Modelling water quality of a quasi-perched lake subject to intensive agricultural development

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1 Introduction

Lake Rerewhakaaitu is a moderate-sized (area = 5.1 km^2), shallow (mean depth = 7 m, max depth=15 m), polymictic lake. It is one of several of volcanic origin in the Rotorua region, known collectively as the Te Arawa lakes. The volcanic soils of Lake Rerewhakaaitu have high porosity and are known to be highly retentive of phosphorus (Fish, 1978). The topographic catchment is of moderate size (53 km^2; (Reeves et al., 2008) and highly developed for intensive pastoral agriculture (70 %; (Reeves et al., 2008), which belies the relatively moderate nutrient (mesotrophic) status of the lake (McIntosh et al., 2001;Burns et al., 2009). The reason for this may be related to lake water levels which are higher than groundwater levels within most of the topographic catchment area, thus categorising the lake as at least partially perched (White et al., 2003; White et al., 2015). Most studies of perched lakes have focused on monitoring habitat distributions (Squires et al., 2002; Chikita et al., 2004; Emmerton et al., 2008; Armiento et al., 2015) or hydrodynamics (Baiocchi et al., 2006; Ayenew and Tilahun, 2008 ;Ito et al., 2009; Taviani and Henriksen, 2015) and few have sought to use a model to relate the area and location of the inflows to the water quality of the lake. We simulated the catchment hydrology and estimated nutrient loads to Lake Rerewhakaaitu, and linked these outputs to a coupled hydrodynamic−water quality model of this quasi-perched lake system. Our objective was to provide an evidential basis for understanding why widespread land use intensification in the surface topographic catchment had apparently not severely impacted lake water quality. We hypothesized that there would be a ‘water sensitive zone’ of the surface topographic catchment where land use activities would most impact lake water quality but that this area would be sufficiently small to limit the potential degradation of water quality. Given the unusual hydrology of the Lake Rerewhakaaitu ecosystem, we were also particularly interested in how a future climate might impact the hydrology and water quality of the lake, and addressed this question through simulations using meteorological data inputs adjusted to this future climate. Assessments of effects of a future climate were tied in closely to an uncertainty analysis to identify the key forcing factors generating differences between observed data and simulation data.

Table 1: Comparison of surface-water model simulations with field data using root mean square error (RMSE) and normalized RMSE (NRMSE), for temperature (Temp.), dissolved oxygen concentration (DO), total nitrogen, ammonium-N, nitrate-N, total phosphorus, phosphate-P, suspended solid concentration (SS), total chlorophyll *a* (TChl *a*), and Secchi depth.

	RMSE	NRMSE (%)
Temp. (°C)	0.7639	4.5
DO (g m^{-3})	1.5602	18.0
TN (g m^{-3})	0.0955	16.7
NH_4-N (g m^{-3})	0.0163	18.2
NO_3-N (g m^{-3})	0.0124	20.8
TP (g m^{-3})	0.0038	19.1
PO_4-P (g m^{-3})	0.0041	11.2
SS (g m^{-3})	0.5735	13.0
TChl *a* (mg m^{-3})	2.58	13.7
Secchi depth (m)	2.47	25.8

Table 2: Land use by area and percentage for the surface topographic catchment (Surface catchment) and the total and specific catchment area contributing to the lake (Effective catchment) which was calculated from a Digital Elevation Model and a water balance for Lake Rerewhakaaitu.

	Total area (km^2)	Land use area (km^2)					
		Grassland – High[1]	Grassland – Low[2]	Natural Forest	Planted Forest	Settlements	Wetlands
Surface catchment	51.83	30.13 (58 %)*	9.2 (18%)	3.59 (7%)	7.74 (15%)	0.09 (0%)	1.09 (2%)
Effective catchment	5.10	1.35 (27%)	1.28 (25%)	0.03 (1%)	2.25 (44%)	0.01 (0%)	0.16 (3%)
Groundwater	3.74	0.73 (19%)	0.75 (20%)	- (-)	2.25 (60%)	0.01 (0%)	< 0.01 (0%)
Mangakino stream	0.82	0.55 (67%)	0.27 (33%)	- (-)	- (-)	- (-)	< 0.01 (0%)
Awaroa stream	0.10	0.05 (53%)	0.03 (36%)	< 0.01 (0%)	0.01 (5%)	< 0.01 (0%)	< 0.01 (0%)
Runoff	0.44	0.03 (7%)	0.22 (50%)	0.03 (7%)	- (-)	- (-)	0.16 (36%)

* Cropland or high-producing grassland
[1] High-producing grassland
[2] Low-producing grassland or woody biomass

Table 3: Results of Mann-Kendall test and linear regression analysis for total nitrogen, ammonium-N, nitrate-N, total phosphorus, phosphate-P, suspended solids concentration (SS), total chlorophyll *a* (TChl *a*), and Secchi depth for the lake (2001-2016) and stream inflows (1995-2016). Figures in bold indicate $p < 0.05$.

	Lake Rerewhakaaitu				Mangakino stream				Awaroa stream			
	Mann-Kendall		Linear regression		Mann-Kendall		Linear regression*		Mann-Kendall		Linear regression*	
	Z	p-value	R^2	p-value	Z	p-value	R^2	p-value	Z	p-value	R^2	p-value
TN	-2.6	**8.60×10^{-3}**	1.01×10^{-2}	1.82×10^{-1}	9.5	**2.22×10^{-16}**	5.41×10^{-1}	**5.46×10^{-27}**	0.1	9.28×10^{-1}	-	-
NH_4-N	-1.8	6.62×10^{-2}	-	-	0.4	6.53×10^{-1}	-	-	-0.5	6.50×10^{-1}	-	-
NO_3-N	3.5	**4.92×10^{-4}**	4.90×10^{-3}	3.53×10^{-1}	11	**2.22×10^{-16}**	7.09×10^{-1}	**4.35×10^{-43}**	2.1	**3.20×10^{-2}**	3.53×10^{-1}	**4.50×10^{-3}**
TP	4.1	**3.35×10^{-5}**	1.01×10^{-1}	**1.07×10^{-5}**	6.8	**9.34×10^{-12}**	3.20×10^{-2}	**2.65×10^{-2}**	-0.6	5.26×10^{-1}	-	-
PO_4-P	1.7	8.06×10^{-2}	-	-	4.6	**4.24×10^{-6}**	8.11×10^{-2}	**3.13×10^{-4}**	-0.5	6.03×10^{-1}	-	-
SS	1.6	1.14×10^{-1}	-	-	-4.1	**3.68×10^{-5}**	2.80×10^{-3}	5.24×10^{-1}	-0.2	8.46×10^{-1}	-	-
TChl *a*	1.1	2.66×10^{-1}	-	-	-	-	-	-	-	-	-	-
Secchi depth	0.3	7.40×10^{-1}	-	-	-	-	-	-	-	-	-	-

* Linear regression with log-transformed data

Table 4: Slope, y-intercept, p-value, and correlation coefficient (R^2) of linear regression results for lake water level, short wavelength intensity, and air temperature Figures in bold indicate $p < 0.05$ and in blue indicate $p < 0.005$.

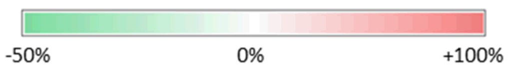
	Lake water level				Short wavelength intensity				Air temperature			
	Slope	**Y-intercept**	**p-value**	**R^2**	**Slope**	**Y-intercept**	**p-value**	**R^2**	**Slope**	**Y-intercept**	**p-value**	**R^2**
DO	-8.98×10^{-1}	$1.16 \times 10^{+1}$	**3.87×10^{-31}**	1.81×10^{-1}	-8.79×10^{-5}	-9.50×10^{-1}	8.76×10^{-1}	3.64×10^{-5}	-6.21×10^{-3}	-8.89×10^{-1}	5.96×10^{-1}	4.17×10^{-4}
TN	2.85×10^{-2}	-3.45×10^{-1}	**5.09×10^{-4}**	5.02×10^{-2}	1.85×10^{-4}	1.76×10^{-2}	**2.02×10^{-3}**	3.98×10^{-2}	2.86×10^{-3}	1.51×10^{-2}	**2.99×10^{-2}**	1.99×10^{-2}
NH_4-N	2.39×10^{-3}	-2.68×10^{-2}	1.13×10^{-1}	1.03×10^{-2}	1.91×10^{-5}	3.13×10^{-3}	7.79×10^{-2}	1.27×10^{-2}	5.44×10^{-4}	-2.28×10^{-4}	**1.95×10^{-2}**	2.22×10^{-2}
NO_3-N	4.02×10^{-3}	-6.17×10^{-2}	**2.49×10^{-4}**	5.54×10^{-2}	5.16×10^{-5}	-1.49×10^{-2}	**2.12×10^{-11}**	1.73×10^{-1}	1.27×10^{-3}	-2.16×10^{-2}	**3.96×10^{-14}**	2.16×10^{-1}
TP	2.57×10^{-3}	-3.54×10^{-2}	**3.97×10^{-12}**	1.80×10^{-1}	1.05×10^{-5}	-1.60×10^{-3}	**1.36×10^{-4}**	5.83×10^{-2}	2.83×10^{-4}	-3.24×10^{-3}	**1.44×10^{-6}**	9.13×10^{-2}
PO_4-P	5.84×10^{-4}	-5.85×10^{-3}	9.21×10^{-2}	1.16×10^{-2}	1.51×10^{-6}	2.00×10^{-3}	5.45×10^{-1}	1.50×10^{-3}	5.15×10^{-5}	1.63×10^{-3}	3.38×10^{-1}	3.76×10^{-3}
SS	5.47×10^{-1}	-7.57×10^{0}	6.24×10^{-2}	1.64×10^{-2}	-3.90×10^{-3}	7.48×10^{-1}	5.60×10^{-2}	1.72×10^{-2}	-6.10×10^{-2}	8.25×10^{-1}	1.65×10^{-1}	9.11×10^{-3}
TChl *a*	7.98×10^{-2}	-9.31×10^{-1}	2.66×10^{-1}	6.35×10^{-3}	3.02×10^{-4}	1.40×10^{-1}	5.13×10^{-1}	2.20×10^{-3}	-1.34×10^{-2}	3.57×10^{-1}	1.50×10^{-1}	1.06×10^{-2}
Secchi depth	-1.20×10^{0}	$1.51 \times 10^{+1}$	**1.45×10^{-9}**	1.58×10^{-1}	1.80×10^{-3}	-1.99×10^{0}	2.07×10^{-1}	7.45×10^{-3}	5.48×10^{-2}	-2.36×10^{0}	6.94×10^{-2}	1.54×10^{-2}

Table 5: Percentage difference of median simulated value for each scenario and the base simulation. Colours show magnitude of change of each variable (see scale).

