IMPACTS OF EXTREME METEOROLOGICAL EVENTS ON METABOLISM OF LAKE EYMIR USING HIGH FREQUENCY AUTOMATED LAKE OBSERVATION STATION

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ABSTRACT

IMPACTS OF EXTREME METEOROLOGICAL EVENTS ON METABOLISM OF LAKE EYMIR USING HIGH FREQUENCY AUTOMATED LAKE OBSERVATION STATION

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May 2018, 72 pages

One year measurements between September 2015 and August 2016 from high frequency automated lake observation station were collected to estimate metabolism of Lake Eymir based on diel oxygen changes. Estimated gross primary production (GPP), respiration (RES) and net ecosystem production (NEP) were used to assess the role of Lake Eymir in carbon cycling and the response of lake ecosystem to extreme meteorological events. In addition to compare different approaches seven distinct k_{600} methods and five metabolism models were used.

According to results, even Lake Eymir has been experiencing eutrophication more than 20 years, the lake acts as carbon source to atmosphere throughout the year except the algal bloom periods. Despite the fact that, during extreme wind events, disruption of thermal stratification induced emission of CO_2, mixing of the lake increased unrealistic estimations of metabolism probably due to lack of model inputs. In addition, it has been found that results of piston velocity methods vary more than the results of metabolism models.

Keywords: lakes, lake metabolism, climate change, global carbon cycle, extreme meteorological events, high frequency monitoring

ÖZ

METEOROLOJİK UÇ OLAYLARIN EYMİR GÖLÜ METABOLİZMASI ÜZERİNDEKİ ETKİLERİNİN YÜKSEK ÇÖZÜNÜRLÜKLÜ OTOMATİK GÖL İZLEME İSTASYONU İLE BELİRLENMESİ

Tolunay, Duygu
Yüksek Lisans, Biyoloji Bölümü
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Mayıs 2018, 72 sayfa

Eylül 2015 ve Ağustos 2016 yılları arasında, Eymir Gölü'ne tesis edilen yüksek çözünürlüklü otomatik göl izleme istastonundan alınan veriler ile günlük oksijen değişiminden göl metabolisması hesabı yapılmıştır. Tahmin edilen toplam birincil üretim (GPP), solunum (RES) ve net ekosistem üretimi (NEP) ile Eymir Gölü'nün karbon döngüsündeki rolü ve şiddetli meteorolojik olaylara verdiği tepkiler değerlendirilmiştir. Buna ek olarak, farklı yaklaşımları karşılaştırmak için yedi farklı k_{600} metodu ve beş metbolizma modeli kullanılmıştır.

Elde edilen sonuçlara göre, Eymir Gölü uzun süreden beri ötrofik statüde olmasına rağmen yıl boyunca alg artışı olduğu dönemler haricinde atmosfere karbon salınımı yapmaktadır. Fırtınalar, sıcaklık tabakalaşmasını ortadan kaldırmış; epilimniondaki klorofil-*a* konsantrasyonunun azalmasına, flurosan çözünmüş organik madde miktarının artmasına yol açmış, göldeki karbon salınımını tetiklemiştir. Ayrıca gölün karışması, model girdilerinden kaynaklanması muhtemel metabolizma tahminlerinde hatalı sonuçlar vermiştir Buna ek olarak piston hızı metodları arasında farklılık daha belirgin iken metabolizma modellerinde bu fark fazla gözlemlenmemiştir.

Anahtar kelimeler: göller, göl metabolizması, iklim değişikliği, küresel karbon döngüsü, meteorolojik uç olaylar, yüksek çözünürlüklü göl izleme sistemleri,

To My Sister, Mother, Father and Nephew

*

To Elif, Erdinç and Doğa Taşel

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INTRODUCTION

1.1 Importance of Lakes

Natural lakes and ponds constitute approximately 4.2 million km^2 of Earth surface and most of them are considered as small and shallow lakes (Downing et al., 2006; Wetzel, 2001). Shallow lakes are defined as a lake with mean depth less than 3 meter and relatively well-mixed water column throughout the year (Moss, 1998). Their limited buffering capacity makes shallow lakes more vulnerable to environmental changes than deeper water bodies (Beklioglu et al., 2011; Grizzetti et al., 2015). Due to the strong feedback between lakes and their environment, internal physical, chemical and biological dynamics can only be understood in the context of the surrounding environment and changes therein.

Despite direct benefits to human like water supply, electricity, food and recreation facilities, lakes supply shelter 10% of the known species in the world (WWF, 2016) (Table1.1). However, increase in anthropogenic activities cause deprivation of ecosystem services of lakes (Moss, 1998; Schallenberg et al., 2013; Wetzel, 2001).

Table 1.1 Main ecosystem services of lakes (Revised from Schallenberg et al., 2013)

Type of Services	Ecosystem services
Global Convention	Biodiversity and climate change mitigation
Provisioning	Drinking water, waterfowl, fisheries
Support and regulation	Nutrient and sediment processing, sequestration,
Cultural	recreation and tourism, spiritual morals

1.2 Threats to Lake Ecosystems

As an essential source for all life, water requires our undivided attention if it comes to its protection. As a consequences of anthropogenic activities, resilience of the water sources has been under threat (Steffen et al., 2011). According to the Food and Agriculture Organization of United Nations (FAO), pressures on water resources today reached critical levels as a result of increasing human populations in combination with changing consumption patterns (FAO, 2016). Climate change, agriculture, mining, nutrient loading, habitat degradation, pollution and overfishing are just few perils that compel changes in lake ecosystems functions and services.

It is estimated that more than half of the world’s population will be living water scarcity by 2025 (Matthews, 2016). Concerns over water scarcity leads to intensifying management actions to protect lakes. As a result, previously underestimated lakes have become hotspots for creation of management plans for sustainable water usage.

1.3 Climate Change and Extreme Meteorological Events

Climate change is known as increase in greenhouse gases in the atmosphere which leads an alteration of weather pattern that is expected to affect all ecosystems either directly or indirectly (Groffman et al., 2014).These effects are scale-specific, and differ in space and time (Jeppesen et al., 2015) making it arduous to understand the current and ultimate effects of climate change. Major forcing factors of climate change are structural changes in solar radiation, air temperature, and precipitation (Williamson et al., 2009).

Despite the small portion of the Earth surface that is covered by lakes, their responses to these forcing factors may give valuable information since they are sentinels (Adrian et al., 2009), integrators, and regulators of climate change (Tranvik et al., 2009) (Figure 1.1). Previous studies have shown that lakes have been experiencing warmer water temperatures, long-term thermal stratification, and changes in water level due to climate change. These changes, in turn, have led to anoxic layers, fish kills, loss of biodiversity, drought and flooding. (Vincent, 2009; Williamson et al., 2009)

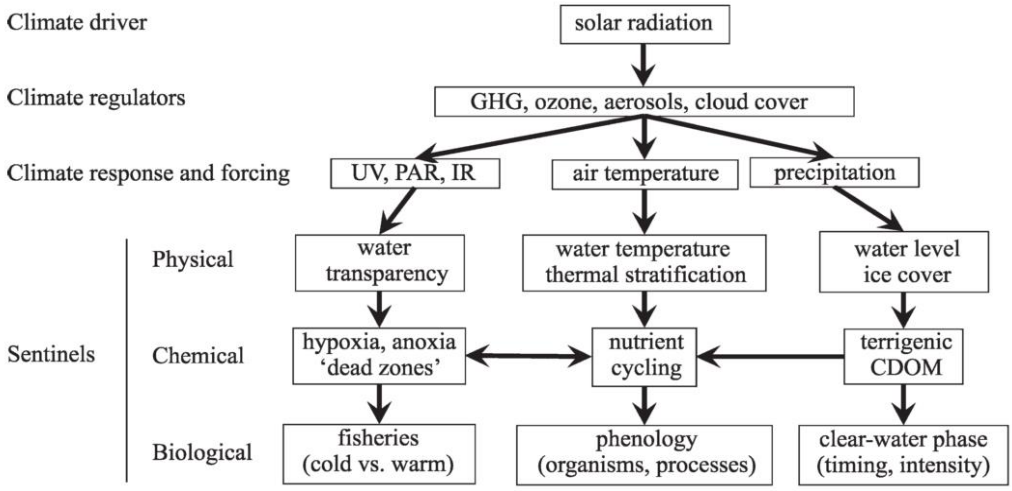


Figure 1.1 Major climate regulators, climate response and forcing and few example for response of lakes (retrieved from (Williamson et al., 2009))

Other visible effect of climate change is increase in extreme weather events. Extreme events are defined as rare and intense events which have severe consequences on ecosystems and socio-economy (Beniston et al., 2007). Today, extreme events such as heat waves, heavy precipitations, droughts, and wind storms were recorded in high frequency than past times (Melillo et al., 2014; Tsai et al., 2011)

Heat waves during summer have increased that induced drought and vegetation problems in the lakes (Frich et al., 2002; Houghton JT et al., 2001; Schär et al., 2004). In addition, according to climate change models, decline in heavy winter and summer and with earlier and longer droughts in the Mediterranean will affect lake ecosystems severely (Beniston et al., 2007). Also, increase in wind storms is expected to disrupt thermal stratification and mix lake that influence distribution of the organic and inorganic matters within as well as between the systems (Bontes et al., 2005; Tranvik et al., 2009; Zwart et al., 2016). After discovering of roles of lakes in global carbon cycle, effects of climate change and extreme weather events on lake ecosystem became hotspot of the scientific world (Cole et al., 2007).

1.4 Eutrophication

The other world-wide problem that affects lake ecosystems is eutrophication defined as excessive water plant or algal growth due to increase in access of limiting factor/s that is crucial for photosynthesis such as light, nutrient and carbon dioxide (CO_2) (Schindler, 2006).

Although eutrophication is natural process occurs over centuries, anthropogenic activities combining with climate change have hastened its rate and extented its range (Carpenter et al., 1998). Domestic, industrial wastes and agriculture have been accelerating accumulation of nutrients especially phosphorus and nitrogen in lakes that decrease limitation one of the important limiting factor for photosynthesis. Increase in availability of nutrients combining with climate change enhances blooms of certain species of primary producers which can tolerate extreme conditions like high temperatures and storms (Jeppesen et al., 2010; Moss, 2010; Rigosi et al., 2014).

The consequences of the eutrophication are severe both for ecosystem functions and services. Decrease in water quality because of algal blooms causes losing drinking water, fisheries, and recreational ecosystem services of the lakes. In addition, extensive growth of primary producers unbalances the oxygen level and distribution in the lake that leads to anoxic water bodies result in death of many organisms and eventually decline in biodiversity (Arend et al., 2011; Burkholder et al., 1992; Diaz and Rosenberg, 2008; Jeppesen et al., 1997).

Since main driver of C budget in lakes is primary producers, eutrophication has important role in global C cycle. Interaction of eutrophication and climate change/ extreme meteorological events has also influence on transportation, transformation and storage of the organic carbon (Cole et al., 2007; Tranvik et al., 2009).

1.5 Roles of Lakes in the Global Carbon Cycle

Since lands and oceans cover larger surface area than inland waters, its contribution to carbon (C) cycle were neglected for a long time (Cole et al., 2007). However, climate change impelled scientist focusing on greenhouse gasses and carbon cycle which has an active role in the Earth's energy budget (Raymond et al., 2013). As a consequence, it was discovered that lakes play important role in transport, transformation and storage of carbon (Tranvik et al., 2009). While stream and rivers emit 1.8 petagrams of carbon per year (Pg C yr^{-1}), lakes release 0.32 Pg C yr^{-1} (Raymond et al., 2013). Inland waters are generally supersaturated with CO_2 which contribute substantial portion of atmospheric C budget. The reasons of net of CO_2 emission to the atmosphere from lakes are respiration by organisms (RES), burying organic C in their sediments and also terrestrial input exceed CO_2 uptake by primary producers (Duarte and Prairie, 2005; Kortelainen et al., 2004; Molot and Dillon, 1997; Pace and Prairie, 2005; Rantakari and Kortelainen, 2005; Sobek, Tranvik, and Cole, 2005) (Figure 1.2). While earlier studies were used alkalinity, pH and dark/light chambers for CO_2 budgets in the lakes today, most common way to understand C cycling is assessing lake metabolism (Staehr et al., 2012(a)).

