Restoration of Lake Hakanoa: Results of model simulations

CBER Contract Report 118

Prepared for Waikato District Council

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Front cover – Photo: Wendy Paul

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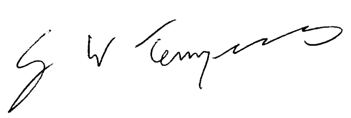

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Executive Summary

This report was requested by Waikato District Council. It covers the lake water quality of, and possible restoration scenarios for, Lake Hakanoa a riverine lake situated in Huntly. The lake is used as a recreational resource by the community. In the past it has been reported to have had very poor water quality and is known to be eutrophic. It is currently in an algal-dominated, devegetated state and has low water clarity. The shallowness of this lake makes it potentially susceptible to resuspension of sediments through wind action. A community group, Friends of Hakanoa, has been responsible for the formation of a path around the perimeter of the lake, retiring about 3.6% of the catchment from pastoral farming and creating a riparian margin. Results from more recent reports and this report indicate a trend of improving water quality which may be related to recent restoration actions such as re-establishment of a riparian margin.

After consideration of possible restoration scenarios applicable to Lake Hakanoa, two main scenarios were modelled; wetland creation and change of land use in the catchment from pastoral farming to exotic forestry. A third scenario combining those two actions and the removal of septic tanks was also modelled. Some scenarios were discounted for financial, cultural and practical reasons and thus were not modelled. These included removal of invasive fish, sediment removal and sediment capping with a chemical flocculant. Although experimental at this stage, an option that may also be considered by the council is the possibility of floating wetlands.

All modelled scenarios showed that there would be an improvement in lake water quality. The actual degree of improvement is not absolute since nutrient exports for exotic forestry in particular are variable. Nitrogen and phosphorus exports from exotic forestry are usually less than those from dairy farming and dry stock farming, and therefore, for each scenario of increased land use in forestry, there was an improvement in water quality.

The combination of land use change from pastoral to forestry, expansion of wetlands, and removal of septic tanks produced the best outcome in terms of water quality evaluated by trophic state, specifically, the Trophic Level Index (TLI). Based on these results it is clear that substantial improvements in lake water quality will only be possible with a substantial reduction in catchment nutrient export to the lake, and the council will need to consider incentives or legislation that will reduce the nutrient export. Investigation into incentives for conversion of pastoral land to exotic forestry, utilising the carbon credits scheme, are encouraged. Removal of septic tanks should not be discounted as means of improvement but we recommend that the status of septic tank usage in the catchment first be assessed. We recommend that the council gains professional advice on the best methods to form a treatment wetland as their effect can be enhanced by appropriate design and use of nutrient-adsorbing materials.

Introduction

Lake Hakanoa is one of the Lower Waikato riverine lakes (Hamill, 2006) formed through volcanic activity, floods and changes in the course of Waikato River over 14,000 years ago (McCraw, 2002).

The lake was classified as hypertrophic with a trophic level index (TLI) of 6.7 in 2006 (Hamill, 2006). It has frequent cyanobacterial blooms (Hudson et al., 2008) and is likely to be in a de-vegetated state (Edwards et al., 2007) being rated as having a 'poor' LakeSPI classification (Hamill, 2006). Accelerated eutrophication through human activity, herbicide spraying, and subsequent collapse of invasive submerged macrophytes contribute to the present algal-dominated, turbid state of this lake (Champion et al., 1993). Lake Hakanoa supports invasive fish species also known to contribute to poor water quality (Hudson et al., 2008). The maximum lake depth is 2.5 m (Hamill, 2006), the area is 0.56 km^2, and thus the lake is likely to be susceptible to resuspension of sediments through wind action.

A community group, Friends of Hakanoa, has been responsible for the formation of a 3.62 km path around the perimeter of lake. The riparian margin was to be completed by the end of 2004 (Environment Waikato, 2002) and is continually being improved with landscaping and planting by this group (Waikato Enterprise Agency, 2010).

This report gives the water quality results measured in Lake Hakanoa from September 2009 to August 2010 and reports on the results of various restoration scenarios using the one-dimensional water quality model DYRESM-CAEDYM (DYnamic RESservoir Simulation Model - Computational Aquatic Ecosystem DYnamics Model). A focus was placed on modelling of two scenarios which included wetland creation over about 3% of the catchment and a change of land use in the catchment from pastoral farming to exotic forestry. A third scenario combined these two actions and the removal of septic tanks also.

Methods

Site description

Lake Hakanoa is close to Huntly township, with a park domain, motor camp, walkway and various plantings adjacent to the lake. It has become a focal point for recreational walkers, boaters, picnickers and coarse fishers. The 5.5 km^2 catchment supports a small area of native bush, urban housing, commercial and industrial properties and pastoral (mainly sheep and cattle) farmland. There is a small willow-dominated wetland adjacent to the southern end of the lake which intercepts flow from the built-up area. Based on Jenkins & Vant (2007) the land use composition of the Lake Hakanoa catchment is 55.8% pastoral, with 21.4% dairy and 34.4% drystock in the catchment. For the rest of the catchment 10% was indigenous forest, 2% was exotic forest, 17% was scrubland and 16% was urban land (Jenkins & Vant, 2007; Figure 1). There are three permanent and two ephemeral inflows and a number of minor flows and seeps into Lake Hakanoa, and one outflow from Lake Hakanoa and into Waikato River.

A mid-lake sampling station was located at the deepest point near the centre of the lake, located at 37.54806S 175.6022E. Sampling was conducted monthly. Secchi disk depth readings for water clarity were taken on the sunny side of the boat using a black and white Secchi disk and an underwater viewer. Water samples for total and dissolved nutrients, total and inorganic suspended solids, phytoplankton, zooplankton and chlorophyll *a* were collected with a Schindler-Patellas trap at 0.5 m depth. Samples for chlorophyll *a* and filtered nutrients were filtered on site through a 0.45 µm glass fibre filter (GC50, Advantec) using a Swinnex filter holder and syringe. Dissolved oxygen concentrations and water temperature within the lake were measured using a Yellow Springs Instrument dissolved oxygen meter (Model 30) at 0.4 m intervals through the depth of the water column. Water samples were placed on ice and returned to the laboratory where samples were frozen until analysis. Nutrient analyses were performed using a discrete analyser, (Aquakem 200 Cd, Finland). Analyses for ammonium (NH_4-N), nitrite (NO_2-N), oxidized nitrogen (NO_2-N + NO_3-N) and dissolved reactive phosphorus (PO_4-P) were carried out using the standard Aquakem methods and total nitrogen (TN) and total phosphorus (TP) were analysed using modified EPA Methods 365.3 and 353.1. Water samples were analysed for total and inorganic suspended solids according to a method adapted from HACH (2008*)* and APHA (2005). Chlorophyll *a* samples were analysed according to an acetone-extraction protocol adapted from Arar and Collins (1997), APHA (1995), Hauer and Lamberti (1996) and Wetzel and Likens (1990), suing a 10 AU Fluorometer (Turner designs). The trophic level index (TLI), an indicator of lake water quality was calculated according to Burns et al. (2000) using TN, TP, chlorophyll *a* concentrations and Secchi depth. Phytoplankton samples were preserved with Lugol's iodine were analysed according to methods adapted from Hötzel & Croome (1999) and USEPA (2007). Zooplankton samples were collected by pouring a known quantity of water from the Schindler-Patellas trap through a 40 µm zooplankton net and preserving with 70% ethanol. Samples were enumerated by order.

The five inflows and one outflow were sampled on the same days as the lake. The locations of the inflows are given in Table 1. For the inflows, flow was gauged using a Marsh-McBirney flow meter. Dissolved oxygen and temperature were measured with a Yellow Springs Instrument dissolved oxygen meter (Model 30). Water samples were collected for nutrient and suspended sediment concentrations and analysed by the same methods as those used for lake samples. For the outflow, flow was measured by the same means as the inflows and the height of the outflow was measured.

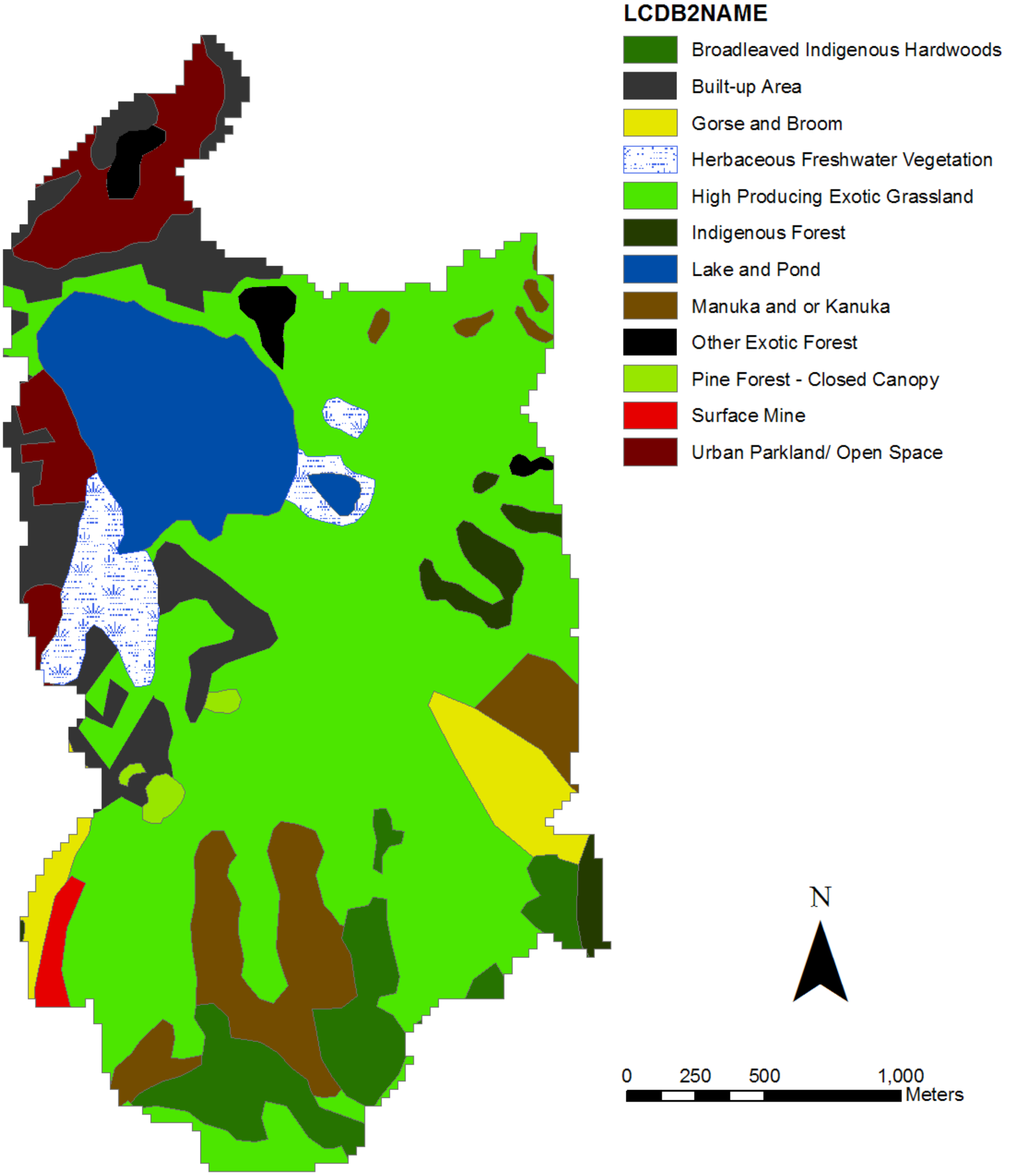


Figure 1. Land use for Lake Hakanoa catchment using the Land use Cover Database (LCDB) 2, 2002.

