisation

Model parameterisation, focused specifically on the Lake Horowhenua catchment, is summarised in Table 6**.** These parameters were adjusted as part of the model parameterisation process described in Section 2, guided by previously published data and information. Model performance, with respect to reasonably replicating these reported historical conditions, is summarised in Table 7. The “reported” data are outdated and are unlikely to represent current lake conditions. Therefore, they were used as approximate guides only, and no effort was made to exactly reproduce the numbers with the model at this time.

The groundwater catchment “attenuation coefficients” presented here are not intended to represent true subsurface pathway attenuation. Rather, they should be viewed as the fraction of the total nutrient export from the recharge zone that migrates to the subsurface, and is then delivered to the lake, that is not already included in the lake surface catchment (Hoki_1a). As such, it is sensible that the quantified TP attenuation coefficient is high. We don’t expect a large fraction of the recharge zone TP export to migrate to the subsurface, because TP exports are typically dominated by surface runoff processes. The contribution of groundwater TN to the overall lake nutrient budget is higher than the contribution of groundwater TP.

Source load distribution summaries for example model locations are provided in Figure 2 and Table 8*.* These are provided as examples of the model load accounting utility and can be generated for any chosen model location. The modelled lake external nutrient mass budget distribution between surface and sub-surface sources is another example of model accounting utility, as shown in Figure 3.

As noted above, all parameters should be viewed as placeholders at this stage until completion of the in-progress HRC lake modelling study and, potentially further discussion with groundwater modellers at that time.