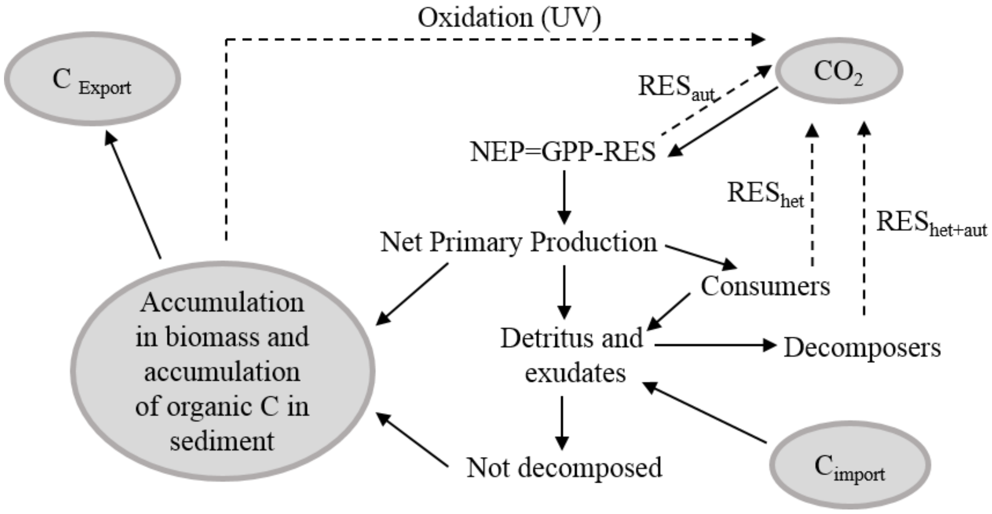


Figure 1.2 Organic Carbon (C) cycling in aquatic systems (revised from (Staehr et al., 2012(a))) RES_{het}: respiration of heterotrophs, RES_{aut}: respiration of autotrophs, NEP: Net ecosystem production, GPP: Gross primary production.

1.6 Lake Metabolism

Lake metabolism represents formation and utilization of organic matter in lakes by estimating net ecosystem production (NEP) (Hoellein, Bruesewitz, and Richardson, 2013; Staehr et al., 2012 (a); Staehr et al., 2012(b)). Lake metabolism provides information about trophic status of lake and biochemical cycles in lake. Also, it is a powerful tool to monitor responses of lake ecosystem to environmental changes. There are several techniques to estimate lake metabolism such as using dissolved oxygen (DO) concentration or CO_2 concentration changes, oxygen isotopes and incubations of water taken from lakes (Staehr et al., 2012(a)). Today, the most common and cost effective way is measuring diel dissolved oxygen concentration changes (Cole et al., 2000; Hall, 1972; Hanson et al., 2003; Smith and Key, 1975; Staehr et al., 2010; Van de Bogert et al., 2007). In this technique, bottles and chambers incubation were used in past but today, high frequency measurements obtained from automatic buoy systems provide more reliable results. It is assumed that diel DO changes depends on gross primary production (GPP) and respiratory consumption (RES) as well as the physical exchange of oxygen between air and water (F) (Equation 1.1). Other possible effects on dynamic of oxygen concentration are neglected (A). Other assumption is photosynthetic production occurs only during daylight. Equal amount of respiration during night and daylight is the third assumption.

$$NEP = GPP - R \pm F \ \pm A \qquad (Equation\ 1.1)$$

The basic equation is generated with algebra. However, after discovering non-linear pattern of dissolved oxygen, GPP, RES and F were tried to be explained with different parameters and different statistical approaches (Odum, 1956; Staehr et al., 2012(b); Winslow et al., 2016). Balance between these values also represent the CO_2 dynamics in lakes. Most of the studies were done by using lake metabolism is to estimate carbon budget of the ecosystem because the other methods such as C^{13} isotopes or chamber approaches are expensive and labor intensive (Staehr et al., 2012(a)) (Figure 1.3).

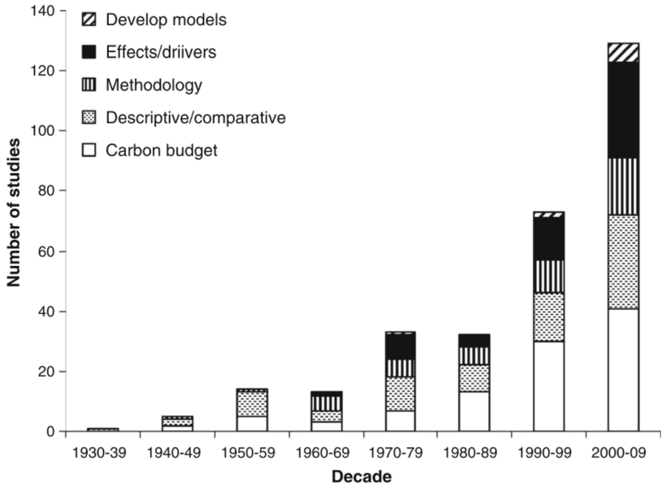


Figure 1.3 Applications of lake metabolism for 80 years studies (retrieved from (Staehr et al., 2012(a))

According to studies for carbon budget, it has been recorded that respiration (RES) in lakes exceeds the gross primary production (GPP) due to inflow of organic matter from catchment area and burial of carbon in the sediment that leads emission of CO_2 (Kosten et al., 2010; Sobek et al., 2005). In the literature, if lakes are source of CO_2 called heterotrophic (GPP < RES; NEP<0), if they store carbon, called autotrophic (GPP > RES; NEP>0) (Borges et al., 2014; Odum, 1956; Sadro, Melack, and MacIntyre, 2011; Staehr and Sand-Jensen, 2007; Staehr et al., 2010). The balance between RES and GPP depend on both metabolic processes in lakes and interaction with environments. However, these processes have not been fully understood yet. In addition, by means of incline in anthropogenic pressures and climate change, the role of lakes in the global carbon cycle is also affected (Jeppesen et al., 2015).

1.7 Importance of High Frequency Monitoring in Lake Metabolism

As pressures on water resources have been increasing day by day due to human activities and climate change, effective monitoring approaches are critical to design proper management programs (Myers, 2009; Water Scarcity Drafting Group, 2006; WHO, 2003). Traditional long-term monitoring develops gaps due to biweekly sampling frequency that misses the effects of short term and abrupt changes on lake ecosystems. With recent technologies, high frequency buoy systems have been developed which is cost effective, less time and labor intensive (Burkholder et al., 2004). Global Lake Ecological Observatory Network (GLEON, http://gleon.org/) and Networking Lake Observatories in Europe (NETLAKE, http://www.netlake.org) have spreaded this advance technogly all over the world.

High frequency buoys generally combine meteorological stations above the water and sondes in a lake. Sondes have several probes which can measure different chemical and biological parameters such as dissolved oxygen, chlorophyll-*a*, dissolved organic carbon (DOC) concentrations, salinity and pH. The frequency of data collection may vary from minutes to hours. As real time measurements with sondes are obtained automatically, it minimizes human errors and time delays and increases the quantity and quality of data.

Despite the fact that climate change will alter precipitation and temperature for long term period, more extreme events (storms, heatwaves and extreme precipitation) are predicted that may affect ecosystem stability (Thompson et al., 2013). In order to spot the possible effects of short term extreme events, high frequency monitoring is crucial.

1.8 Aim of the Study

There are two major goals of this thesis. First, to assess the ecosystem metabolism of biomanipulated eutrophic Lake Eymir using high frequency measurements of diel oxygen changes. This aim also includes possible effects of extreme meteorological events on the metabolism and also assessment of CO_2 fluxes of biomanipulated eutrophic Lake Eymir. Since Lake Eymir is an eutrophic lake, we hypothesize to observe more carbon storage (autotrophy) during the year which may change during extreme events. Second aim is whether using different approaches to calculating gas flux and metabolism models give significant results that may effect the assessment which shouldn't be the case. Also, effects of using raw data or aggregated data on results were examined. Moreover, this thesis may set a case study that involves high frequency monitoring in lakes in Turkey.

CHAPTER 2

MATERIAL AND METHODS

2.1 Study Site

Lake Eymir (39°57’ N, 32°53’ E) is a relatively shallow lake, located 20 km south of Ankara (Figure 2.1). The surface area of the lake varies between 100-130 ha with mean depth of 3.2 m (Coppens et al., 2016). The catchment area of Lake Eymir is 971 km^2 and includes a suburban town, Gölbaşı, which is located between Lake Mogan and Lake Eymir (Özen et al., 2010). The main inflow point (Inflow I) is located at the southern end of Lake Eymir, where it connects to the upstream Lake Mogan. A secondary ephemeral inflow is located on the northern end, and is called Kışlakçı brook (Inflow II). Inflow from this brook is associated with snow melt and therefore only runs in spring.

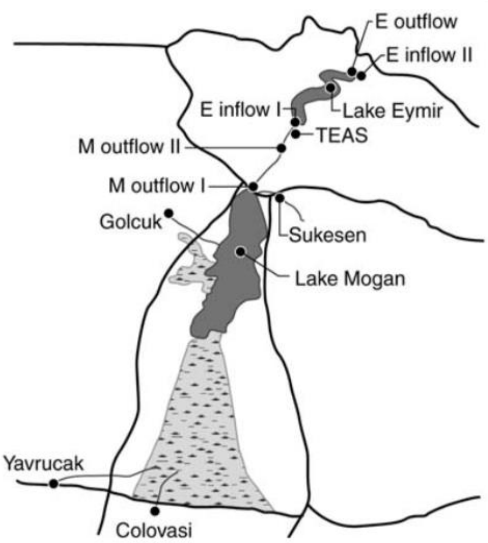


Figure 2.1 Lake Eymir and its catchment area (Taken from Özen et al. 2010)

Lake Eymir is situated in an arid cold steppe climate, with hot dry summers, and cold snowy winters (Peel, Finlayson, and McMahon, 2006). The lake is most of the time dimictic but also can be monomictic during warm winters.

From 1979 until 1995, the lake has received sewage effluent from Gölbaşı town. This has led to eutrophication of the lake (727 ± 433 $\mu g l^{-1}$, 1.49 ± 0.82 mg l^{-1} and 27 ± 22 $\mu g l^{-1}$, of Total Phosphorus (TP), Dissolved Inorganic Nitrogen (DIN) and chlorophyll-*a*, respectively) between 1993 and 1995 (Beklioğlu *et. al*. 2003). In 1995, sewage effluent diversion was undertaken to restore and prevent further eutrophication (Beklioglu, Ince, and Tuzun, 2003). This significantly reduced nutrient concentrations, and led, for example to a three-fold decrease in TP without recovering water clarity (Beklioglu, Burnak, and Ince, 2000; Beklioglu et al., 2003; Beklioglu et al., 2017) From 1997 onwards, lake ecological monitoring program of METU- Limnology laboratory has started (http://www.limnology.bio.metu.edu.tr/). In order to restore Lake Eymir, a first biomanipulation was conducted in 1998-1999 by removing 57% of tench and carp population (Beklioglu et al., 2000). The fish removal increased Secchi depth 4.3-fold through a decrease in chlorophyll-*a* concentration and suspended solids (Beklioglu et al., 2000). In addition, submerged plants started to re-develop, reaching their highest coverage by spreading to 90% of the lake surface area in 2001 (Beklioglu and Tan, 2008). However, during the drought period between 2003 and 2009, water quality shifted back to its pre-biomanipulation state, with lower macrophyte coverage and higher abundance of tench and carp (Özen, 2006). As a result, a new biomanipulation period was initiated in 2006 and continued till 2014. This attempt improved water quality (2-fold and 1.5-fold decline in chlorophyll-*a* and suspended solids, respectively) but not the coverage of submerged plants (Özen et al., 2010). Moreover, release of the predator stress on the zooplankton community had led to an increase in the grazing pressure on phytoplankton. In Lake Eymir, the zooplankton community was dominated by large sized calanoid copepods and cladocerans (Beklioğlu et al., 2017). Today, Lake Eymir cycles through a clear water state with a high abundance of zooplankton during spring, and a turbid water state during algal blooms occurring at the end of the summer and/or beginning of the autumn.