Table 1. Locations of inflows and outflow to Lake Hakanoa.

	Description	GPS S deg	GPS E deg
Flow 1	Drain, S side of domain	37.76511	175.1917
Flow 2	Culvert, Rayner St, 100 m from Starr St	37.56202	175.1686
Flow 3	Culvert, Rayner St, further east from Site 2	37.55803	175.1751
Flow 4	End of Rayner Rd, down in valley	37.55706	175.1789
Flow 5	End of James St, valley	37.55289	175.1783
Outflow	Near caravan park entrance	37.55048	175.1604

Modelling Methods

DYRESM (DYnamic REServoir Simulation Model) is a one-dimensional model which simulates the vertical distribution of temperature, salinity and density. The foundation for DYRESM is a horizontal layer structure that changes according to heat, mass and momentum exchanges (Imberger & Patterson, 1981; Gal et al., 2003). CAEDYM (Computational Aquatic Ecosystem DYnamics Model), is an ecological model which is coupled with DYRESM and used to simulate phytoplankton biomass, DO, nitrogen, phosphorus and carbon, using partial differential equations that utilise rate constants (Robson and Hamilton, 2004). These equations and constants are manipulated by the modeller whilst being maintained within realistic limits for the ecological rates being simulated. In the model, the lake bottom is the repository for particulate matter and acts as a source of dissolved nutrients generated according to the physical nature of the water column and of particulate matter based on shear stress; a function of lake morphology and wind speed. The DYRESM-CAEDYM model was run with daily input data, including inflows, outflows and meteorology, from 16 September 2009 to 15 September 2010.

Meteorological data

Daily meteorological data required as input to the DYRESM-CAEDYM model were taken from the Te Akatea Station, Ruakura, Whatawhata and Hamilton Aero (Hamilton Airport) weather stations. The data sets for cloud cover (CC) and air pressure (e_s) were taken from Hamilton Aero; wind speed (u_0) was taken from Whatawhata; rainfall (m) from Te Akatea Station, solar radiation (SW: shortwave), air temperature (T_{air}) and relative humidity from Ruakura. Daily averages were used for all meteorological data except rainfall for which the sum of daily rainfall was used.

Evaporation data from pastures in the Waikato region (Rukuhia, 10 km south of Hamilton; Scott Farm, 7 km east of Hamilton) were used to calculate evaporation rates within the catchment (McAneney et al., 1982; Dave Campbell, unpub; Kuske, 2009).

Bathymetry

The morphometry of Lake Hakanoa was determined on 7 May 2010, by surveying the lake in a boat with a depth sonar and simultaneously recording the GPS location using a Garmin GPS receiver. The edge co-ordinates for the lake were recorded from Google Earth 2010. These data were used as input to ArcGIS to produce a bathymetric map of the lake and find the volume and area of the lake at each height measured. The greatest lake depth measured during the bathymetry survey was used as a datum to calculate monthly lake heights using the change in depth at the outlet.

Water balance

Lake volume was determined from the bathymetric data with linear interpolation used to provide a coherent coverage over the whole lake. Change in lake water storage ($\Delta V/t$) was calculated as the difference in lake volume from one day to the next.

A combination of water balance equations for the catchment and for the lake was used to resolve the values for the different components of the lake water balance.

Groundwater inflow from the catchment to the lake was calculated using:

$$GI = R_C - E_C - SI \quad (1)$$

To rectify numerical problems of occasional negative groundwater inflow values it was necessary to use a 75-day moving average, as well as including an offset value and multiplier to return the original yearly value and retain the general shape of the curve. We interpret this time frame as indicative of the lag between rainfall on the catchment and its transport to the lake as groundwater.

Outflow from the lake was calculated using:

$$O = SI + R_L + GI + \Delta V/t - E_L \quad (2)$$

Where GI is the groundwater inflow to the lake, R_c is the rainfall on the lake, E_c is the evaporation from the catchment, SI is the surface inflow to the lake, R_L is the rainfall on the lake, $\Delta V/t$ is the change of lake volume over time and E_L is the evaporation from the lake.

Evaporation from the lake was calculated as a function of wind speed and air vapour pressure from the daily average evaporative heat flux (Fischer et al., 1979, Eq. 6.20) using data from Ruakura, Whatawhata and Hamilton Aero weather stations and water temperatures from the surface measurements at the mid-lake sampling station.

$$Q_{lh} = \min\left(0 \geq \frac{0.622}{P} C_L \rho_A L_E U_a (e_a - e_s(T_s)) \Delta t\right) \quad (3)$$

where:

Q_{lh} is the evaporative heat flux in J m^{-2} s^{-1},
P is the atmospheric pressure in hPa,
C_L is the latent heat transfer coefficient for wind speed at height 10m (1.3×10^{-3}),
ρ_A is the density of air in kg m^{-3},
L_E is the latent heat evaporation of water (2.453×10^6 J kg^{-1}),
U_a is the wind speed in at 10 m height above ground level in m s^{-1},
$e_s(T_s)$ the saturation vapour pressure at the water surface temperature in hPa,
e_a is the vapour pressure of the air in hPa.

The condition that $Q_{lh} < 0$ allows for inclusion of when there is condensation on the water surface. The saturated vapour pressure $e_s(T_s)$ is calculated via the Magnus-Tetens formula (TVA, 1972, Eq. 4.1):

$$e_s(T_S) = exp\left(2.3026\left(\frac{7.5T_S}{T_S+237.3} + 0.7858\right)\right) \quad (4)$$

Where T_s is the water surface temperature in °C.

The change in mass in the surface layer (layer N) due to latent heat flux is calculated as

$$\Delta M_N^{lh} = \frac{-Q_{lh} A_N}{L_V} \quad (5)$$

where:

ΔM_N^{lh} is the change in mass in kg s^{-1} (assumed to be L s^{-1}),
A_N is the surface area of the lake in m²,
and L_V is the latent heat of vaporisation for water (2.258 x 10^6 J kg^{-1}).

The result of this calculation was multiplied by 86400 s day^{-1} to produce a daily evaporation value (E_L).

For evaporation from the catchment an evaporation curve was derived from the data in McAneney et al. (1982) with daily values derived using linear interpolation, to gain a percent of the total evaporation that is typically found over Waikato pasture each day. The evaporation rate was then calculated as the percent of total evaporation day^{-1} and multiplied by 71 percent of the total rainfall yr^{-1}, approximating the values found by Campbell (unpub.) and Kuske (2009).

Inflows

Whilst measurements were made monthly for the inflows for volume of water day^{-1}, temperature, dissolved oxygen, suspended solids and nutrients, input to the model required daily values for several variables. Missing values for daily volume of water in the inflows were derived by linear interpolation between the measured values. To estimate temperature values, a regression analysis was performed between the measured values in each inflow and a preceding three-day average of the air temperature, then the resulting regression equation used to obtain the missing data. Values for dissolved oxygen concentrations between the measured values were estimated as a function of water temperature using the model of Mortimer (1981) which is based on data from Benson and Krause (1980). Nutrient and suspended sediment concentrations were a result of linear interpolation between the results. Groundwater inflow volumes for each day were calculated as the unknown term in the catchment water balance (Eq. 1); all other values were calculated as the average of the other inflows.

Initial Profile

The depth and temperature for the initial profile were measured with a Yellow Springs Instruments dissolved oxygen meter (Model 30) at 0.4 m intervals through the depth of the water column on 16 September, 2009.

Phytoplankton

Two phytoplankton groups, represented by equivalent chlorophyll *a* concentration, were simulated in the model. This simulation represents phytoplankton as a cyanobacteria group and as ‘other’ groups representing all remaining phytoplankton taxa. Initial lake water column concentrations of chlorophyll *a* for each phytoplankton group were determined from biovolumes to estimate their relative proportion and chl *a* concentrations at several depths.

Zooplankton

The zooplankton data were not used in the model.

Suspended solids

Total suspended solids (SSOL) has been integrated into the model because of their potential impacts in shallow lakes like Lake Hakanoa. For example, SSOL affects the temperature profile through increased attenuation of light which in turn affects a lake's heat budget (Sullivan et al., 2006). The initial concentration of suspended solids was taken from the samples collected on the first day.

Modelling scenarios

We assumed values for nutrient losses from dairy pasture on Waikato farms as 19.4 kg N ha^{-1} yr^{-1} and 1.1 kg P ha^{-1} yr^{-1} (Wilcock, 1986; Judge & Ledgard, 2004; Wheeler & Elliot, 2008), and from dry stock of 5 kg N ha^{-1} yr^{-1} and 0.77 kg P ha^{-1} yr^{-1} (Judge & Ledgard, 2004; Jenkins & Vant, 2007). The losses from exotic forestry systems in New Zealand were estimated as 0.08 kg P ha^{-1} yr^{-1} and 7.56 kg N ha^{-1} yr^{-1} (Wilcock, 1986; Cooper & Thomsen, 1988; Parfitt et al., 2003; Elliot et al., 2005).

Three restoration scenarios were simulated. The first was conversion of all pastoral land within the lake catchment to exotic forest. Using the values above, it was estimated that this land use change would result in a 22% reduction in total nitrogen (TN) and 72% reduction in total phosphorus (TP) in the nutrient loads of the inflows.

The second scenario was the construction of a wetland covering 3% of the catchment, estimated to reduce TN entering the wetland by 60% and particulate phosphorus by 65% (Hudson et al., 2008). The number of residents and septic tanks in the catchment are unknown. It was estimated that 20 people were using septic tanks, and we assumed each person was responsible for 3.65 kg yr^{-1} N and 0.37 kg yr^{-1} P (John McIntosh, pers. comm.). This equates to only 2% of the calculated nutrient export for both TN and TP.

The third scenario included the combination of conversion of pastoral land to exotic forest, a wetland covering 3% of the catchment, and removal of septic tanks servicing 20 people. In order to combine these three actions, nutrient load reductions due to septic tank removal and pasture conversion were absolute, whereas the percentage reduction due to wetland construction was applied to the reduced nutrient load after the two catchment modifications.

Results

Water temperatures ranged from 8.19°C in the bottom waters on 26 August, 2010 to 24.4°C through the water column on 15 February, 2009 (Figure 2). The lake was almost always isothermal (i.e. vertically uniform temperature) throughout the entire sampling period.

Dissolved oxygen concentrations ranged from 4.9 mg L^{-1} in the bottom waters on 15 February, 2009 to 14 mg L^{-1} in the surface waters on 26 August, 2010 (Figure 3). There was a small decrease in dissolved oxygen concentration with depth in the water column.

Secchi disk depths were less than 1 m for the entire sampling period, ranging from 0.29 to 0.61 m. Clarity was greatest during October and November 2009 and least in February 2010 (Figure 4). There was a general inverse relationship of Secchi depth with chlorophyll *a* concentrations (Figure 5).Chlorophyll *a* concentrations ranged from 36.5 µg L^{-1} in January to 4.6 µg L^{-1} in May (Figure 5).