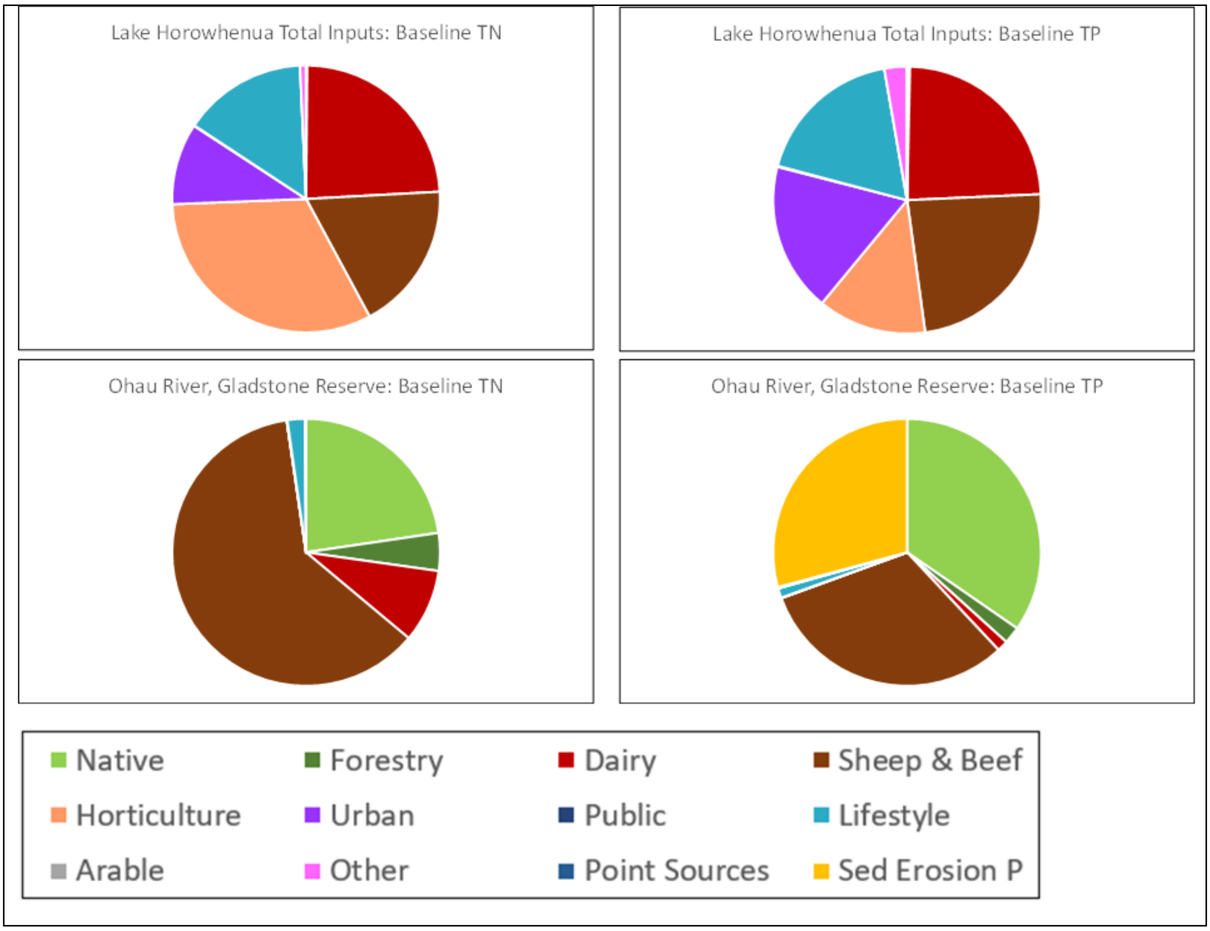


Figure 2. *Example baseline model source load distributions.*

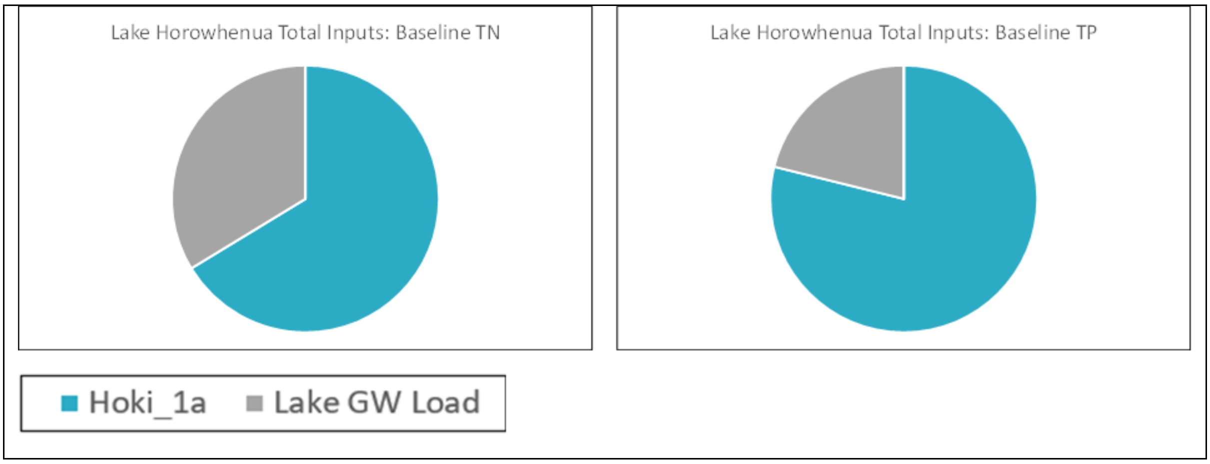


Figure 3. *Contribution of surface catchment and ground water to loads of TN and TP to Lake Horowhenua in the baseline model.*

Table 6. Lake Horowhenua catchment model parameters.

Lake Water Quality:			
TP k_1	*(All other lake parameters maintained at default values; See Table 1)*		
-0.22			
Lake Catchment:			
Hoki_1a TN Attenuation Coefficient	**Groundwater TN Attenuation Coefficient**	**Hoki_1a TP Attenuation Coefficient**	**Groundwater TP Attenuation Coefficient**
0.2	0.5	0.7	0.9

Table 7. Lake Horowhenua catchment model baseline simulation results compared to published values (all values are mean annual concentration).