	Lake water level	Temp (Surface)	Temp (Bottom)	DO (Surface)	DO (Bottom)
0. Base	0%	0%	0%	0%	0%
1. Climate change	-5%	17%	17%	-4%	-7%
2. Land use intensification	0%	0%	0%	2%	1%
3. Empirical change	0%	0%	0%	1%	1%
4. Combination (1-3)	-5%	17%	17%	-2%	-6%
5. Nutrient reduction	-5%	17%	17%	-4%	-7%

	TN	NH_4-N	NO_3-N	TP	PO_4-P	SS
0. Base	0%	0%	0%	0%	0%	0%
1. Climate change	23%	-8%	-36%	49%	-4%	39%
2. Land use intensification	20%	25%	16%	14%	1%	13%
3. Empirical change	13%	22%	34%	1%	-1%	5%
4. Combination (1-3)	61%	50%	22%	66%	-8%	58%
5. Nutrient reduction	15%	-17%	-41%	42%	-1%	34%

	TChl *a*	Cyanobacteria	Chlorophytes	Diatoms	Secchi depth
0. Base	0%	0%	0%	0%	0%
1. Climate change	47%	10%	238%	-71%	-29%
2. Land use intensification	12%	1%	-5%	26%	-12%
3. Empirical change	4%	0%	-16%	17%	-5%
4. Combination (1-3)	62%	8%	208%	-49%	-38%
5. Nutrient reduction	42%	13%	256%	-79%	-26%



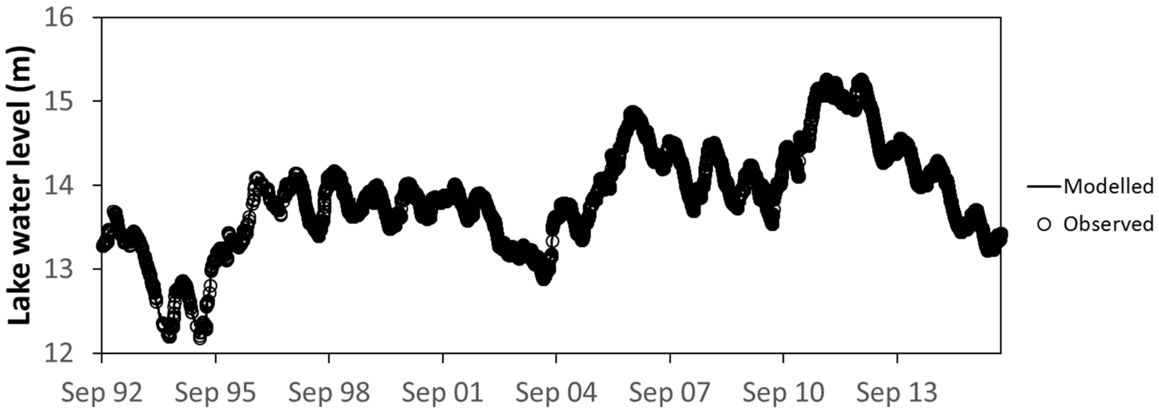


Figure 1: Simulated (line) and observed (dots) lake water level.

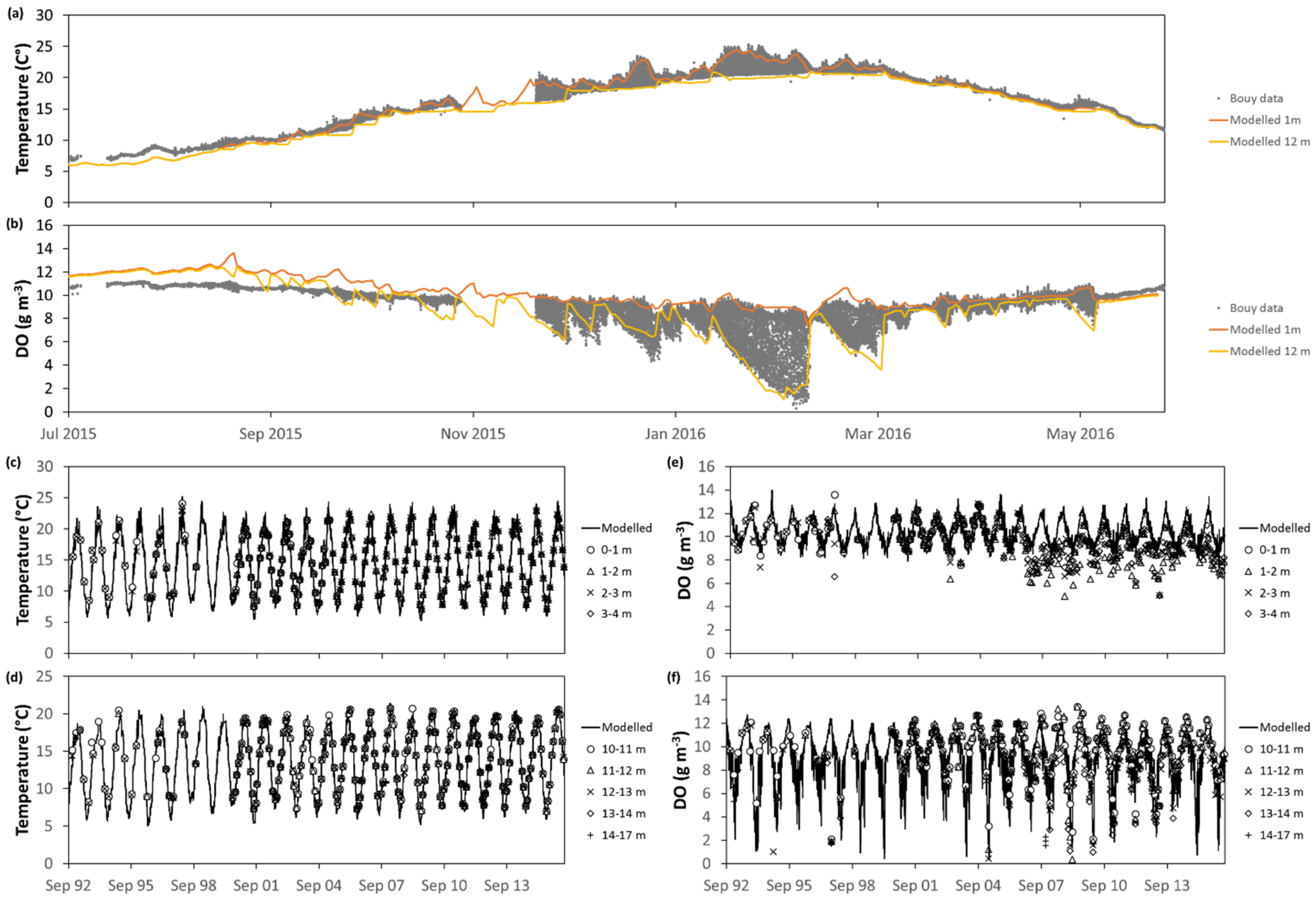


Figure 2: Calibration of model simulations (line) with high frequency data (dots) for the surface and bottom of the lake, for (a) water temperature and (b) dissolved oxygen (DO) concentration. Validation of model simulations (line) with observed data (dots) from BoPRC for (c) water temperature on surface of the lake, (d) water temperature on bottom of the lake, (e) dissolved oxygen (DO) concentration on surface of the lake, (f) DO concentration in bottom waters of the lake.

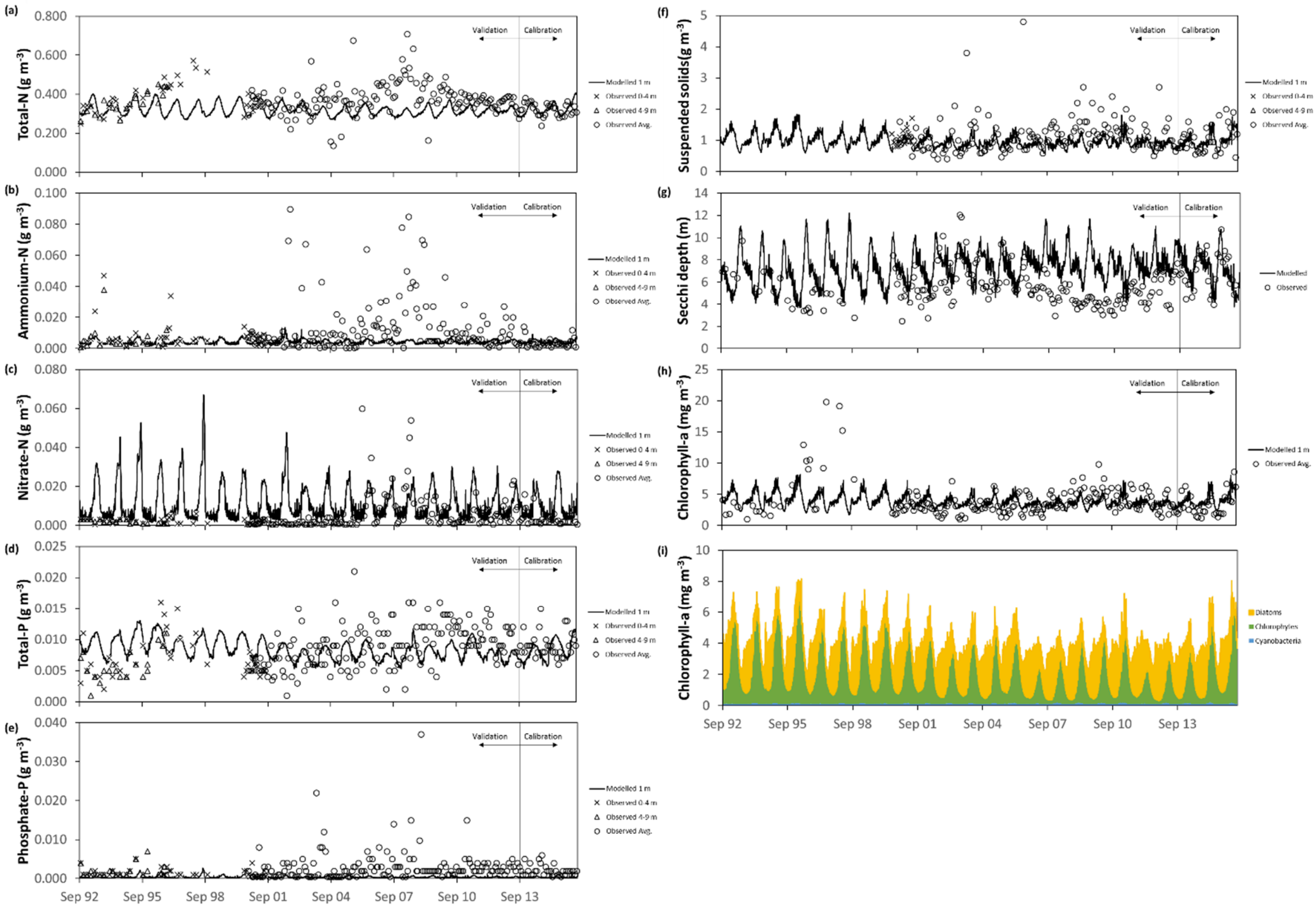


Figure 3: Model simulations (line) and observed data (dots), for (a) total nitrogen, (b) ammonium-N, (c) nitrate-N, (d) total phosphorus, (e) phosphate-P, (f) suspended solids, (g) Secchi depth, (h) total chlorophyll-a, and (i) the portion of phytoplankton groups in total chlorophyll-a. The name of dots in the legend in graph (a-f) shows the observed depth range. X dot, triangle dot, and circle dot in (a)-(f) graphs mean observed data at 0-4 m depth, 4-9 m depth, and averaged of the lake respectively. The modelled data in graph (a)-(f) and (h)-(i) was obtained at 1 m depth of the lake. The calibration and validation periods for nutrient and biomass are shown in the graphs.