Total nutrient concentrations are shown in Figure 6. Total phosphorus (TP) concentrations ranged from 0.016 mg L^{-1} on 6 October 2009 to 0.073 mg L^{-1} on 14 December 2009. Total phosphorus followed a similar pattern to total nitrogen (TN) concentrations. Total nitrogen concentrations ranged from 0.37 mg L^{-1} on 12 October, 2009 to 0.72 mg L^{-1} on 13 January 2010. The average TN:TP ratio was 18:1 by mass. Filtered nutrient concentrations are shown in Figure 7. There was very little or no nitrate (as NO_3-N) with the exception of 29 June 2009 when the concentration was 39 mg m^{-3}. Phosphate (PO_4-P) concentrations ranged from 0.0024 mg L^{-1} to 0.005 mg L^{-1} for most of the year with the exception of 0.008 mg L^{-1} in October and November 2009. Ammonium (NH_4-N) concentrations decreased from 0.032 mg L^{-1} in September to 0.010 mg L^{-1} in December then increased from April to August, to a final concentration of 0.043 mg L^{-1} on 26 August 2010. Suspended solid concentrations are shown in Figure 8. SSOL concentrations ranged from 18 mg L^{-1} in September to 44 mg L^{-1} in December 2009. Inorganic suspended solid (ISS) concentrations followed a similar pattern to total suspended solid concentrations (SSOL). The inorganic fraction amounted to 47 – 72 % of the SSOL and ranged from 11 mg L^{-1} in October 2009 and May 2010 to 28 mg L^{-1} in November 2009.

The average TLI score, based on concentrations of TN, TP and Chl *a*, and Secchi disk, was 4.99 over twelve months which classifies this lake as eutrophic according to the criteria of Burns et al. (2000).

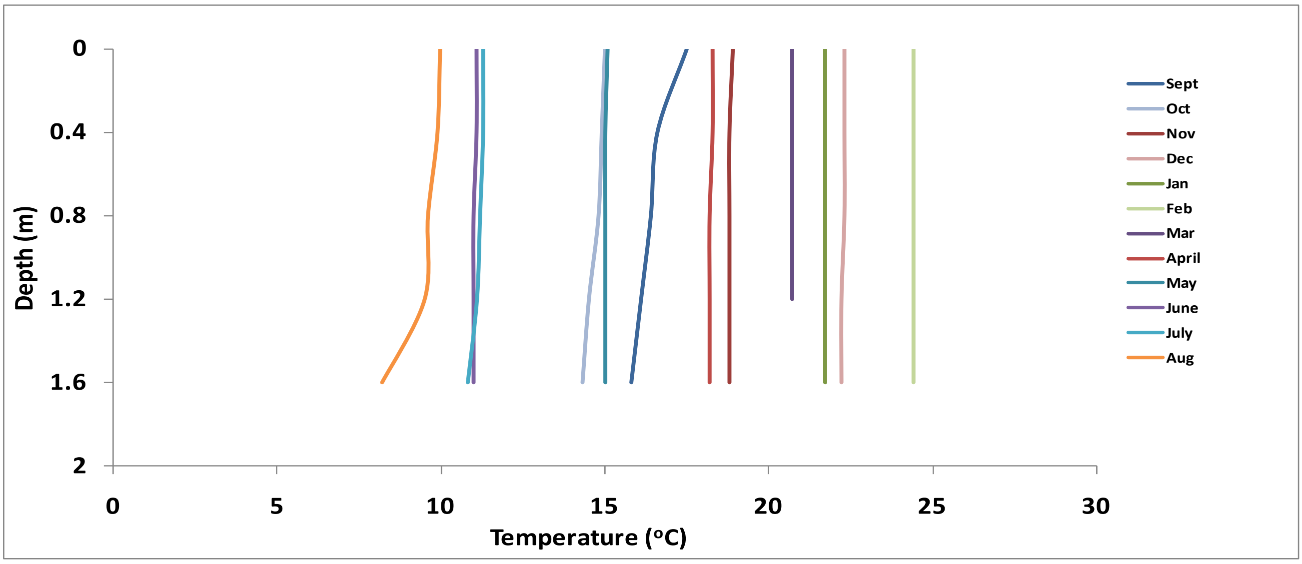


Figure 2. Temperatures through the water column in Lake Hakanoa from 16 September, 2009 to 26 August, 2010.

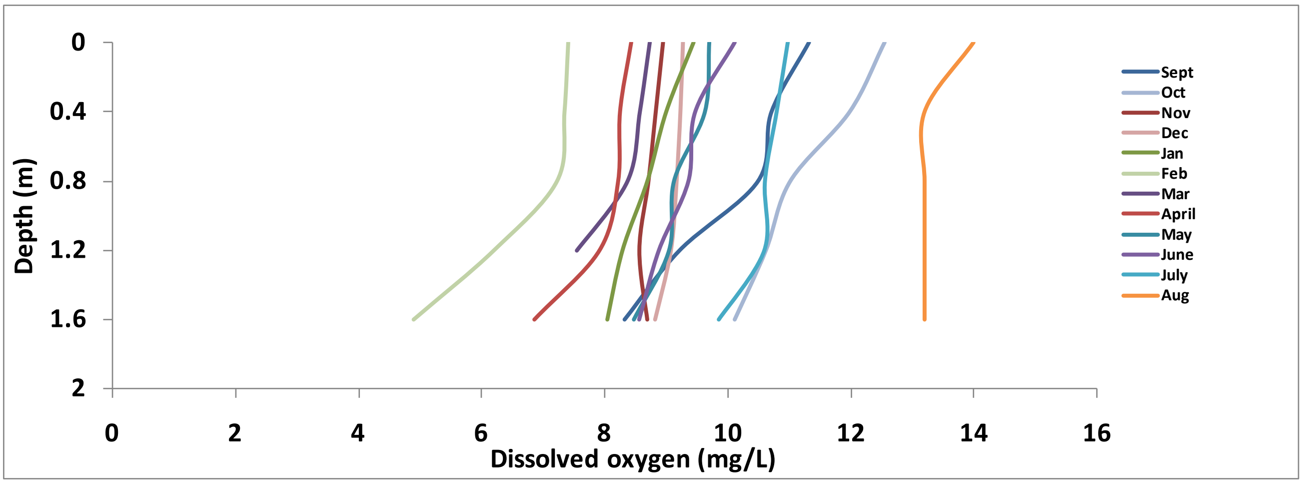


Figure 3. Dissolved oxygen concentrations through the water column in Lake Hakanoa from 16 September, 2009 to 26 August, 2010.

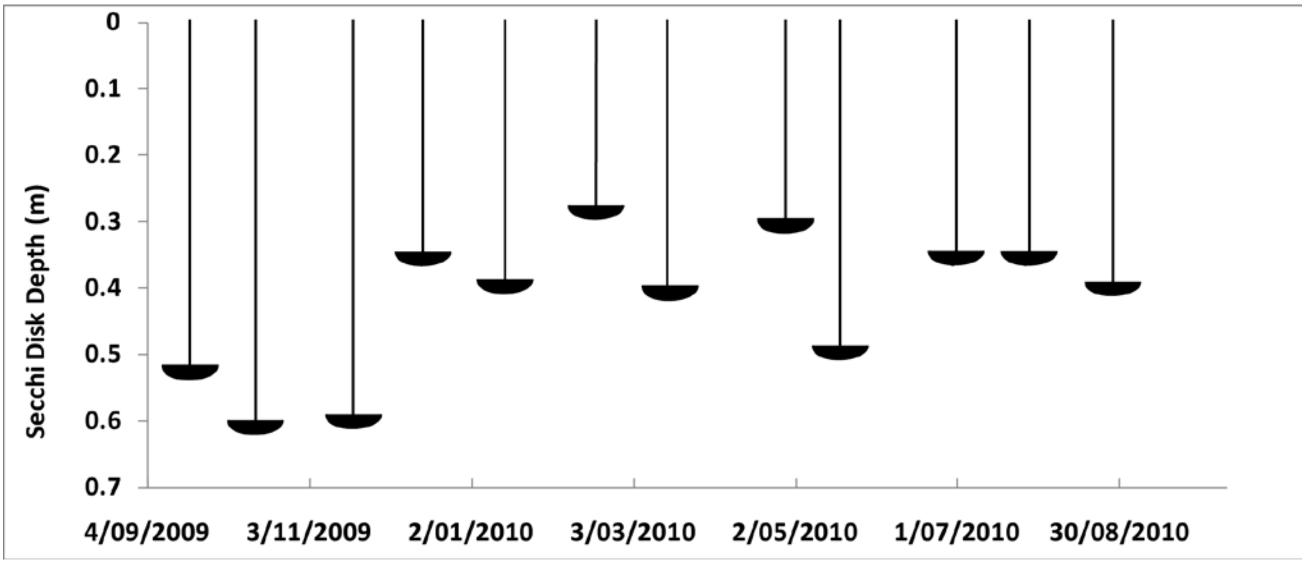


Figure 4. Secchi disk depths in Lake Hakanoa from 16 September, 2009 to 26 August, 2010.

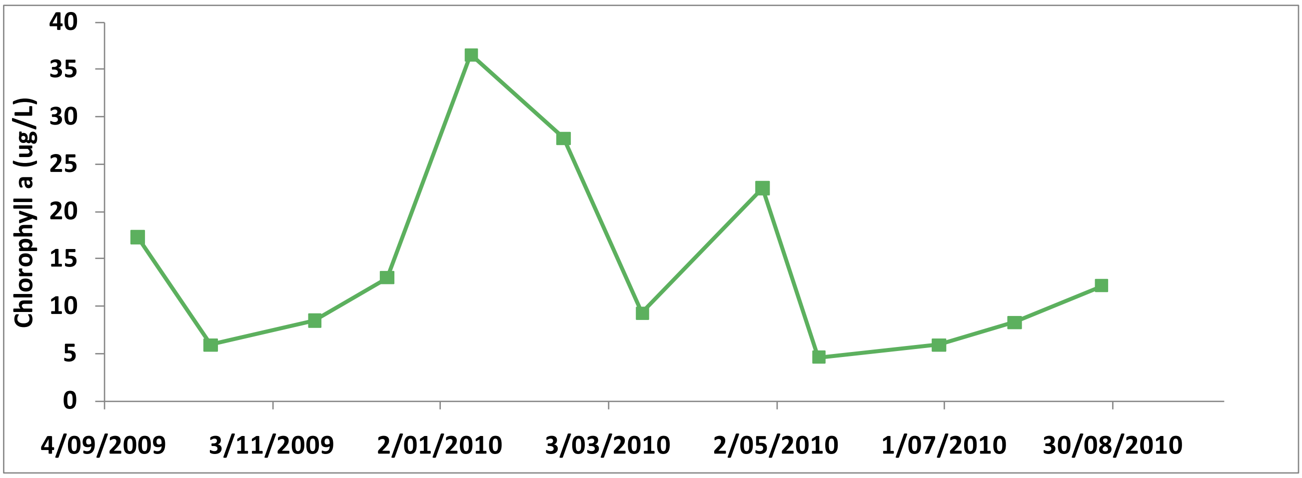


Figure 5. Chlorophyll *a* concentrations in Lake Hakanoa from 16 September, 2009 to 26 August, 2010.