Source of values	**Inflow TN (mg L^{-1})**	**Inflow TP (mg L^{-1})**	**In-lake TN (mg L^{-1})**	**In-lake TP (mg L^{-1})**	**In-lake Chl-a (µg L^{-1})**
Modelled	5.8	0.1	3.2	0.3	95
Reported	10 (6.8 – 14)[1]	0.03 (0.01 – 0.3)[1]	3.1 (2 – 4.7)[2]	0.2 (0.1 – 0.3)[2]	83 (27 – 211)[2]

[1] Period of record = 1988 – 1989 (Gibbs 2014)
[2] Period of record = 2000 – 2010 (Gibbs 2011)

Table 8. Baseline model TN source load distributions for example model locations.

Land Use Class	Example model locations				
	Manakau at S.H.1 Bridge	Waikawa at North Manakau Road	Ohau at Gladstone Reserve	Arawhata Stream	Horowhenua Total Inputs
Native	0.5%	7.4%	22.7%	0.1%	0.1%
Forestry	5.6%	2.1%	4.6%	0.1%	0.1%
Dairy	0.0%	63.8%	8.9%	29.3%	24.0%
Sheep & Beef	76.2%	9.0%	61.6%	19.9%	18.0%
Horticulture	2.8%	5.4%	0.0%	29.0%	32.2%
Urban	0.0%	0.7%	0.0%	8.9%	9.8%
Public	0.2%	0.1%	0.1%	0.1%	0.1%
Lifestyle	14.3%	11.0%	2.1%	11.9%	15.0%
Arable	0.0%	0.0%	0.0%	0.0%	0.0%
Other	0.3%	0.5%	0.1%	0.8%	0.7%
Point Sources	0.0%	0.0%	0.0%	0.0%	0.0%

Table 9. Baseline model TP source load distributions for example model locations.

Land Use Class	Example model locations				
	Manakau at S.H.1 Bridge	Waikawa at North Manakau Road	Ohau at Gladstone Reserve	Arawhata Stream	Horowhenua Total Inputs
Native	1.6%	22.3%	34.6%	0.3%	0.3%
Forestry	5.1%	1.9%	2.1%	0.1%	0.1%
Dairy	0.0%	50.2%	1.3%	27.0%	24.0%
Sheep & Beef	77.0%	9.4%	31.4%	25.0%	23.6%
Horticulture	0.0%	2.0%	0.0%	12.2%	13.1%
Urban	0.0%	1.1%	0.0%	16.8%	18.0%
Public	0.3%	0.3%	0.1%	0.1%	0.1%
Lifestyle	15.0%	11.4%	1.2%	15.5%	18.1%
Arable	0.0%	0.0%	0.0%	0.0%	0.0%
Other	1.0%	1.4%	0.2%	3.0%	2.7%
Point Sources	0.0%	0.0%	0.0%	0.0%	0.0%
Sediment Erosion	0.0%	0.0%	29.2%	0.0%	0.0%

3.2 Predictive Simulation results

Results of the predictive simulations are summarised in Table 10 (for Lake Horowhenua), Table 11 (for estuaries) and in Figure 4 (river periphyton) and Figure 5 (lake phytoplankton). Lake water quality results (Table 10) indicate incremental improvements in Lake Horowhenua water quality resulting from the established and developing farm mitigation measures (Scenarios 1 and 2), constructed wetlands (Scenario 3 and 4), and the combination of the two (Scenarios 5 and 6). For example, the combination of a 70-ha wetland and full implementation of both established and developing (2035) pastoral farm mitigations (Scenario 6) is predicted to reduce mean annual lake phytoplankton concentrations by approximately 30% compared to the baseline.

Table 10. Model simulation results for Lake Horowhenua. The table shows predicted lake water quality for three variables (TN, TP and Chla-a) for the baseline and the six scenarios (see Table 5 for scenario details).