Water budget		$L\ s^{-1}$	%	Sum
	Precipitation	210	66	
	Groundwater inflow	82	26	
Inflow	Runoff	8	2	317 $L\ s^{-1}$
	Mangakino stream flow	15	5	
	Awaroa stream flow	2	1	
Outflow	Groundwater outflow	192	61	317 $L\ s^{-1}$
	Evaporation	125	39	

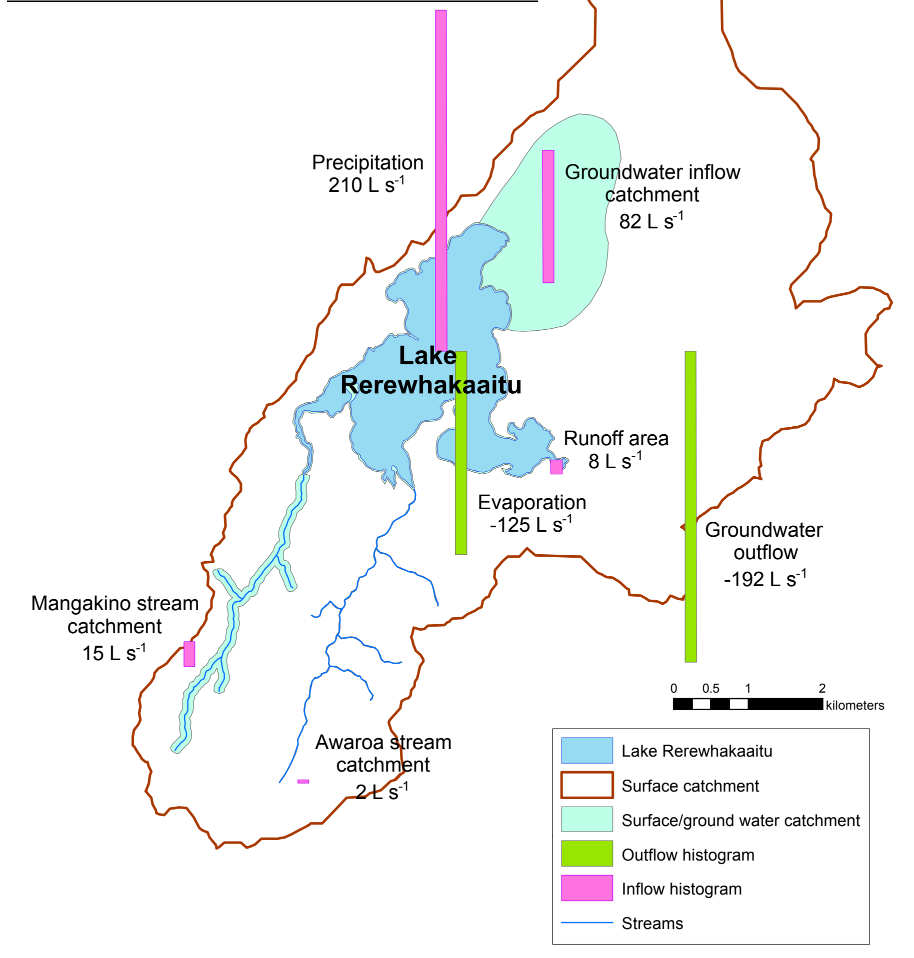


Figure 4: Map of the surface catchment by digital elevation method and effective catchment by water balance of Lake Rerewhakaaitu. Histograms represent the relative value of water entering (positive values) or leaving (negative values) the lake, respectively.

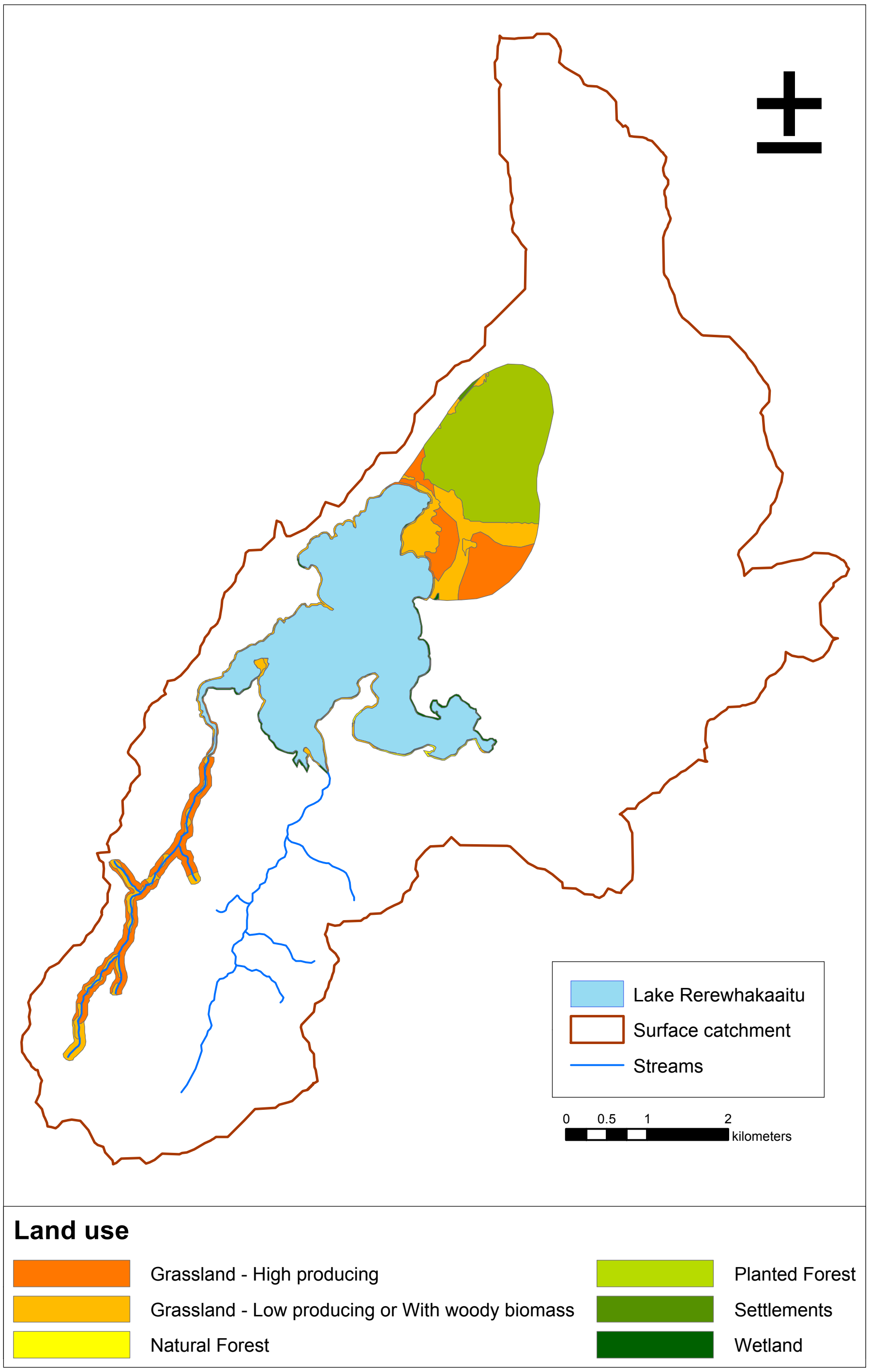


Figure 5: Effective catchment contributing water to the lake.

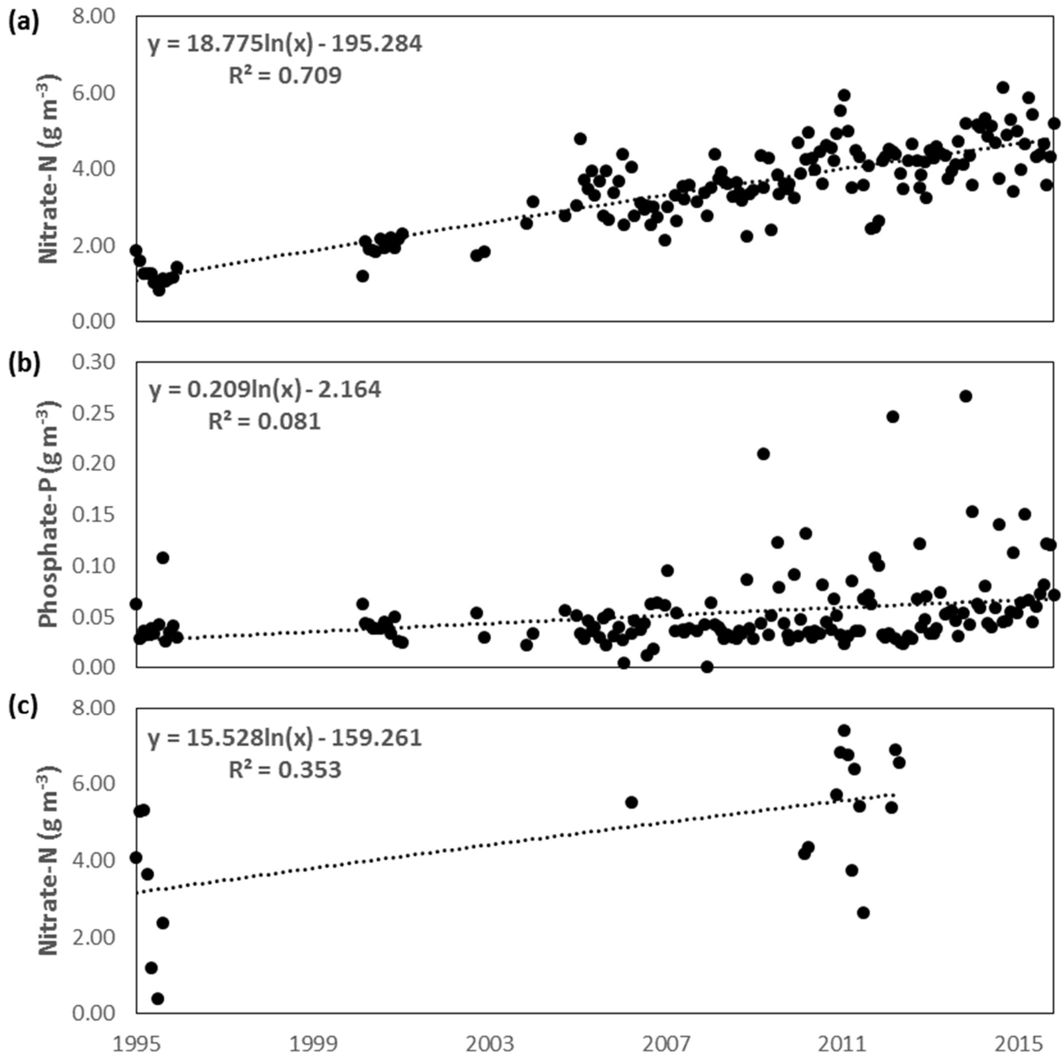


Figure 6: Observed data with empirical trend, linear regression with logarithmic transformation, for (a) nitrate-N and (b) phosphate-P concentrations (p-value = 3.13 x 10^{-4}) in Mangakino stream and (c) nitrate-N concentration (p-value = 4.50 x 10^{-3}) in Awaroa stream.

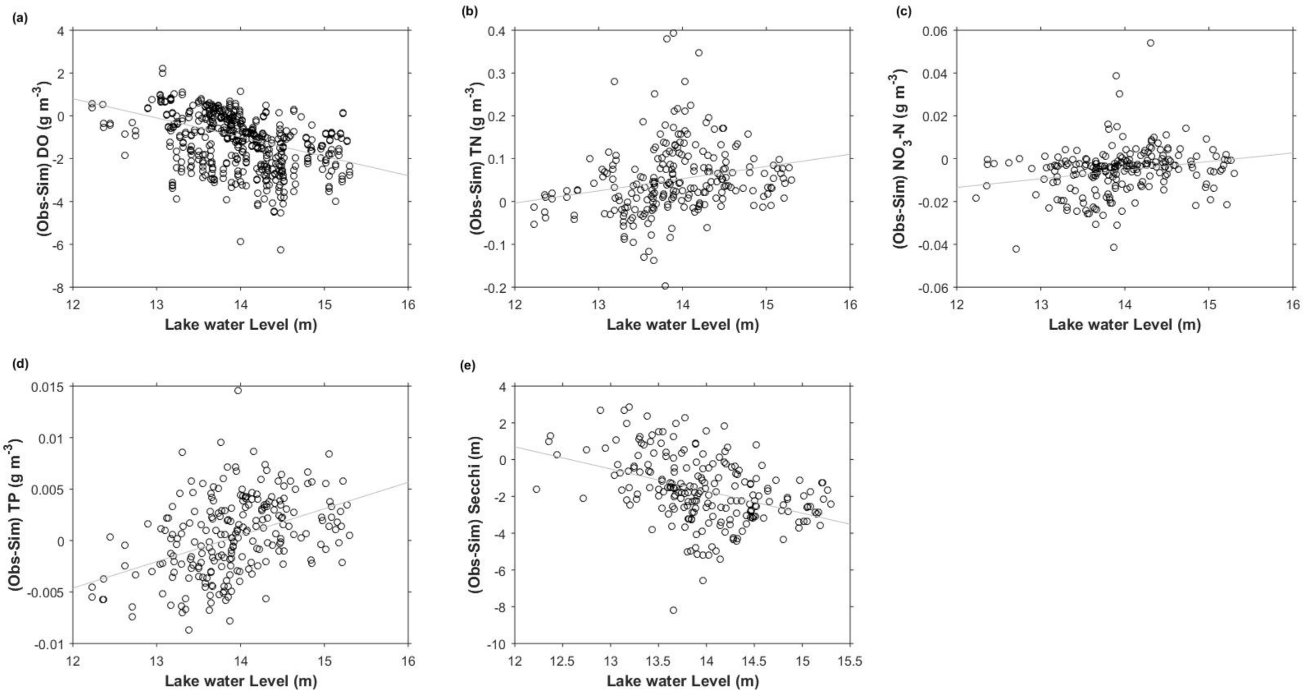


Figure 7: Linear regression model for the error of (a) DO, (b) TN, (c) nitrate-N, (d) TP, and (e) Secchi depth with lake water level. The error of each variable means the difference between observed and simulated data.

