MODELING IMPACTS OF EUTROPHICATION AND CLIMATE CHANGE IN LAKE EYMİR USING PCLAKE MODEL

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ESRA KUZYAKA

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
BIOLOGY

SEPTEMBER 2015

Approval of the thesis:

MODELING IMPACTS OF EUTROPHICATION AND CLIMATE CHANGE IN LAKE EYMİR USING PCLAKE MODEL

submitted by **ESRA KUZYAKA** in partial fulfillment of the requirements for the degree of **Master of Science in Biology Department, Middle East Technical University** by,

Prof. Dr. Gülbin Dural Ünver _____
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Orhan Adalı _____
Head of Department, **Biology**

Prof. Dr. Meryem Beklioğlu
Supervisor, **Biology Dept., METU** _____

Examining Committee Members:

Prof. Dr. Ayşen Yılmaz _____
Institute of Marine Sciences, METU

Prof. Dr. Meryem Beklioğlu _____
Biology Dept., METU

Assoc. Prof. Dr. C. Can Bilgin _____
Biology Dept., METU

Assist. Prof. Dr. Arda Özen _____
Forestry Dept., Çankırı Karatekin University

Assoc. Prof. Nusret Karakaya _____
Environmental Engineering, Abant İzzet Baysal University

Date: 14.09.2014

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Esra Kuzyaka

Signature:

ABSTRACT

MODELING IMPACTS OF EUTROPHICATION AND CLIMATE CHANGE IN LAKE EYMİR USING PCLAKE MODEL

Kuzyaka, Esra
M.S., Department of Biology
Supervisor: Prof. Dr. Meryem Beklioğlu

September 2015, 92 Pages

The earliest studies in Lake Eymir showed that the lake used to be in a clear water state with submerged and emergent plants; however 25 years of raw sewage effluent led to eutrophication of the lake. Therefore, restoration measures were carried out including diversion of the sewage effluent and biomanipulation and Lake Eymir is the first well-known successfully biomanipulated freshwater lake of Turkey. Although raw sewage effluent was diverted and the external nutrient loading was reduced, Lake Eymir still suffers from internal phosphorus loading coming from the sediment. Additionally, climate change projections are expected to complicate the water quality of the lake in the future as higher temperatures can lead to lower water levels, higher nutrient concentrations and more cyanobacteria blooms.

In this study, the aim was to understand the possible responses of Lake Eymir to nutrient loading increase and decrease scenarios, and water temperature increase scenarios using the *PCLake* lake ecosystem model. The model was calibrated (2001-2005) and validated (2006-2010) for five variables (i.e. chlorophyll *a*, PO_4 and total phosphorus, NO_3–N, NH_4–N and zooplankton biomass). Most of the variables were adequately calibrated and validated (i.e. PO_4 and total phosphorus, chlorophyll *a* and zooplankton biomass), while the other variables (i.e. NH_4–N and NO_3–N) were underestimated.

According to the tested scenario runs both nutrient and climate scenarios showed significant differences compared to baseline simulation for all of the variables. Nutrient scenario results showed that Chl *a*, P and N increased and decreased when nutrient loading was increased and reduced respectively and were in agreement with the other studies. The water temperature scenario results, on the other hand, showed increases in Chl *a* with increasing temperature, but decreases in P and N concentrations which differed from predictions in the other model studies. Reasons for that might be the lake's relative deepness and stratification; and uncertainty issues of the model. With the model it was observed that increasing nutrient load and water temperature lead to eutrophication of the lake.

Key words: PCLake, nutrient load, climate change, eutrophication, water level change

ÖZ

ÖTROFİKSYON VE İKLİM DEĞİŞİKLİĞİ ETKİLERİNİN PCLAKE MODELİ KULLANILARAK EYMİR GÖLÜNDE MODELLENMESİ

Kuzyaka, Esra
Yüksek Lisans, Biyoloji Bölmü
Tez Yöneticisi: Prof. Dr. Meryem Beklioğlu

Eylül 2015, 92 Sayfa

Eymir Gölünde yapılan ilk çalışmalar gölün berrak su durumunda olduğunu ve suiçi bitkilerine sahip olduğunu göstermektedir, ancak 25 yıl boyunca evsel atık sularının arıtılmadan göle verilmesi gölün ötrofikleşmesine sebep olmuştur. Bu sebeple arıtılmamış evsel atık suyunun uzaklaştırılması ve biyomanipülasyonla gölü iyileştirme çalışmaları başlatılmıştır ve Eymir Gölü Türkiye'nin başarılı bir biyomanipülasyon geçirmiş ilk tatlısu gölüdür. Evsel atık su uzaklaştırılması ve dışarıdan besin tuzu yüklemesi azaltılmasına rağmen, Eymir Gölü halen göl çökelinden fosfor salınımına maruz kalmaktadır. Ayrıca, iklim değişikliği senaryolarına göre artan su sıcaklığının su seviyesinde düşüşe, besin tuzu yoğunluğu artışına ve alg patlamasına sebep olması ve göl suyu kalitesini bozması öngörülmektedir.

Bu çalışmanın amacı Eymir Gölü'nün artan ve azalan besin tuzu yüklemesine ve artan su sıcaklığı senaryolarına gösterebileceği olası tepkileri göl ekosistem modeli *PCLake* kullanarak anlamaktır. Bu model beş değişken için (klorofil a, PO_4, toplam fosfor, NO_3–N, NH_4–N ve zooplankton biyokütlesi) 2001-2005 yılları arası için kalibre edilip 2006-2010 yılları arası için doğrulandı. Pek çok değişken yeterli oranda kalibre edilip doğrulandı (PO_4, toplam fosfor, klorofil a ve zooplankton biyokütlesi) ancak diğer değişkenler gözlenen değerlerine göre daha düşük simüle edildi (NO_3–N, NH_4–N).

Test edilen seneryo sonuçlarına göre hem besin tuzu hem de su sıcaklığı senaryoları bütün değişkenler için referans simülasyonuna göre anlamlı farklılıklar göstermiştir. Besin tuzu senaryo sonuçları klorofil a, fosfor ve azotun besin tuzu artışıyla artıp azalışıyla azaldığını gösterip bu sonuçlar literatürdeki diğer çalışmalarla örtüşmektedir. Diğer taraftan, literatürdeki çalışmalardan farklı olarak, su sıcaklığı senaryo sonuçları artan sıcaklıkla klorofil a'nın artıp fosfor ve azotun azaldığını göstermektedir. Bunun nedenleri, Eymir Gölü'nün derin bir göl oluşu, gölde tabakalaşma görülmesi ve modelden kaynaklı belirsizlikler olabilir. Çalıştırdığımız bu modelle artan besin tuzu ve su sıcaklığının gölün ötrofikleşmesine sebep olduğu görülmektedir.

Anahtar kelimeler: PCLake, besin tuzu yüklemesi, ötrofikasyon, su seviyesi değişimi

To my family

ACKNOWLEDGEMENT

I want to offer my gratitude to Prof. Dr. Meryem Beklioğlu. You have accepted and encourage me during my Master education and thesis processes. The things I learned from you, both academic and social, cannot be underestimated. Also, I visited Denmark as an ERASMUS student for learning modeling thanks to you.

I am grateful for being among Limnology group. All of them are great friends and they are open to share their knowledge and experiences. A special thank is for Jan Coppens, Tuba Bucak, Eti Levi, Zeynep Ersoy and Gizem Bezirci for always being there for me, solving my endless questions and guiding me through this process. I am grateful to Eylül Şen, Duygu Tolunay, Ali Serhan Çağan, Uğur Işkın, Nur Filiz, Nihan Yazgan Tavşanoğlu and İdil Çakıroğlu and Elçin Çalışkan. I have learned so much from them. Also, all the available data was collected thanks to Limnology family. They have been patiently doing fieldwork and laboratory analysis and the monitoring data have been growing. Starting from 1997, everyone that has ever come to study in this family had their hard work on establishing Lakes Eymir and Mogan dataset.

For everyone that has stood by me: Mert Elverici, Duha Alioğlu, Cemre Topcu, Betül Hız, Esra Önen, my aunt Hicran Kurtuluş and my siblings. Also, to my father and my deceased mother. Every one of these people and others that I cannot put their names in has built me for who I am today, thanks for being there.

I would like to offer my gratitude to Melike Dönertaş and Olcay Özdemir for their help on my statistical questions.

Kind regards to Dennis Trolle and his team; Jan Janse and Wolf Mooij and their team for giving me another perspective and for reshaping my thoughts for *PCLake* model.

I kindly offer my regards to my examining committee members for their time and patience.

This study was supported by METU Office of Scientific Research Projects Coordination (project no: BAP-07-02-2014-007-017).

TABLE OF CONTENTS

LIST OF TABLES

TABLES

LIST OF FIGURES

FIGURES

LIST OF ABBREVIATIONS

TP	Total Phosphorous
Chl *a*	Chlorophyll a
TN	Total Nitrogen
N	Nitrogen
P	Phosphorous
DIN	Dissolved Inorganic Nitrogen
RMSE	Root Mean Square Error
IPL	Internal Phosphorus Loading

CHAPTER 1

INTRODUCTION

1.1 Ecology of Shallow Lakes

Freshwaters are crucial for the establishment of any human community and for the conservation of all land based wild life. Most of the world's freshwater areas are shallow and consisted of small individual lakes dominated by mostly littoral communities. Those littoral areas are more productive per unit area of water than deep ones and more versatile for the uses to which they have been put up to (Moss, 1998).

Lakes can typically be found in one of two alternative states: clear water state and turbid water state. Clear-water state is submerged plant dominated due to low nutrient loading, whereas turbid water state is phytoplankton and suspended solid dominated due to high nutrient loading (Scheffer et al. 1993). Lakes might switch to turbid state when nutrient loads (Beklioğlu et al. 2000; Özen et al. 2010), phytoplankton biomass, or benthi-planktivorous fish (Beklioğlu et al. 2000; Beklioğlu et al. 2003) increase. Also, decreasing water levels causes nutrient concentrations to increase and size of zooplanktons to decrease (Beklioğlu et al. 2003). When lakes became turbid, additional nutrient load reduction below the critical threshold is necessary to enable vegetation recolonization (Scheffer et al. 1993). This switch between states is often referred as "regime shift". Not only nutrient loading but also disturbances to the ecosystem can stimulate the transition between those two states (Scheffer et al. 1993).

1.2 Eutrophication and Restoration

During the past century, increased urbanization and sewage disposal, regulation of wetlands and streams, and more intensive crop and animal farming practices had increased the amount of nutrients, especially nitrogen and phosphorus (N and P, respectively) loading to many shallow lakes causing a world-wide problem of eutrophication (Jeppesen 1998). Eutrophication of shallow lakes may result in deterioration of water clarity and loss of ecological and conservation values through the disappearance of submerged plants, predatory fish and waterfowl (Scheffer et al. 1993; Moss et al. 1996; Jeppesen et al. 2003). Since the integrity of the whole system is quite crucial for maintaining the values for nature conservation and people, the results of eutrophication can be quite catastrophic for lake ecosystems as high algal biomass often accompanied by massive summer blooming of cyanobacteria or green algae, few submerged macrophytes, dominance of planktibenthivorous fish and low water clarity (Moss, 1998). Moreover, feeding behavior of benthivorus fish (carp and bream) might deteriorate the ecological value and water quality of shallow lakes as well since they feed from the bottom of the lake and cause resuspension of the sediment (Beklioğlu et al. 2000).

According to Jeppesen et al. (2007), nutrient levels were reduced mostly due to improved sewage treatment and possibly reduced fertilization in the catchment for Lake Arreso, Denmark, and there were significant improvements in total nitrogen (TN), total phosphorus (TP), chlorophyll *a* (Chl *a*) levels and biotic life. However, in warmer lakes, restoration is a complex process due to higher productivity and abrupt water level changes in Mediterranean climate (Jeppesen et al. 2007; Beklioğlu & Tan, 2008). Moreover, nutrients stored in lake sediment may complicate lake restoration due to internal phosphorus loading (IPL) by having low concentrations of P in the water column triggers the P release from the sediment (Sondergaard et al. 1999).

During the past 30 years, several countries have put on a great effort to improve the ecological quality of lakes by combating external loadings (Sas, 1989), sometimes with using additional restoration measures such as biomanipulation (Hansson et al., 1998; Meijer et al., 1999; Beklioğlu et al., 2003). Eventhough, some lakes showed resistance to recovery due to their complex food web interactions, suspended solid or Chl *a* concentrations; top-down control in the food web is usually applied as a restoration measure. Reduction of benthivorous and zooplanktivorous fish reduces the effects of suspended matter and predation pressure on zooplankton (Beklioğlu et al. 2000; Jeppesen et al. 2007). This can be followed after sewage effluent reduction in order to enhance large zooplanktons like *Daphnia*, since they are essential for lake ecosystems through grazing on phytoplankton and promoting water clarity. To overcome the biological resilience, planktibenthivorous fish removal has been widely applied in north temperate lakes with some success (Hansson et al. 1998, Mehner et al. 2002, Gulati & Van Donk 2002), whereas the success of this method has been debatable in warm temperate and subtropical lakes (Scasso et al. 2001, Beklioğlu et al. 2003, Beklioğlu & Tan, 2008; Jeppesen et al. 2005). However, trophic structure varies among warm lakes depending on whether they are located in dry or wet and low or high altitudes. For example; whole lake fish removal study that carried out in a semi-dry high altitude shallow Mediterranean lake (i.e. Lake Eymir) successfully initiated a clear-water state (Beklioğlu et al. 2003).

1.3 Lake Modeling

The need for predictive water quality modeling had arisen largely as a result of increased eutrophication of lakes throughout the world (Forsberg, 1987; Canfield & Hoyer, 1988). When future climate change scenarios are considered, modeling is a valuable tool to predict lake's response to the environmental changes. There are numerous lake models, varying from very simple models to very complex ones. Lake models can be in 0-dimension (0D), 1-dimension (1D), 2-dimension (2D), or 3-dimension (3D) (Mooij et al.

2010, Trolle et al. 2012). The most common modeling approach is exemplified by the development and application of steady state, input-output models. Ecological water quality modeling, specifically addresses many of the biological and chemical factors that are absent in the simple input-output models. This approach has evolved in order to obtain a more fundamental understanding and representation of the major physical, chemical and biological processes that affect the biomass of phytoplankton and higher trophic levels of lake ecosystems. However, calibration of the model is influenced by its complexity (Mooij et al. 2010). Good fit of observations to simulation of the calibrated model is crucial to conclude that the model can represent the real lake system.

1.4 The *PCLake* Model

PCLake is an ecological model that combines the food web with nutrient cycling and integrates bottom-up and top-down effects in a lake ecosystem (Janse et al. 1995). The model is a 0-D model which neglects the vertical and horizontal variation in lakes and is suitable for shallow and non-stratified lakes. The model describes phytoplankton, macrophytes and a simplified food web, within the framework of closed nutrient cycles. The model is mainly developed for investigating the probability of a shift from the vegetation-dominated clear-water state to the phytoplankton-dominated turbid state, or vice versa, considering the external nutrient loading, water temperature and other factors (i.e. biotic environment, wind speed, biomanipulation) (Mooij et al. 2010, Janse 2005). Moreover, *PCLake* has been used for climate change studies (Mooij et al. 2010, Trolle et al. 2015, Nielsen et al. 2014).

PCLake describes a completely mixed water body and comprises both the water column and the sediment top layer (10 cm), using the most important biotic and abiotic components (Janse, 1997; Mooij et al. 2010). General processes in *PCLake* include mineralization, nitrification, denitrification, phosphorus absorption, exchange of nutrients and settling of phytoplankton and detritus. The model comprises both the water

column and upper sediment layer (Janse et al. 1998). In the model, primary production is described as two modules (i.e. phytoplankton and macrophytes). Food web is also kept as simple as possible and it comprises zooplankton, macrozoobenthos, whitefish and predatory fish (Janse, 2005). The model is designed to simulate effects of biomanipulation and food web structure on nutrient cycle (Janse, 1997; Janse et al. 1998). It includes food web relations with empirical relations (i.e. the dotted lines in Figure 1) (Janse et al. 1995). Janse et al. (2008) showed that within the model, hydraulic loading rate, water depth, fetch, N/P ratio, marsh area (adjacent to lake), sediment type and fishery rate have different impacts on critical nutrient load. Although the model contains many of the processes and parameters of a natural lake ecosystem, it still represents a simple form of a real ecosystem.

PCLake inputs include radiation ($J/m^2/day$), evaporation (mm/day), inflow (mm/day), outflow (mm/day), wind speed (m/s), water temperature (ºC), and PO_4, organic phosphorus, NH_4, NO_3, organic nitrogen loads ($g/m^2/day$) and fish harvesting rate (day^{-1}), while the model outputs and the interactions in the food web were summarized in Figure 1. *PCLake* gives outputs on a number of state variables from both the sediment and the water body. The condition of a lake, represented by these variables, and changes might happen depending on the external forcing (i.e. external nutrient loads, biotic environment, physical changes or temperature).

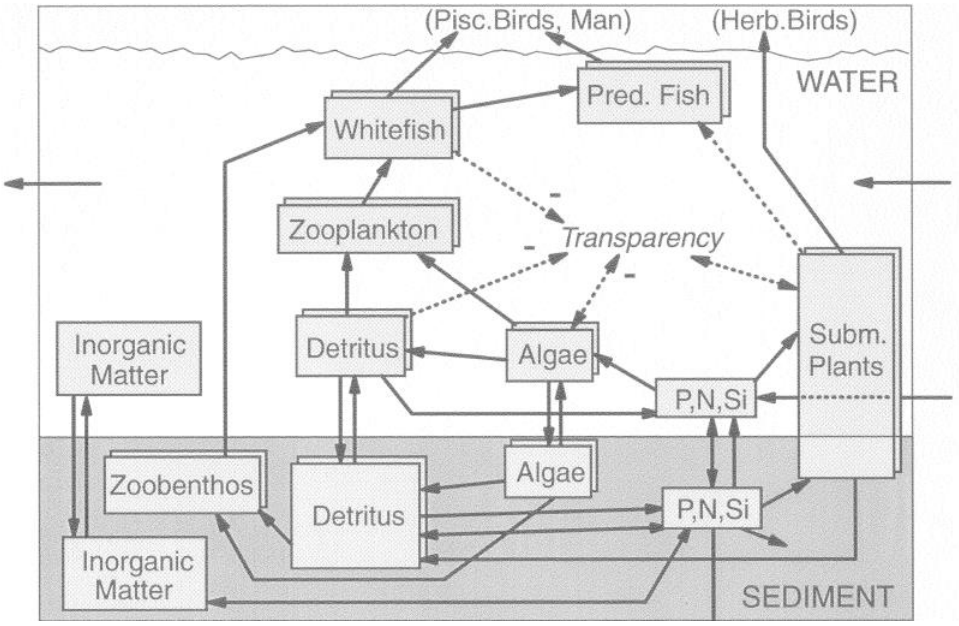

Figure 1: The *PCLake* Model Structure: The boxes in the figure represent the *PCLake* output data. Doubled blocks represent compartments modelled in both dry weight and nutrient units. In *PCLake* three functional groups of phytoplankton, namely cyanobacteria, diatoms and small edible algae, and two whitefish groups are considered that are juvenile (zooplanktivorous) and adult (benthivorous). Solid arrows denote food relations, broken arrows denote empirical relations and negative sign on broken arrows denotes negative influence, otherwise it is a positive influence (Taken from Janse, 1997).

PCLake was calibrated for lakes in Netherlands, and validated for lakes in Denmark and Spain (Janse, 2005). Scope of the *PCLake* model and possible modifications is given in Figure 2. For example, with *PCLake*, marsh zone can be added to the model, temperature, fish harvest rate, water level or nutrient loads can be modified accordingly.

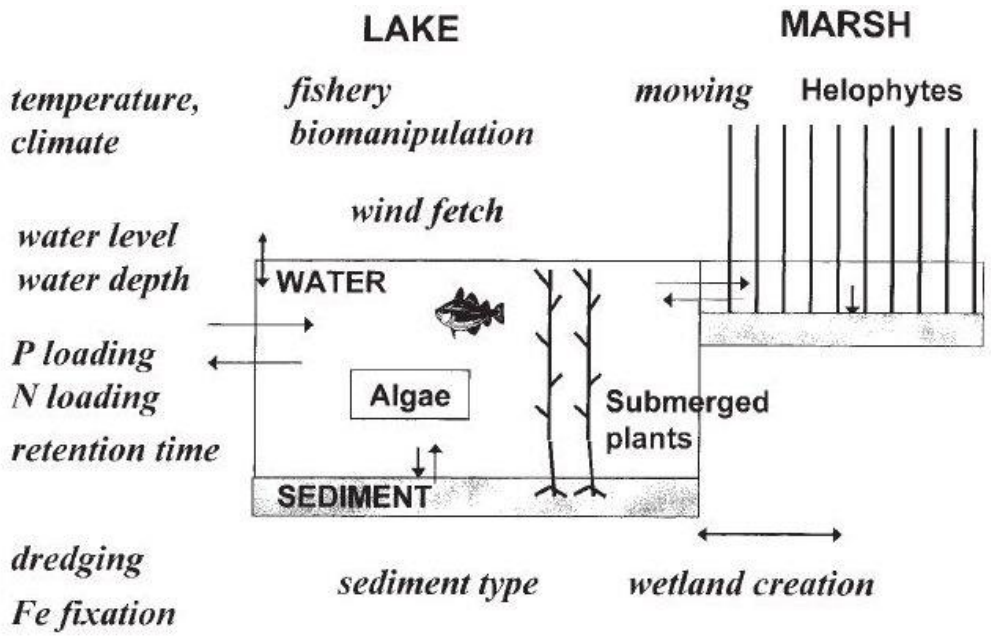

Figure 2: The scope of *PCLake* with the modifications that can be made. Arrows denote transport or exchange of matter between spatial compartments (Taken from Mooij et al. 2010 and Janse, 2005).

1.5 Aim of this study

The study aims to determine the effects of nutrient load change and temperature increase on Lake Eymir ecosystem structure using a model called *PCLake*. The hypothesis of this study is that doubling nutrients in the inflows would have negative effects in the lake ecosystem, while halving nutrients would improve the quality of the ecosystem. Furthermore, water temperature increases would affect Chl *a*, nutrient concentrations and zooplankton biomass since freshwater systems tend to be more fragile with increasing temperature.

CHAPTER 2

MATERIAL AND METHODS

2.1 Study Site

Lake Eymir is located 20 km south of Ankara, Turkey (39° 57’ N, 32° 53’ E). It is a biomanipulated Mediterranean lake with an area of 125 ha. It is relatively shallow with the mean depth of 4.25 meter. In addition, its fetch (estimated from Google Maps) is 500 meters. The lake has two inflows and the major one comes from Lake Mogan, which is located in the upstream of Lake Eymir. Other inflow, Kışlakçı Brook, is a seasonal inflow and it dries up in summer. Figure 3 summarizes the catchment area of lake.

