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A coupled hydrodynamic-ecological model of management options for restoration of Lake Ohinewai

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Lake Ohinewai

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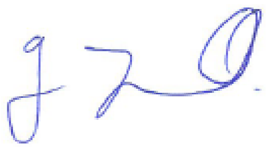

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EXECUTIVE SUMMARY

Koi carp (*Cyprinus carpio*) is regarded as one of the ecologically most destructive invasive freshwater species capable of degradation of shallow aquatic ecosystems. This degradation is largely due to their benthic foraging activity which resuspends sediment and increases nitrogen (N) and phosphorus (P) concentrations, leading to algal blooms. In addition, carp have the potential to excrete large quantities of nutrients into the water column. This report describes a modelling study of a shallow Waikato lake subject to invasive fish removal to investigate how carp contribute to the overall nutrient cycling at an ecosystem scale. The study site was Lake Ohinewai, a relatively small shallow, polymictic, hypertrophic riverine lake located in the northern Waikato region. Evidence of water quality degradation has been documented since the 1980's, before the introduction of carp. Lake Ohinewai has undergone an intensive programme of invasive fish removal and a permanent adult koi carp barrier was installed on the outflow drain of Lake Ohinewai to prevent passage into the lake, but allow carp to exit.

We applied DYRESM-CAEDYM (DYCD), a 1-D water quality model that has been developed at the Centre for Water Research, University of Western Australia. Daily inflows into Lake Ohinewai were derived from INCA, a process-based model. Carp-driven sediment resuspension was estimated using results from experimental ponds stocked with varying densities of carp. Carp-suspended sediment was then used to estimate carp-translocated pore-water due to benthic feeding. Koi carp excretion was estimated using an allometric scaling model. Nine catchment and riparian management scenarios were tested with no fish (NF) and with current invasive koi carp removal (F). These scenarios included: simulation of current biomass; pre-removal fish biomass; reduction of external load by 50%; an all native forest catchment; climate change; DOC administered land sub-catchment retirement; enhanced lake riparian margins; stream riparian zones; and creation of a wetland. For all scenarios, specified changes in nutrient concentrations were applied to internal loads (phosphate and ammonium release rates) from the sediment.

Simulations demonstrated that, at a density of 374 kg ha^{-1} and assuming they are feeding on the benthos, koi carp can contribute 21% of total phosphorous load and 10% of total nitrogen load via nutrient translocation. The major proportion of this load was due to koi carp excretion. While koi carp introduction in Lake Ohinewai has contributed to its current

hypertrophic state based on this modelling exercise, evidence of water quality degradation was originally documented prior to koi carp introduction, and has most likely been occurring since the catchment land use was originally modified from its natural state. The simulations suggest that the removal of koi carp decreased Trophic Level Index (TLI4) from 6.45 to 6.28, indicating that koi carp removal alone is not sufficient for a significant restoration of lake water quality. In order to return the system to a stable clear water state, water clarity must improve to a level to permit significant macrophyte re-establishment. However, restoration simulations showed that at a lower TLI4 the removal of koi carp is critical to lake restoration. Simulations estimated that the removal of koi carp decreased TSS concentrations by approximately two-thirds in most of the scenarios. However, in the all-native catchment scenario, removal of koi carp was predicted to increase Secchi depth by c. 2.5 m, and reduce TSS by c. 13 mg l^{-1}.

The scenario simulations within the present study showed that integrated catchment management involving use of stream riparian zones and constructed wetlands would be required in order to restore lake water quality significantly. Using these mitigation techniques a TLI4 target of 5.27 would likely be achieved. This mesotrophic TLI4 may enable the re-establishment of macrophytes.

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TABLE OF CONTENTS

TABLE CAPTIONS

FIGURE CAPTIONS

Introduction

In freshwater ecosystems, invasive fish can account for a large proportion of animal biomass, and therefore play a significant role in ecosystem processes related to nutrient concentrations (Holmlund & Hammer, 1999). Fish can exert both top-down and bottom-up influence on lake nutrient status. The extent of this influence will depend on the biomass of the fish, and their predominant feeding activity. For example, zooplanktivorous fish can decrease concentrations of zooplankton, allowing enhanced growth of phytoplankton and altering nutrient concentrations within lakes. Fish can also have a direct influence on primary productivity via nutrient recycling (Villéger et al., 2012). This nutrient recycling can occur from benthic foraging activity, which can translocate nutrients from the sediments to the water column, stimulating new primary productivity (Vanni, 2002). In addition, fish metabolism produces waste excreted in the form of ammonia and phosphate that becomes directly available to primary producers (Vanni, 2002; Schaus et al., 1997).

Koi carp (*Cyprinus carpio*) is regarded as one of the ecologically most destructive invasive species capable of degradation of shallow aquatic ecosystems (Lowe et al., 2000; Weber & Brown, 2015). This degradation is largely due to their benthic foraging activity which resuspends sediment and increases nitrogen (N) and phosphorus (P), leading to high chlorophyll *a* concentrations (Breukelaar et al., 1994). In addition, carp have potential to excrete large quantities of nutrients into the water column (Matsuzaki et al., 2007; Morgan & Hicks, 2013). Manipulation experiments have found that carp nutrient excretion is a primary mechanism of water quality deterioration (Matsuzaki et al., 2007). The low N:P ratio of carp excretion (Morgan et al., 2013) may favour the growth of cyanobacteria (Havens et al., 2003), and therefore modify population structure of phytoplankton. However, cyanobacteria dominance associated with low N:P ratios is a controversial topic, and other authors have suggested that cyanobacteria blooms are more strongly correlated to total P, total N and standing algal biomass (Downing et al., 2001). Once a critical biomass of carp is reached, shallow lakes can reach an alternate stable state characterised by high turbidity and a lack of macrophytes (Zambrano et al., 2001). Macrophyte populations collapse due to a combination of uprooting during carp feeding activities and light limitation in turbid water (Miller & Crowl, 2006).

Koi carp was most likely introduced into New Zealand in the 1960s, however, large feral populations were only discovered in the 1980s in the Whangamarino Wetland, Waikato. Koi became widespread throughout the Waikato River system shortly after their discovery (Pullan, 1986), and now dominate fish biomass in many lowland shallow lake systems in northern New Zealand. Based on studies discussed above, the removal of carp is likely to have positive effects on lake water quality. However, the costs and benefits of doing this relative to catchment and riparian management in terms of restoration of lake health need to be evaluated. Ecosystem models provide a cost effective and efficient means to gain insight into the role of fish in the feedbacks and interactions of the system. However, lake ecosystem models typically simulate nutrient-phytoplankton interactions (e.g., Özkundakci et al., 2011) and the structure populations of zooplankton (Trolle et al., 2011). The effect of fish and other consumers on the planktonic food web is usually only crudely parameterised as simple loss terms. This neglects more complicated effects of fish on water quality such as trophic cascades, sediment resuspension and nutrient recycling. While there have been attempts to measure the impact of common koi carp on aquatic communities, the small scale nature of such studies (i.e. mesocosm scale) makes it difficult to extrapolate the results to whole ecosystems (e.g., Kloskowski, 2011). However within pond ecosystems enclosure/exposure experiments have shown that high carp density is associated with lower biodiversity and higher turbidity.

To enable effective lake restoration, an integrated approach of catchment and in-lake management is required. These management options may include riparian buffer zones, constructed wetlands, land-use change, and best practice management techniques within agricultural land to reduce nutrient loss. However it should be noted that the effectiveness of these integrated management techniques can vary widely. For example, riparian afforestation can significantly reduce run-off, sediment yield and nutrient loss from pastoral catchments (Menneer et al., 2004), but results can be highly variable (Parkyn et al., 2000).

This report describes a modelling study of a shallow Waikato lake subject to invasive fish removal to address the questions:

- How much do carp contribute to the overall nutrient cycling at an ecosystem scale?
- Does 'top-down' control meet expectations or is a more integrated approach of catchment and in-lake management necessary?

- Can we optimise lake restoration by simulating different ‘bottom-up’ control and ‘top-down’ control scenarios?

Method

Study site

Lake Ohinewai is a relatively shallow, polymictic, hypertrophic riverine lake (area 16.2 ha) located in the northern Waikato region. While carp introduction in Lake Ohinewai contributed to its current hypertrophic state, evidence of water quality degradation has been documented since the 1980’s (Thompson et al., 1983). A survey in 1981 recorded that 80% of the substrate of Lake Ohinewai was covered with *Egeria* (invasive freshwater aquatic herb). By 1991 there was no submerged vegetation present in Lake Ohinewai (Edwards et al., 2010). The catchment (360 ha) is mainly comprised of dry stock (84%) with some dairy (13%) and the remaining area comprised of riparian and wetland zones (Fig. 1).

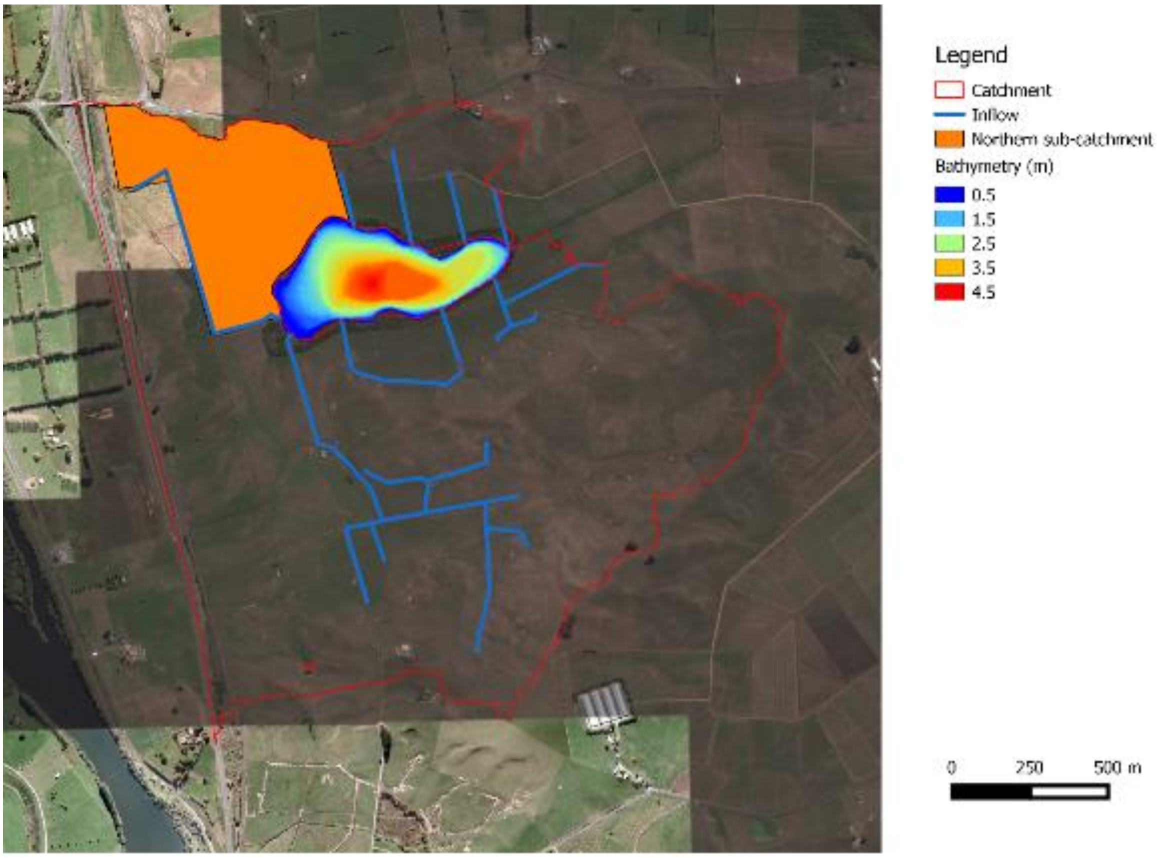


Figure 1. Lake Ohinewai study site spatial information, overlaid on aerial photography.

Lake Ohinewai has undergone an intensive programme of invasive fish removal (Fig. 2). In addition to pest fish removal, on 5 May 2011 a permanent adult koi carp barrier was installed on the outflow drain of Lake Ohinewai to prevent passage into the lake but enable carp to exit (Daniel & Morgan, 2011).

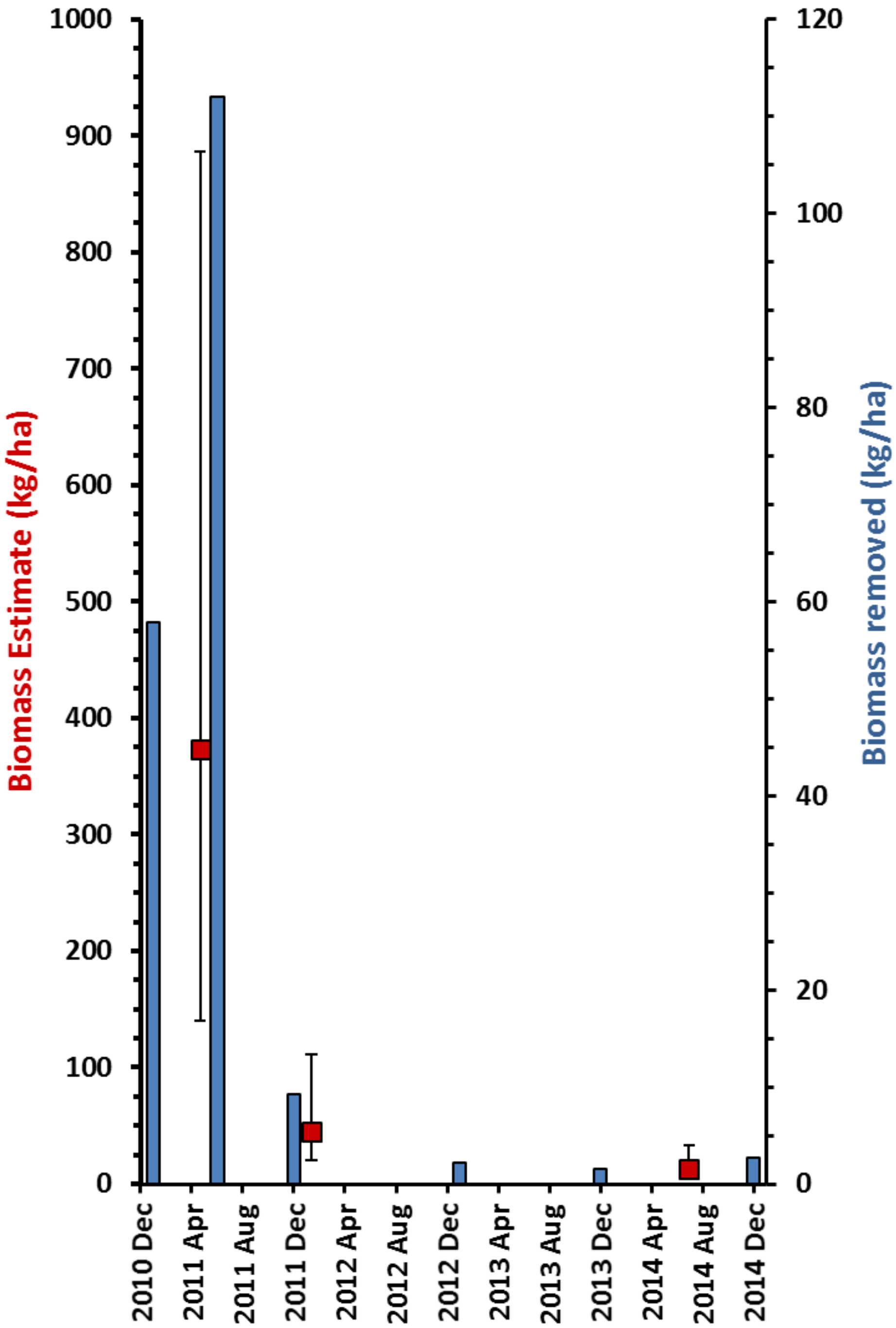


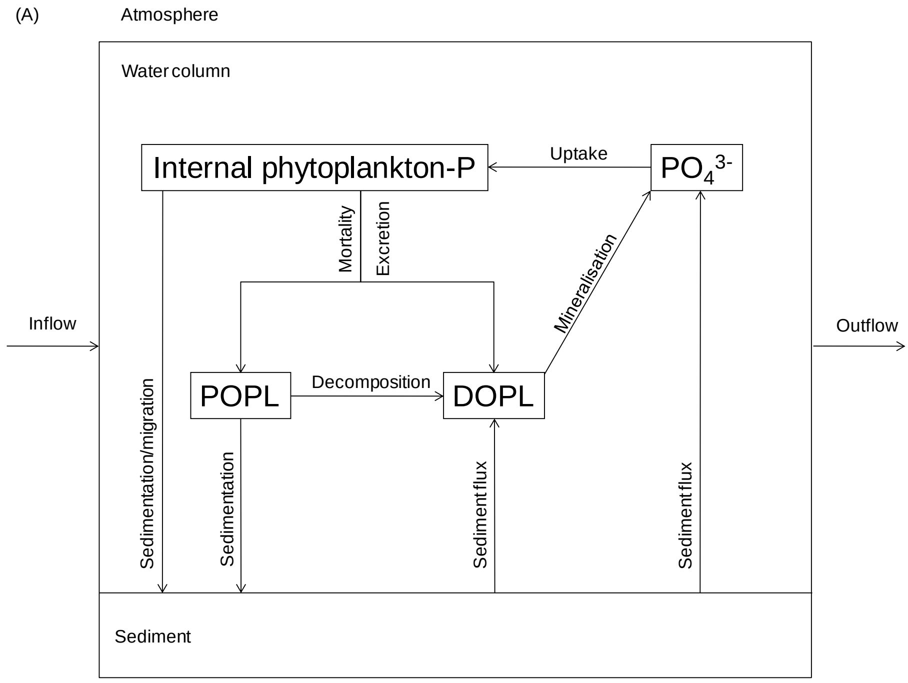
Figure 2. Estimated koi carp biomass in Lake Ohinewai on various dates (red squares; initial biomass) and the biomass removed (blue bars) (see Tempero et al., 2015 for further details). Error bars are 95% confidence interval.

Water quality modelling

DYRESM-CAEDYM (DYCD) is a 1-D water quality model that has been developed at the Centre for Water Research, University of Western Australia (Gal et al., 2009). DYRESM (DYnamic REservoir Simulation Model) simulates vertical distribution of temperature, salinity and density using a horizontal Lagrangian layer approach. The horizontal Lagrangian layers are free to move vertically and can contract and expand based on changes in inflows, outflows and surface mass fluxes. The layer thicknesses also adjust during model simulations in order to effectively represent vertical density gradients. DYRESM is based on an assumption of one dimensionality where variations in the vertical dimension are assumed to be greater than variations in the horizontal dimension (Imerito, 2007). The DYRESM model coupled to CAEDYM (Computational Aquatic Ecosystem Dynamics Model) enables simulation of several biological and chemical variables broadly constituting 'water quality'. CAEDYM is a general biogeochemical model that can simulate specific ecological interactions between species or groups. A detailed description of the model can be found in Hamilton & Schladow (1997).

The model includes comprehensive process representations for carbon (C), N, P (Fig. 3), and dissolved oxygen (DO) cycles, and several size classes of inorganic suspended solids. Several applications have been made of DYRESM-CAEDYM to different lakes (e.g. Burger et al., 2008; Gal et al., 2009; Özkundakci et al., 2011), and these publications have detailed descriptions of the model equations.

The biogeochemical variables in CAEDYM may be configured according to the goals of the model application and availability of data. In this study, two groups of phytoplankton were included in CAEDYM, representing generically diatoms and cyanobacteria. The interactions between phytoplankton growth and losses, sediment mineralisation and decomposition of particulate organic matter influence N and P cycling in the model, as shown in Fig. 3. Fluxes of dissolved inorganic and organic nutrients from the bottom sediments are dependent on temperature, nitrate and DO concentrations of the water layer immediately above the sediment surface.



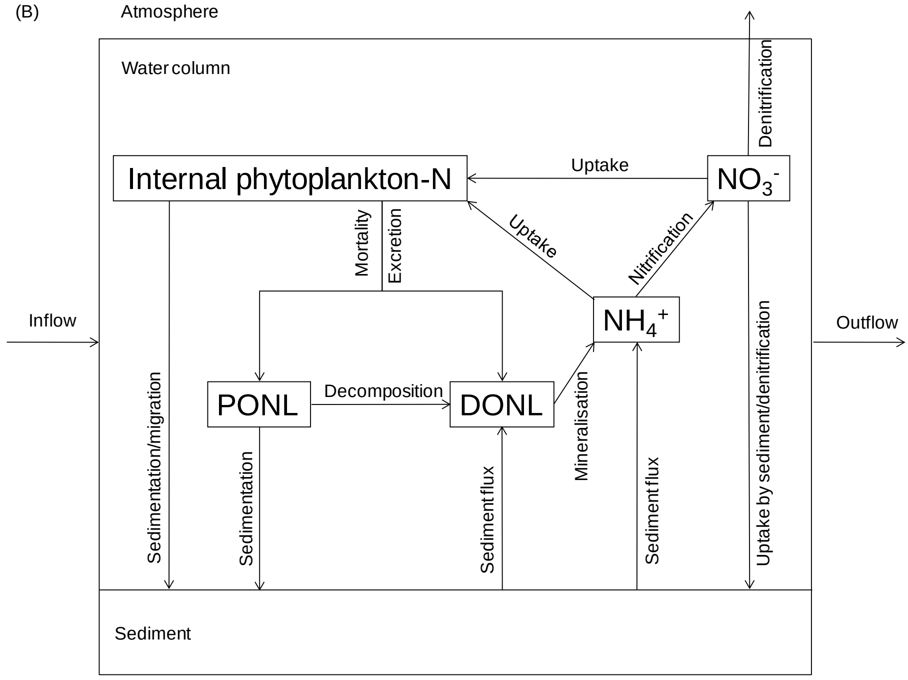


Figure 3. Conceptual model of the (A) phosphorus and (B) nitrogen cycles represented in DYRESM-CAEDYM for the present study. POPL, PONL, DOPL and DONL represent particulate labile organic phosphorus and nitrogen, and dissolved labile organic phosphorus and nitrogen, respectively.

Koi carp are not explicitly formulated in DYCD, but their effect on sediment resuspension and excretion was modelled by adding appropriate inflows. Carp-driven sediment resuspension (CSS, mg day^{-1}) was calculated as a linear function of carp density (CD, kg ha^{-1}) according to Breukelaar et al. (1994):

$$CSS = 0.236CD * 1000 * LA \qquad (1)$$

Where 0.236 represents the slope of the linear relationship with origin zero between *CD* and the sediment found in traps over time (g m^{-2} day^{-1}) in Breukelaar's experimental ponds, *LA* is lake area (m^2) and the factor of 1000 converts from g to mg. CSS was added to the model lake in an inflow of 10 m^3 water per day.

Carp-suspended sediment was also used to estimate carp-translocated pore water (*CTPW*) (L day^{-1}) due to benthic feeding. An empirical relationship between dried Lake Okareka sediment and pore water volume was used to estimate *CTPW* from *CSS*:

$$CTPW = 5.99CSS / 1000 \qquad (2)$$

where the factor 1000 converts g of pore water to L of pore water. This equates to a sediment water content of approximately 86%, which is within the range measured in Waikato lakes (Faithfull et al., 2005). Ammonium (NH_4-N) and phosphate (PO_4-P) translocated within this pore water was calculated based on concentrations measured within pore water taken from two cores taken at approximately 3 m water depth in the north and south ends of Lake Ohinewai:

$$NH_4\text{-N} = CTPW * [NH_4] \qquad (3)$$

$$PO_4\text{-P} = CTPW * [PO_4] \qquad (4)$$

The average concentration of NH_4-N and PO_4-P in the surface pore waters of Lake Ohinewai was 2.82 mg L^{-1} and 0.005 mg L^{-1}, respectively. This was then also added to the lake as a 10 m^3 flow.

Koi carp excretion (mg $fish^{-1}$ hr^{-1}) was estimated using an allometric scaling model (Morgan & Hicks, 2013), using daily lake water temperature in kelvin (*T*) simulated by DYRESM and assuming a mean fish mass (*M*) of 550 g $fish^{-1}$.

$$TP = e^{(b \ln(M) + \ln(Po) - E / (kT))} / 1000 \qquad (5)$$

$$TN = e^{(b \ln(M) + \ln(Po) - E / (kT))} / 1000 \quad (6)$$

$$NH_4\text{-}N = e^{(b \ln(M) + \ln(Po) - E / (kT))} / 1000 \quad (7)$$

$$PO_4\text{-}P = e^{(b \ln(M) + \ln(Po) - E / (kT))} / 1000 \quad (8)$$

where *b* is the slope and P_o is a normalisation constant for temperature corrected excretion rates in Morgan & Hicks (2013), see Table 1. *k* is the Boltzmann constant (8.62 x 10^{-5}), and E is the average activation energy of metabolic reactions (0.65 eV). The division by 1000 converts the units from µg to mg.

Table 1. Least-squares regression estimates of whole-body, temperature-corrected N and P excretion for common carp against the natural log of fish wet mass, directly reproduced from Morgan & Hicks (2013).

Nutrient and rate	*N*	$\ln(P_0)$	*b*	r^2	*P*
ln (µg NH_4 $fish^{-1}$ h^{-1} $e^{E/kT}$)	28	29.98	0.729	0.91	<0.001
ln (µg PO_4 $fish^{-1}$ h^{-1} $e^{E/kT}$)	28	28.72	0.439	0.37	0.001
ln (µg TN $fish^{-1}$ h^{-1} $e^{E/kT}$)	26	31.46	0.595	0.79	<0.001
ln (µg TP $fish^{-1}$ h^{-1} $e^{E/kT}$)	26	31.28	0.330	0.26	0.008

Forcing variables for DYRESM

Meteorological forcing of DYRESM included daily average air temperature (°C), shortwave radiation (W m^{-2}), cloud cover (fraction of whole sky), vapour pressure (hPa), wind speed (m s^{-1}) and rainfall (m) (Fig. 4). All met data was acquired from the National Institute of Water and Atmospheric Research (NIWA) weather station at Ruakura, Hamilton (latitude 37.776°S, longitude 175.305°E).

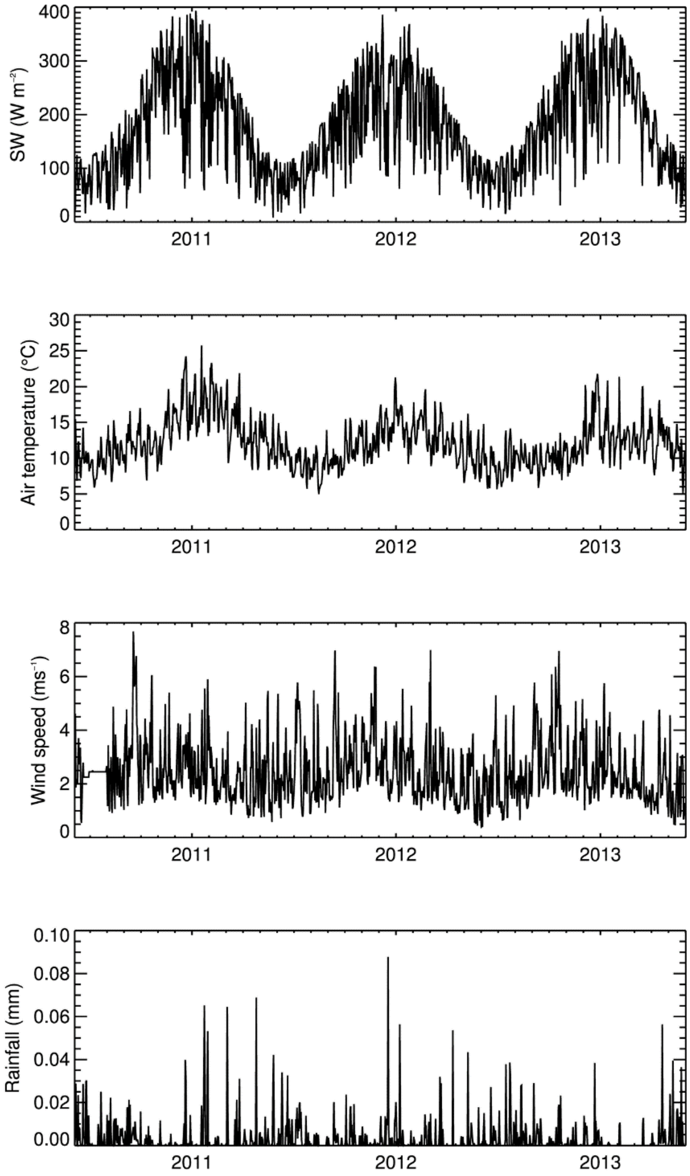


Figure 4. Meteorological data used as input to DYRESM. SW is shortwave radiation. Data were obtained from the NIWA weather station at Ruakura, Hamilton (latitude 37.776°S, longitude 175.305°E).

Catchment modelling INCA-N INCA-P

Daily inflows into Lake Ohinewai were derived from INCA (INtegrated CAtchment model), a process-based model which aims to minimise data requirements and model complexity (Wade et al., 2002; Whitehead et al., 1998a,b). INCA is spatial at the level of stream reaches, enabling spatial variations in land use at the sub-catchment scale so that management actions can be simulated. INCA-N estimates daily discharge, and stream water NO_3-N and NH_4-N concentrations. INCA-P simulates daily stream flow, TP, total dissolved phosphorous (TDP), soluble reactive phosphorous and suspended sediment concentrations (Crossman et al., 2013).

The inputs to both INCA P and N are common and include:

- **Hydrological and meteorological data** – daily air temperature, hydrologically effective rainfall, soil moisture deficit, actual precipitation and solar radiation;
- **Reach structure** – reach length, velocity/flow relationship parameters, latitude and longitude or upstream reach boundary;
- **Sub-catchments** – area, land use proportions, base flow index.

Meteorological data were sourced from the NIWA weather station at Ruakura, Hamilton (latitude 37.776^{o}S, longitude 175.305^{o}E). Reach structure was determined from aerial photography (via QGIS) and field measurements. Sub-catchments were determined from LIDAR data (Waikato Regional Council), and land use was determined from a combination of aerial photography, LCDB4 and Agribase.

Fertiliser applications were estimated as follows:
Dairy – Application rates of fertiliser on a typical Waikato dairy farm of 150 kg TN per hectare and 40 kg TP per hectare, applied over 10 days, were used (A. Dewes, personal communication);
Sheep and beef – Based on18 kg TP per hectare (applied via superphosphate) (personal communication with land owner), and 70 kg TN per hectare (A. Dewes, personal communication). The land owner stated that urea was only applied to some paddocks, however more information is needed to get more specific estimates of fertiliser use.

Simulated N inputs include atmospheric deposition/fertiliser inputs of ammonium and nitrate (wet and dry); organic matter mineralisation producing NH_4-N, nitrification producing NO_3-N, and nitrogen fixation are also included. Output fluxes are subtracted including plant uptake, immobilisation and denitrification. These inputs and outputs are separated by landscape type and influenced by soil moisture and temperature. INCA-N simulates mass of NO_3-N and NH_4-N stored in the soil and ground water systems, and estimates fluxes from catchments to the waterbodies. Also simulated is flow through the plant/soil system to deliver the nitrate and ammonium load to the river system, which is then directed downstream after accounting for effluent discharges, and in-stream processes of nitrification and de-nitrification.

A total of three inflow water quality measurements were available, and were used to estimate particulate organic nitrogen. To do this, ratio method was used, whereby PON was estimated as:

$$PON = TN - (NH_4 + NO_3) \quad (9)$$

The ratio of dissolved organic nitrogen (DIN) to TN was calculated from three in-situ measurements.

TLI calculation

A lake Trophic Level Index (TLI4) value was calculated for each year of the simulation period to indicate overall changes in water quality. The relevant equations for determination of the TLI are:

$$TL_{Chla} = 2.22 + 2.54 \log(Chla) \quad (10)$$

$$TL_{SD} = 5.1 + 2.27 \log\left(\frac{1}{SD} - \frac{1}{40}\right) \quad (11)$$

$$TL_{TP} = 0.218 + 2.92 \log(TP) \quad (12)$$

$$TL_{TN} = -3.61 + 3.01 \log(TN) \quad (13)$$

$$TLI\text{-}4 = \frac{1}{4}\sum(TL_{Chla}, TL_{SD}, TL_{TP}, TL_{TN}) \quad (14)$$

$$TLI\text{-}3 = \frac{1}{4}\sum(TL_{Chla}, TL_{TP}, TL_{TN}) \quad (15)$$

where:

TL_{Chla}, TL_{SD}, TL_{TP} and TL_{TN} represent the individual level trophic level indices for the individual variables of chl *a*, Secchi depth, total phosphorus and total nitrogen, respectively.

As Secchi depth is not explicitly included in the model, so this variable was derived from the model-predicted attenuation coefficient as (Holmes, 1970):

$$z_{SD} = 1.44\,K_d \tag{16}$$

where:

z_{SD} is the Secchi depth (m);

K_d is the diffuse attenuation coefficient for PAR (m^{-1}).

K_d is calculated as (Gallegos, 2001):

$$K_d = K_w + K_c * chl_a + K_y * DOC + K_s * TSS \tag{17}$$

where:

K_w is the background extinction coefficient with a value of 0.3315 (m^{-1});

K_c is the specific attenuation coefficient for chl *a* with a value of 0.0122 (m^2 (mg chl *a*)$^{-1}$);

K_y is the specific attenuation coefficient for dissolved organic carbon with a value of 0.0507 (m^2 (g DOC)$^{-1}$);

K_s is the specific attenuation coefficient for total suspended sediment with a value of 0.0778 (m^2 (g TSS)$^{-1}$).

Management scenario input data

Nine catchment and riparian management scenarios were tested with no fish (NF) and with current invasive koi carp removal (F). **Note that F scenarios are based on the calibration model, with fish removals as per Fig. 2**. **However result statistics are calculated for the period before fish removals (carp biomass 374 Kg ha^{-1}), allowing for the comparison of the scenario with the presence of carp at pre-removal biomass**. For all scenarios, specified changes in nutrient concentrations were applied to internal loads from the sediment (phosphate and ammonium release rates). Table 2 gives a brief description of the assumptions for each scenario. Simulations including fish had time-varying populations due to fish removal and effects of the one-way barrier.

Table 2. A brief description of scenario assumptions including a "Reference" scenario (100% catchment in native forest; S4) which will be referred to in results and figures henceforth. ICM = Integrated Catchment Management.

REFERENCE	SCENARIO	DESCRIPTION
CALIBRATION	Calibration	Assumes current (2015) koi carp biomass of 10 kg ha^{-1} and includes simulation of carp removals
S1	Current biomass	Assumes current (2015) koi carp biomass of 10 kg ha^{-1}
S2	Pre-removal	Koi carp biomass prior to removal (374 kg ha^{-1})
S3	ICM	External and internal load reduced by approximately 50%
S4	Native	All catchment native forest
S5	Climate change	Climate change 2.1˚C warmer by 2090 (from 1990). Current land use assumed
S6	Sub-catchment retirement	Retirement/planting of northern sub-catchment
S7	Lake riparian	Kahikatea 55 m high surrounding lake
S8	Stream riparian	Riparian zone around streams
S9	Wetland	Constructed wetland near inflow inlet

Calibration

Simulates current lake conditions, including the effects of pest fish removal yielding a koi carp biomass of 10 kg ha^{-1}.

S1 Current biomass

Simulates current koi carp biomass of 10 kg ha^{-1}.

S2 Pre-removal

Simulates conditions prior to pest fish removal, with koi carp biomass of 374 kg ha^{-1}.

S3 50% reduction

50% reduction in external nutrients, and an assumption of 50% reduction of internal loading. This assumes integrated catchment management (Jenkins & Vant, 2007; Menneer et al., 2004). S3F koi carp biomass of 374 kg ha^{-1}.

S4 Native

Entire catchment is native forest. INCA-N and INCA-P re-run and outputs are used to run DYCD. S4F koi carp biomass of 374 kg ha^{-1}.

S5 Climate change

Climate change predictions where air temperature is an average of 2.1˚C warmer by 2090 (MFE, 2008). S5F koi carp biomass of 374 kg ha^{-1}.

S6 Retirement/planting of northern sub catchment

Public conservation land to the north of Lake Ohinewai (currently c. 30.2 ha dairy) is retired to become native forest. INCA simulations were then run using land cover classes: sheep 8%, riparian 11.4%, and dairy 4.6%. S6F koi carp biomass of 374 kg ha^{-1}.

S7 Lake riparian buffer

Lake riparian margin is fully grown with 55 m tall kahikatea trees. This scenario aims to test the effect of wind sheltering on the biophysical water quality attributes. This was achieved by modifying the bulk aerodynamic momentum transfer coefficient (C_m) as in Read et al. (2014). The C_m parameter was scaled using a cubic relationship between the wind sheltering coefficient (W_s: Markfort et al., 2010):

$$C_m = 0.0013\ W_s^{1/3}$$

$$Ws = \frac{2}{\pi} cos^{-1}\left(25\ h_s \sqrt{\left(\frac{\pi}{A}\right)}\right) - \frac{50\ h_s}{A\sqrt{\pi}} \quad \sqrt{A - 625\ h_s^2\ \pi}$$

Where h_s is the elevation difference between the top of the canopy and the lake surface (m), A is lake are (m^3). S7F koi carp biomass of 374 kg ha^{-1}. S7NF koi carp biomass of 0 kg ha^{-1}.