Supplementary Figures

Table S1: Nitrogen and phosphorus loading from the Lake Rerewhakaaitucatchment according to the simplified land use

	Nitrogen loading (kg N ha^{-1} yr^{-1})	Phosphorus loading (kg P ha^{-1} yr^{-1})
Grassland - High producing	31	1.1
Grassland - Low producing or With woody biomass	3.67	0.12
Wetland	0	0
Natural Forest	3.67	0.12
Planted Forest	2.81	0.18
Settlements	0	0

McIntosh, J.: Lake Rerewhakaaitu Nutrient Budget, Bay of Plenty Regional Council, 2012.
Hamilton, D.: Memo: Nutrient Budget for Lake Tarawera, 2014.

Table S2: Statistical comparison of model simulation with field data according to the depth, using root mean squared error (RMSE) and normalized RMSE (NRMSE), for temperature (Temp.), dissolved oxygen concentration (DO), total nitrogen, ammonium-N, nitrate-N, total phosphorus, phosphate-P, suspended solid concentration (SS), total chlorophyll-a (TChl-a), and Secchi depth.

	RMSE			NRMSE (%)		
	1 m	6 m	12 m	1 m	6 m	12 m
Temp. (C°)	0.7639	-	0.8103	4.5	-	5.9
DO (g m^{-3})	1.5602	-	1.7942	18.0	-	14.6
TN (g m^{-3})	0.0955	0.0928	0.0986	16.7	16.2	17.2
NH_4-N (g m^{-3})	0.0163	0.0169	0.0284	18.2	18.9	31.8
NO_3-N (g m^{-3})	0.0124	0.0135	0.0270	20.8	22.7	45.4
TP (g m^{-3})	0.0038	0.0037	0.0036	19.1	18.3	17.8
PO_4-P (g m^{-3})	0.0041	0.0043	0.0037	11.2	11.9	10.1
SS (g m^{-3})	0.5735	0.6556	0.7840	13.0	14.9	10.7
TChl-a (mg m^{-3})	2.58	-	-	13.7	-	-
Secchi depth (m)	2.47	-	-	25.8	-	-

Table S3: Average nutrient concentrations for 24 years in Lake Rerewhakaaitu.

TN	0.3711 g m^{-3}	PO_4-P	0.0023 g m^{-3}
NH_4-N	0.0138 g m^{-3}	SS	1.1 g m^{-3}
NO_3-N	0.0055 g m^{-3}	TChl-a	3.9 mg m^{-3}
TP	0.0085 g m^{-3}	Secchi depth	5.8 m

Table S4: Parameters used in DYRESM for Lake Rerewhakaaitu

Parameter	Unit	Calibrated value	Reference
Critical wind speed	m s^{-1}	4.0	Best fit to data
Emissivity of water surface	-	0.96	Imberger & Patterson (1981)
Mean albedo of water	-	0.08	Patten et al. (1975)
Potential energy mixing efficiency	-	0.2	Spigel et al. (1986)
Shear production efficiency	-	0.08	Yeates and Imberger (2003)
Wind stirring efficiency	-	0.4	Spigel et al. (1986)
Vertical mixing coefficient	-	200	Yeates and Imberger (2003)
Effective surface area coefficient	m^2	1.5×10^7	Best fit to data

Table S5: Parameters used in CAEDYM for Lake Rerewhakaaitu

Parameter	Unit	Calibrated value
Sediment parameters		
Sediment oxygen demand	g m^{-2} d^{-1}	0.7
Half-saturation coefficient for sediment oxygen demand	mg L^{-1}	1.0
Maximum potential PO_4 release rate	g m^{-2} d^{-1}	0.0028
Oxygen and nitrate half-saturation for release of phosphate from bottom sediments	g m^{-3}	1.5
Maximum potential NH_4 release rate	g m^{-2} d^{-1}	0.013
Oxygen half-saturation constant for release of ammonium from bottom sediments	g m^{-3}	0.1
Maximum potential NO_3 release rate	g m^{-2} d^{-1}	-0.03
Oxygen half-saturation constant for release of nitrate from bottom sediments	g m^{-3}	1.5
Temperature multiplier for nutrient release	-	1.06
Nutrient parameters		
Decomposition rate of POPL to DOPL	d^{-1}	0.017
Mineralisation rate of DOPL to PO_4	d^{-1}	0.07
Decomposition rate of PONL to DONL	d^{-1}	0.017
Mineralisation rate of DONL to NH_4	d^{-1}	0.016
Denitrification rate coefficient	d^{-1}	0.9
Oxygen half-saturation constant for denitrification	mg L^{-1}	1.5
Temperature multiplier for denitrification	-	1.03
Nitrification rate coefficient	d^{-1}	0.2
Nitrification half-saturation constant for oxygen	mg L^{-1}	1.5
Temperature multiplier for nitrification	-	1.03
Phytoplankton parameters		**Cyanobacteria, Chlorophytes, Diatoms**
Maximum potential growth rate at 20°C	d^{-1}	0.5, 1, 2.4
Irradiance parameter non-photoinhibited growth	µmol m^{-2} s^{-1}	300, 100, 15
Half saturation constant for phosphorus uptake	mg L^{-1}	0.005, 0.003, 0.006
Half saturation constant for nitrogen uptake	mg L^{-1}	0.04, 0.02, 0.06
Minimum internal nitrogen concentration	mg N (mg chl *a*)$^{-1}$	3, 4, 5
Maximum internal nitrogen concentration	mg N (mg chl *a*)$^{-1}$	11, 14, 12
Maximum rate of nitrogen uptake	mg N (mg chl *a*)$^{-1}$ d^{-1}	4.4, 8.8, 21.12
Minimum internal phosphorus concentration	mg P (mg chl *a*)$^{-1}$	0.4, 0.3, 0.2
Maximum internal phosphorus concentration	mg P (mg chl *a*)$^{-1}$	1.3, 2.5, 2
Maximum rate of phosphorus uptake	mg P (mg chl *a*)$^{-1}$ d^{-1}	0.63, 1.26, 3.024
Temperature multiplier for growth limitation	-	1.09, 1.10, 1.07
Standard temperature for growth	°C	20, 18, 14
Optimum temperature for growth	°C	32, 28, 23
Maximum temperature for growth	°C	39, 37, 30
Respiration rate coefficient	d^{-1}	0.05, 0.1, 0.24
Temperature multiplier for respiration	-	1.07, 1.06, 1.06
Fraction of respiration relative to total metabolic loss rate	-	0.8, 0.8, 0.8
Fraction of metabolic loss rate that goes to DOM	-	0.7, 0.7, 0.7
Constant settling velocity	m s^{-1}	$5x10^{-7}$, 0, $-3x10^{-6}$

Table S6: Slope, y-intercept, p-value, and correlation coefficient (R^2) of linear regression results for lake water level and short wavelength intensity. Bold means p-value < 0.05 (95 % confidence) and blue colour means p-value < 0.005 (99.5 % confidence).

	Lake water level				Short wavelength intensity			
	Slope	**Y-intercept**	**p-value**	**R^2**	**Slope**	**Y-intercept**	**p-value**	**R^2**
DO (1 m)	-8.98×10^{-1}	1.16×10^{1}	**3.87×10^{-31}**	1.81×10^{-1}	-8.79×10^{-5}	-9.50×10^{-1}	8.76×10^{-1}	3.64×10^{-5}
DO (12 m)	-9.72×10^{-1}	1.32×10^{1}	**5.87×10^{-20}**	1.08×10^{-1}	1.30×10^{-3}	-7.11×10^{-1}	8.12×10^{-2}	4.16×10^{-3}
TN (1 m)	2.85×10^{-2}	-3.45×10^{-1}	**5.09×10^{-4}**	5.02×10^{-2}	1.85×10^{-4}	1.76×10^{-2}	**2.02×10^{-3}**	3.98×10^{-2}
TN (6 m)	2.48×10^{-2}	-3.00×10^{-1}	**6.25×10^{-3}**	3.73×10^{-2}	1.57×10^{-4}	1.91×10^{-2}	**1.73×10^{-2}**	2.84×10^{-2}
TN (12 m)	1.92×10^{-2}	-2.21×10^{-1}	**1.12×10^{-2}**	1.85×10^{-2}	1.68×10^{-4}	1.90×10^{-2}	**1.98×10^{-3}**	2.75×10^{-2}
NH_4-N (1 m)	2.39×10^{-3}	-2.68×10^{-2}	1.13×10^{-1}	1.03×10^{-2}	1.91×10^{-5}	3.13×10^{-3}	7.79×10^{-2}	1.27×10^{-2}
NH_4-N (6 m)	2.42×10^{-3}	-2.78×10^{-2}	1.72×10^{-1}	9.06×10^{-3}	1.41×10^{-5}	3.65×10^{-3}	2.67×10^{-1}	6.00×10^{-3}
NH_4-N (12 m)	3.66×10^{-3}	-4.26×10^{-2}	1.22×10^{-1}	6.72×10^{-3}	4.27×10^{-5}	1.43×10^{-3}	**1.06×10^{-2}**	1.82×10^{-2}
NO_3-N (1 m)	4.02×10^{-3}	-6.17×10^{-2}	**2.49×10^{-4}**	5.54×10^{-2}	5.16×10^{-5}	-1.49×10^{-2}	**2.12×10^{-11}**	1.73×10^{-1}
NO_3-N (6 m)	4.74×10^{-3}	-7.49×10^{-2}	**4.10×10^{-5}**	8.16×10^{-2}	2.70×10^{-5}	-1.33×10^{-2}	**1.30×10^{-3}**	5.10×10^{-2}
NO_3-N (12 m)	6.52×10^{-3}	-1.10×10^{-1}	**1.63×10^{-4}**	4.05×10^{-2}	-4.56×10^{-5}	-1.05×10^{-2}	**2.40×10^{-4}**	3.85×10^{-2}
TP (1 m)	2.57×10^{-3}	-3.54×10^{-2}	**3.97×10^{-12}**	1.80×10^{-1}	1.05×10^{-5}	-1.60×10^{-3}	**1.36×10^{-4}**	5.83×10^{-2}
TP (6 m)	2.32×10^{-3}	-3.19×10^{-2}	**3.93×10^{-9}**	1.57×10^{-1}	8.66×10^{-6}	-1.06×10^{-3}	**2.84×10^{-3}**	4.28×10^{-2}
TP (12 m)	1.47×10^{-3}	-2.06×10^{-2}	**1.88×10^{-6}**	6.27×10^{-2}	4.33×10^{-6}	-7.53×10^{-4}	5.15×10^{-2}	1.08×10^{-2}
PO_4-P (1 m)	5.84×10^{-4}	-5.85×10^{-3}	9.21×10^{-2}	1.16×10^{-2}	1.51×10^{-6}	2.00×10^{-3}	5.45×10^{-1}	1.50×10^{-3}
PO_4-P (6 m)	5.15×10^{-4}	-4.81×10^{-3}	2.09×10^{-1}	7.70×10^{-3}	1.23×10^{-6}	2.18×10^{-3}	6.75×10^{-1}	8.60×10^{-4}
PO_4-P (12 m)	7.30×10^{-4}	-8.89×10^{-3}	**1.52×10^{-2}**	1.65×10^{-2}	-4.77×10^{-6}	2.19×10^{-3}	**2.54×10^{-2}**	1.40×10^{-2}
SS (1 m)	7.98×10^{-2}	-9.31×10^{-1}	2.66×10^{-1}	6.35×10^{-3}	3.02×10^{-4}	1.40×10^{-1}	5.13×10^{-1}	2.20×10^{-3}
SS (6 m)	4.92×10^{-2}	-3.67×10^{-1}	5.19×10^{-1}	2.29×10^{-3}	1.07×10^{-3}	1.43×10^{-1}	**3.13×10^{-2}**	2.52×10^{-2}
SS (12 m)	1.61×10^{-2}	1.20×10^{-1}	8.11×10^{-1}	1.68×10^{-4}	8.82×10^{-4}	1.96×10^{-1}	5.03×10^{-2}	1.13×10^{-2}
Chl-a	5.47×10^{-1}	-7.57×10^{0}	6.24×10^{-2}	1.64×10^{-2}	-3.90×10^{-3}	7.48×10^{-1}	5.60×10^{-2}	1.72×10^{-2}
Secchi	-1.20×10^{0}	1.51×10^{1}	**1.45×10^{-9}**	1.58×10^{-1}	1.80×10^{-3}	-1.99×10^{0}	2.07×10^{-1}	7.45×10^{-3}