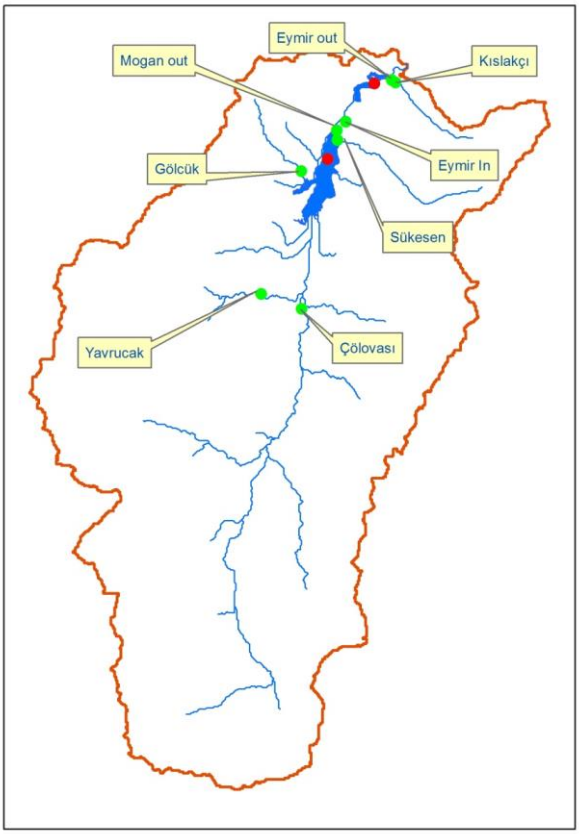

Figure 3: Catchment area of Lake Eymir. Green dots represent the inflow and outflow of the lakes, red dots represent the lakes.

Lake Eymir and Lake Mogan have been sampled fortnightly in spring, summer and fall, and monthly in winter with their inflows and outflows since 1997 by METU Limnology Laboratory (www.bio.limnology.metu.edu.tr). While Secchi depth, light attenuation and maximum depth were measured during the field work, dissolved oxygen concentration, salinity, conductivity, TDS and temperature were measured every half a meter until the bottom of the lake using a YSI multiprobe. Water samples were collected with Ruttner Water Sampler for every half a meter until the bottom of the lake and lake water quality parameters (i.e. Chl *a*, TP, phosphate (PO_4), TN, suspended solids, ammonium (NH_4-N),

nitrite-nitrate (NO_2-N, NO_3-N); and phytoplankton diversity and concentration) were measured from the collected water samples at METU Limnology Laboratory. Table 1 summarizes the monitoring data that were used for calibration of the model.

Table 1: Available data used in this study.

	Chl *a* (mg/m3)	**TP (mg/l)**	**PO_4 (mg/l)**	**NO_3–N (mg/l)**	**NH_4–N (mg/l)**
Number of Data	183	194	193	181	179
Minimum	0.01	0.07	0.00083	0.0004	0.00164
Maximum	98.82	0.69	0.64	1.061	1.76
Mean	17.86	0.29	0.19	0.19	0.28
Years	1998-2010	1998-2010	1998-2010	1998-2010	1998-2010

The water sample was filtered with the 20 μm zooplankton filter and samples were kept in 4% Lugol's solution for zooplankton analysis. Inflow, outflow and flow rates were provided by Electrical Power, Resource Survey and Development Administration (EİE) until 2010; however starting from 2010, METU Limnology Laboratory started to measure flow rates of inflows and outflows by a hand held flow meter. Total nitrogen has been measured since 2007.

The earliest studies conducted in Lake Eymir showed that the lake was in a clear water state with submerged and emergent plants (Geldiay, 1949). Lake Eymir received raw sewage effluent discharge for over 25 years from the city and recreational sites around the lake. As of 1994 the effluent was diverted to İmrahor Valley using a by-pass channel (Beklioğlu et al. 2000). Before the diversion, the effluent running into Lake Eymir was rich in dissolved inorganic nitrogen (DIN) and TP (1.49±0.82 mg l^{-1} and 727±43 mg l^{-1}, respectively) (Beklioğlu et.al. 2003). Figure 4 shows the annual nutrient loads through

inflows and outflows between the years of 1998-2010. As a result of high nutrient loading, the lake shifted from submerged plant dominated state (i.e. clear water state) to phytoplankton dominated state (i.e. turbid water state).

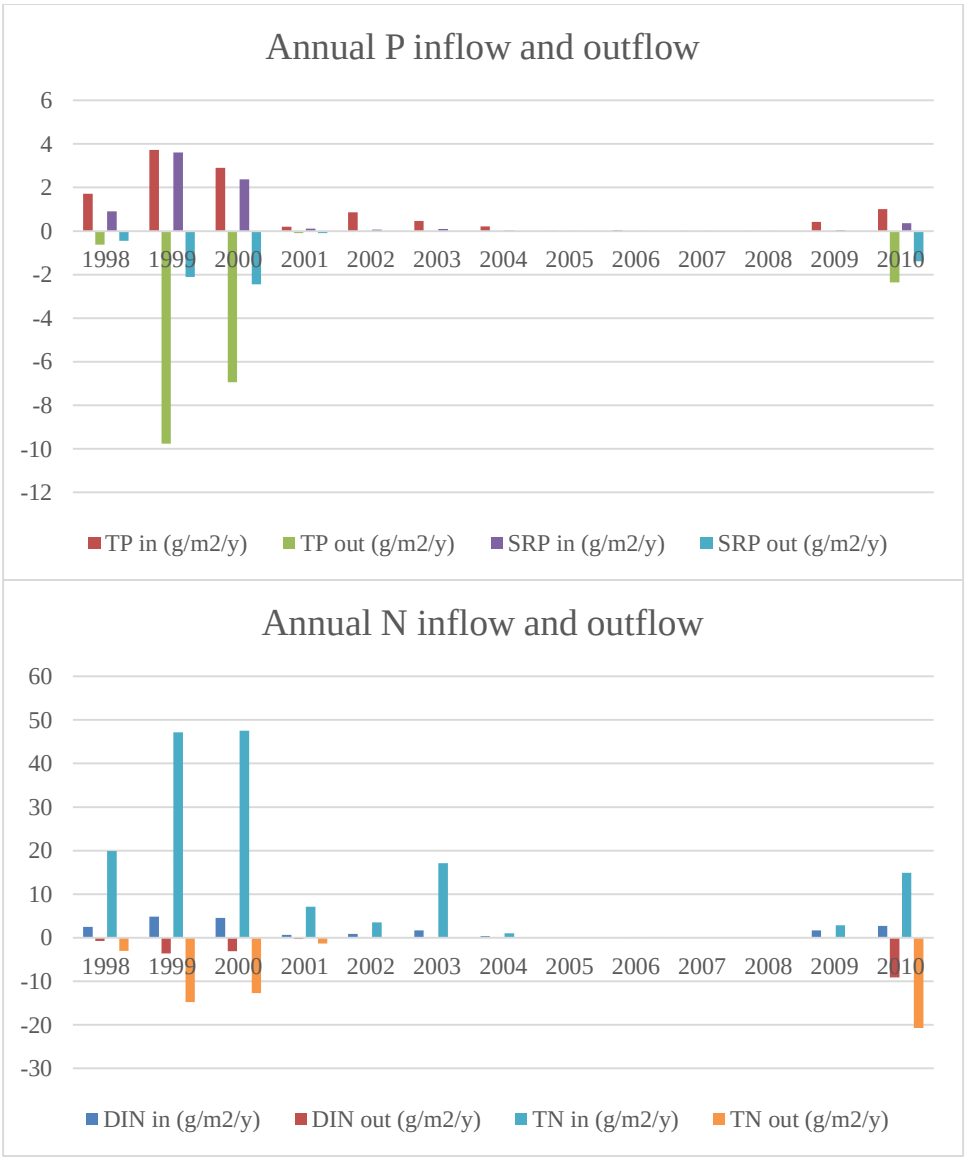

Figure 4: Annual N and P ($g/m^2/y$) loads to the Lake Eymir (inflow) and out of Lake Eymir (outflow). Outflows are denoted as minus values and inflows are denoted as positive values.

2.1.1 Sewege Effluent Diversion and First Biomanipulation of Lake Eymir

Sewage effluent that was discharging to Lake Eymir was successfully diverted in 1995 and the TP loading was decreased to its 88% values and dissolved DIN decreased to its 95%. A succesful biomanipulation was carried out in Lake Eymir (Beklioğlu et al., 2003; Jeppesen et al. 2007). Substantial benthivorous fish removal (57% reduction in the fish stock) initiated a 2.5-fold increase in spring Secchi disk transparency and 4.5 fold decrease in the inorganic suspended solid concentration and Chl *a* were observed, also spring euphotic depth increased from 162 cm to 702 cm (Beklioğlu et al. 2003). Furthermore, fish removal resulted in significant increase in density and size of *Daphnia pulex*, which had a positive impact on controlling phytoplankton growth and suspended solid availability (Beklioğlu et al. 2003). Benthivorous fishes (carp, grass carp) were removed from the lake because they were stirring up the sediment and were increasing the phosphorus levels and suspended matter in the water column (Beklioğlu et al. 2003) and benthi-planktivorous fish had strong predation pressure on the large zooplankton like Daphnia, and lead to high algal biomass and low water clarity (Beklioğlu et al. 2003).

Following biomanipulation, the lake was in a clear water state in 2001 with low water levels, and high submerged macrophytes coverage (90%), however there was an increase in in-lake TP (Tan & Beklioğlu, 2005). In 2004, water level dropped significantly and the in-lake phosphorus concentrations doubled with comparing to 2001 (Beklioğlu & Tan, 2008).

2.1.2 Second Biomanipulation of Lake Eymir

Starting from 2001, deterioration signs were observed in Lake Eymir. For instance, Chl *a* concentration surpassed its pre-biomanipulation levels in 2002 and 2003, suspended solid concentration increased in 2003; therefore, Secchi disk transparency declined. In

2002 submerged plant cover was 60%, whereas in 2003 it dropped to 45%. Furthermore, DIN (mostly ammonium) concentrations increased due to the decrease in summer dissolved oxygen concentrations, especially in the hypolimnion. Moreover, large zooplanktons like *Daphnia pulex* decreased in years 2002 and 2003 and tench biomass was recorded at its pre-biomanipulation levels in 2003 (Beklioğlu & Tan, 2008).

Lake Eymir shifted back to turbid state due to longer hydraulic residence time and low water levels induced by drought (Beklioğlu & Tan, 2008). In response, submerged plant cover decreased, tench and carp biomass increased and pike biomass decreased in 2004. In 2006, second biomanipulation started with removal of tench and carp. The fish removal caused Chl *a* and suspended solid to decrease (2 fold and 1.5 fold, respectively). Furthermore, Secchi disc transparency improved by 50%. However, macrophyte coverage did not change significantly. Although in-lake TP concentrations decreased due to biomanipulation and slight increase in water level, in 2007, when water level of the lake was at its lowest, in-lake TP concentration increased again (Özen at al. 2010). Second biomanipulation lasted for 8 years (2006-2014).

2.2 Model setup for Lake Eymir

Monitoring data was obtained by METU Limnology Laboratory. Hydrological and meteorological data were obtained from the General Directorate of State Hydraulic Works (DSİ), the Electrical Power, Resource Survey and Development Administration (EİE) and the Turkish Meteorological Service. Monitoring data is composed of field studies that has been going on in Lakes Eymir and Mogan since 1997.

Complex models like *PCLake* are usually difficult to calibrate and they can be referred as “data hungry” (Mooij et al. 2010). Firstly, input data were extracted from the available data in this study. The model was initialized with the available data for Lake Eymir made up the default model. Secondly, sensitive parameters were found and they

were used for calibration and validation of the model. After calibration, scenario runs were performed for some possible projections using the model.

Input variables which are available for Lake Eymir are initial water depth, oxygen, nitrate, ammonium, organic nitrogen, phosphorus and organic phosphorus concentrations, N/P ratio, fraction of nutrients (nitrate, ammonium and phosphorus) in inflows, summer and winter inflows, standard water inflow, summer and winter nutrient loading (N and P), standard nutrient loading (N and P), annual average and variations of water temperature, radiation, evaporation, wind speed, N and P loads.

PCLake was built with a main focus on Dutch lakes; therefore the model calibration was needed for the model to represent Lake Eymir. Available Lake Eymir data were implemented as an input to the default model and were given in Table 2. The model also requires first day values of inputs, which are called the state inputs. The state inputs were given in Table 3 and they were based on the data for 01.01.1998. Description of the model parameters were given in Appendix A.

Table 2: The parameters that were set for Lake Eymir.

Id	Parameter Name	Unit	Default
1	EndTime	day	4745
3	ConstDepth	-	0
10	UseWindFunc	-	1
89	cFetch	m	500
93	cLDayAve	$J/m^2/day$	15285478
94	cLDayVar	$J/m^2/day$	8070176
142	cNLoad	$gN/m^2/day$	0.04
144	cNLoadSum	$gN/m^2/day$	0.01

Table 2: continued

Id	Parameter Name	Unit	Default
145	cNLoadWin	$gN/m^2/day$	0.06
148	cNPLoadMeas	gN/gP	12.09
184	cPLoad	$gP/m^2/day$	3.5e-3
185	cPLoadSum	$gP/m^2/day$	7.9e-4
186	cPLoadWin	$gP/m^2/day$	3.9e-3
197	cQEvAve	mm/day	4.81
198	cQEvVar	mm/day	5.58
199	cQIn	mm/day	7.56
203	cQInSum	mm/day	7.78
204	cQInWin	mm/day	7.13
240	cTmAve	^oC	13.64
252	cTmVar	^oC	6.63
270	cVWind	m/s	2.30
323	fNH4DissIn	-	0.06
333	fPO4In	-	0.04
388	kHarvFishSum	-	txt/Biomanip.txt
389	kHarvFishWin	-	txt/Biomanip.txt
461	sDepthW0	m	4.25
480	sNH4W0	mgN/l	0.27
483	sNO3W0	mgN/l	0.25
484	sO2W0	mgO_2/l	6.05
494	cDepthWMax	m	6

Table 3: State inputs with the first day (01.01.1998) values used for the model.

Id	State Name	Unit	Default	Description
11	sDepthW	m	4.25	Water depth
50	sNH4W	mgN/l/d	0.27	Ammonium in water
56	sNO3W	mgN/l	0.25	Nitrate in water
63	sO2W	mgO_2/l	6.05	Oxygen in water
88	sPO4S	gP/m^2	0.18	Pore P
90	sPO4W	mgP/l	0.22	SRP in water

Since Lake Eymir is a biomanipulated lake, biomanipulation was included in the default model set up. The days of biomanipulation were July 1998- January 1999, October 2005- April 2006, February 2007-October 2007, April 2008- November 2008, January 2009 – August 2009 and November 2009 – June 2010. In the set-up, the fish harvest rate was determined by visual calibration. Biomanipulation strength (fish harvesting rate) was set to be 0.007 day^{-1}; meaning 7 fish out of 1000 fishes in the lake were harvested daily. In the literature the same biomanipulation rate was used by Nielsen et al. (2013, 2014).

PCLake was setup for the years 1998-2010 where the first 3 years of the data were used as warm up period to minimize the effects of the uncertainty related to initial conditions due to possible delay in response to parameter set. For the following five years (2001-2005) the model was calibrated based on the observation data, and the next five years (2006-2010) were used to validate the calibrated model.

2.2.1 Sensitivity Analysis and Calibration

To evaluate the model performance; sensitivity analysis and model calibration are crucial. *PCLake* model's default settings were calibrated for 43 lakes including Dutch, Belgian, Irish and Polish lakes and validated for 9 Danish and Spanish lakes (Janse, 2005).

Usually *PCLake* calibration was done by only one set of parameters and this study was no exception. Calibrating one set of parameters at a time was time consuming and very complex process. In order to calibrate a set of parameters, calibration of a parameter and other parameters follow. Constituting one parameter set, lots of interactions occur in the model and the calibration results may change considerably. Months of trying to fit the simulation to observation, the calibration results did not seem to respond well. As one set of parameters for calibration was not enough, a series of parameters were considered and a band of simulations obtained to fit the observation.

First, the default model was set for Lake Eymir using available data, then sensitivity analysis was performed and quantified over PO_4, TP, NO_3–N, NH_4–N and Chl *a* since they are crucial for the model and the lake; also they were monitored throughout the study period.

For sensitivity analysis, each parameter was given two different values: 20% more of the default and 20% less of the default. The reason for keeping the of default values within 20% range is to avoid unrealistic results (Jan Janse, personal communication). The two runs were compared by t-test to see if the means of the runs were significantly different from each other. Table 4 gives the sensitive parameters of the model with their sensitivity levels concerning the variables.

Table 4: Sensitive parameters and their sensitivity levels of the variables. *** denotes high significance ($p<0.001$), ** denotes significance ($p<0.01$), ns means not significant ($p<0.05$).

Parameter name	**Unit**	**Chl *a***	**NH_4-N**	**NO_3-N**	**PO_4**	**TP**
cFiltMax	ltr/mgDW/day	***	ns	ns	**	ns
cMuMaxBlue	day-1	***	***	***	***	***
cMuMaxDiat	day-1	**	ns	ns	***	**
cNDBlueMin	mgN/mgDW	***	***	***	***	***
coPO4Max	mgP/l	ns	ns	ns	***	***
cPDBlueMax	mgP/mgDW	ns	ns	ns	***	***
cPrefBlue	-	***	ns	ns	**	ns
cThetaDif	-	***	**	ns	***	***
cThetaMinS	-	ns	***	***	ns	ns
cThetaMinW	-	ns	**	ns	ns	ns
cThetaNitr	-	***	ns	ns	***	***
cTmOptBlue	^oC	***	***	***	***	***
cVSetBlue	m/day	**	ns	ns	ns	ns
fDAssZoo	-	**	ns	ns	ns	ns
fDepthDifS	-	**	ns	ns	ns	ns
hFilt	mgDW/l	***	ns	ns	ns	ns
kDRespBlue	day^{-1}	***	**	ns	***	***
kDRespDiat	day^{-1}	ns	ns	ns	*	*
kDRespZoo	day^{-1}	**	ns	ns	ns	ns
kMortBlueW	day^{-1}	***	ns	ns	**	ns
kPDifPO4	m^2/day	ns	ns	ns	ns	***

The 21 most sensitive parameters in Table 4 usually concerned blue-green algae because in the default model, green algae and diatoms were outcompeted by blue-greens. Although sensitive parameters were the ones concerning blue-green algae, the same parameters were assumed to be sensitive for other phytoplankton groups (i.e. diatoms and green algae) as well to keep the model realistic. For example, cMuMaxBlue (Maximum growth rate of Bluegreens) was one of the most sensitive parameters. Since the system had green algae and diatoms in smaller amounts, their growth rate generally was not observed as sensitive for the model. However, for the sake of the model calibration if a growth parameter was sensitive for blue-greens, it was assumed to be sensitive for other phytoplankton groups. That is the reason why sensitive parameters of blue-greens were assumed to be sensitive for all three phytoplankton groups. Therefore, 38 parameters were considered sensitive including the ones for all the phytoplankton group (Table 5).

For calibration, 38 most sensitive parameters' default values were changed within 20% range to avoid complex interactions of the parameters if the given values were too extreme. The ranges of values of parameters were given randomly using Microsoft Excel's RAND-function. Simulation and observation results were compared to see how much of the monitoring data of Chl *a*, NO_3-N, NH_4-N, PO_4 and TP could be captured by simulation result band. However, 20% range crashed the model for two parameters (i.e. cThetaDif and cThetaMinS), that's why the parameter ranges for these two parameters were set accordingly. Default value for cThetaDif (Temperature coefficient for diffusion) is 1.02 and the possible 20% range of this parameter is between 0.816 to 1.224. However, the model crashed outside the range 0.819-0.912. Another parameter that crashed the model was cThetaMinS (Exponential temperature constant of sediment mineralization). Its default value is 1.07 and the model crashed if the parameter was outside the range 1.156-1.281. Therefore, these two parameters were kept within these ranges, not the original 20% range.

Cautions were taken for cThetaDif and cThetaMinS parameters and in total 500 runs were performed. Sensitive parameters and their randomly assigned ranges were given in Table 5.

Table 5: Calibration set of parameters of the model and their range of change.

Id	Name	Unit	Default	Min	Max
91	cFiltMax	ltr/mgDW/day	4.5	3.619652	5.344357
104	cMuMaxBlue	day^{-1}	0.6	0.482235	0.716458
105	cMuMaxDiat	day^{-1}	2	1.604641	2.398178
106	cMuMaxGren	day^{-1}	1.5	1.208906	1.796756
***107**	cMuMaxVeg	g/g	0.2	0.06	0.06
113	cNDBlueMin	mgN/mgDW	0.03	0.024007	0.035985
120	cNDDiatMin	mgN/mgDW	0.01	0.008104	0.011841
125	cNDGrenMin	mgN/mgDW	0.02	0.016053	0.023983
151	coPO4Max	mgP/l	1	0.800166	1.197491
157	cPDBlueMax	mgP/mgDW	0.025	0.020079	0.029979
163	cPDDiatMax	mgP/mgDW	0.005	0.004022	0.005998
168	cPDGrenMax	mgP/mgDW	0.015	0.012005	0.017929
188	cPrefBlue	-	0.125	0.100632	0.149622
190	cPrefDiat	-	0.75	0.602901	0.898836
191	cPrefGren	-	0.75	0.603066	0.899343
234	cThetaDif	-	1.02	0.924899	1.217588
235	cThetaMinS	-	1.07	0.858521	1.099539
236	cThetaMinW	-	1.07	0.866323	1.276342
237	cThetaNitr	-	1.08	0.867146	1.290587

Table 5: continued

Id	Name	Unit	Default	Min	Max
244	cTmOptBlue	^{o}C	25	23.0019	26.96864
245	cTmOptDiat	^{o}C	18	16.03592	19.9606
247	cTmOptGren	^{o}C	25	23.00999	26.93163
250	cTmOptZoo	^{o}C	25	23.01516	26.88798
265	cVSetBlue	m/day	0.06	0.048568	0.071625
267	cVSetDiat	m/day	0.5	0.401212	0.593787
268	cVSetGren	-	0.2	0.16041	0.239252
281	fDAssZoo	-	0.35	0.285282	0.416917
288	fDepthDifS	-	0.5	0.4002	0.599142
352	hFilt	mgDW/l	1	0.809618	1.195726
378	kDRespBlue	day^{-1}	0.03	0.024112	0.035823
379	kDRespDiat	day^{-1}	0.1	0.080232	0.119909
382	kDRespGren	day^{-1}	0.075	0.060445	0.089838
***385**	kDRespVeg	day^{-1}	0.02	0.006	0.006
386	kDRespZoo	day^{-1}	0.15	0.121888	0.179478
402	kMortBlueW	day^{-1}	0.01	0.008085	0.011978
404	kMortDiatW	day^{-1}	0.01	0.008014	0.011993
408	kMortGrenW	day^{-1}	0.01	0.008037	0.011985
418	kPDifPO4	m^2/day	0.000072	5.79E-05	8.63E-05

* The most sensitive parameters for vegetation. These parameters were kept constant throughout, because the model overestimated the vegetation result. To keep the vegetation results as expected the most sensitive two parameters of vegetation were fixed accordingly.