2.2 High Frequency Lake Eymir Monitoring System: Installment, Deployment and Maintenance

A high frequency Lake Eymir monitoring system (HFLEMS) was set up at the deepest part of Lake Eymir (~5.5 m) (Figure 2.2). The system consists of a meteorological module above the surface and an underwater sonde array, thus allowing coupled monitoring of atmospheric and aquatic conditions. A solar panel and a backup power supply provide the energy to the station.

The meteorological module was mounted 2 m above water surface and measures weather parameters like wind speed, air temperature, and barometric pressure. The sonde array is comprised of two sondes at different depths (1.5 m and 4.5 m, respectively) and a thermostat chain covering the entire depth of the lake water with 0.5 m intervals. The underwater sondes are capable of measuring biological, physical and chemical parameters, while the thermostat chain allows monitoring of changes in thermal stratification. The whole system collects data with 10 minute intervals.

HFLEMS was established at the end of the August 2015 and sampling period were conducted between 5th of September 2015 until 18th of August 2016 excluding winter period. Prior to establishment, probes were introduced to the sondes and calibrated according to the user manuals. During the study period, the system was visited every Friday to clean the probes and check the battery level. In addition, data were collected from each system using a computer and a hand-held equipment, into an excel document for further analysis. Sondes and probes of thermostat chain were taken out from the lake when water temperature drops 10 ^{o}C and kept under suitable conditions at laboratory, unlike the meteorological module remained throughout the year.

Meteorological module measures average, maximum and minimum of wind speed (m/s) together with wind direction, air temperature (^{o}C), barometric pressure (mbar), relative humidity (%) and solar wave radiation (W/m^2), and the two sondes record water temperature (^{0}C), saturated dissolved oxygen (%), dissolved oxygen (mg/l), chlorophyll-*a* (µg/l, RFU), total dissolved solids, TDS (mg/l), conductivity (µs/cm), salinity (psu) and. In addition, sonde at 1.5 meter takes measurements of turbidity

(FNU), fluorescent dissolved organic matter-fDOM (RFU), oxidation reduction potential-ORP (mV) and phycoerythrin blue green algae-BGA-PE (µg/l, RFU) (Table 2.1).

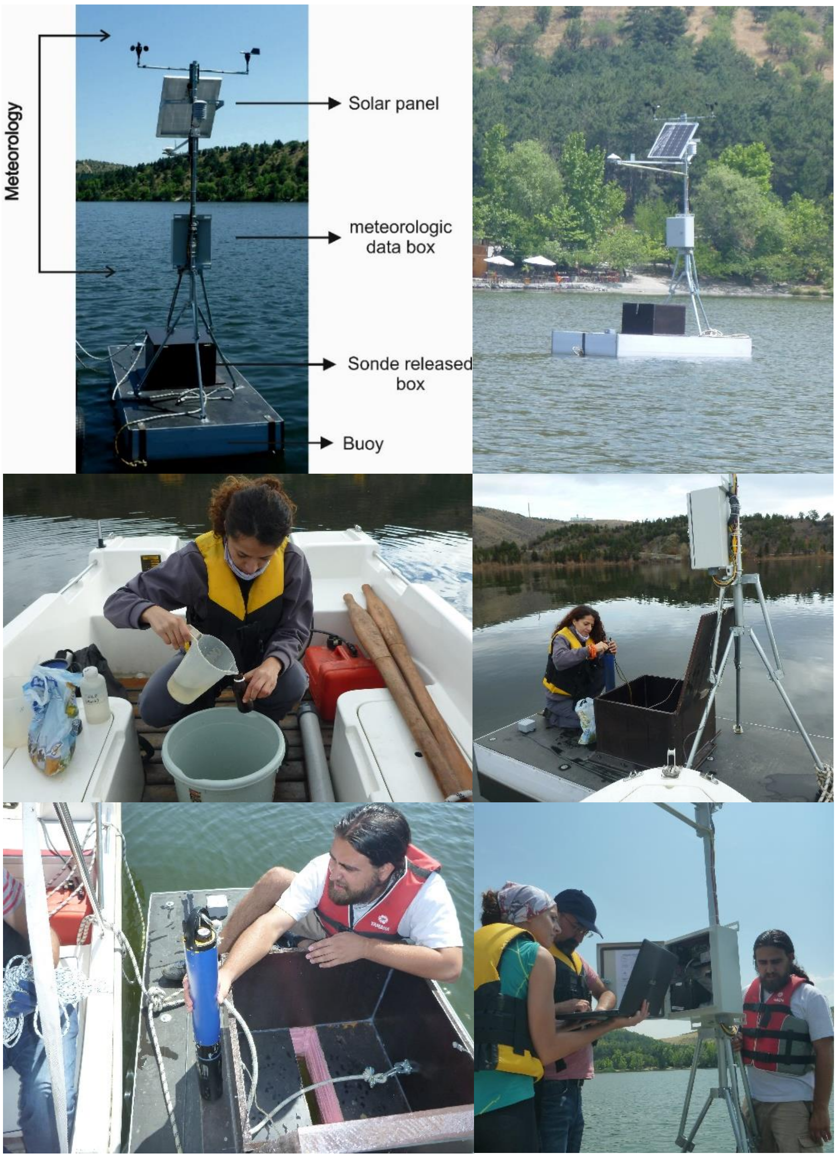


Figure 2.2 High Frequency Lake Eymir Monitoring System and field works

Table 2.1 Measured Parameters from High Frequency Lake Eymir Monitoring System

Meteorological Module	Sonde Module*	
	Sonde 1 (1.5 m)	Sonde 2 (4.5 m)
Average Wind Speed (m/s)	Water Temperature(^{o}C)	Water Temperature(^{o}C)
Minimum Wind Speed (m/s)	Saturated Dissolved Oxygen (%)	Saturated Dissolved Oxygen (%)
Maximum Wind Speed (m/s)	Dissolved Oxygen (mg/l)	Dissolved Oxygen (mg/l)
Wind Direction (degree)	Chlorophyll-*a* (µg/l, RFU)	Chlorophyll-*a* (µg/l, RFU)
Air Temperature (^{o}C)	Total Dissolved Solids, TDS (mg/l)	Total Dissolved Solids, TDS (mg/l)
Barometric Pressure (mbar)	Conductivity (µS/cm)	Conductivity (µS/cm)
Relative Humidity (%)	Salinity (psu)	Salinity (psu)
Shortwave Radiation (W/m^2)	pH	pH
	Turbidity (FNU)	
	Fluorescent Dissolved Organic Matter, fDOM (RFU)	
	Oxidation Reduction Potential, ORP (mV)	
	Phycoerythrin Blue Green Algae, BGA-PE (µg/l, RFU)	

*In addition to the two sondes, nine temperature probes were installed at a 0.5 m interval throughout the water column (thermostat chain)

2.3 Sampling Procedures and Laboratory Analysis

In order to validate the measurements taken by HFLEMS, manual on site measurements were conducted manually throughout the study period. During the growing season, measurements were conducted bi-weekly, otherwise measurements were done once a month. No sampling was conducted through the ice covered period.

In each sampling, water temperature (ºC), dissolved oxygen concentration (mg/l), salinity (psu), conductivity (mS), total dissolved solids (g/l) and pH were measured manually with a YSI 556 MPS multi-probe field meter (YSI Incorporated, Yellow Springs, OH, USA through the water column in 0.5 m intervals, starting from the surface. Water depth and Secchi depth were recorded to monitor water level fluctuation and water clarity by using by using white disc with a diameter of 20 cm and Laylin SM5 depthmeter portable sounder (Laylin Associates, Unionville, USA), respectively.

A water sampler (volume: 3.5 L, KC-Denmark, Silkeborg, Denmark) was used to retrieve 40 L of water throughout the water column in 0.5 m intervals to obtain a composite water sample. Phytoplankton sample for enumeration was prepared from a 100 mL unfiltered composite water sample that was preserved in 2% Lugol's solution. Samples for zooplankton enumeration were stored in 4% Lugol's solution after filtering 20 L of composite water through a 20 µm mesh size filter. In addition, 1 L of composite water was stored and kept frozen until further analyses of nutrients and other ions.

Laboratory analysis were carried out to determine total phosphorus (TP), soluble reactive phosphorus (SRP), nitrite-nitrate (NO_2-N and NO_3-N), total nitrogen (TN), alkalinity, silicate, suspended solid and chlorophyll-*a* concentrations. TP analysis was carried out with unfiltered water sample by using acid hydrolysis method (Mackereth, Heron, and Talling, 1978). Molybdate reaction method was used for SRP by using filtered water sample. TN, NO_2-N and NO_3-N analysis were performed using Scalar Autoanalyzer Standard Methods (Krom, 1980; Searle, 1984) Acid titration with phenolphtaleine and B.D.H. indicators was used for alkalinity analysis (Mackereth et al., 1978). Silicate was determined by molybdate reaction (Golterman et al., 1987). The concentration of suspended solids was estimated after filtering a known volume of water sample through a filter paper (mesh size= 1.2µ) of known weight under vacuum and after drying it in an oven at 105°C for 12 hours (Standard Methods, 22. Edition. American Association, 1996). For determination of the chlorophyll-*a* concentration, ethanol extraction method was performed, with three technical replicates which were measured the absorbance 663 nm and 750 nm on spectrometer (Jespersen and Christoffersen, 1987).

Zooplankton identification was operated at a genus level only for two periods (May and August 2016). Magnification of 40X in a stereomicroscope (LEICA MZ 16) and 630X in an inverted microscope (LEICA DMI 4000) were used for counting. Genus for both littoral and pelagic samples were presented as individual/litter. Phytoplankton were identified for most abundant genus. After settling samples in Utermöhl chambers for 16-24 hours, inverted microscope was used with 400X or 630X magnification (LEICA DMI 4000). Identifications for zooplankton and phytoplankton were carried out by Uğur Işkın and Nur Filiz, respectively Counting were done only for zooplankton.