Scenario	**Mean Lake TN (mg L^{-1})**	**Mean Lake TP (mg L^{-1})**	**Mean Lake Chl-a (mg L^{-1})**
Baseline	3.2	0.25	95
Scenario 1	3.1	0.22	85
Scenario 2	2.9	0.19	76
Scenario 3	3.2	0.24	92
Scenario 4	3.1	0.21	83
Scenario 5	2.9	0.18	74
Scenario 6	2.8	0.16	67

Total terminal loads for the four major modelled river and stream systems, which are loads entering the estuaries at each river mouth, are shown in Table 11. The terminal loads are predicted to decrease for all scenarios, compared to baseline. Full implementation of farm mitigation options (i.e., Scenario 2) is predicted to reduce nitrogen loads by 10 – 30% compared to the baseline. Under Scenario 2 phosphorus load reductions are smaller than for nitrogen for the Waiwiri Stream and Ōhau River estuaries (< 10%). However, for the Hōkio and Waikawa Streams full implementation of farm mitigation options (Scenario 2) is predicted to achieve nearly a 30% reduction in estuary TP load.

Table 11. Model simulation results for annual estuary TN and TP loads. The table shows predicted load entering each estuary from its major catchment, for TN and TP for the baseline and the six scenarios (see Table 5 for scenario details).

Scenario	***TN (t yr^{-1})***				***TP (t yr^{-1})***			
	Hōkio	**Waiwiri**	**Ōhau**	**Waikawa**	**Hōkio**	**Waiwiri**	**Ōhau**	**Waikawa**
Baseline	158	90	211	51	2.9	9.5	50	2.8
Scenario 1	144	85	181	45	2.4	9.3	49	2.3
Scenario 2	131	81	156	40	2.1	9.2	47	2
Scenario 3	155	90	211	51	2.6	9.5	50	2.8
Scenario 4	145	90	211	51	2.3	9.5	50	2.8
Scenario 5	132	85	181	45	2.1	9.3	49	2.3
Scenario 6	121	81	156	40	1.8	9.2	47	2

Figure *4* provides example periphyton simulation results, based on phosphorus only, for one of the model water quality stations (Manakau Stream at SH1). Only results of Scenarios 1 and 2 are displayed because the simulated wetland in Scenarios 3 – 6 will not impact stream periphyton at this site. Similar results are available for nitrogen-based periphyton predictions and for other model water quality stations. For this site, only modest decreases in periphyton biomass are predicted for the simulated mitigation scenarios.