Table S7: Slope, y-intercept, p-value, and correlation coefficient (R^2) of linear regression results for air temperature, vapour pressure, and wet temperature. Bold means p-value < 0.05 (95 % confidence) and blue colour means p-value < 0.005 (99.5 % confidence).

	Air temperature				Vapour pressure				Wet temperature			
	Slope	Y-intercept	p-value	R^2	Slope	Y-intercept	p-value	R^2	Slope	Y-intercept	p-value	R^2
DO (1 m)	-6.21×10^{-3}	-8.89×10^{-1}	5.96×10^{-1}	4.17×10^{-4}	-2.12×10^{-2}	-7.11×10^{-1}	1.63×10^{-1}	2.88×10^{-3}	-1.88×10^{-2}	-6.15×10^{-1}	1.65×10^{-1}	3.43×10^{-3}
DO (12 m)	6.54×10^{-2}	-1.29×10^{0}	**4.22×10^{-5}**	2.27×10^{-2}	6.64×10^{-2}	-1.29×10^{0}	**1.39×10^{-3}**	1.39×10^{-2}	6.56×10^{-2}	-1.06×10^{0}	**6.50×10^{-4}**	1.93×10^{-2}
TN (1 m)	2.86×10^{-3}	1.51×10^{-2}	**2.99×10^{-2}**	1.99×10^{-2}	4.24×10^{-3}	-6.41×10^{-4}	**1.42×10^{-2}**	2.53×10^{-2}	3.70×10^{-3}	2.14×10^{-2}	**2.26×10^{-2}**	2.65×10^{-2}
TN (6 m)	2.01×10^{-3}	2.18×10^{-2}	1.60×10^{-1}	1.00×10^{-2}	2.71×10^{-3}	1.38×10^{-2}	1.48×10^{-1}	1.06×10^{-2}	2.63×10^{-3}	3.08×10^{-2}	1.47×10^{-1}	1.34×10^{-2}
TN (12 m)	2.12×10^{-3}	2.21×10^{-2}	6.05×10^{-2}	1.02×10^{-2}	2.88×10^{-3}	1.35×10^{-2}	5.18×10^{-2}	1.09×10^{-2}	2.86×10^{-3}	3.47×10^{-2}	**4.76×10^{-2}**	1.49×10^{-2}
NH_4-N (1 m)	5.44×10^{-4}	-2.28×10^{-4}	**1.95×10^{-2}**	2.22×10^{-2}	7.76×10^{-4}	-2.88×10^{-3}	**1.09×10^{-2}**	2.62×10^{-2}	6.34×10^{-4}	1.04×10^{-3}	**2.96×10^{-2}**	2.31×10^{-2}
NH_4-N (6 m)	4.03×10^{-4}	1.11×10^{-3}	1.37×10^{-1}	1.08×10^{-2}	6.34×10^{-4}	-1.60×10^{-3}	7.22×10^{-2}	1.57×10^{-2}	5.23×10^{-4}	2.13×10^{-3}	1.35×10^{-1}	1.36×10^{-2}
NH_4-N (12 m)	1.38×10^{-3}	-8.34×10^{-3}	**6.59×10^{-5}**	4.39×10^{-2}	1.88×10^{-3}	-1.41×10^{-2}	**3.01×10^{-5}**	4.79×10^{-2}	1.78×10^{-3}	-7.56×10^{-3}	**1.24×10^{-4}**	5.26×10^{-2}
NO_3-N (1 m)	1.27×10^{-3}	-2.16×10^{-2}	**3.96×10^{-14}**	2.16×10^{-1}	1.47×10^{-3}	-2.36×10^{-2}	**2.87×10^{-11}**	1.71×10^{-1}	1.27×10^{-3}	-1.93×10^{-2}	**1.49×10^{-9}**	1.71×10^{-1}
NO_3-N (6 m)	4.73×10^{-4}	-1.45×10^{-2}	**1.03×10^{-2}**	3.28×10^{-2}	4.88×10^{-4}	-1.45×10^{-2}	**4.18×10^{-2}**	2.08×10^{-2}	4.05×10^{-4}	-1.30×10^{-2}	8.62×10^{-2}	1.86×10^{-2}
NO_3-N (12 m)	-1.72×10^{-3}	3.16×10^{-3}	**2.05×10^{-11}**	1.23×10^{-1}	-2.21×10^{-3}	8.62×10^{-3}	**3.30×10^{-11}**	1.20×10^{-1}	-1.84×10^{-3}	8.92×10^{-4}	**2.91×10^{-8}**	1.11×10^{-1}
TP (1 m)	2.83×10^{-4}	-3.24×10^{-3}	**1.44×10^{-6}**	9.13×10^{-2}	3.91×10^{-4}	-4.46×10^{-3}	**3.70×10^{-7}**	1.01×10^{-1}	3.26×10^{-4}	-3.34×10^{-3}	**4.93×10^{-6}**	9.84×10^{-2}
TP (6 m)	2.05×10^{-4}	-2.08×10^{-3}	**9.27×10^{-4}**	5.25×10^{-2}	2.80×10^{-4}	-2.94×10^{-3}	**5.41×10^{-4}**	5.71×10^{-2}	2.33×10^{-4}	-2.12×10^{-3}	**2.62×10^{-3}**	5.42×10^{-2}
TP (12 m)	4.35×10^{-5}	-5.41×10^{-4}	3.46×10^{-1}	2.53×10^{-3}	8.07 E-05	-9.82×10^{-4}	1.80×10^{-1}	5.12×10^{-3}	4.69×10^{-5}	-5.40×10^{-4}	4.14×10^{-1}	2.48×10^{-3}
PO_4-P (1 m)	5.15×10^{-5}	1.63×10^{-3}	3.38×10^{-1}	3.76×10^{-3}	6.69 E-05	1.46×10^{-3}	3.42×10^{-1}	3.70×10^{-3}	6.20×10^{-5}	1.67×10^{-3}	3.62×10^{-1}	4.10×10^{-3}
PO_4-P (6 m)	3.24×10^{-5}	1.99×10^{-3}	6.05×10^{-1}	1.31×10^{-3}	4.23 E-05	1.88×10^{-3}	6.05×10^{-1}	1.31×10^{-3}	4.42×10^{-5}	2.04×10^{-3}	5.90×10^{-1}	1.77×10^{-3}
PO_4-P (12 m)	-1.41×10^{-4}	3.11×10^{-3}	**1.47×10^{-3}**	2.81×10^{-2}	-1.68×10^{-4}	3.41×10^{-3}	**3.56×10^{-3}**	2.37×10^{-2}	-1.34×10^{-4}	2.85×10^{-3}	**2.34×10^{-2}**	1.87×10^{-2}
SS (1 m)	-1.34×10^{-2}	3.57×10^{-1}	1.50×10^{-1}	1.06×10^{-2}	-1.78×10^{-2}	4.07×10^{-1}	1.40×10^{-1}	1.11×10^{-2}	-2.02×10^{-2}	4.30×10^{-1}	8.19×10^{-2}	1.95×10^{-2}
SS (6 m)	1.20×10^{-2}	1.77×10^{-1}	2.43×10^{-1}	7.48×10^{-3}	1.37×10^{-2}	1.59×10^{-1}	3.01×10^{-1}	5.87×10^{-3}	4.89×10^{-3}	3.06×10^{-1}	7.09×10^{-1}	9.92×10^{-4}
SS (12 m)	1.02×10^{-2}	2.21×10^{-1}	2.73×10^{-1}	3.54×10^{-3}	1.29×10^{-2}	1.90×10^{-1}	2.84×10^{-1}	3.38×10^{-3}	3.31×10^{-3}	3.72×10^{-1}	7.88×10^{-1}	2.83×10^{-4}
Chl-a	-6.10×10^{-2}	8.25×10^{-1}	1.65×10^{-1}	9.11×10^{-3}	-2.16×10^{-2}	3.35×10^{-1}	7.07×10^{-1}	6.73×10^{-4}	-5.32×10^{-2}	7.65×10^{-1}	3.43×10^{-1}	5.29×10^{-3}
Secchi	5.48×10^{-2}	-2.36×10^{0}	6.94×10^{-2}	1.54×10^{-2}	3.53×10^{-2}	-2.11×10^{0}	3.69×10^{-1}	3.79×10^{-3}	5.73×10^{-2}	-2.49×10^{0}	1.06×10^{-1}	1.51×10^{-2}