Out of the 500 runs that were performed, 100 runs with the smallest RMSE (Root Mean Square Error) were selected as the calibration of the model since they were the best fit of the model to Lake Eymir's observation data. The 100 simulations were considered as baseline simulations, and the scenario runs were compared to the baseline simulation.

Since the parameters were given a set of values for every run, a band of results were acquired for every day, for that the 5 percentile from the bottom and top were excluded from the resulting simulations. The reason for the simulations to be represented by a band was to show how many of the observation points are captured by the band of simulated results, which explains how well the model represents the real lake.

2.2.2 Scenario runs

PCLake was used to simulate the lake's response to various scenarios. In this study; effect of nutrient load change and the effect of temperature increase were modeled by *PCLake*.

In total 100 runs were carried out for each scenario and baseline model. The model was set for 13 years of data (1998-2010) with the first three years to be warm-up years, and scenarios were also run for 13 years. The results are the monthly averages of the 100 runs for 10 years with the exclusion of the first three years.

The model's responses to nutrient loads were included in the scenario runs. Both phosphorus and nitrogen loads throughout the study period were set to be twice as much and half of the observation values.

Furthermore, with anticipated global warming, water temperatures are expected to increase. Therefore, water temperature was increased 2ºC, 4ºC and 6ºC for each scenario run and their significance levels were evaluated compared to base scenario for each temperature scenario.

2.3 Statistical analysis

2.3.1 t-test

For sensitivity analysis every parameter was set to be its 20% more or 20% less value at a time to determine their sensitivity in the model performance. Each parameter was given a value at a time and all the other parameters were kept constant, so that the model complexity due to parameter interactions would be eliminated. Every two runs concerning the same parameter were compared by t-test with 95% confidence interval using RStudio.

2.3.2 RMSE

In this study RMSE was used for selecting the best 100 parameter sets as calibration set from the 500 runs with random values. RMSE values were calculated by Equation 1 using Microsoft Excel. RMSE value being closer to 0 means that the simulation of the model predicted the observation values closely. Since smallest RMSE values gave the best prediction, the 100 parameter sets with the smallest RMSE values were chosen as the calibration set for good representation.

Also, RMSE was calculated for calibration and validation of the variables, so that mean values for every band was calculated and the values were compared against the observation values. RMSE values of each variable are given in Table 7.

Equation 1: The formula of RMSE calculation.

$$\mathbf{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

2.3.3 Wilcoxon signed-rank test

To compare differences of scenarios to baseline scenario paired Wilcoxon signed-rank test was used. In this test each month of data were compared for different scenarios; therefore a paired and a non-parametric test was applied. The p-values to not to show much difference is because the test was non-parametric. This particular test requires multiple test correction and as a method FDR (False Discovery Rate) multiple test correction was applied to acquire the p-values. This test was done using RStudio.

CHAPTER 3

RESULTS

3.1 Sensitivity Analysis, Calibration and Validation

Sensitive parameters of Lake Eymir and their sensitivity levels according to variables were determined by t-test. According to the sensitivity analysis, the most sensitive parameter for all five water quality variables was maximum growth rate of blue-greens (cMuMaxBlue), minimum N/day ratio of Bluegreens (cNDBlueMin) and optimum temperature for blue-greens (cTmOptBlue).

Calibration and validation results of the main variables (Chl *a*, PO_4, TP, NH_4-N, NO_3-N) were given in Figure 5-8. The bands in the figures represent the minimum and maximum values of 100 simulations with the exception of 5 percentile from the bottom and top of the simulations. Observation points being seen inside the band shows that the simulation was captured the observation and was a good representation. Percentages of the observation points which were captured by the band for each variable are given in Table 6 and their RMSE values are given in Table 7.

Table 6: Percentage of data that fell within the band of simulation data.

Variable name	**Calibration period percentages in the band**	**Validation period percentages in the band**
Chl *a*	46%	61%
PO_4	58%	100%
TP	62%	100%
NO_3-N	24%	40%
NH_4-N	19%	21%
Zooplankton biomass	67%	41%

Table 7: RMSE values for calibration and validation periods

Variable name	**Calibration period**	**Validation period**
	RMSE	**RMSE**
Chl *a*	27.02	25.67
PO_4	0.40	0.14
TP	0.40	0.10
NO_3-N	0.23	0.26
NH_4-N	0.33	0.58
Zooplankton biomass	0.42	0.66

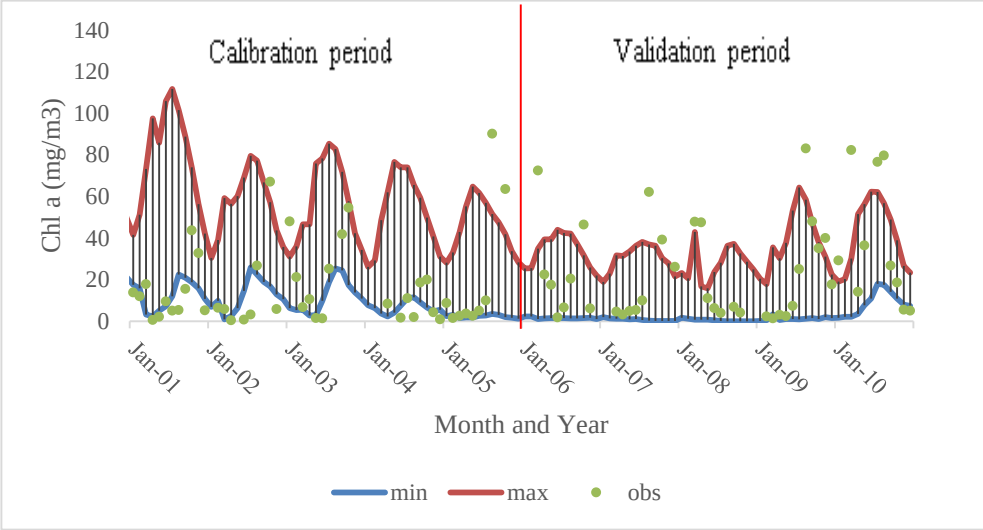

Figure 5: Minimum, maximum results of 100 run-sets and observations of chlorophyll *a* concentrations.

Calibration results of Chl *a* show that the model representation of Chl *a* can be acceptable since 46% of the data was captured in calibration period and 61% of the data was captured in validation period by the band of results. Although the model did not fully capture some low and high values, other values are usually within the range. Higher Chl *a* concentrations were observed usually in autumn, however the band did not capture all of them. Lower Chl *a* concentrations were usually observed in summer months, nevertheless some of them usually stayed out of the band of simulations.

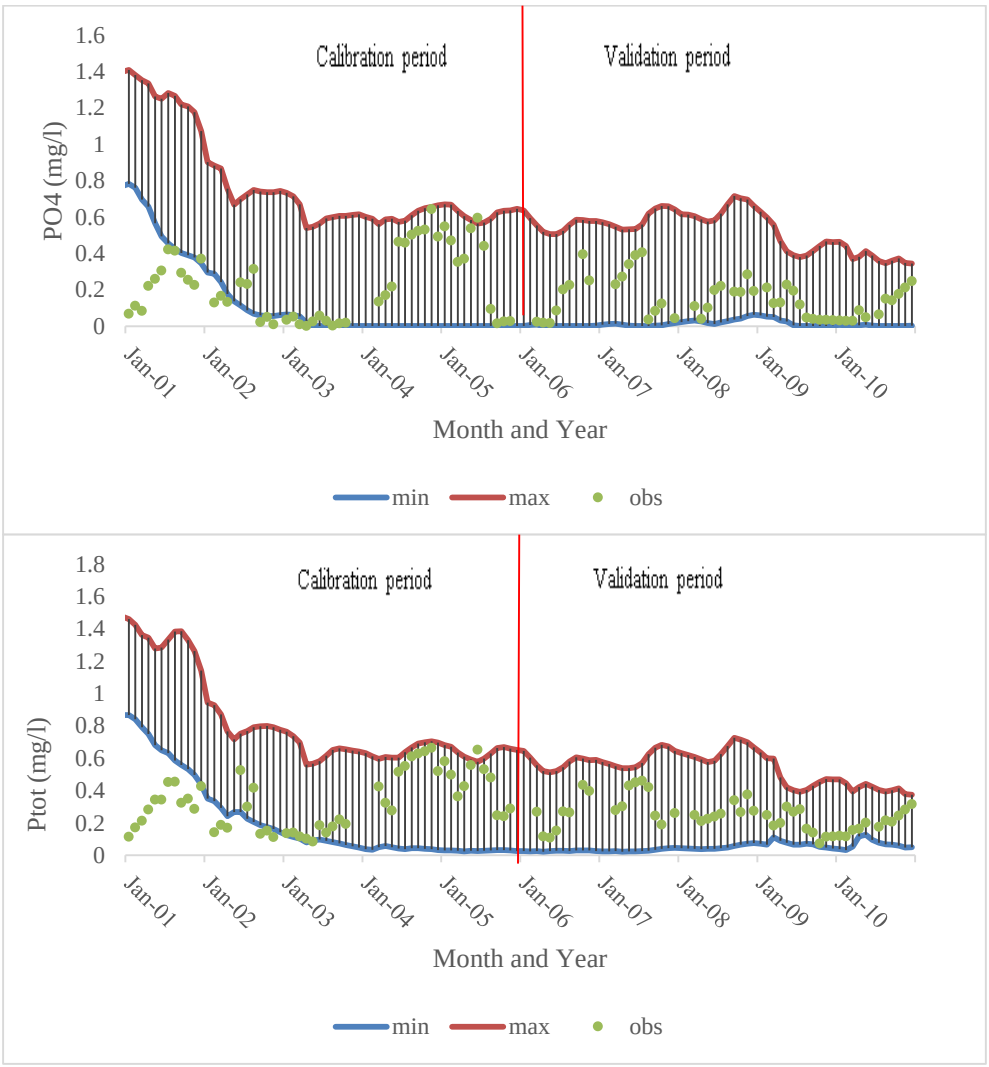

Figure 6: Minimum, maximum and observation results of 100 run-sets of PO_4 and TP concentrations.

Both PO_4 and TP concentrations seem to be nicely captured by the model simulations with the exception of years 2001 and 2002. For years 2001, 2002 and 2003, the model simulated higher concentrations of PO_4 and TP.

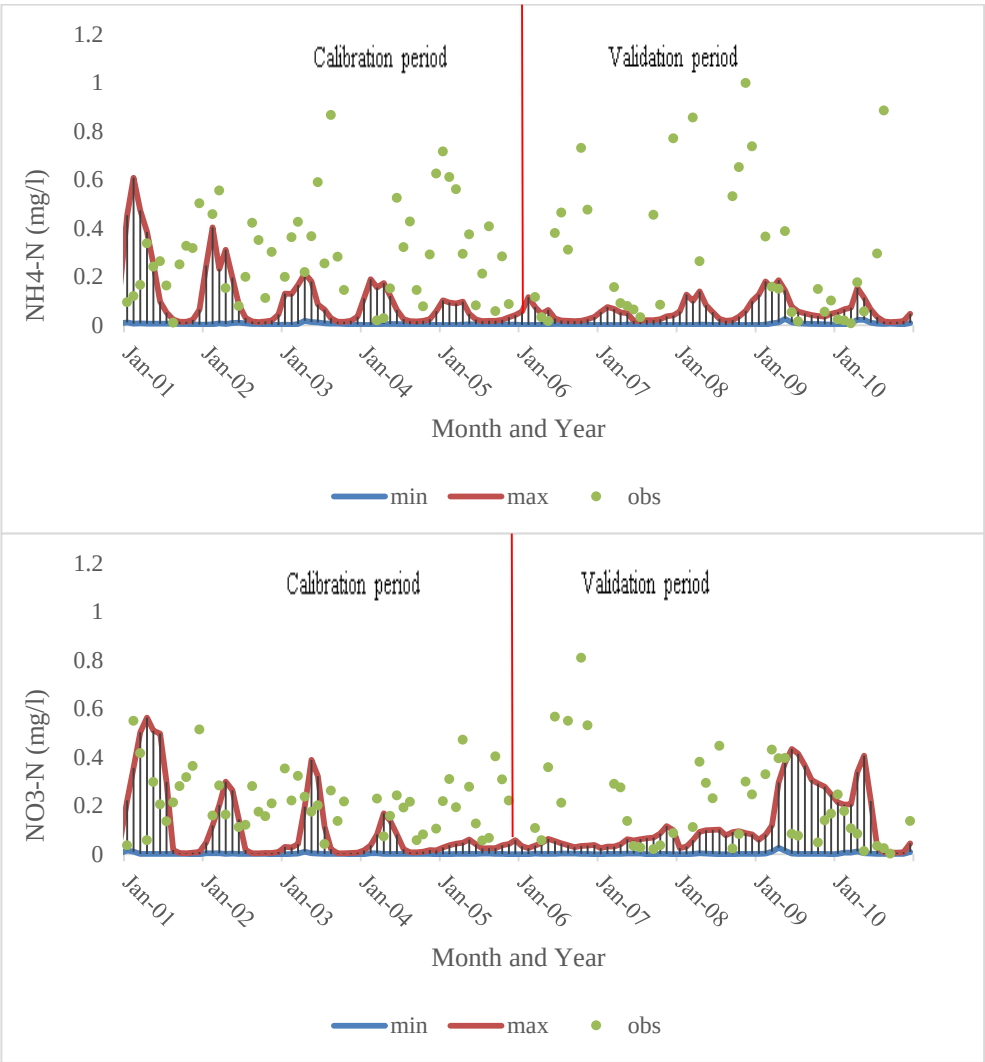

Figure 7: Minimum, maximum and observation results of 100 run-sets of NH_4-N and NO_3-N concentrations.

NH_4-N and NO_3-N concentrations were usually underestimated by the model simulations. Out of all the variables, these two are the ones that were poorly calibrated. Only 19% of NH_4-N was captured within the simulation band for calibration years; whereas only 24% of NO_3-N was captured for calibration years. On the other hand,

validation results of NH_4-N and NO_3-N were also poor, observations that were captured by the simulation bands were 21% and 40%, respectively.

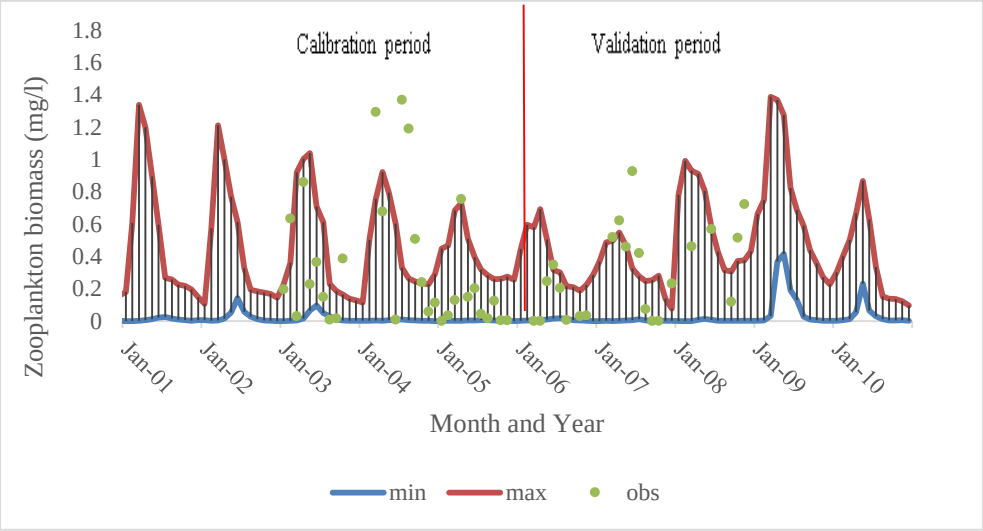

Figure 8: Minimum and maximum simulations and observation data of 100 run-sets of total zooplankton biomass.

Zooplankton biomass seems to be represented well by the model. For the calibration period 67% of the observations in the calibration period fell within the band. Validation bands capture 41% of the observation results.

3.2 Effects of nutrient loading change

Figure 9 - 12 show the projections of inflow nutrient's increment and decrement scenarios compared to the base run. Nutrient increase and decrease in the inflow affected the system highly significantly ($p<0.001$) for all the variables except for zooplankton biomass. On the other hand doubling and halving nutrients in the inflow significantly affected zooplankton biomass (both $p<0.005$). Paired Wilcoxon signed-rank test was used to compare the differences of scenario and baseline scenario. To acquire the p-value of the test FDR (False Discovery Rate) multiple test correction is applied. p-values of nutrient load change are given in Table 8.

Table 8: The p values of variables with significance levels for and nutrient scenarios compared to baseline scenario.

Variable name	**Double nutrient p value**	**Half nutrient p value**
Chlorophyll *a*	0.000586***	0.000586***
PO_4	0.000586***	0.000586***
TP	0.000586***	0.000586***
NO_3-N	0.000586***	0.000586***
NH_4-N	0.000586***	0.000586***
Zooplankton biomass	0.0024*	0.0016*

Chl *a* concentrations were changed between 13.3 mg/m^3 and 30.0 mg/m^3 in baseline nutrient scenario with the average of 20.4 mg/m^3. Halving nutrients in the inflow caused Chl *a* concentration to decrease to 13.9 mg/m^3 on average. The minimum concentration was projected to be 9.9 mg/m^3, whereas the maximum value was predicted to be 19.2 mg/m^3 for half nutrient scenario. On the other hand, doubling nutrient load caused Chl *a* concentration to increase to 30.9 mg/m^3 on average. The minimum and the maximum concentrations for increase in nutrient scenarios were predicted to be as 18.0 mg/m^3 and 49.4 mg/m^3, respectively. Doubling of nutrients caused Chl *a* to increase 49% on average; however, halving nutrients caused it to decrease 31% on average. Doubling and halving nutrients had significant difference (both had $p<0.001$) on Chl *a*, when compared to baseline scenario.

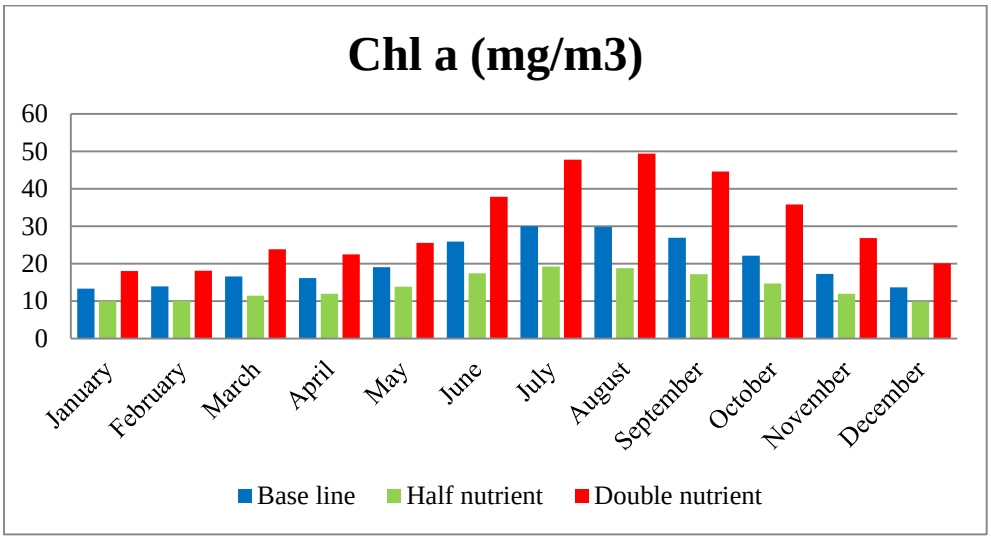

Figure 9: The baseline, half and doubled nutrient scenarios effects on average monthly Chl *a* concentrations. Each month has a value which was the average of the month for 10 years of scenario runs (First 3 years of 13 years were excluded for eliminating the results of warm-up years).

Nutrient doubling and halving had significant effects on both PO_4 and TP (both had $p<0.005$). Both PO_4 and TP concentration in the water column increased with increasing nutrient loading, and decreased with decreasing loading. PO_4 concentrations were changed between 0.30 mg/l and 0.39 mg/l with the average of 0.32 mg/l, while TP concentrations were changed between 0.34 mg/l and 0.42 mg/l in baseline nutrient scenario with the average of 0.37 mg/l. Halving nutrient loading caused PO_4 to drop 24% on average and minimum value was observed as 0.22 mg/l, however doubling nutrient in the inflow resulted in 58% increase in and the maximum PO_4 was observed as 0.62 mg/l. Figure 10 shows PO_4 and TP projections for doubling and halving nutrients scenarios.