2.4 Estimation of Lake Metabolism

Lake metabolism was estimated by using air temperature (^{0}C), wind speed (m/s), barometric pressure (mbar), relative humidity (%) and solar wave radiation (W/m^2) data from meteorological module; water temperature (^{0}C), dissolved oxygen (mg/l), salinity (psu) from sonde at 1.5 meter which represent epilimnion (Table 2.1). In addition, thermostat chain data were used to determine mixing depth. Missing days with no data due to technical problems or maintaining the probes were excluded. In order to assess smoothing effects on noisy measurements, raw data with 10-minute intervals (non-aggregated) and averaged hourly data (aggregated) for 145 days were used for metabolism estimation. Before estimating gross primary production (GPP), respiration (RES) and net ecosystem production (NEP), mixing depth (z.mix), piston velocity (k_{gas}) and photosynthetically active radiation (PAR) were estimated by using the raw data from HFLEMS. Seven different methods were used to estimate k_{gas}. Piston velocity result for each method were run in five distinct models and for each model, unrealistic results (negative GPP or positive RES) were determined. Totally, 35 different results (7 methods X 5 models = 35 GPP, 35 RES and 35 NEP) were obtained for each aggregated and non-aggregated dataset (APPENDIX). Methods were compared within the metabolism models. On the other hand, in order to analyze five metabolism models, results from seven piston velocity (k_{gas}) methods in each model were averaged to obtain single GPP, RES and NEP for each model. All calculations were conducted using the R 3.2.3 programming language for statistical computing (R core team, 2017). Further analysis was done by averaging all model results to reduce variation and rates of error. In order to examine effects of etreme meteorological events on lake ecosystems, abrupt changes in the ecosystem were determined from results of lake metabolism. Extreme meteorological events were defined as periods that cause sudden and visible changes in lake metabolism and was confirmed by Prof. Dr. Fatih Evrendilek who used Inter Quartile Range (IQR) approach in the final report of the TUBİTAK COST Project (No:114Y415).

2.4.1 Estimation of Mixing Depth

Thermostat chain was composed of 9 temperature probes, which were laid out in 0.5 m intervals. At the depths of sonde, there were no temperature probes. Instead, temperature data from sonde were added to thermostat chain for two depths, 1.5 m and 4.5 m.

Thermostat chain data were used to estimate the mixing depth. It was estimated by using “rLakeAnalyzer” package (Winslow et al 2016) in R programming language for statistical computing (R core team, 2017). The function “meta.depths” was used to determine top and bottom depths of the metalimnion. Metalimnion was determined with the steepest thermal gradient and demarcated by the bottom of the epilimnion and the top of the hypolimnion. The top of the metalimnion was assumed to represent the mixing depth. Mixing depth was added to metabolism equation with physical gas flux (F) and irradiance data. For further estimation of relevant metabolism parameters, surface water temperature was quantified as the temperature measured by the top probe at 0.5 m depth.

2.4.2 Estimation of Physical Gas Flux (F)

Physical gas flux indicates gas exchange between atmosphere and lake. Following the general equation of physical gas flux, (F) depends on the difference between the actual (O_{2meas}) and saturated (O_{2sat}) concentrations of dissolved oxygen and on the piston velocity (k_{gas}) (Equation 2.1).

O_2 saturation is represented as 100% saturation of dissolved oxygen at a given salinity, temperature, and barometric pressure. Method by Garcia and Gordon (1992) was applied for estimating O_{2sat}. Water temperature and DO% were operated for O_{2meas} calculation.

$$F = k_{gas}(O_{2meas} - O_{2sat}) \qquad \textit{equation 2.1}$$

The piston velocity (k_{gas}) is the molecular diffusion of a gas, and depends on many factors such as wind, wind fetch, convection, rainfall and surfactants. It is calculated from the estimate of the piston velocity constant (k_{600}) and Schmidt number (Equation 2.2-2.3).

$$k_{gas}(mh^{-1}) = k_{600}(mh^{-1})(Sc/600)^{-0.5} \qquad \textit{equation 2.2}$$

$$Sc = 1568 - 86.04T + 2.142T^2 - 0.0216T^3 \qquad \textit{equation 2.3}$$

There are many methods to estimate k_{600}. However, none of them universally renders the best results for all lakes. Therefore, in order to find whether using different methods give significant results for Lake Eymir, 7 different methods were used to estimate k_{600} (Table 2.2). All methods took wind speed into account as a main variable to determine k_{600}. Wind speed at 10 m above from surface water (U_{10}) is calculated for all models from the HFLMS data collected 2 m above the surface water using following equation. (Equation 2.4).

$$U_{10} = \left(measured\ wind\ speed(m/s)\right)\left(\frac{10}{height(m)}\right)^{1/7} \qquad \textit{equation 2.4}$$

The method as developed by Cole and Caraco (1998) used wind speed as the only determinant of piston velocity (*k.cole*)

Crusius and Wanninkhof (2003) defined four alternative methods, also with wind speed as their only input. In this study, Crusius (*k.crusius*) method with only one mathematical approach known as "power" model was used (Crusius and Wanninkhof, 2003).

A third method (*k.vachon*) included lake area as a factor, in order to increase its accuracy as compared to the previous methods. Vachon and Prairie (2013) proved that even though wind and k_{600} are strongly related, accuracy of models changes in different lake ecosystems based on lake size.

Further studies focused on surface renewal methods. MacIntyre *et al.* (2010) asserted an idea that temperature difference between day and night causes heat loss in eplimnion, affecting gas exchange especially in small lakes. In this method (*k.macIntyre*), k_{600} depends on the kinematic viscosity of water (ϑ) and the rate of dissipation of turbulent kinetic energy (ε).

Heiskanen *et al.* (2014) included wind shear and buoyancy flux into the equation (*k.heiskanen*). Piston velocity calculated with Schmidt number (Sc), wind speed at 10 meter (U10) and penetrative convective velocity (m/s).

Read *et al.* (2012) parameterized k600 as a function of surface mixed layer turbulence (*k.read*). The estimation of k600 is similar with MacIntyre method with different constants. In addition, tangential shear stress (τ_t) and thickness of the viscous sublayer (δ_v) were added to kinetic energy (ε) calculation.

The Last method (*k.soloviev*) is an expanded version of Read *et al.* (2012) by adding breaking wave (Soloviev et al., 2007).

All methods are available in "LakeMetabolizer" package in R programming (Winslow et al. 2016) . Each k_{600} from seven methods was used to estimate seven k_{gas} and each k_{gas} was run into five metabolism models to obtain physical gas flux (F).

Table 2.2 The methods and needed parameters for estimation of piston velocity constant (k_{600})

Model	Air Temperature (°C)	Barometric Pressure (mbar)	Net Longwave Radiation (W/m^2)	Relative Humidity (%)	Shortwave radiation (W/m^2)	Surface Water Temperature (°C)	Wind Speed (m/s)	Lake Area (m^2)	Latitude (Degrees North)
k.cole							X		
k.crusius							X		
k.vachon							X	X	
k.macIntyre	X	X	X	X	X	X	X		
k.heiskanen	X	X	X	X	X	X	X		
k.read	X	X	X	X	X	X	X	X	X
k.soloviev	X	X	X	X	X	X	X	X	X

2.4.3 GPP, RES and NEP estimation

Basic estimation of biological components of gross primary production (GPP), respiration (RES), and net ecosystem production (NEP) depend on a number of assumptions (Equation 2.5). First, GPP occurs only at daylight. Second, RES at night (RES_{night}) is equal to respiration at during daylight ($RES_{daytime}$). Finally, the metabolism is not affected by any other factors except atmospheric exchange, primary production and respiration.

Hourly net ecosystem production (NEP_{hr}) is estimated by using the change in the dissolved oxygen concentration (DO), physical gas exchange (F) and mixing depth (z.mix) data (Figure 2.3). After that, irradiance data is used to calculate dayfraction, which is the ratio of light hours to 24h period in order to determine net ecosystem production during daylight ($NEP_{daytime}$). Since, there is no primary production at night, respiration at night (RES_{hr}) equals to net ecosystem production at night ($NEP_{hr(darkness)}$). Also, because respiration at night equals to respiration during daylight, $RES_{daytime}$ can be estimated by using RES_{hr} and dayfraction. Before daily NEP estimation, GPP is equals to sum of $NEP_{daytime}$ and RES_{day}. Finally, daily net ecosystem production (NEP) is defined as difference between GPP and RESday .

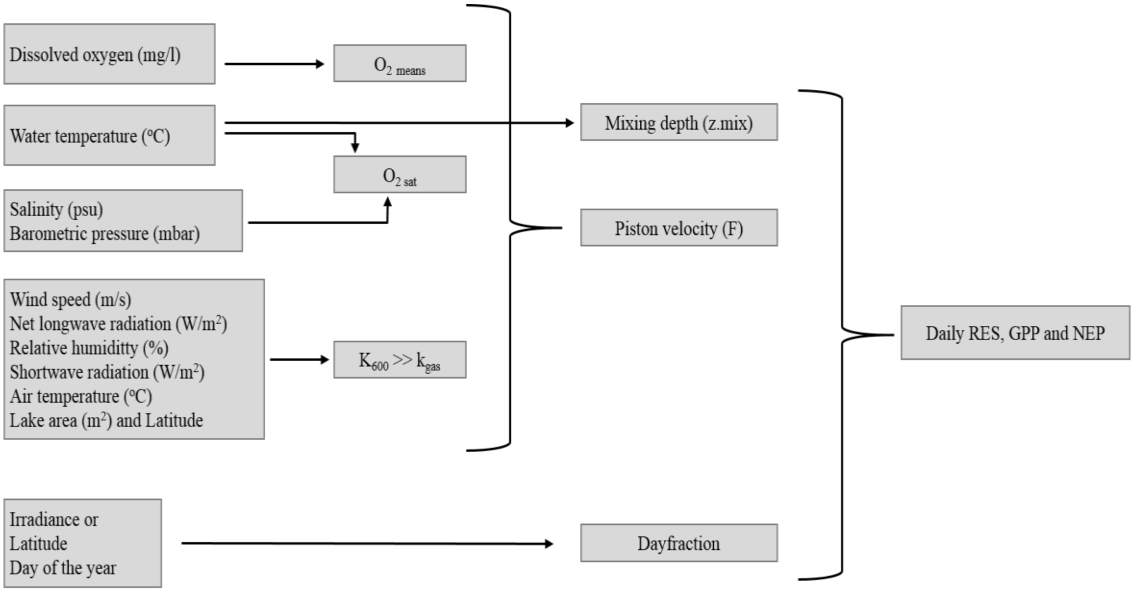


Figure 2.3. Parameters to estimate metabolic processes in Lake Eymir

$$NEP_{hr} = \Delta O_2 - (F/z_{mix}) \qquad \textit{equation 2.5}$$

$$NEP_{daytime} = meanNEP_{hr(daylight)} * dayfraction * 24$$

$$RES_{hr} = meanNEP_{hr(darkness)}$$

$$RES_{daytime} = RES_{hr} * dayfraction * 24$$

$$RES_{day} = RES_{hr} * 24$$

$$GPP = NEP_{daytime} + RES_{daytime}$$

$$NEP = GPP - RES_{day}$$

For the estimation of metabolism, five different approaches used, are found in “Lake Metabolizer” package in R programming (Table 2.3). *Bookkeep* is the simplest model that does not include error terms (Cole et al., 2000; Odum, 1956) also does not use irradiance data. In *Ordinary Least Squares (OLS)* models, linear regression is used to estimate changes in dissolved oxygen and model is fitted by using OLS approach and it takes process error into account. Maximum likelihood estimation (MLE) however, adds process and observation errors into the equation and the regression model does not contain pervious oxygen observation like in OLS approach. Instead it uses estimated value from previous estimation. The Kalman filter follows the same approach but smooths dissolved oxygen data prior to further calculation (Batt and Carpenter, 2012). Similar to the MLE approaches, the Bayesian model also distinguishes observation and process error (Mutshinda, Finkel, and Irwin, 2013). Both *Kalman* and *Bayesian* models operates approaches with precisions not with variance.

As a result of faulty assumptions, metabolism estimation is problematic in some cases. Problems include negative estimations of GPP and positive RES values result in biased metabolism outcomes. However, these unrealistic results also indicate when model falls into error that can help to improve further models. Therefore, faulty assumptions were also considered.