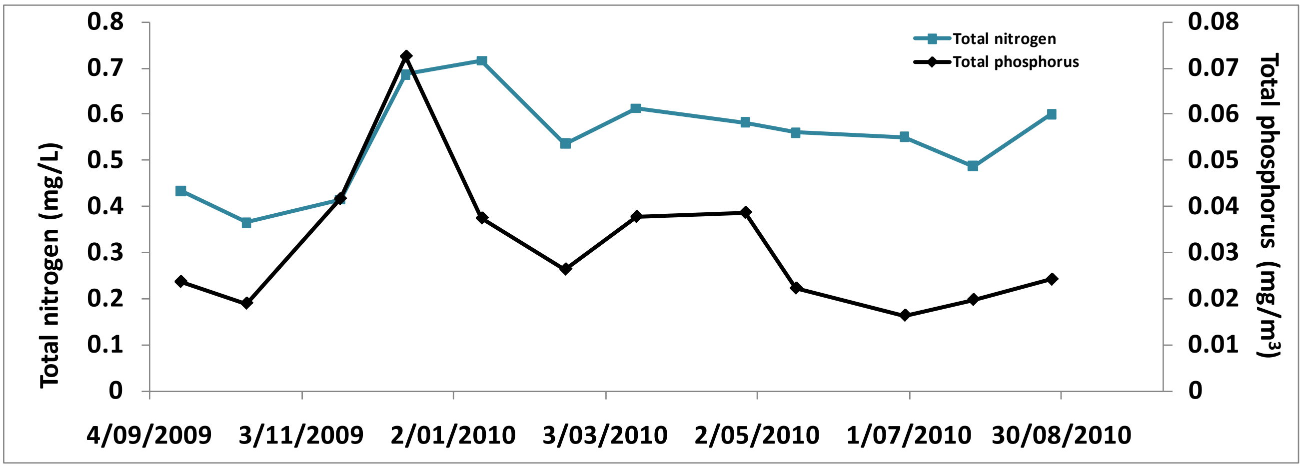


Figure 6. Total phosphorus and total nitrogen concentrations in Lake Hakanoa from 16 September, 2009 to 26 August, 2010.

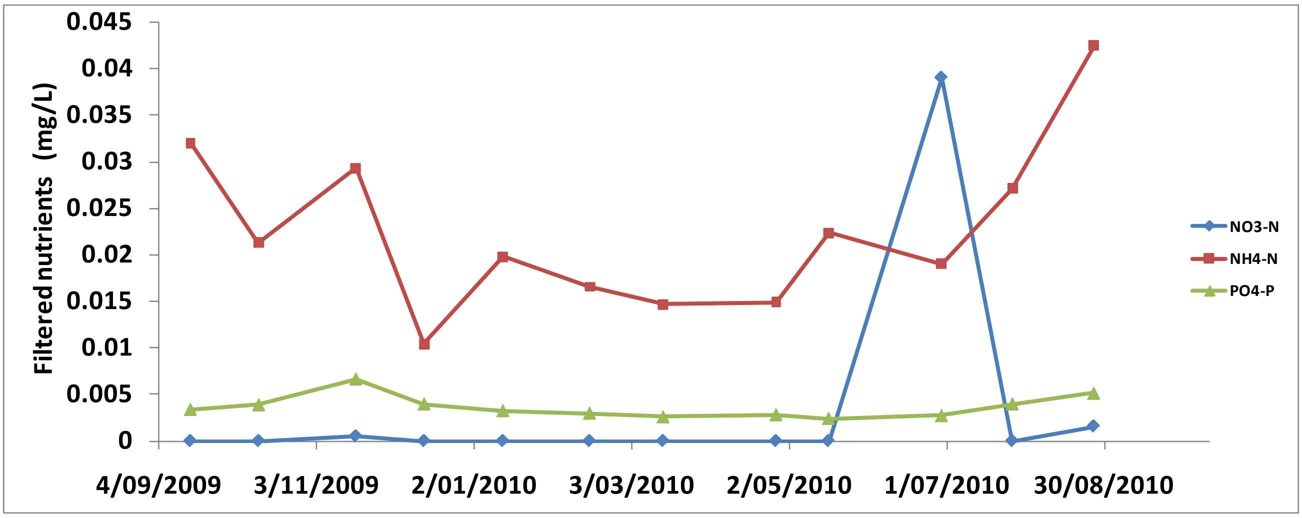


Figure 7. Filtered nutrient concentrations (NO_3-N, NH_4-N, PO_4-P) in Lake Hakanoa from 16 September, 2009 to 26 August, 2010.

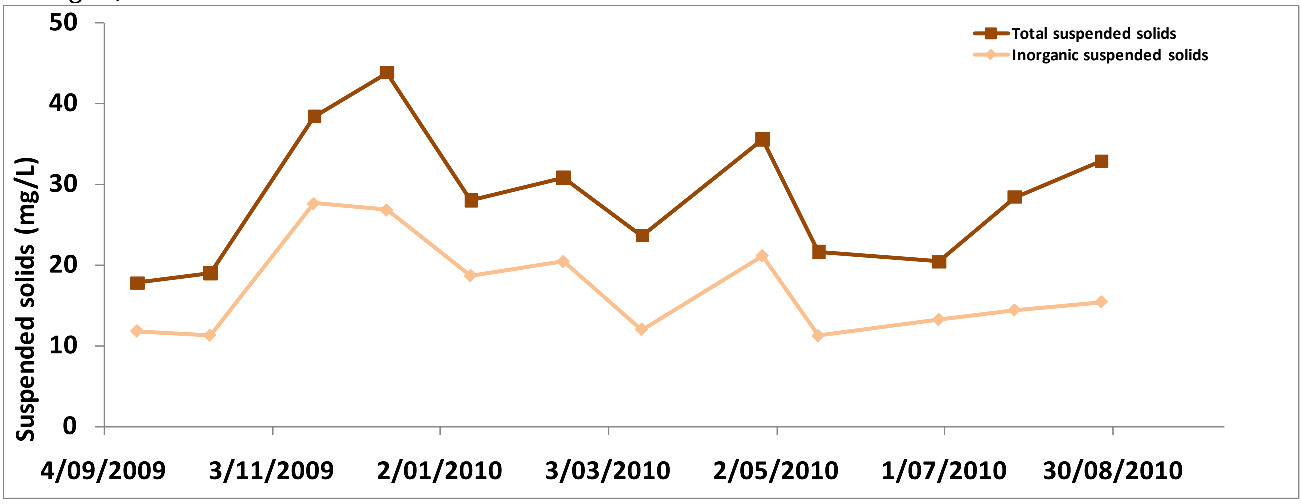


Figure 8. Total and inorganic suspended solids in Lake Hakanoa from 16 September, 2009 to 26 August, 2010.

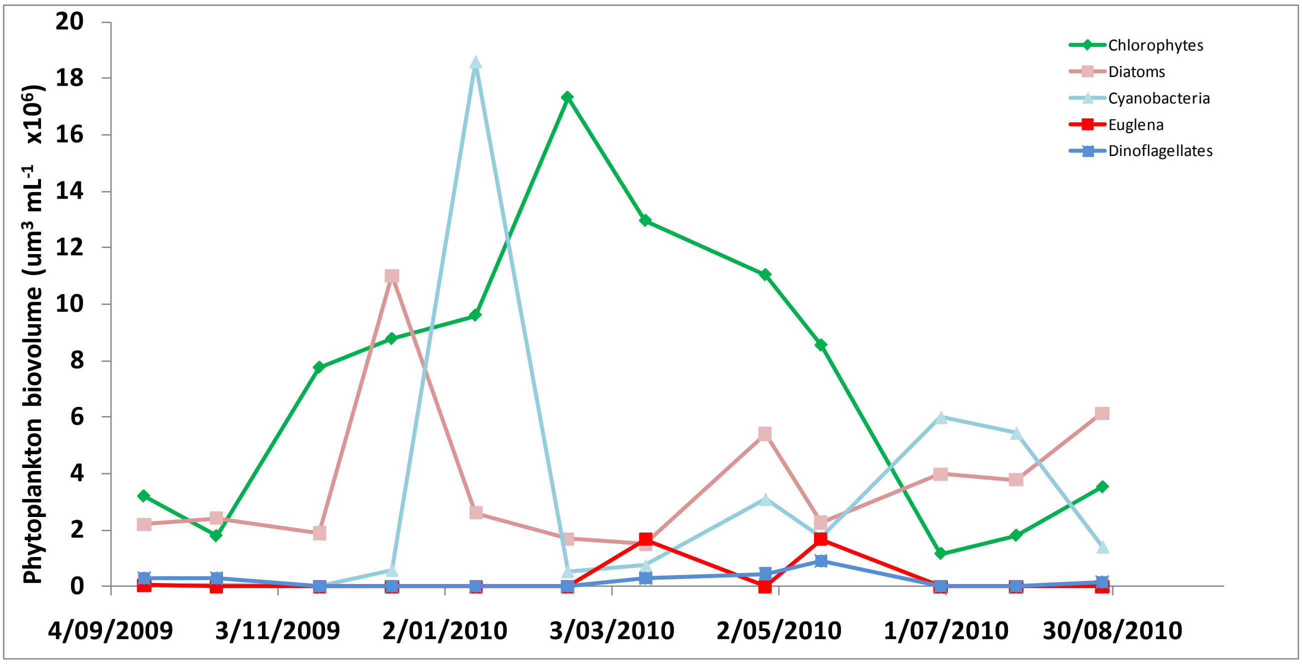


Figure 9. Phytoplankton biovolume for the phyla in Lake Hakanoa from 16 September, 2009 to 26 August, 2010.

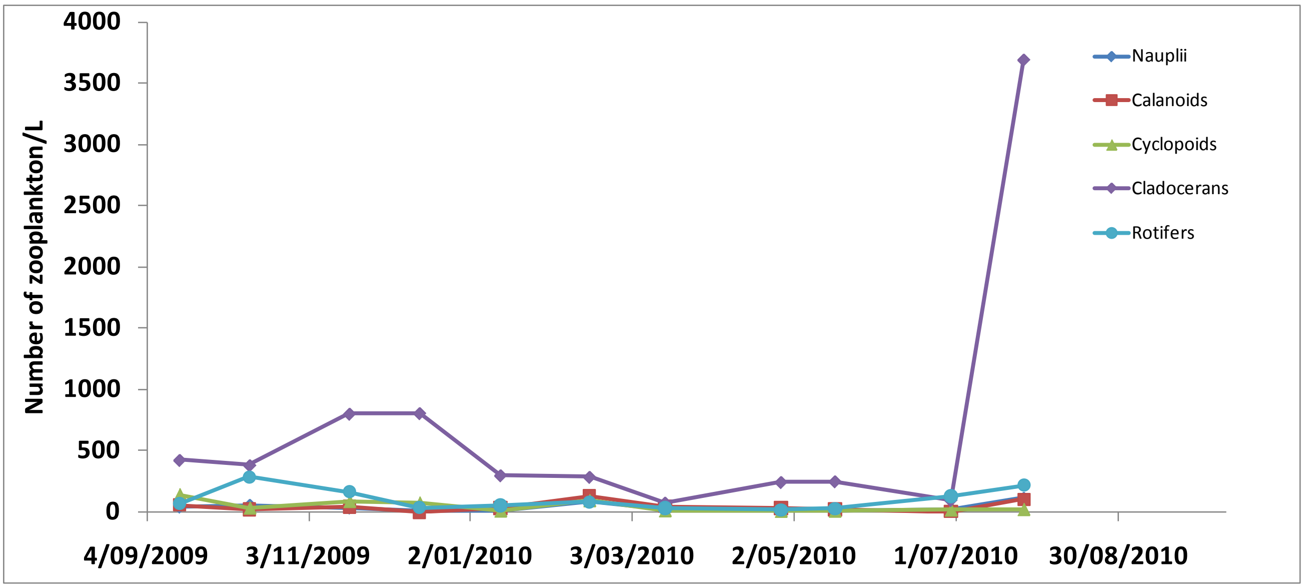


Figure 10. Zooplankton numbers by order in Lake Hakanoa from 16 September, 2009 to 26 July, 2010.