S8 Stream riparian buffer

All streams have a riparian buffer of 10 m based on assumptions by Senthilkumar et al. (2009). Inflows estimated by INCA in the calibration scenario are modified (reduced) with 81.6% reduction of TSS, 61.5% reduction of N and 58.9% reduction of P. It should be noted here that the effect of riparian buffers within New Zealand has been shown to be highly variable. For example, canopy closure of buffered sections with unprotected upstream areas may actually increase the nutrient export from a rehabilitated reach due to reduced in-stream assimilation (Parkyn et al., 2000).

S9 Constructed wetland

2.5% of catchment is transformed into a constructed wetland, which has the potential for 40% nitrate removal (Tanner et al., 2010). Inflows estimated by INCA in the calibration scenario are modified depending on dry weather conditions (rainfall less than two mm per day) or wet weather conditions (rainfall between two and 35 mm day^{-1}). During dry weather conditions TSS, phosphate and nitrate were retained in the wetland in proportions of 15, 54 and 70%, respectively. During wet weather conditions retention percentages were 78, 75 and 84% (Schulz & Peall, 2001).

Results

INCA

For both INCA-N and INCA-P, there were limited data available for calibration. However, INCA parameters were modified to match nutrient concentrations of the available field data. The small number of field data did not allow the calculation of a useful quantitative estimate of goodness of fit between model and observations. This limits an analysis of the effect of uncertainty in catchment processes on the predictions of the lake water quality model. For inflow and load calculations, estimated INCA-P flows were adopted (Fig. 5).

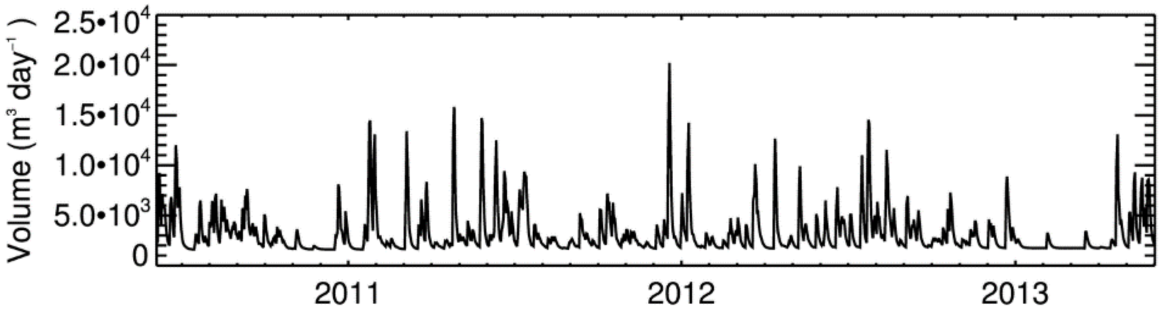


Figure 5. Freshwater inflow volume (m^3 day^{-1}).

INCA-N calibration

For the INCA-N simulation within S4 (all native forest), yearly TN simulated from the catchment was unrealistically low. The native INCA-N parameters were modified until average N loss was within the range of literature values (0.58 kg ha^{-1} yr^{-1}) (McDowell & Wilcock, 2008) (Table 3). The total TN load was estimated as 4.45 T yr^{-1}, which equates to 13.36 kg ha^{-1} yr^{-1} (Table 10). McDowell & Wilcock (2008) report that the average N loss from mixed stock agricultural land was 11 kg ha^{-1} yr^{-1} and from dairy 27 kg ha^{-1} yr^{-1}.

Table 3. Calibrated values for INCA-N of the Lake Ohinewai catchment. Land cover includes native (N), sheep/beef (S/B), dairy (D), and riparian (R).

PARAMETER	UNIT	TYPICAL RANGE	N	S/B	D	R	
DENITRIFICATION	m day^{-1}	0.01 – 19.0	0.0020	0.0050	0.0050	0.2000	
FIXATION	kg N ha^{-1} day^{-1}	0.0 – 0.0001	0.1000	0.1000	0.1000	0.0010	
NITRIFICATION	m day^{-1}	1.0 – 54.0	0.0100	0.0010	0.0005	0.0200	
MINERALISATION	kg N ha^{-1} day^{-1}	1.0 – 292.0	0.0300	0.5000	0.9000	0.0100	
IMMOBILISATION	m day^{-1}	0.0 – 0.1	0.0001	0.0001	0.0001	0.0040	
INITIAL SOIL WATER FLOW	m^3 s^{-1}	0.0 – 1.0	0.0010	0.0010	0.0010	0.0010	
INITIAL SOIL WATER NO_3	mg N l^{-1}	0.0 – 10.0	0.0010	0.0100	0.0100	1.0000	
INITIAL SOIL WATER NH_4	mg N l^{-1}	0.0 – 2.0	0.0050	0.1200	0.1100	0.1500	
FERTILISER ADDITION START DAY	Julian day	0 – 366		100.0000	100.0000		
FERTILISER ADDITION PERIOD	days	0 – 366		10.0000	10.0000		
NO_3 ADDITION RATE	kg N ha^{-1} day^{-1}	0.0 – 100.0		3.5000	7.5000		
NH_4 ADDITION RATE	kg N ha^{-1} day^{-1}	0.0 – 100.0		3.5000	7.5000		
NITRATE UPTAKE RATE	m day^{-1}	0.0 – 162.0	0.0800	0.1000	1.0000	0.0070	
AMMONIUM UPTAKE RATE	m day^{-1}	0.0 – 162.0	0.0100	0.0100	0.0010	0.0020	
MAXIMUM NITROGEN UPTAKE	kg N ha^{-1} yr^{-1}	5.0 – 80.0	200.0000	200.0000	300.0000	400.0000	
CATCHMENT			**1**	**2**	**3**	**4**	**5**
REACH LENGTH	m	1.0 – 10000.0	1361.0000	1361.0000	1361.0000	1361.0000	1361.0000
FLOW A	Æ	0.3 – 0.99	0.0000	0.0000	0.0000	0.0000	0.0060
FLOW B	Æ	0.001 – 0.2	0.5500	0.5500	0.5500	0.7500	0.8500
INSTREAM DENITRIFICATION	day^{-1}	0.04 – 0.09	0.1000	0.1000	0.1000	0.1000	0.2000
INSTREAM NITRIFICATION	day^{-1}	0.1 – 5.0	0.8000	0.7000	1.2000	1.2000	0.8000
GROUNDWATER RESIDENCE TIME	days	10.0 – 200.0	100.0000	100.0000	100.0000	100.0000	100.0000
INITIAL GROUNDWATER FLOW	m^3 s^{-1}	0.0 – 1.0	0.0020	0.0020	0.0020	0.0020	0.0020
INITIAL GROUNDWATER NO_3	mg N l^{-1}	0.0 – 10.0	0.0400	0.0500	0.0500	0.0500	0.0500
INITIAL GROUNDWATER NH_4	mg N l^{-1}	0.0 – 2.0	0.0200	0.0133	0.0200	0.0150	0.0400
POINT-SOURCE NH_4	mg N l^{-1}	0.0 – 1.0					
SUB-CATCHMENT AREA	km^2	0.001 – 10000.0	0.7200	0.7200	0.7200	0.7200	0.7200
BASE FLOW INDEX	Æ	0.0 – 1.0	0.0010	0.0010	0.0100	0.0300	0.0200
GROWTH SEASON START DAY	Julian day	0 – 366	0.0000	0.0000	0.0000	0.0000	0.0000
GROWTH SEASON PERIOD	days	0 – 366	365.0000	365.0000	365.0000	365.0000	365.0000
PARAMETER	**Unit**	**Typical range**	**Calibrated value**				
MAXIMUM SOIL MOISTURE DEFICIT	mm	100.0 – 170.0	200.0000				
INITIAL INSTREAM FLOW	m^3 s^{-1}	0.0 – 2.0	0.0010				
INITIAL INSTREAM NO_3	mg N l^{-1}	0.0 – 10.0	0.0000				
INITIAL INSTREAM NH_4	mg N l^{-1}	0.0 – 2.0	0.0001				

INCA-P calibration

For S4, modelled TP loads were much higher than that would be expected from using literature aerial export rates from native catchments in New Zealand (McDowell & Wilcock, 2008). Therefore native land cover INCA-P parameters were modified to produce realistic values (Tables 4-6), and native P load was 0.19 kg ha^{-1} yr^{-1}. The current calibration (current land use) total TP load was estimated as 0.28 t yr^{-1}, which equates to 0.78 kg ha^{-1} yr^{-1} (Table 10).

Table 4. Calibrated values for INCA-P hydrological calibration of Lake Ohinewai catchment.

Parameter		Unit	Land cover	Calibrated value
b Base flow index				
a b	Velocity–discharge parameters for stream flow	m2	– –	0.1
		–		0.5
	Rainfall excess proportion	–	–	0.2
TSF	Threshold soil zone flow	m^3 s^{-1}	–	0.01
R	Ratio of total to available water in soil	–	N	1.5
			S/B	1.5
			D	1.5
			R	1.5
IR	Maximum infiltration rate	mm day^{-1}	N	32
			S/B	32
			D	32
			R	32
T_1	Direct run-off residence time	days	N	0.3
			S/B	0.3
			D	0.3
			R	0.3
T_2	Soil water residence time	days	N	2
			S/B	
			D	2
			R	2
T_3	Groundwater residence time	days	–	5.00E+01

Table 5. Calibrated parameter values P transport.

Parameter	Unit	Land cover	Calibrated value	Source (for calibrated value)
Soil-inactive P initial condition	mg P kg^{-1} soil	N	1000	
		S/B	1000	
		D	1000	
		R	1000	
Soil-labile P initial condition	mg P kg^{-1} soil	N	30	
		S/B	30	
		D	30	
		R	30	
Freundlich isotherm constant for soil P	–	N	0.50000	Farkas et. al. (2013)
		S/B	9.00000	
		D	9.00000	
		R	0.10000	
Weathering factor (soil)	mm day^{-1}	N	1.0E10-08	
		S/B	0.00001	
		D	0.00001	
		R	0.00001	
Sorption coefficient (soil)	m^3 kg^{-1} g	N	14	
		S/B	14	
		D	14	
		R	14	
Equilibrium P concentration in soil	mg P L-1	N	0.05	
		S/B	0.05	
		D	0.05	
		R	0.05	
Maximum P plant uptake	kg P ha^{-1} yr^{-1}	N	7	
		S/B	100	
		D	100	
		R	100	
Immobilisation	m day^{-1}	N	0.40000	
		S/B	0.30000	
		D	0.50000	
		R	0.40000	

Table 6. Calibrated values of erosion.

Parameter		Unit	Land use	Calibrated value
Erosion a1	Flow erosion linear multiplier	–	–	8
a2	Flow erosion threshold	$m^2\ s^{-1}$	–	0
a3	Flow erosion power coefficient	–	–	0.15
a4	Transport capacity linear multiplier	$kg\ m^{-2}$	–	120
	Transport capacity threshold	$m^2\ s^{-1}$	–	0
a6	Transport capacity power coefficient	–	–	0.8
a7	In-stream friction factor	–	–	0.003
a8	Constant scaling in-stream sediment entrainment function	$kg\ s^{-2}$	–	0.001
a9 a10	Constants in function for in-stream sediment sources	$kg\ m^{-2}$	–	5.90E-08
		⁄ m3	–	5
E_S	'E' parameter for splash detachment	$kg\ m^{-2}\ s^{-1}$	N	1.60E-04
			S/B	0.005
			D	0.007
			W	1.60E-04
E_F	'E' parameter for flow erosion	$kg\ m^{-2}\ s^{-1}$	N	1.60E-04
			S/B	3.00E-03
			D	4.00E-03
			W	1.60E-04
A	'A' parameter for splash detachment	$s\ m^{-1}$	N	0.8
			S/B	3
			D	4
			W	0.4

DYCD calibration

The model parameters adjusted during the calibration of DYRESM are presented in Table 7 and for CAEDYM in Table 8. At this stage, there is not sufficient field data to support a separate calibration validation period, however, it is recommended that this be completed once there are at least four years of field data available at monthly intervals.

The model was able to reproduce the dominant temporal variation of TLI and Secchi depth (Figs 6a,b, Table 9), however some water quality parameters were less well simulated. For example, observed peaks in ammonium concentration were not simulated and simulated peaks were not observed. Similar observation-model misfits are seen in TN and TP.

During the simulation period, DYCD simulated a number of low oxygen events within the hypolimnion, associated with short periods of stratification (lasting up to a few days) in the summers of 2007, 2009, 2011 and 2013. These anoxic events were also associated with nutrient release from lake sediments (Fig. 7).

The simulated effect of carp-mediated sediment resuspension (below 0.5 m above bottom) is evident as elevated TSS concentrations near the lake bottom. Within the model, the rate of TSS resuspension by fish is constant for any specified koi carp biomass. However, how much of the resuspended sediment stays in suspension depends on the hydrodynamic conditions, such as vertical mixing rate. The general downwards trend in observed TSS following fish removals was simulated by the model, however two unusually high TSS concentrations observed in the field data near the end of the simulation period were not simulated (Fig. 6).

Table 7. Assigned values for parameters used in DYRESM.

Parameter	Unit	Calibrated value	Reference/remarks
Critical wind speed	m s^{-1}	3.0	Default value
Emissivity of water surface	-	0.96	Imberger & Patterson (1981)
Mean albedo of water	-	0.09	
Potential energy mixing efficiency	-	0.2	
Shear production efficiency	-	0.3	
Vertical mixing coefficient	-	500	
Wind stirring efficiency	-	0.4	
Effective surface area coefficient	m^{-2}	1.0×10^{5}	

Table 8. Assigned values for parameters used in CAEDYM for Lake Ohinewai; DOPL and DONL are dissolved organic phosphorus and nitrogen, respectively.

Parameter	Unit	Calibrated value
Sediment parameters		
Sediment oxygen demand	g m^{-2} d^{-1}	4.50
Half-saturation coefficient for sediment oxygen demand	mg L^{-1}	0.25
Maximum potential PO_4-P release rate	g m^{-2} d^{-1}	0.01
Oxygen and nitrate half-saturation for release of phosphate from bottom sediments	g m^{-3}	4.50
Maximum potential NH_4-N release rate	g m^{-2} d^{-1}	0.15
Oxygen half-saturation constant for release of ammonium from bottom sediments	g m^{-3}	4.50
Maximum potential NO_3 release rate	g m^{-2} d^{-1}	0.00
Oxygen half-saturation constant for release of nitrate from bottom sediments	g m^{-3}	4.00
Temperature multiplier for nutrient release	-	1.06
Nutrient parameters		
Decomposition rate of POPL to DOPL	d^{-1}	0.01
Mineralisation rate of DOPL to PO_4-P	d^{-1}	0.006
Decomposition rate of PONL to DONL	d^{-1}	0.05
Mineralisation rate of DONL to NH_4-N	d^{-1}	0.05
Denitrification rate coefficient	d^{-1}	0.6
Oxygen half-saturation constant for denitrification	mg L^{-1}	6.50
Temperature multiplier for denitrification	-	1.07
Nitrification rate coefficient	d^{-1}	0.6
Nitrification half-saturation constant for oxygen	mg L^{-1}	2.50
Temperature multiplier for nitrification	-	1.03
Phytoplankton parameters		
		Cyanophytes, Diatoms
Maximum potential growth rate at 20°C	d^{-1}	0.76, 0.9
Irradiance parameter non-photoinhibited growth	µmol m^{-2} s^{-1}	150, 20
Half saturation constant for phosphorus uptake	mg L^{-1}	0.003, 0.004
Half saturation constant for nitrogen uptake	mg L^{-1}	0.17, 0.065
Minimum internal nitrogen concentration	mg N (mg chl *a*)$^{-1}$	3.5, 3.4
Maximum internal nitrogen concentration	mg N (mg chl *a*)$^{-1}$	9.5, 10.2
Maximum rate of nitrogen uptake	mg N (mg chl *a*)$^{-1}$ d^{-1}	3.8, 3.3
Minimum internal phosphorus concentration	mg P (mg chl *a*)$^{-1}$	0.3, 0.1
Maximum internal phosphorus concentration	mg P (mg chl *a*)$^{-1}$	2.1, 2.2
Maximum rate of phosphorus uptake	mg P (mg chl *a*)$^{-1}$ d^{-1}	0.3, 0.24
Temperature multiplier for growth limitation	-	1.08, 1.06
Standard temperature for growth	°C	20.0, 20.0
Optimum temperature for growth	°C	34.0, 29.0
Maximum temperature for growth	°C	39.0, 34.0
Respiration rate coefficient	d^{-1}	0.9, 0.160
Temperature multiplier for respiration	-	1.06, 1.10
Fraction of respiration relative to total metabolic loss rate	-	0.1, 0.7
Fraction of metabolic loss rate that goes to DOM	-	0.1, 0.3
Constant settling velocity	m s^{-1}	0, -0.23×10^{-7}

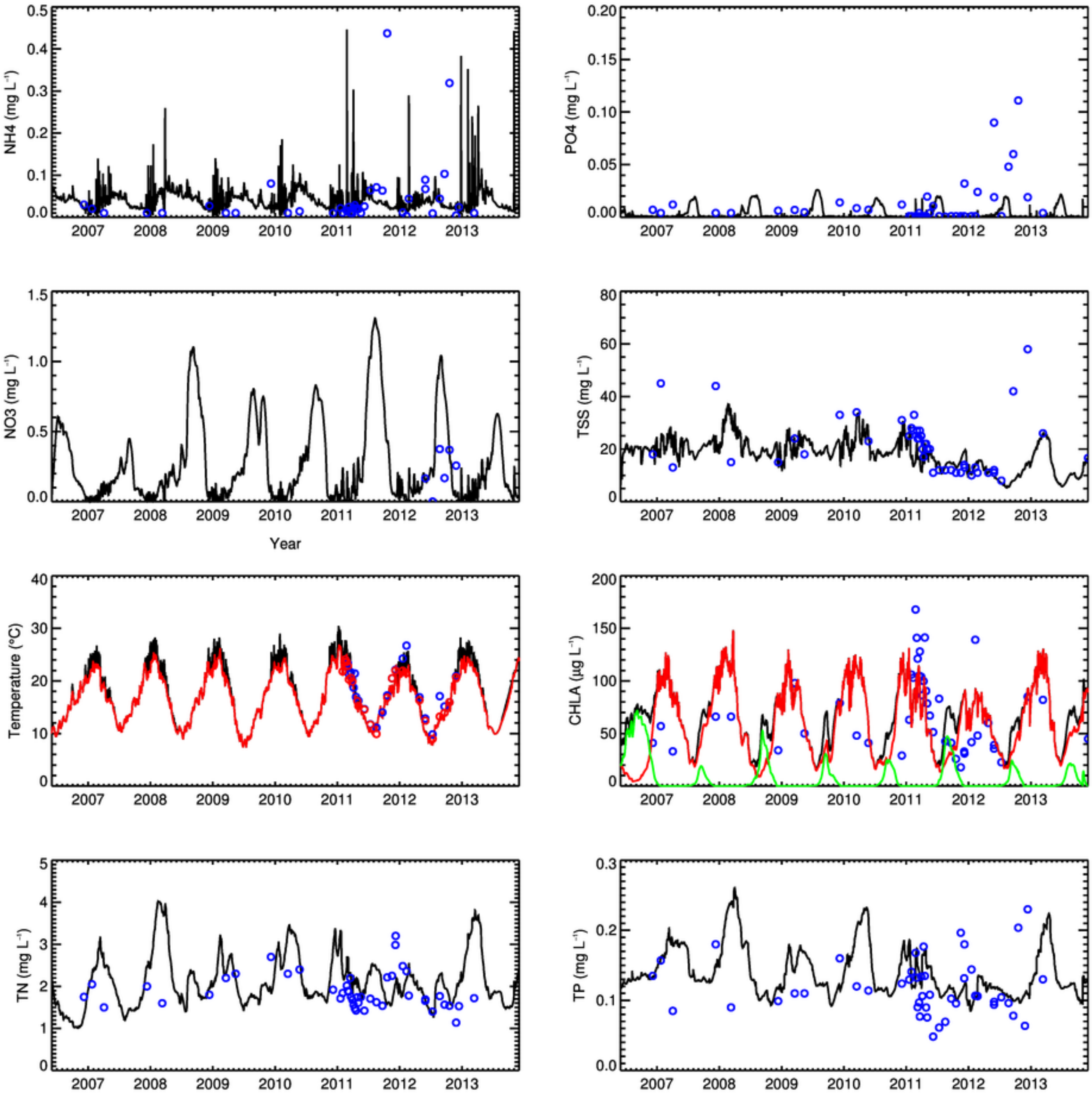


Figure 6a. Water surface model results and observations (0.5 m depth) for scenario S1. Simulations are presented using a black line and observations using blue open circles. Cyanobacteria simulations are represented with a red line with diatom represented with a green line. Temperature at 3 m depth is represented with a red line and in-situ data at 3 m with red open circle.

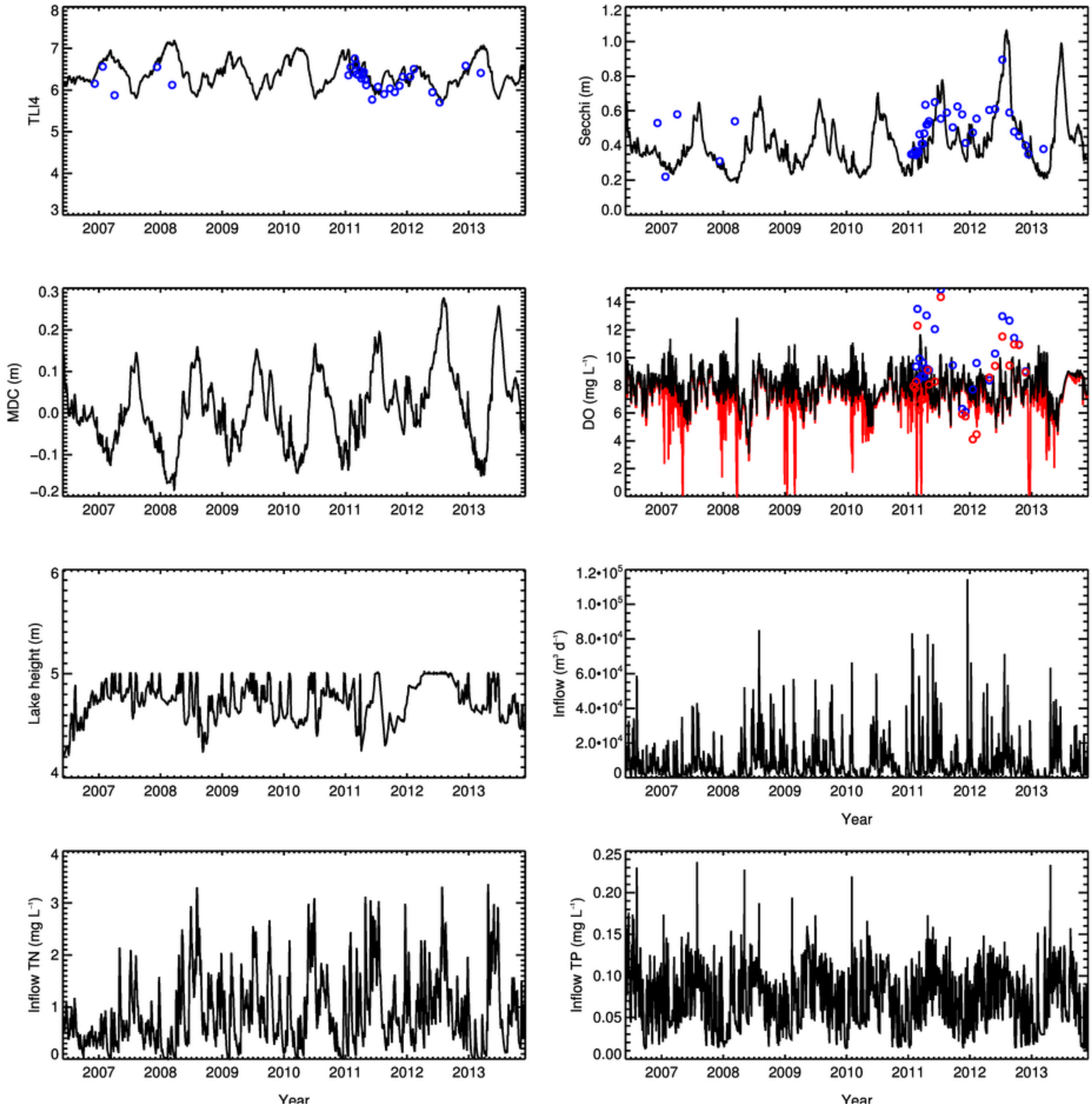


Figure 6b. Water surface model results (black lines) and observations (blue open circles). Dissolved oxygen simulations at 3 m depth are represented with a red line and in situ data at 3 m with red open circle. MDC is maximum depth of macrophyte colonisation (Canfield & Langeland, 1985).

Table 9. Pearson's correlation coefficient (r), root mean squared error (RMSE), and normalised root mean squared error (NRMSE) between observations and calibrated model output in the surface waters of Lake Ohinewai (statistics calculated for the period from 2011 until end of 2013).

Variable	r	RMSE	NRMSE
Chlorophyll *a* (µg L^{-1})	0.31	37.83	0.25
Ammonium (mg L^{-1})	-0.11	0.23	0.23
Nitrate (mg L^{-1})	-0.01	0.25	1.21
Phosphate (mg L^{-1})	-0.06	0.24	0.15
Secchi depth (m)	0.59	0.15	0.22
Temperature (°C)	0.96	1.75	0.10
TLI4	0.54	0.34	0.32
Total nitrogen (mg L^{-1})	0.02	0.73	0.36
Total phosphorus (mg L^{-1})	-0.05	0.06	0.31
Total suspended solids (mg L^{-1})	0.26	11.46	0.23

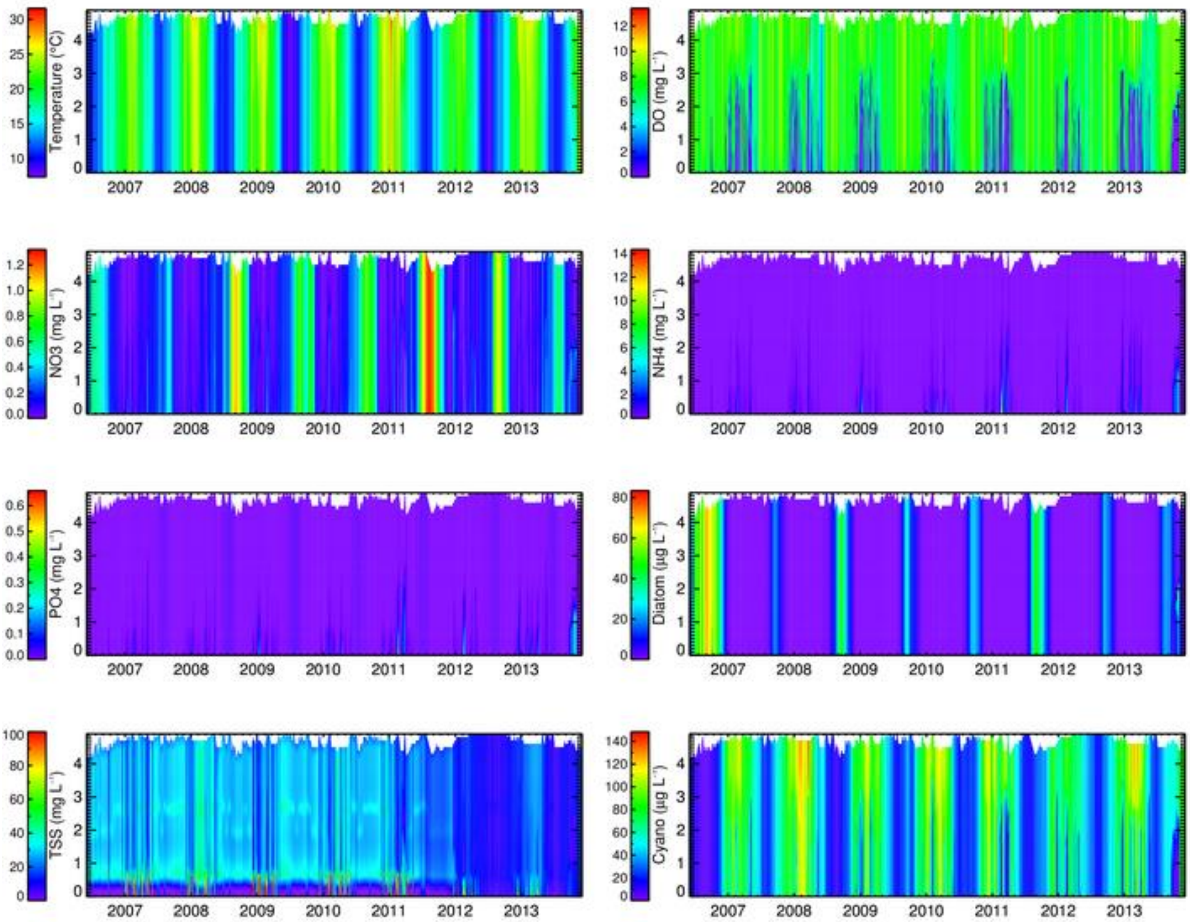


Figure 7. Colour contour plots of DYCD simulations of the current calibration.

Scenario modelling results

The simulated TLI4 ranged from 6.48 under climate change Scenario 5 with fish (S5F), to TLI4 3.67 for reference conditions native catchment (S4NF) (Table 10). Of the scenarios aimed at realistic water quality mitigation, the lowest TLI4 was achieved with the constructed wetland, Scenario 9 No Fish (S9NF). The implementation of Scenario 7 (lake riparian 55 m tree) yielded little change in TLI4. While the sheltering effect of the riparian zone meant less TSS resuspension and faster settling of koi carp resuspended sediment, this positive effect was counteracted by more stratification promoting lower oxygen concentrations leading to nutrient release and associated elevated algal biomass (see Appendix S7).

Scenario 1

Under Scenario 1 (S1F) (current koi carp biomass) simulated water quality was significantly improved over pre-removal scenario (Scenario S2F). TLI4 decreased from 6.45 to 6.29, and Secchi depth increased from pre-removal (0.37 to 0.51 m). Chlorophyll *a*, TN and TP also decreased. Average TSS decreased from 21.2 to 11.5 mg L^{-1}.

Scenario 2 (pre-removal koi carp biomass 374 kg ha^{-1})

Scenario 2F demonstrated the large contribution koi carp can have to nutrient budgets at high biomass (Fig. 9). At this density, koi carp contribute 10% of TN load, 21% of TP load, and resuspended 5457 tonnes of sediment per year.

Scenario 3

Scenario 3NF simulated fish removal combined with integrated catchment management can further reduce TLI4 to 5.68, as opposed to TLI4 of 6.29 with present fish removal regime, with significantly higher clarity (Secchi depth of 0.73 m).

Scenario 4

Scenario 4NF with an all native forest catchment and no fish predicted a TLI4 of 3.67, which is mesotrophic. A simulated Secchi depth of 3.21m would provide more favourable conditions for macrophyte growth.

Scenario 5

The simulated TLI4 with increased temperature due to climate change was 6.33 (no fish), as opposed to 6.28 (S1NF). The increase of the average air temperature of 2.1°C resulted in average lake temperature increasing from 17.2 to 18.4 ˚C (an increase of 1.2°C).

Scenario 6

Retirement of the northern sub-catchment (shown in Fig. 1) combined with fish removal reduced TLI from 6.28 to 6.20.

Scenario 7

Simulation of the sheltering effect of fully grown kahikatea trees showed a slight reduction in TLI4. Compared to pre-fish removal TSS concentrations, average TSS reduced from 21.2 (S2F) to 10.6 mg L^{-1} (S7F). However, greater stratification caused higher internal loading (Fig. 8). Coexistence of diatoms and cyanobacteria was simulated under this scenario, with the highest concentrations of diatoms observed near the thermocline.

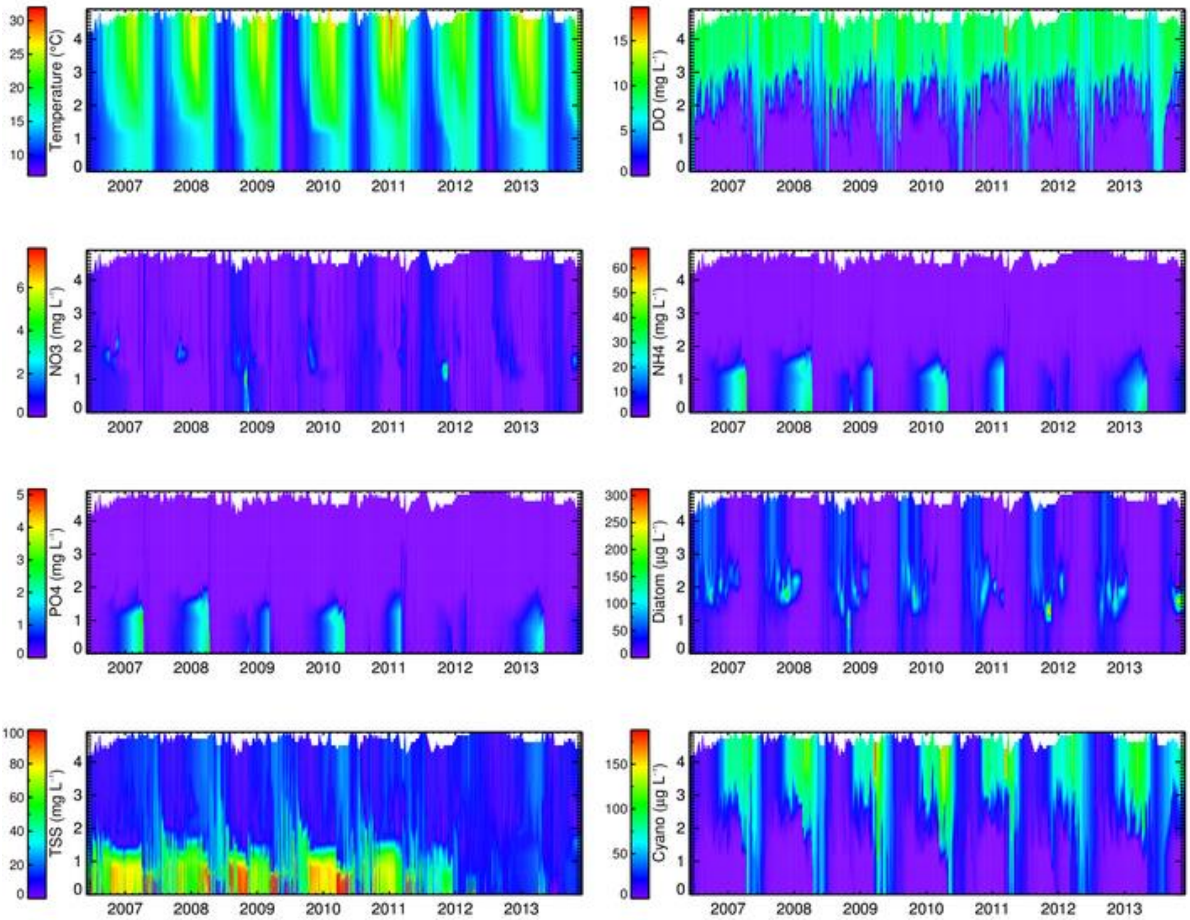


Figure 8. Colour contour plots of DYCD simulations of the S7F.

Scenario 8

Under Scenario 8NF TLI4 reduces to below 5.53, and Secchi depth increased to 0.82 m.

Scenario 9

Excluding S4, scenario 9NF simulated the lowest TLI4 of 5.27, and the highest Secchi depth (0.88 m).