Table 2.3 Different approaches of five metabolism models (Revised from Winslow *et. al* 2016)

Model	Statistics	Error Type	Primary production – irradiance relationship	Respiration – temperature relationship
Bayesian	Bayesian	Gaussian	Linear	Log-linear
Bookkeep	Algebra	None	None	None
Kalman	MLE & Kalman filter	Gaussian	Linear	Log-linear
MLE	MLE	Gaussian	Linear	Log-linear
OLS	Linear regression	Gaussian	Linear	Log-linear

2.5 Statistical Analysis

All statistical analyses were done in R programming version 3.2.2. For 5 models and 7 methods, non-parametric Mann Whitney- u test were applied to compare GPP, RES and NEP parameters. Pearson correlation between environmental variables and metabolism parameters were reported by corrplot package in R programming after averaging ten-minutes data into monthly data. Missing temperature data from thermostat chain because of technical problems were completed by linear interpolation method.

Extreme events were spotted by Prof. Dr. Fatih Evrendilek with inter-quartile range approach and outliers/extremes 1.5X IQR rule were applied to the data.

CHAPTER 3

RESULTS

3.1 Physico-chemical Parameters

The high frequency Lake Eymir monitoring system (HFLEMS) collected integrative data between September 2015 to August 2016 on both the atmosphere and the water column until the water temperature dropped under 10 ^{0}C, at which point only meteorological data were collected (Table 3.1).

Table 3.1 Mean values ± standard errors of parameters measured by HFLEMS

Parameters	Mean ± sd
Wind speed (m/s)	1.4 ± 1.5
Air temperature (^{o}C)	17.2 ± 8.2
Relative humidity (%)	60.3 ± 22.9
Short wave radiation (W/m^{2})	205.2 ± 290.4
Barometric pressure (mbar)	905.4 ± 3.4
Saturated dissolved oxygen (%)	71.4 ± 35.2
Dissolved oxygen (mg/l)	6.5 ± 3.1
Water temperature at 1.5 m (^{o}C)	20.2 ± 5.7
Mixing depth (z.mix)	3.6 ± 1.6
pH	8.7 ± 0.2
Fluorescent dissolved organic matter, fDOM (mV)	21.3 ± 2.1
Turbidity (FNU)	4.2 ± 2.6
Conductivity (µS/cm)	2327 ± 328.3
Salinity (psu)	1.0 ± 0.1

While relative humidity and barometric pressure reached their maxima in November 2015, highest short wave radiation was observed in June 2016. Yearly average wind speed was 1.4 m/s, while maxima of 10 m/s was observed in Spring 2016 (Figure 3.2). Wind speed above 4 m/s altered the temperature profile, dissolved oxygen and chlorophyll-*a* concentrations of the lake, with its severity depending on magnitude and continuity of winds.

The sonde placed at 1.5 meter measured highest water temperature as 28 ^{0}C in June 2016 two days after air temperature reached its maximum value (Figure 3.2). Furthermore, fluorescent dissolved organic matter (fDOM) declined with increasing air temperatures (Pearson: $r = -0.81$, $p < 0.01$), and reached its maximum value of 25.9 Relative Fluorescence units (RFU) at the end of the autumn 2015 (Figure 3.2). In September and October 2015 depletion of dissolved oxygen (DO) concentration co-occurred with continuous strong wind events above 4 m/s. DO concentration recover to a max of 18 mg/l in the following winter. Daily diel dissolved oxygen dynamics followed a different pattern between the seasons (Figure 3.3). During the day DO concentration increased and generally reached its maxima around 07:00 pm. During night DO concentration decreased sharply.

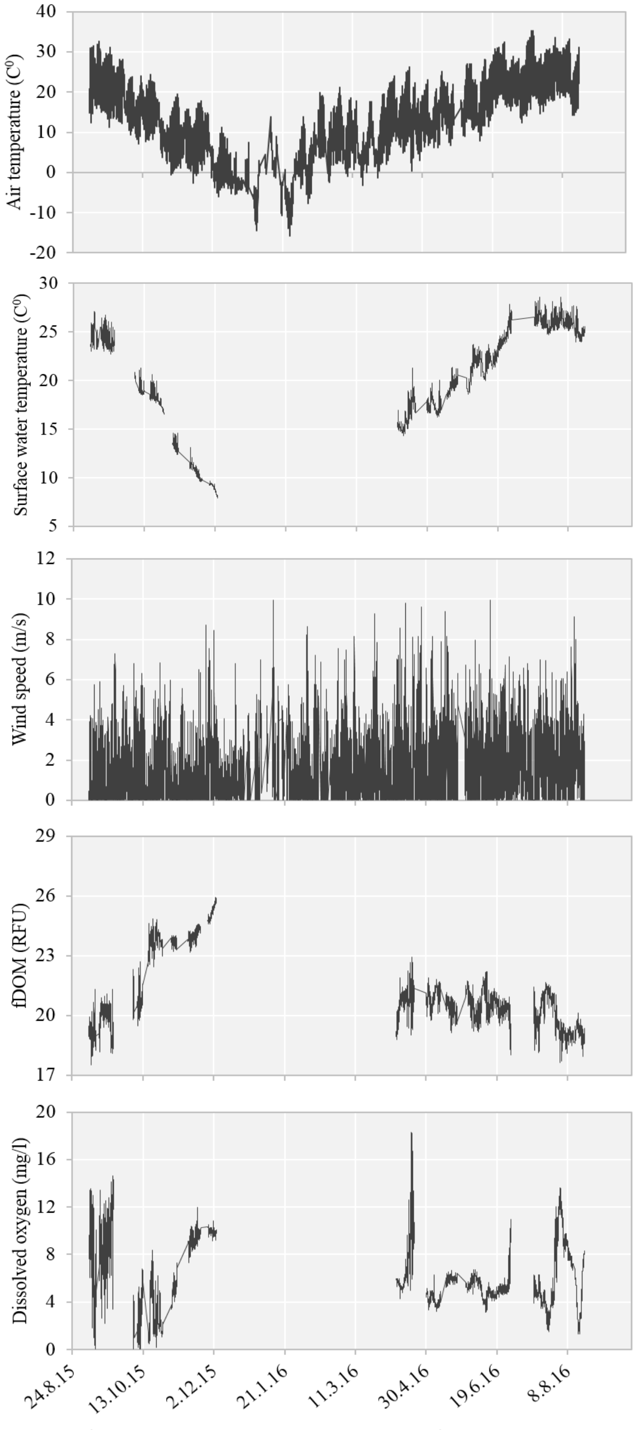


Figure 3.1. Raw data of air temperature (^{o}C), surface water temperature (0.5m) (^{o}C), wind speed (m/s), fDOM-RFU and dissolved oxygen (mg/l)

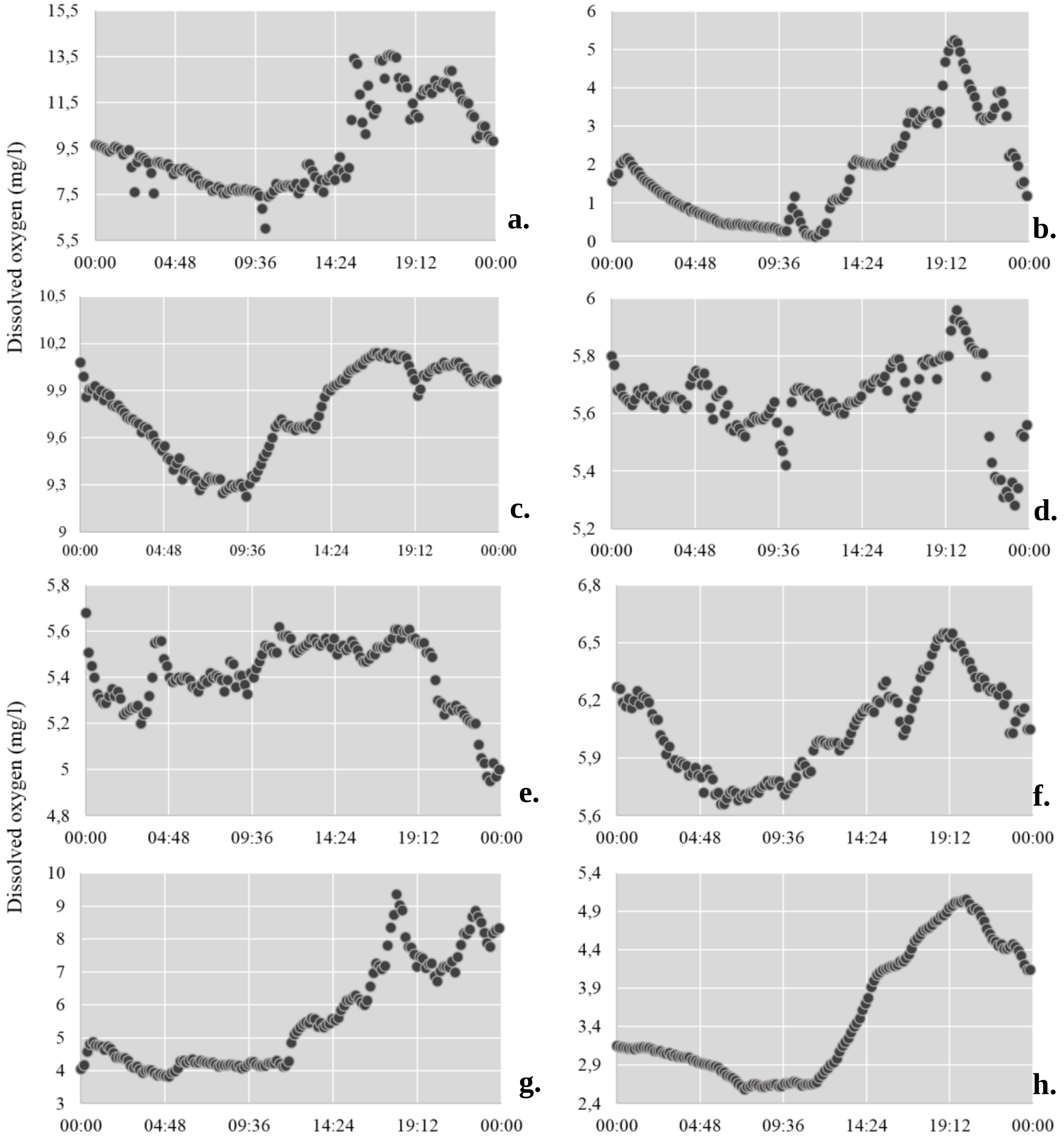
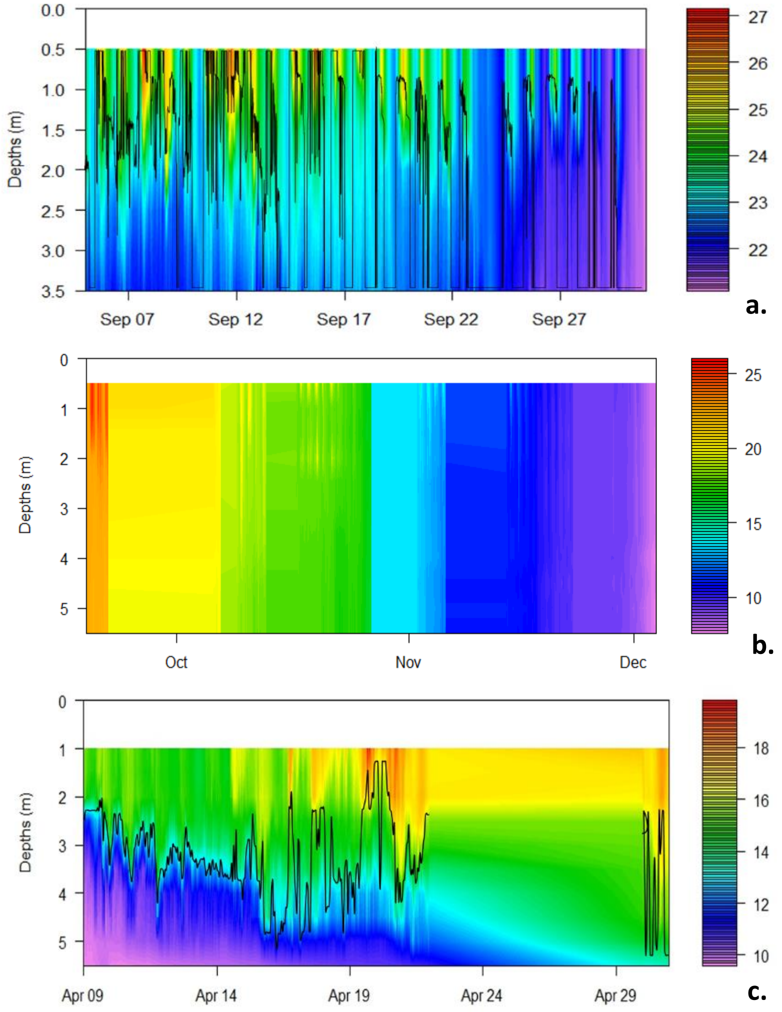