Modelled Results

Calibration

The field data that the model was calibrated against were measured from September 2009 to August 2010. Figures 11 to 14 provide a visual comparison of the closeness of fit between the model and measurements. Temperature and dissolved oxygen are aligned but the other variables are not always so closely matched.

The modelled and observed temperatures of Lake Hakanoa consistently showed a fully mixed water column over the study period. Simulated temperatures ranged from 29.8 ^{o}C in January to 8.1 ^{o}C in

July (Figure 11a) which was consistent with the measured water temperatures. The difference between simulated and measured values is generally < 1 ^{o}C.

The modelled and observed results show a difference in dissolved oxygen concentration of generally <1 mg L^{-1} between the 0.4 m and 1.2 m depths for the study period (Figure 11b). The modelled results for DO concentrations followed a similar pattern to the observed measurements. There is an average of 4% difference between the observed and modelled results.

The modelled chlorophyll *a* concentrations range from 1.4 to 17.2 μg L^{-1} Although there is a good match between most observed and modelled chlorophyll *a* results, the model does not align with the some of the measured concentrations of chlorophyll *a* over the summer months (Figure 11c).

The modelled SSOL results range from 1.3 to 23.8 mg L^{-1} and concentrations follow a similar pattern to the observed results with the exception of the last three months (Figure 11d).

Modeled results for TP range from 0.01 to 0.03 mg L^{-1} and are fairly closely matched with, and follow the same trend as, the observed results with the exception of the December result (Figure 11e).

Modeled results for TN concentrations range from 0.2 to 0.5 mg L^{-1} and, on average, are close to the observed results. With the exception of the August result, the modelled results follow a similar pattern to the observed results (Figure 11f).

Pasture to exotic forest scenario

Changing pastoral land to exotic forestry made a negligible difference to the temperature and dissolved oxygen concentrations in Lake Hakanoa (Figures 12a and 12b) compared with the calibration and the observed results. In relation to the scenarios, when nutrient reductions were made to represent a change from pastoral land use to exotic forestry, chlorophyll *a* concentrations decreased by an average of 30% (Figure12c), concentrations of SSOL decreased by an average of 29% (Figure 12d), TP concentrations decreased by an average of 36% (Figure 12e), and TN concentrations decreased by an average of 8% (Figure 12f).

Creation of a wetland that covers 3% of the catchment

Creating a wetland that covers 3% of the Lake Hakanoa catchment made very little difference to the temperature and dissolved oxygen concentrations in Lake Hakanoa (Figures 13a and 13b) against the calibrated and observed results. In relation to the calibrated results, when nutrient reductions were made to simulate the creation of a wetland covering 3% of the Lake Hakanoa catchment chlorophyll *a* concentrations decreased by an average of 31% (Figure 13c), concentrations of SSOL by an average of 26% (Figure 13d), TP by an average of 37% (Figure 13e), and TN by an average of 21% (Figure 13f).

Combined scenarios plus removal of septic tanks for 20 people

Changing pastoral land to exotic forestry, creating a wetland that covers 3% of the Lake Hakanoa catchment and removal of septic tanks servicing twenty people again made very little difference to the temperature and dissolved oxygen concentrations in simulations of Lake Hakanoa (Figures 14a and 14b). In relation to the calibrated results, this combined scenario decreased chlorophyll *a* concentrations by an average of 42% (Figure 14c), SSOL concentrations by 32% (Figure 14d), TP concentrations by 50% (Figure 14e), and TN concentrations by 24% (Figure 14f).

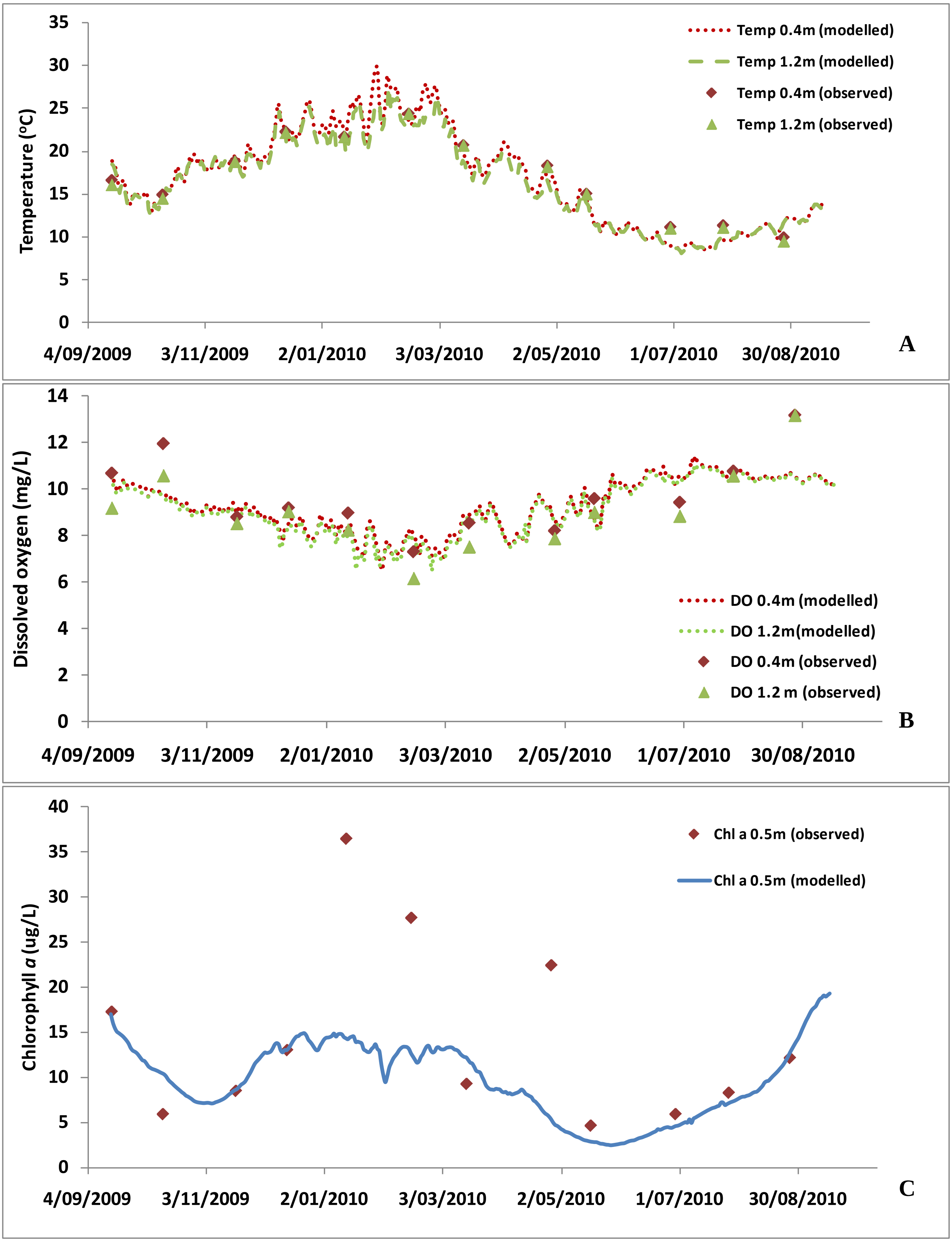


Figure 11. Temperature and concentrations of water quality variables for Lake Hakanoa from 16 September, 2009 to 26 July, 2010 (observed) and modelled results: a) temperature b) dissolved oxygen and c) chlorophyll *a*.