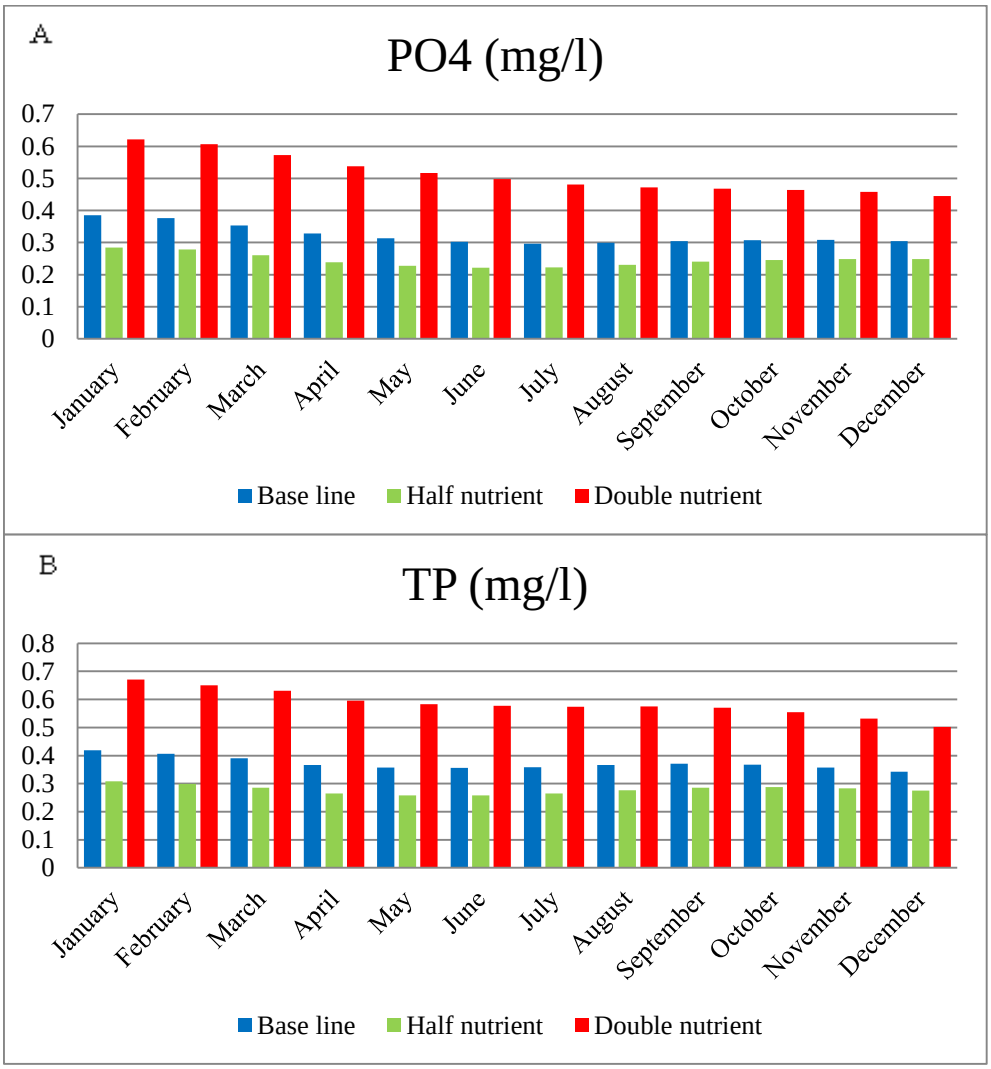

Figure 10: The base scenario, halving and doubling nutrient scenario effects on PO_4 (A) and TP (B).

Both NH_4-N and NO_3-N concentrations changed highly significantly with doubling and halving nutrient loading compared to baseline scenario ($p<0.01$) In Figure 11, NH_4-N concentration in the water body was observed between 0.009 mg/l to 0.05 mg/l with the average of 0.03 mg/l in the baseline scenario. NH_4-N concentration increased 58% on

average with doubling nutrient inflow; however, when nutrient inflow was halved, on average, 27% decrease in NH_4-N concentration was projected in the scenario runs. In response to halving nutrients, the minimum NH_4-N concentration was 0.008 mg/l; however, doubling nutrients caused the maximum NH_4-N concentration to be 0.09 mg/l.

On average 180% increase in NO_3-N concentration was predicted for doubling nutrients; however, halving nutrients caused 34% decrease. The maximum concentration of NO_3-N for doubling nutrient load was observed as 0.27 mg/l; however, NO_3-N concentration in the water body was the minimum (0.01 mg/l) in response to halving of nutrient loading.

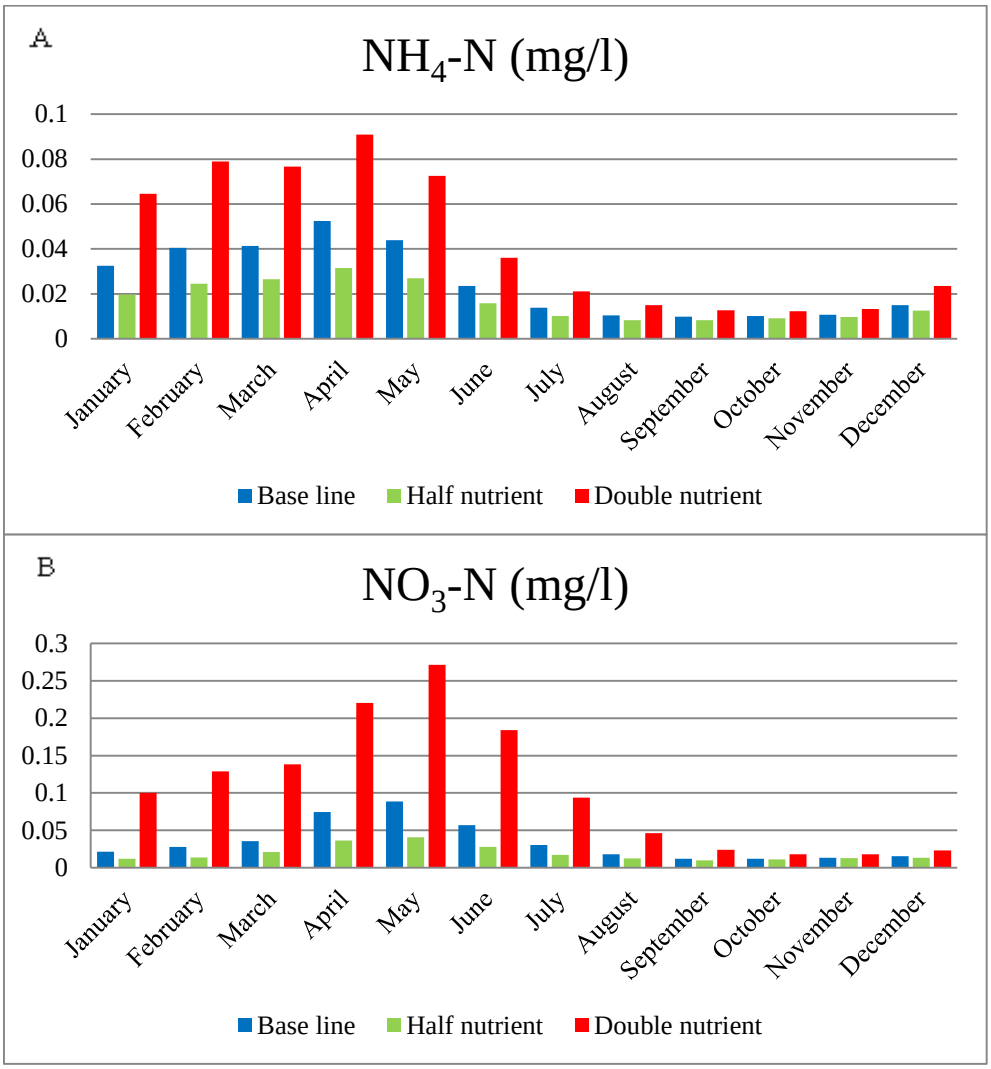

Figure 11: The base scenario, halving and doubling nutrient effects on NH_4-N (A) and NO_3-N (B) concentrations.

Zooplankton biomass showed significant difference to nutrient load changes compared to baseline scenario (both had $p<0.005$). When nutrient load was doubled, zooplankton biomass in the system was increased by 13% on average; however, when the nutrient load was halved, zooplankton biomass decreased to its 12%. In response to increase of

nutrient loading, maximum zooplankton biomass was observed as 0.52 mg/l; whereas, decrease of nutrient loading caused zooplankton biomass to decrease 0.07 mg/l. Figure 12 shows zooplankton response to nutrient scenarios.

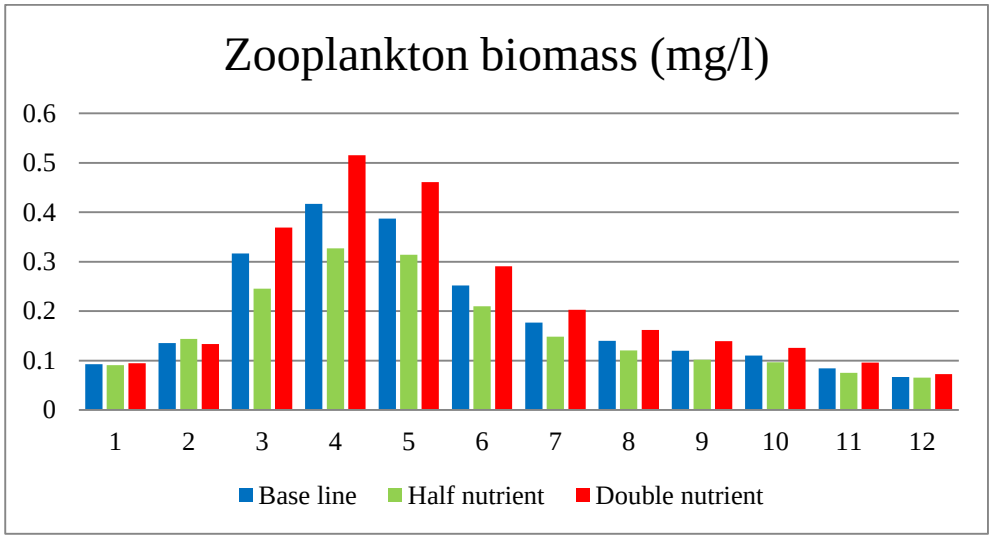

Figure 12: The base, halved and doubled nutrient scenario effects on zooplankton biomass.

3.3 Effects of temperature increase

Water temperature was considered to increase 2, 4 and 6ºC for each scenario and each scenario was compared to base scenario separately. It was shown that increasing temperature effected the lake system significantly for all the variables. Significance levels of temperature scenarios were given in Table 9.

Table 9: The p values of variables with significance levels for 2ºC, 4ºC and 6ºC water temperature increase

Variable name	2ºC water temperature increase	4ºC water temperature increase	6ºC water temperature increase
Chlorophyll a	0.00063***	0.00063***	0.00063***
PO_4	0.00063***	0.00063***	0.00063***
TP	0.00063***	0.00063***	0.00063***
NO_3-N	0.00063***	0.0342*	0.0222*
NH_4-N	0.00063***	0.00063***	0.00176***
Zooplankton biomass	0.00063***	0.00063***	0.00275***

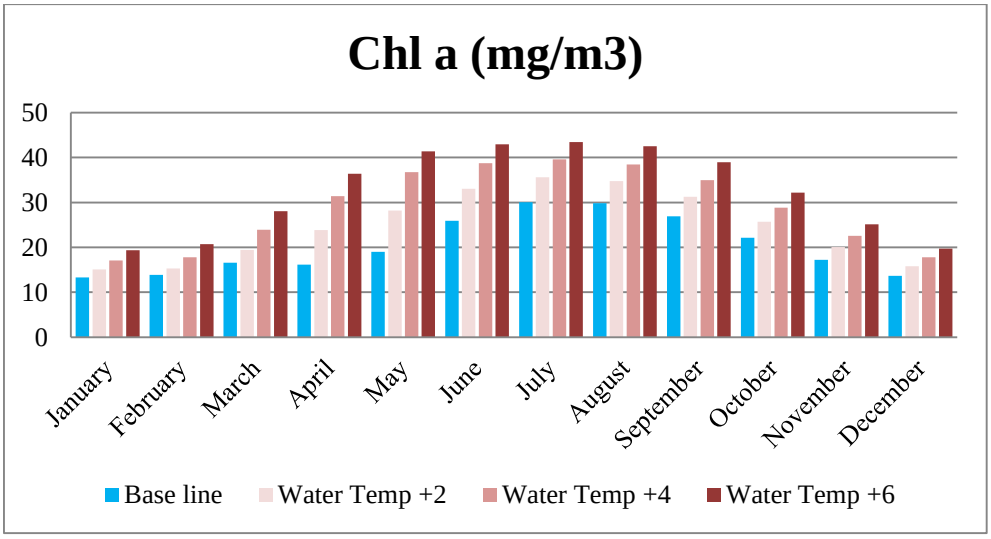

Figure 13: The effect of increasing water temperature 2, 4 and 6 degrees Celsius for each scenario on Chl *a*.

Increasing the water temperature by 2ºC, 4ºC and 6ºC caused significant differences in Chl *a* concentration ($p<0.001$ for all) compared to baseline scenario. Figure 13 revealed that Chl *a* concentrations were increased along with increasing temperature. 2ºC increase in the water temperature caused 22% increase in Chl *a* concentration, 4ºC increase caused 43% increase and 6ºC increase caused 62% increase in Chl *a* concentration on average. In response to increasing water temperature, the minimum Chl *a* occurrence was observed to be 15.1 mg/m^3, 17.1 mg/m^3 and 19.3 mg/m^3 for 2ºC, 4ºC and 6ºC, respectively; whereas, the maximum Chl *a* occurrence was observed to be 35.6 mg/m^3, 39.6 mg/m^3 and 43.4 mg/m^3 for 2ºC, 4ºC and 6ºC, respectively.

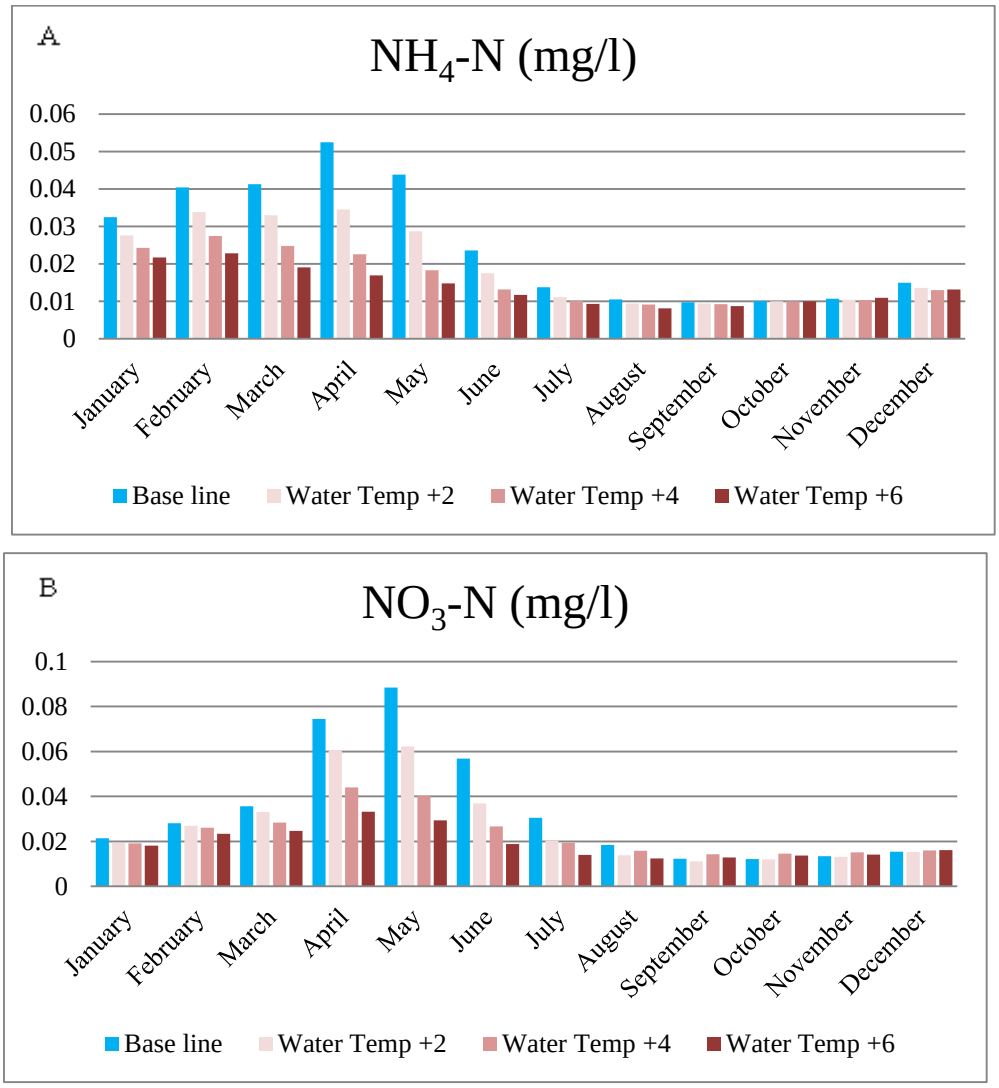

Figure 14: The effect of increasing water temperature 2, 4 and 6 degrees Celsius for each scenario on NH_4-N (A) and NO_3-N (B).

Both NH_4-N and NO_3-N concentrations in water column were decreased with increasing temperatures (Figure 14A & Figure 14B) highly significantly ($p<0.05$). As seen in Figure 14a, when the water temperature increased 2ºC, 4ºC and 6ºC the minimum NH_4-N concentration was observed as 9.4e-3 mg/l, 9.1e-3 mg/l and 8.1e-3 mg/l, respectively.

On the other hand, by increasing water temperature 2ºC, 3ºC and 4ºC the maximum NH_4-N concentration was observed as 3.5e-2 mg/l, 2.7e-2 mg/l and 2.3e-2 mg/l, respectively. Moreover, NH_4-N was projected to decrease by 16%, 27% 33% on average when water temperature increased 2ºC, 4ºC and 6ºC, respectively.

In Figure 14b, increasing water temperature 2ºC, 4ºC and 6ºC projected to cause the minimum NO_3-N concentration as 1.1e-2 mg/l, 1.5e-2 mg/l and 1.2e-2, respectively; however, the maximum value for increasing water temperature 2ºC, 4ºC and 6ºC were 6.2e-2 mg/l, 4.4e-2 mg/l and 3.3e-2, respectively. On average, 2ºC and 4ºC increase in water temperature caused 15% decrease, and 6ºC increase caused 26% decrease in the NO_3-N concentration.

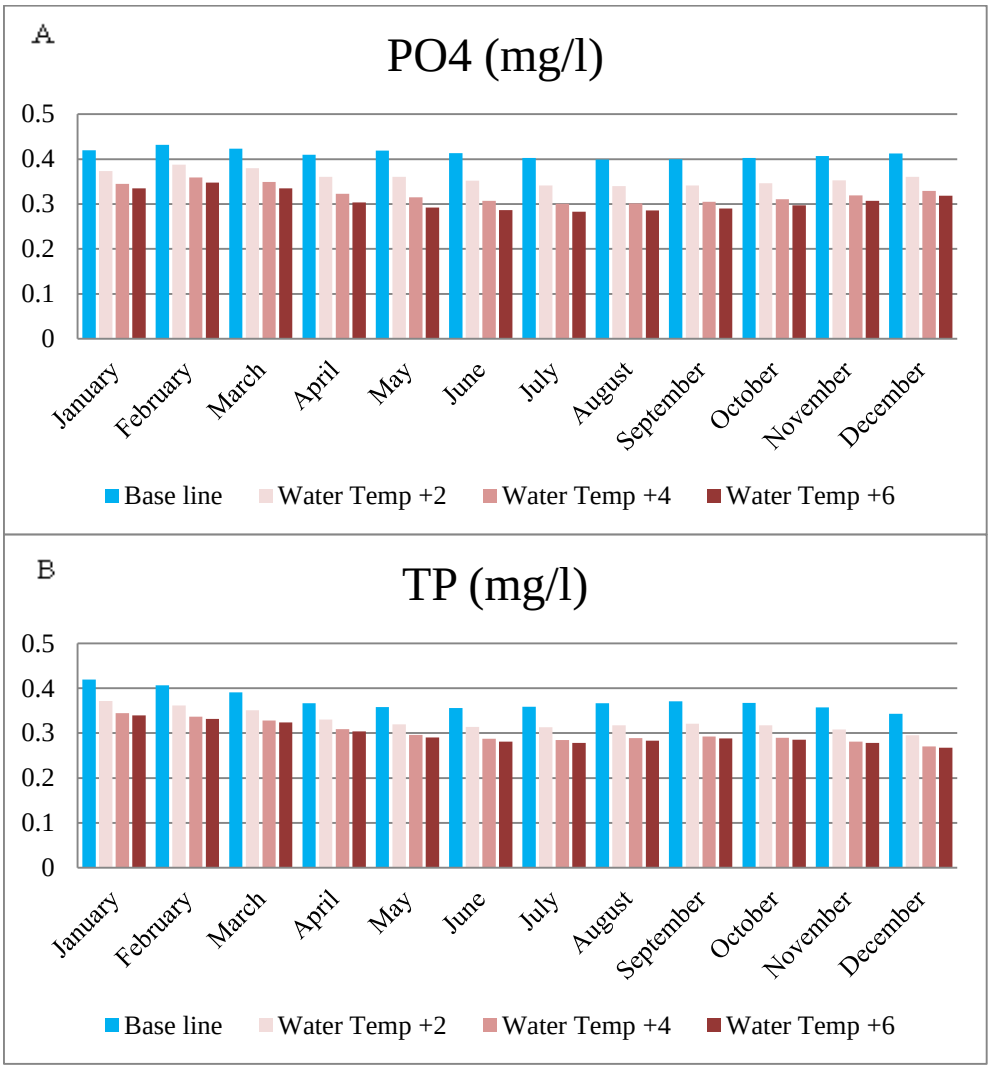

Figure 15: The effect of increasing water temperature 2, 3 and 4 degrees Celsius for each scenario on PO_4 (A) and TP (B).

Figure 15A & B showed that the concentrations of PO_4 in the water column decreased with increasing water temperature. 2ºC, 4ºC and 6ºC increase in water temperature caused the maximum PO_4 concentrations to be 0.39, 0.36 and 0.35 mg/l, respectively. Increasing water temperature 2ºC, 4ºC and 6ºC caused the minimum values to be 0.34

mg/l, 0.30 mg/l and 0.28 mg/l. On average, PO_4 decreased 13%, 22% and 26% for 2ºC, 4ºC and 6ºC, respectively. For TP, 2ºC, 4ºC and 6ºC increase in the water temperature resulted in minimum TP concentrations to be 0.30, 0.27 and 0.26 mg/l, respectively, while the maximum TP was 0.37, 0.34 and 0.33 mg/l, respectively. Moreover, TP decreased 12%, 19% and 20% for 2ºC, 3ºC and 4ºC, respectively on average compared to baseline scenario. Both PO_4 and TP show high significance compared to baseline scenario ($p<0.01$).