Figure 3.2. Monthly averaged diel dissolved oxygen concentration changes (a) September 2015 (b) October 2015 (c) November 2015 (d) April 2016 (e) May 2016 (f) June 2016 (g) July 2016 (h) August 2016

When present, thermal stratification had a mean depth of 3.6 m during study period with fluctuations up to 1.6m. Air temperature, precipitation and wind were the main predictors of thermal stratification. Long term thermal stratification was broken down after continuous strong wind events in September 2015 with the decline of air temperature (Figure 3.4). Nonetheless, mild temperatures in October prolonged the micro-stratification until the second week of the month. In late autumn and during winter thermal stratification was absent. Thermal stratification reoccurred in mid-April and continued through the summer (Figure 3.4). Nevertheless, throughout the summer thermal stratification was occasionally disrupted by precipitation and strong winds.



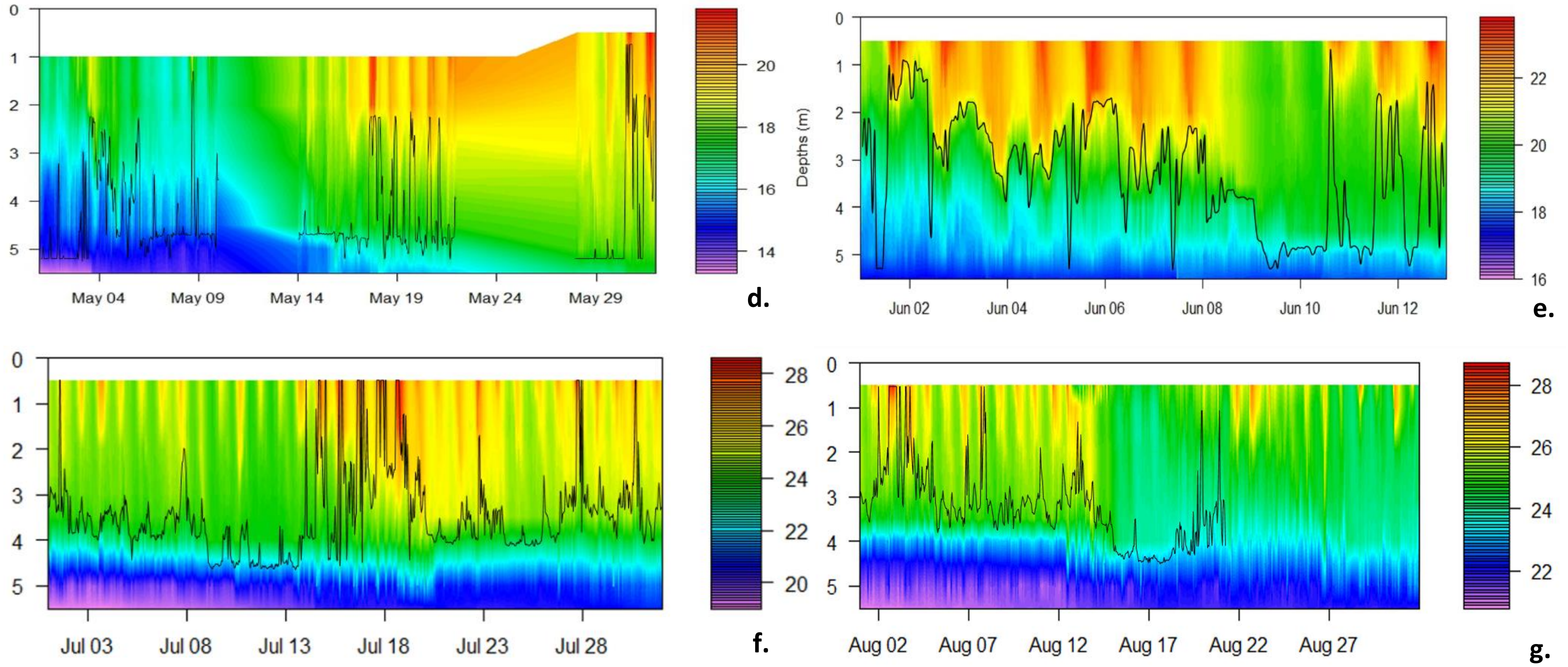


Figure 3.3 Temperature profiles of Lake Eymir (a) September 2015 (b) October, November and December 2015 (c) April 2016 (d) May 2016 (e) June 2016 (f) July 2016 and (g) August 2016

In addition to automated monitoring, seventeen manual in-situ measurements and water chemistry analysis were carried out every other week (Table 3.2). These data show an increase in Secchi depth during spring, followed by a sharp decline in July2016. While a TN:TP ratio below 10 indicated nitrogen limitation, averaged soluble reactive phosphorus (SRP) was around 31.5 µg/l.

Table 3.2 Mean values ± standard errors of parameters measured at biweekly monitoring during sampling period

Parameters	Mean±sd
Max. depth (m)	5.8 ± 0.3
Secchi depth (cm)	213.5 ± 180.2
Total Phosphorus (µg/l)	106.5 ± 33.5
Soluble Reactive Phosphorus (µg/l)	26.6 ± 24.8
Nitrite + Nitrate (µg/l)	26.6 ± 42.7
Total Nitrogen (µg/l)	561.8 ± 343.6
Suspended Solids (mg/l)	9.4 ± 5.3
Silicate (ppb)	4.1 ± 2.0
Alkalinity (meq/l)	8.1 ± 3.0
Averaged Water Temperature ^{o}C	17.7 ± 6.9
Conductivity (mS)	1.7 ± 0.3
Total Dissolved Solids (g/l)	1.3 ± 0.06
Salinity (psu)	1.0 ± 0.05
Dissolved Oxygen (mg/l)	5.6 ± 4.2
pH	8.4 ± 0.41

3.2 Biological Parameters

While HFLEMS recorded both chlorophyll-*a* and blue green algae (BGA) concentrations at 1.5 meter, only chlorophyll-*a* were measured during manual monitoring. The timing of the highest recorded values of chlorophyll-*a* differed between the manual biweekly and the automated high frequency monitoring (Figure 3.5). However, higher chlorophyll-*a* measurements in both time series coincided with the period of algal blooms. In addition, chlorophyll-*a* concentration correlated negatively with Secchi depth (Pearson: r = -0.8, p<0.01).

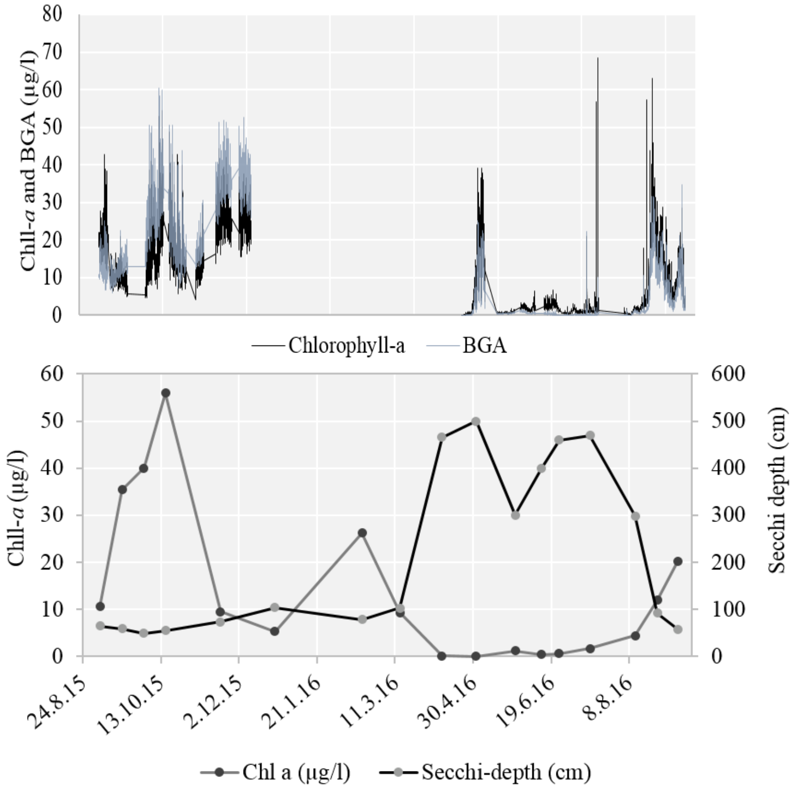


Figure 3.4 Chlorophyll-*a* and Blue green algae (BGA) concentrations from high frequency measurements and biweekley monitoring of chlorophyll-*a* and relation with Secchi depth

Chlorophyll-*a* concentrations generally exceeded BGA concentration during the sampling period, although BGA concentrations exceeded those of chlorophyll-*a* during algal blooms in the late summer and autumn. (Figure 3.5).

Chlorophyll-*a* and BGA concentrations at 1.5 meter correlated negatively with air and water temperature (Pearson: r = -0.42, -0.6, -0.39, -0.6, p<0.01, respectively). There was, however, a strong time dependency: when spring 2016 was disregarded, Chlorophyll-*a* and BGA concentrations at 1.5 meter correlated positively with air and water temperature.

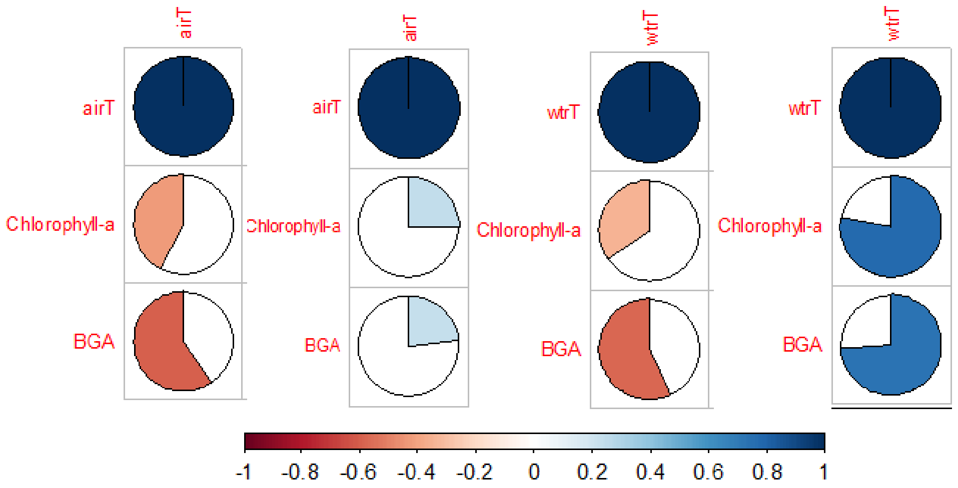


Figure 3.5 Pearson correlation between algal production and air, water temperature with whole data and during growing period of phytoplankton (spring).