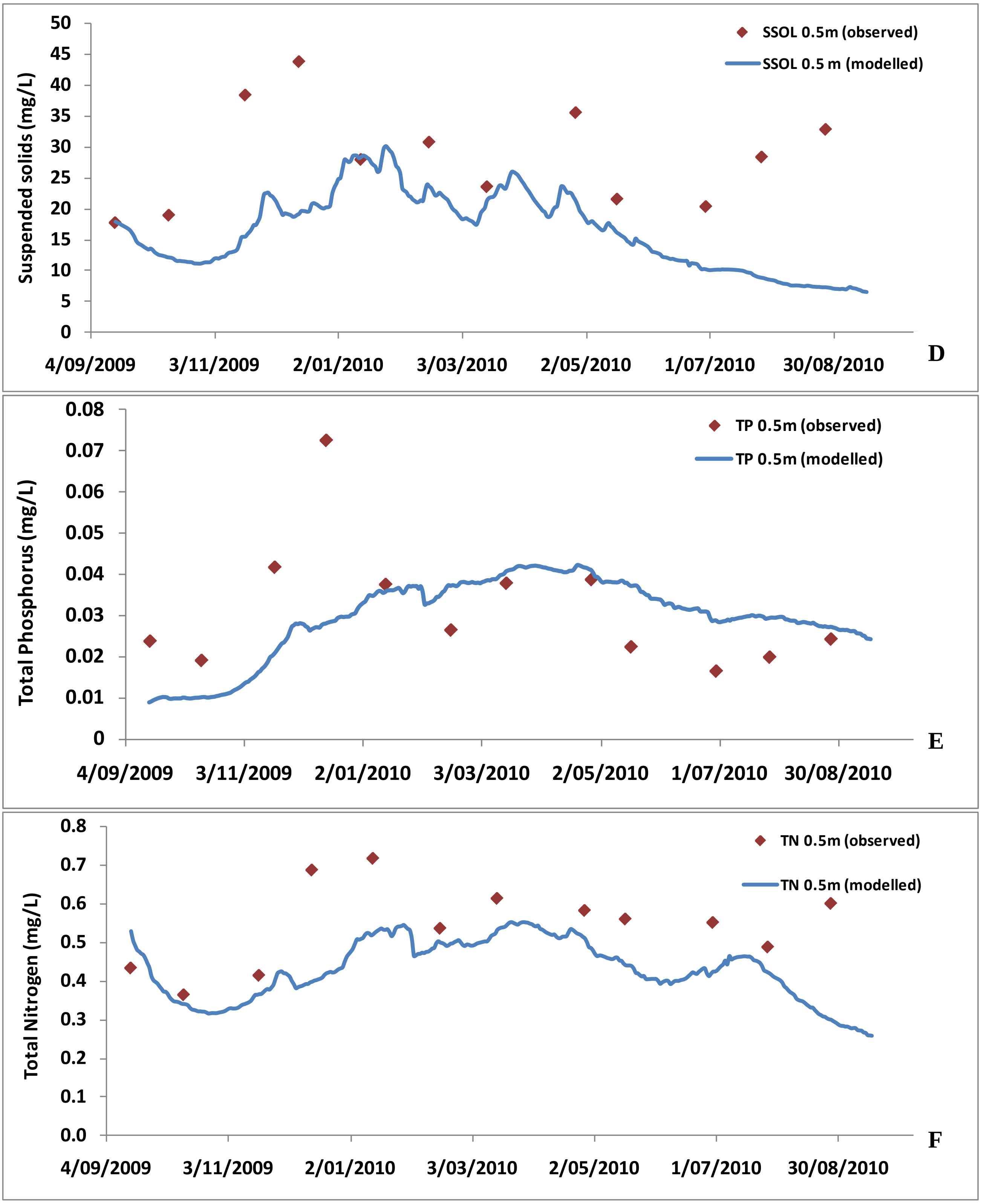
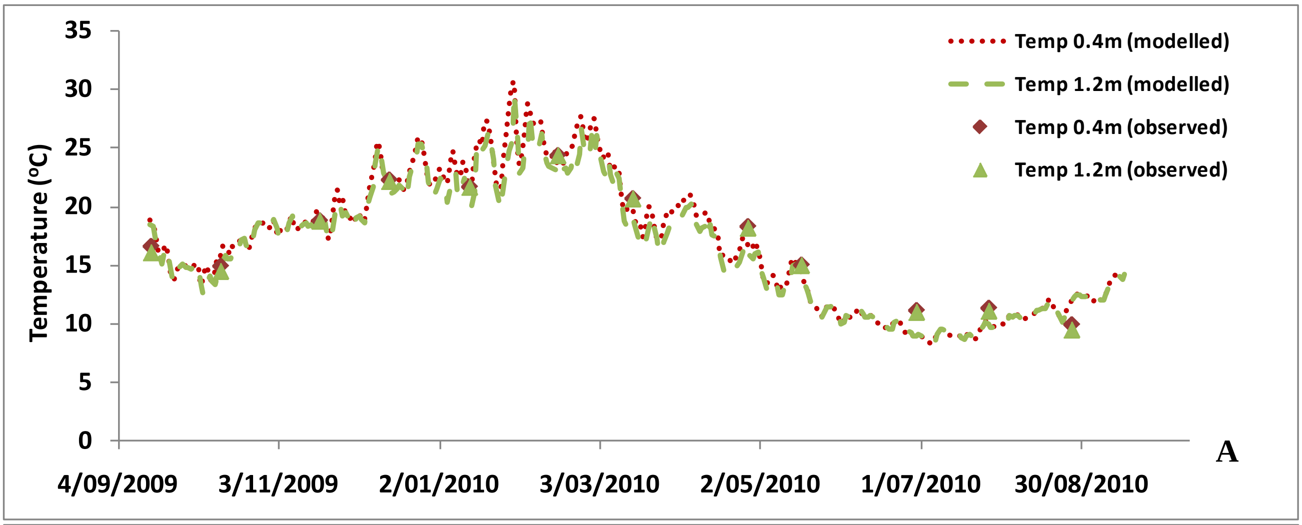
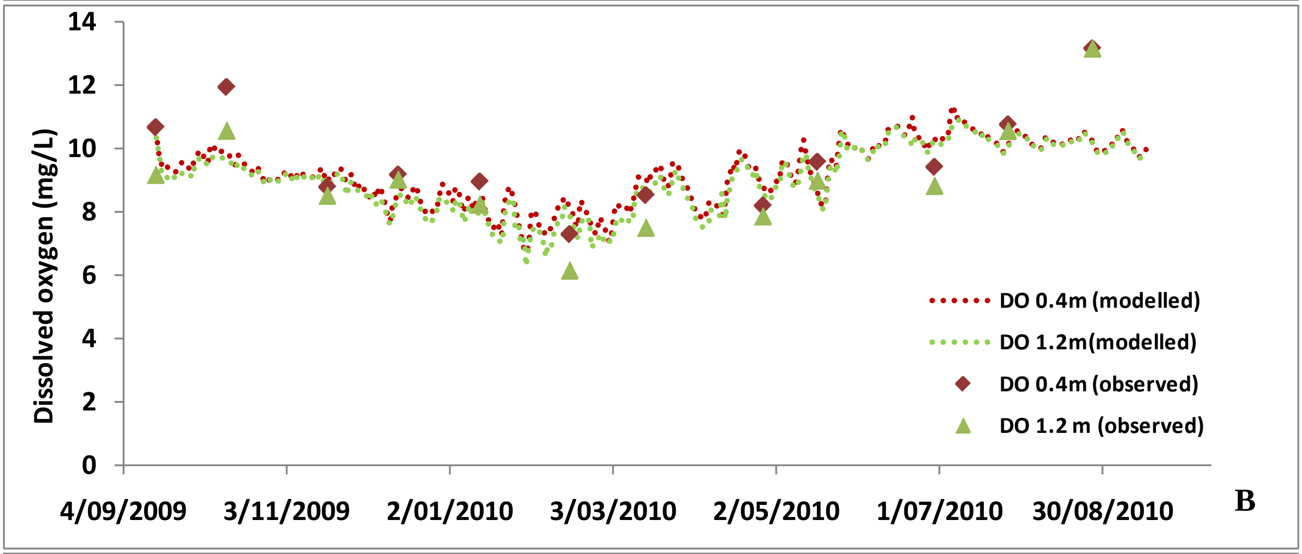


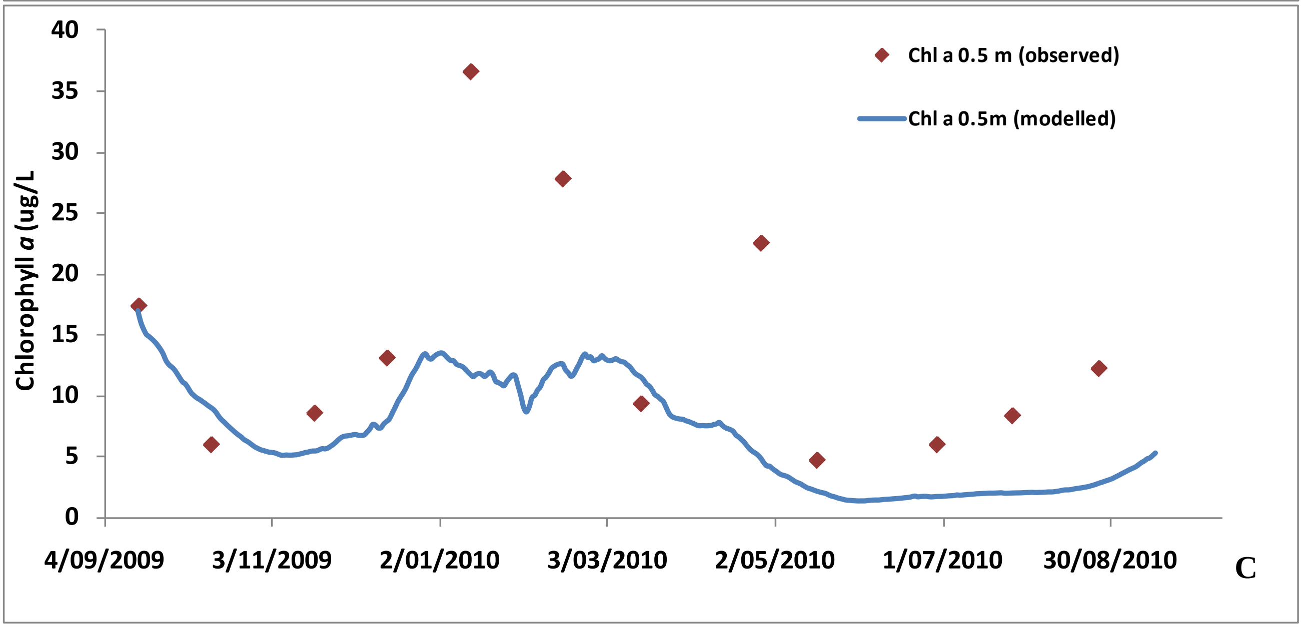
Figure 12 (cont.). Concentrations of water quality variables for Lake Hakanoa from 16 September, 2009 to 26 July, 2010 (observed) and modelled results: d) suspended solids e) total phosphorus and f) total nitrogen.



Temperature (°C)
35
30
25
20
15
10
5
0
4/09/2009
3/11/2009
2/01/2010
3/03/2010
2/05/2010
1/07/2010
30/08/2010
Temp 0.4m (modelled)
Temp 1.2m (modelled)
Temp 0.4m (observed)
Temp 1.2m (observed)
A



Dissolved oxygen (mg/L)
14
12
10
8
6
4
2
0
4/09/2009
3/11/2009
2/01/2010
3/03/2010
2/05/2010
1/07/2010
30/08/2010
DO 0.4m (modelled)
DO 1.2m(modelled)
DO 0.4m (observed)
DO 1.2 m (observed)
B



Chlorophyll a (ug/L
40
35
30
25
20
15
10
5
0
4/09/2009
3/11/2009
2/01/2010
3/03/2010
2/05/2010
1/07/2010
30/08/2010
Chl a 0.5 m (observed)
Chl a 0.5m (modelled)
C

Figure 13. Temperature and concentrations of water quality variables for Lake Hakanoa from 16 September, 2009 to 26 July, 2010 (observed) and modelled results for changing land use from pastoral farming to exotic forest: a) temperature b) dissolved oxygen and c) chlorophyll *a*.

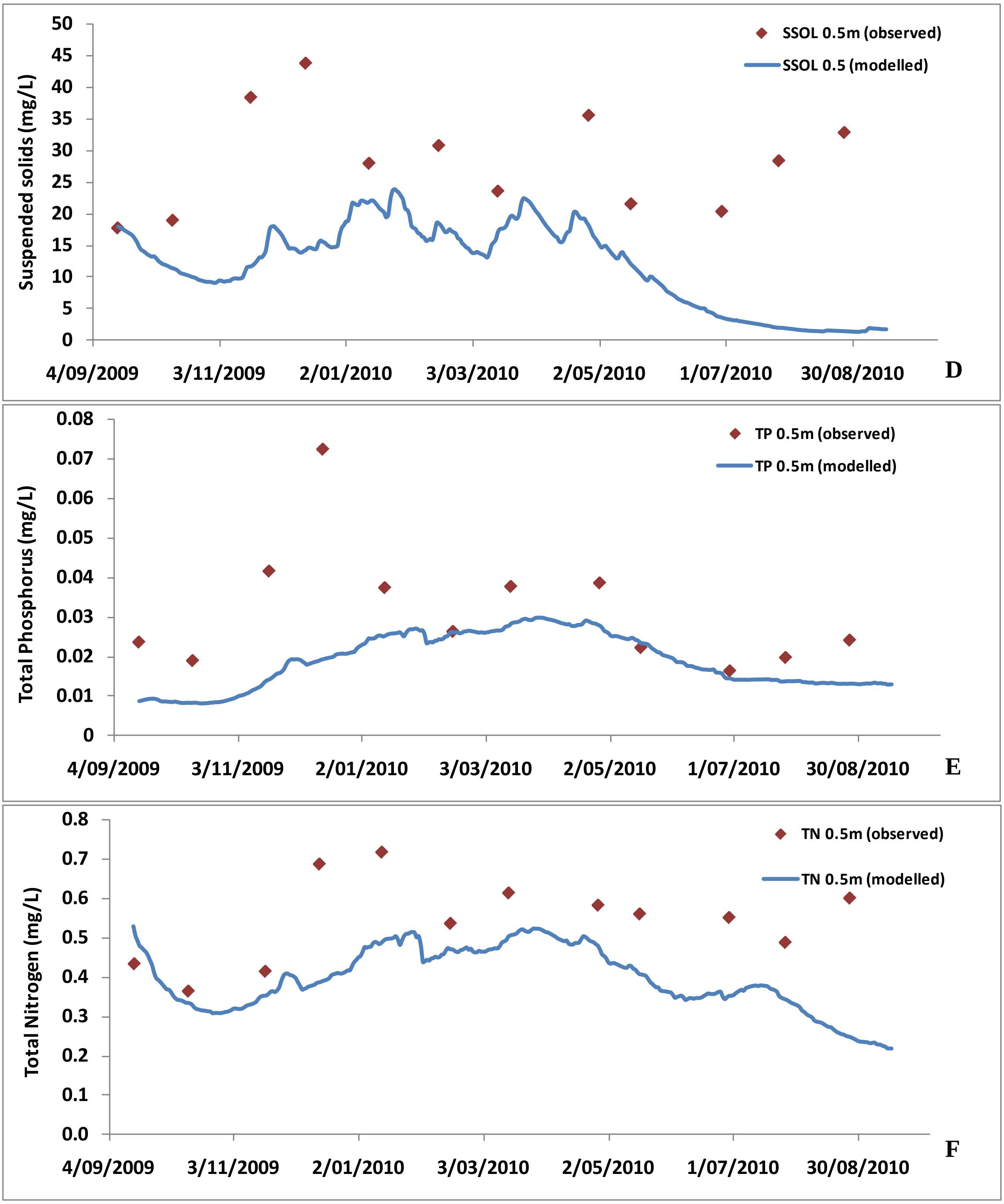


Figure 14 (cont.). Concentrations of water quality variables for Lake Hakanoa from 16 September, 2009 to 26 July, 2010 (observed) and modelled results for changing land use from pastoral farming to exotic forest: d) suspended solids e) total phosphorus and f) total nitrogen.