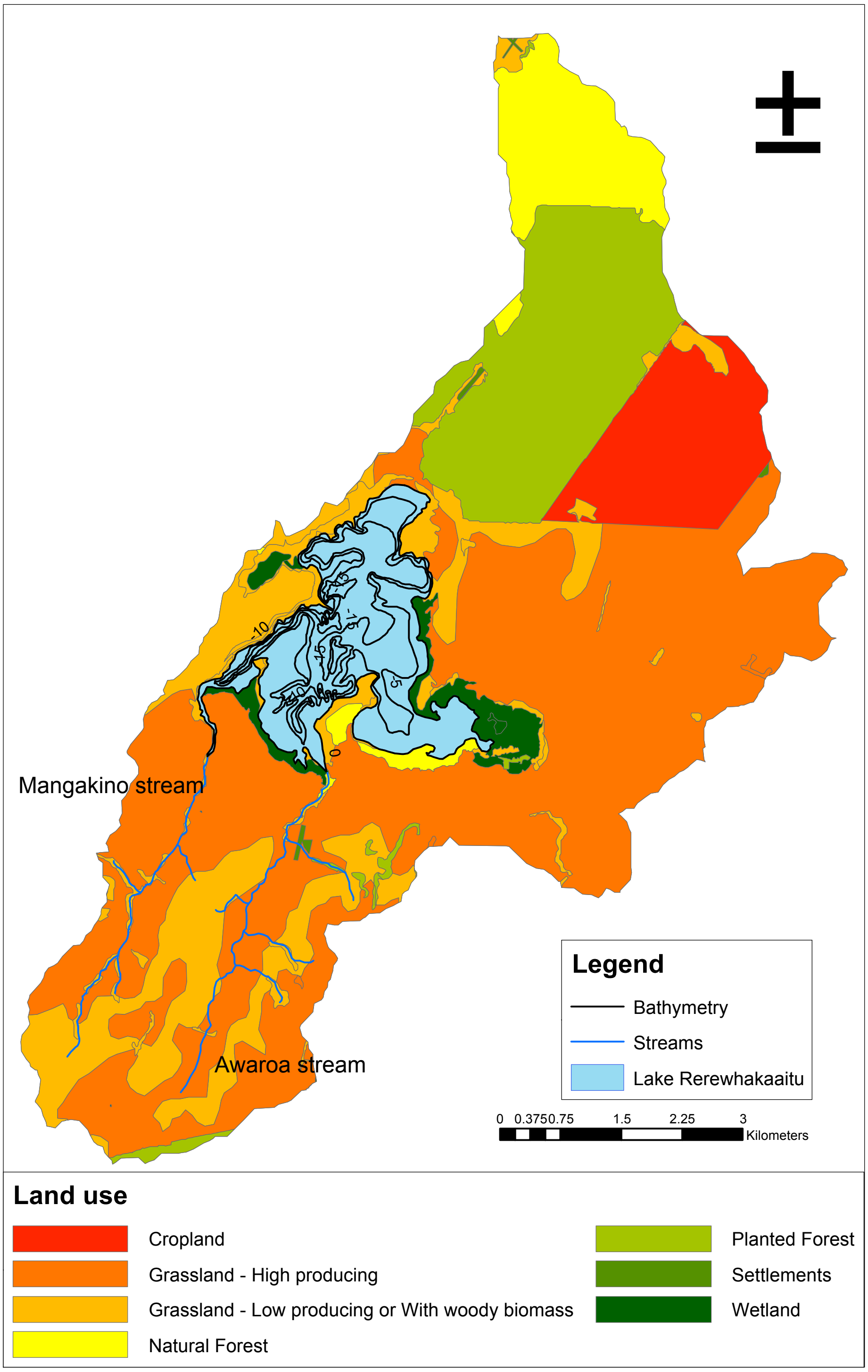


Figure S8: Current land use by simplified classification based on surface catchment and bathymetry of Lake Rerewhakaaitu with Mangakino and Awaroa stream.

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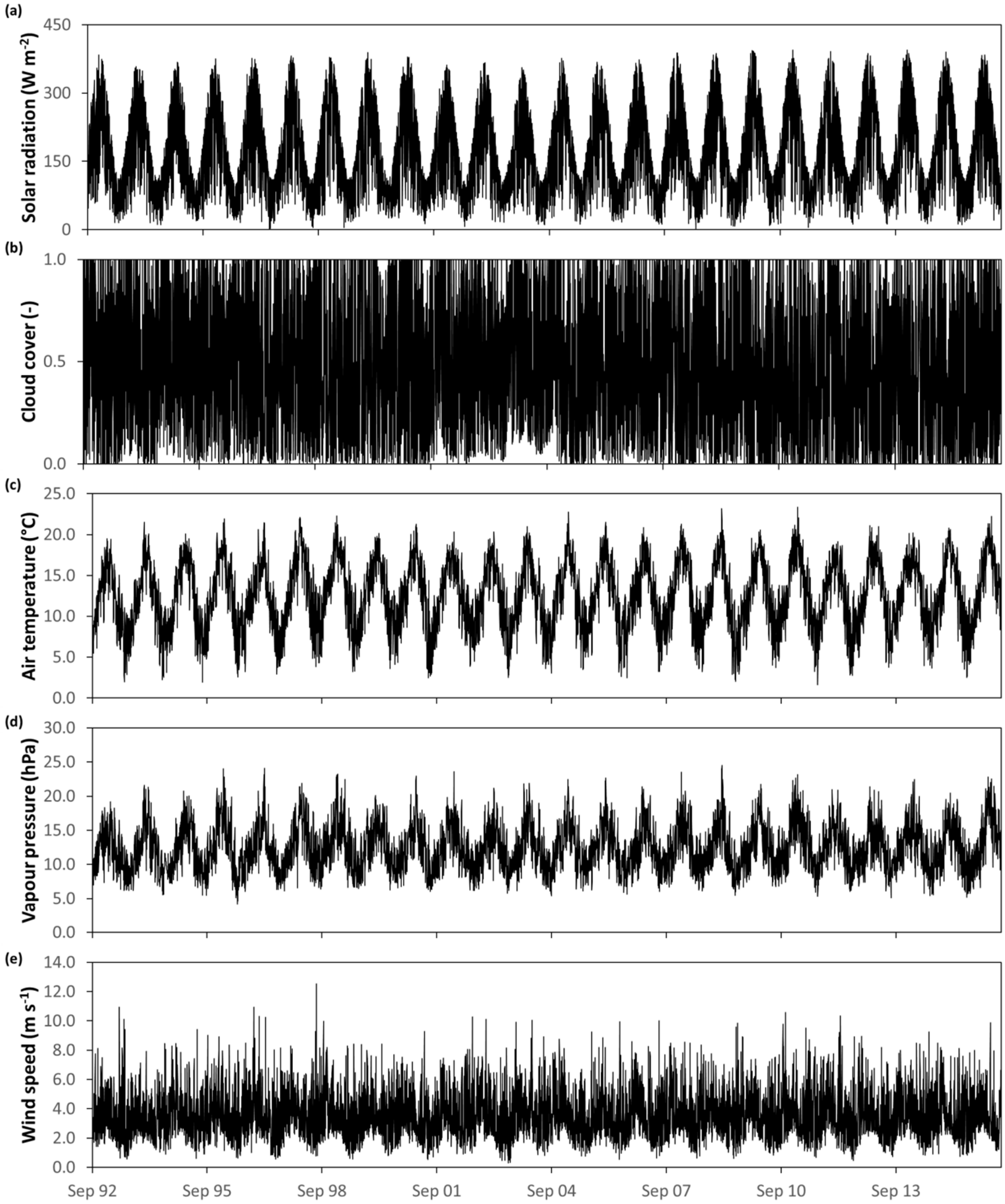

Figure S9: Meteorological input data for (a) solar radiation, (b) cloudy cover, (c) air temperature, (d) vapour pressure, (e) wind speed.

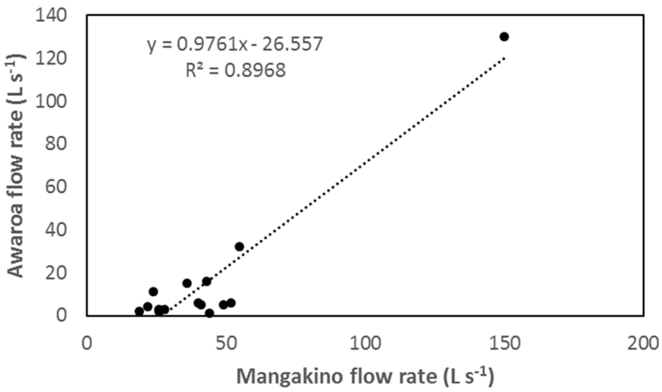

Figure S10: Linear relation between Mangakino stream flow rate and Awaroa stream flow rate.

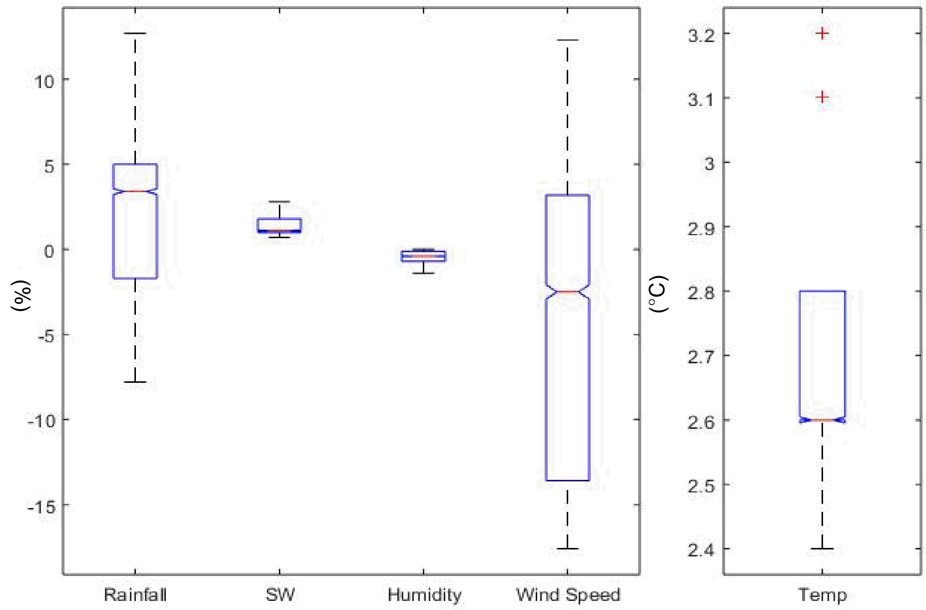

Figure S11: Variation for percentage or absolute value of meteorological data by monthly for climate change scenario based on Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC AR5), from left to right rainfall, short wavelength (SW), humidity, wind speed, and air temperature (Temp).

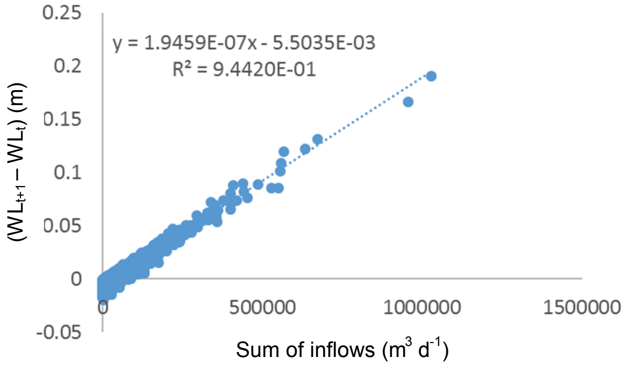

Figure S12: Linear regression model between the difference of daily water level and sum of inflows including two stream flows and residual flow.

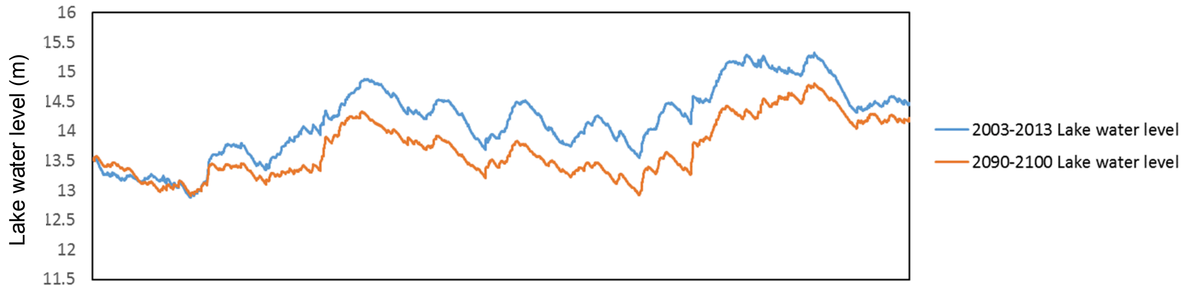

Figure S13: Present and estimated future lake water level calculated iteration using Excel-VBA.