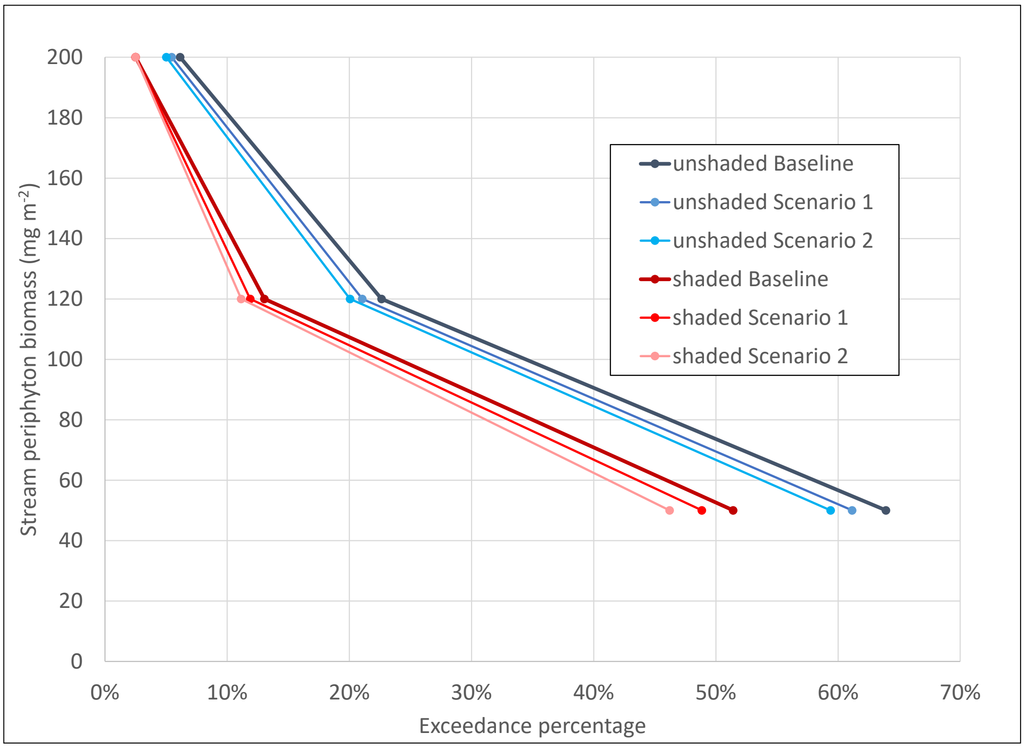


Figure 4. Example model simulation results for periphyton. The plot indicates the probability of exceeding the three periphyton attribute states (A, B and C, which are defined by biomass thresholds of 50, 120 and 200 mg m^{-2}) at Manakau Stream at SH1 under the Baseline,

Scenario 1, and Scenario 2. Results include both shaded and unshaded assumptions for each scenario.

Figure 5 provides a 'sizing curve' that shows predicted lake phytoplankton (as Chl-*a*) as a function of a range of potential constructed wetland design sizes. These simulations indicate improvements in lake water quality (i.e., reducing Chl-*a*) as wetland size increases. Although the rate of decrease in Chl-*a* with increasing wetland size decreases as size increases (i.e., the improvement curve shown in Figure 5 flattens), model simulations indicate that significant gains in lake water quality could be achieved with increases in wetland area beyond the current design maximum of 70 ha.

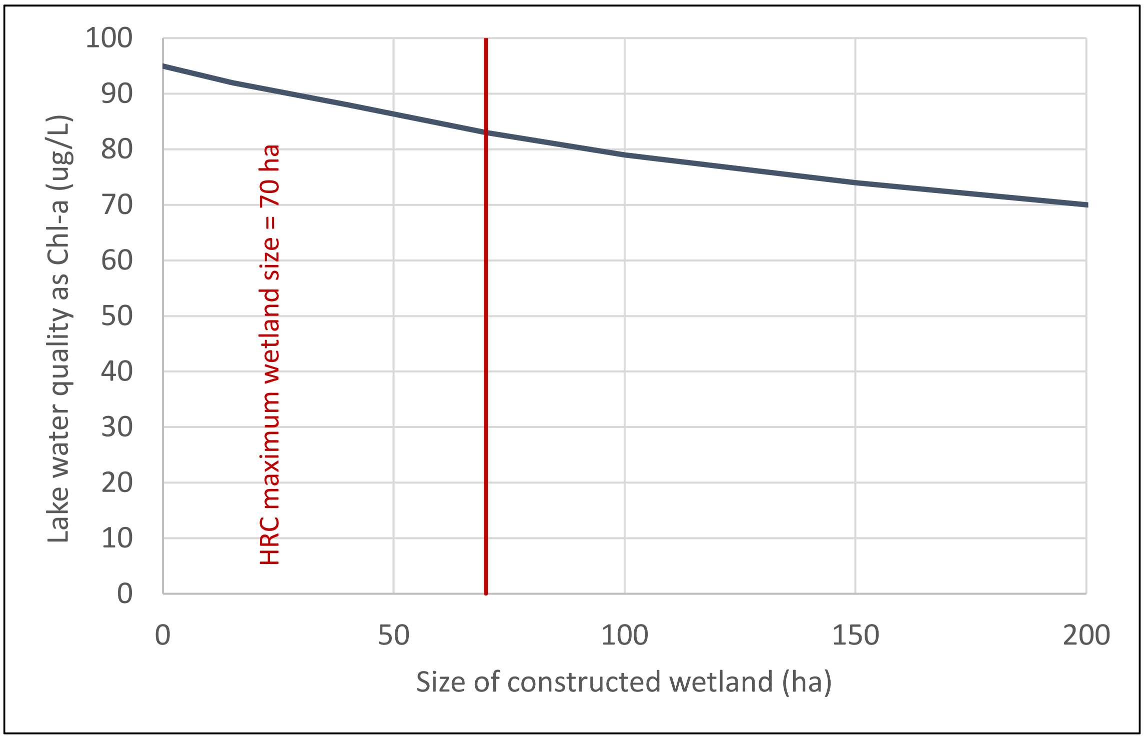


Figure 5. Predicted water quality in Lake Horowhenua as Chl-a as a function of the size of the upstream constructed wetland.