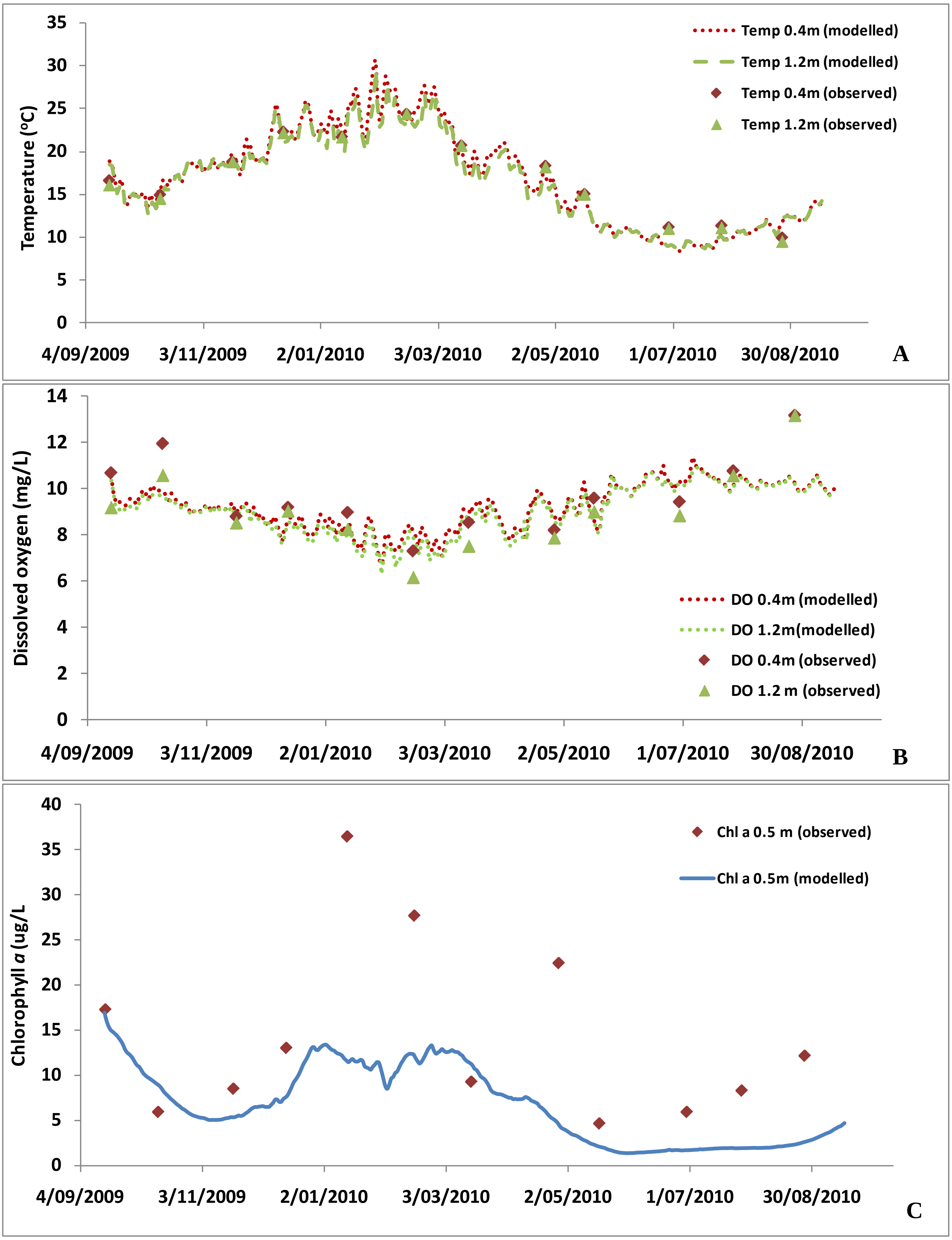


Figure 15. Temperature and concentrations of water quality variables for Lake Hakanoa from 16 September, 2009 to 26 July, 2010 (observed) and modelled results for creation of a wetland that covers 3% of the catchment: a) temperature b) dissolved oxygen and c) chlorophyll *a*.

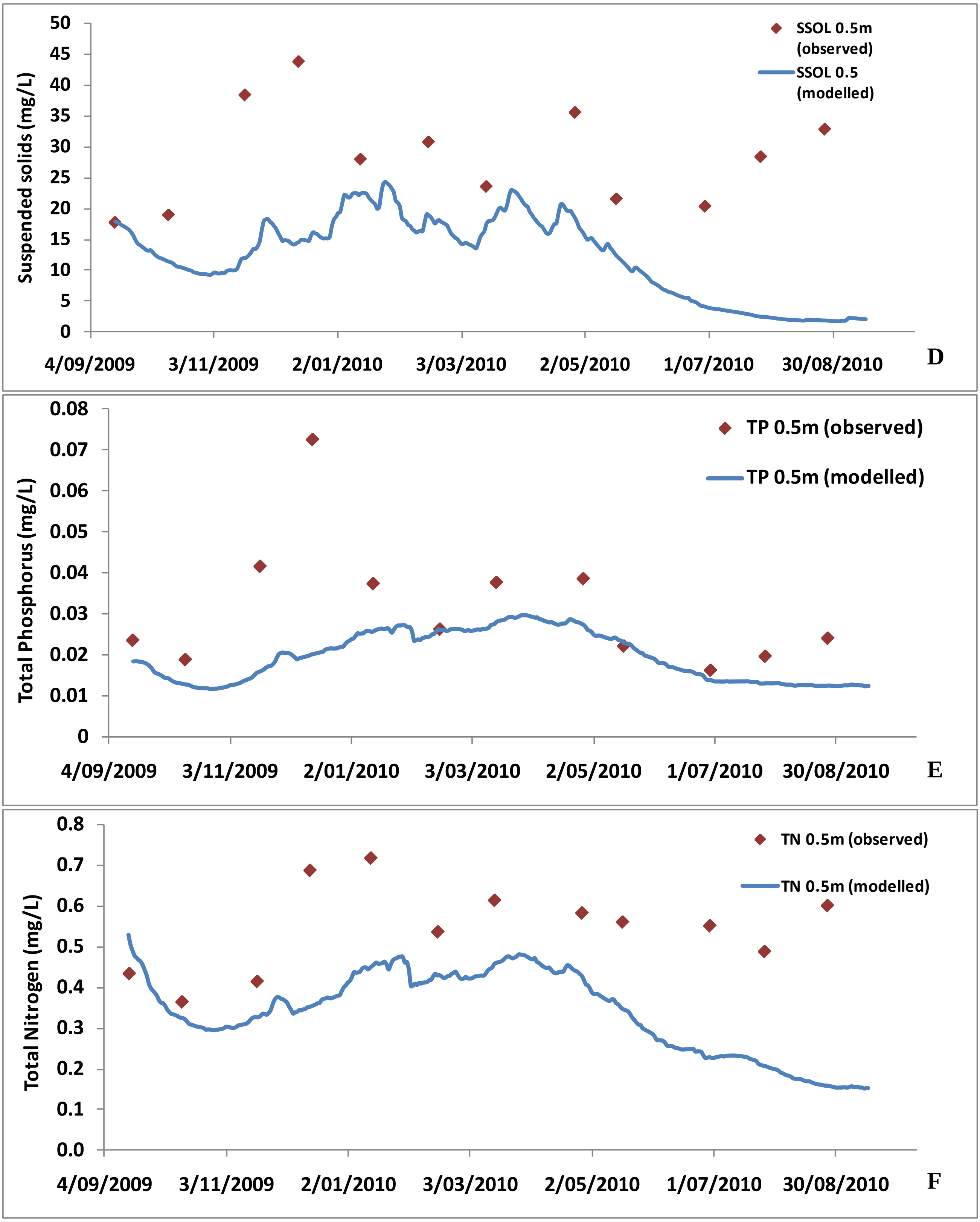


Figure 16 (cont.). Concentrations of water quality variables for Lake Hakanoa from 16 September, 2009 to 26 July, 2010 (observed) and modelled results for creation of a wetland that covers 3% of the catchment: d) suspended solids e) total phosphorus and f) total nitrogen.