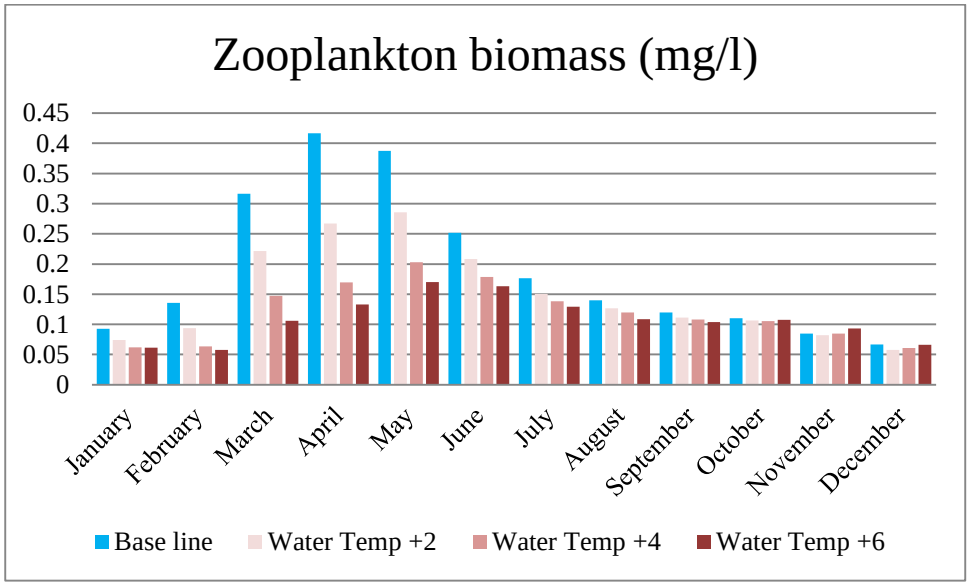

Figure 16: The effect of increasing water temperature 2, 3 and 4 degrees Celsius for each scenario on zooplankton biomass.

In Figure 16, it is shown that increasing water temperature 2ºC, 4ºC and 6ºC the minimum zooplankton biomass was observed as 5.7e-2 mg/l, 6.1e-2 mg/l and 5.8e-2 mg/l, respectively) and the maximum zooplankton biomass was expected to be observed as 0.29 mg/l, 0.20 mg/l and 0.17 mg/l, respectively). Increasing water temperature 2ºC, 4ºC and 6ºC caused a decrease of 18%, 28% and 31% in the zooplankton biomass. Furthermore, biomass changes were significant compared to base scenario ($p<0.01$) for 2ºC, 4ºC and 6ºC.

CHAPTER 4

DISCUSSION

In this study, *PCLake*, an integrated and complex lake model, was applied to Lake Eymir to study the ecosystem changes during the last decades initiated through several restoration efforts from sewage effluent diversions to biomanipulation and to study the possible effects of future nutrient loading and water temperature scenarios. The *PCLake* model was chosen for this study due to its ability for combining biotic and abiotic environments of shallow lakes. However, the model did not give optimal results for calibration and validation. The calibration and validation results of the model were far from representing the true values of some variables (i.e. NO_3–N and NH_4–N) but for PO_4, TP, Chl *a* and zooplankton biomass, the model gave acceptable results. Moreover, nutrient loading change and water temperature increase scenarios seemed to produce acceptable results.

In total 13 years of data were used (1998-2010). The first three years of it were used as a warm-up period (1998-2000) for minimizing the effects of model's response to the uncertainty regarding the initial values of some parameters and state variables. The remaining 10 years were divided into two parts as calibration (2001-2005) and validation periods (2006-2010).

For determining the sensitive parameters of the model, sensitivity analysis was carried out. The sensitive parameters of this study showed resemblance to other studies that used the *PCLake* model. Sensitivity analysis was done using t-test (p=0.05) and was used for determining the calibration parameter set. Janse (2005) suggested 26 sensitive parameters, 13 of which (parameters that usually concern biological activity) were found

to be sensitive in this study. This study and Nielsen et al. (2013) had 18 sensitive parameters (parameters that usually concern temperature and biological activity) in common. On the other hand, 14 sensitive parameters (parameters that usually concern temperature, chemical composition of organisms and biological activity) of Rolighed (2013) were used in this study. In this study 21 sensitive parameters were found, however most of the sensitive parameters did not cover all the phytoplankton groups. Since the modelled system in this study lacked green algae, parameters concerning green algae were not found as sensitive. However, the model should present all the phytoplankton groups, therefore these sensitive parameters were considered for all the phytoplankton groups. Considering those parameters for all three phytoplankton groups 38 parameters were determined as the calibration set in this study. Janse (2005), Nielsen et al. (2013) and Rolighed (2013) had 26, 43 and 34 parameters in their calibration sets, respectively. In these studies all the phytoplankton groups were included in the calibration sets since all phytoplankton groups are important in a lake ecosystem. Number of sensitive parameters differed due to different conditions of lakes and the model's response to different environmental conditions.

The sensitive parameters were used for determining the calibration parameter set. A range of values were given to the set of parameters and for every parameter in the calibration set a random value inside the range was chosen for every run. A total of 500 runs were made and successful simulations were determined by their smallest RMSE values with respect to their observed values. 100 successful simulations were selected as the baseline set. The baseline parameter set was considered to be the calibrated parameter set of the model, and the same data set was used for the scenario runs. In the literature, some studies used only one set of simulation results and they produced the best simulation line (Trolle et al. 2008; Nielsen et al. 2013; Janse et al. 1995), while others used a set of values to produce a simulation band (Nielsen et al. 2014; Trolle et al. 2015). In this study, 100 parameter set were run and a band of results were obtained for each variable with the aim of fitting the observation points in the band. After calibration,

validation of the model was expected to verify the calibration results. Validation results were close to the calibration results, so that the validation of the model was considered as good.

Most of the studies that used *PCLake* model in the literature (Lake Arreskov, Nielsen et al. 2013; Lake Søbygaard, Rolighed, 2013; Lake Zwemlust, Janse et al 1995) showed relatively good results, partly because the default dataset was calibrated for those lakes (Janse, 2005), also they used an ensemble modeling approach, combining the results of either several calibrated models or several model runs of one model. There could be several reasons for why the calibration results of the model were not as successful for Lake Eymir as the other studies. *PCLake* model might be more suitable for northern shallow cold temperate non-stratifying lakes and ponds; such as Lake Arreskov (Nielsen et al. 2013), Zwemlust (Janse et al 1995), Lake Søbygaard (Rolighed, 2013). However, Lake Eymir is relatively deep with a maximum depth of 6 meters and it shows stratification. Since Lake Eymir was formed through damming of the river through alluvial matters, its morphometry is also steeply sloped. Thus, equations defined for flat bottom and U-shaped non-stratifying shallow lakes in *PCLake* model may not have fully captured the processes that took place in Lake Eymir.

PCLake is an integrated and a complex model; therefore its main limitation is the large number of process parameters, and the interaction of these parameters complicates the system. However, the model becomes more reliable if it includes more parameters. (Mooij et al 2010). Furthermore, scenario simulations of two equally representative parameter set combinations could be quite different (Nielsen et al. 2014) due to different interactions of different parameter sets. Therefore, using a band simulation for the results rather than one parameter set would be more appropriate for scenario runs.

Although simplification of some formulas in the model were promising, some other factors were overlooked, such as water level change and nitrate on processes that lead to internal nutrient cycling and eutrophication (Mooij et al. 2010). Especially, since the

model was designed for northern temperate lakes, water level or hydrological alterations in general were not integrated into the model and the model lacked capturing the impact of water level changes (J. Janse personal communication by M. Beklioğlu). Also, the model is 0D (i.e. it does not include horizontal or vertical differences), therefore the whole lake was simplified to one m^2. This might also be another reason for this model to not to work well for Lake Eymir. The studies on Northern lakes also did not include the effects of water fluctioation, but water levels in Lake Eymir fluctuated over 2 meters during the study period and water level fluctuations are very critical for controlling ecosystem structures (e.g. availability of nutrients), and ecosystem states (e.g. presence of macrophytes or phytoplankton domination) in warmer lakes (Özen et al. 2010; Bucak et al. 2012; Jeppesen et al. 2015). During the study periods, concentrations of major ions and nutrients highly increased in the dry years due to limited nutrient loading and outflow, which was observed between 2003-2008. Also, the years that the lake was modelled included biomanipulation, dry and wet years. For a 0D model that represents the lake as its simplest form, a lake that had gone through such phases over the years can be quite complex to calibrate.

Furthermore, ecosystem models contain lots of uncertainties, the model's parameter values may not be suitable for all ecosystems; or initial conditions may affect the whole results that the model gives (Janse, 2005). On the other hand, some of the problems could be the inaccuracies of the monitoring dataset itself, such as the errors associated with sampling, handling, analysis or unusual events.

Agreement between the observations and simulations created by the model is very crucial for calibration since it represents the model performance. Calibration of the model for this study was started as calibrating the parameters one by one in only one dataset. A lot of interactions in the model were encountered as the calibration parameter set grows. It was time consuming and the results were not satisfying. Therefore, instead of using only one dataset that is not enough to represent the lake, a set of parameters were decided to be used, which was also seen in the literature. Also, as Nielsen et al.

(2014) suggested, there can be more than one set of parameters that can be representative of an ecosystem. As the model used for future scenarios, they might predict different results. Therefore, it is recommended to use a simulation band for calibration and scenario simulations.

The model in this study was set without any vegetation, because the model could not reflect the changes between macrophyte dominated clear water state and phytoplankton dominated turbid water state accurately for Lake Eymir. Vegetation affects the model performance since the model was developed primarily for shifting of shallow lakes between clear water with vegetation and turbid water with eutrophic conditions Therefore, the calibration success was found less successful in this study as it underestimated the vegetation for the first years of the study period.

Calibration results showed that the highest percentages of observations were captured within the simulation bands were PO_4 and TP with 58% and 62%, respectively. Actually, PO_4 and TP were the two best simulations since all the observational data were captured within the bands with the exception of first three years of calibration (i.e. 2001-2003). This trend was followed by zooplankton biomass, Chl *a* concentration and NO_3–N concentration. Their observations were covered by the simulation band for calibration period was 67%, 46% and 24%, respectively. Nevertheless, NH_4–N was mostly underestimated by the model and only 19% of the observation data were observed within the calibration band. On the other hand, validation results followed more or less the same pattern. PO_4 and TP had the highest percentages in the validation period as well with 100% and 100%, respectively. That was followed by Chl *a* concentration, zooplankton biomass and NO_3–N concentration for validation period as well (61%, 41% and 40%, respectively). Nonetheless, NH_4–N was underestimated by validation band as well, and only 21% of the observation data were observed within the validation band. Nielsen et al. (2014) had 70-90% of their observations captured within the calibration band. The reason for the better calibration of that study might be due to the ensemble

model approach, which is using a combination of models to cover parts that one model cannot.

After the calibration of the model, scenarios were run in order to have some insight for future projections. In this study, results showed that doubling nutrients caused an increase for all the variables (i.e. Chl *a*, PO_4, TP, NH_4–N and NO_3–N concentrations and zooplankton biomass), while and halving nutrients decreased their concentrations. The results of doubling and halving nutrient scenarios were supportive of other studies (Jeppesen et al. 2007, Özen et al. 2010). Both high and low nutrient load results of those studies showed similarity to the model simulations of this study. In these simulations, all the variables showed significant response to increase and decrease of nutrient load to the system ($p<0.01$ for Chl *a* and nutrient concentrations, $p<0.05$ for zooplankton biomass).

Increasing water temperature caused Chl *a* concentrations to increase, likely because of increasing cyanobacteria biomass, which have a higher optimal temperature. Nielsen et al. (2014) also reported in his model study that with increasing temperature, Chl *a* concentrations in the lake increases. However, other variables (nutrient concentrations and zooplankton biomass) decreased with increasing temperature. That seems to contradict with the other increasing water temperature studies indirectly, since it was suggested that if the water temperature was to increase external nutrient loading should be reduced to retain vegetation (Trolle et al. 2015, Nielsen et al. 2014).

PCLake was primarily developed for eutrophication studies; however, lately it has also been applied for climate change studies on shallow lakes (Janse et al. 2008, Mooij et al. 2007, 2010). As stated by Mooij et al. (2010), climate change studies have not been formally verified due to scarce field data; however the model has been used for modelling climate change effects on shallow lakes by Trolle et al. (2015), Nielsen et al. (2014) and Rolighed (2013). In the scenario runs, increased temperature by 2ºC, 4ºC and 6ºC caused an increase in Chl *a* highly significantly ($p<0.01$). Nielsen et al. (2014) also reported that with increasing temperature, Chl *a* concentrations and contribution by

cyanobacteria increased in the lake. However, other variables (nutrient concentrations and zooplankton biomass) seemed to decrease with increasing temperature. That seems to contradict with the other modeling studies in which increasing water temperature scenarios were run. Those studies revealed that with increasing temperature the lakes might shift to turbid state even though nutrient loading was reduced (Rolighed, 2013; Nielsen et al. 2014; Trolle et al. 2015). Simulation results revealed that increasing water temperature caused a highly significant decrease ($p<0.01$) in PO_4 and TP concentrations. The scenario results might predict the PO_4 concentration because with increase in water temperature, extensive uptake by phytoplankton may likely to reduce PO_4 concentrations. However, TP concentrations would have increase in warm lakes as increasing temperature occurs together with reduced precipitations as well as enhanced evaporation that reduces water levels and volume in total that cause up-concentrations of nutrients (Özen et al., 2010; Coppens et al., in prep.).

Increasing temperature had significant effects on other variables (Table 9) as well; however simulations predict that the remaining variables (NH_4–N, NO_3–N concentrations and zooplankton biomass) decreased with increasing temperature. Denitrification – which is a bacterial process that uses nitrogenous products to produce atmospheric N (N_2) – is likely to increase with increasing temperature (Bachand & Horne, 2000) and that seems to go hand in hand with the results that the model predicts which is decreasing N concentrations. In Lake Eymir in-lake NH_4–N, NO_3–N concentrations increased with biomanipulation, recovery of macrophytes and dry years; however the concentrations were decreased with sevege effluent diversion (Özen et al. 2010).

Even though the model had some difficulty in adequately capturing the processes in Lake Eymir, some results correlated with other studies, while others contradicted with the literature. The model might have worked better if the history of Lake Eymir was not so complicated and the lake bottom was flat as most lakes in the North. Also, maybe some technical reason behind the model that does not allow good calibration due to

some unusual values for Lake Eymir that were out of the range for the original model. Also, there is a work in progress for PCLake that is going to be developed as a 3D model in Denmark and it is going to work for stratified and deeper lakes as well.

CHAPTER 5

CONCLUSION

In this study, the aim was to fit the model's calibration and validation results as close to the observation data as possible since a good calibration means a good representation of the ecological system. For calibration and validation, sensitivity analysis was carried out and the sensitive parameters of this study showed resemblance to other studies that used *PCLake* model. Sensitivity analysis was done using t-test. Later, sensitivity analysis was used for determining calibration parameter set. In total, 500 runs were carried out to select the best 100 runs for as calibration set. Calibration and validation results were very similar; therefore, both calibration and validation results can be recognized as good representation.

Some of the simulations in the model calibration was captured the observations successfully (PO_4, TP and Chl *a* concentrations), however NO_3–N concentration and zooplankton biomass were captured weakly and NH_4–N concentration was underestimated by the model. Conducting sensitivity analysis and setting the calibration parameters accordingly, all the possible approaches were tried to enhance the capacity of the model to capture the processes that took place in Lake Eymir.

Although the model calibration was poor, the model predictions of possible future scenarios were acceptable especially for Chl *a* concentration. The results of doubling and halving nutrient scenarios were supportive of other studies. As the nutrient load increased, Chl *a* and nutrient concentrations increased along with zooplankton biomass. Decreasing nutrient load caused these variables to decrease as supported by other

studies. All the variables showed significant response to increase and decrease of nutrient load to the system.

On the other hand, increasing temperature scenario results can be debatable. With increasing temperature Chl *a* concentration increases, and the model results are in concert with this idea. However, with increasing temperature the model predicted decreasing nutrients and zooplankton. These results contradict with the idea that with increasing temperature, biological and chemical activity in the lake increases.

Furthermore, this study revealed that *PCLake* model could not handle the complex history of the lake. It can be concluded that *PCLake* might not give good results if the lake has complex history, if water level fluctuation is a major event for the lake or the lake bottom is not flat as most of the lakes in the North (i.e. Dutch and Danish lakes).

To sum up, *PCLake* was not an appropriate model to explain processes and changes taken place in Lake Eymir probably due to the lake's stratification, morphometry and water fluctuation issues. However, the *PCLake* model could have worked better if it was being used with another model (i.e. ensemble) for some of its weaknesses. For future studies, the model's weaknesses and strengths should be considered more carefully.

REFERENCES

Beklioğlu M., Burnak S. L. & İnce Ö. (2000). Benthi-planktivorous fish-induced low water quality of Lake Eymir before biomanipulation. *Turkish Journal of Zoology*, 24, 315-326.

Beklioğlu M., İnce Ö. & Tüzün I. (2003). Restoration of the eutrophic Lake Eymir, Turkey, by biomanipulation after a major external nutrient control I. *Hydrobiologia* (489), 93–105.

Beklioğlu M. & Tan C. O. (2008). Restoration of a shallow Mediterranean lake by biomanipulation complicated by drought. *Fundamental and Applied Limnology*, 171, 105–118.

Bucak T., Saraoğlu E., Levi E. E., Tavşanoğlu Ü. N., Çakıroğlu A. İ., Jeppesen E. & Beklioğlu M. (2012). The influence of water level on macrophyte growth and trophic interactions in eutrophic Mediterranean shallow lakes: a mesocosm experiment with and without fish. *Freshwater Biology* 57: 1631–1642.

Canfield Jr. D. E., & Hoyer M. V. (1988). Influence of nutrient enrichment and light availability on the abundance of aquatic macrophytes in Florida streams. *Canadian Journal of Fisheries and Aquatic Sciences* 45: 1467-1472.

Coppens J., Hejzlar J., Šorf M., Jeppesen E., Erdoğan Ş., Scharfenberger U., Mahdy A., Nõges P., Tuvikene A., Baho D.L., Trigal C., Papastergiadou E., Stefanidis K., Olsen S. & Beklioğlu M. (2015). The influence of nutrient loading and climate on nitrogen and phosphorus retention in shallow lakes: a pan-European mesocosm experiment ran at contrasting depths. Submitted to *Hydrobiologia*.

Forsberg C. (1987). Evaluation of lake restoration in Sweden. *Swiss Journal of Hydrology*, 49(2), 260-274.

Geldiay R. (1949). Çubuk barajı ve Emir Gölünün makro ve mikro faunasının mukayeseli incelenmesi. *Ankara Üniversitesi Fen Fakültesi Mecmuası* Cilt 2.

Gulati R. D. & Van Donk E. (2002). Lakes in the Netherlands, their origin, eutrophication and restoration: state-of-the-art review. *Hydrobiologia* 478:73–106.

Hansson L. A., Annadotter H., Bergman E., Hamrin S. F., Jeppesen E., Kairesalo T., Luokkanen E., Nilsson P. A., Søndergaard M. & Strand J. (1998). Biomanipulation as an application of food-chain theory: constraints, synthesis, and recommendations for temperate lakes. *Ecosystems* 1: 558–574.

Janse J. H., Van Donk E. & Gulati R. D. (1995). Modelling nutrient cycles in relation to food web structure in a biomanipulated shallow lake. *Netherlands Journal of Aquatic Ecology*, 29 (1), 67-79.

Janse J. H. (1997). A model of nutrient dynamics in shallow lakes in relation to multiple stable states. *Hydrobiologia*, 342/343, 1-8.

Janse J. H., Van Donk E. & Aldenberg T. (1998). A model study on the stability of the macrophyte-dominated state as affected by biological factors. *Water Research*, 32 (9), 2696-2706.

Janse J. H. (2005). Model studies on the eutrophication of shallow lakes and ditches. Wageningen University: Wagenin gen.

Janse J. H., De Senerpont Domis L. N., Scheffer M., Lijklema L., Van Liere L., Klinge M. & Mooij W. M. (2008). Critical phosphorus loading of different types of shallow lakes and the consequences for management estimated with the ecosystem model PCLake. *Limnologica* (38), 203–219.

Janse J. H., Scheffer M., Lijklema L., Van Liere L., Sloot J. S. & Mooij W. M. (2010). Estimating the critical phosphorus loading of shallow lakes with the ecosystem model PCLake: Sensitivity, calibration and uncertainty. *Ecological Modelling* (221), 654–665.

Jeppesen E., Jensen J. P., Søndergaard M., Lauridsen T., Pedersen L. J. & Jensen L. (1997). Top-down control in freshwater lakes : the role of nutrient state, submerged macrophytes and water depth, *Hydrobiologia*, 342-343,151–164.

Jeppesen E. (1998). The ecology of shallow lakes – Trophic interactions in the pelagial. Doctor's dissertation (DSC). NERI Technical Report No.247. Silkeborg. pp. 358.

Jeppesen E., Jensen J. P., Søndergaard M., Hansen K. S., Møller P. H., Rasmussen H. U., Norby V. & Larsen S. E. (2003). Does resuspension, prevent a shift to a clear state in shallow lakes during re-oligotrophication? *Limnol. Oceanogr*. 48(5): 1913-1919.

Jeppesen E., Jensen J. P., Søndergaard M. & Lauridsen T. L. (2005). Response of Fish and Plankton to Nutrient Loading Reduction in Eight Shallow Danish Lakes with Special Emphasis on Seasonal Dynamics. *Freshwater Biology* (50), 1616–1627.

Jeppesen E., Meerhoff M., Jacobsen B. A., Hansen R. S., Søndergaard M., Jensen J. P., Lauridsen T. L., Mazzeo N. & Branco C. W. C. (2007). Restoration of shallow lakes by nutrient control and biomanipulation—the successful strategy varies with lake size and climate. *Hydrobiologia*, 581 (1), 269-285.

Jeppesen E., Brucet S., Naselli-Flores L., Papastergiadou E., Stefanidis K., Noges T. Noges P., Attayde L. J., Zohary T., Coppens J., Bucak T., Menezes R. F., Freitas F. R. S., Søndergaard M. & Beklioğlu M. (2015). Ecological impacts of global warming and water abstraction on lakes and reservoirs due to changes in water level and related changes in salinity. *Hydrobiologia*, 750(1), 201-227.

Mehner T., Benndorf J., Kasprzak P. & Koschel R. (2002). Biomanipulation of lake ecosystems: successful applications and expanding complexity in the underlying science. *Freshwater Biology* 47**:** 2453–2465.

Meijer M. L., de Boois I., Scheffer M., Portielje R. & Hosper H. (1999). Biomanipulation in shallow lakes in The Netherlands: an evaluation of 18 case studies. In Shallow Lakes' 98 (pp. 13-30). Springer Netherlands.

Mooij W. M., Janse J. H., Domis L. D. S., Hülsmann S. & Ibelings B. W. (2007). Predicting the effect of climate change on temperate shallow lakes with the ecosystem model PCLake. In Shallow Lakes in a Changing World (pp. 443-454). Springer Netherlands.

Mooij W., Trolle D., Jeppesen E., Arhonditsis G., Belolipetsky P., Chitamwebwa D., Degermendzhy A., DeAngelis D., De Senerpont Domis L., Downing A., Elliott J., Fragoso C., Gaedke U., Genova S., Gulati R., Håkanson L., Hamilton D., Hipsey M., 't Hoen J., Hülsmann S., Los F., Makler-Pick V., Petzoldt T., Prokopkin I., Rinke K., Schep S., Tominaga K., Van Dam A., Van Nes E., Wells S. & Janse J. (2010). Challenges and opportunities for integrating lake ecosystem modelling approaches. *Aquatic Ecology* 44. 633-667.