4 Summary and Conclusions

A catchment water quality model of the Waiopehu FMU was developed using an enhanced version of the Simplified Contaminant Allocation Modelling Platform (SCAMP). In addition to catchment nutrient generation, transport and transformation (i.e., attenuation) calculations, the model includes multiple receiving water quality response calculations. Lake Horowhenua is explicitly represented in the model with in-lake nutrient and phytoplankton concentrations simulated as a function of catchment nutrient loads to the lake. Groundwater loads are included as a significant portion of the total lake nutrient budget. Also included are stream periphyton calculations, estuary trophic NOF band estimates, and the simulation of wetland nutrient dynamics and attenuation. The mathematical models and model parameterisation associated with these new features in SCAMP have been derived from previous studies.

The Waiopehu FMU model provides a spatially explicit ledger of all nutrient sources and their fates as well as being a tool to simulate nutrient management options in the FMU. The ledger provides the basis for a coarse freshwater quality accounting system for nitrogen and phosphorus for the Waiopehu FMU. Under clause 3.29 of the National Policy Statement – Freshwater Management (NPS-FM), every council must operate and maintain a freshwater quality accounting system. The purpose of the accounting system is to provide information that is relevant to limit setting, assess whether an FMU is over-allocated, and to track over time the cumulative effects of activities. We consider that the ledger provided by the catchment water quality model of the Waiopehu FMU can fulfil these functions. However, the spatial resolution is limited to categorical descriptions of land use type within the eight sub-catchments that are represented by the model. This resolution is coarser than individual properties and the question of whether this is adequate can only be answered once HRC have formulated policies for managing land and freshwater under the NPS-FM. In addition, the ledger will need to be periodically updated if it is to be used to track the cumulative effects of activities. Updating would need to include representing within the ledger the effects of changes in land use and management and the implementation of mitigations and other management actions over time.

The spatial resolution of the model allows for investigations of nutrient source mitigation, design choices for a proposed wetland complex, and nutrient allocation at a sub-catchment scale. The model has been developed within a user-friendly and easily portable Excel-based platform, to enable quick “what if” type simulations by a range of potential end users.

The developed modelling platform can be used to support decision making with respect to catchment management, mitigation, and limit and objective setting. It can be used to support decision making in the following ways:

1. It simulates the source of nutrients (N and P) and where those nutrients go and the transformations (i.e., attenuation) along the drainage path.

2. It represents the impact of the nutrients on the receiving environments in terms of measurable indicators, such as receiving water concentrations and NOF attribute states or equivalents thereof (for estuaries).

3. It enables the impacts of management and mitigation actions on nutrient loads, concentrations, and the associated NOF attribute states to be predicted across multiple assessment points. In general terms, management and mitigation actions can be represented in the model in two ways: 1) by reducing source loads, and 2) by changing attenuation (in particular, by changing the rate of reduction of N and P in the wetland complex).

4. It provides the basis for a coarse freshwater quality accounting system for nitrogen and phosphorus for the Waiopehu FMU.

A set of example predictive simulations have been presented. These results demonstrate the potential for moderate, but significant, improvements in catchment water quality from available on-farm mitigation options and/or the construction of an intercepting wetland. A sizing curve has been generated using the model, equating wetland area with predicted in-lake phytoplankton concentrations, to be used to guide design. Additional simulations can be performed in the future to either demonstrate and verify concepts ("proof of concept" or to investigate specific proposed catchment management and mitigation scenarios. Model parameterisation will be refined upon release of an in-progress Lake Horowhenua water quality modelling study.

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