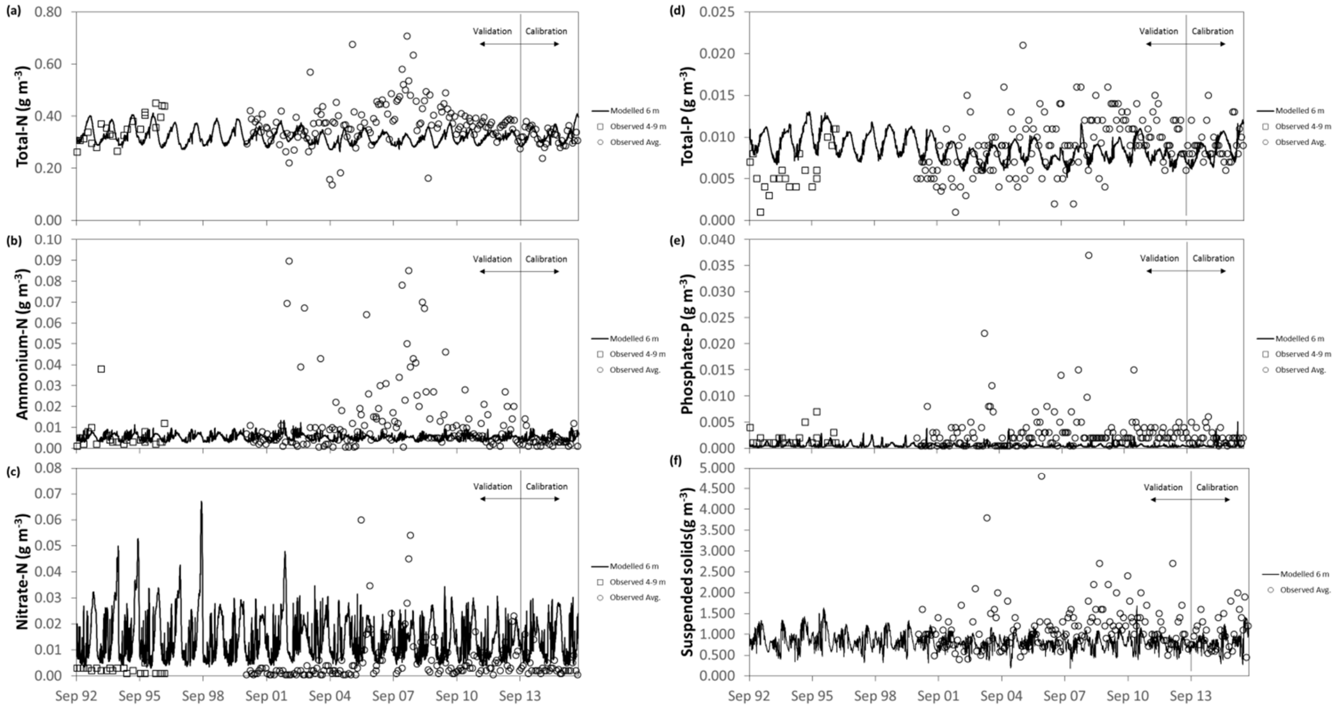

Figure S14: Comparison of model simulations (line) with observed data (dots), for (a) total nitrogen, (b) ammonium-N, (c) nitrate-N, (d) total phosphorus, (e) phosphate-P, and (f) suspended solid concentration. The name of dots in legend shows the observed depth range. Rectangular dot and circle dot mean observed data at 4-9 m depth and averaged of the lake respectively. The modelled data in graph was obtained at 6 m depth of the lake. The calibration and validation periods are shown in the graphs.

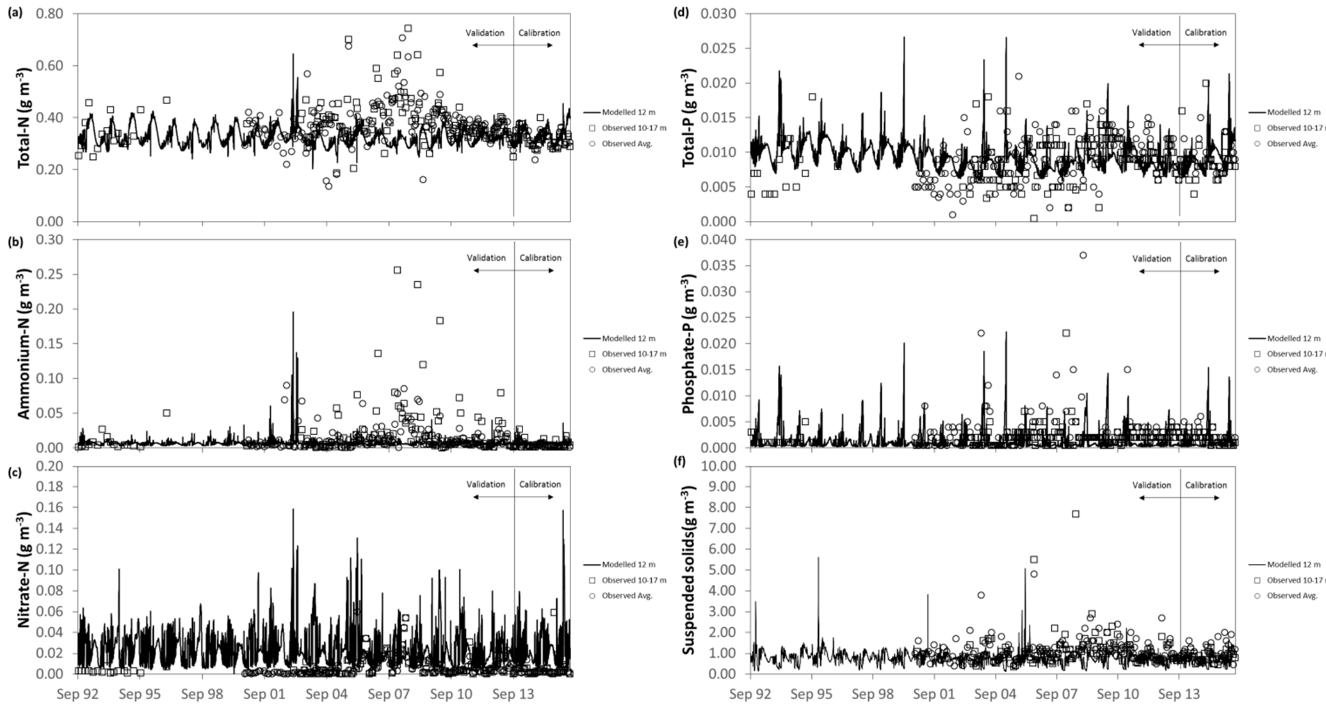

Figure S15: Comparison of model simulations (line) with observed data (dots), for (a) total nitrogen, (b) ammonium-N, (c) nitrate-N, (d) total phosphorus, (e) phosphate-P, and (f) suspended solid concentration. The name of dots in legend shows the observed depth range. Rectangular dot and circle dot mean observed data at 10-17 m depth and averaged of the lake respectively. The modelled data in graph was obtained at 12 m depth of the lake. The calibration and validation periods are shown in the graphs.

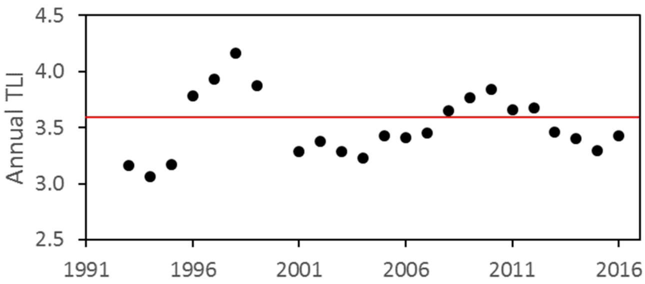

Figure S16: Annual trophic level index (TLI) variation with goal of BOPRC (red line).

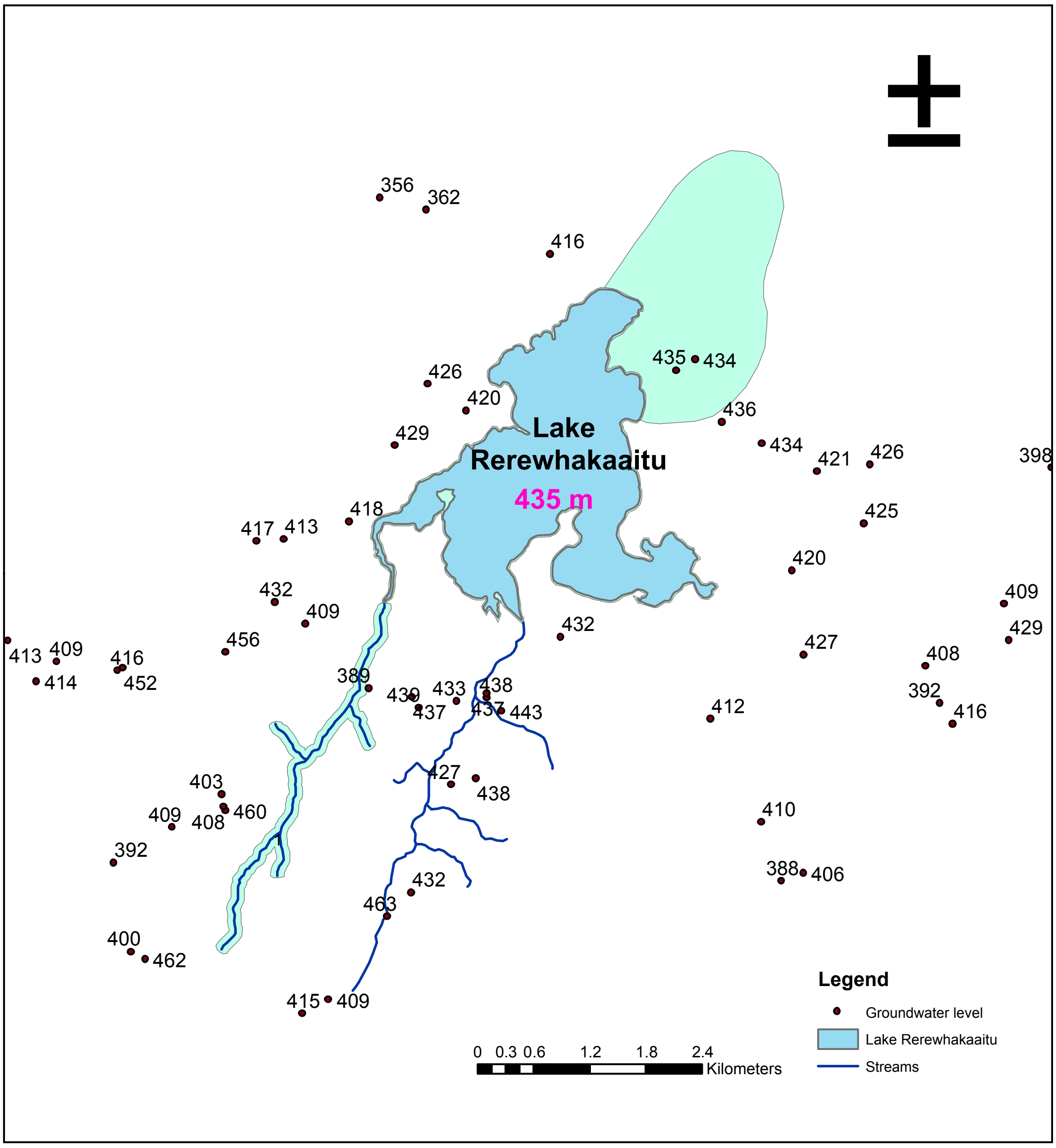

Figure S17: Groundwater level around Lake Rerewhakaaitu.