Moss B., Madwewick J. & Phillips G. (1996). A guide to the restoration of nutrient-enriched shallow lakes. W.W. Hawes, UK, 177 pp.

Moss, B. (1998). The ecology of freshwaters, man and medium, past to future 3rd edn. Blackwell Science, Oxford, 557 pp.

Nielsen A., Trolle D., Me W., Luo L., Han B., Liu Z., Olesen J. E., & Jeppesen E. (2013). Assessing ways to combat eutrophication in Chinese drinking water reservoir using SWAT. *Marine and Freshwater Research*, **64**, 475-492.

Nielsen A., Trolle D., Bjerring R., Søndergaard M., Olesen J. E., Janse J. H. & Jeppesen E. (2014). Effects of climate and nutrient load on the water quality of shallow lakes assessed through ensemble runs by PCLake. Ecological Applications, 24 (8), 1926-1944.

Rolighed J. (2013). Climate change makes re-oligotrophication more difficult - A PCLake model study of shallow, Danish Lake Søbygaard, Aarhus University

Sas H. (1989). Lake restoration by reduction of nutrient loading: Expectations, Experiences, Extrapolations. St. Augustin 1: Akademia Verl. Richarz. ISBN 3-88345379-X.

Scasso F., Mazzeo N., Gorga J., Kruk C., Lacerot G., Clemente J., Fabian D. & Bonilla S. (2001). Limnological changes in a sub-tropical shallow hypertrophic lake during its restoration: two years of a whole-lake experiment. *Aquatic Conservation: Marine & Freshwater Ecosystems* 11: 31–44.

Scheffer M., Hosper S. H., Meijer M. L., Moss B. & Jeppesen E. (1993). Alternative Equilibria in Shallow Lakes. *TREE*, 8 (8), 275-279.

Søndergaard M., Jensen J. P. & Jeppesen E. (1999). Internal phosphorus loading in shallow Danish lakes. In Shallow Lakes' 98 (pp. 145-152). Springer Netherlands.

Søndergaard M., Jensen P. J. & Jeppesen E. (2003). Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia*, 506 (509), 135–145.

Tan C. O. & Beklioğlu M. (2005). Catastrophic-like shifts in shallow Turkish lakes: a modeling approach. *Ecological Modelling*, 183 (4), 425-434.

Trolle D., Skovgaard H., Jeppesen E. (2008). The water framework directive: setting the phosphorus loading target for a deep lake in Denmark using the 1D lake ecosystem model DYRESM-CAEDYM. *Ecological Modelling* 219:138–152.

Trolle D., Hamilton D. P., Hipsey M. R., Bolding K., Bruggeman J., Mooij W. M., Janse, J. H., Nielsen A., Jeppesen E., Elliott J. A., Makler-Pick V., Petzoldt T., Rinke K., Flindt M. R., Arhonditsis G. B., Gal G., Bjerring R., Tominaga K., Hoen J., Downing A. S., Marques D. M., Fragoso Jr. C. R., Sondergaard M., Hanson P. C., (2012). A community-based framework for aquatic ecosystem models. *Hydrobiologia* 1001BF-01, 27/05/2013 March 2012, 683, 1, pp 25-34.

Trolle D., Nielsen A., Rolighed J., Thodsen H., Andersen H. E., Karlsson I. B., Refsgaard J. C., Olesen J. E., Bolding K., Kronvang B., Søndergaard M. & Jeppesen E. (2015). Projecting the future ecological state of lakes in Denmark in a 6 degree warming scenario. *Climate Research*, 64, 55-72.

Özen A., Karapınar B., Kucuk İ., Jeppesen E. & Beklioğlu M. (2010). Drought-induced changes in nutrient concentrations and retention in two shallow Mediterranean lakes subjected to different degrees of management. *Hydrobiologia*, 646 (1), 61-72.

APPENDIX A

LIST OF PARAMETERS

Table A: IDs, names, units and descriptions of the parameters given by Janse (2005).

ID	Name	Unit	Description
0	BeginTime	day	BeginTime [0.0] day ; begintime
1	EndTime	day	EndTime [365.0] day ; (=1 year)
2	InitCalc	-	InitCalc [1.0] ; If T, skip calculation of initial values; used in case of REINIT command.
3	ConstDepth	-	ConstDepth [1.0] ; If T, water depth kept constant by "daily dredging".
4	InclTran	-	InclTran [1.0] ;
5	InclPrim	-	InclPrim [1.0] ;
6	InclPhytS	-	InclPhytS [1.0] ;
7	InclBed	-	InclBed [1.0] ;
8	InclWeb	-	InclWeb [1.0] ;
9	InclMarsh	-	InclMarsh [1.0] ;
10	UseWindFunc	-	UseWindFunc [0.0] ; FALSE = no wind function for shear stress,
11	ReadTemp	-	ReadTemp [0.0] ; If TRUE use measured time-series of temperature, otherwise sinus
12	ReadLOut	-	ReadLOut [0.0] ; If TRUE use measured time-series of light, otherwise sinus
13	ReadVWind	-	ReadVWind [0.0] ; If TRUE use measured time-series of wind, otherwise constant
14	RewindInput	-	RewindInput [0.0] ; Only important if time-series are being used.
15	YearZero	-	YearZero [0.0] ; Note: also Dayno 1 = 1. Jan. of this year.
16	cAerLin	s/day	cAerLin [-0.371] s/day ; coefficient for VWind (is negative.)
17	cAerRoot	-	cAerRoot [0.727] ; coefficient for VWind^0.5
18	cAerSquare	-	cAerSquare [0.0376] ; coefficient for VWind^2

Table A: continued

ID	Name	Unit	Description
19	cAffNUptBlue	l/mgDW/day	cAffNUptBlue [0.2] l/mgDW/day ; initial N uptake affinity Bluegreens
20	cAffNUptDiat	l/mgDW/day	cAffNUptDiat [0.2] l/mgDW/day ; initial N uptake affinity Diatoms
21	cAffNUptGren	l/mgDW/day	cAffNUptGren [0.2] l/mgDW/day ; initial N uptake affinity greens
22	cAffNUptPhra	l/mgD/day	cAffNUptPhra [0.0002] l/mgD/day ; N uptake affinity reed
23	cAffNUptVeg	l/mgD/day	cAffNUptVeg [0.2] l/mgD/day ; initial N uptake affinity vegetation
24	cAffPUptBlue	l/mgDW/day	cAffPUptBlue [0.8] l/mgDW/day ; initial P uptake affinity Bluegreens
25	cAffPUptDiat	l/mgDW/day	cAffPUptDiat [0.2] l/mgDW/day ; initial P uptake affinity Diatoms
26	cAffPUptGren	l/mgDW/day	cAffPUptGren [0.2] l/mgDW/day ; initial P uptake affinity greens
27	cAffPUptPhra	l/mgD/day	cAffPUptPhra [0.0002] l/mgD/day ; P uptake affinity reed
28	cAffPUptVeg	l/mgD/day	cAffPUptVeg [0.2] l/mgD/day ; initial P uptake affinity vegetation
29	cBirdsPerha	n/ha	cBirdsPerha [0.0] n/ha ; number of birds per ha vegetated lake (Default = 0)
30	cChDBlueMax	mgChl/mgDW	cChDBlueMax [0.015] mgChl/mgDW ; max. chlorophyll/C ratio Bluegreens
31	cChDBlueMin	mgChl/mgDW	cChDBlueMin [0.005] mgChl/mgDW ; min. chlorophyll/C ratio Bluegreens
32	cChDDiatMax	mgChl/mgDW	cChDDiatMax [0.012] mgChl/mgDW ; max. chlorophyll/C ratio Diatoms
33	cChDDiatMin	mgChl/mgDW	cChDDiatMin [0.004] mgChl/mgDW ; min. chlorophyll/C ratio Diatoms
34	cChDGrenMax	mgChl/mgDW	cChDGrenMax [0.02] mgChl/mgDW ; max. chlorophyll/C ratio greens
35	cChDGrenMin	mgChl/mgDW	cChDGrenMin [0.01] mgChl/mgDW ; min. chlorophyll/C ratio greens
36	cCovSpPhra	gD/ m^2	cCovSpPhra [0.1] % cover per gD/m^2 ; specific coverage
37	cCovSpPhyt	gD/ m^2	cCovSpPhyt [2.0] % per gD/m^2 ; specific coverage Tentative
38	cCovSpVeg	gD/ m^2	cCovSpVeg [0.5] % cover per gD/m^2 ; specific cover

Table A: continued

39	cCovVegMin	%	cCovVegMin [40.0] % ; min. subm.veg. coverage for Pisc
40	cCPerDW	gC/gDW	cCPerDW [0.4] gC/gDW ; C content of organic matter
41	cCyDBlueMax	mgChl/mgDW	cCyDBlueMax [0.06] mgChl/mgDW ; max. c-phycocyanin/C ratio Bluegreens
42	cCyDBlueMin	mgChl/mgDW	cCyDBlueMin [0.004] mgChl/mgDW ; min. c-phycocyanin/C ratio Bluegreens
43	cDayApril1	day	cDayApril1 [91.0] day ; April 1
44	cDayEndBirds	day	cDayEndBirds [288.0] day ; yearly last day of birds' presence
45	cDayManPhra	day	cDayManPhra [255.0] day ; time of management
46	cDayManVeg1	day	cDayManVeg1 [-9999000.0] day ; first mowing day (default: non-existent)
47	cDayManVeg2	day	cDayManVeg2 [-9999000.0] day ; second mowing day (Note: 259 = 16 Sep)
48	cDayOct1	day	cDayOct1 [273.0] day ; October 1
49	cDayReprFish	-	cDayReprFish [120.0] - ; reproduction date of fish = 1 May
50	cDayStartBirds	day	cDayStartBirds [46.0] day ; yearly first day of birds' presence
51	cDayWinPhra	day	cDayWinPhra [259.0] day ; begin autumn(16 sept.)
52	cDayWinVeg	day	cDayWinVeg [259.0] day ; end of growing season = 16 Sep
53	cDBentIn	gD/ m^2	cDBentIn [0.01] gD/m^2 ; external zoobenthos density
54	cDCarrBent	-	cDCarrBent [10.0] ; tentative
55	cDCarrFish	gDW/ m^2	cDCarrFish [15.0] gDW/m^2 ; carrying capacity of fish(= 100 gFW/m2,Grimm 1983)
56	cDCarrPiscBare	gDW. m^{-2}	cDCarrPiscBare [0.1] gDW.m^{-2} ; carrying capacity of Pisc for lake without marsh zone
57	cDCarrPiscMax	gDW. m^{-2}	cDCarrPiscMax [1.2] gDW.m^{-2} ; maximum carrying capacity of Pisc(=75 kg/ha)
58	cDCarrPiscMin	gDW. m^{-2}	cDCarrPiscMin [0.1] gDW.m^{-2} ; minimum carrying capacity of Pisc(=6 kg/ha)
59	cDCarrVeg	gDW/ m^2	cDCarrVeg [400.0] gDW/m^2 ; max. vegetation standing crop

Table A: continued

ID	Name	Unit	Description
60	cDCarrZoo	mg/l	cDCarrZoo [25.0] mg/l ; carrying capacity of zooplankton
61	cDensStemPhra	m^{-2}	cDensStemPhra [61.5] m^{-2} ; density stem(+/- 13.9)
62	cDepthRef	day	cDepthRef [0.00000000000000000000000000000001] day ; reference water depth for dredging
63	cDepthS	m	cDepthS [0.1] m ; sediment depth
64	cDepthSM	m	cDepthSM [0.1] m ; sediment depth
65	cDErosTot	g/ m^2/day	cDErosTot [0.1] g/m^2/day ; Erosion input (tentative)
66	cDFiAdIn	gD/ m^2	cDFiAdIn [0.005] gD/m^2 ; external fish density
67	cDFiJvIn	gD/ m^2	cDFiJvIn [0.005] gD/m^2 ; external fish density
68	cDGrazPerBird	gD/coot/day	cDGrazPerBird [45.0] gD/coot/day ; daily grazing of birds
69	cDIMIn	mgD/l	cDIMIn [5.0] mgD/l ; IM conc. in inflow
70	cDLayerVeg	gD/ m^2	cDLayerVeg [0.0] gD/m2 ; biomass of a single layer floating leaves
71	cDPhraMinPisc	gD. m^{-2}	cDPhraMinPisc [50.0] gD.m^{-2} ; min. reed biomass for Pisc
72	cDPiscIn	gD/ m^2	cDPiscIn [0.001] gD/m^2 ; external Pisc density
73	cDredInterval	y	cDredInterval [9999000.0] y ; dredging interval
74	cDredStart	y	cDredStart [9999000.0] y ; first dredging year (should be n times cDredInterval)
75	cDShootPhraMax	gD/ m^2	cDShootPhraMax [3500.0] gD/m^2 ; max. shoot biomass of reed
76	cDStemPhra	g/m	cDStemPhra [6.0] g/m ; average stem weight
77	cDVegIn	-	cDVegIn [1.0] gD/m^2 ; "external vegetation density"
78	cDZooIn	mgD/l	cDZooIn [0.1] mgD/l ; zoopl. conc. in inflowing water
79	cEuph	-	cEuph [1.7] - ; conversion constant Secchi depth -> euphotic depth
80	cExtSpBlue	m^2/gDW	cExtSpBlue [0.35] m^2/gDW ; specific extinction Bluegreens
81	cExtSpDet	m^2/gDW	cExtSpDet [0.15] m^2/gDW ; specific extinction detritus
82	cExtSpDiat	m^2/gDW	cExtSpDiat [0.25] m^2/gDW ; specific extinction Diatoms

Table A: continued

ID	Name	Unit	Description
83	cExtSpGren	m^2/gDW	cExtSpGren [0.25] m^2/gDW ; specific extinction greens
84	cExtSpIM	m^2/gDW	cExtSpIM [0.05] m^2/gDW ; specific extinction inert matter
85	cExtSpVeg	m^2/gDW	cExtSpVeg [0.01] m^2/gDW ; specific extinction
86	cExtWat	m^{-1}	cExtWat [0.5] m^{-1} ; background extinction
87	cfDayAve	-	cfDayAve [0.5] - ; average day length
88	cfDayVar	-	cfDayVar [0.2] - ; annual variation in day length
89	cFetch	m	cFetch [1000.0] m ; wind fetch
90	cFetchRef	-	cFetchRef [1000.0] ;
91	cFiltMax	ltr/mgDW/day	cFiltMax [4.5] ltr/mgDW/day ; maximum filtering rate(when DOMW=0)
92	cKPAdsOx	m^3/gP	cKPAdsOx [0.6] m^3/gP ; P adsorption affinity at oxidized conditions
93	cLDayAve	$J/ m^2/day$	cLDayAve [10000000.0] $J/m^2/day$; annual average radiation
94	cLDayVar	$J/ m^2/day$	cLDayVar [8000000.0] $J/m^2/day$; annual variation in radiation
95	cLengAllo	day	cLengAllo [15.0] day ; duration of allocation and reallocation phase
96	cLengChange	day	cLengChange [10.0] day ; length of season change
97	cLengDred	day	cLengDred [10.0] day ; length of dredging period
98	cLengMan	day	cLengMan [10.0] day ; length of mowing period
99	cLengMort	day	cLengMort [15.0] day ; duration of autumn mortality period
100	cLengMortShoot	day	cLengMortShoot [42.0] day ; length of shoot mort. period
101	cLOptRefBlue	W/ m^2	cLOptRefBlue [13.6] W/m^2 ; optimum PAR for blue-greens at 20 oC(Steele function)
102	cLOptRefDiat	W/ m^2	cLOptRefDiat [54.0] W/m^2 ; optimum PAR for Diatoms at 20 oC(Steele function)
103	cLOptRefGren	W/ m^2	cLOptRefGren [1000.0] W/m^2 ; optimum PAR at 20 oC(Steele function) Fake value
104	cMuMaxBlue	day-1	cMuMaxBlue [0.6] day^{-1} ; maximum growth rate Bluegreens
105	cMuMaxDiat	day-1	cMuMaxDiat [2.0] day^{-1} ; maximum growth rate Diatoms

Table A: continued

ID	Name	Unit	Description
106	cMuMaxGren	day-1	cMuMaxGren [1.5] day^{-1} ; maximum growth rate greens
107	cMuMaxVeg	g/g	cMuMaxVeg [0.2] g/g shoot/day ; maximum growth rate of vegetation at 20oC
108	cMuPhraMax	1/day	cMuPhraMax [0.030] 1/day ; maximum growth rate reed
109	cNBackLoad	-	cNBackLoad [0.0] ; 0.009
110	cNDBentRef	mgN/mgDW	cNDBentRef [0.07] mgN/mgDW ; reference N/C ratio of zoobenthos
111	cNDBlue0	gN/gD	cNDBlue0 [0.1] gN/gD ; initial N fraction in blue-green algae
112	cNDBlueMax	-	cNDBlueMax [0.15] ; 0.12
113	cNDBlueMin	mgN/mgDW	cNDBlueMin [0.03] mgN/mgDW ; minimum N/day ratio Bluegreens
114	cNDCera0	gN/gD	cNDCera0 [0.02] gN/gD ; initial N fraction in Cera.
115	cNDChar0	gN/gD	cNDChar0 [0.02] gN/gD ; initial N fraction in Char.
116	cNDDet0	gN/gDDet	cNDDet0 [0.025] gN/gDDet ; initial N fraction in detritus
117	cNDDetIn	gN/gD	cNDDetIn [0.07] gN/gD ; N/P ratio of detrital input
118	cNDDiat0	gN/gD	cNDDiat0 [0.1] gN/gD ; initial N fraction in diatoms
119	cNDDiatMax	mgN/mgDW	cNDDiatMax [0.05] mgN/mgDW ; max. N/day ratio Diatoms
120	cNDDiatMin	mgN/mgDW	cNDDiatMin [0.01] mgN/mgDW ; minimum N/day ratio Diatoms
121	cNDElod0	gN/gD	cNDElod0 [0.02] gN/gD ; initial N fraction in Elod.
122	cNDFishRef	mgN/mgDW	cNDFishRef [0.1] mgN/mgDW ; reference N/C ratio of Fish
123	cNDGren0	gN/gD	cNDGren0 [0.1] gN/gD ; initial N fraction in green algae
124	cNDGrenMax	mgN/mgDW	cNDGrenMax [0.1] mgN/mgDW ; max. N/day ratio greens
125	cNDGrenMin	mgN/mgDW	cNDGrenMin [0.02] mgN/mgDW ; minimum N/day ratio greens
126	cNDHelo0	gN/gD	cNDHelo0 [0.02] gN/gD ; initial N fraction in Helo.

Table A: continued

ID	Name	Unit	Description
127	cNDHum0	gN/gDDet	cNDHum0 [0.05] gN/gDDet ; initial N fraction in humus
128	cNDLemn0	gN/gD	cNDLemn0 [0.05] gN/gD ; initial N fraction in Lemn.
129	cNDNymp0	gN/gD	cNDNymp0 [0.02] gN/gD ; initial N fraction in Nymp.
130	cNDPhra0	gN/gD	cNDPhra0 [0.02] gN/gD ; initial N/day ratio of reed
131	cNDPhraMax	-	cNDPhraMax [0.03] - ; max.Phra N/day -ratio
132	cNDPhraMin	-	cNDPhraMin [0.008] - ; min.Phra N/day -ratio
133	cNDPhyt0	gN/gD	cNDPhyt0 [0.1] gN/gD ; initial N fraction in algae
134	cNDPhytIn	gN/gD	cNDPhytIn [0.07] gN/gD ; N/day ratio of algal input
135	cNDPisc	mgN/mgDW	cNDPisc [0.1] mgN/mgDW ; reference N/C ratio of Pisc
136	cNDSoilOM	gN/gD	cNDSoilOM [0.01] gN/gD ; N/day ratio of soil organic matter
137	cNDVeg0	gN/gD	cNDVeg0 [0.02] gN/gD ; initial N fraction in veg.
138	cNDVegMax	mgN/mgD	cNDVegMax [0.035] mgN/mgD ; maximum N/day ratio vegetation
139	cNDVegMin	mgN/mgD	cNDVegMin [0.01] mgN/mgD ; minimum N/day ratio vegetation
140	cNDZooRef	mgN/mgDW	cNDZooRef [0.07] mgN/mgDW ; reference N/C-ratio herb. zooplankton
141	cNH4Ground	mgN/l	cNH4Ground [1.0] mgN/l ;
142	cNLoad	gN/ m^2/day	cNLoad [0.05] gN/m^2/day ; standard N loading
143	cNLoadS	gN/ m^2/day	cNLoadS [0.0] gN/m^2/day ; N fertilizer to sediment
144	cNLoadSum	gN/ m^2/day	cNLoadSum [0.05] gN/m^2/day ; summer N loading
145	cNLoadWin	gN/ m^2/day	cNLoadWin [0.05] gN/m^2/day ; winter N loading
146	cNO3Ground	mgN/l	cNO3Ground [0.1] mgN/l ;
147	cNPDetIn	gP/gD	cNPDetIn [7.0] gP/gD ; N/P ratio of detrital input
148	cNPLoadMeas	gN/gP	cNPLoadMeas [7.0] gN/gP ; N/P loading if P is measured and N not
149	cNPPhytIn	gP/gD	cNPPhytIn [7.0] gP/gD ; N/P ratio of algal input
150	cO2In	mgO_2/l	cO2In [5.0] mgO2/l ; O_2 conc. in inflow