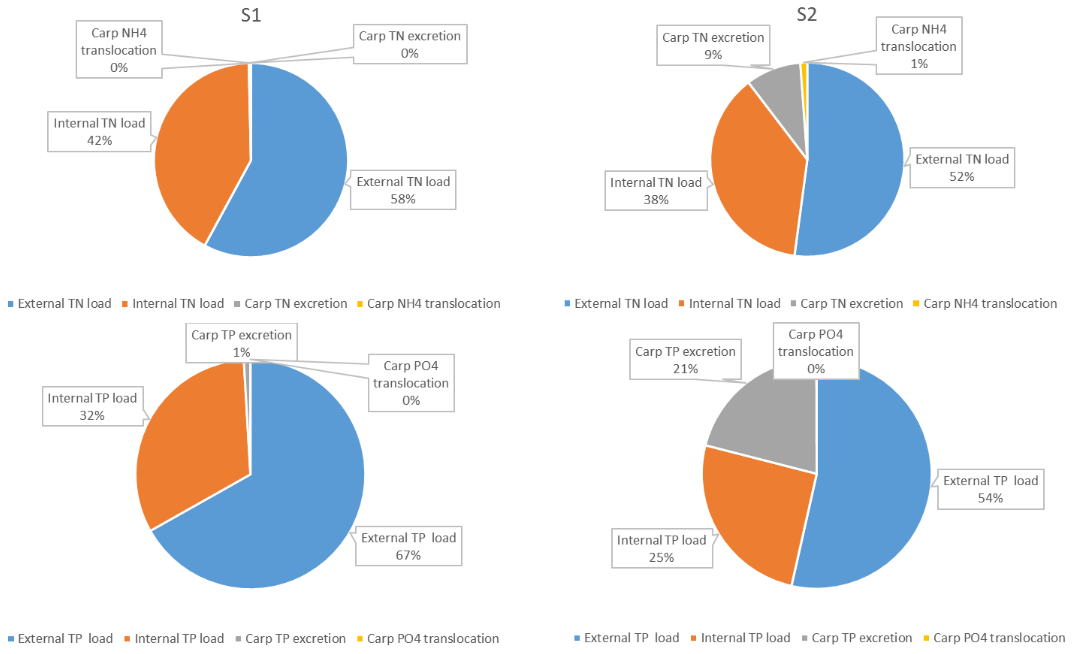


Figure 9. Koi carp nutrient load contribution under scenario one (S1; carp biomass 10 kg ha^{-1}) and scenario two (S2; carp biomass 374 kg ha^{-1}).

Table 10. Scenario modelling results, all load units in tonne yr^{-1}.

Scenario	S1 Calibration (current)		S2 koi carp pre-removal		S3 ICM		S4 Native		S5 climate change		S6 sub-catchment retirement		S7 Lake riparian		S8 stream riparian		S9 wetland	
	Fish 10.31	**No Fish**	**Fish**	**No Fish**	**Fish**	**No Fish**	**Fish**	**No Fish**	**Fish**	**No Fish**	**Fish**	**No Fish**	**Fish**	**No Fish**	**Fish**	**No Fish**	**Fish**	**No Fish**
External TN load	4.84	4.84	4.84	4.84	2.42	2.42	0.24	0.24	4.84	4.84	4.03	4.03	4.84	4.84	2.86	2.86	1.09	1.09
External TP load	0.33	0.33	0.33	0.33	0.17	0.17	0.09	0.09	0.33	0.33	0.30	0.30	0.33	0.33	0.14	0.14	0.12	0.12
Internal TN load	3.49	3.49	3.48	3.49	1.76	1.77	0.06	0.06	3.71	3.73	2.81	2.82	3.04	3.11	1.35	1.36	0.81	0.81
Internal TP load	0.16	0.16	0.16	0.16	0.08	0.09	0.14	0.15	0.18	0.18	0.16	0.16	0.20	0.20	0.07	0.07	0.06	0.07
Koi carp TN excretion	0.03	0.00	0.86	0.00	0.77	0.00	0.77	0.00	0.77	0.00	0.77	0.00	0.77	0.00	0.77	0.00	0.77	0.00
Koi carp TP excretion	4.61E-03	0.00	0.13	0.00	0.12	0.00	0.12	0.00	0.12	0.00	0.12	0.00	0.12	0.00	0.12	0.00	0.12	0.00
Koi carp NH_4-N translocation	2.96E-03	0.00	0.11	0.00	0.11	0.00	0.11	0.00	0.11	0.00	0.11	0.00	0.11	0.00	0.11	0.00	0.11	0.00
Koi carp PO_4 –P translocation	5.51E-06	0.00	0.00	0.00	2.00E-04	0.00	2.00E-04	0.00	2.00E-04	0.00	2.00E-04	0.00	2.00E-04	0.00	2.00E-04	0.00	2.00E-04	0.00
Koi carp TSS resuspension	150.28	0.00	5456.91	0.00	5456.91	0.00	5456.91	0.00	5456.91	0.00	5456.91	0.00	5456.91	0.00	5456.91	0.00	5456.91	0.00
Total koi carp TN	0.03	0.00	0.96	0.00	0.88	0.00	0.88	0.00	0.88	0.00	0.88	0.00	0.88	0.00	0.88	0.00	0.88	0.00
Total koi carp TP	0.00	0.00	0.13	0.00	0.12	0.00	0.12	0.00	0.12	0.00	0.12	0.00	0.12	0.00	0.12	0.00	0.12	0.00
Av. TLI4	6.29	6.28	6.45	6.28	5.97	5.68	5.11	3.67	6.48	6.33	6.38	6.20	6.39	6.26	5.87	5.53	5.68	5.27
Av. Secchi (m)	0.51	0.51	0.37	0.51	0.46	0.73	0.74	3.21	0.36	0.49	0.37	0.52	0.43	0.50	0.49	0.82	0.50	0.88
Av TP (mg L^{-1})	0.13	0.1	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.0
Av.TN (mg L^{-1})	1.97	2.0	2.1	2.0	1.3	1.1	0.3	0.1	2.2	2.0	1.9	1.7	1.8	1.8	1.2	1.0	0.8	0.6
Av. Chl *a* (µg L^{-1})	65.11	64.9	70.4	64.9	49.0	40.9	17.0	3.3	73.1	67.7	68.7	63.2	75.4	67.3	44.4	35.4	41.5	32.1
Av TSS (mg l^{-1})	11.5	11.2	21.2	11.2	18.2	7.4	14.0	0.6	21.0	12.0	20.9	10.9	12.4	10.6	17.3	6.2	16.9	5.7

Discussion

The present study has demonstrated that in a shallow hypertrophic lake, koi carp at high density have a significant negative impact on water quality. The simulations demonstrated that at a density of 374 kg ha^{-1}, and assuming that they are feeding on benthos, koi carp can contribute 21% of total phosphorous load and 10% of total nitrogen load via nutrient translocation. The major proportion of this load is due to koi carp excretion.

Koi carp excrete N and P in soluble forms, which are immediately available to phytoplankton (Schaus et al., 1997). The low N:P ratio at which koi carp excrete (Morgan et al., 2013) may favour the growth of cyanobacteria (Havens et al., 2003), and therefore can modify population structure of phytoplankton. However, cyanobacteria dominance associated with low N:P ratios is a controversial topic and other authors have suggested that cyanobacteria blooms are more strongly correlated to TP, TN and standing algal biomass (Downing et al., 2001). The simulations in the present study suggest that at high density, koi carp increase TN and TP concentrations, and increase the magnitude of cyanobacterial blooms. Manipulation experiments have found that koi carp nutrient excretion can be a primary mechanism initiating such blooms (Matsuzaki et al., 2007).

The present study employed a process-based model for lake water quality, with the effect of koi carp added using empirical relationships. We note here that the fish-water quality relationships are based on very few experiments and are highly uncertain, and not well established in the literature. The inclusion of carp-mediated sediment resuspension (Breukelaar et al., 1994) resulted in the expected behaviour of TSS concentrations, i.e., a higher TSS with more fish and vice versa. The TSS dynamics propagated through the model by affecting light attenuation, i.e., water clarity. Decreased water clarity can have negative impacts on macrophyte survival, their growth rates and, potentially, affect their re-establishment after they have been removed (Canfield & Langeland, 1985; Gallegos, 2001). Submerged macrophytes themselves have significant impacts on lake ecosystem structure, in particular through their ability to reduce turbulence thus promoting a clear water state of the system. Furthermore, they influence nutrient dynamics and increase habitat diversity (Dokulil & Teubner, 2003; Scheffer, 1998).

While koi carp introduction in Lake Ohinewai has contributed to its current hypertrophic state based on this modelling exercise, evidence of water quality degradation was originally documented prior to koi carp introduction (Bird, 1986), and has most likely been occurring since the catchment land use was originally modified from its natural state. Our simulations suggest that the removal of koi carp decreased TLI from 6.45 to 6.28 indicating that koi carp removal alone is not sufficient for significant restoration of lake water quality. In order to return the system to a stable clear-water state, water clarity must improve to a level to permit significant macrophyte re-establishment. However, restoration simulations showed that at a lower TLI4, the removal of koi carp is critical to lake restoration. Simulations estimated that the removal of koi carp decreased TSS concentrations by approximately two-thirds in most of the scenarios. However in an all-native catchment the removal of koi carp was simulated to increase Secchi in depth by c. 2.5 m, and reduce TSS by c. 13 mg l^{-1}.

The scenario simulations within the present study showed that integrated catchment management involving use of stream riparian zones and constructed wetlands would be required in order to restore lake water quality significantly, and using these mitigation techniques a TLI4 target of 5.27 would likely be achieved. This mesotrophic TLI4 may enable the re-establishment of macropytes.

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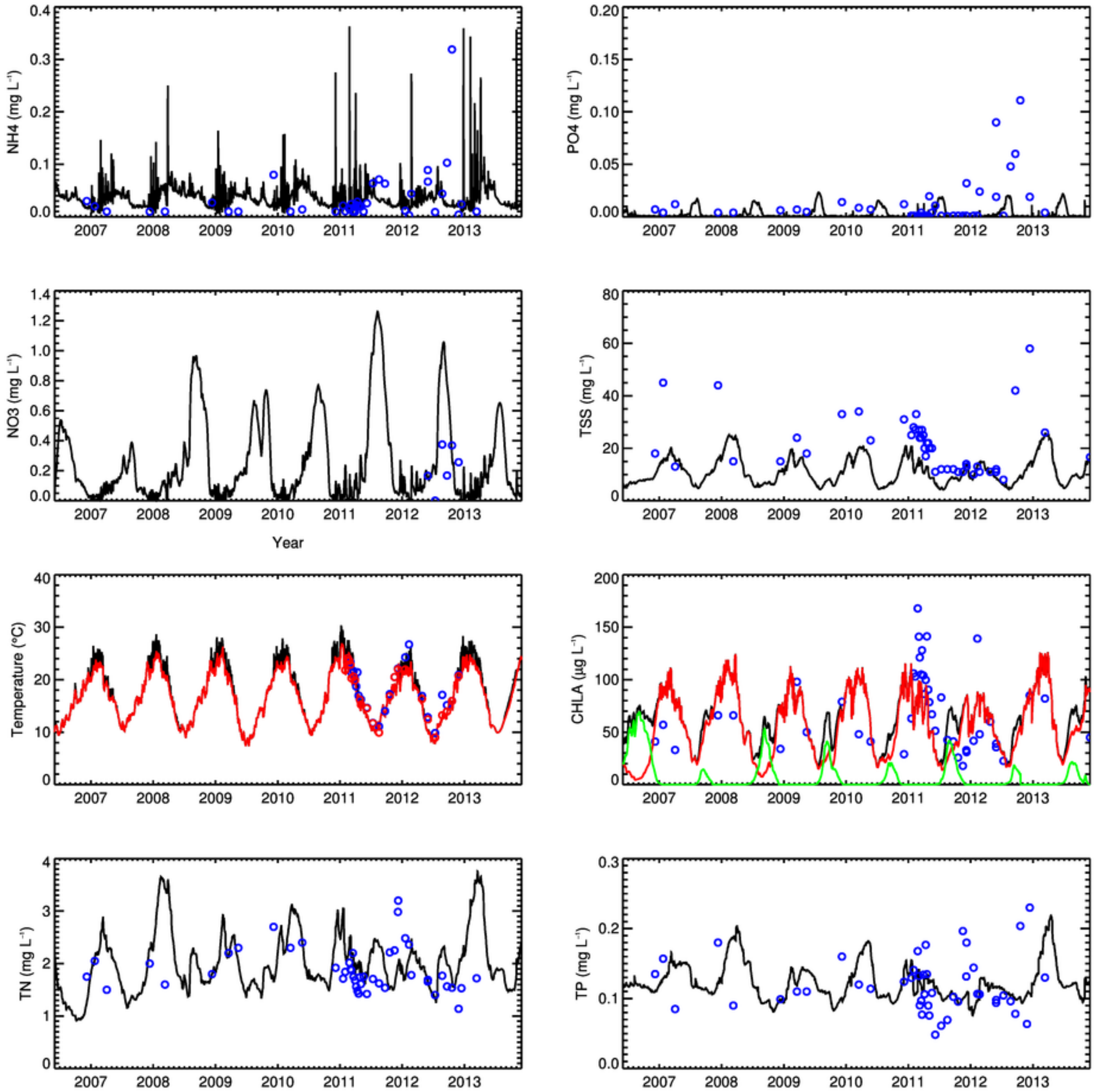
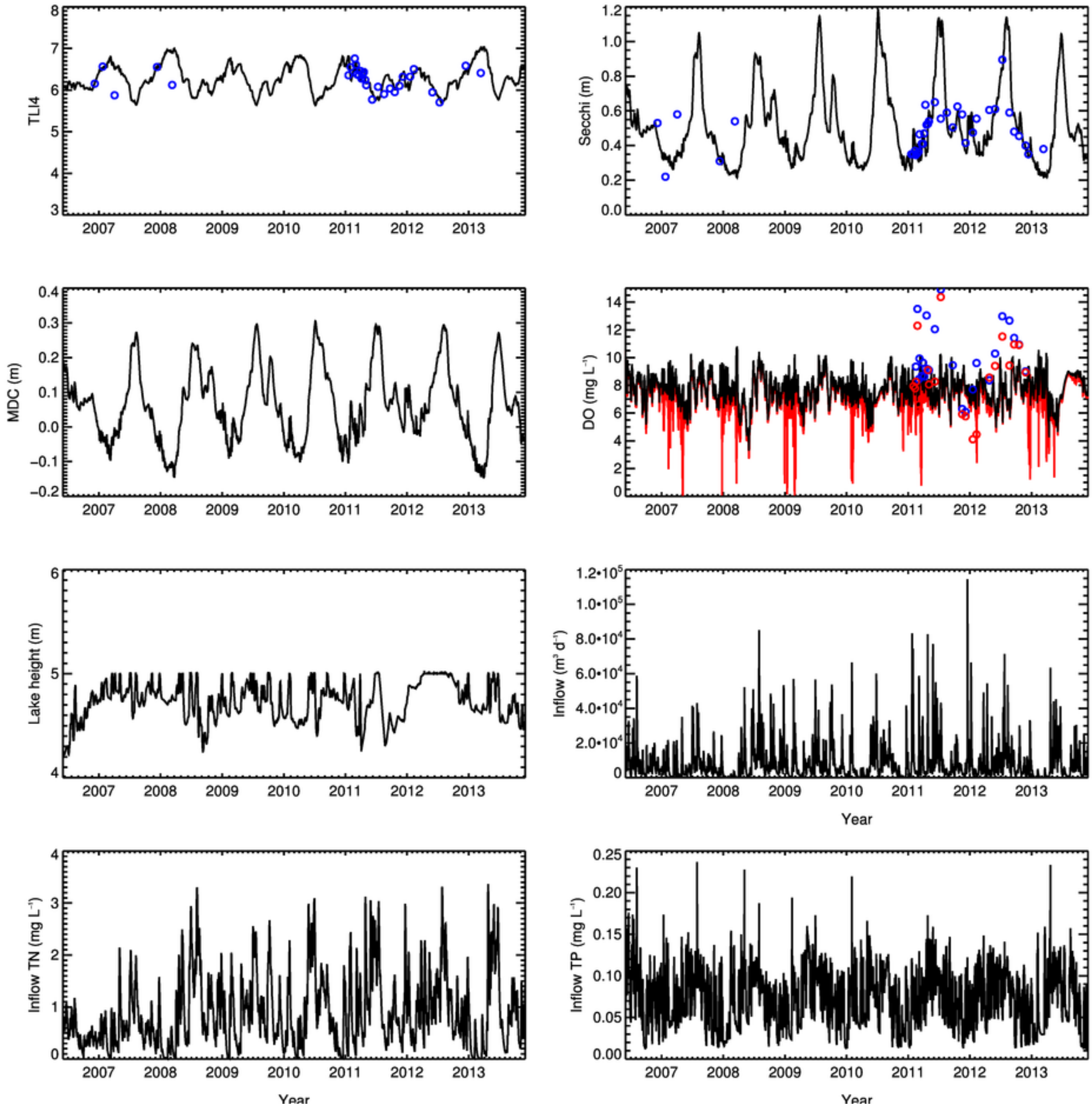
Appendix 1. Detailed results of scenario model runs

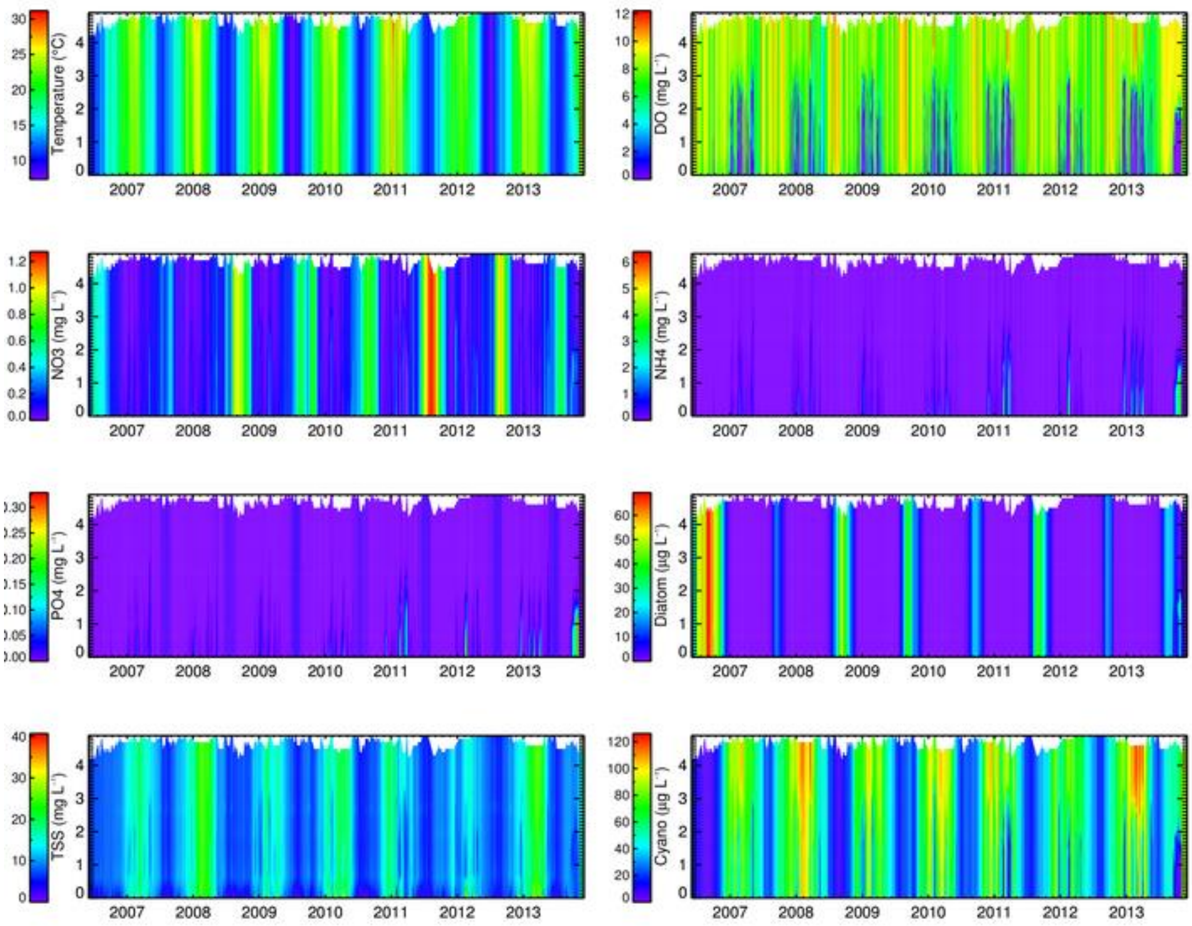
S1F



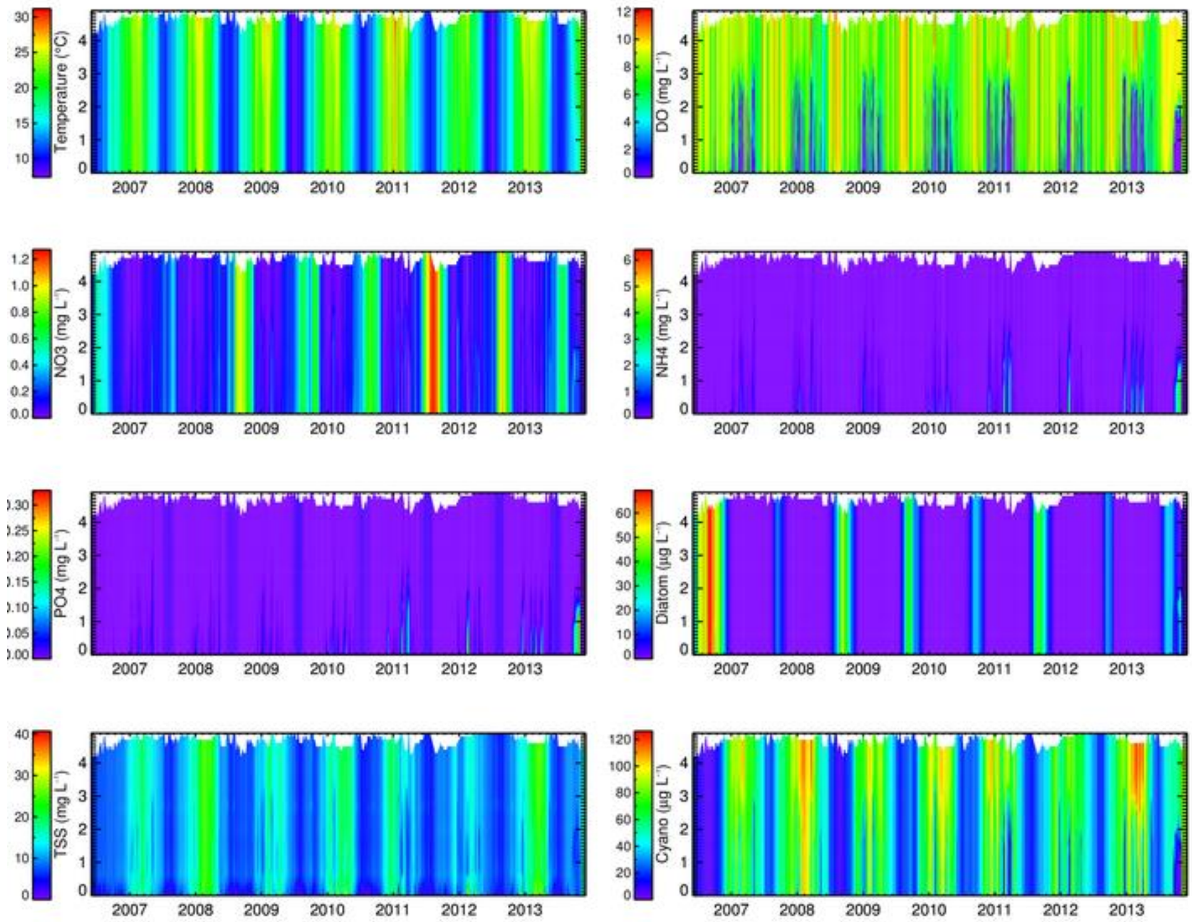
Water surface model results and observations (0.5 m depth) for scenario S1. Simulations are presented using a black line and observations using blue open circles. Cyanobacteria simulations are represented with a red line with diatom represented with a green line. Temperature at 3 m depth is represented with a red line and in-situ data at 3 m with red open circle.



Water surface model results (black lines) and observations (blue open circles). Dissolved oxygen simulations at 3 m depth are represented with a red line and in situ data at 3 m with red open circle. MDC is maximum depth of macrophyte colonisation (Canfield & Langeland, 1985).



Colour contour plots of DYCD simulations.


Temperature (°C)
DO (mg L⁻¹)
NO3 (mg L⁻¹)
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
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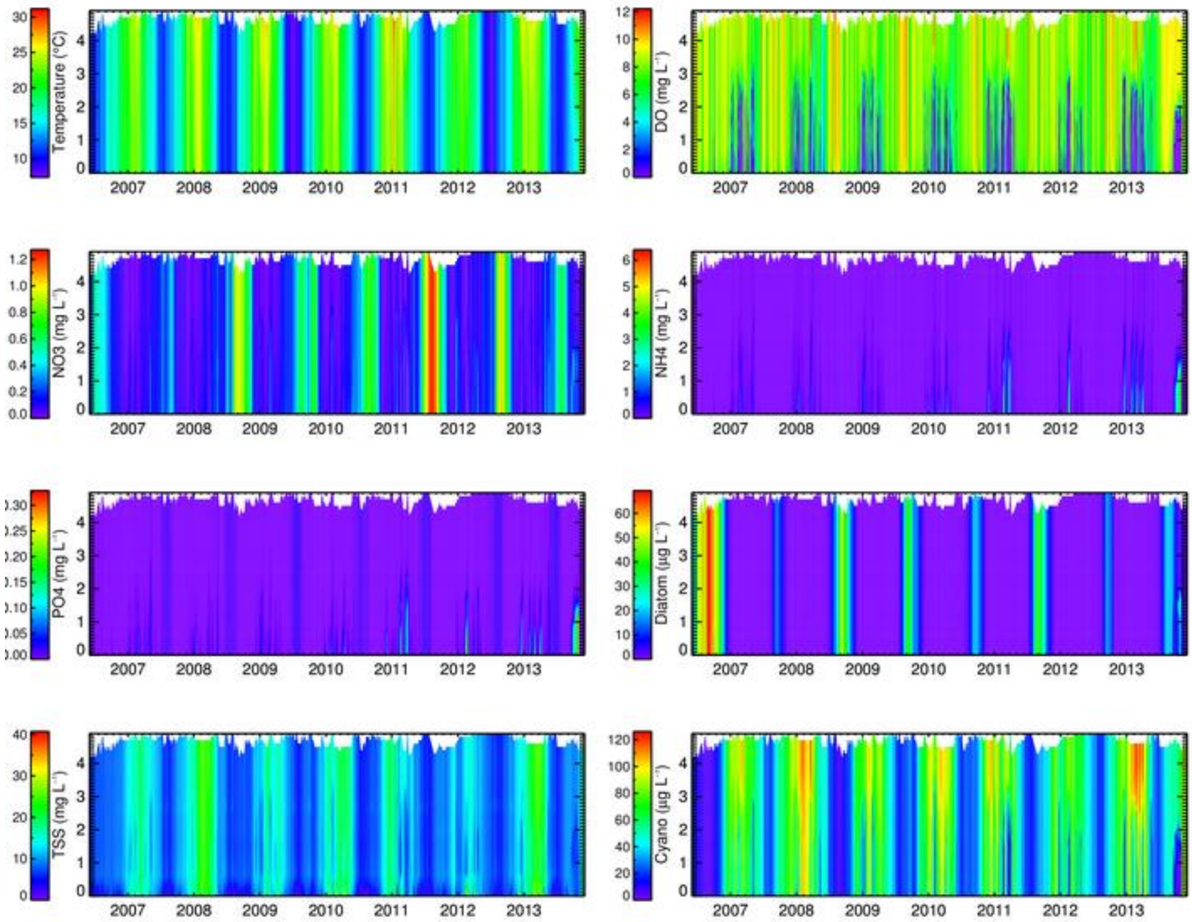
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DO (mg L⁻¹)
NO3 (mg L⁻¹)
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
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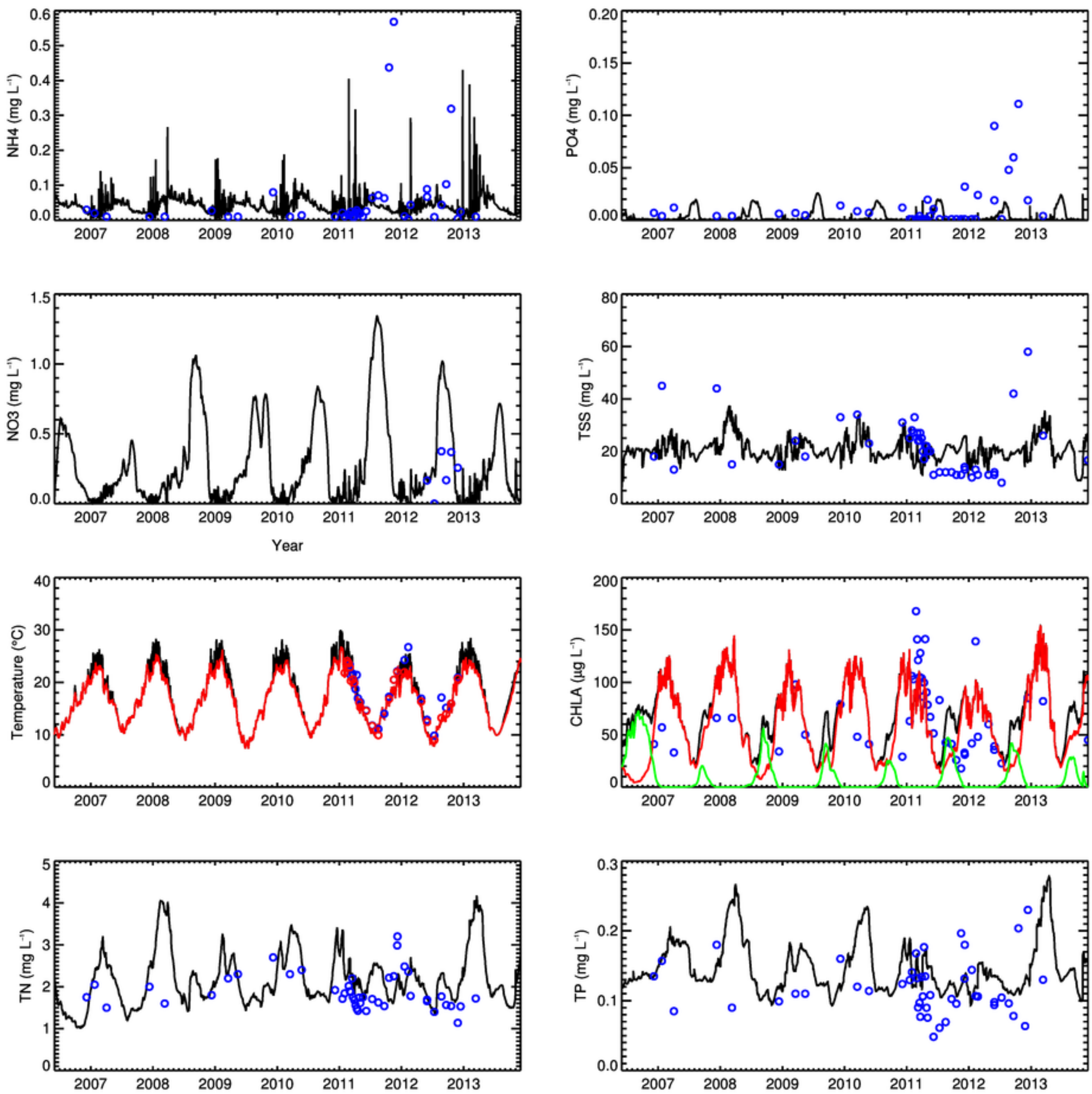
S2F



NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
Year
TSS (mg L⁻¹)
Temperature (°C)
CHLA (µg L⁻¹)
TN (mg L⁻¹)
TP (mg L⁻¹)
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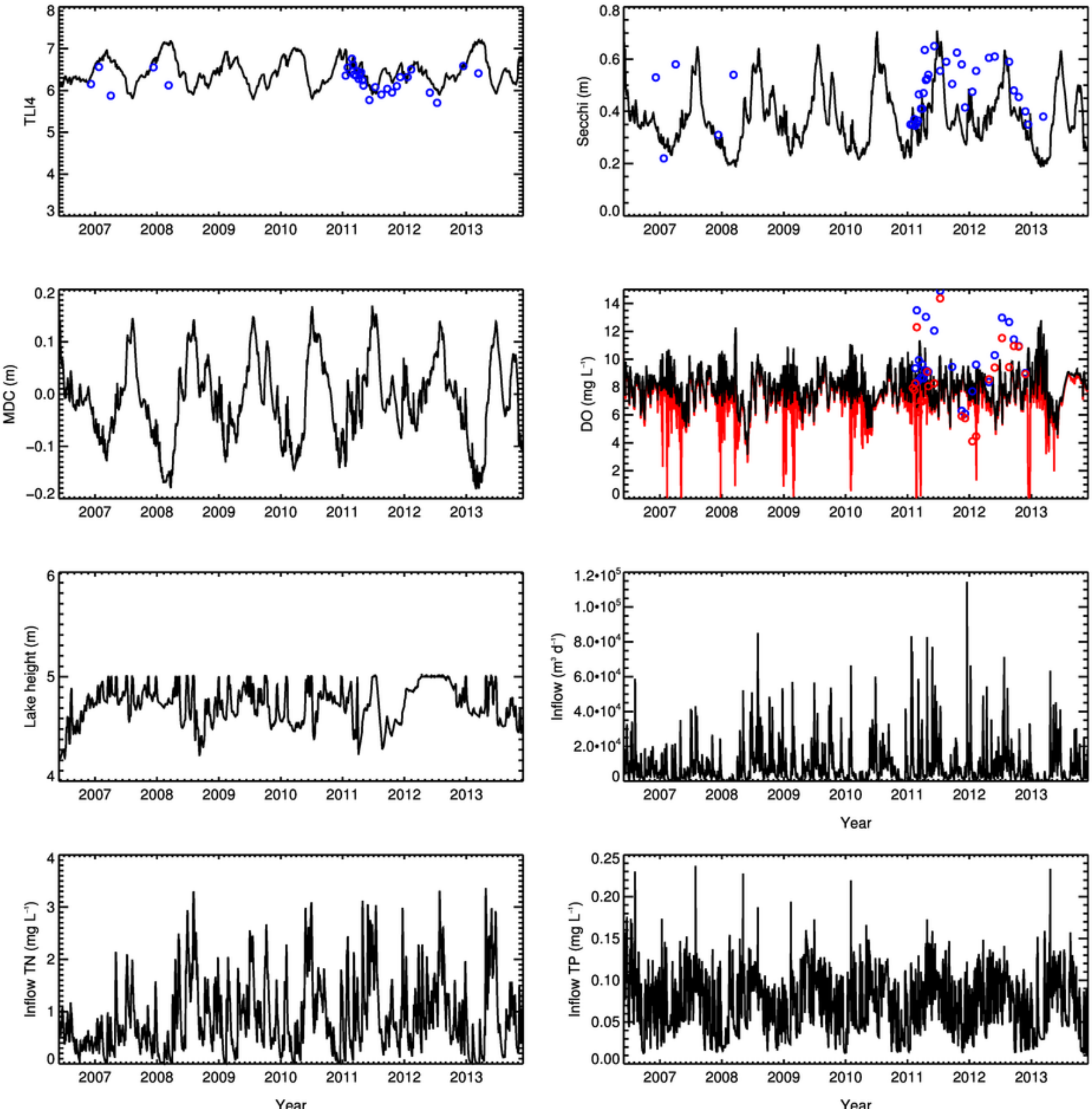
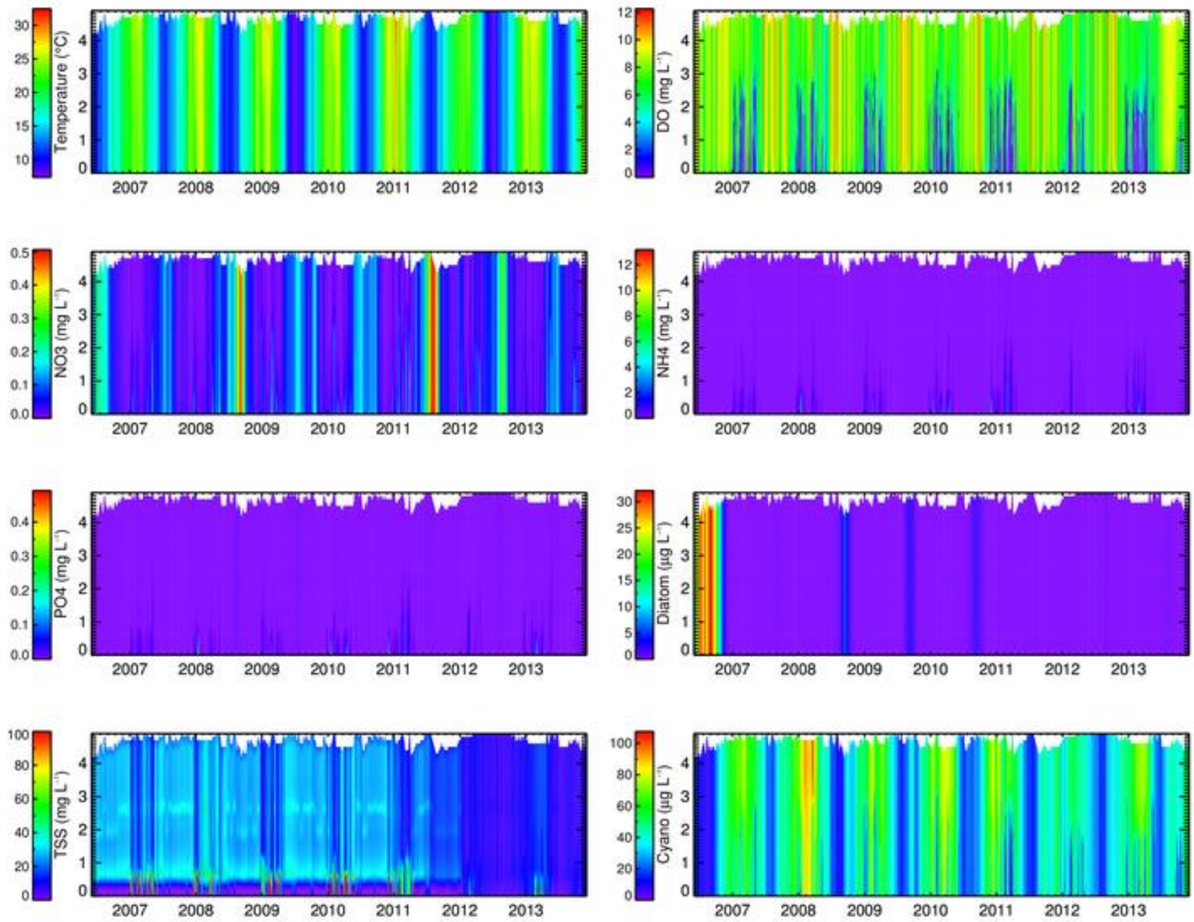

TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
2007 2008 2009 2010 2011 2012 2013
Year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DO (mg L⁻¹)
NO3 (mg L⁻¹)
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
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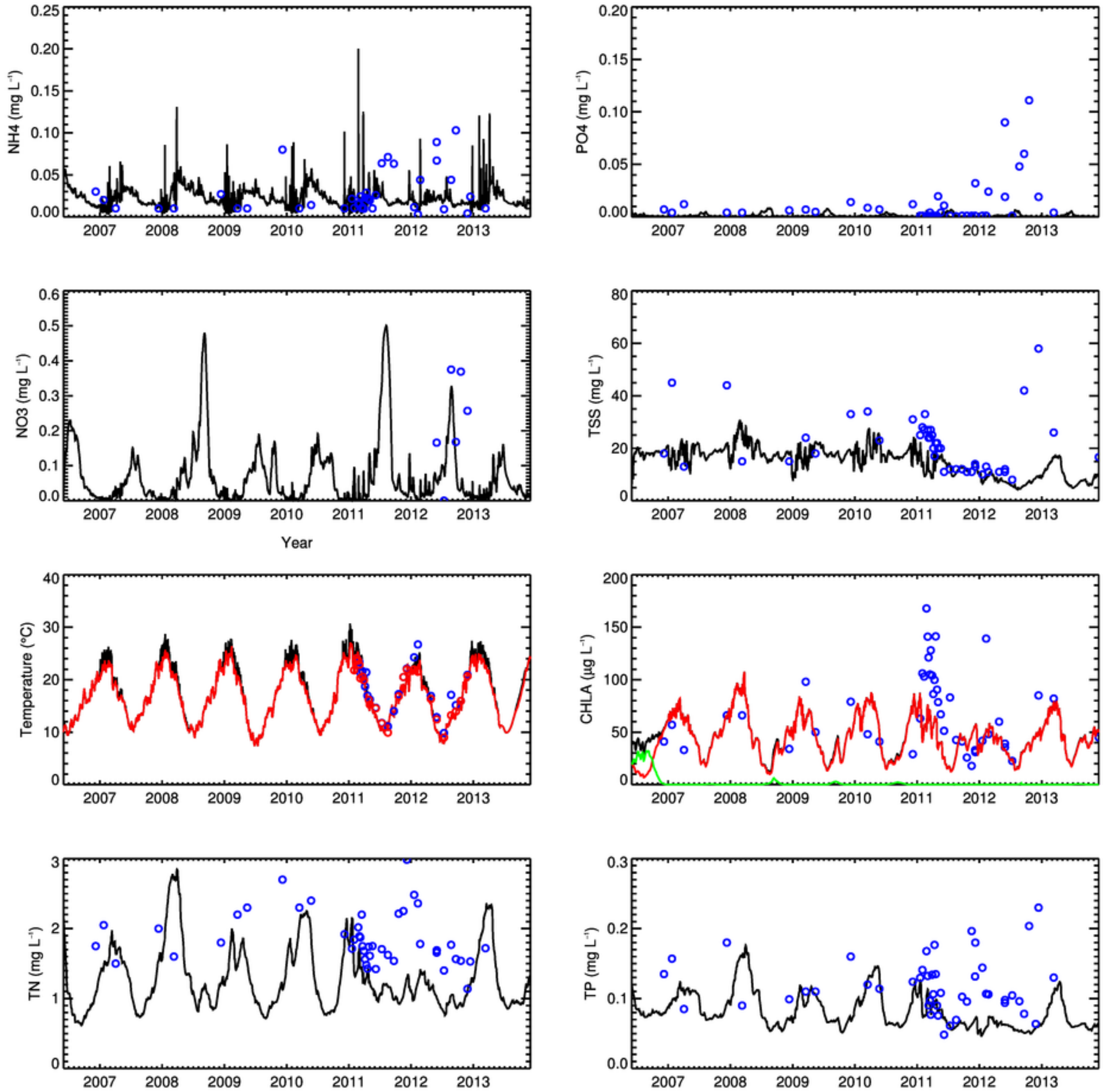
S3F



NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
TSS (mg L⁻¹)
Year
Temperature (°C)
CHLA (µg L⁻¹)
TN (mg L⁻¹)
TP (mg L⁻¹)
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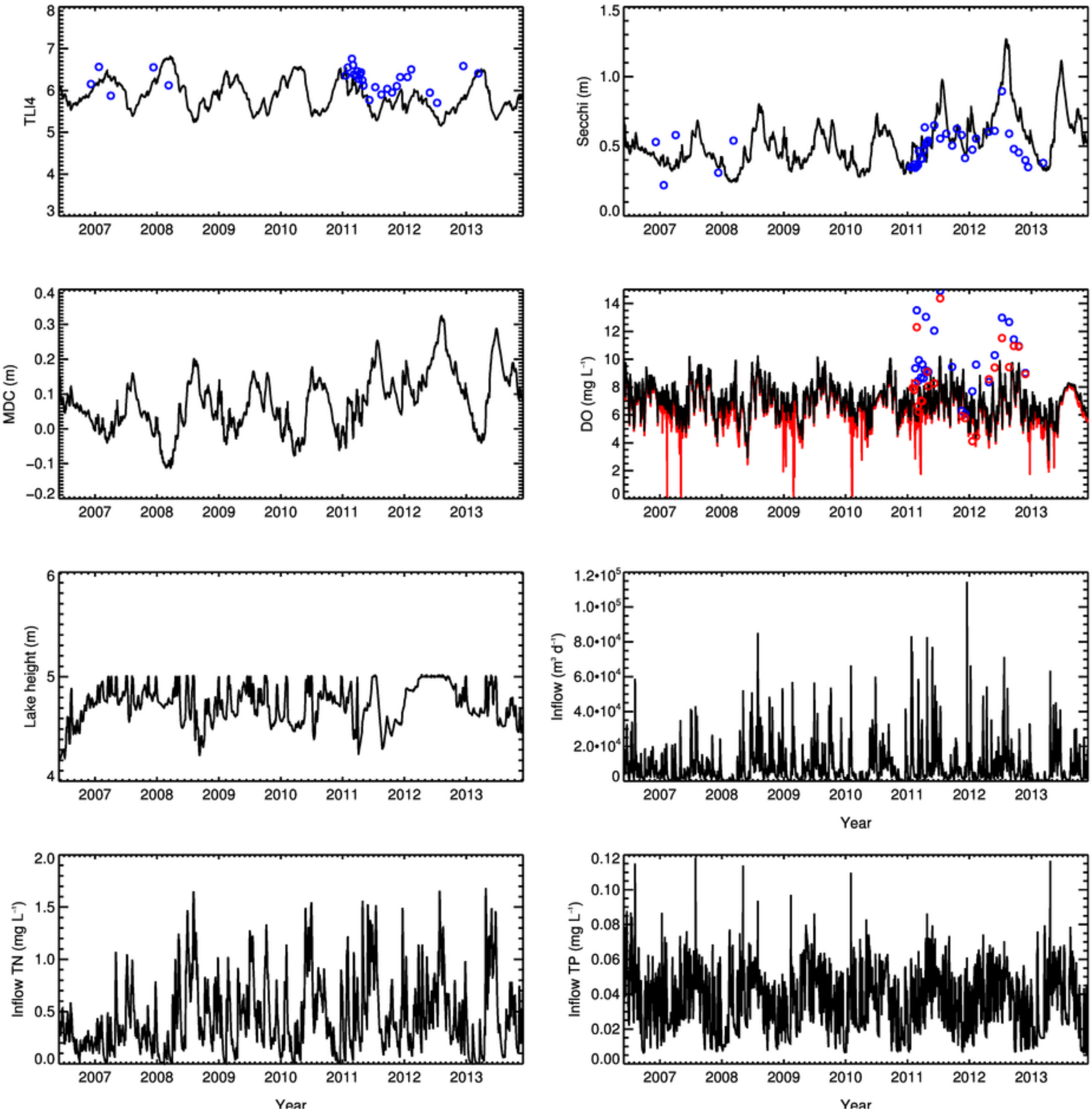

TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
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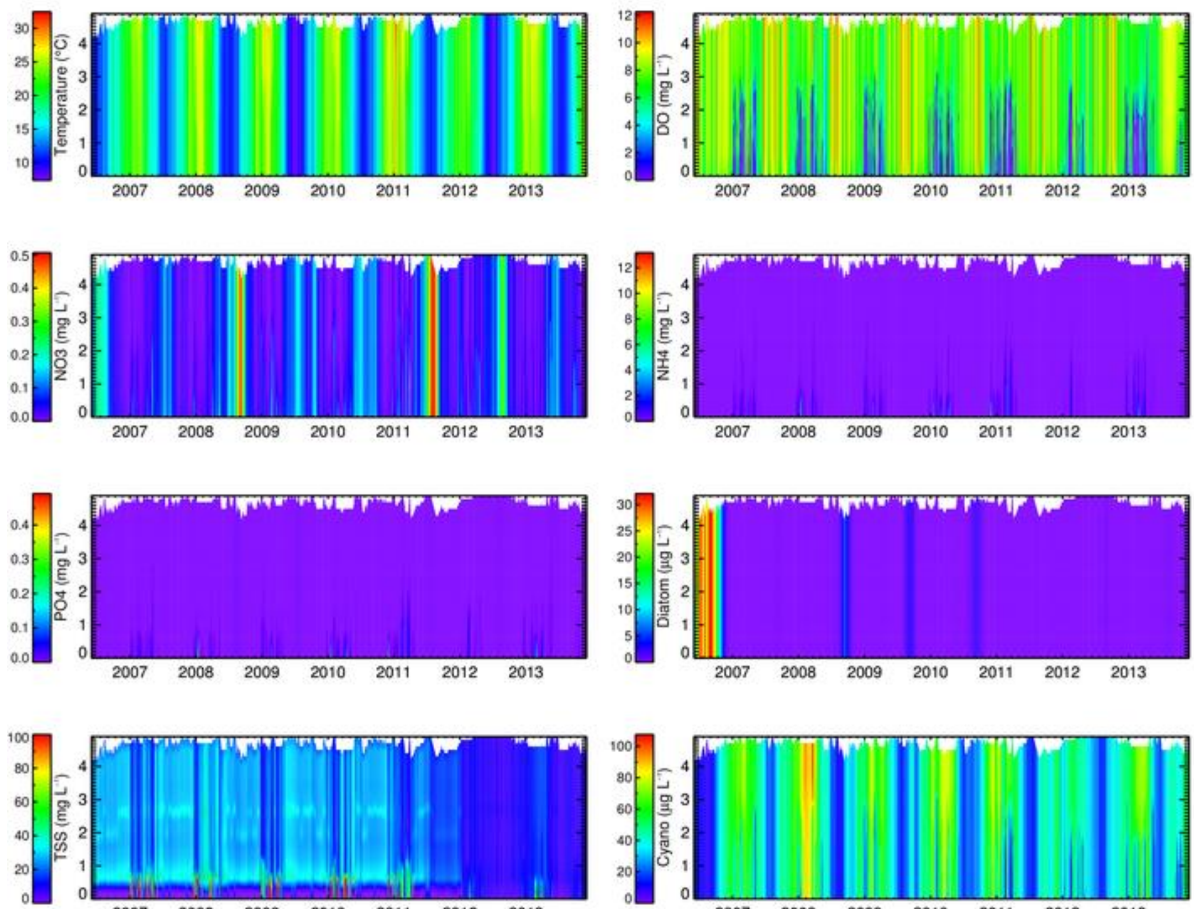

Temperature (°C)
DO (mg L⁻¹)
NO3 (mg L⁻¹)
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PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
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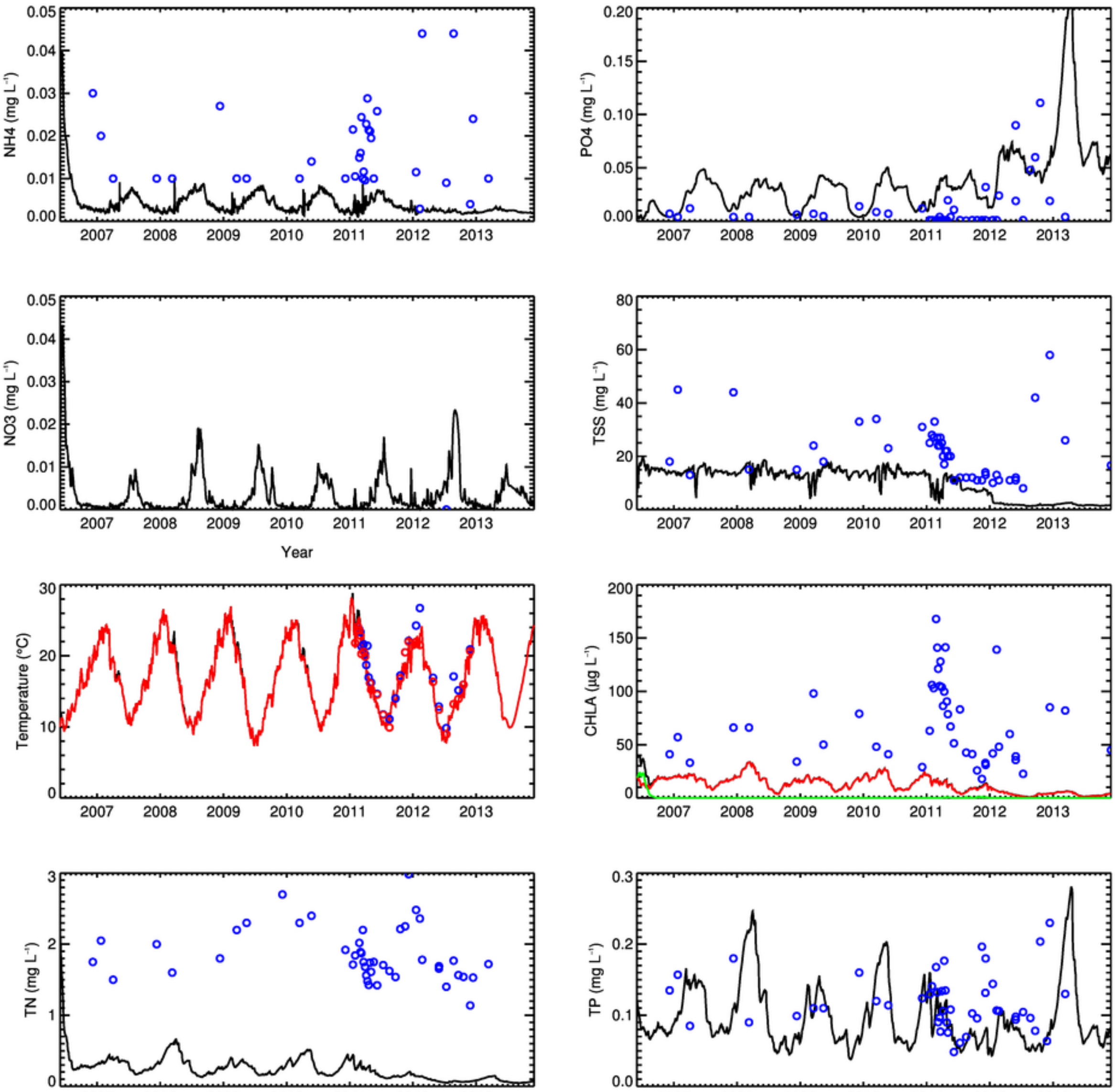
S4F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PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
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TSS (mg L⁻¹)
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TN (mg L⁻¹)
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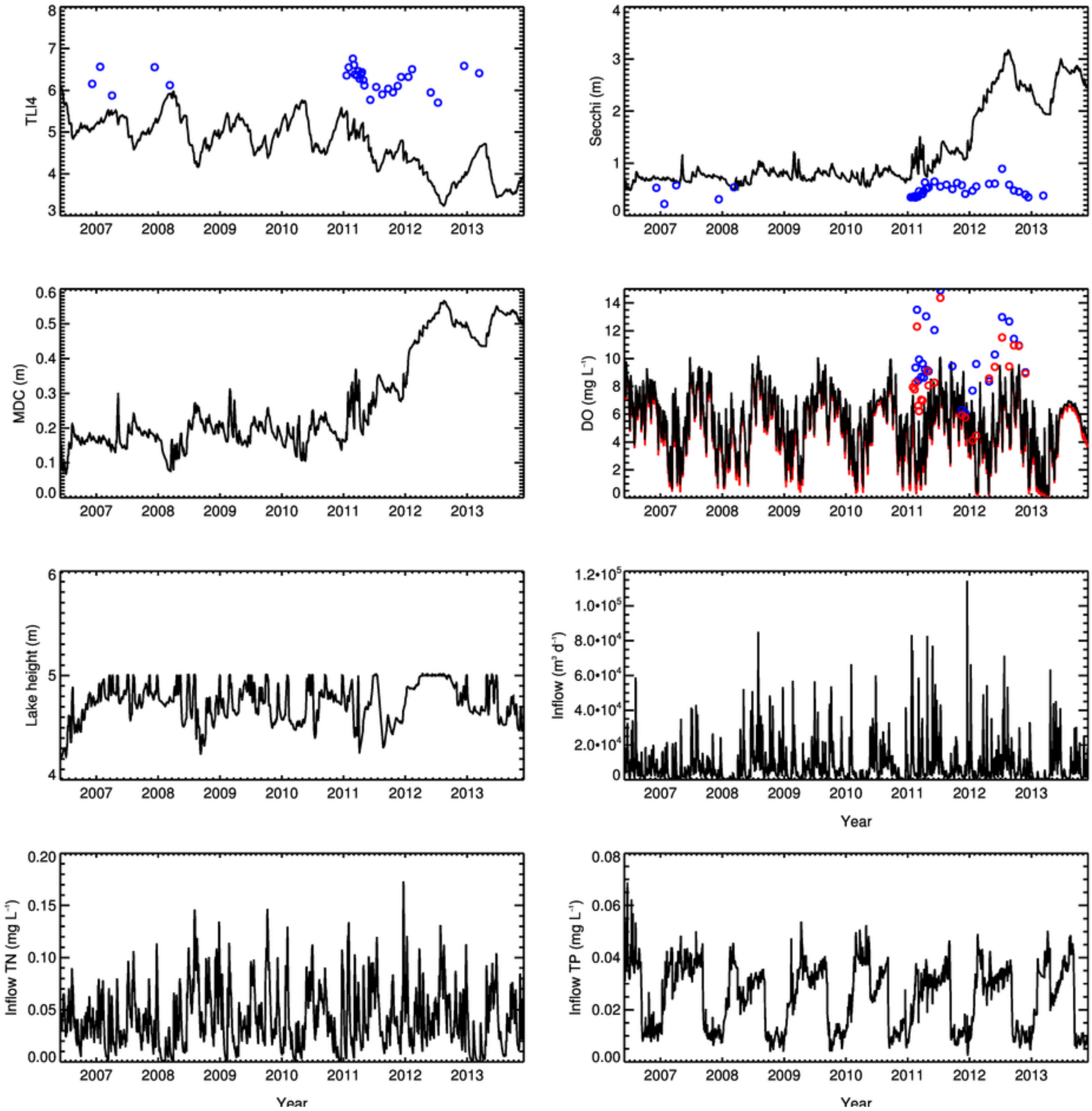
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Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
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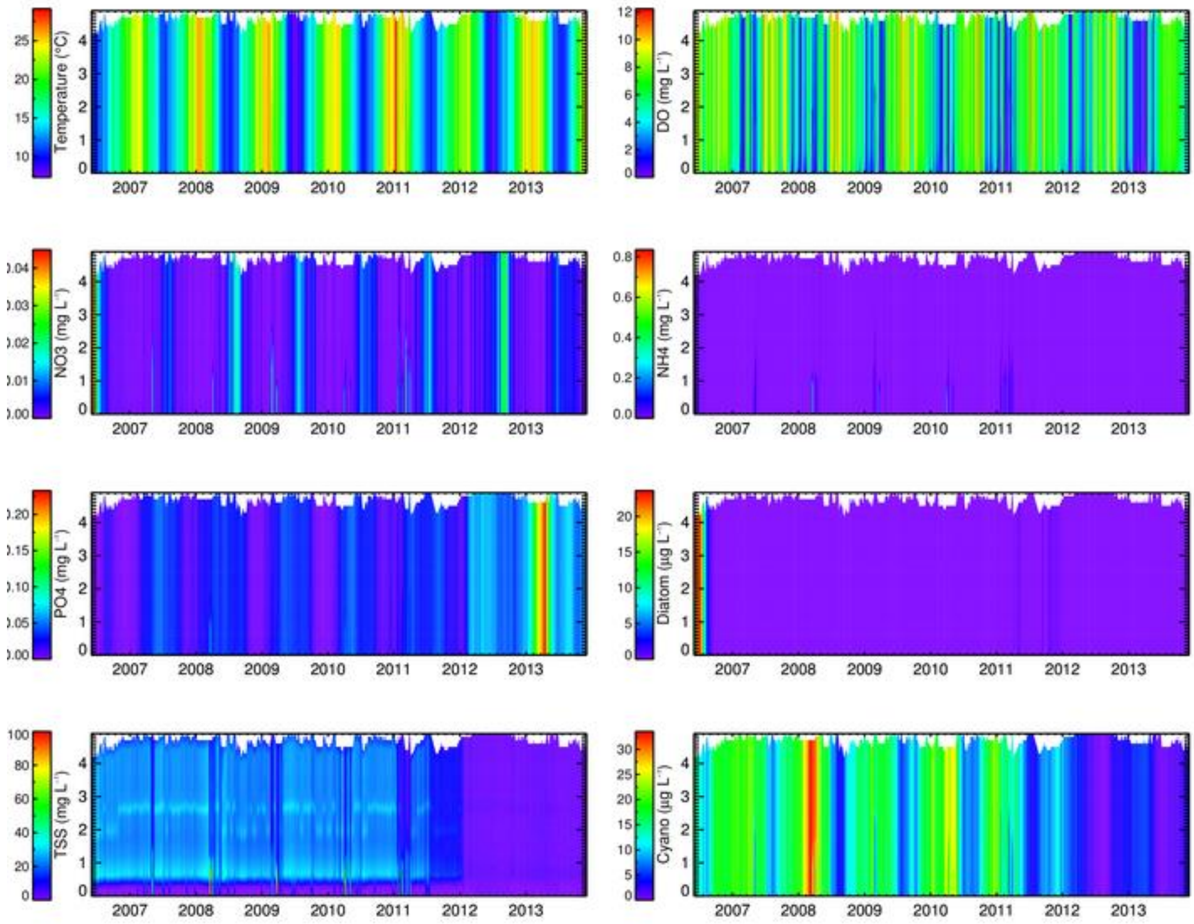
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
Year
Year
2007 2008 2009 2010 2011 2012 2013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NH4 (mg L⁻¹)
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Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
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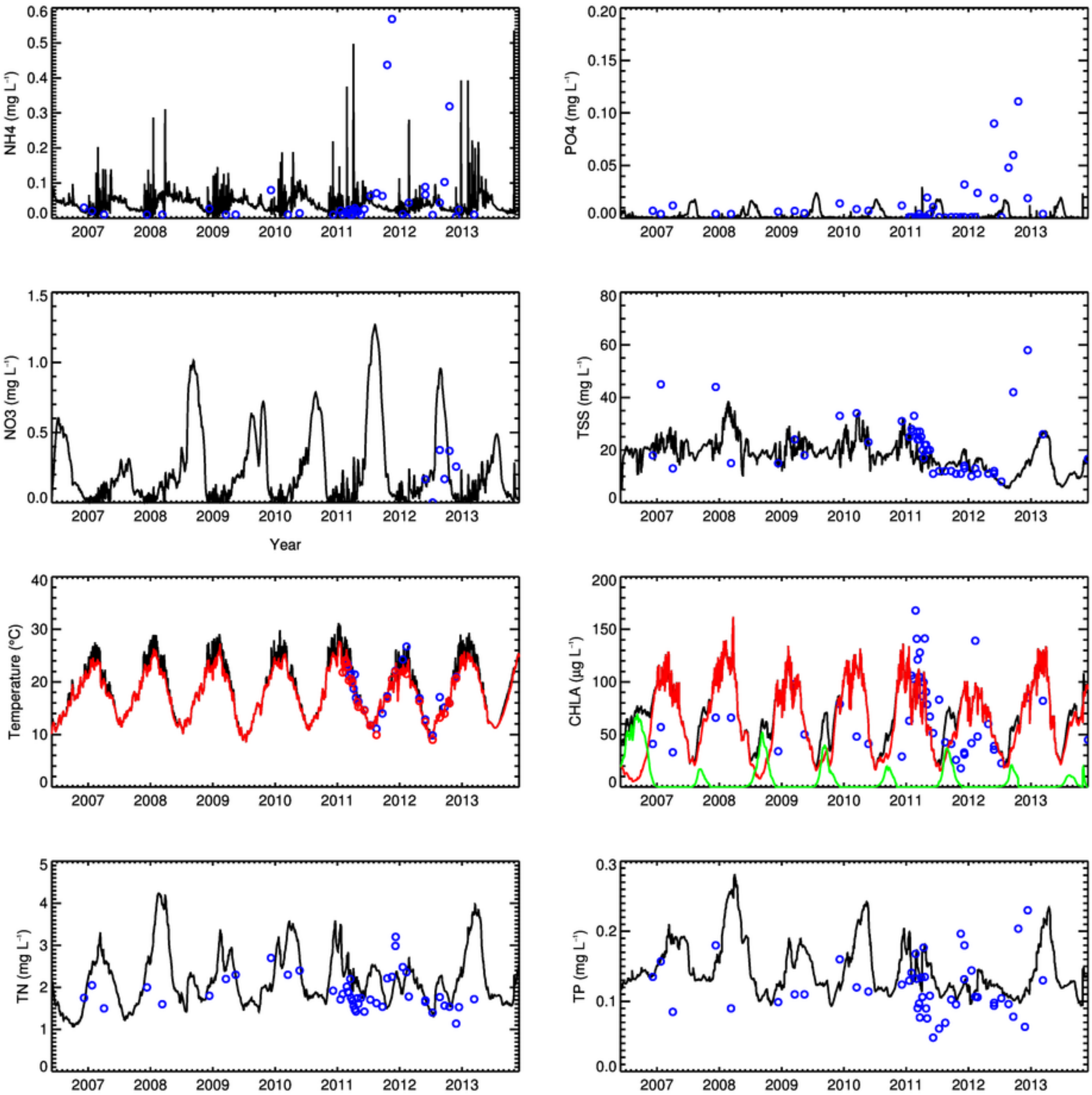
S5F



NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
Year
TSS (mg L⁻¹)
Temperature (°C)
CHLA (µg L⁻¹)
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TP (mg L⁻¹)
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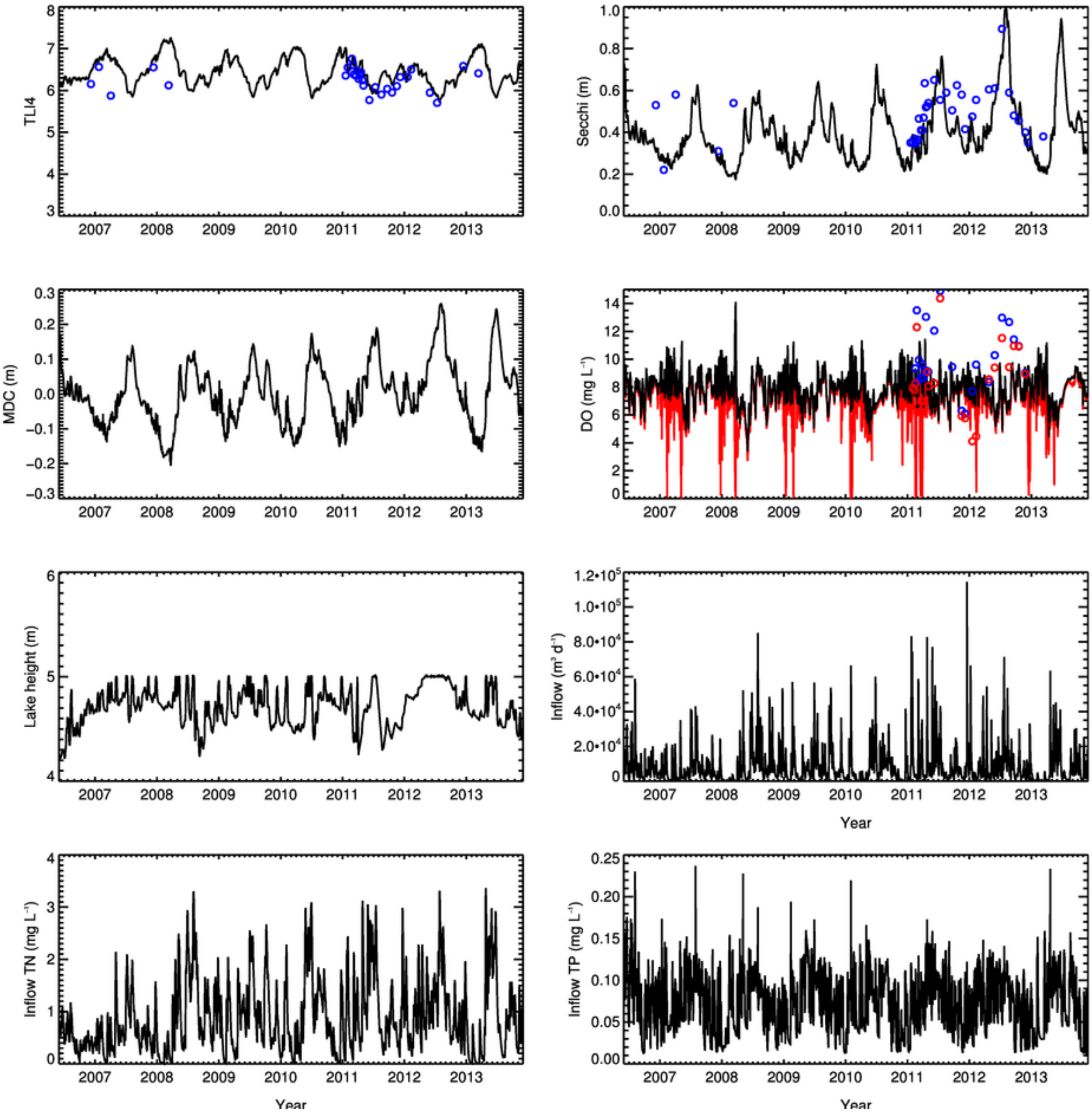

TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
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Inflow TP (mg L⁻¹)
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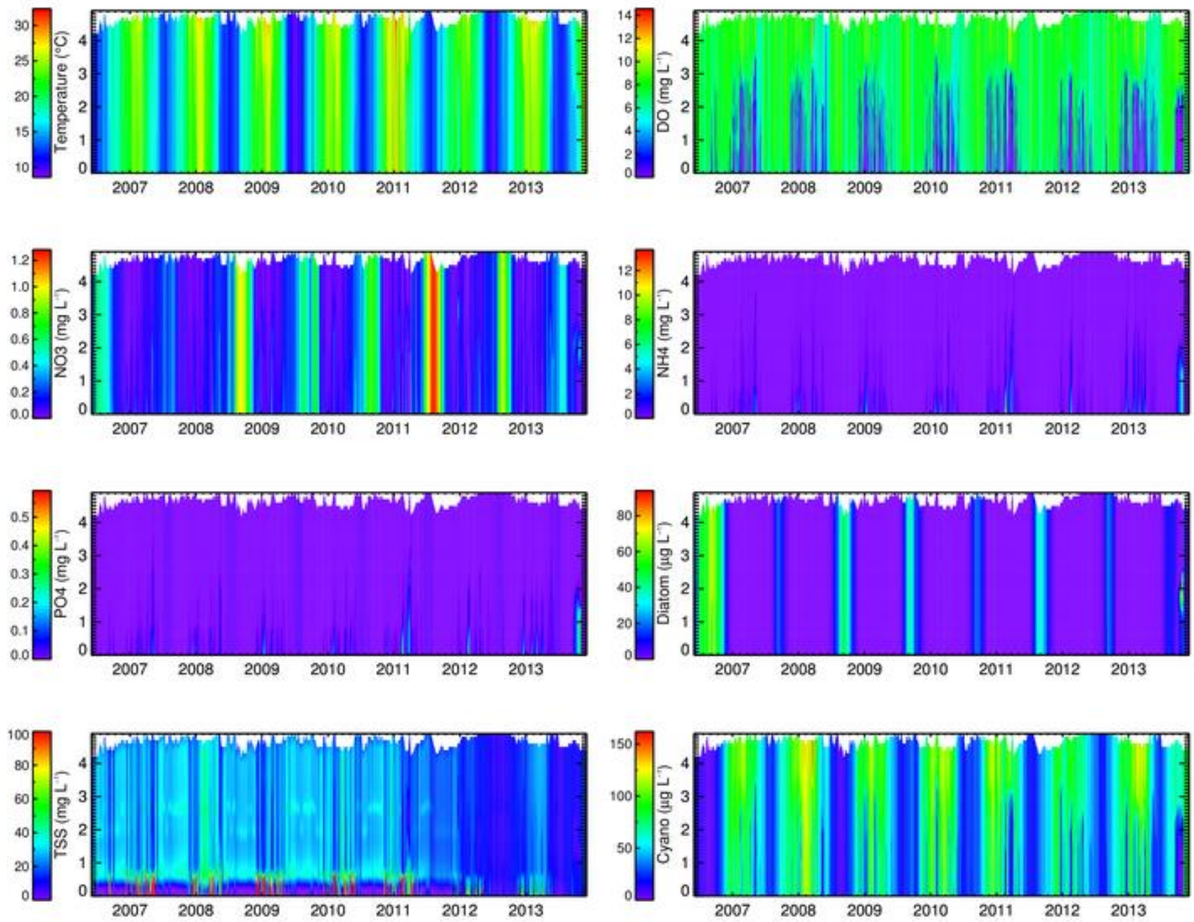
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PO4 (mg L⁻¹)
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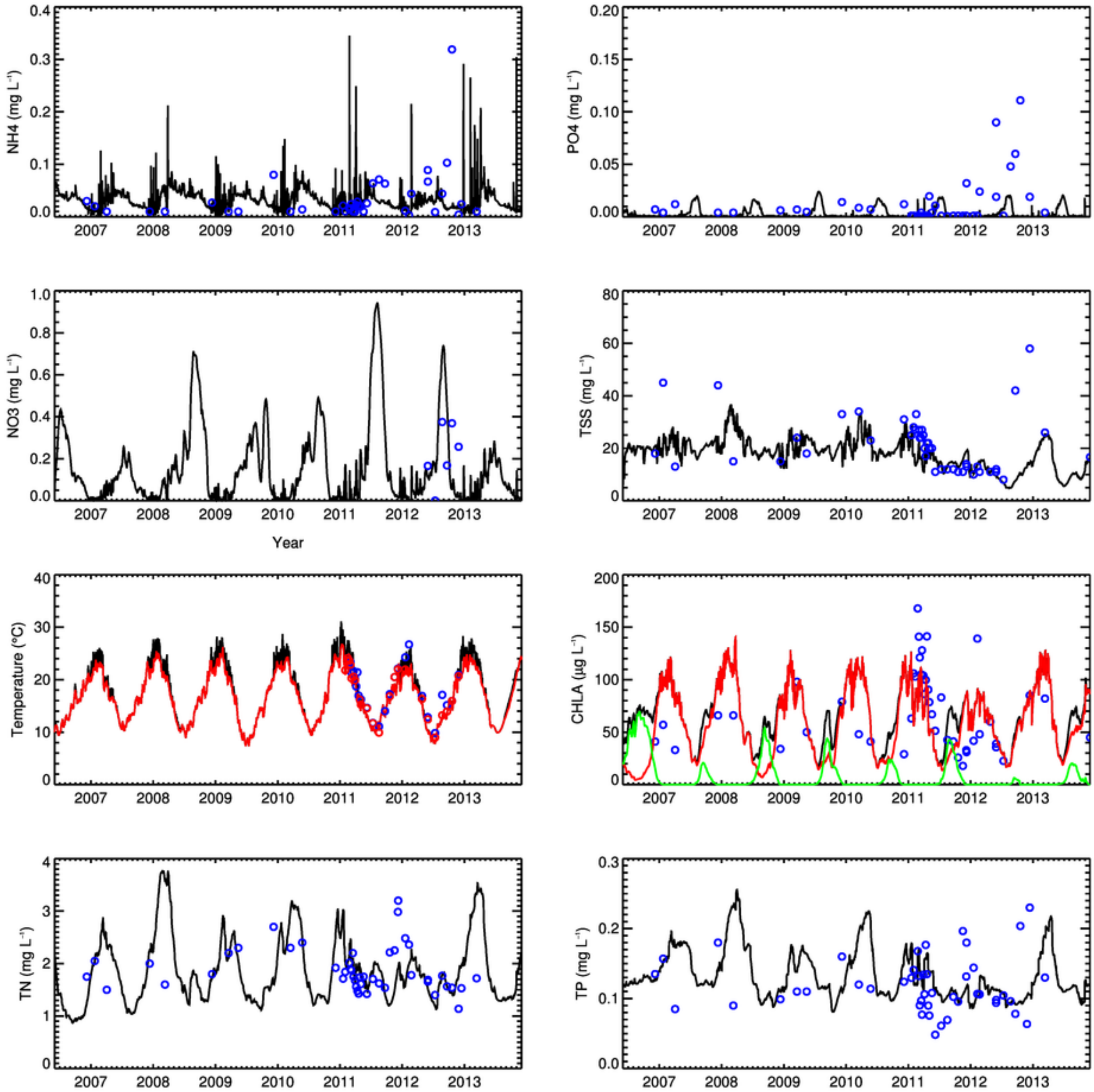
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PO4 (mg L⁻¹)
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Temperature (°C)
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TP (mg L⁻¹)
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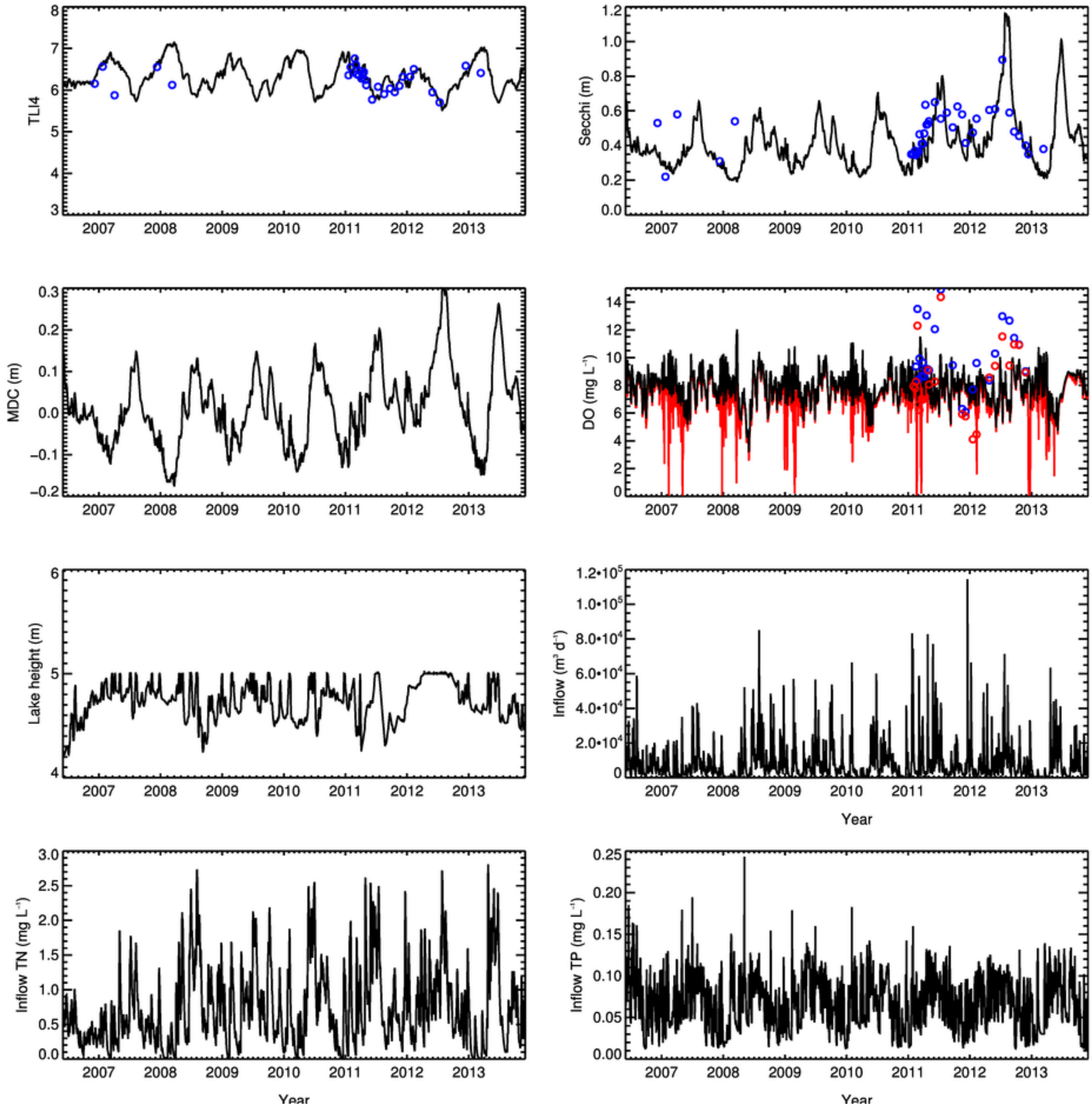
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Inflow TP (mg L⁻¹)
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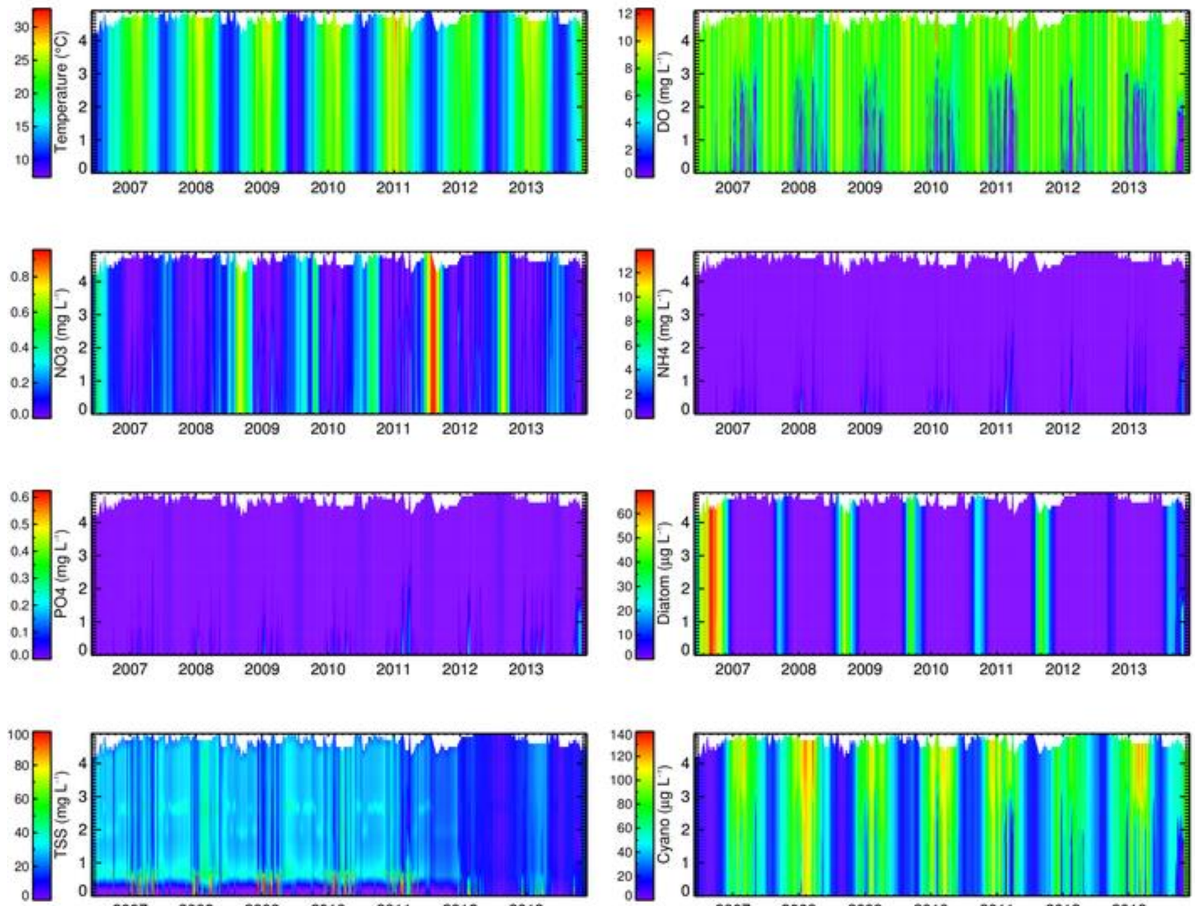
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Cyano (µg L⁻¹)
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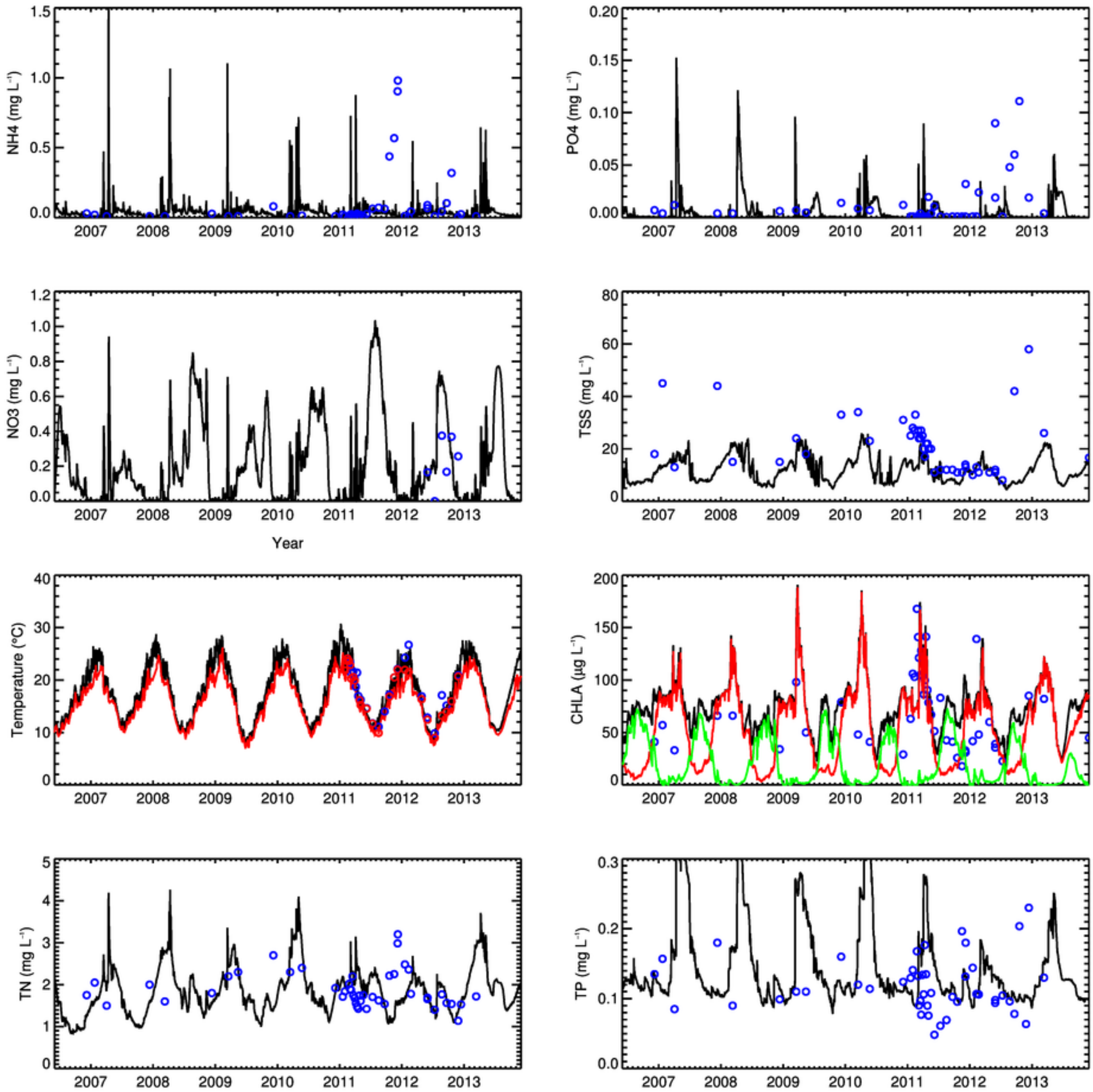
S7F



NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
TSS (mg L⁻¹)
Year
Temperature (°C)
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TP (mg L⁻¹)
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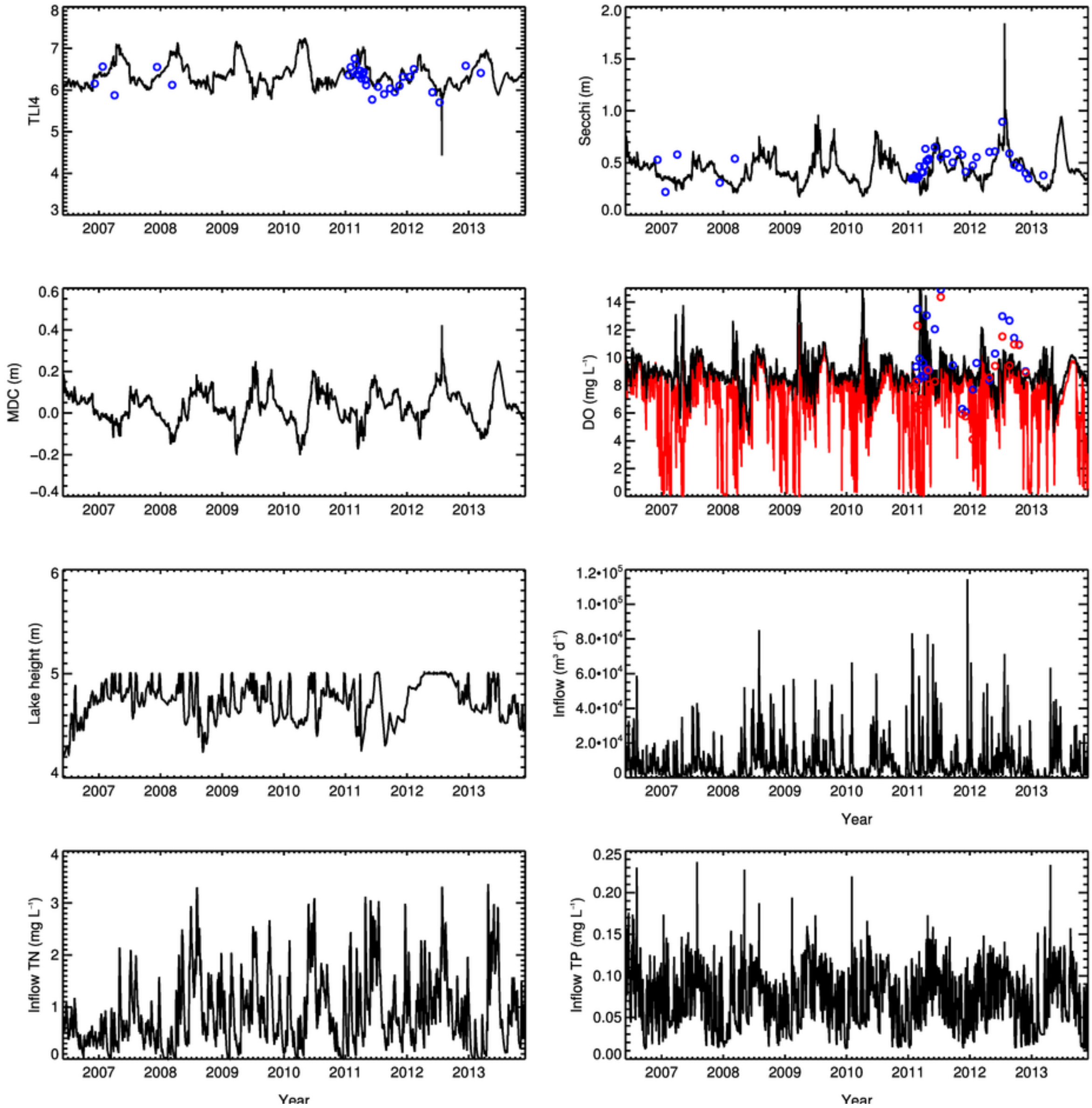
TLI4
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Lake height (m)
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Inflow TP (mg L⁻¹)
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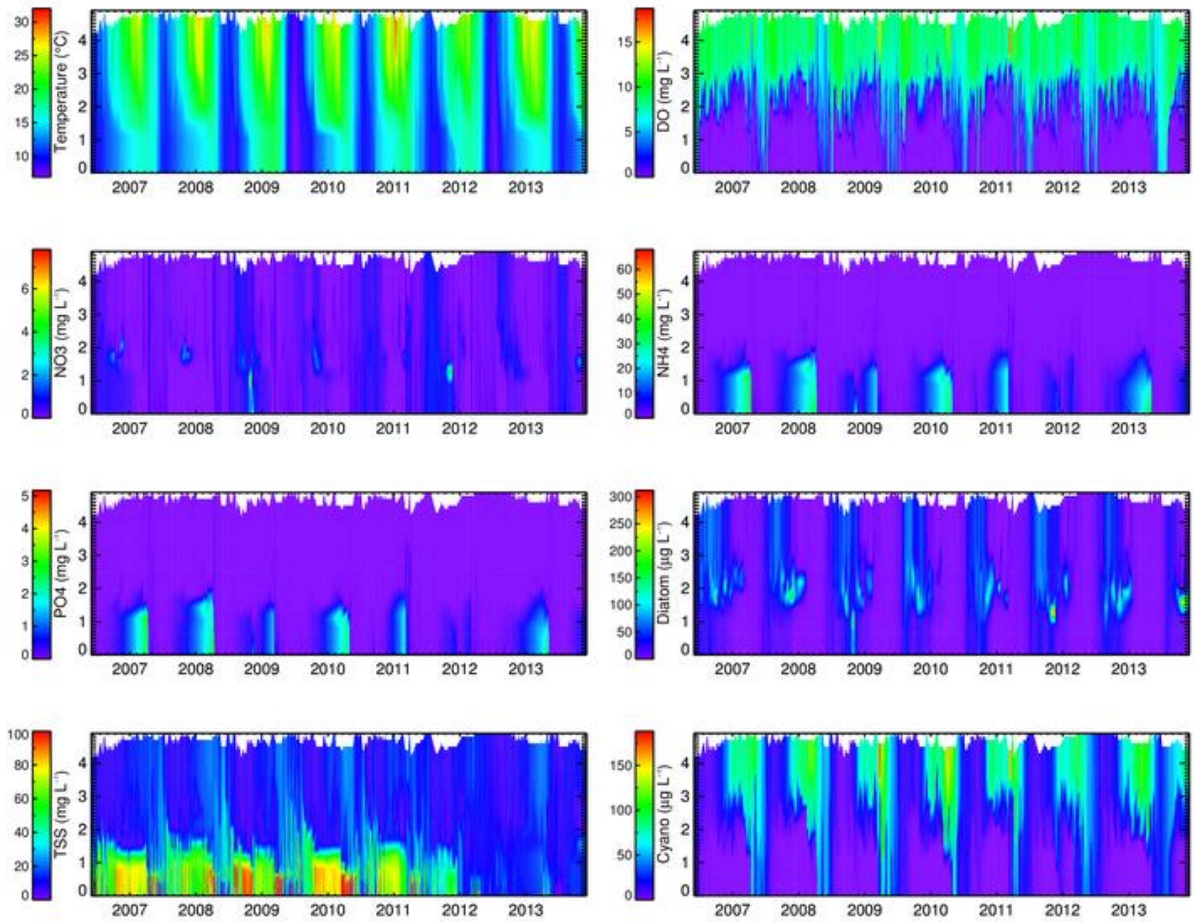
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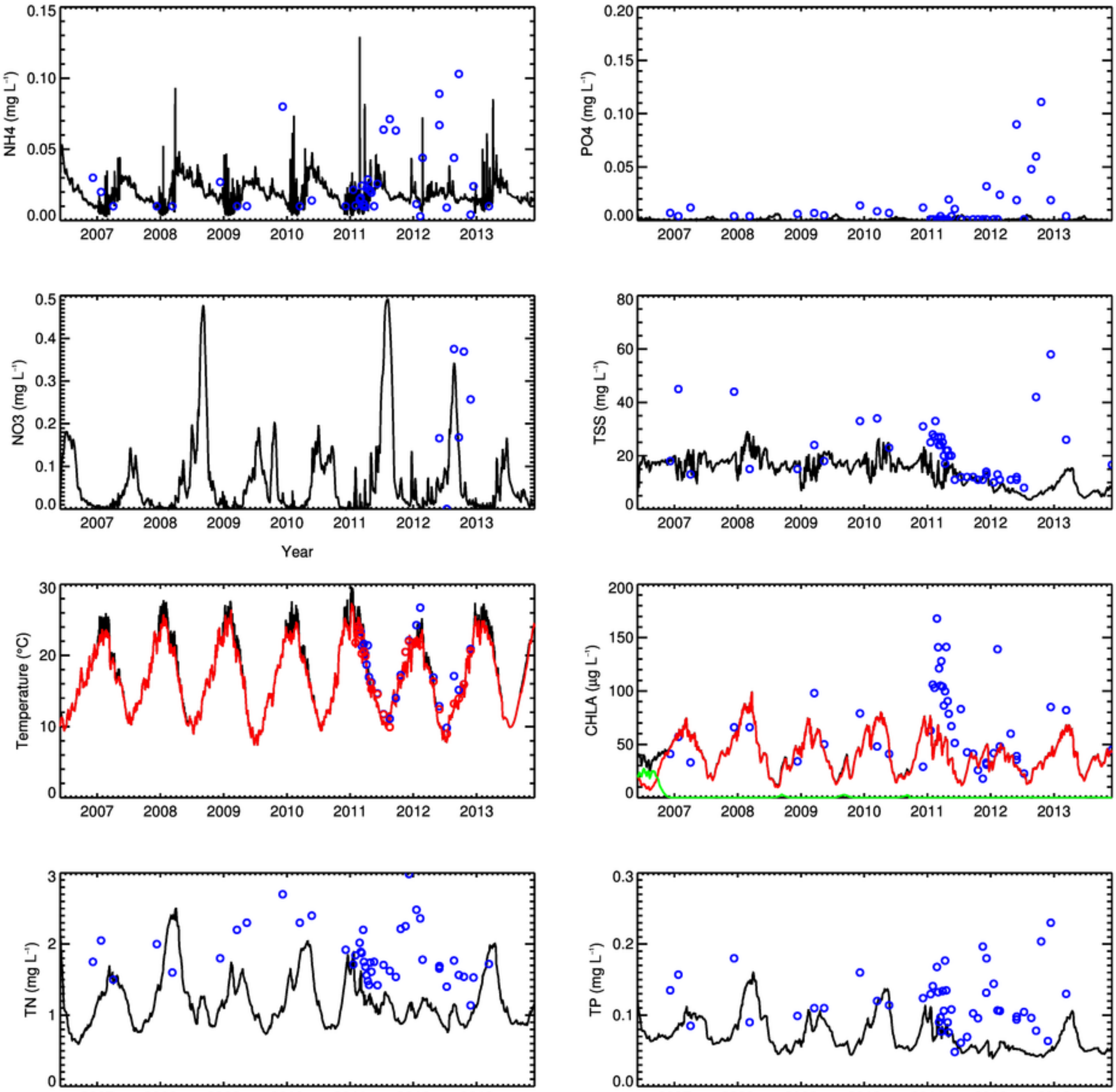
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
2007 2008 2009 2010 2011 2012 2013

S8F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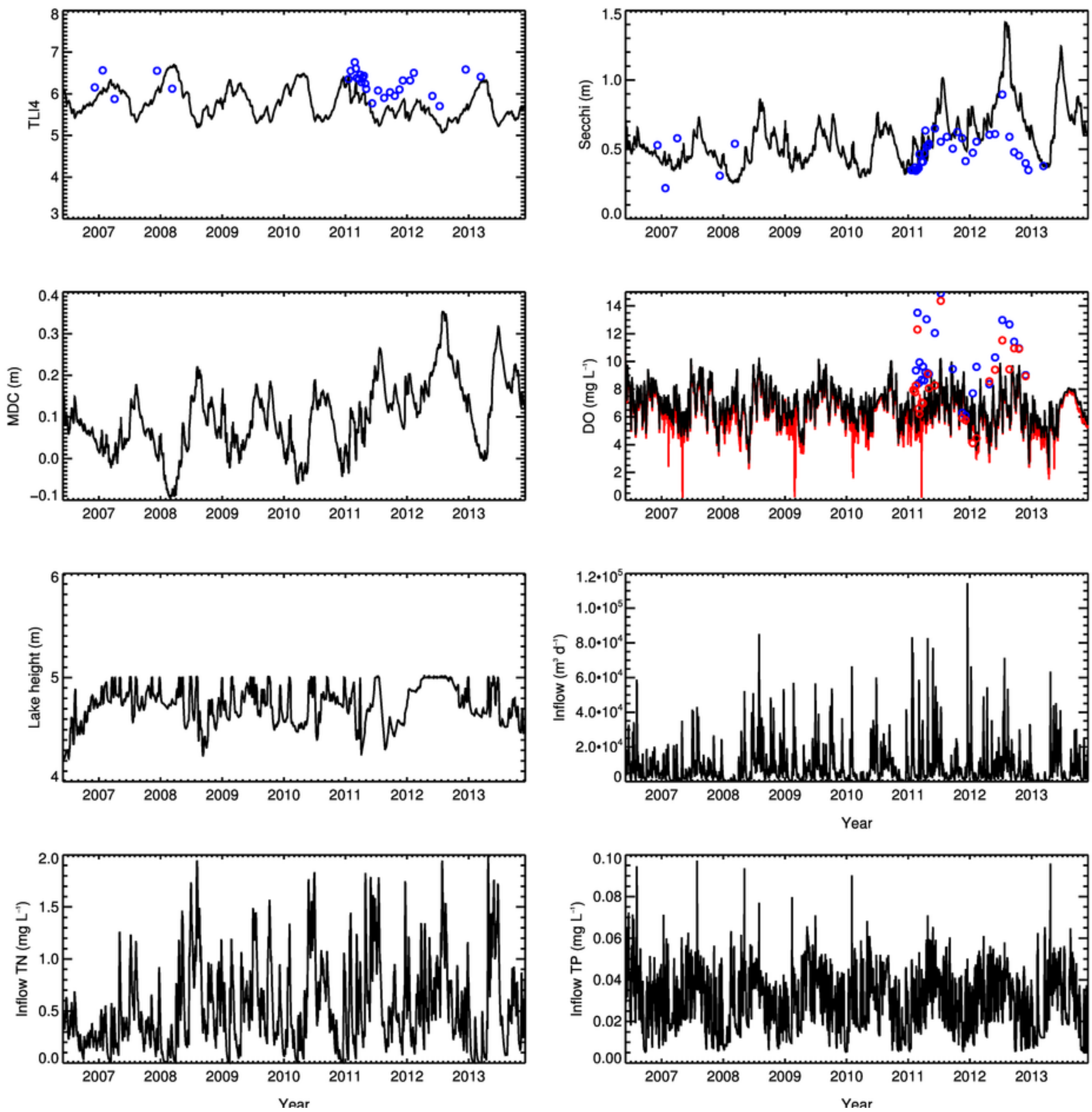
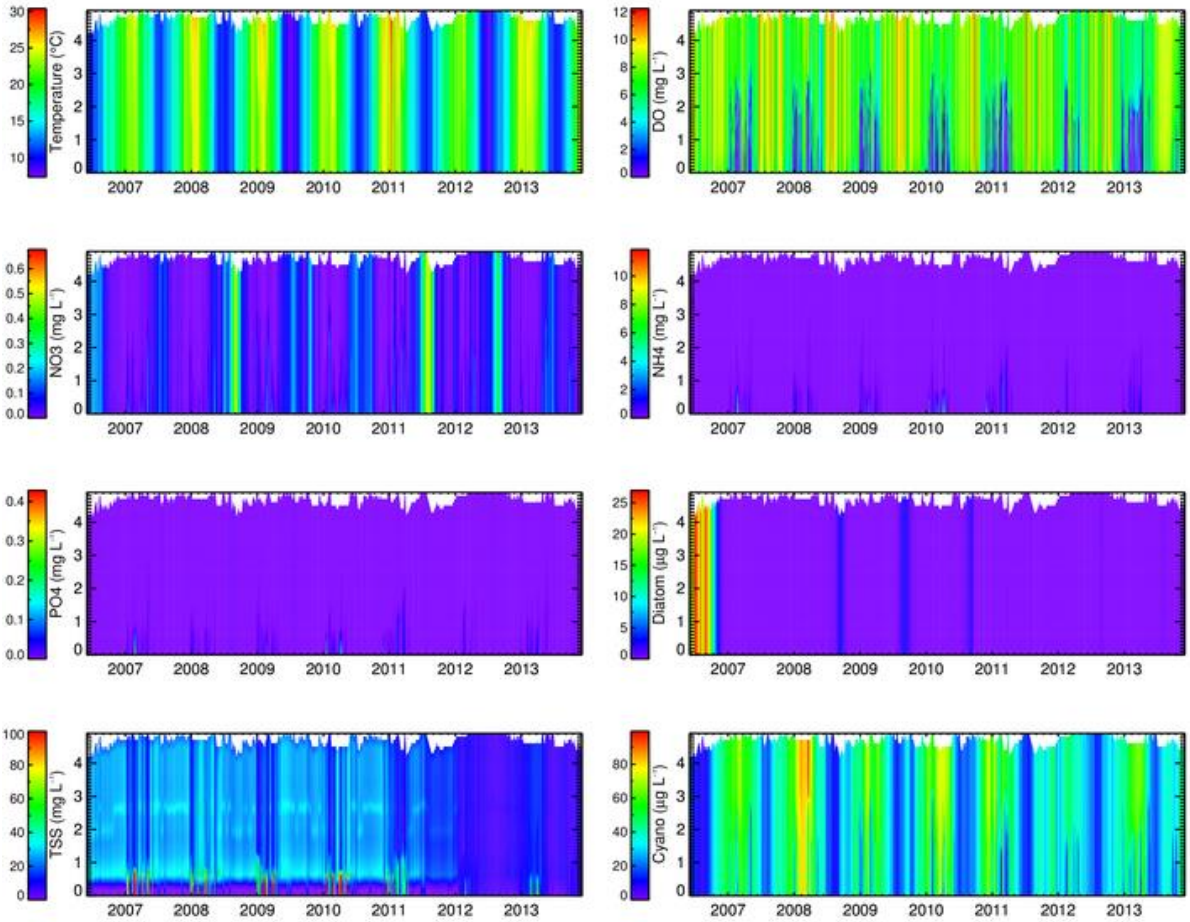
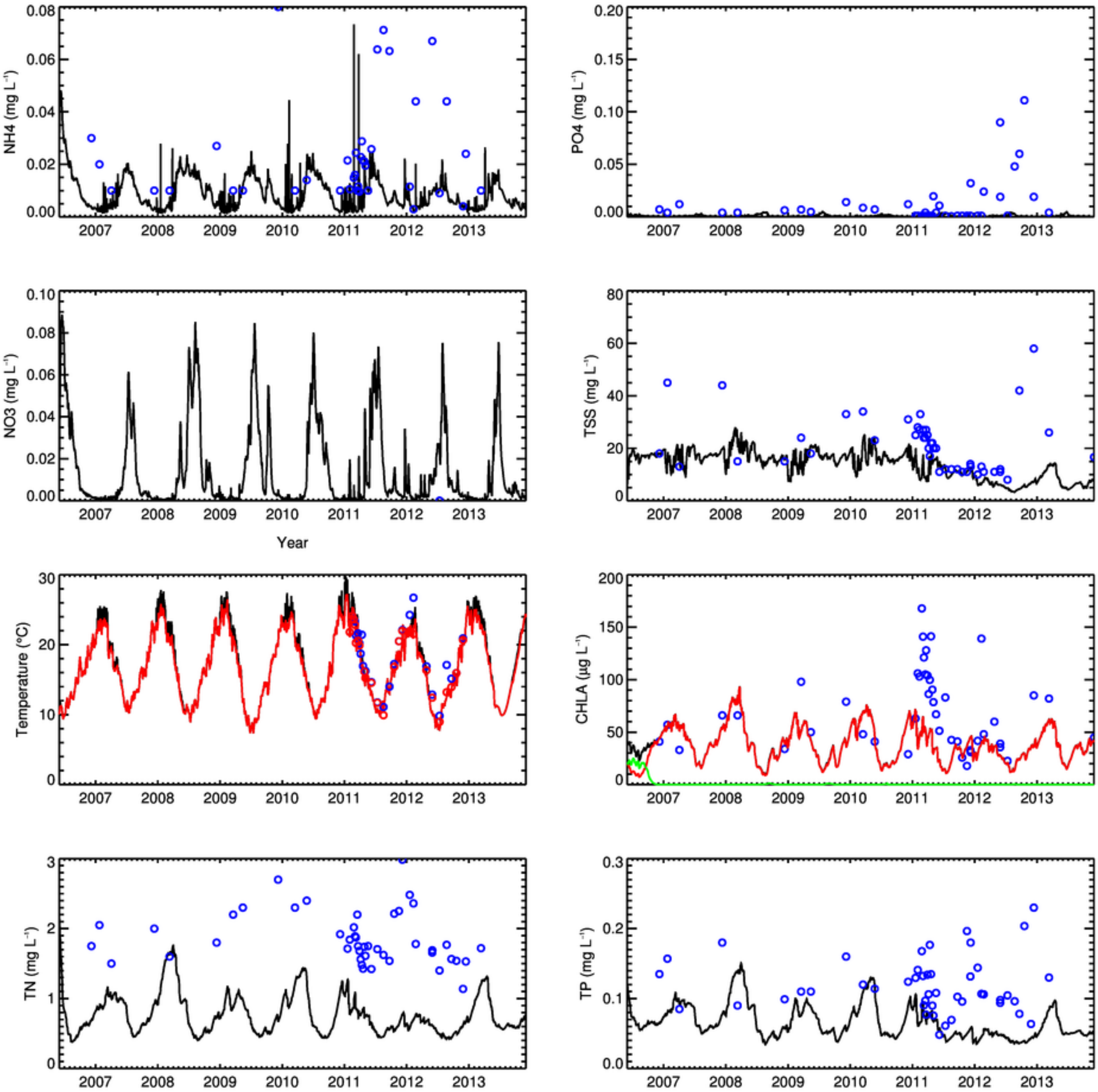
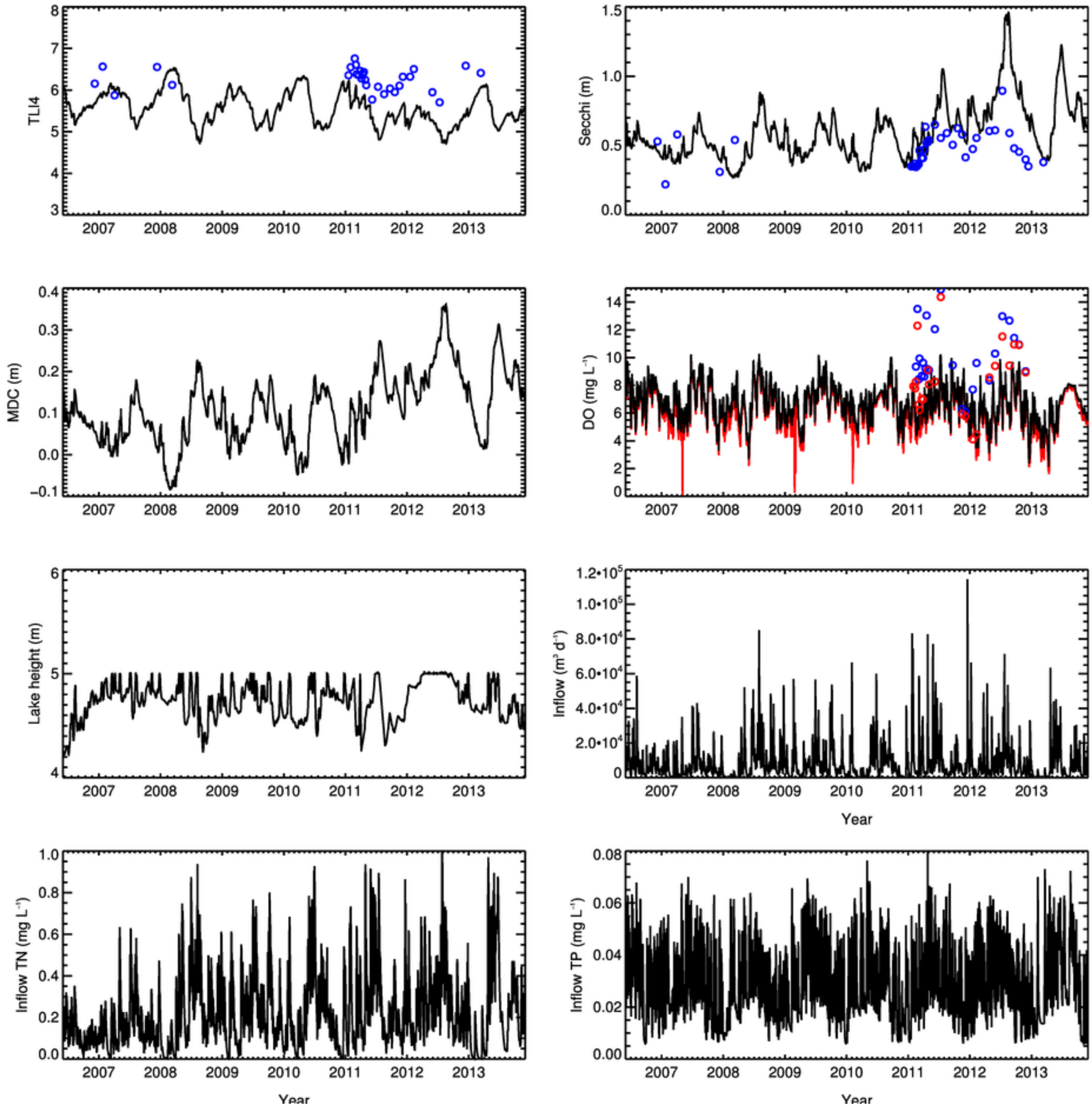
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
TSS (mg L⁻¹)
Year
Temperature (°C)
CHLA (µg L⁻¹)
TN (mg L⁻¹)
TP (mg L⁻¹)
2007
2008
2009
2010
2011
2012
2013


TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
2007
2008
2009
2010
2011
2012
2013
Year

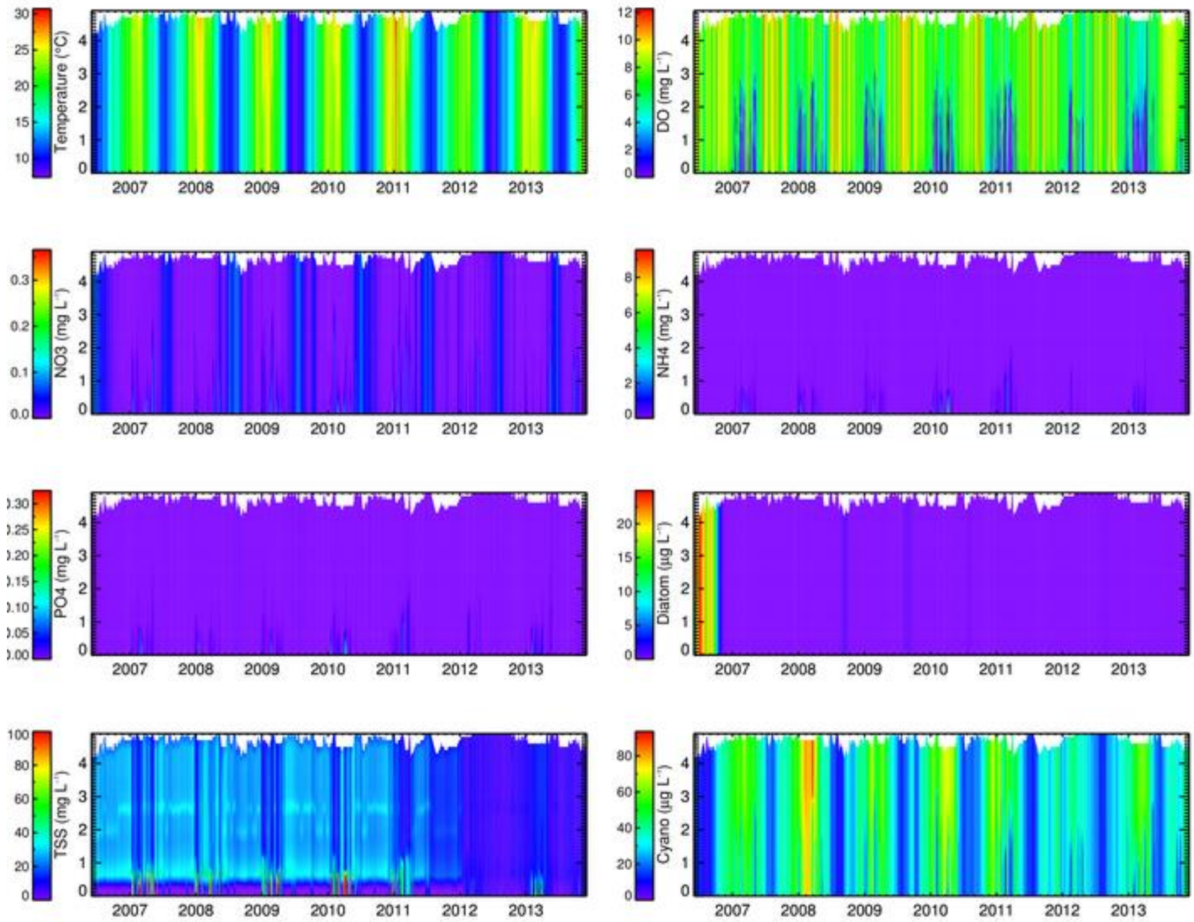

Temperature (°C)
DO (mg L⁻¹)
NO3 (mg L⁻¹)
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
2007
2008
2009
2010
2011
2012
2013

S9F

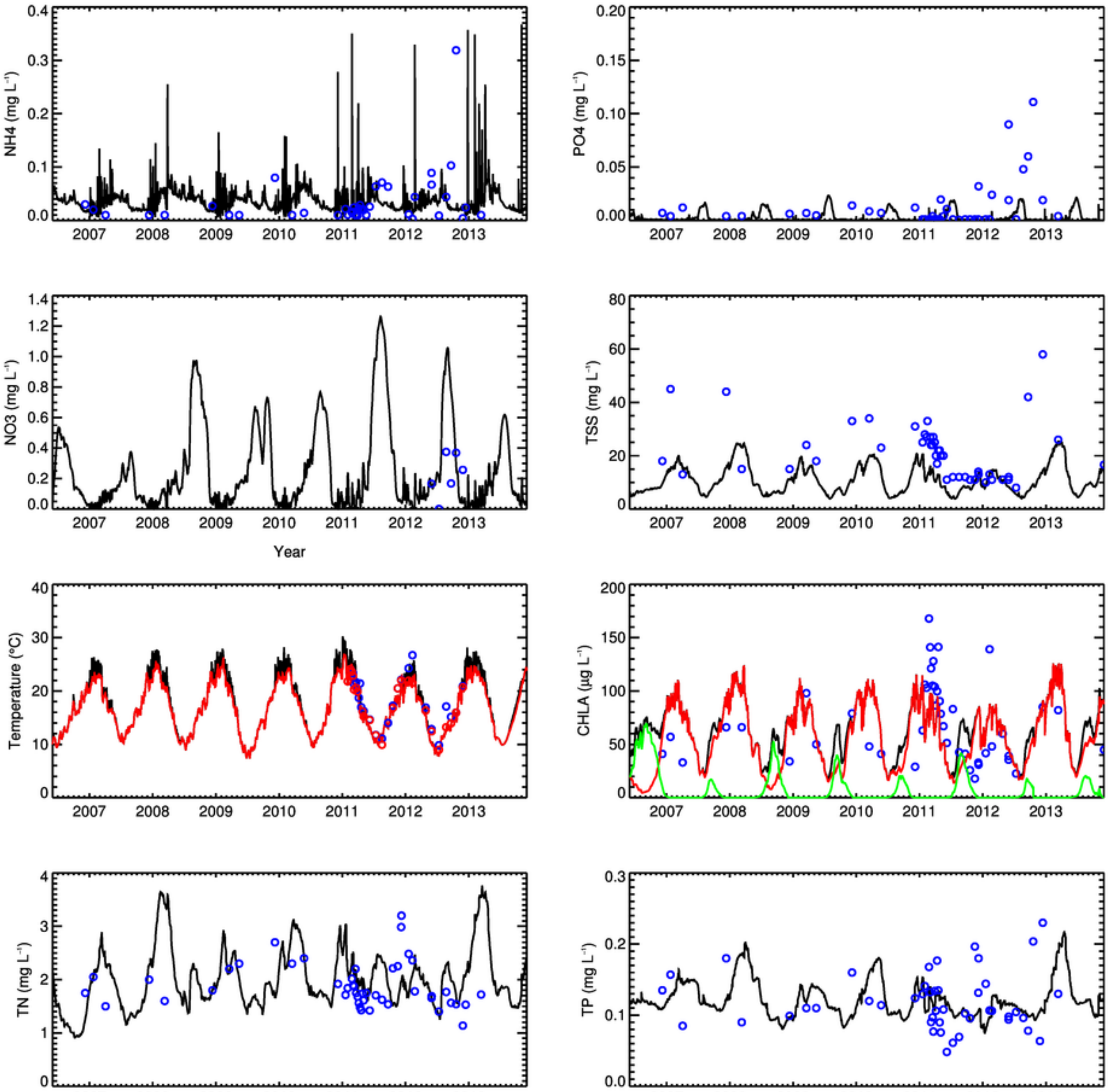

NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
TSS (mg L⁻¹)
Year
Temperature (°C)
CHLA (µg L⁻¹)
TN (mg L⁻¹)
TP (mg L⁻¹)
2007
2008
2009
2010
2011
2012
2013

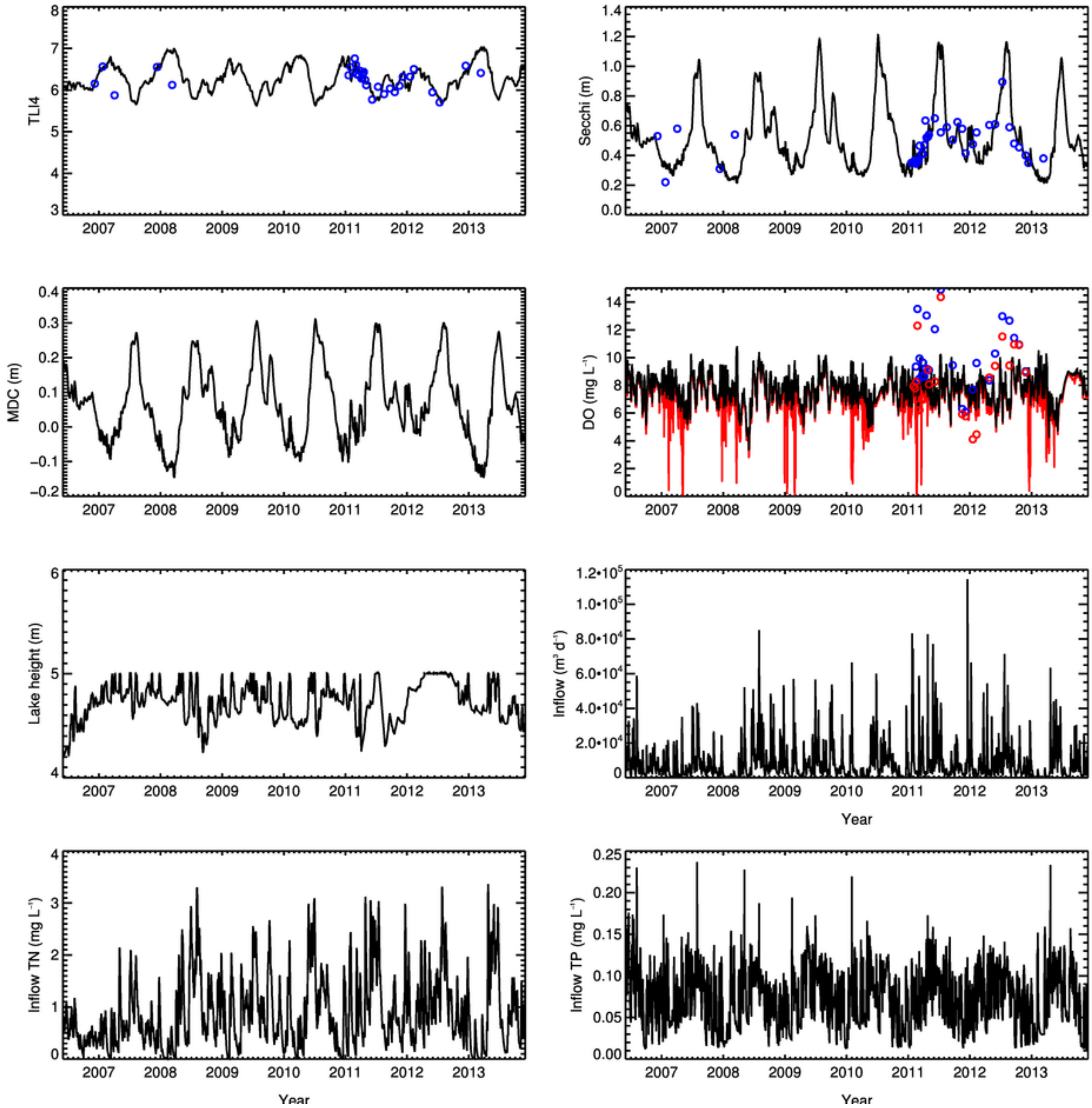


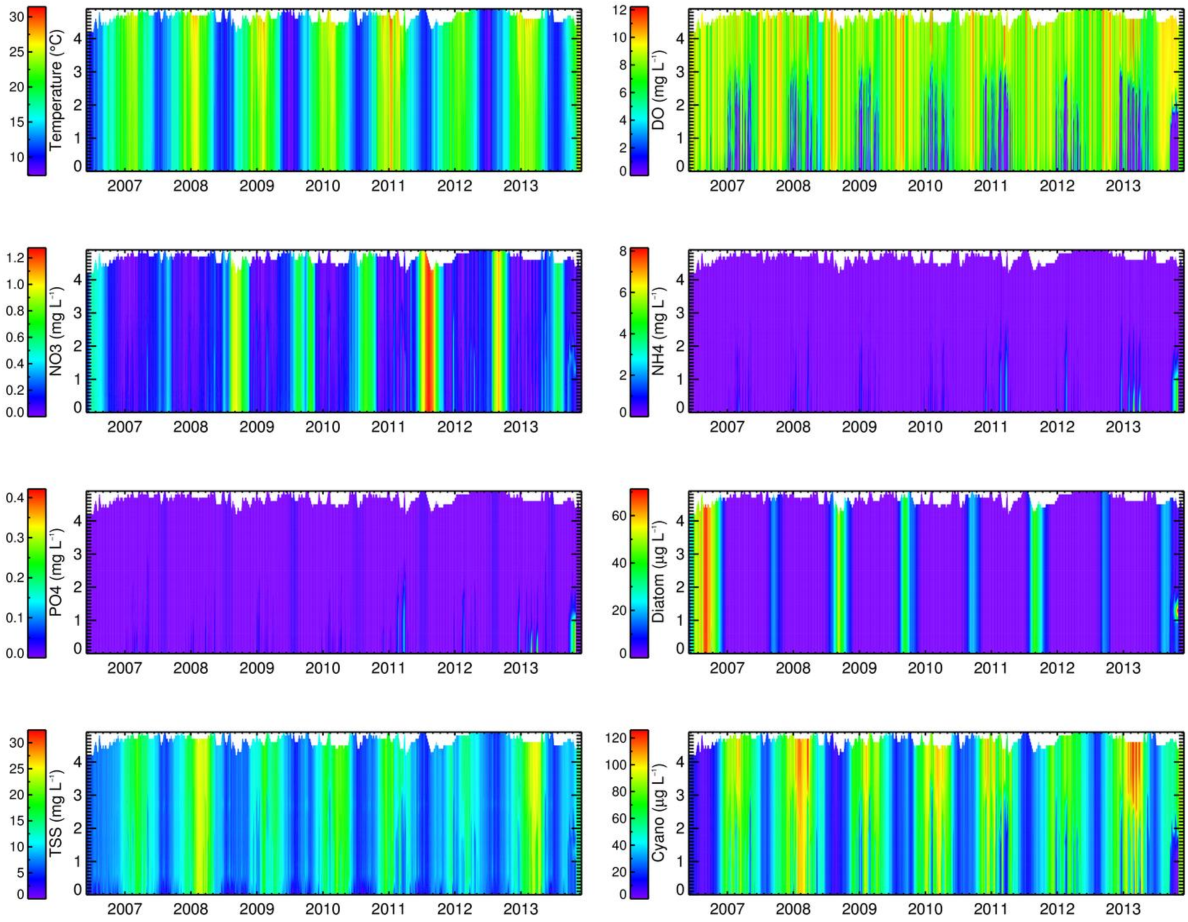
TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
Year


Temperature (°C)
DO (mg L^{-1})
NO3 (mg L^{-1})
NH4 (mg L^{-1})
PO4 (mg L^{-1})
Diatom (µg L^{-1})
TSS (mg L^{-1})
Cyano (µg L^{-1})
2007
2008
2009
2010
2011
2012
2013

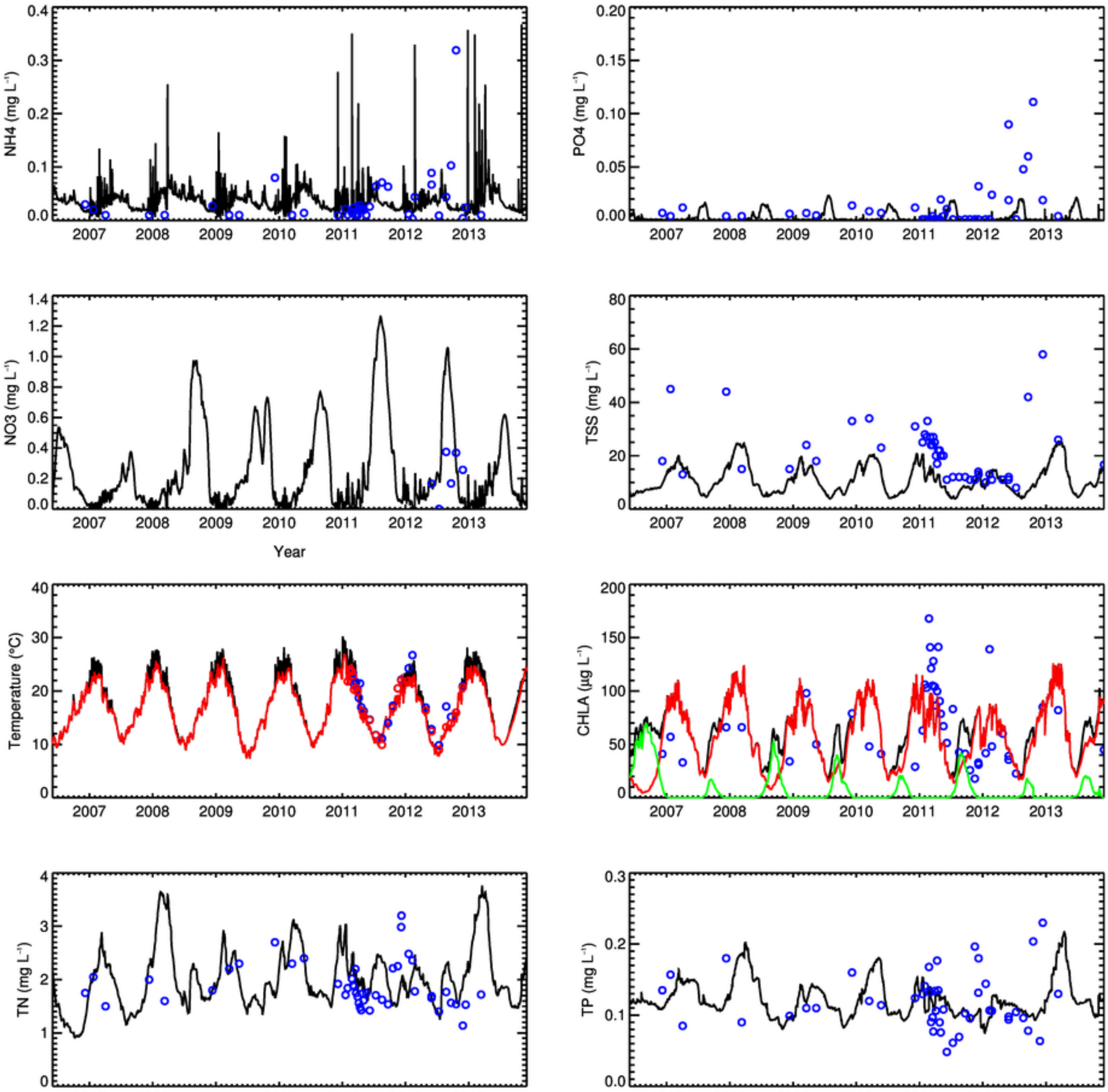
S1NF

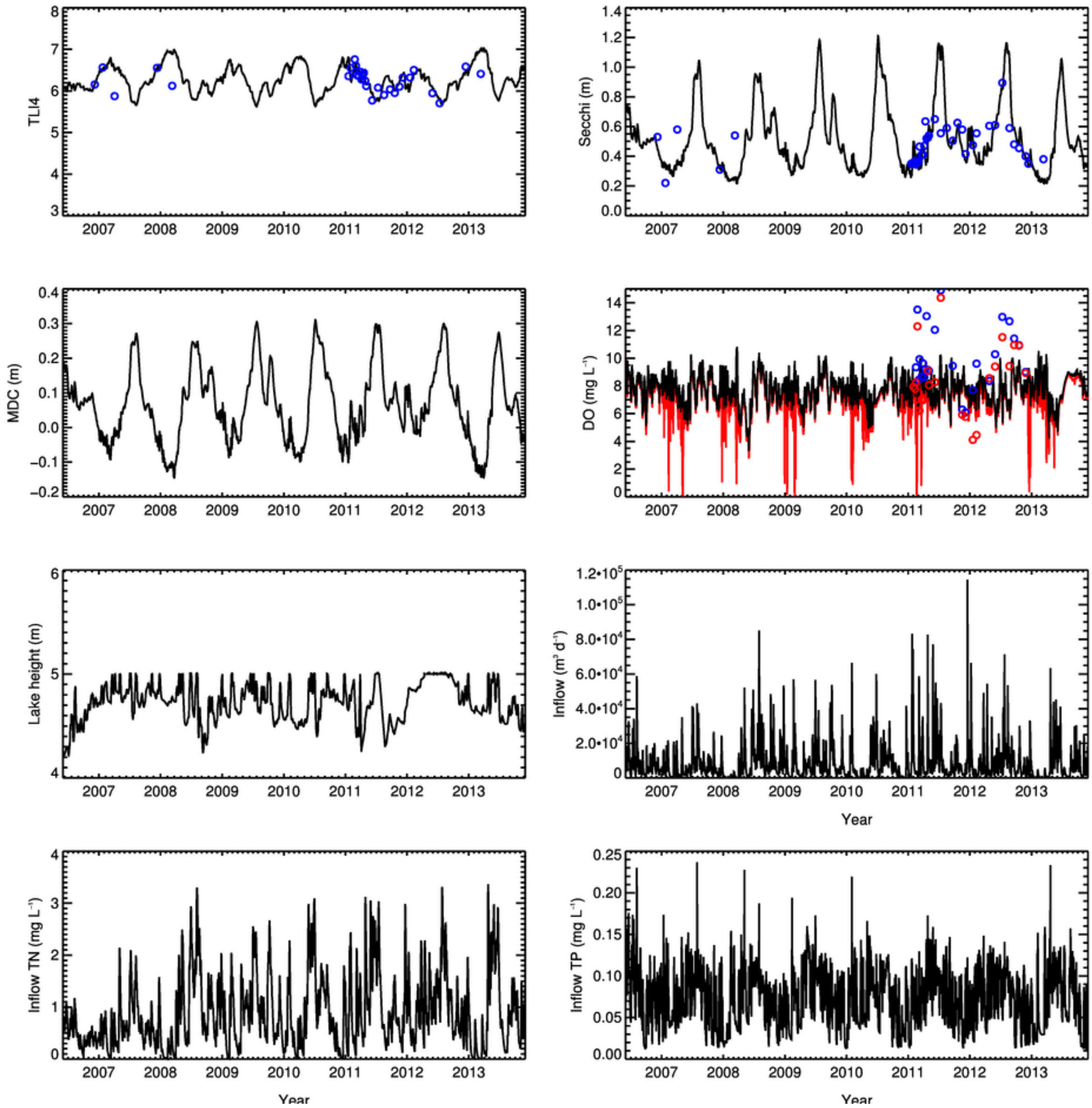

NH4 (mg L^{-1})
PO4 (mg L^{-1})
NO3 (mg L^{-1})
TSS (mg L^{-1})
Temperature (°C)
CHLA (µg L^{-1})
TN (mg L^{-1})
TP (mg L^{-1})
Year
2007
2008
2009
2010
2011
2012
2013

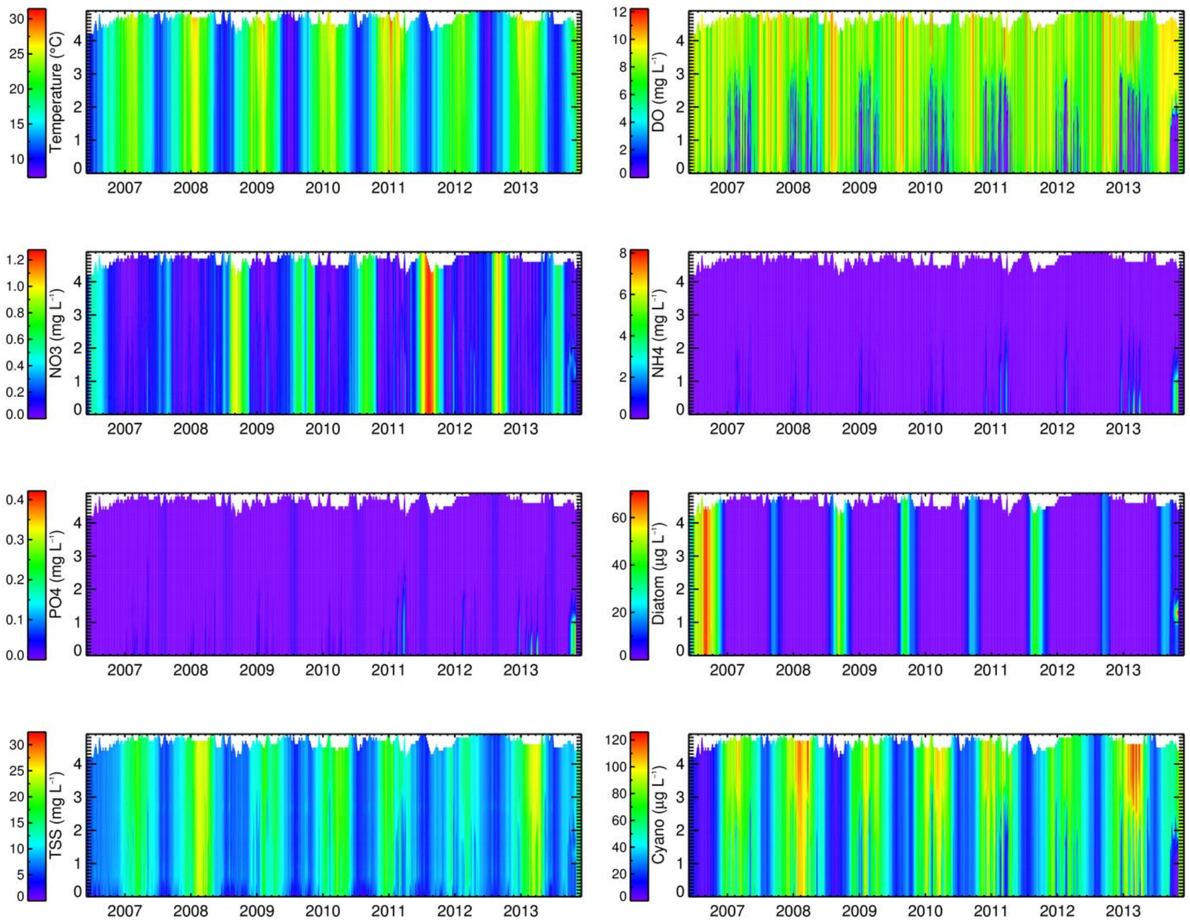

TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
Year
2007
2008
2009
2010
2011
2012
2013


Temperature (°C)
DO (mg L⁻¹)
NO3 (mg L⁻¹)
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
2007 2008 2009 2010 2011 2012 2013

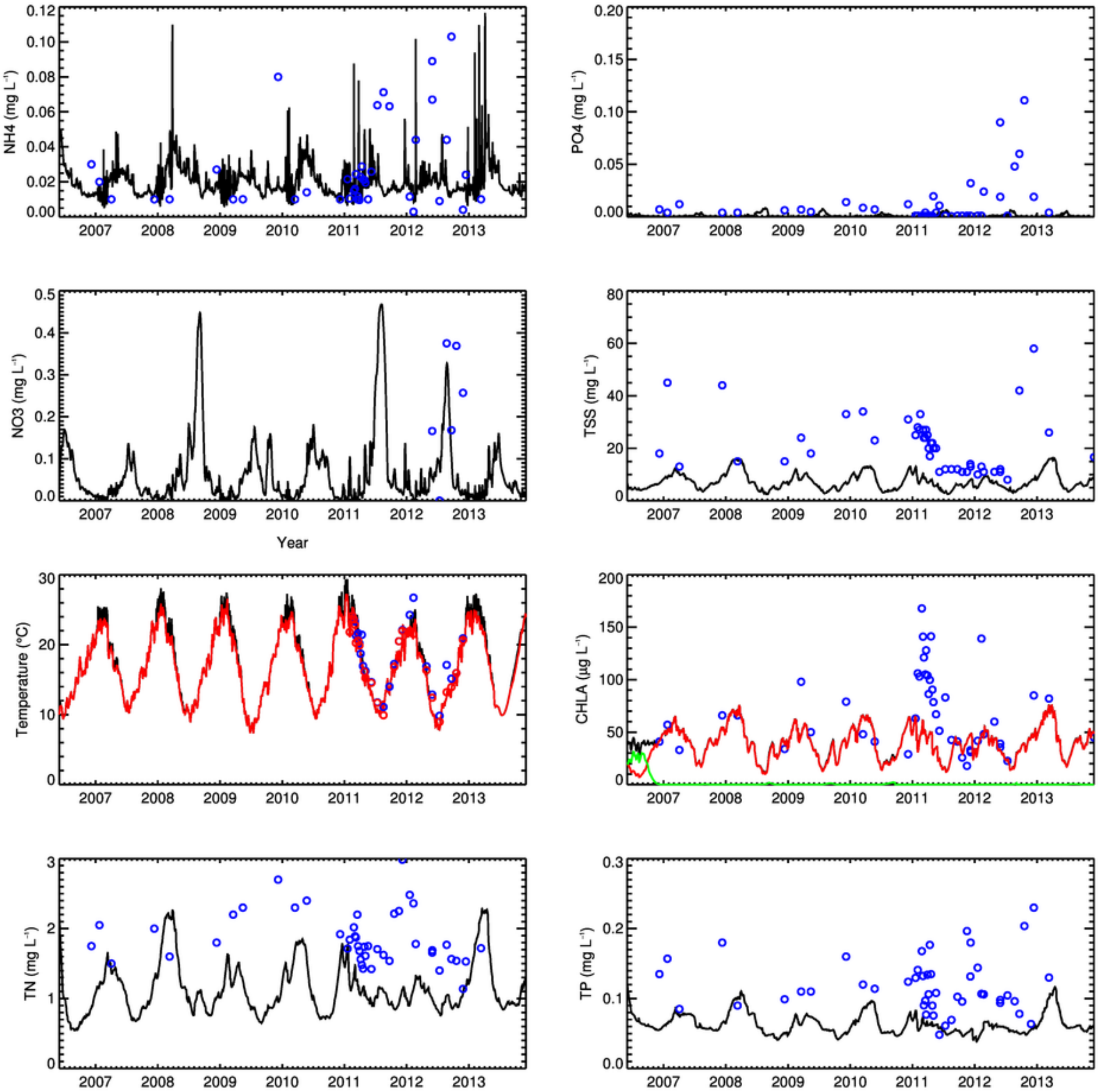
S2NF


NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
TSS (mg L⁻¹)
Year
Temperature (°C)
CHLA (µg L⁻¹)
TN (mg L⁻¹)
TP (mg L⁻¹)
2007
2008
2009
2010
2011
2012
2013

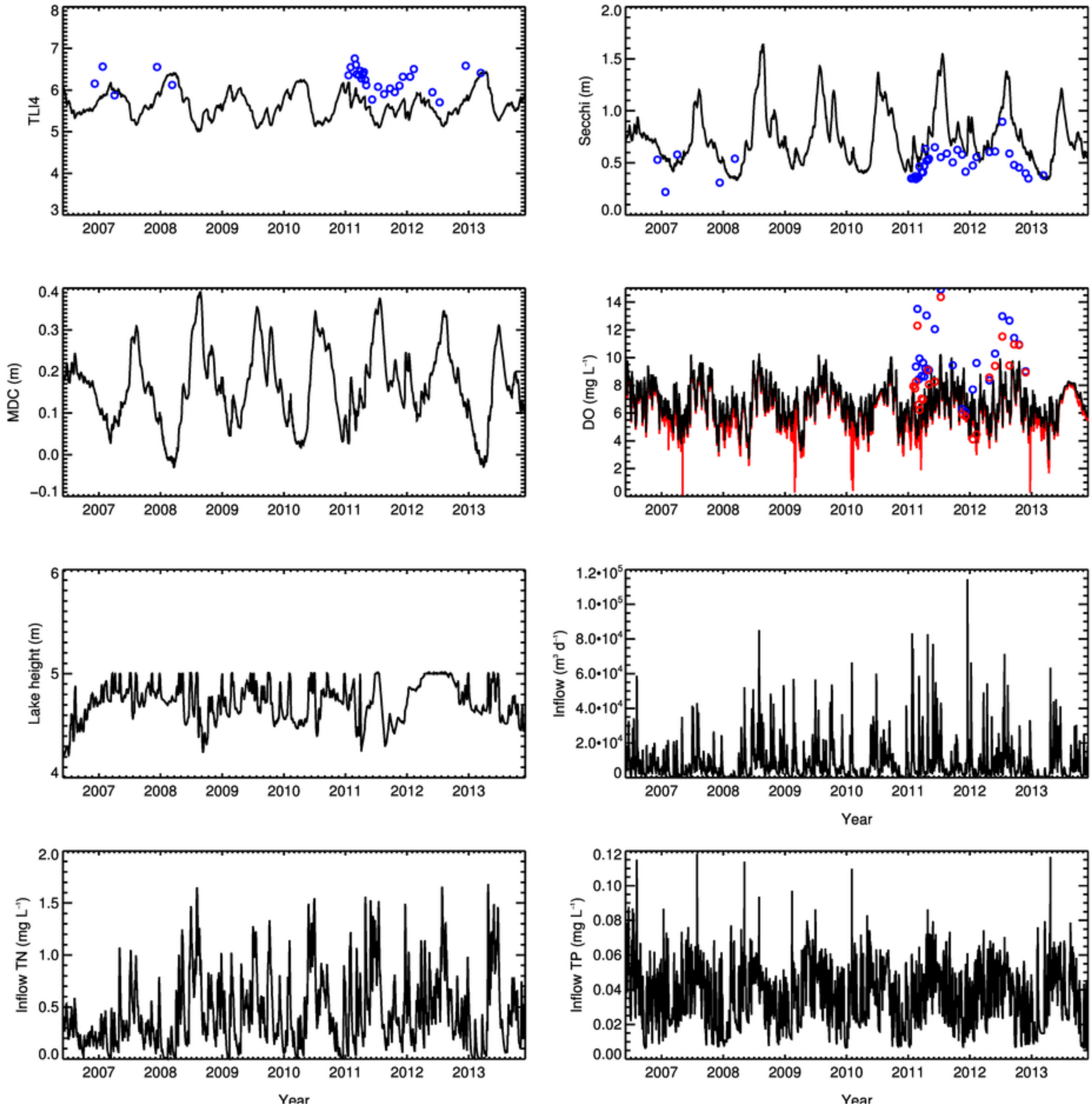

TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
2007
2008
2009
2010
2011
2012
2013
Year