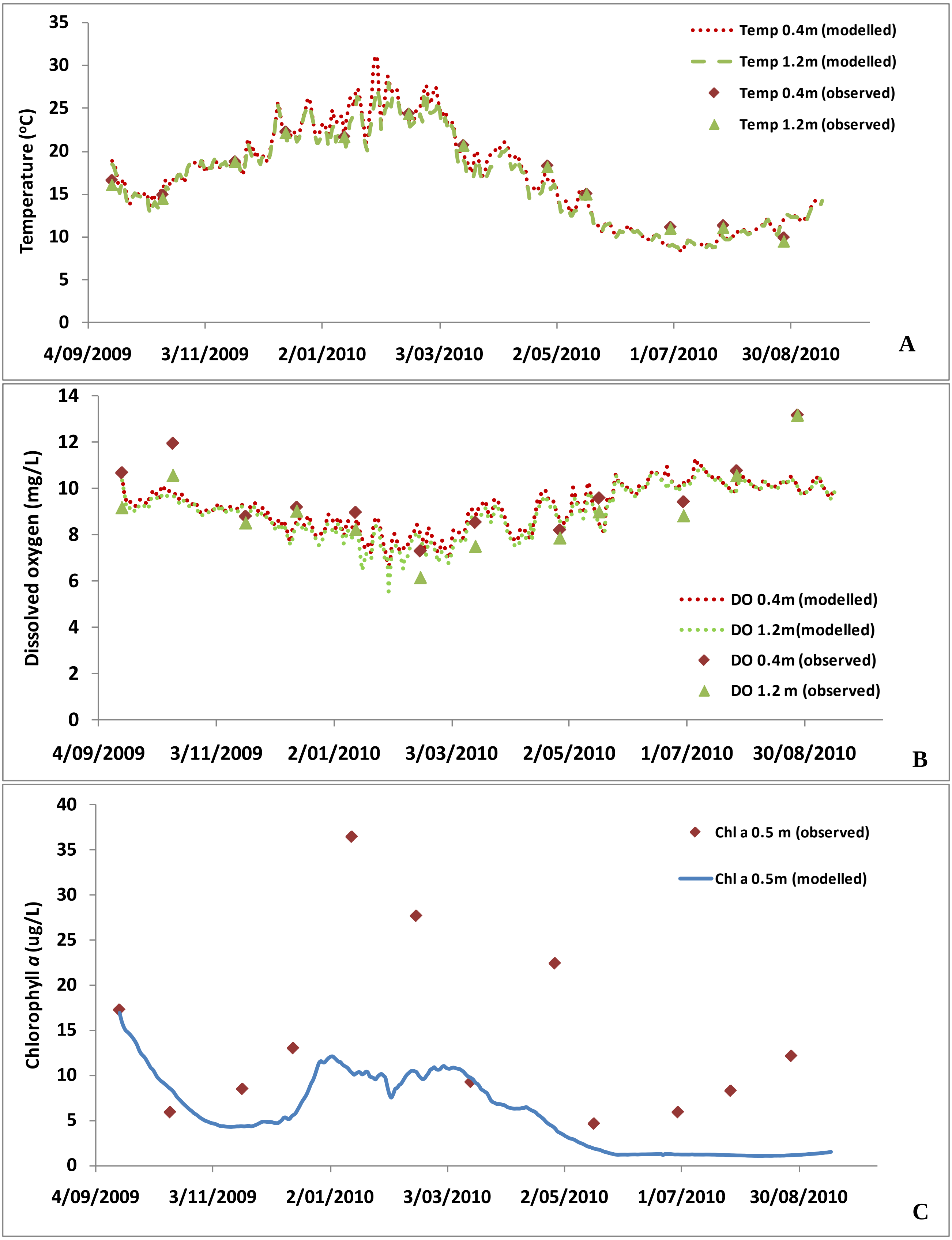


Figure 17. Concentrations of water quality variables for Lake Hakanoa from 16 September, 2009 to 26 July, 2010 (observed) and modelled results for creation of a wetland that covers 3% of the catchment, conversion of pastoral land to exotic forest and removal of septic tanks servicing 20 people: a)temperature b) dissolved oxygen and c) chlorophyll *a*.

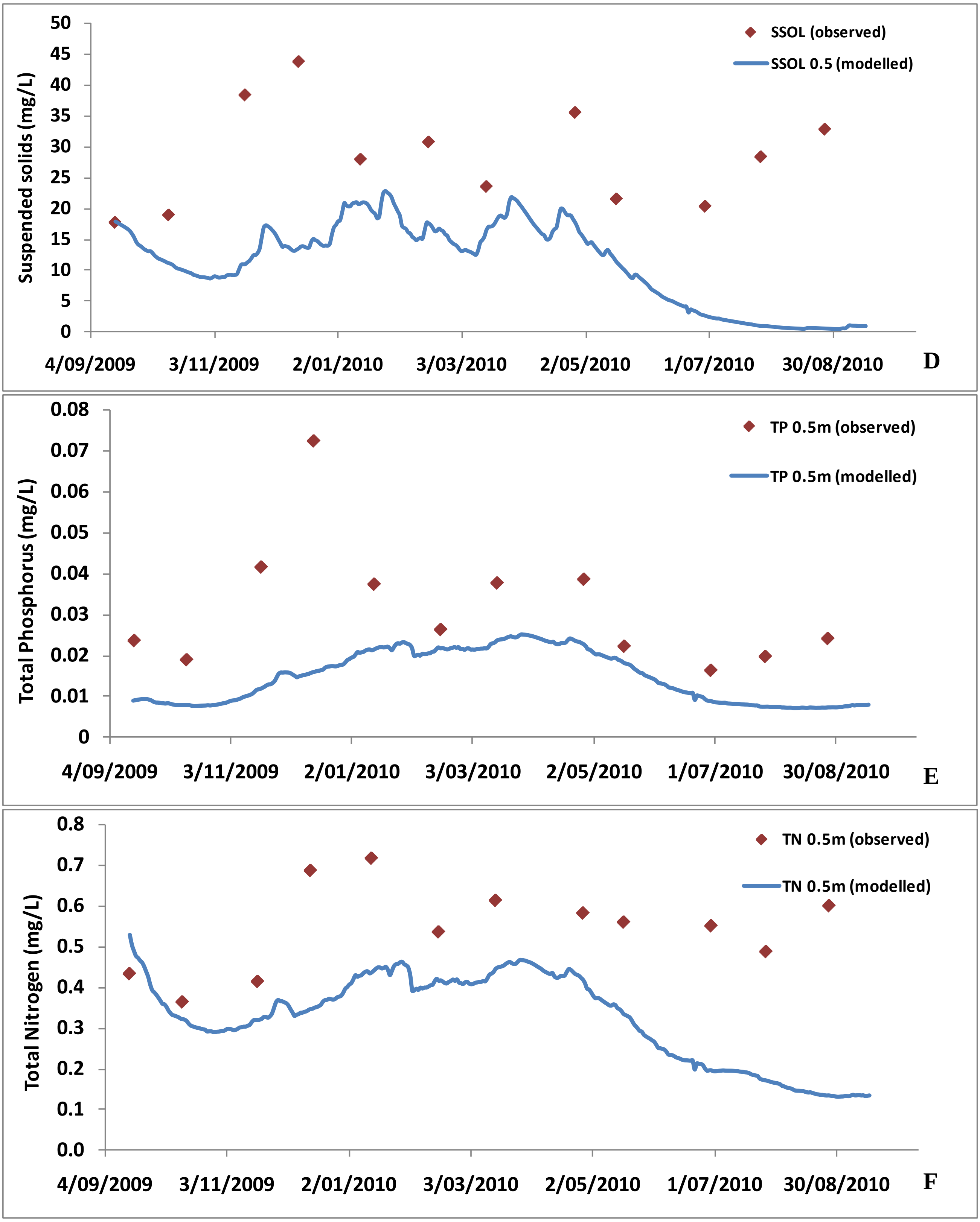


Figure 18 (cont.). Concentrations of water quality variables for Lake Hakanoa from 16 September, 2009 to 26 July, 2010 (observed) and modelled results for creation of a wetland that covers 3% of the catchment, conversion of pastoral land to exotic forest and removal of septic tanks servicing 20 people: d) suspended solids e) total phosphorus and f) total nitrogen.

Discussion

After visual assessment of 2002 and 2007 data collected from Lake Hakanoa, sourced mostly from Environment Waikato, Hudson et al. (2008) considered that water quality was improving, with nutrient concentrations and chlorophyll *a* decreasing over time and clarity increasing. Our results reveal similar trends for nutrients and chlorophyll *a* concentrations as those found in 2007, but with further decreases in TN concentrations. This may be consistent with retirement of land around the riparian margin for plantings and increased replacement of mostly pastoral land use by suburban land use within the catchment. When we simulated a 75 m wide riparian margin and 2.7 km lake perimeter, the area encompassed was 3.6 percent of the 5.5 km^2 catchment. This change would be likely to improve (reduce) the TLI value.

As it is shallow, Lake Hakanoa does not stratify to any great extent (Figure 1; Hudson et al., 2008). Being shallow does, however, make the lake prone to sediment resuspension through wind generated wave action (Figure 8; Nixdorf & Denke, 1997) especially since it is in a devegetated state. Resuspension of sediments most commonly occurs in shallow lakes due to benthic shear stress (Hamilton & Mitchell, 1997). Intense mixing, as a result of convective heat exchanges (Spigel & Imberger, 1987) may also penetrate the sediments and entrain nutrient-rich sediment porewaters, particularly in winter when overlying water is likely to be cooler than the temperature of the bottom sediments. The resulting entrainment of pore-waters would ensure both a light climate and nutrient supply to phytoplankton, rendering restorative measures less effective under this condition of high internal nutrient loading (Nixdorf & Denke, 1997).

Two main restoration scenarios were considered for this project, namely change of land use in the catchment from pastoral farming to exotic forestry and creation of a wetland that covers 3% of the catchment. The decreases in chlorophyll *a*, suspended solids and TP were very similar for these two scenarios. The wetland option resulted in a greater decrease in TN concentrations compared to changing land use from pastoral farming to exotic forestry. The nutrient exports used to model the change in land use scenario were estimated from New Zealand studies , with the main focus on the Waikato region and with the wetland scenario values specific to Lake Hakanoa (Hudson et al., 2008). Nutrient exports under different land uses can vary widely depending on, tree harvesting and regeneration stages, soil type and topography (Hamilton, 2005), dry and wet years (Quinn and Stroud, 2002) and stocking rates (Wilcock et al., 1999). Nitrogen exports from exotic forestry have been found to vary from 1.31 to 21 kg N ha^{-1} yr^{-1} (Cooper and Thomsen, 1988; Parfitt et al., 2003). Phosphorus export from exotic forestry ranges from 0.095 to 0.1 kg P ha^{-1} yr^{-1} (Wilcock, 1986; Cooper and Thomsen, 1988) and varies similarly on a relative scale to nitrogen (Cooper and Thomsen, 1988). It is, however, anticipated that both scenarios would improve the state of the lake despite difficulty in prescribing absolute export values (Figs 11 and 12). Changing from pastoral farming to exotic forestry would remove the nitrate leached from domestic animal urine patches (Menneer et al., 2004) and there would be less particulate phosphorus attached to soil particles during periods of tree growth, as soil disturbance is an issue with pastoral farming (Wilcock et al., 1999). Exotic forestry nutrient exports can be variable and harvesting can cause major soil disturbance (Quinn & Stroud, 2002; Abell et al., 2011) but these can also be managed through the use of riparian buffers at critical source points (Fennessy & Cronk, 1997; Quinn, 2005).

Wetlands are efficient at capturing sediment from the catchment and nutrient uptake by the wetland plants. Wetlands need careful planning and construction to be effective, as once a wetland becomes anoxic that inorganic phosphorus can be released from the sediment (Tanner et al., 2005). Tanner et al., (2005; 2009) have formulated methods for construction of wetlands that incorporate chemicals that adsorb phosphorus and systems that aerate the water. Floating wetlands are a new technology under experimentation and may be worth investigating as a restoration measure (Hudson et al., 2008).

Other scenarios were examined but were not considered viable. Sediment removal and deepening of the lake would likely have a positive effective but would likely result in spoil containing elevated levels of heavy metals and requiring disposal to landfill or extensive areas for disposal, which would be very expensive (Faithfull et al., 2005). Sediment capping with a chemical flocculant as a means of ‘locking up’ phosphorus is another possibility but since this lake is continuously mixed and does not appear to become anoxic in bottom waters, it would necessitate sufficient doses of flocculant to be effective over a considerable depth of the sediments (10 cm or more depth), which would also necessitate considerable expense (Søndergaard et al., 2003). Aeration with a destratifier would not be effective since the lake does not stratify. Fish removal would be another option but the community wishes to retain its recreational coarse fishing activities (Hudson et al., 2008).

More frequent data collection over another year would improve the calibration and increase the validity of the modeled outputs. The council may wish to consider creation of a wetland in the immediate future and potentially to use incentives or legislation to cap nutrient export for the future. Incentives for conversion of pastoral land to exotic forestry utilising the carbon credits scheme may be worthwhile and could be examined for its economic viability, i.e., to provide an economically viable change in land use of benefit to lake water quality. Planting of permanent vegetation would be advantageous in key source areas where forest operations were undertaken, should exotic forests be harvested and planted. Removal of septic tanks should also be used to improve water quality but would first require an inventory of septic tank use around the catchment. We recommend that the council gains professional advice on the best methods to create additional treatment wetlands as their effect can be enhanced by proper design and use of adsorption materials in some cases.

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