Table A: continued

ID	Name	Unit	Description
151	coPO4Max	mgP/l	coPO4Max [1.0] mgP/l ; max. SRP conc. in pore water
152	cPACoefMax	-	cPACoefMax [2.5] ; 3.0
153	cPACoefMin	-	cPACoefMin [1.5] - ; minimum Poole-Atkins coefficient
154	cPBackLoad	-	cPBackLoad [0.0] ; 0.00016
155	cPDBentRef	mgP/mgDW	cPDBentRef [0.01] mgP/mgDW ; reference P/C ratio of zoobenthos
156	cPDBlue0	gP/gD	cPDBlue0 [0.01] gP/gD ; initial P fraction in blue-green algae
157	cPDBlueMax	mgP/mgDW	cPDBlueMax [0.025] mgP/mgDW ; max. P/day ratio blue-greens
158	cPDBlueMin	mgP/mgDW	cPDBlueMin [0.0025] mgP/mgDW ; minimum P/day ratio Bluegreens
159	cPDCera0	gP/gD	cPDCera0 [0.002] gP/gD ; initial P fraction in Cera.
160	cPDChar0	gP/gD	cPDChar0 [0.002] gP/gD ; initial P fraction in Char.
161	cPDDet0	gP/gDDet	cPDDet0 [0.0025] gP/gDDet ; initial P fraction in detritus
162	cPDDiat0	gP/gD	cPDDiat0 [0.01] gP/gD ; initial P fraction in diatoms
163	cPDDiatMax	mgP/mgDW	cPDDiatMax [0.005] mgP/mgDW ; max. P/day ratio Diatoms
164	cPDDiatMin	mgP/mgDW	cPDDiatMin [0.0005] mgP/mgDW ; minimum P/day ratio Diatoms
165	cPDElod0	gP/gD	cPDElod0 [0.002] gP/gD ; initial P fraction in Elod.
166	cPDFishRef	mgP/mgDW	cPDFishRef [0.022] mgP/mgDW ; reference P/C ratio of Fish
167	cPDGren0	gP/gD	cPDGren0 [0.01] gP/gD ; initial P fraction in green algae
168	cPDGrenMax	mgP/mgDW	cPDGrenMax [0.015] mgP/mgDW ; max. P/day ratio greens
169	cPDGrenMin	mgP/mgDW	cPDGrenMin [0.0015] mgP/mgDW ; minimum P/day ratio greens
170	cPDHelo0	gP/gD	cPDHelo0 [0.002] gP/gD ; initial P fraction in Helo.
171	cPDHum0	gP/gDDet	cPDHum0 [0.005] gP/gDDet ; initial P fraction in humus

Table A: continued

ID	Name	Unit	Description
172	cPDLemn0	gP/gD	cPDLemn0 [0.005] gP/gD ; initial P fraction in Lemn.
173	cPDNymp0	gP/gD	cPDNymp0 [0.002] gP/gD ; initial P fraction in Nymp.
174	cPDPhra0	gP/gD	cPDPhra0 [0.002] gP/gD ; initial P/day ratio of reed
175	cPDPhraMax	-	cPDPhraMax [0.003] - ; max.Phra P/day -ratio
176	cPDPhraMin	-	cPDPhraMin [0.0008] - ; min.Phra P/day -ratio
177	cPDPhyt0	gP/gD	cPDPhyt0 [0.01] gP/gD ; initial P fraction in algae
178	cPDPisc	mgP/mgDW	cPDPisc [0.022] mgP/mgDW ; reference P/C ratio of Pisc
179	cPDSoilOM	gP/gD	cPDSoilOM [0.001] gP/gD ; P/day ratio of soil organic matter
180	cPDVeg0	gP/gD	cPDVeg0 [0.002] gP/gD ; initial P fraction in veg.
181	cPDVegMax	mgP/mgD	cPDVegMax [0.0035] mgP/mgD ; maximum P/day ratio vegetation
182	cPDVegMin	mgP/mg	cPDVegMin [0.0008] mgP/mg ; minimum P/day ratio vegetation
183	cPDZooRef	mgP/mgDW	cPDZooRef [0.01] mgP/mgDW ; reference P/C-ratio herb. zooplankton
184	cPLoad	gP/ m^2/day	cPLoad [0.005] gP/m^2/day ; standard P loading if not measured
185	cPLoadSum	gP/ m^2/day	cPLoadSum [0.005] gP/m^2/day ; summer P loading if not measured
186	cPLoadWin	gP/ m^2/day	cPLoadWin [0.005] gP/m^2/day ; winter P loading if not measured
187	cPO4Ground	mgP/l	cPO4Ground [0.1] mgP/l ;
188	cPrefBlue	-	cPrefBlue [0.125] - ; selection factor for Bluegreens Cal.
189	cPrefDet	-	cPrefDet [0.25] - ; selection factor for detritus
190	cPrefDiat	-	cPrefDiat [0.75] - ; selection factor for Diatoms
191	cPrefGren	-	cPrefGren [0.75] - ; selection factor for Greens
192	cPrefVegBird	-	cPrefVegBird [1.0] - ; edibility for birds
193	cQ10ProdPhra	-	cQ10ProdPhra [2.0] - ; temp. quotient of production
194	cQ10ProdVeg	-	cQ10ProdVeg [1.2] - ; temperature quotient of production

Table A: continued

ID	Name	Unit	Description
195	cQ10RespPhra	1/e^°C	cQ10RespPhra [2.5] 1/e^°C ; temp. quotient of respiration
196	cQ10RespVeg	-	cQ10RespVeg [2.0] - ; temperature quotient of respiration
197	cQEvAve	mm/day	cQEvAve [1.5] mm/day ; standard average evaporation
198	cQEvVar	mm/day	cQEvVar [1.3] mm/day ; standard variation in evaporation
199	cQIn	mm/day	cQIn [20.0] mm/day ; standard water inflow if not measured
200	cQInExtraApril1	mm/day	cQInExtraApril1 [0.0] mm/day ; extra inflow at start of summer
201	cQInExtraOct1	mm/day	cQInExtraOct1 [0.0] mm/day ; extra inflow at start of winter
202	cQInf	mm/day	cQInf [0.0] mm/day ; infiltration rate
203	cQInSum	mm/day	cQInSum [20.0] mm/day ; summer water inflow if not measured
204	cQInWin	mm/day	cQInWin [20.0] mm/day ; winter water inflow if not measured
205	cQOutExtraApril 1	mm/day	cQOutExtraApril1 [0.0] mm/day ; extra outflow at start of summer
206	cQOutExtraOct1	mm/day	cQOutExtraOct1 [0.0] mm/day ; extra outflow at start of winter
207	cRelPAdsAl	gP/gAl	cRelPAdsAl [0.134] gP/gAl ; max. P adsorption per g Al
208	cRelPAdsD	gP/gD	cRelPAdsD [0.00003] gP/gD ; max. P adsorption per g DW
209	cRelPAdsFe	gP/gFe	cRelPAdsFe [0.065] gP/gFe ; max. P adsorption per g Fe
210	cRelPhraPisc	gD.m-2.%-1	cRelPhraPisc [0.075] gD.m-2.%$^{-1}$; rel. Pisc density per % reed if subm.veg. absent
211	cRelVegFish	-	cRelVegFish [0.009] - ; decrease of fish feeding per % vegetation cover(max. 0.01)
212	cRelVegPisc	gD.m-2.%-1	cRelVegPisc [0.03] gD.m-2.%$^{-1}$; extra rel. Pisc density per % reed if aCovVeg > cCovVegMin
213	cResusPhytExp	(gD/m2/day)-1	cResusPhytExp [-0.379] (gD/m2/day)$^{-1}$; exp. par. for phytopl. resuspension
214	cRhoIM	g/m3	cRhoIM [2500000.0] g/m^3 solid ; density of sediment IM

Table A: continued

ID	Name	Unit	Description
215	cRhoOM	g/m3	cRhoOM [1400000.0] g/m^3 ; density of sediment detritus
216	cSecchiPlus	m	cSecchiPlus [0.0] m ; maximum Secchi depth above water depth
217	cSiDDet0	gSi/gDDet	cSiDDet0 [0.01] gSi/gDDet ; initial Si fraction in detritus Tentative
218	cSiDDetIn	gSi/gD	cSiDDetIn [0.05] gSi/gD ;
219	cSiDDiat	-	cSiDDiat [0.15] ; (Mylius, 1991)
220	cSigTmBent	^oC	cSigTmBent [16.0] ^oC ; temperature constant of zoobenthos(sigma in Gaussian curve)
221	cSigTmBlue	^oC	cSigTmBlue [12.0] ^oC ; temperature constant blue-greens(sigma in Gaussian curve)
222	cSigTmDiat	^oC	cSigTmDiat [20.0] ^oC ; temperature constant diatoms(sigma in Gaussian curve)
223	cSigTmFish	^oC	cSigTmFish [10.0] ^oC ; temperature constant of fish(sigma in Gaussian curve)
224	cSigTmGren	^oC	cSigTmGren [15.0] ^oC ; temperature constant greens(sigma in Gaussian curve)
225	cSigTmLoss	^oC	cSigTmLoss [13.0] ^oC ; temperature constant of grazing(sigma in Gaussian curve)
226	cSigTmPisc	^oC	cSigTmPisc [10.0] ^oC ; temperature constant of Pisc(sigma in Gaussian curve)
227	cSigTmZoo	^oC	cSigTmZoo [13.0] ^oC ; temperature constant zooplankton(sigma in Gaussian curve)
228	cSiO2In	mgSi/l	cSiO2In [3.0] mgSi/l ; SiO_2 conc. in inflow
229	cSuspMax	-	cSuspMax [25.2] ;
230	cSuspMin	-	cSuspMin [6.1] ;
231	cSuspRef	-	cSuspRef [0.5] ; CONSTANT cVCritResus = 0.1
232	cSuspSlope	-	cSuspSlope [2.1] ;
233	cThetaAer	1/e^^{o}C	cThetaAer [1.024] 1/e^^{o}C ; Temperature coeff. for reaeration (Downing & Truesdale 1955)
234	cThetaDif	-	cThetaDif [1.02] ; Temperature coefficient for diffusion
235	cThetaMinS	-	cThetaMinS [1.07] - ; expon. temp. constant of sediment mineralization
236	cThetaMinW	-	cThetaMinW [1.07] - ; expon. temp. constant of mineralization in water
237	cThetaNitr	-	cThetaNitr [1.08] ;

Table A: continued

ID	Name	Unit	Description
238	cThetaSet	1/e^°C	cThetaSet [1.01] 1/e^°C ; temp. parameter of sedimentation
239	cTimeLag	day	cTimeLag [40.0] day ; time lag for temperature
240	cTmAve	°C	cTmAve [12.0] °C ; average water temperature
241	cTmInitPhra	°C	cTmInitPhra [8.0] °C ; temp.start initial growth
242	cTmInitVeg	°C	cTmInitVeg [9.0] °C ; temperature for initial growth
243	cTmOptBent	°C	cTmOptBent [25.0] °C ; optimum temp. of zoobenthos
244	cTmOptBlue	°C	cTmOptBlue [25.0] °C ; optimum temp. blue-greens
245	cTmOptDiat	°C	cTmOptDiat [18.0] °C ; optimum temp. diatoms
246	cTmOptFish	°C	cTmOptFish [25.0] °C ; optimum temp. of fish
247	cTmOptGren	°C	cTmOptGren [25.0] °C ; optimum temp. of greens
248	cTmOptLoss	°C	cTmOptLoss [25.0] °C ; optimum temp. for grazing
249	cTmOptPisc	°C	cTmOptPisc [25.0] °C ; optimum temp. of Pisc
250	cTmOptZoo	°C	cTmOptZoo [25.0] °C ; optimum temp. zooplankton
251	cTmRef	°C	cTmRef [20.0] °C ; reference temperature
252	cTmVar	°C	cTmVar [10.0] °C ; annual temperature variation
253	cTurbDifNut	-	cTurbDifNut [5.0] - ; bioturbation factor for diffusion
254	cTurbDifO2	-	cTurbDifO2 [5.0] - ; bioturbation factor for diffusion
255	cVNUptMaxBlue	mgN/mgDW/day	cVNUptMaxBlue [0.07] mgN/mgDW/day ; maximum N uptake capacity of Bluegreens
256	cVNUptMaxDiat	mgN/mgDW/day	cVNUptMaxDiat [0.07] mgN/mgDW/day ; maximum N uptake capacity of Diatoms
257	cVNUptMaxGren	mgN/mgDW/day	cVNUptMaxGren [0.07] mgN/mgDW/day ; maximum N uptake capacity of greens
258	cVNUptMaxVeg	mgN/mgD/day	cVNUptMaxVeg [0.1] mgN/mgD/day ; maximum N uptake capacity of vegetation
259	cVNUptPhraMax	mgN/mgD/day	cVNUptPhraMax [0.1] mgN/mgD/day ; max. uptake rate N 0.01
260	cVPUptMaxBlue	mgP/mgDW/day	cVPUptMaxBlue [0.04] mgP/mgDW/day ; maximum P uptake capacity of Bluegreens

Table A: continued

ID	Name	Unit	Description
261	cVPUptMaxDiat	mgP/mgDW/day	cVPUptMaxDiat [0.01] mgP/mgDW/day ; maximum P uptake capacity of Diatoms
262	cVPUptMaxGren	mgP/mgDW/day	cVPUptMaxGren [0.01] mgP/mgDW/day ; maximum P uptake capacity of greens
263	cVPUptMaxVeg	mgP/mgD/day	cVPUptMaxVeg [0.01] mgP/mgD/day ; maximum P uptake capacity of vegetation
264	cVPUptPhraMax	mgP/mgD/day	cVPUptPhraMax [0.01] mgP/mgD/day ; max. uptake rate P 0.001
265	cVSetBlue	m/day	cVSetBlue [0.06] m/day ; sedimentation velocity Blue-greens
266	cVSetDet	m/day	cVSetDet [0.25] m/day ; max. sedimentation velocity of detritus
267	cVSetDiat	m/day	cVSetDiat [0.5] m/day ; sedimentation velocity Diatoms
268	cVSetGren	-	cVSetGren [0.2] ; 0.08
269	cVSetIM	m/day	cVSetIM [1.0] m/day ; max. sedimentation velocity of inert org. matter (1.0)
270	cVWind	m/s	cVWind [5.0] m/s ; average wind speed
271	cYearStartBirds	y	cYearStartBirds [0.0] y ; first year of birds' presence
272	fAgeFish	-	fAgeFish [0.5] - ; yearly ageing fraction of young fish
273	fAlDIM	gAl/gD	fAlDIM [0.01] gAl/gD ; Al content of inorg. matter
274	fBluePhytIn	-	fBluePhytIn [0.33] - ; blue-greens fraction of algal input
275	fDAllPhra	-	fDAllPhra [0.3] - ; allocation fraction
276	fDAssBent	-	fDAssBent [0.3] - ; C ass. efficiency of zoobenthos
277	fDAssBird	-	fDAssBird [0.5] - ; birds assim. efficiency
278	fDAssFiAd	-	fDAssFiAd [0.4] - ; C assimilation efficiency of adult fish
279	fDAssFiJv	-	fDAssFiJv [0.4] - ; C assimilation efficiency of young fish
280	fDAssPisc	-	fDAssPisc [0.4] - ; C ass. efficiency of Pisc
281	fDAssZoo	-	fDAssZoo [0.35] - ; DW-assimilation efficiency of herb. zooplankton
282	fDayWin	-	fDayWin [0.52] ; Start autumn

Table A: continued

ID	Name	Unit	Description
283	fDBone	-	fDBone [0.35] - ; fraction of fish C fixed in bones and scales
284	fDDetS0	g/g	fDDetS0 [0.05] g/g ; initial detritus fraction of sediment organic matter
285	fDDetSM0	g/g	fDDetSM0 [0.05] g/g ; initial detritus fraction of sediment organic matter
286	fDepth1Veg	-	fDepth1Veg [0.0] - ; max. upper depth of submerged veget. layer, as fraction of water depth
287	fDepth2Veg	-	fDepth2Veg [1.0] - ; max. lower depth of submerged veget. layer, as fraction of water depth
288	fDepthDifS	-	fDepthDifS [0.5] - ; nutrient diffusion distance as fraction of sediment depth
289	fDetWMortVeg	-	fDetWMortVeg [0.1] - ; fraction of shoot mortality becoming water detritus
290	fDiatPhytIn	-	fDiatPhytIn [0.33] - ; diatoms fraction of algal input
291	fDissEgesBent	-	fDissEgesBent [0.25] - ; soluble nutrient fraction of by zoobenthos egested food
292	fDissEgesBird	-	fDissEgesBird [0.25] - ; fraction dissolved nutrient of coot egestion
293	fDissEgesFish	-	fDissEgesFish [0.25] - ; soluble nutrient fraction of by fish egested food
294	fDissEgesPisc	-	fDissEgesPisc [0.25] - ; soluble P fraction of by fish egested food
295	fDissEgesZoo	-	fDissEgesZoo [0.25] - ; soluble nutrient fraction of by herb.zoopl. egested food
296	fDissLoss	-	fDissLoss [0.25] - ; dissolved nutrient fraction of grazing loss
297	fDissMortBent	-	fDissMortBent [0.1] - ; soluble P fraction of died zoobenthos P
298	fDissMortFish	-	fDissMortFish [0.1] - ; soluble nutrient fraction of died fish(excl. bones and scales
299	fDissMortPhyt	-	fDissMortPhyt [0.2] - ; soluble nutrient fraction of died Algae
300	fDissMortPisc	-	fDissMortPisc [0.1] - ; soluble nutrient fraction of died Pisc(excl. bones and scales
301	fDissMortVeg	-	fDissMortVeg [0.25] - ; fraction dissolved nutrients from died plants

Table A: continued

ID	Name	Unit	Description
302	fDissMortZoo	-	fDissMortZoo [0.1] - ; soluble nutrient fraction of died zooplankton
303	fDOrgS0	g/g	fDOrgS0 [0.1] g/g ; initial organic fraction of sediment DW
304	fDOrgSM0	g_AFDW_g^{-1}	fDOrgSM0 [0.1] g AFDW g^{-1} solid ; initial organic fraction of sed.
305	fDOrgSoil	-	fDOrgSoil [0.1] - ; fraction soil organic matter
306	fDRealPhra	-	fDRealPhra [0.85] - ; reallocated fraction day
307	fDTotS0	g	fDTotS0 [0.3] g solid g^{-1} sediment ; initial dry-weight fraction in sediment
308	fDTotSM0	g	fDTotSM0 [0.3] g solid g^{-1} sediment ; initial dry-weight fraction in sediment
309	fEffDred	-	fEffDred [0.95] - ; dredging efficiency (<1.0)
310	fEffDredBent	-	fEffDredBent [0.5] - ; dredging efficiency for zoobenthos (<1.0)
311	fEffDredLemn	-	fEffDredLemn [0.5] - ; dredging efficiency for duckweed (<1.0)
312	fEmergVeg	g	fEmergVeg [0.0] g floating / g shoot ; emergent fraction of shoot
313	fFeDIM	gFe/gD	fFeDIM [0.01] gFe/gD ; Fe content of inorg. matter
314	fFloatVeg	g	fFloatVeg [0.0] g floating / g shoot ; floating fraction of shoot
315	fGrenPhytIn	-	fGrenPhytIn [0.34] - ; greens fraction of algal input
316	fLutum	-	fLutum [0.1] - ; lutum content of inorg. matter
317	fLutumRef	-	fLutumRef [0.2] ;
318	fManHelo	-	fManHelo [0.0] - ; Fraction of helophytes and nymphaeids removed by management
319	fManLemn	-	fManLemn [0.0] - ; Fraction of duckweed removed by management
320	fManPhra	-	fManPhra [0.0] - ; fraction biomass loss
321	fManVeg	-	fManVeg [0.0] - ; Fraction removed by management , for submerged plants
322	fMarsh	m^2	fMarsh [0.0] m^2 marsh m^{-2} lake ; relative marsh area
323	fNH4DissIn	-	fNH4DissIn [0.5] - ; NH_4 fraction of dissolved N load (if NH4 not measured)

Table A: continued

ID	Name	Unit	Description
324	fNH4LoadS	-	fNH4LoadS [0.5] - ; NH_4 fraction of N fertilizer to sediment
325	fObstrLemn	-	fObstrLemn [1.0] - ; obstructed fraction of duckweed outflow
326	fPAdsS0	-	fPAdsS0 [0.99] - ; initial adsorbed fraction of inorg. P in sed.
327	fPAR	-	fPAR [0.48] - ; fraction photosynthetically active radiation (PAR)
328	fPBone	-	fPBone [0.50] - ; fraction of fish P fixed in bones and scales
329	fPhytInSum	-	fPhytInSum [0.1] - ; maximum algal fraction in organic P input
330	fPhytInWin	-	fPhytInWin [0.02] - ; minimum algal fraction in organic P input
331	fPInorgS0	gP/gD	fPInorgS0 [0.0005] gP/gD ; initial inorg. P fraction in sed.
332	fPInorgSM0	gP/gD	fPInorgSM0 [0.0005] gP/gD ; initial inorg. P fraction in sed.
333	fPO4In	-	fPO4In [0.5] - ; fraction PO_4 in input (if PO_4 input not measured)
334	fRedMax	-	fRedMax [0.9] - ; max. reduction factor of P adsorption affinity
335	fRefl	;	fRefl [0.2] ; 0.1
336	fRefrDetS	-	fRefrDetS [0.15] - ; refractory fraction of sed. detritus
337	fReprFish	-	fReprFish [0.02] - ; yearly reproduction fraction of adult fish
338	fRootVegSum	g	fRootVegSum [0.1] g root / g veg ; root fraction outside growing season
339	fRootVegWin	g	fRootVegWin [0.6] g root / g veg ; root fraction outside growing season
340	fSedErosIM	-	fSedErosIM [0.95] - ; instantly sedimentating fraction of IM
341	fSedUptVegCoef	-	fSedUptVegCoef [2.66] - ; sigm. regr. coeff. for sediment fraction of nutrient uptake
342	fSedUptVegExp	-	fSedUptVegExp [- 0.83] - ; exponent in sigm. regr. for sediment fraction of nutrient uptake
343	fSedUptVegMax	-	fSedUptVegMax [0.998] - ; maximum sediment fraction of nutrient uptake
344	fWinVeg	-	fWinVeg [0.3] - ; fraction surviving in winter

Table A: continued

ID	Name	Unit	Description
345	hDBentFiAd	g/m^2	hDBentFiAd [2.5] g/m^2 ; half-saturating zoobenthos biomass for adult fish predation
346	hDepthSusp	-	hDepthSusp [2.0] ;
347	hDFishPisc	g/ m^2	hDFishPisc [1.0] g/m^2 ; half-saturating DFish for Pisc predation
348	hDFoodBent	g/ m^2	hDFoodBent [200.0] g/m^2 ; half-saturating food for zoobenthos
349	hDVegBird	-	hDVegBird [5.0] ; half-sat. vegetation biomass
350	hDVegPisc	g/ m^2	hDVegPisc [5.0] g/m^2 ; half-sat. vegetation biomass for Pisc growth
351	hDZooFiJv	g/ m^2	hDZooFiJv [1.25] g/m^2 ; half-saturating zooplankton biomass for young fish predation
352	hFilt	mgDW/l	hFilt [1.0] mgDW/l ; half-sat. food conc. for filtering
353	hfMarsh	-	hfMarsh [0.1] - ; rel. marsh area where exchange is 50%
354	hLRefBlue	W/ m^2	hLRefBlue [1000.0] W/m^2 ; half-sat. PAR at 20 ^oC(Lehmann function) Fake value
355	hLRefDiat	W/ m^2	hLRefDiat [1000.0] W/m^2 ; half-sat. PAR at 20 ^oC(Lehmann function) Fake value
356	hLRefGren	W/m^2	hLRefGren [17.0] W/m^2 ; half-sat. PAR for green algae at 20 ^oC(Lehmann function)
357	hLRefVeg	W/m^2	hLRefVeg [17.0] W/m^2 PAR ; half-sat. light at 20 oC
358	hNO3Denit	mgN/l	hNO3Denit [2.0] mgN/l ; quadratic half-sat. NO_3 conc. for denitrification
359	hO2BOD	mgO_2/l	hO2BOD [1.0] mgO_2/l ; half-sat. oxygen conc. for BOD
360	hO2Nitr	mgO_2/l	hO2Nitr [2.0] mgO_2/l ;
361	hPACoef	g/ m^2	hPACoef [3.0] g/m^2 ; decrease constant for P.A. coeff. with DOMW
362	hSiAssBlue	mgSi/l	hSiAssBlue [0.0] mgSi/l ; half-sat. Si conc. for growth of blue-greens = 0
363	hSiAssDiat	-	hSiAssDiat [0.09] ;(Pohlmann et al,1989,zie Mylius 1991)
364	hSiAssGren	mgSi/l	hSiAssGren [0.0] mgSi/l ; half-sat. Si conc. for growth of green algae = 0
365	kDAllPhra	1/day	kDAllPhra [0.05] 1/day ; allocation rate