Temperature (°C)
DO (mg L⁻¹)
NO3 (mg L⁻¹)
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
2007
2008
2009
2010
2011
2012
2013

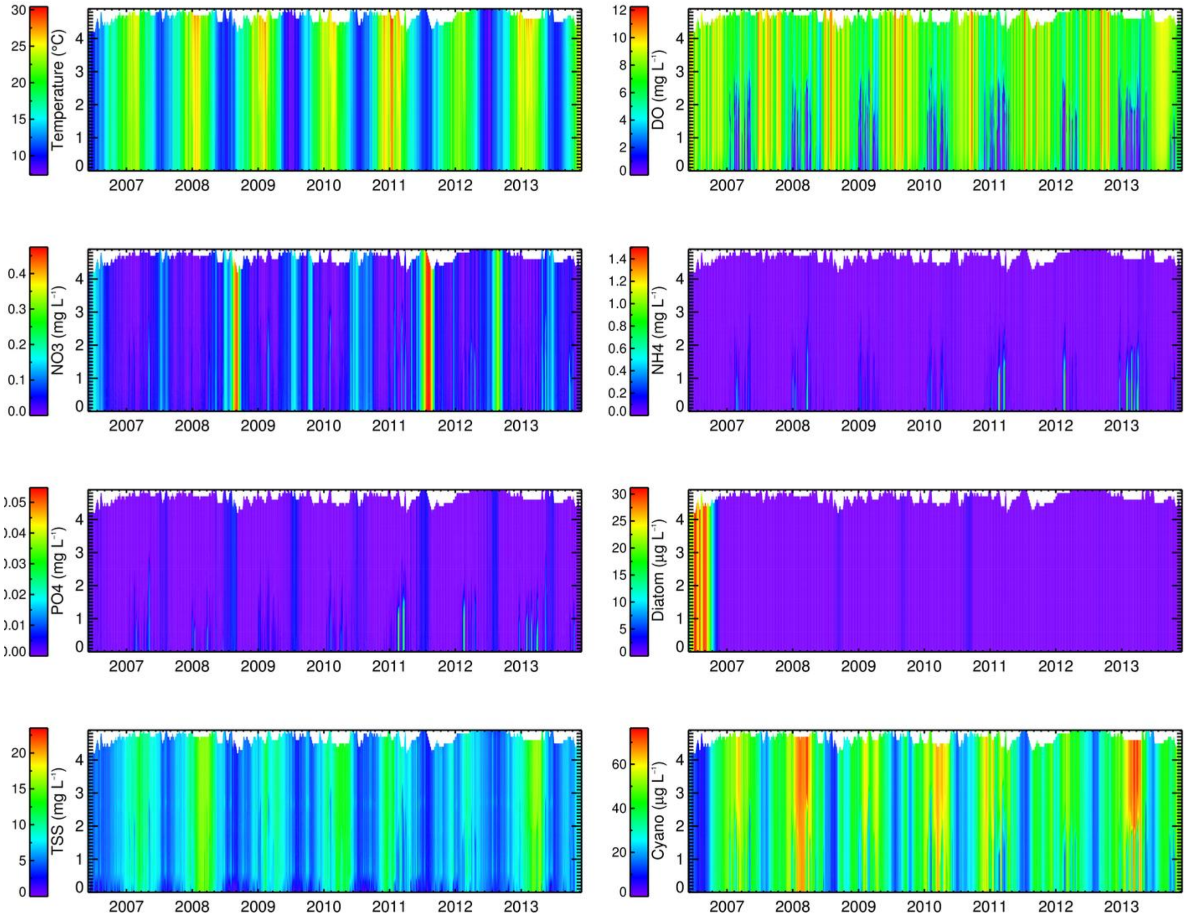
S3NF



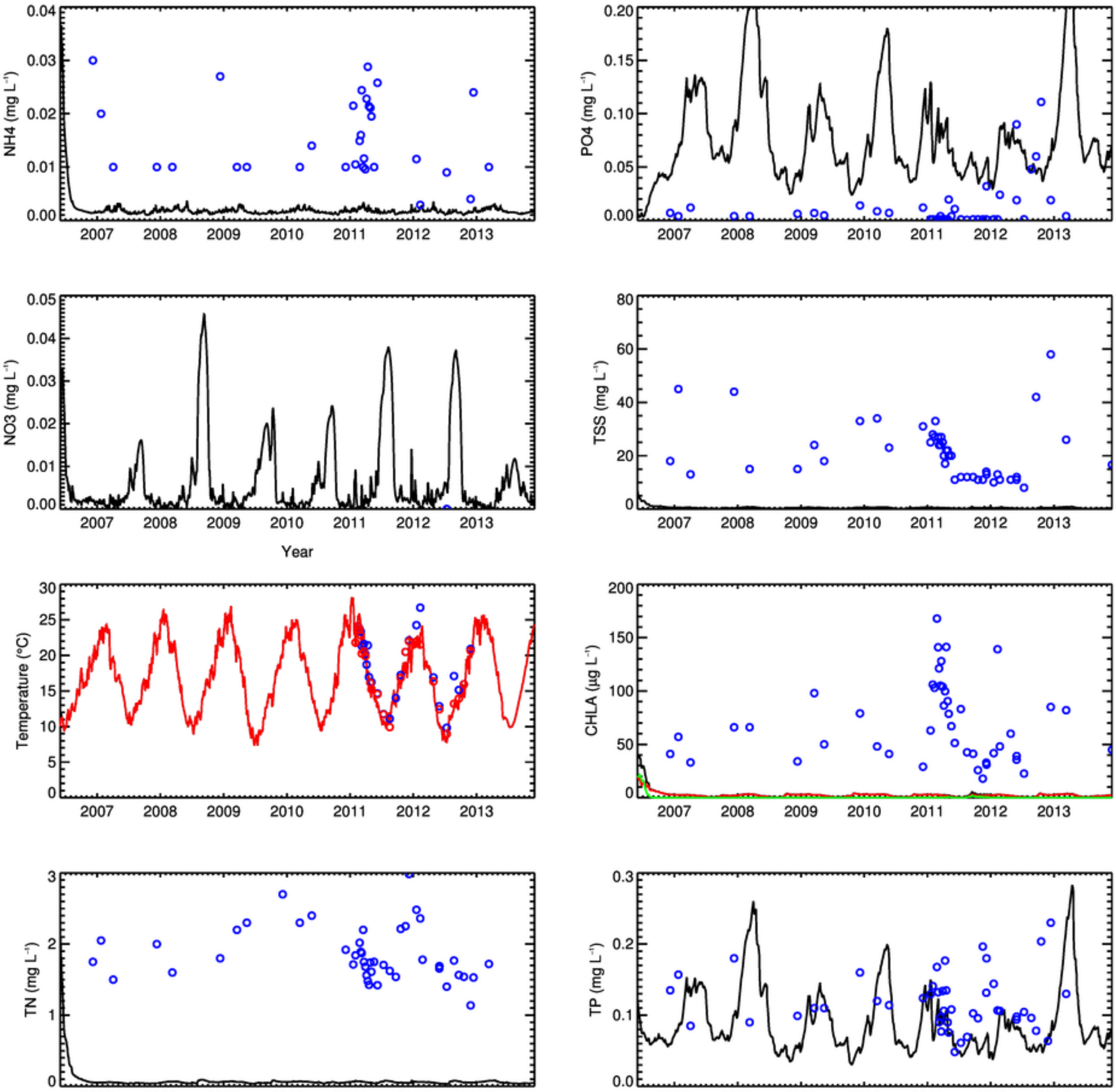
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
TSS (mg L⁻¹)
Year
Temperature (°C)
CHLA (µg L⁻¹)
TN (mg L⁻¹)
TP (mg L⁻¹)
2007
2008
2009
2010
2011
2012
2013



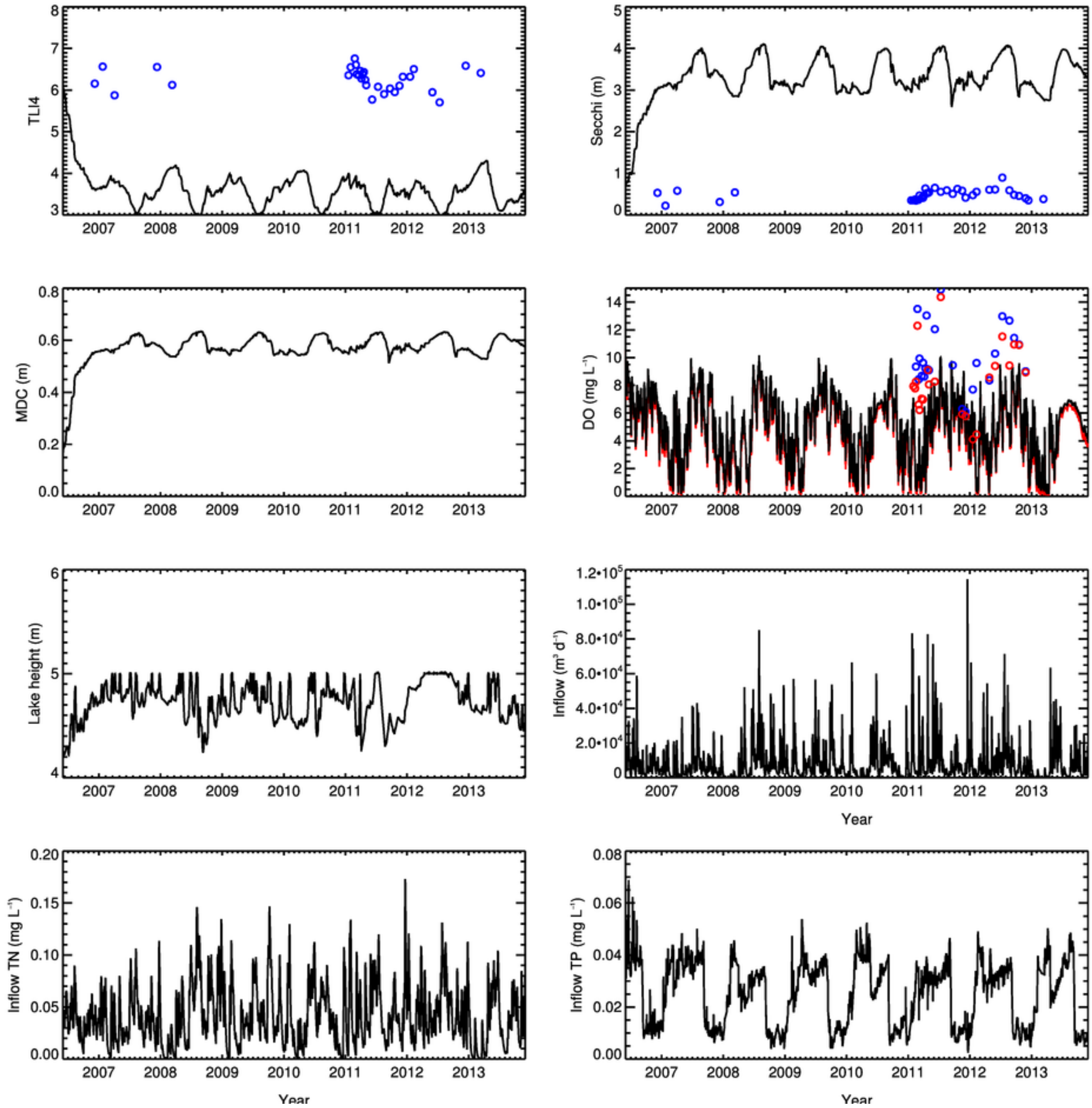
TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Year
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
Year
Year


Temperature (°C)
DO (mg L⁻¹)
NO3 (mg L⁻¹)
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
2007 2008 2009 2010 2011 2012 2013

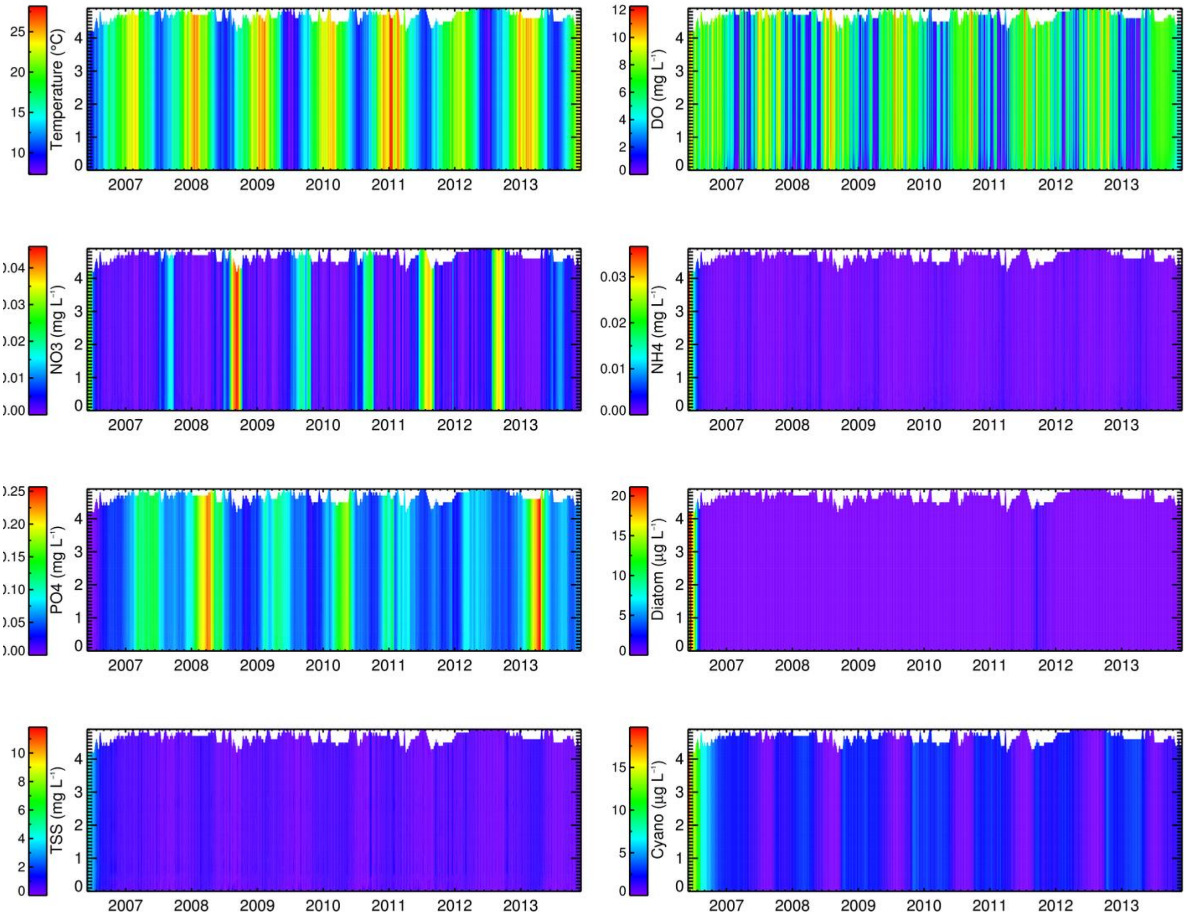
S4NF



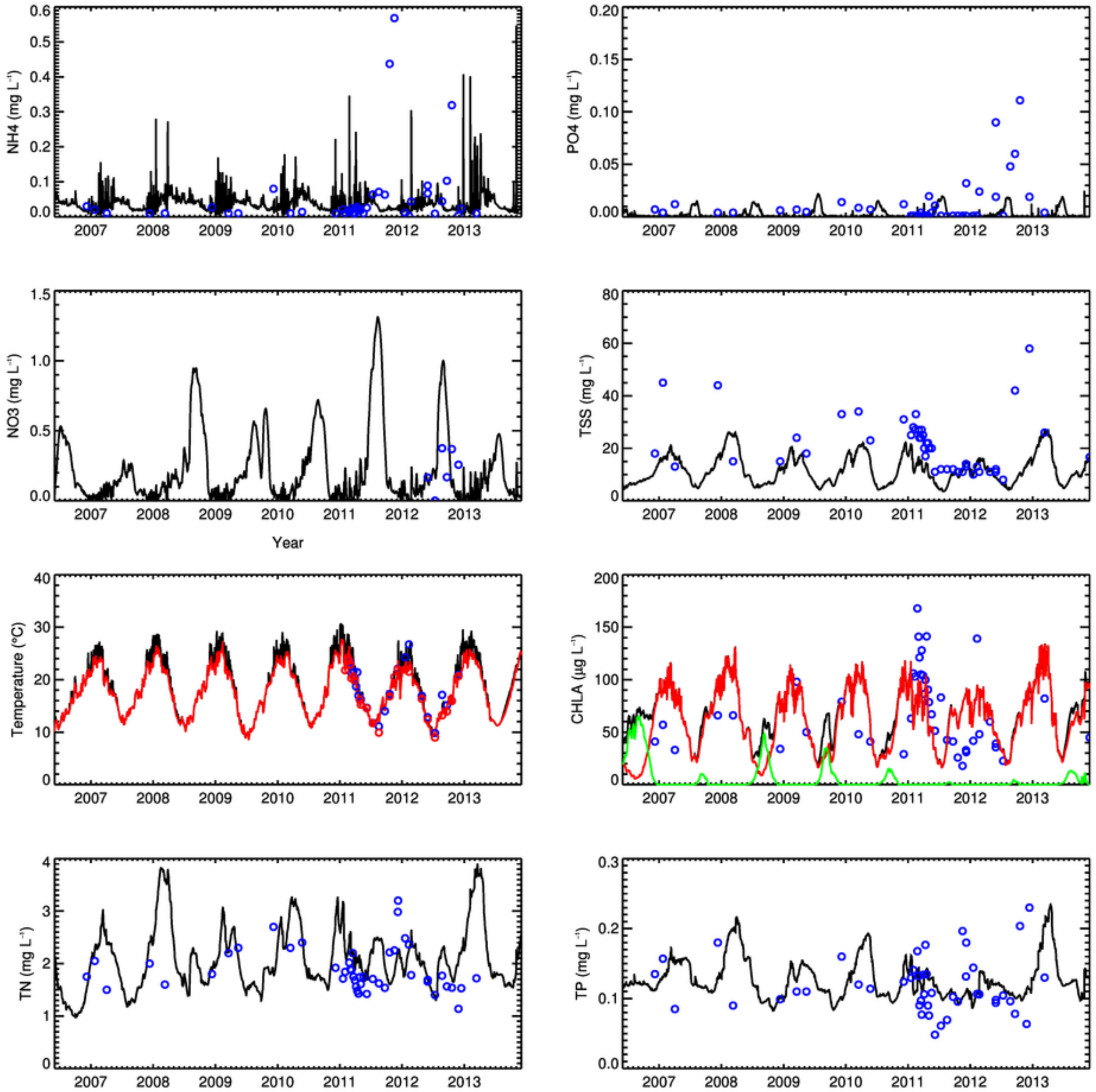
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
Year
TSS (mg L⁻¹)
Temperature (°C)
CHLA (µg L⁻¹)
TN (mg L⁻¹)
TP (mg L⁻¹)
2007
2008
2009
2010
2011
2012
2013

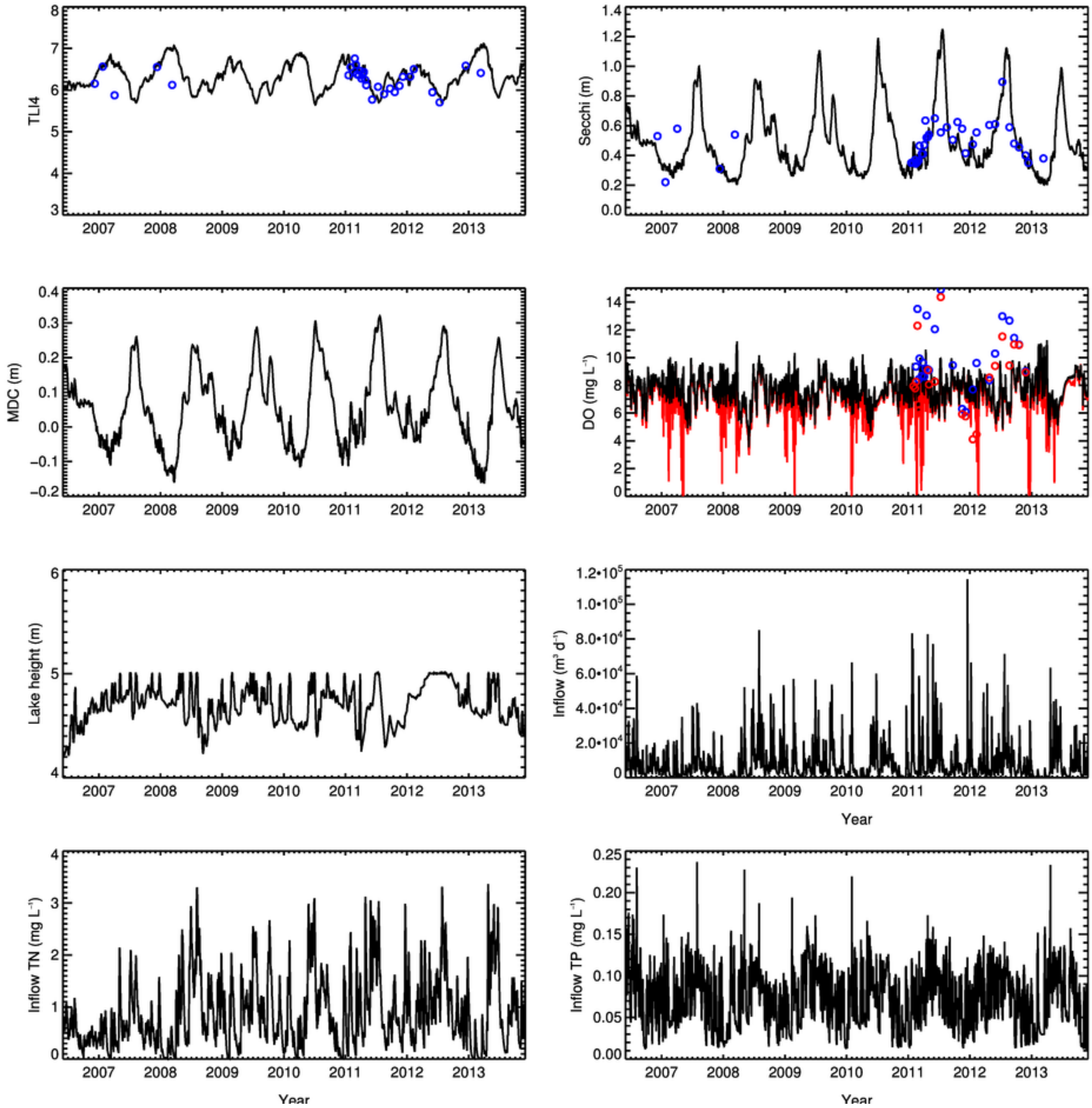


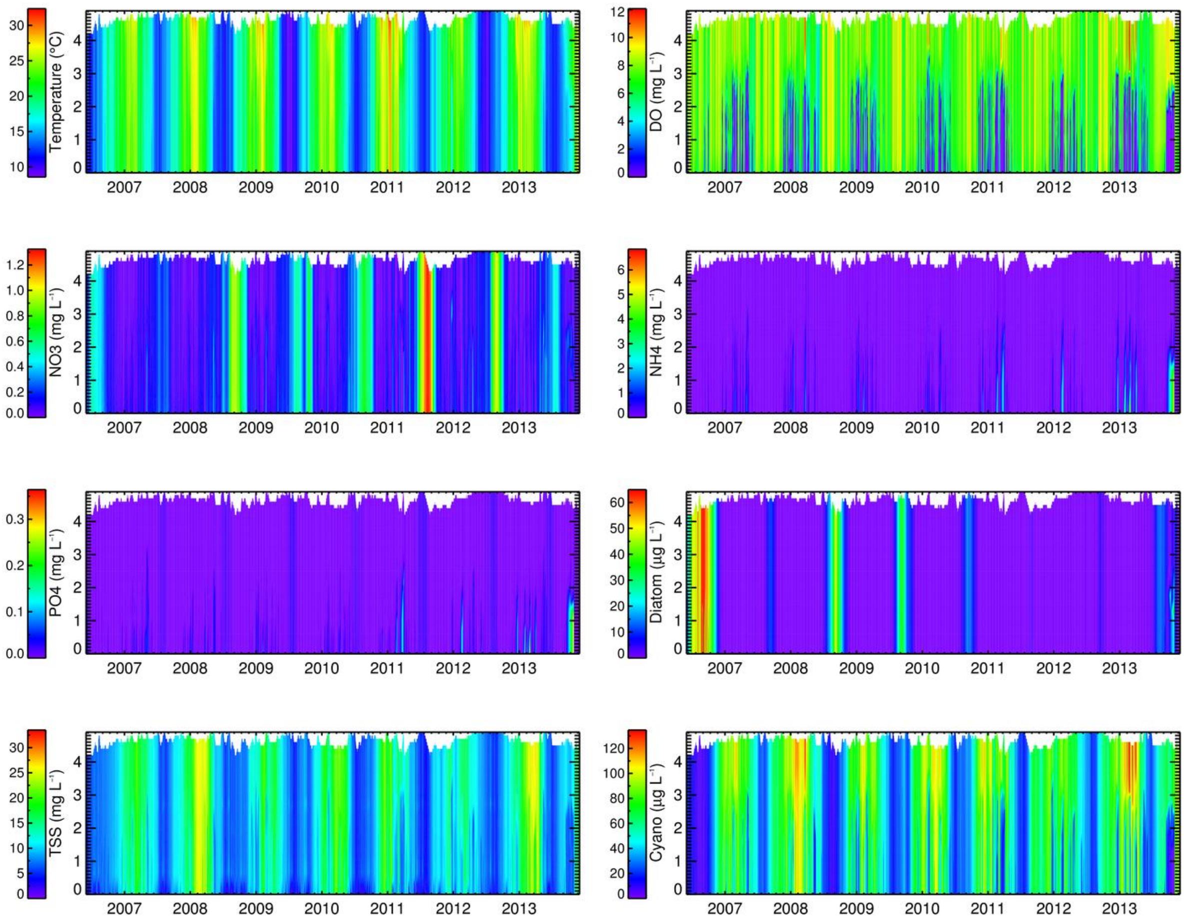
TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
Year


Temperature (°C)
DO (mg L⁻¹)
NO3 (mg L⁻¹)
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
2007
2008
2009
2010
2011
2012
2013

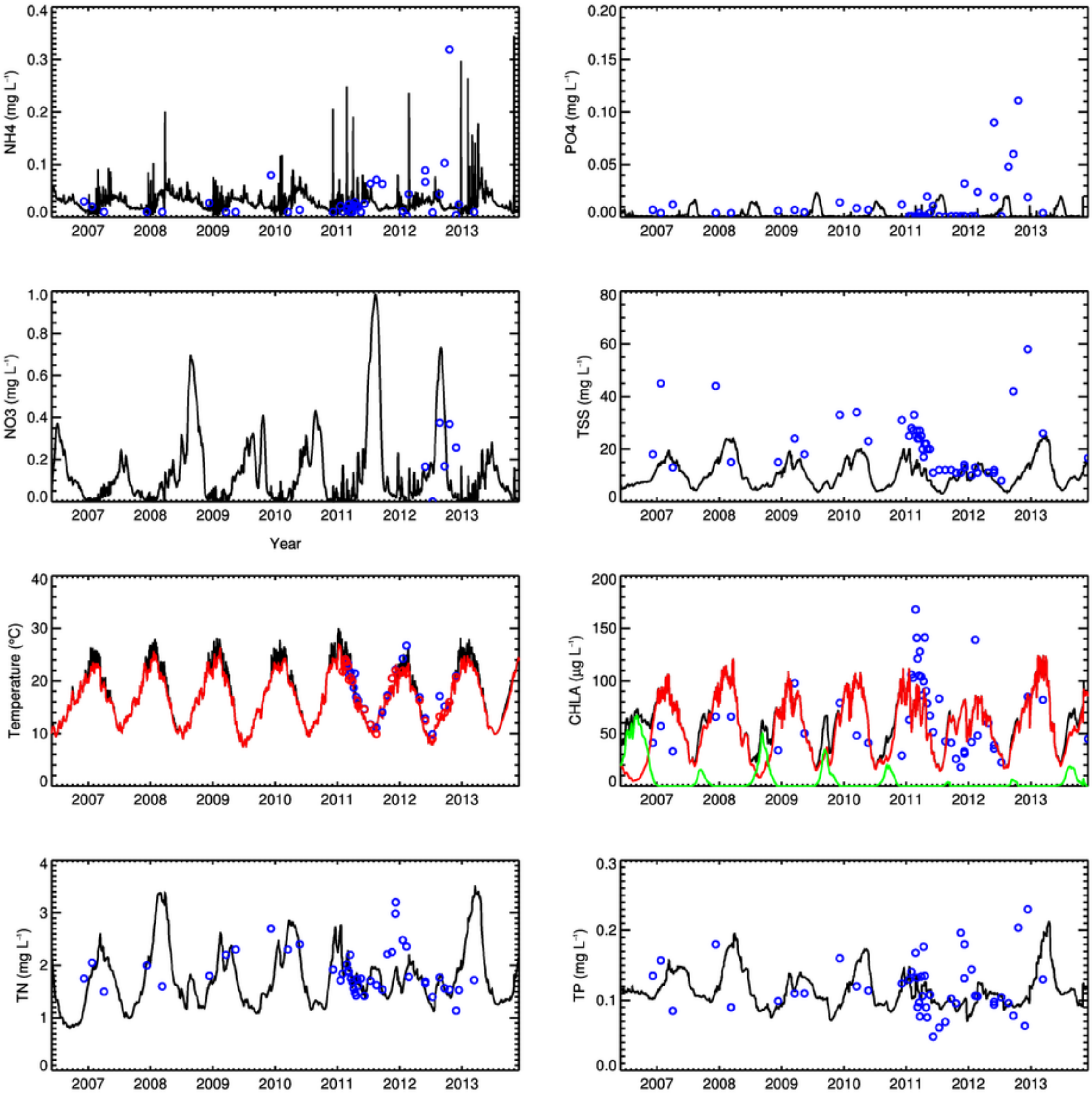
S5NF


NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
TSS (mg L⁻¹)
Year
Temperature (°C)
CHLA (µg L⁻¹)
TN (mg L⁻¹)
TP (mg L⁻¹)
2007
2008
2009
2010
2011
2012
2013

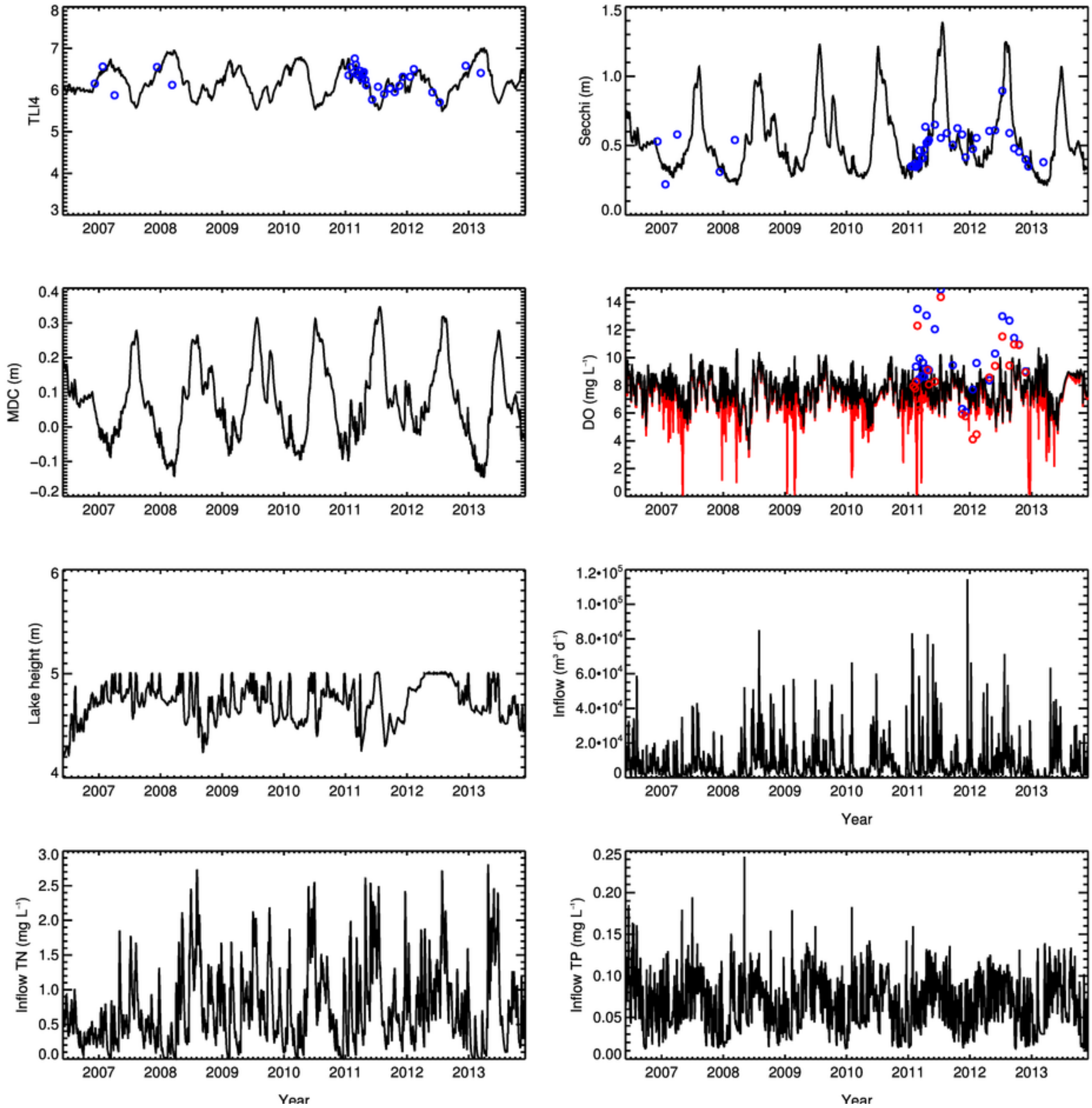

TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Year
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
Year
Year
2007
2008
2009
2010
2011
2012
2013

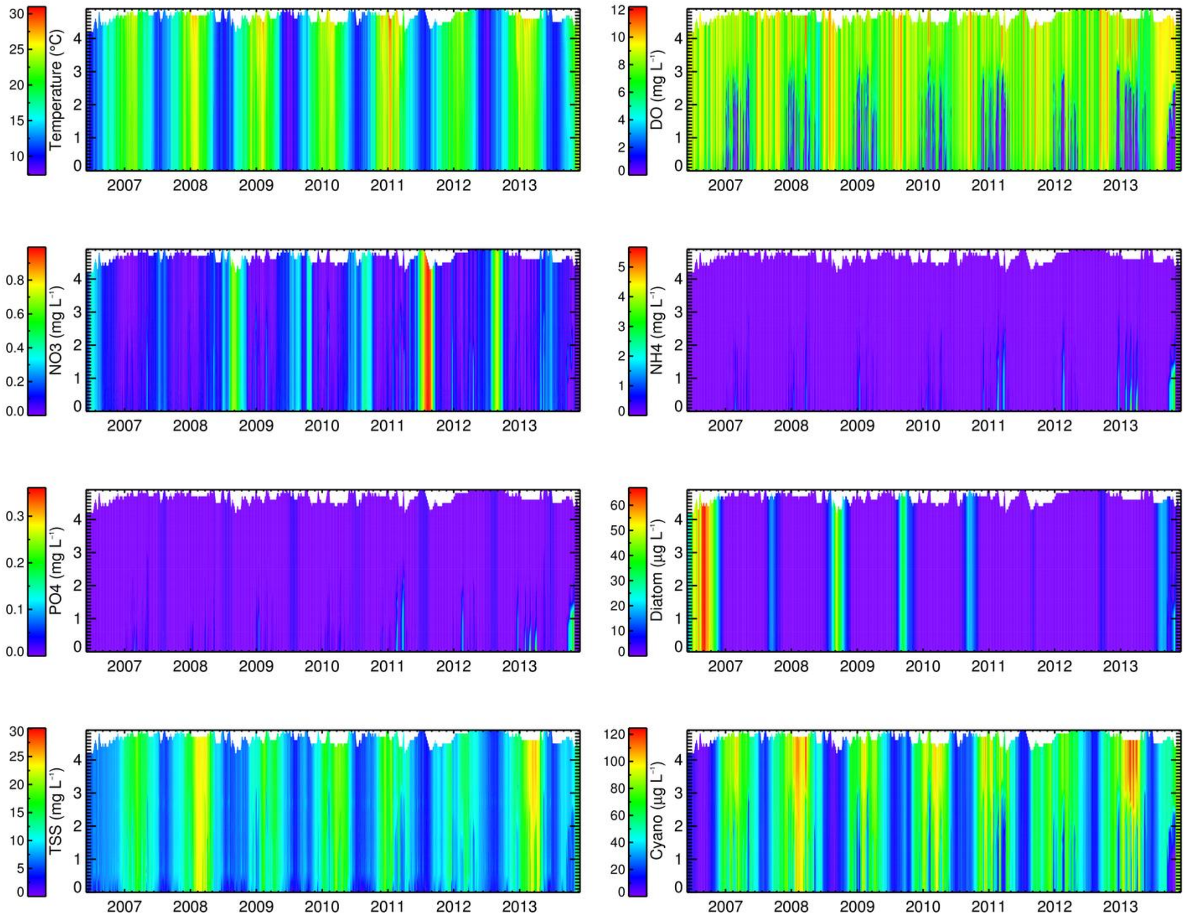

Temperature (°C)
DO (mg L^{-1})
NO3 (mg L^{-1})
NH4 (mg L^{-1})
PO4 (mg L^{-1})
Diatom (µg L^{-1})
TSS (mg L^{-1})
Cyano (µg L^{-1})
2007
2008
2009
2010
2011
2012
2013