Another positive relation was found with turbidity (Pearson, r = 0.74, 0.73, p<0.01, chlorophyll-*a* and BGA, respectively). In October, during mixing period there was a decrease in chlorophyll-a, also coinciding with DO depletion at 1.5 meter (Figure 3.6). Moreover, SRP and TN:TP ratio were negatively correlated with chlorophyll-*a* concentration (Pearson, r = -0.42, -0.53, p<0.01, respectively).

Both for phytoplankton and zooplankton, idenditification were carried on for two different periods. In spring, abundance of zooplankton reached highest values. Throughtout the spring, big-sized zooplankton like daphnids and copepods prevailed. During summer, on the other hand, rotifers dominated the lake (Figure 3.7).

In phytoplankton community, Cryptophyta class (genus: *Cryptomonas* and *Plagioselis*), dominated the lake during April 2016. In May 2016, however, big-size Cryptomonas was replaced by *Ankyra* genus from Chlorophyta class. By increase in temperature, *Chroococcus dispersus* from Cyanobacteria class were found higher in abundace with large centric diatoms.

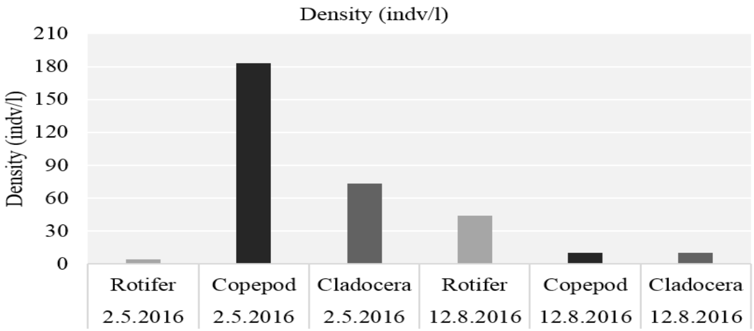


Figure 3.6 Zooplankton abundance during spring and summer periods

3.3 Estimation of Metabolism Results

3.3.1 Piston Velocity (kgas) with Different k600 Methods

Piston velocity, an important determinant of O_2 exchange between air and water, was estimated with seven different k_{600} methods. Each method was applied on the original (10-minute interval) time series, and an aggregated series with an interval of an hour between data points (Table 3.3). Based on the non-aggregated data, the *Heiskanen* and *MacIntyre* methods rendered similar estimates for k_{gas}. In addition, the variance between days was markedly higher as compared to other estimation methods. The *Heiskanen* and *MacIntyre* also differed from *Cole, Crusius, Vachon, Read* and *Soloviev* methods in that they were the only ones to estimate piston velocity to be zero. Estimations on aggregated data, results of all methods were significantly different from each other (Mann Whitney, $p < 0.01$). After assessing methods for piston velocity, each methods were run in five distinct metabolism models.

Table 3.3 Statistical table for different methods of k_{gas} (n=145)

Ten Minutes Data

	Cole	Crusius	Vachon	Heiskanen	Read	Soloviev	MacIntyre
Min.	0.38	0.031	0.10	0.00	0.06	0.06	0.00
Median	0.62	0.14	1.33	2.91	0.78	0.78	2.91
Mean	0.81	0.66	1.52	2.61	1.17	1.26	2.61
Max.	4.84	16.26	7.32	10.01	4.04	11.09	10.01
Sd.	0.81±0.42	0.66±1.12	1.52±0.90	2.61±1.62	1.17±0.82	1.26±1.01	2.61±1.62
Var	0.18	1.25	0.82	2.63	0.67	1.01	2.63

Hourly Data

	Cole	Crusius	Vachon	Heiskanen	Read	Soloviev	MacIntyre
Min.	0.39	0.032	0.48	0.11	0.08	0.08	0
Median	0.63	0.15	1.14	1.33	0.79	0.79	2.90
Mean	0.79	0.60	1.39	1.49	1.15	1.22	2.56
Max.	3.31	9.91	4.54	5.53	3.96	6.51	7.69
Sd.	0.79±0.38	0.60±0.97	1.39±0.77	1.49±0.83	1.15±0.77	1.22±0.91	2.56±1.59
Var	0.15	0.95	0.59	0.69	0.59	0.84	2.51

3.3.2 Comparison of Model Outputs for Metabolism Estimations

Seven distinct methods for piston velocity (kgas) were used to estimate physical gas flux (F), which subsequently used in running five different models for metabolism estimation by using aggregated and non-aggregated data, leading to a total of 70 estimations of gross primary production (GPP), respiration (RES) and net ecosystem production (NEP). In some cases, GPP, RES and NEP estimations differed significantly between methods and/or models (Appendix A).

In each model, GPP estimation from non-aggregated data (mGPP) rendered similar pattern for *MacIntyre* and *Heiskanen* method. These two methods significantly differed from other methods in all models (Mann Whitney, $p<0.01$). When mGPP is aggregated into hourly data (hGPP), estimations were no longer different between methods for *Bayesian*, *Bookeep*, *Mle* and *Ols* models, but with the exception of the *MacIntyre* method. However, in the *Kalman* model, hGPP was different in *Heiskanen* method (Mann Whitney, $p<0.01$) instead of *MacIntyre* method.

While the estimated mGPPs were different for *Heiskanen* and *MacInytre* methods, estimation of mRESs also followed the same pattern for each model. hRES estimations differed for *MacIntyre* method compared to the other methods, except for *Kalman* model like in hGPP results.

The average of the GPP and RES estimations obtained from the seven distinct methods calculated for each model, and no statistical difference was found between these five models. Altering the interval of data (non-aggregated vs aggregated) also did not render different results. Only in *Bookkeep* model, both mGPP and hGPP differed from other models.

3.3.3 Inevitable Errors

Five models occasionally estimated GPP and RES to be unrealistic results (GPP<0 or/and RES>0) (Figure 3.8). These out-of-range estimations in turn led to erroneous estimation for NEP. The number of erroneous RES values declined when aggregated data were used instead of non-aggregated data. On the other hand, the number of negative GPP values was higher when aggregated data were used. Nonetheless, aggregated data rendered the lowest number sub-zero GPP values (8 days) in the *Bayesian-MacIntyre* model. In general, the number of negative estimations for RES were low among models than for estimated GPPs (Figure 3.9).

Number of days with unrealistic estimations from seven methods in each model were averaged to compare metabolism models. unrealistic GPP estimations remained more frequent than unrealistic RES estimations. Unlike RES, unrealistic GPP estimations increased in frequency when data were aggregated. The lowest number of error was observed in *Bayesian* model except in hRES, which had the lowest value in *Mle* approach. Error in *Bookkeep* model increased with averaged dataset for both GPP and RES. Most of the unrealistic estimates coincided with the times of sudden abrupt changes and the times when thermal stratification was broken down during autumn.

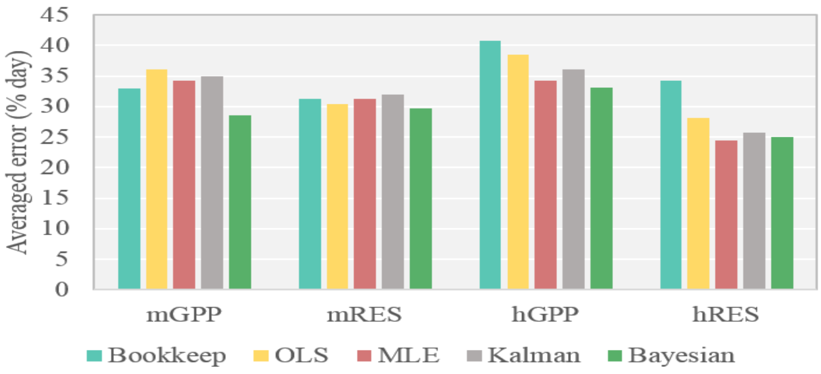


Figure 3.7 Unrealistic metabolism values for each model (erroneous days were averaged from seven different methods and were represented as percentage)

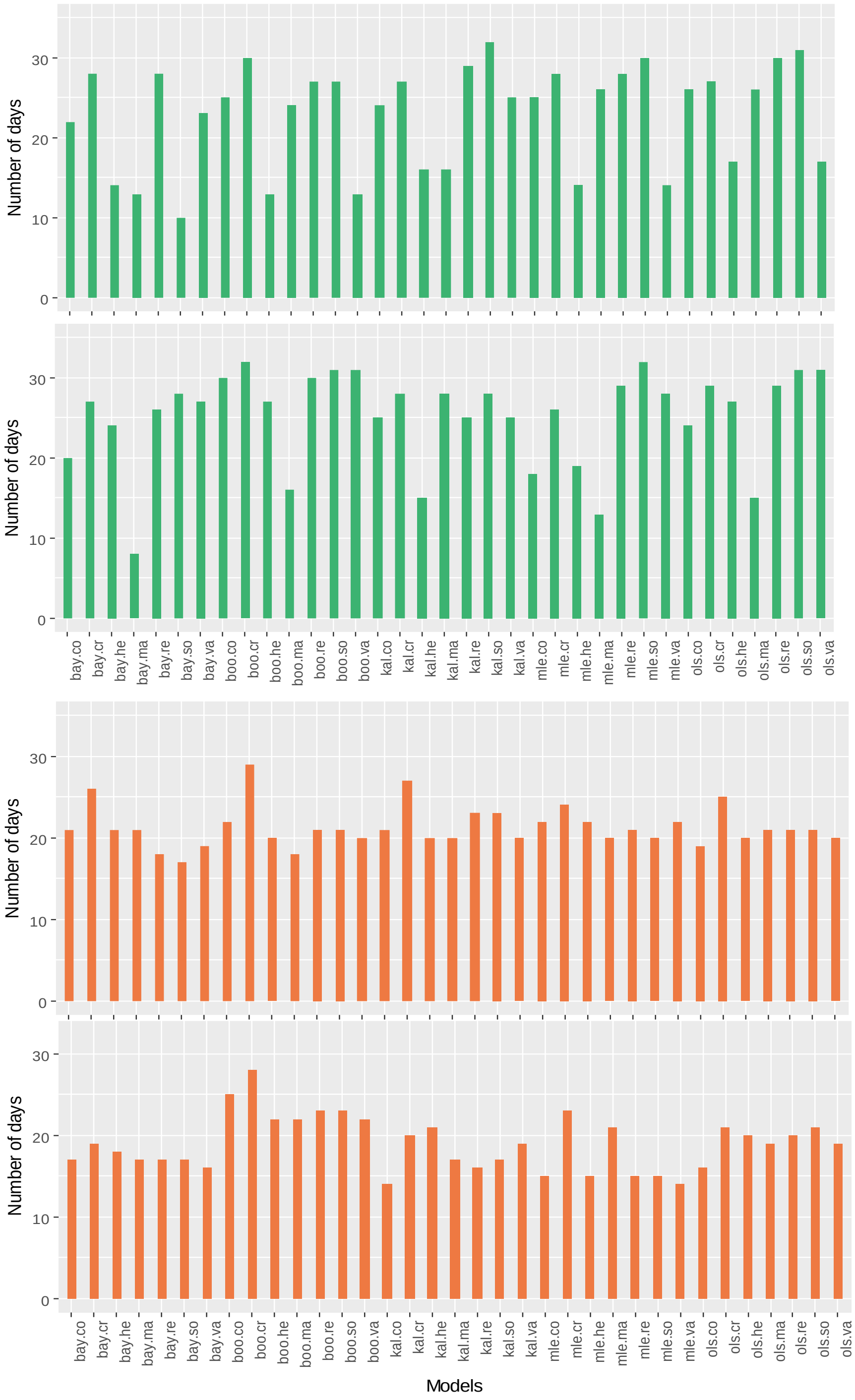


Figure 3.8 Unrealistic values for GPP (green) and RES (orange) for each method and model (mGPP, hGPP, mRES, hRES, respectively)

3.3.4 Results of Metabolism

Analyses of overall metabolism was done by averaging all model results from raw data by eliminating the unrealistic results (GPP<0 or RES>0). According to daily estimation of metabolism, most of the year, Lake Eymir acted as CO_2 source to atmosphere (90/110 days). Monthly results also pointed out net heterotrophy (NEP <0). Only in September, net autotrophy (NEP >0) was recorded as 1.2 mg O_2. $l^{-1}d^{-1}$ coinciding with an extended algal bloom period (Table 3.4). In autumn, after the net autotrophic period, disturbance led to a decrease in GPP. Since GPP supports RES in the epilimnion, the reduction of GPP first caused a decrease in RES, subsequently resulting with the RES exceeding GPP, thus causing the lake to shift back to the heterotrophic system during the mixing periods.