Table A: continued

ID	Name	Unit	Description
366	kDAssBent	day^{-1}	kDAssBent [0.1] day^{-1} ; maximum assimilation rate
367	kDAssFiAd	day^{-1}	kDAssFiAd [0.06] day^{-1} ; maximum assimilation rate of adult fish
368	kDAssFiJv	day^{-1}	kDAssFiJv [0.12] day^{-1} ; maximum assimilation rate of young fish
369	kDAssPisc	day^{-1}	kDAssPisc [0.025] day^{-1} ; maximum assimilation rate
370	kDManShootPhra	1/day	kDManShootPhra [1.0] 1/day ; rate of management
371	kDMinDetS	day^{-1}	kDMinDetS [0.002] day^{-1} ; decomposition constant of sediment detritus
372	kDMinDetW	day^{-1}	kDMinDetW [0.01] day^{-1} ; decomposition constant of detritus
373	kDMinHum	day^{-1}	kDMinHum [0.00001] day^{-1} ; maximum decomposition constant of humic material (1D-5)
374	kDMortRootPhra	1/day	kDMortRootPhra [0.000391] 1/day ; mortality rate roots
375	kDMortShootPhra	1/day	kDMortShootPhra [0.0] 1/day ; mortality rate shoots
376	kDRealPhra	1/day	kDRealPhra [0.05] 1/day ; reallocation rate day
377	kDRespBent	day^{-1}	kDRespBent [0.005] day^{-1} ; maint. respiration constant of zoobenthos
378	kDRespBlue	day^{-1}	kDRespBlue [0.03] day^{-1} ; maintenance respiration constant blue-greens(= 0.05 * MuMax)
379	kDRespDiat	day^{-1}	kDRespDiat [0.10] day^{-1} ; maintenance respiration constant diatoms(= 0.05 * MuMax)
380	kDRespFiAd	day^{-1}	kDRespFiAd [0.004] day^{-1} ; maintenance respiration constant of adult fish
381	kDRespFiJv	day^{-1}	kDRespFiJv [0.01] day^{-1} ; maintenance respiration constant of young fish
382	kDRespGren	day^{-1}	kDRespGren [0.075] day^{-1} ; maintenance respiration constant greens(= 0.05 * MuMax)
383	kDRespPhra	1/day	kDRespPhra [0.001] 1/day ; respiration rate of reed
384	kDRespPisc	day^{-1}	kDRespPisc [0.005] day^{-1} ; maint. respiration constant of Pisc
385	kDRespVeg	day^{-1}	kDRespVeg [0.02] day^{-1} ; dark respiration rate of vegetation

Table A: continued

ID	Name	Unit	Description
386	kDRespZoo	day^{-1}	kDRespZoo [0.15] day^{-1} ; maintenance respiration constant herb.zooplankton
387	kExchMaxM	$m3.m^{-3}$	kExchMaxM [1.0] $m^3.m^{-3}$ marsh water.day^{-1} ; maximum dispersive marsh water exchange coefficient
388	kHarvFishSum	-	kHarvFishSum [0.0] ; fish harvesting fraction in summer
389	kHarvFishWin	-	kHarvFishWin [0.0] ; fish harvesting fraction in winter
390	kHarvPiscSum	-	kHarvPiscSum [0.0] ; Pisc harvesting fraction in summer
391	kHarvPiscWin	-	kHarvPiscWin [0.0] ; Pisc harvesting fraction in winter
392	kLemnAer	m^2/gD	kLemnAer [0.01] m_2/gD ;
393	kLossBlue	-	kLossBlue [0.03] - ; grazing loss rate for Blue-greens
394	kLossDiat	-	kLossDiat [0.25] - ; grazing loss rate for Diatoms
395	kLossGren	-	kLossGren [0.25] - ; grazing loss rate for greens
396	kMigrBent	day^{-1}	kMigrBent [0.001] day^{-1} ; zoobenthos migration rate
397	kMigrFish	day^{-1}	kMigrFish [0.001] day^{-1} ; fish migration rate
398	kMigrPisc	day^{-1}	kMigrPisc [0.001] day^{-1} ; Pisc migration rate
399	kMigrVeg	day^{-1}	kMigrVeg [0.001] day^{-1} ; vegetation migration rate
400	kMortBent	day^{-1}	kMortBent [0.005] day^{-1} ; mortality constant of zoobenthos
401	kMortBlueS	day^{-1}	kMortBlueS [0.2] day^{-1} ; mortality constant Bluegreens
402	kMortBlueW	day^{-1}	kMortBlueW [0.01] day^{-1} ; mortality constant of blue-greens in water
403	kMortDiatS	day^{-1}	kMortDiatS [0.05] day^{-1} ; mortality constant of sed. Diatoms
404	kMortDiatW	day^{-1}	kMortDiatW [0.01] day^{-1} ; mortality constant of Diatoms in water
405	kMortFiAd	day^{-1}	kMortFiAd [0.00027] day^{-1} ; specific mortality of adult fish(= 0.1 y^{-1})
406	kMortFiJv	day^{-1}	kMortFiJv [0.00137] day^{-1} ; specific mortality of young fish(= 0.1 y^{-1})

Table A: continued

ID	Name	Unit	Description
407	kMortGrenS	day^{-1}	kMortGrenS [0.05] day^{-1} ; mortality constant greens
408	kMortGrenW	day^{-1}	kMortGrenW [0.01] day^{-1} ; mortality constant of Diatoms in water
409	kMortPisc	day^{-1}	kMortPisc [0.00027] day^{-1} ; specific mortality of Pisc = 0.1 y^{-1}
410	kMortVegSum	day^{-1}	kMortVegSum [0.005] day^{-1} ; vegetation mortality rate in Spring and Summer (low)
411	kMortZoo	day^{-1}	kMortZoo [0.04] day^{-1} ; mortality constant herb.zooplankton
412	kNDifNH4	m^2/day	kNDifNH4 [0.000112] m^2/day ; mol. NH_4 diffusion constant
413	kNDifNO3	m^2/day	kNDifNO3 [0.000086] m^2/day ; mol. NO_3 diffusion constant
414	kNitrS	-	kNitrS [1.0] ;
415	kNitrW	-	kNitrW [0.1] ;
416	kO2Dif	m^2/day	kO2Dif [0.000026] m^2/day ; mol. O_2 diffusion constant
417	kPChemPO4	day^{-1}	kPChemPO4 [0.03] day^{-1} ; chem. PO_4 loss rate
418	kPDifPO4	m^2/day	kPDifPO4 [0.000072] m^2/day ; mol. PO_4 diffusion constant
419	kPSorp	day^{-1}	kPSorp [0.05] day-1 ; P sorption rate constant not too high -> model speed
420	kResusPhytMax	day^{-1}	kResusPhytMax [0.25] day^{-1} ; max. phytopl. resuspension
421	kTurbFish	g/g	kTurbFish [1.0] g/g fish/day ; relative resuspension by adult fish browsing
422	kVegResus	m^2/gDW	kVegResus [0.01] m^2/gDW ; rel. resuspension reduction per g vegetation
423	mDLoadDet	-	XT mDLoadDet [0.0] ;
424	mDLoadIM	-	XT mDLoadIM [0.0] ;
425	mLOut	-	XT mLOut [0.0] ;
426	mNLoad	-	XT mNLoad [0.0] ;
427	mNLoadNH4	-	XT mNLoadNH4 [0.0] ;
428	mNLoadNO3	-	XT mNLoadNO3 [0.0] ;
429	mNLoadOrg	-	XT mNLoadOrg [0.0] ;
430	mPLoad	-	XT mPLoad [0.0] ;
431	mPLoadOrg	-	XT mPLoadOrg [0.0] ;

Table A: continued

ID	Name	Unit	Description
432	mPLoadPhytTot	-	XT mPLoadPhytTot [0.0] ;
433	mPLoadPO4	-	XT mPLoadPO4 [0.0] ;
434	mQEv	-	XT mQEv [0.0] ;
435	mQIn	-	XT mQIn [0.0] ;
436	mQOut	-	XT mQOut [0.0] ;
437	mTemp	-	XT mTemp [0.0] ;
438	mVWind	-	XT mVWind [0.0] ;
439	NO3PerC	-	NO3PerC [0.8] - ; mol NO_3 denitrified per mol C mineralised
440	O2PerNH4	-	O2PerNH4 [2.0] - ; mol O_2 used per mol NH_4+ nitrified
441	O2PerNO3	-	O2PerNO3 [1.5] - ; mol O_2 formed per mol NO_3- ammonified
442	PulseWidth	day	PulseWidth [1.0] day ;
443	ReadDLoadDet	-	ReadDLoadDet [0.0] ; If TRUE, use measured time-series of DDet loading, otherwise constant
444	ReadDLoadIM	-	ReadDLoadIM [0.0] ; If TRUE, use measured time-series of DIM loading, otherwise constant
445	ReadNLoad	-	ReadNLoad [0.0] ; If TRUE, use measured time-series of N loading, otherwise constant
446	ReadNutFrac	-	ReadNutFrac [0.0] ; If TRUE, use measured time-series of loading with diff. nutrient fractions,
447	ReadPLoad	-	ReadPLoad [0.0] ; If TRUE, use measured time-series of P loading, otherwise constant
448	ReadPLoadPhyt	-	ReadPLoadPhyt [0.0] ; If TRUE, use measured time-series of DDet loading, otherwise constant
449	ReadQEv	-	ReadQEv [0.0] ; If TRUE, use measured time-series of inflow, otherwise constant
450	ReadQIn	-	ReadQIn [0.0] ; If TRUE, use measured time-series of inflow, otherwise constant
451	ReadQOut	-	ReadQOut [0.0] ; If TRUE, use measured time-series of inflow, otherwise constant
452	sDBent0	gDW/m^2	sDBent0 [1.0] gDW/m^2 ; Zoobenthos
453	sDBlueS0	gDW/m^2	sDBlueS0 [0.001] gDW/m^2 ; Sediment blue-greens
454	sDBlueW0	mgDW/l	sDBlueW0 [3.0] mgDW/l ; Blue-greens in water

Table A: continued

ID	Name	Unit	Description
455	sDCera0	gD/m^2	sDCera0 [0.00000000000000000000000000000001] gD/m^2 ;
456	sDChar0	gD/m^2	sDChar0 [0.00000000000000000000000000000001] gD/m^2 ;
457	sDDetW0	mgDW/l	sDDetW0 [2.0] mgDW/l ; water detritus
458	sDDiatS0	gDW/m^2	sDDiatS0 [0.001] gDW/m^2 ; Sediment diatoms
459	sDDiatW0	mgDW/l	sDDiatW0 [0.5] mgDW/l ; Diatoms in water
460	sDElod0	gD/m^2	sDElod0 [0.00000000000000000000000000000001] gD/m^2 ;
461	sDepthW0	m	sDepthW0 [2.0] m ; initial water depth
462	sDepthWM0	m	sDepthWM0 [0.5] m ; marsh water depth
463	sDFiAd0	gDW/m^2	sDFiAd0 [2.0] gDW/m^2 ; Adult whitefish
464	sDFiJv0	gDW/m^2	sDFiJv0 [0.5] gDW/m^2 ; Juvenile whitefish
465	sDGrenS0	gDW/m^2	sDGrenS0 [0.001] gDW/m^2 ; Sediment greens
466	sDGrenW0	mgDW/l	sDGrenW0 [0.5] mgDW/l ; Green algae in water
467	sDHelo0	gD/m^2	sDHelo0 [0.00000000000000000000000000000001] gD/m^2 ;
468	sDIMW0	mgDW/l	sDIMW0 [5.0] mgDW/l ; water IM
469	sDLemn0	gD/m^2	sDLemn0 [0.00000000000000000000000000000001] gD/m^2 ;
470	sDNymp0	gD/m^2	sDNymp0 [0.00000000000000000000000000000001] gD/m^2 ;
471	sDPhytS0	gDW/m^2	sDPhytS0 [0.00000000000000000000000000000001] gDW/m^2 ; sediment algae
472	sDPhytW0	mgDW/l	sDPhytW0 [0.00000000000000000000000000000001] mgDW/l ; phytoplankton
473	sDPisc0	gDW/m^2	sDPisc0 [0.01] gDW/m^2 ; Predatory fish
474	sDRootPhra0	gD/m^2	sDRootPhra0 [5000.0] gD/m^2 ; root biomass
475	sDShootPhra0	gD/m^2	sDShootPhra0 [1000.0] gD/m^2 ; shoot biomass
476	sDVeg0	gDW/m^2	sDVeg0 [1.0] gDW/m2 ; Vegetation

Table A: continued

ID	Name	Unit	Description
477	sDZoo0	mgDW/l	sDZoo0 [0.05] mgDW/l ; Zooplankton
478	sNH4S0	gN/m^2	sNH4S0 [0.02] gN/m^2 ; dissolved N-NH_4 in interstitial water
479	sNH4SM0	gN/m^2	sNH4SM0 [1.0] gN/m^2 ; NH_4 in sediment
480	sNH4W0	mgN/l	sNH4W0 [0.1] mgN/l ; NH_4 in water
481	sNO3S0	gN/m^2	sNO3S0 [0.002] gN/m^2 ; dissolved N-NO_3 in interstitial water
482	sNO3SM0	gN/m^2	sNO3SM0 [0.01] gN/m^2 ; NO_3 in sediment
483	sNO3W0	mgN/l	sNO3W0 [0.1] mgN/l ; NO_3 in water
484	sO2W0	mgO_2/l	sO2W0 [10.0] mgO_2/l ; oxygen in water
485	sPAIMW0	mgP/l	sPAIMW0 [0.0] mgP/l ; adsorbed on IM in water
486	sPO4W0	mgP/l	sPO4W0 [0.01] mgP/l ;
487	sSiO2W0	mgSi/l	sSiO2W0 [3.0] mgSi/l ; dissolved silica in water
488	UseEmpUpt	-	UseEmpUpt [0.0] ; F = do not use this empirical relation.
489	UsePulseLoad	-	UsePulseLoad [0.0] ; If TRUE, use a pulse-wise nutrient loading.
490	UseSeasonLoad	-	UseSeasonLoad [0.0] ; If TRUE, use different inflow and loading for summer and winter periods.
491	UseSteeleBlue	-	UseSteeleBlue [1.0] ; 'Flag': 1 = use Steele function,0 = use Lehman function
492	UseSteeleDiat	-	UseSteeleDiat [1.0] ; 'Flag': 1 = use Steele function,0 = use Lehman function
493	UseSteeleGren	-	UseSteeleGren [0.0] ; 'Flag': 1 = use Steele function,0 = use Lehman function
494	cDepthWMax	m	cDepthWMax [3.0] m ; maximum water depth

APPENDIX B

SOME EQUATIONS USED IN PCLAKE

The following equations were taken from *PCLake* model descrption given in Janse (2005).

In the equations

s- denotes state variables,

d- denotes derivatives,

a- denotes other variables,

o- denotes concentratios,

t- denotes processes per area and

w- denotes processes per volume.

Furthermore, transport parameters were typed in normal, *abiotic, microbial processes and burial and dredging were typed in italics*, **algal processes were typed in bold**, ***the macrophyte processes were typed in bold italics***, the food-web processes were underlined, *the food-web processes in the marsland were in italics and underlined*.

dNO3W = uNLoadNO3/sDepthW - wNDilNO3 + *wNNitrW* - *wNDenitW* + *(tNDifNO3 + tNResusNO3 - tNInfNO3W) / sDepthW* - **wNUptNO3Phyt - *tNUptNO3VegW / sDepthW*** - *aRelDeltaW * sNO3W* - *wNExchNO3*

dNO3W (Nitrate in water [mgN/l/d]) = loading - dilution + nitrification in water – denitrif. in water + diffusion from sediment + resuspension – infiltration - algal uptake - macrophyte uptake from water – burial correction – marsh exchange.

dNH4W = uNLoadNH4/sDepthW - wNDilNH4 + *cNBackLoad* + *wNMinDetW* - *wNNitrW* - *tNInfNH4W / sDepthW* + *(tNDifNH4 + tNResusNH4) / sDepthW* - **wNUptNH4Phyt + wNExcrPhytW + wNMortPhytNH4W – *(tNUptNH4VegW + tNExcrVegW + tNMortVegNH4W + tNEgesBirdNH4) / sDepthW*** + wNExcrZoo + wNEgesZooNH4 + wNMortZooNH4 + (tNExcrFiJv + tNExcrFiAd + tNEgesFishNH4 + tNMortFishNH4 + tNExcrPisc + tNEgesPiscNH4 + tNMortPiscNH4) / sDepthW - *aRelDeltaW * sNH4W* - *wNExchNH4*

dNH4W (ammonium in water [mgN/l/d]) = loading - dilution + background loading + mineralisation – nitrification in water - infiltration + diffusion from sediment + resuspension - algal uptake + algal excretion + part of algal mortality - macrophyte uptake from water + macrophyte excretion in water + part of macrophyte mortality + egestion by birds + zooplankton excretion and part of egestion and mortality + whitefish excretion and part of egestion and mortality + pred.fish excretion and part of egestion and mortality – burial correction – marsh exchange.

dPO4W = uPLoadPO4/sDepthW - wPDilPO4 + *cPBackLoad* + *wPMinDetW* - *wPSorpIMW* + *(tPDifPO4* + *tPResusPO4* - *tPInfPO4W) / sDepthW* **- wPUptPhyt + wPExcrPhytW + wPMortPhytPO4W + *(- tPUptVegW* + *tPExcrVegW* + *tPMortVegPO4W* + *tPEgesBirdPO4) / sDepthW*** + wPExcrZoo + wPEgesZooPO4 + wPMortZooPO4 + (tPExcrFiJv + tPExcrFiAd + tPEgesFishPO4 + tPMortFishPO4 + tPExcrPisc + tPEgesPiscPO4 + tPMortPiscPO4) / sDepthW - *aRelDeltaW * sPO4W* - *wPExchPO4*

dPO4W (PO_4 in water [mgP/l/d]) = loading - dilution + background loading + mineralisation – sorption + diffusion from sediment + resuspension - infiltration - algal uptake + algal excretion + part of algal mortality - macrophyte uptake from water + macrophyte excretion in water + part of macrophyte mortality + egestion by birds + zooplankton excretion and part of egestion and mortality + whitefish excretion and part of egestion and mortality + pred.fish excretion and part of egestion and mortality – burial correction – marsh exchange

Chlorophyll-*a* (Chla) [mg m^{-3}] = algal biomass * Chla/D-ratio, summed for all groups

Total nitrogen (TN) [mgN/l] = NH_4 + NO_3 + detrital N + algal N

Total phosphorus (TP) [mgP/l] = PO_4 + P_{ads} + detrital P + algal P

Temperature effect was not directly involved in the above equations that it was indirectly included through the second order in the equations. Direct effect of temperature on the parameters was given below.

Nitrification:

Nitrification is a process, in that ammonia is transformed into nitrate and it depends on O_2 (O2) and temperature (TM).

uFunTmNitr = cThetaNitr ** (uTm-20) temperature dependence [-]

In the water:

aCorO2NitrW = sO2W ** 2.0 / (hO2Nitr ** 2.0 + sO2W ** 2.0)

wNNitrW (nitrification flux [mgN/l/d]) = kNitrW * uFunTmNitr * aCorO2NitrW * sNH4W

wO2NitrW (O_2 flux due to nitrification [gO2/m3/d]) = O2PerNH4 * molO2molN * wNNitrW

In the sediment:

tNNitrS(nitrification flux [gN/m2/d]) = afOxySed * kNitrS * uFunTmNitr * sNH4S

tO2NitrS (O_2 flux due to nitrification [gO2/m2/d]) = O2PerNH4 * molO2molN * tNNitrS

Nutrient release:

Dissolved inorganic phosphorus, ammonia and nitrate can immobilize from the sediment to the water column.

tPDifPO4 (Diffusion flux of dissolved P from sediment to water [gP/m^2/d]) = kPDifPO4 * uFunTmDif * cTurbDifNut * bPorCorS *(oPO4S - sPO4W) / aDepthDif

in that;

kPDifPO4 diffusion constant of dissolved P [m^2/d]

cThetaDif temperature parameter [$(e\_^C)^{-1}$]

cTurbDifNut bioturbation factor [-]

aDepthDif = 0.5 * cDepthS diffusion distance [m]

Also, the temperature function was defined by an optimum temperature *cTmOpt*.

uFunTmSpec (temperature function of phytoplankton group) = EXP(-0.5/cSigTmSpec**2 * ((uTm - cTmOptSpec)**2 - (cTmRef - cTmOptSpec)**2))

Production (i.e. growth):

Production was defined as daily increase of dry weight in grammes per m^2. The model considers the production a function of maximum growth rate at 20ºC, water temperature, day length, light interception at the water surface, light extinction coefficient, P and N contents of the plants as representing P and N limitation, respectively. The combined growth rate equation of entire biomass was described in the model as:

aMuTmLSpec (growth rate at current light and temperature [d^{-1}]) = ufDay * (1.0 - afCovSurfVeg) * aLLimSpec * uFunTmSpec * cMuMaxSpec

Respiration:

PCLake models maintanace respiration only and it is a tempearture dependent first order process.

ukDRespTmSpec (maintenance respiration rate at current temperature [d^{-1}]) = kDRespSpec * uFunTmSpec

tDRespSpec (maintenance respiration flux [gD m^{-3} d^{-1}]) = ukDRespTmSpec * sDSpec

Mortality:

Out of all the phytoplankton groups cyonobacteria have the lowest maximum growth rate and has a high sensitivity for the temperature in the model. On the other hand, diatoms have the lowest temperature optimum.