S6NF

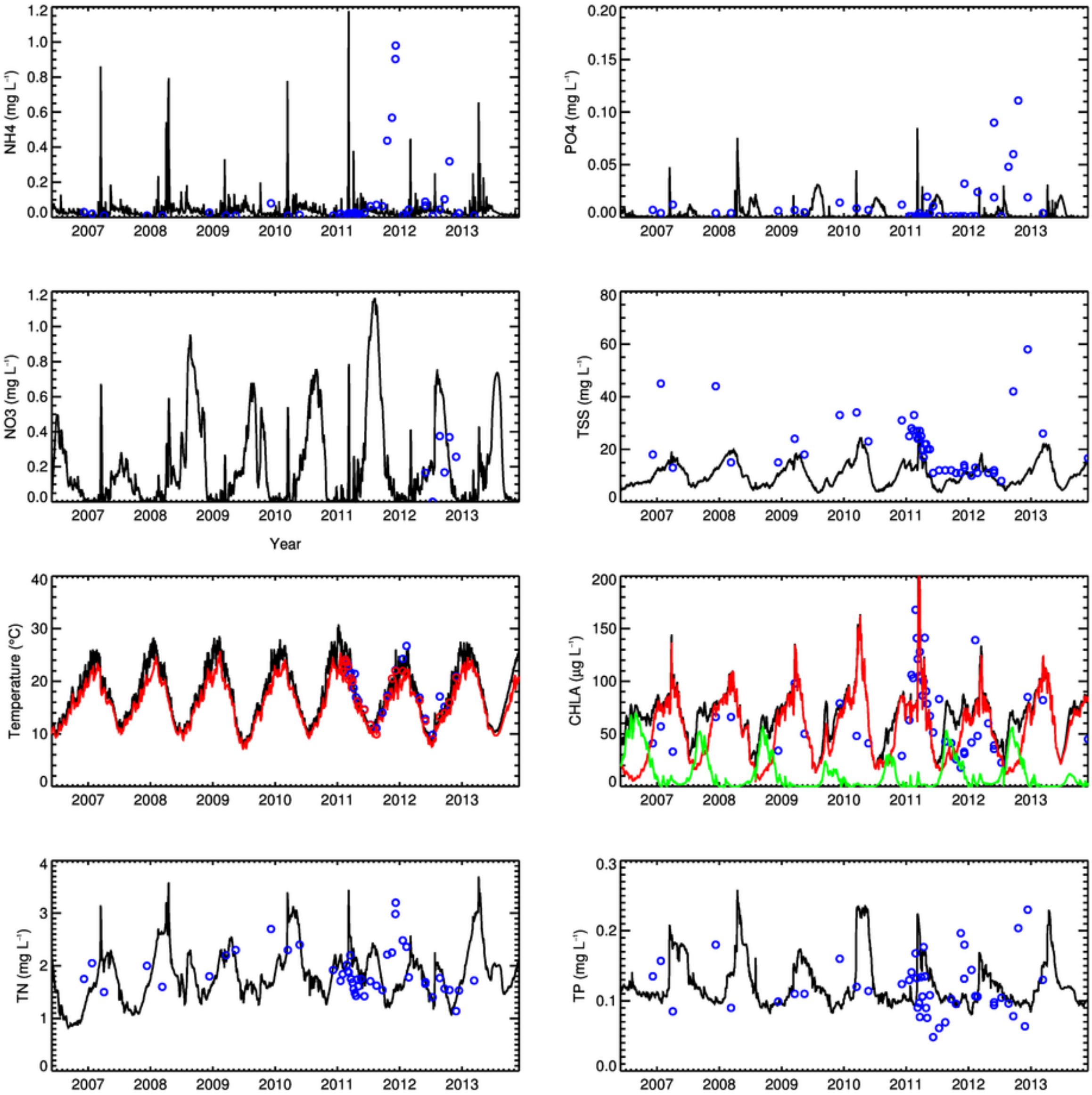


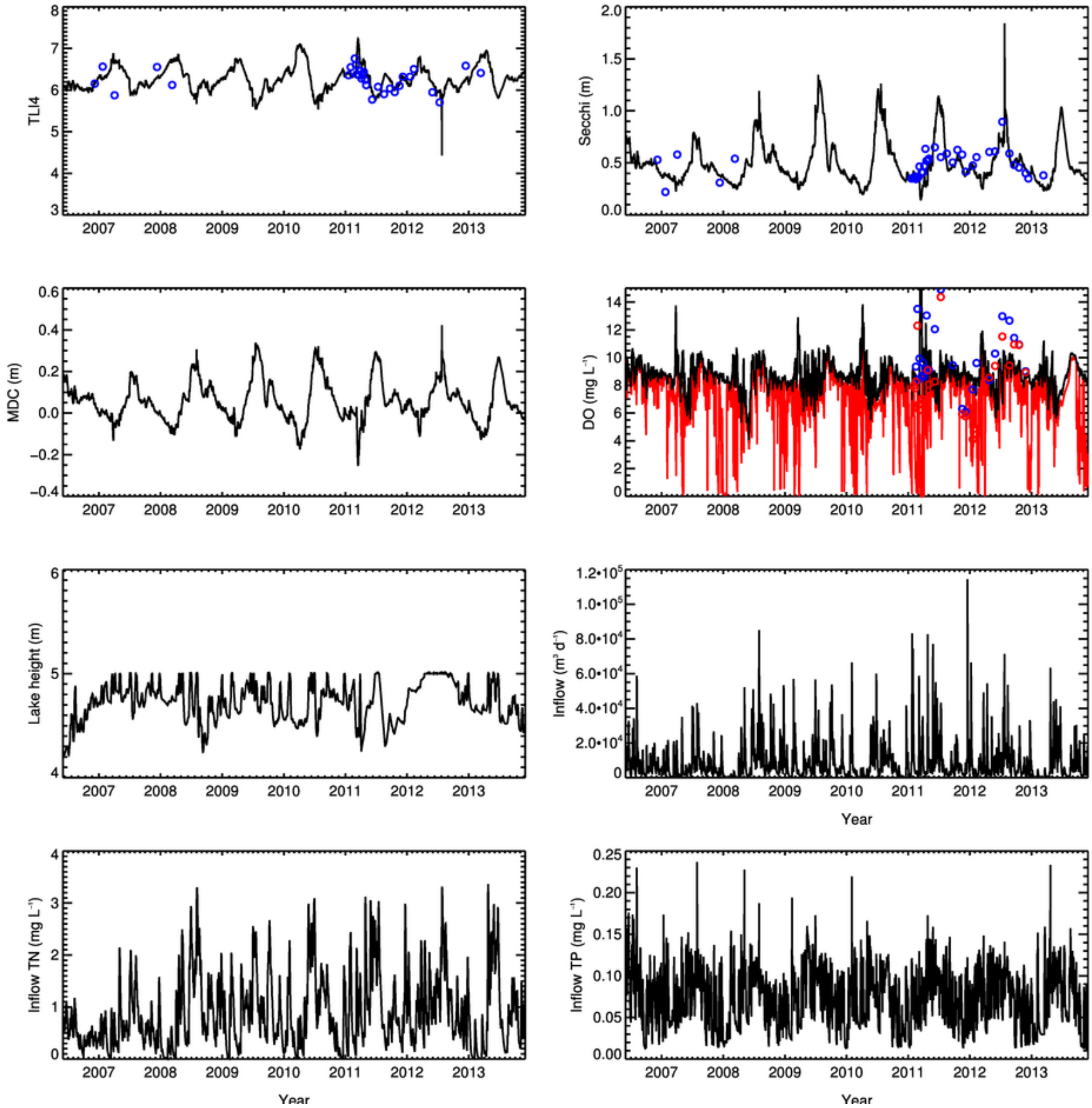
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
Year
TSS (mg L⁻¹)
Temperature (°C)
CHLA (µg L⁻¹)
TN (mg L⁻¹)
TP (mg L⁻¹)
2007
2008
2009
2010
2011
2012
2013

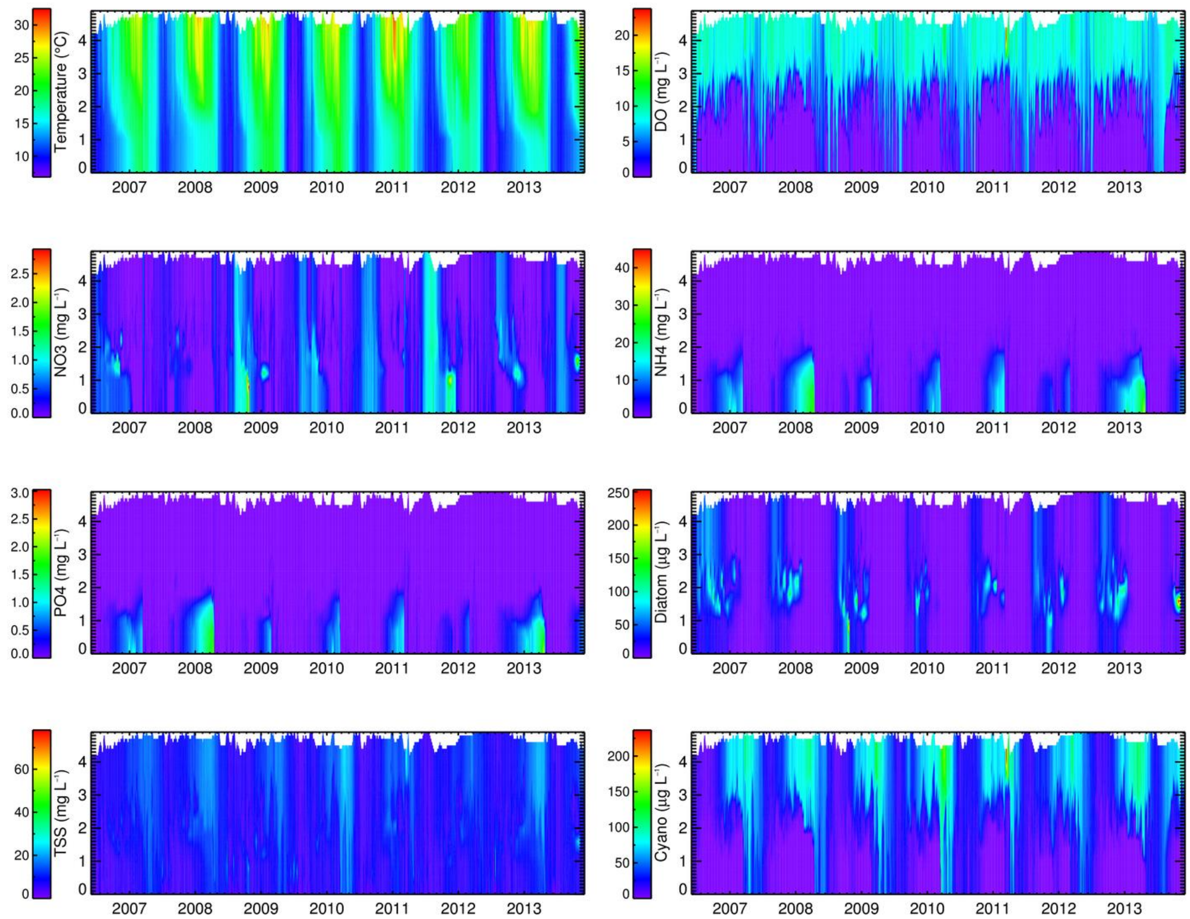

TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
Year


Temperature (°C)
DO (mg L⁻¹)
NO3 (mg L⁻¹)
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
2007
2008
2009
2010
2011
2012
2013

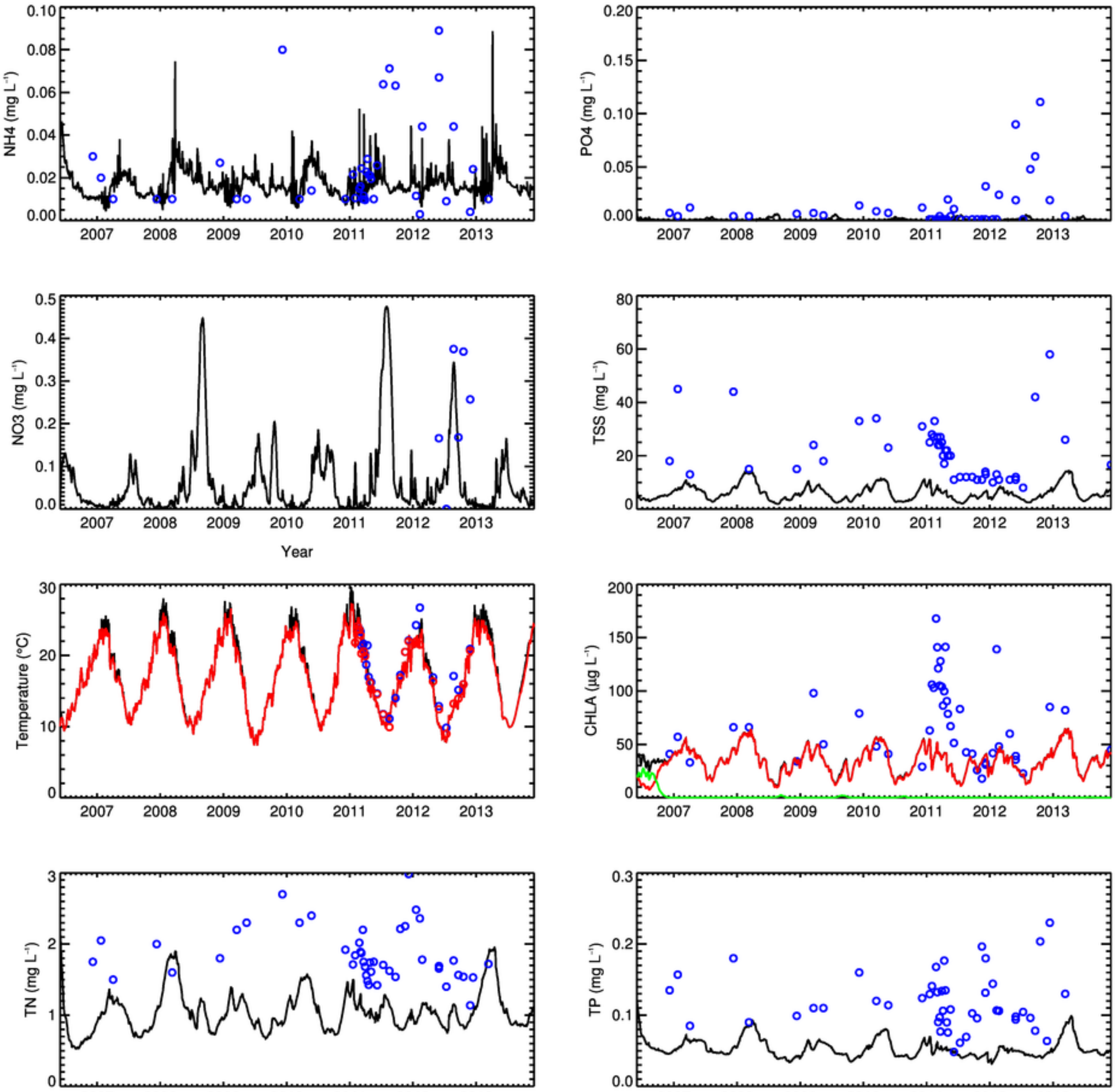
S7NF


NH4 (mg L^{-1})
PO4 (mg L^{-1})
NO3 (mg L^{-1})
Year
TSS (mg L^{-1})
Temperature (°C)
CHLA (µg L^{-1})
TN (mg L^{-1})
TP (mg L^{-1})
2007
2008
2009
2010
2011
2012
2013

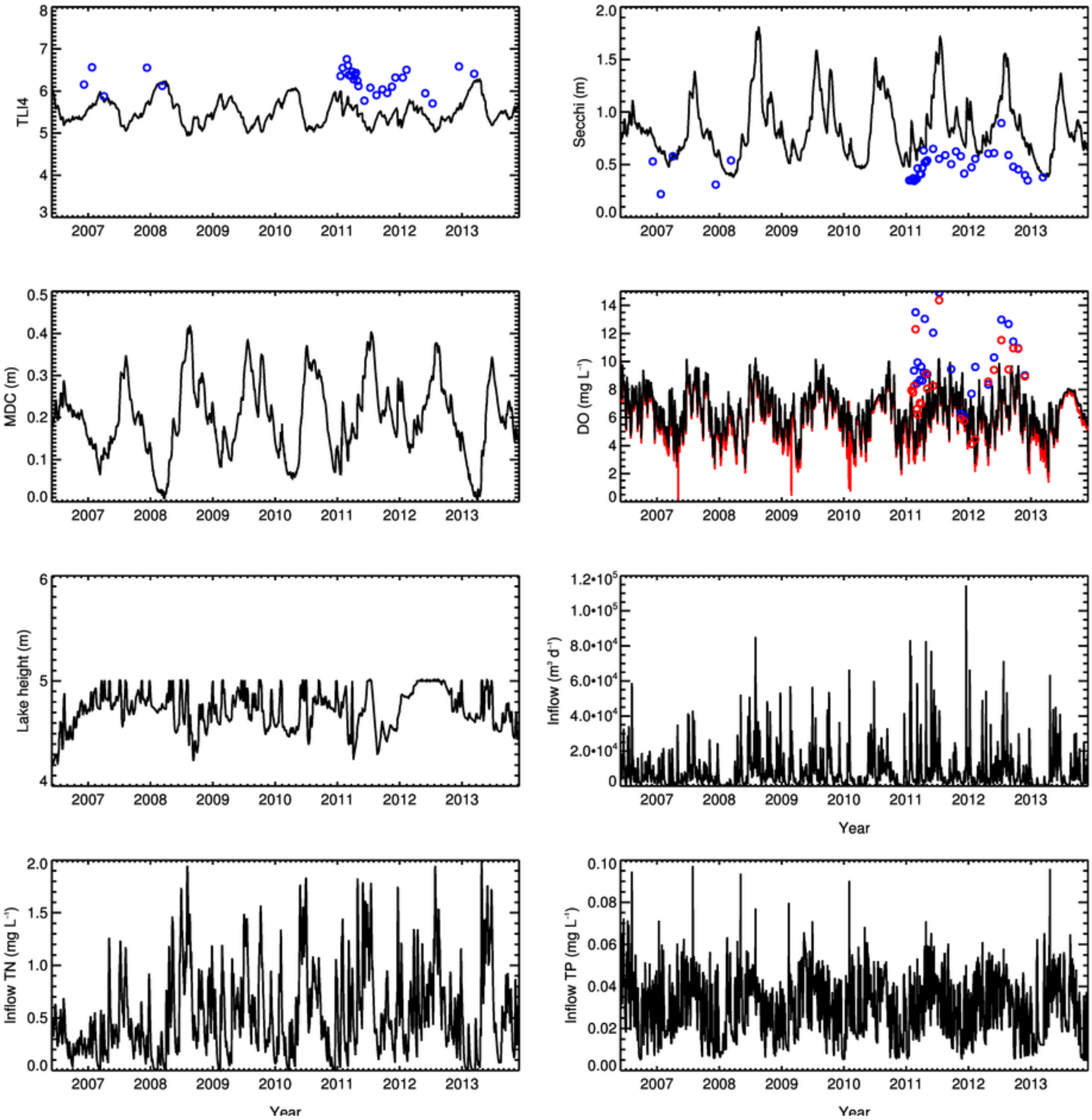

TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
Year
2007
2008
2009
2010
2011
2012
2013

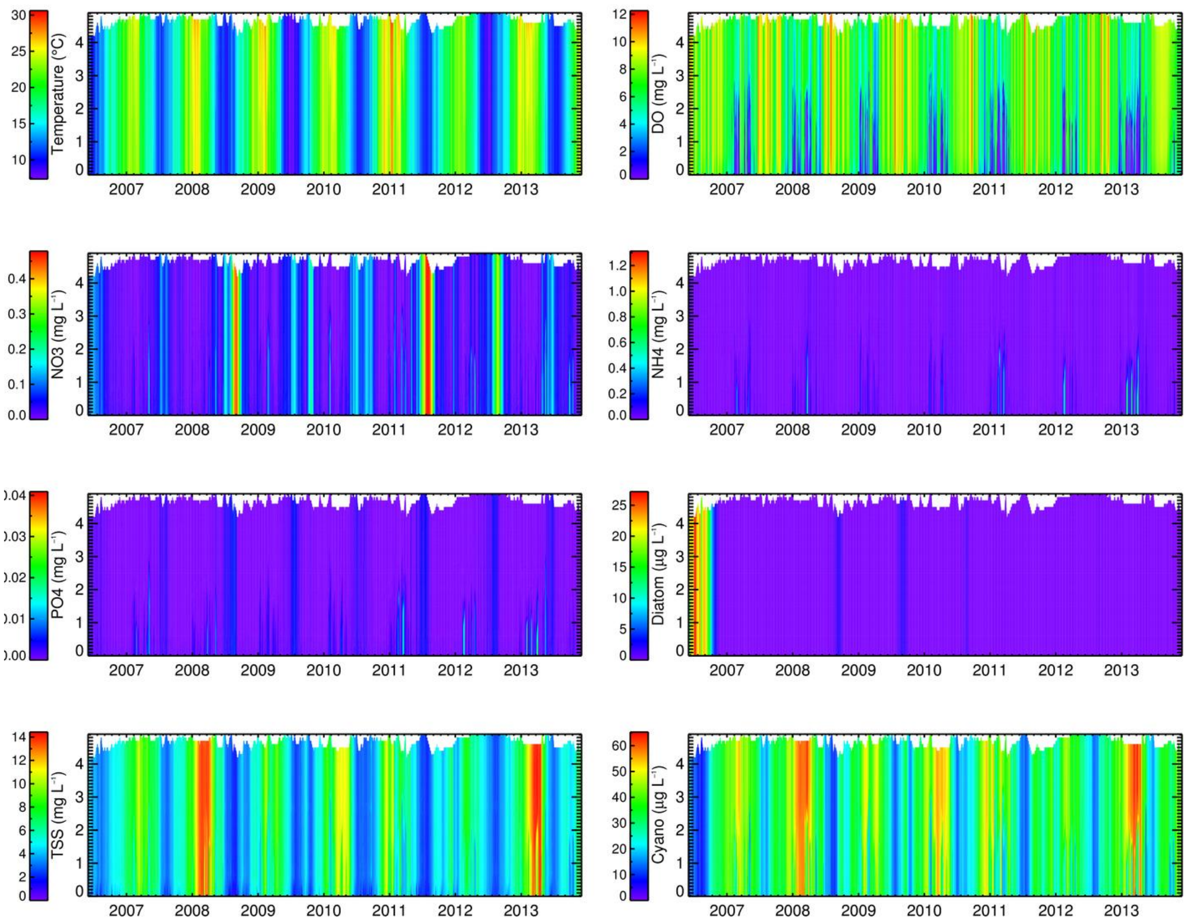

Temperature (°C)
DO (mg L⁻¹)
NO3 (mg L⁻¹)
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
Diatom (µg L⁻¹)
TSS (mg L⁻¹)
Cyano (µg L⁻¹)
2007 2008 2009 2010 2011 2012 2013

S8NF

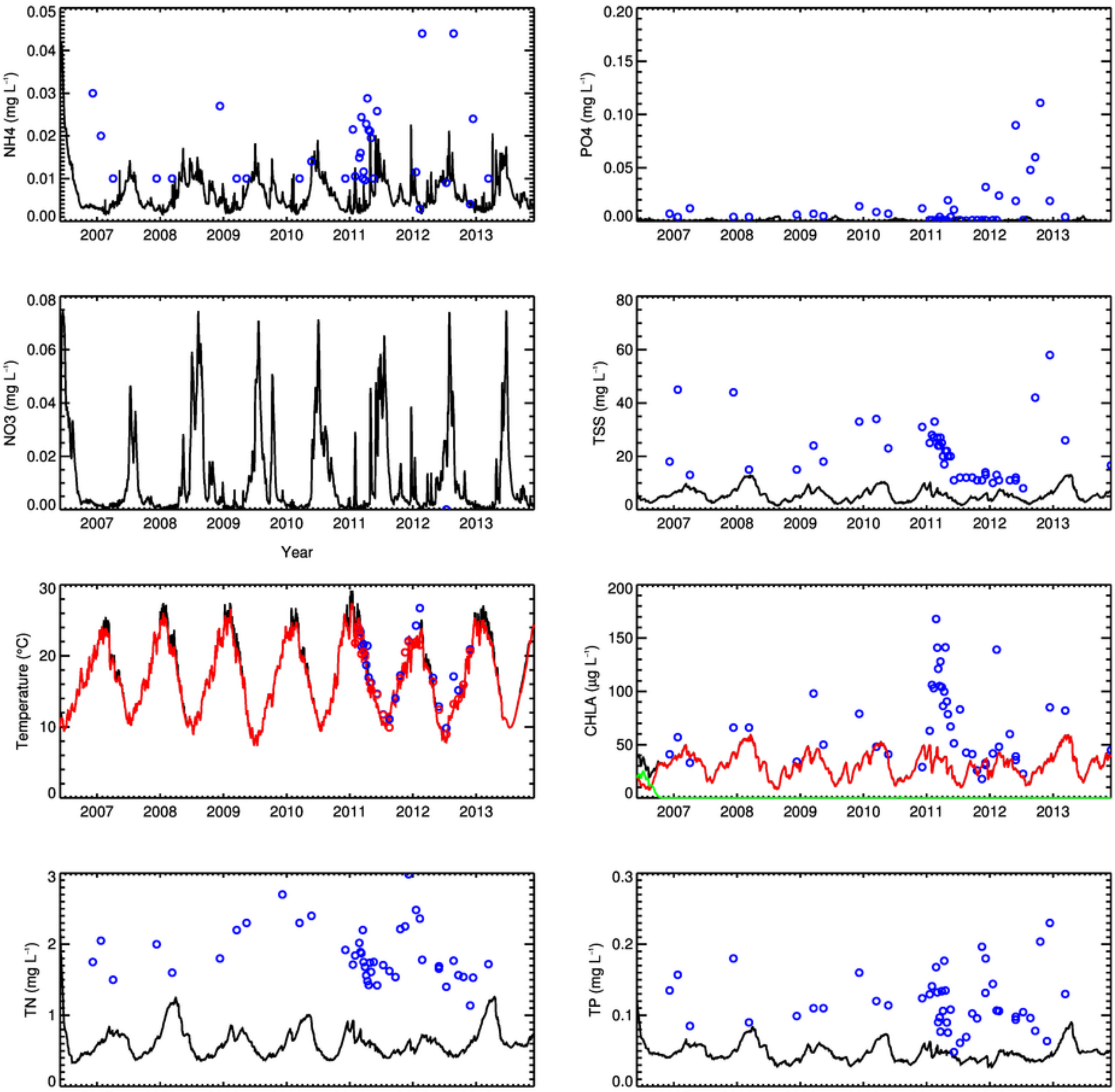


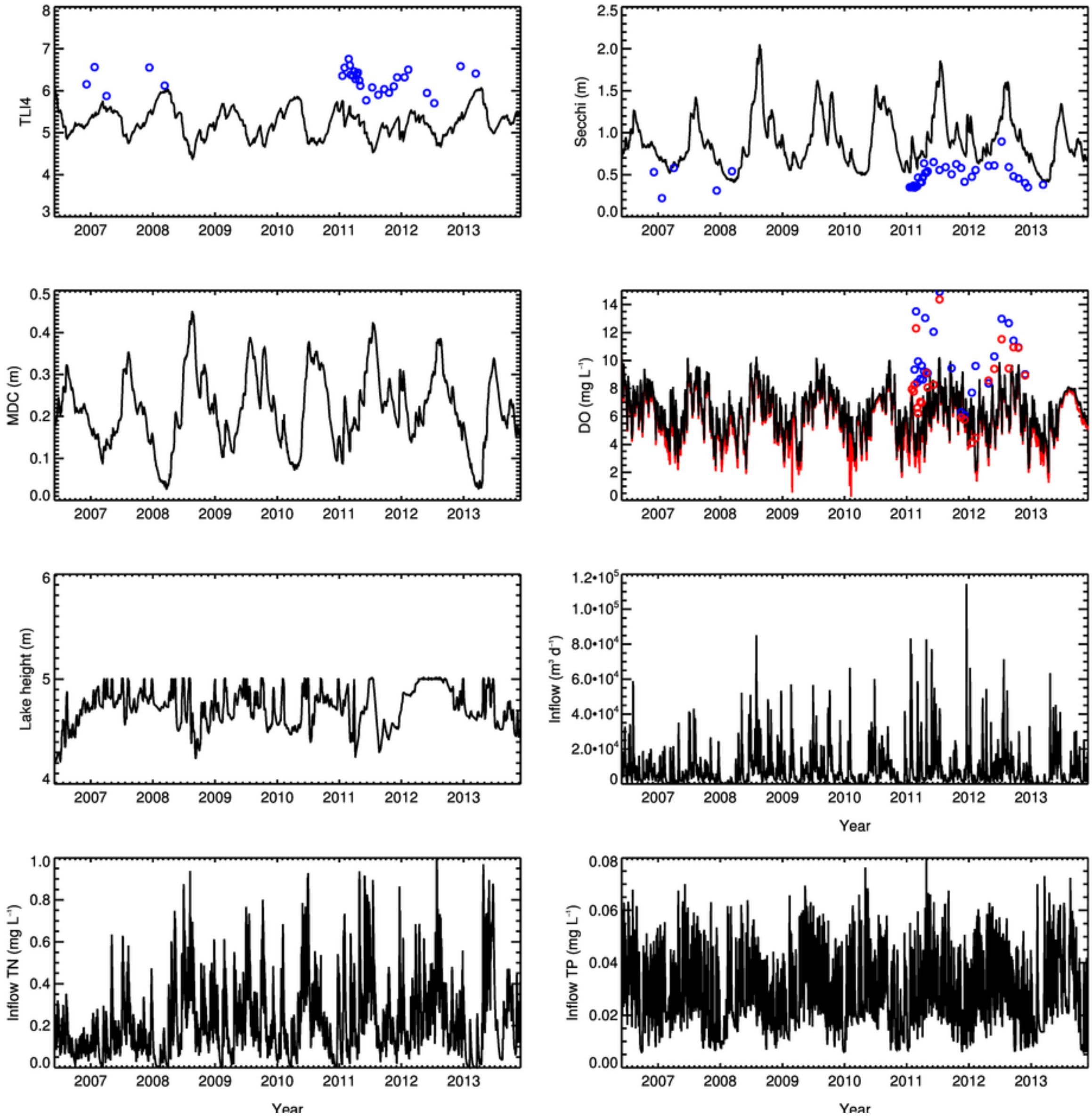
NH4 (mg L⁻¹)
PO4 (mg L⁻¹)
NO3 (mg L⁻¹)
TSS (mg L⁻¹)
Year
Temperature (°C)
CHLA (µg L⁻¹)
TN (mg L⁻¹)
TP (mg L⁻¹)
2007 2008 2009 2010 2011 2012 2013

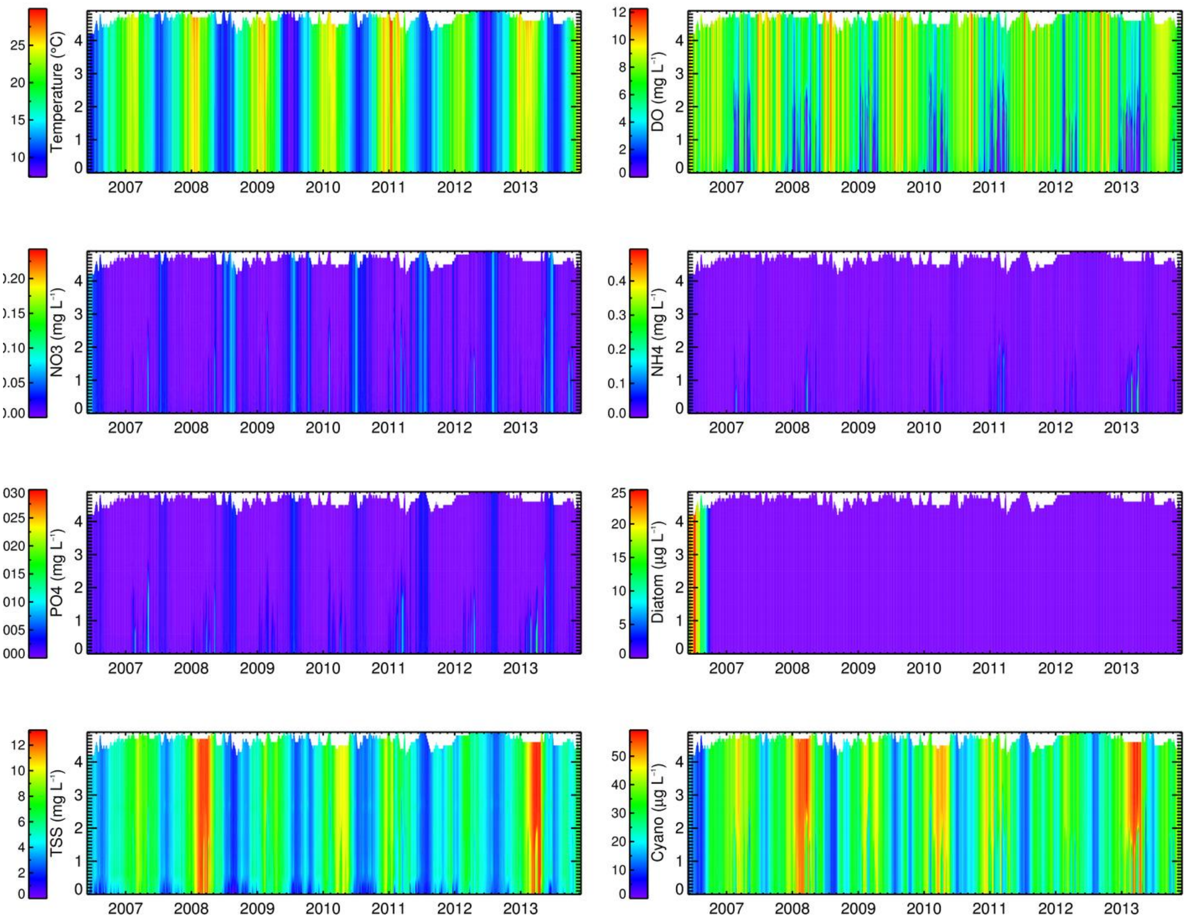

TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
Year


Temperature (°C)
DO (mg L^{-1})
NO3 (mg L^{-1})
NH4 (mg L^{-1})
PO4 (mg L^{-1})
Diatom (µg L^{-1})
TSS (mg L^{-1})
Cyano (µg L^{-1})
2007
2008
2009
2010
2011
2012
2013

S9NF


NH4 (mg L⁻¹)
0.05
0.04
0.03
0.02
0.01
0.00
PO4 (mg L⁻¹)
0.20
0.15
0.10
0.05
0.00
NO3 (mg L⁻¹)
0.08
0.06
0.04
0.02
0.00
Year
TSS (mg L⁻¹)
80
60
40
20
0
Temperature (°C)
30
20
10
0
CHLA (µg L⁻¹)
200
150
100
50
0
TN (mg L⁻¹)
3
2
1
0
TP (mg L⁻¹)
0.3
0.2
0.1
0.0
2007
2008
2009
2010
2011
2012
2013


TLI4
Secchi (m)
MDC (m)
DO (mg L⁻¹)
Lake height (m)
Inflow (m³ d⁻¹)
Inflow TN (mg L⁻¹)
Inflow TP (mg L⁻¹)
2007
2008
2009
2010
2011
2012
2013
Year


Temperature (°C)
DO (mg L-1)
NO3 (mg L-1)
NH4 (mg L-1)
PO4 (mg L-1)
Diatom (µg L-1)
TSS (mg L-1)
Cyano (µg L-1)
2007
2008
2009
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2012
2013