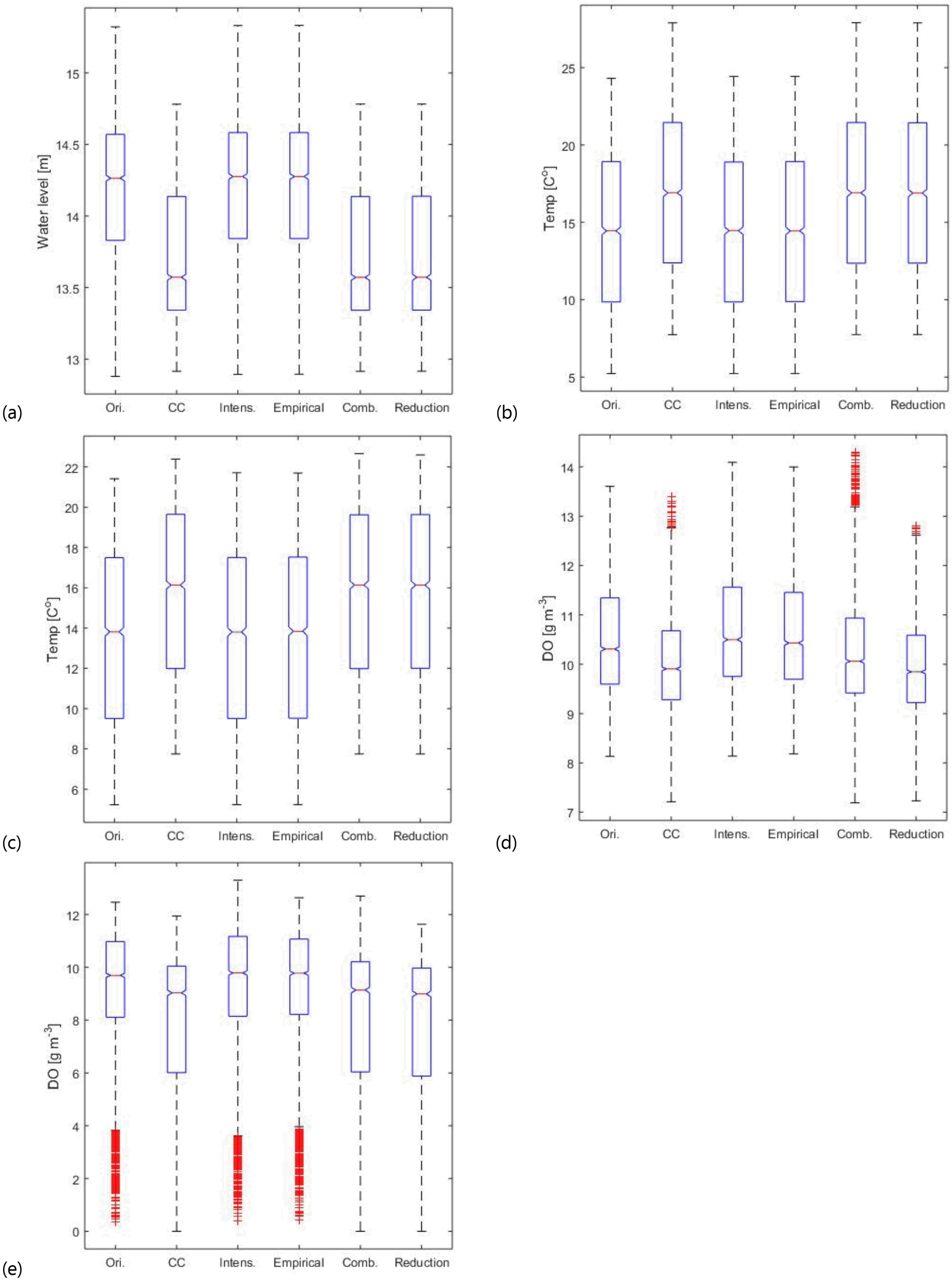

Figure S18: Box plots for all scenario simulation, for a) lake water level, b) surface water temperature, c) bottom water temperature, d) surface dissolved oxygen concentration, and e) bottom dissolved oxygen concentration. Ori., CC, Intens., Empirical, Comb., Reduction mean base simulation, climate change scenario, land use intensification scenario, empirical scenario, combination scenario, and nutrient reduction scenario, respectively.

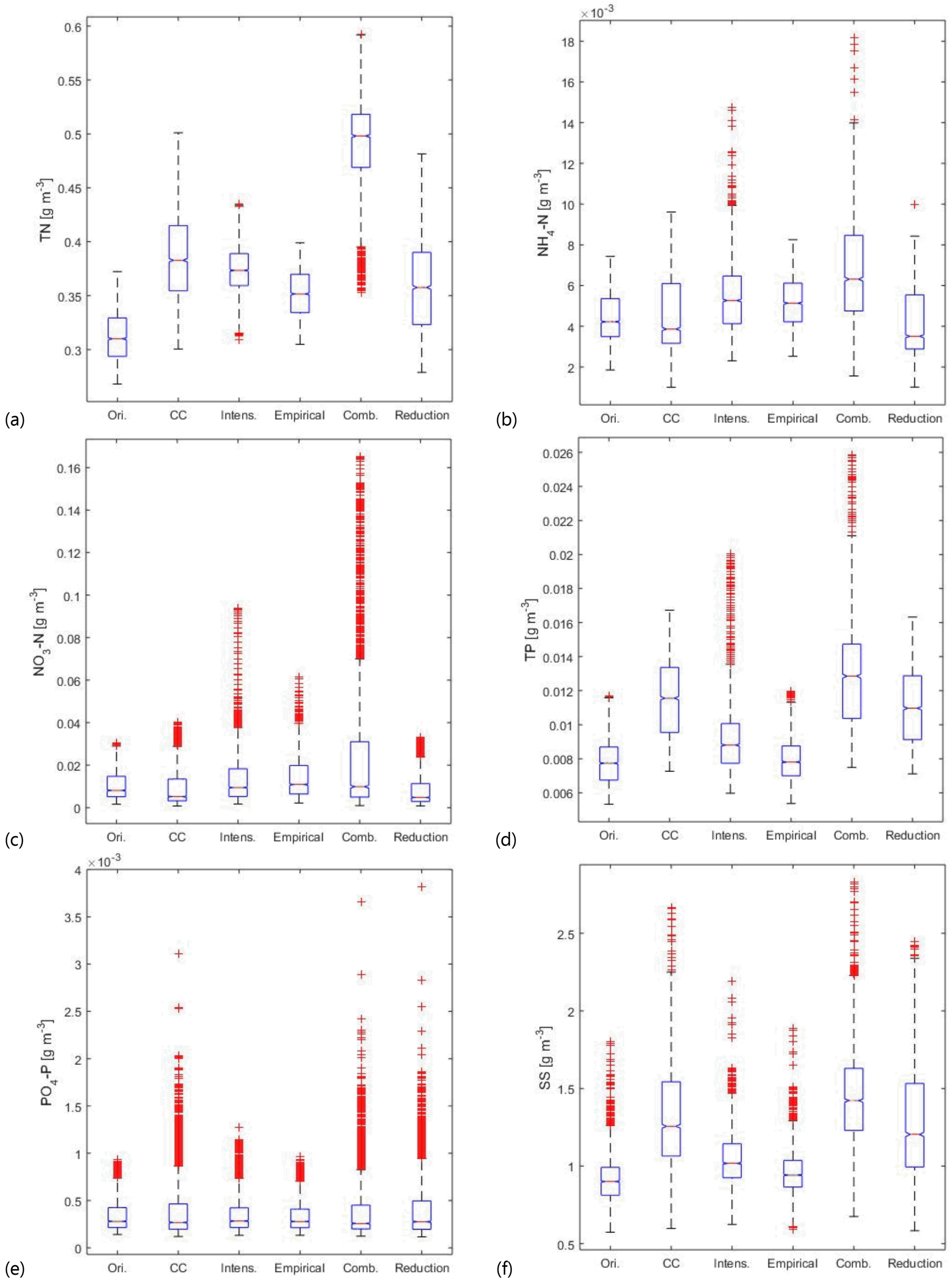

Figure S19: Box plots for all scenario simulation, for a) total nitrogen, b) ammonium-N, c) nitrate-N, d) total phosphorus, e) phosphate-P, (f) suspended solid concentration. Ori., CC, Intens., Empirical, Comb., Reduction mean base simulation, climate change scenario, land use intensification scenario, empirical scenario, combination scenario, and nutrient reduction scenario, respectively.

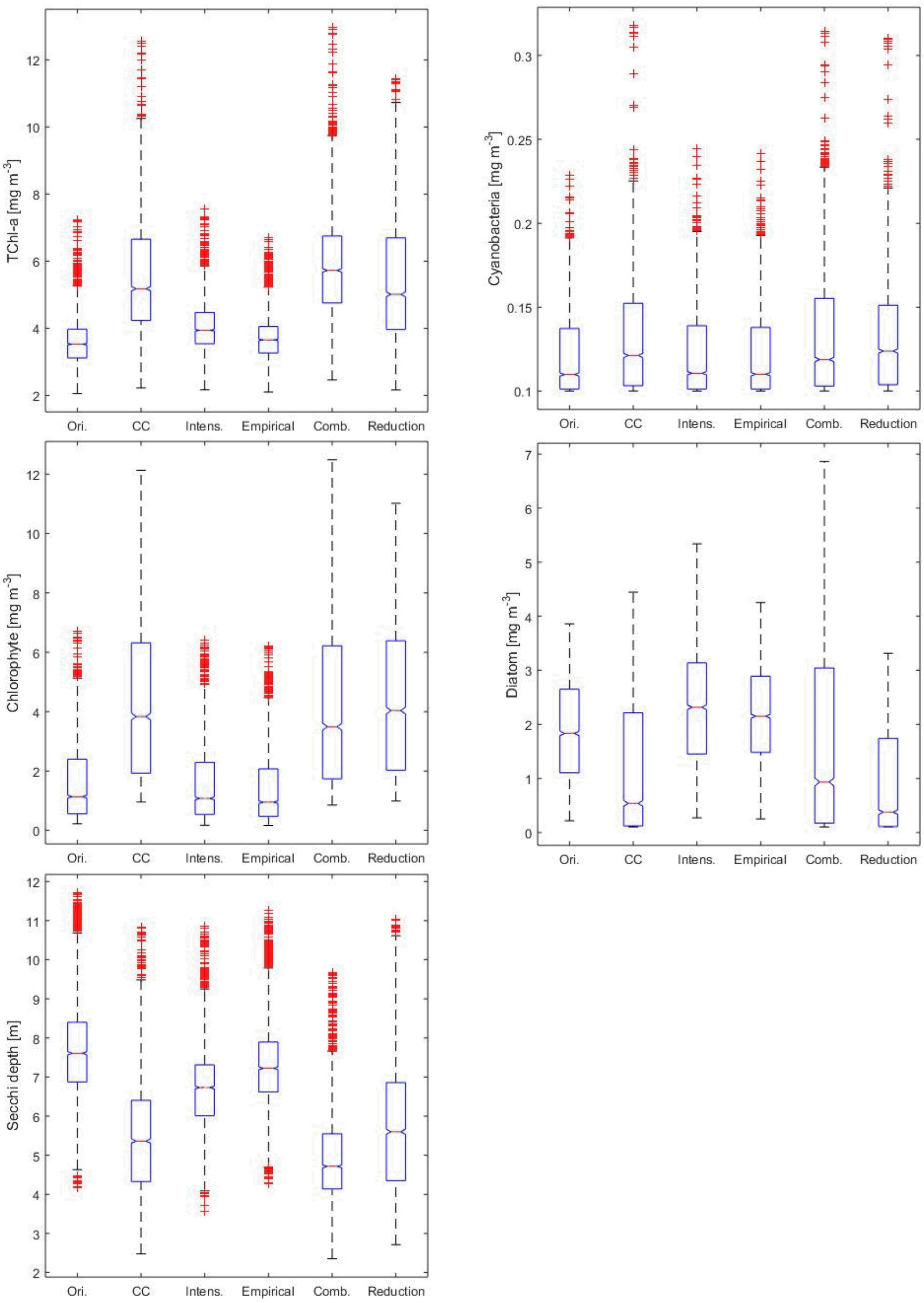

Figure S20: Box plots for all scenario simulation, for a) total chlorophyll-a, b) cyanobacteria, c) chlorophyte, d) diatom, and e) Secchi depth. Ori., CC, Intens., Empirical, Comb., Reduction mean base simulation, climate change scenario, land use intensification scenario, empirical scenario, combination scenario, and nutrient reduction scenario, respectively.