Table 3.4 Monthly metabolism parameters (mg. $O_{2.}$ l^{-1}. d^{-1})

Month	GPP.avg	RES.avg	NEP.avg
September 2015	8.8	-7.6	1.2
October 2015	3.1	-4.8	-1.7
November 2015	1.6	-1.7	-0.1
April 2016	3.7	-4.5	-0.8
May 2016	1.1	-2.0	-0.9
June 2016	1.5	-2.8	-1.3
July 2016	3.1	-4.7	-1.6
August 2016	2.0	-3.6	-1.6

3.3.5 Metabolism and Environmental Parameters

During the manual monitoring, water samples were every other week analyzed for both N and P, to investigate correlations with metabolic processes (Figure 3.10). Both GPP and RES exhibited a negative correlation with TN:TP ratio (Pearson, r = -0.3, -0.7, respectively, $p<0.01$). SRP also decreased with increasing GPP. For Net ecosystem production (NEP) relations with environmental parameters were similar to RES and GPP.

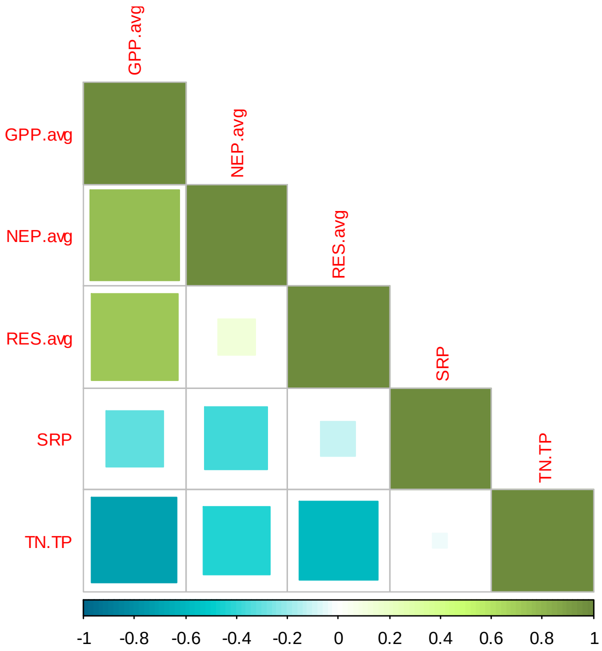


Figure 3.9 Pearson Correlation matrix between metabolism parameters and environmental parameters

3.3.6 Extreme Meteorological Events

Metabolism showed three distinct episodes (Figure 3.11). The first period (09 - 21.09.2015) coincided with an algal bloom which included high GPP, and RES dropped with heavy rainfall and strong winds and followed by increase in RES. In the second period (15 - 22.04.2016), rising air temperatures triggered an increment of phytoplankton leading higher GPP than RES. In the last period (01 - 20.08.2016) environmental conditions returned to values similar to the first period. This period starts with an algal bloom followed by a storm events disturbing lake thermal stratification.

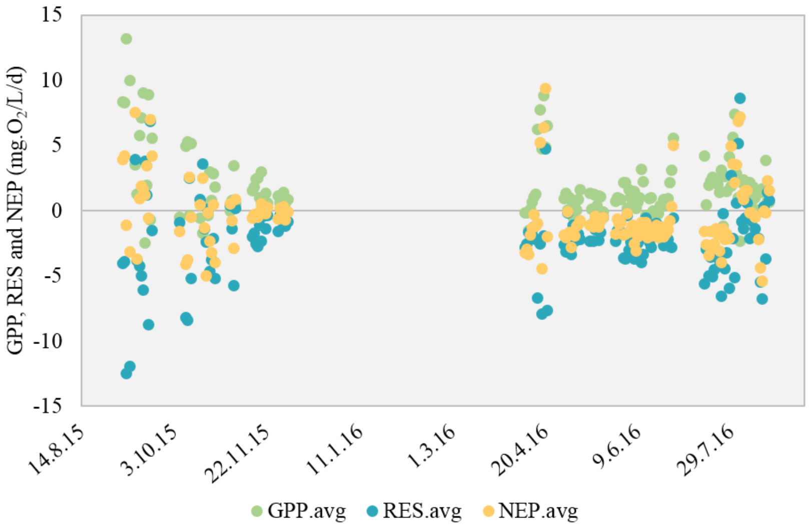


Figure 3.10 Metabolism parameters for 145 days with errors (mg. $O_{2.}$ l^{-1}. $d^{-1)}$

On the ninth of September 2016, a strong storm marked the beginning of a period with strong continuous winds. As a result of this storm thermal stratification broke down, ending the algal bloom (BGA ≈ 40 µg/L) that maintained a high GPP and RES in the prior period (Figure 3.12). After two strongest winds, metebolism models failed to explain RES. However, fluctuation between heterotrophy and autotrophy ended up with net heterotrophy in the lake. This sudden change coincided with the reduction in the chlorophyll-*a* concentration as well.(Figure 3.12). Moreover, mixing and precipitation increased fDOM. Shortly after this first storm on the 9th of September, dissolved oxygen strongly decreased and induced a large-scale fish kill.

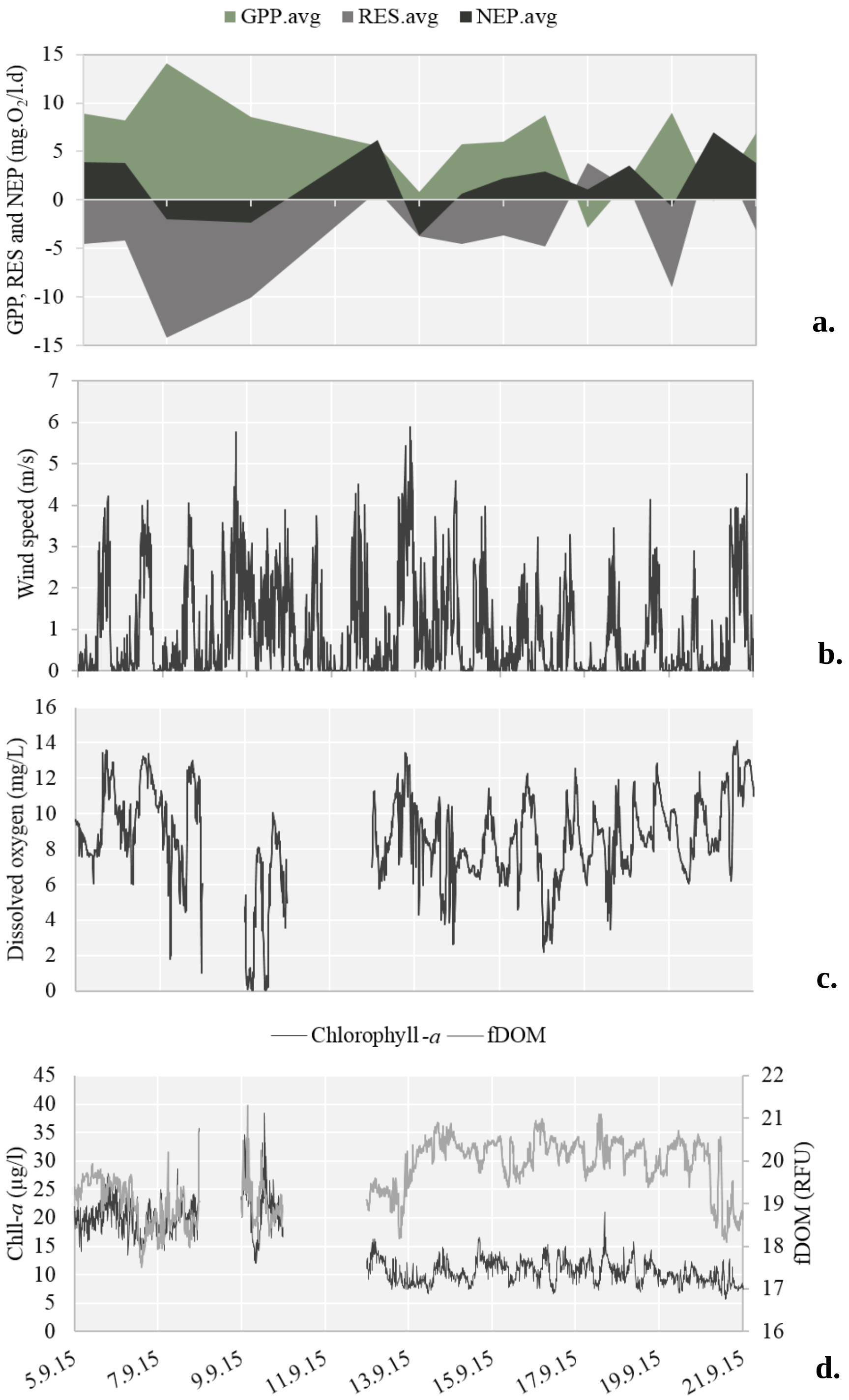


Figure 3.11 (a) Metabolism parameters, (b) Wind speed (m/s), (c) Dissolved oxygen concentration (mg/L), (d) Primary producers and fDOM concentrations in September

Increasing in temperatures and the onset of light breezes triggered an increase of GPP after 15th of April (Figure 3.13). However, 21th of April a sudden drop in air temperature by $11^{O}C$ led to mixing and sharp decline in chlorophyll-*a* concentration. During sudden changes of temperature, the metabolism models gave faulty assumption for RES same as in the first episode. Even though the air temperature increased gradually after this day, GPP was still lower than RES (Figure 3.14). During this period, fDOM did not change, as it was the case in September 2015. Turbidity, however, increased with chlorophyll-*a* concentration. Although, dissolved oxygen levels showed a fluctuating pattern reminiscent of that of chlorophyll-*a*, no oxygen depletion was observed.

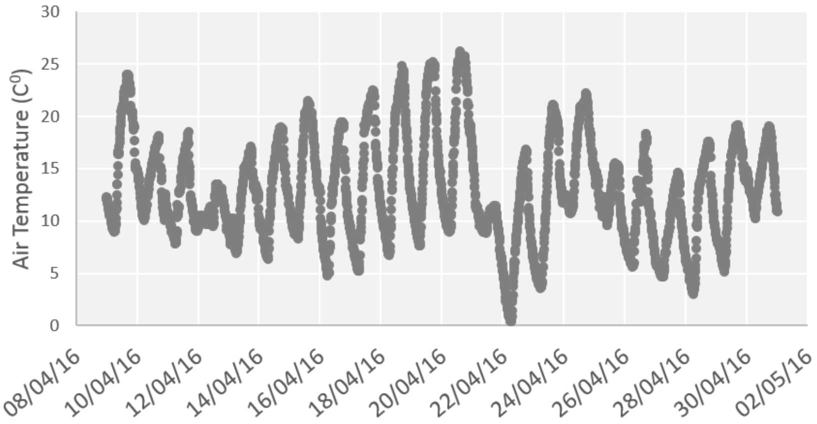


Figure 3.12 Air temperature changes during spring 2016

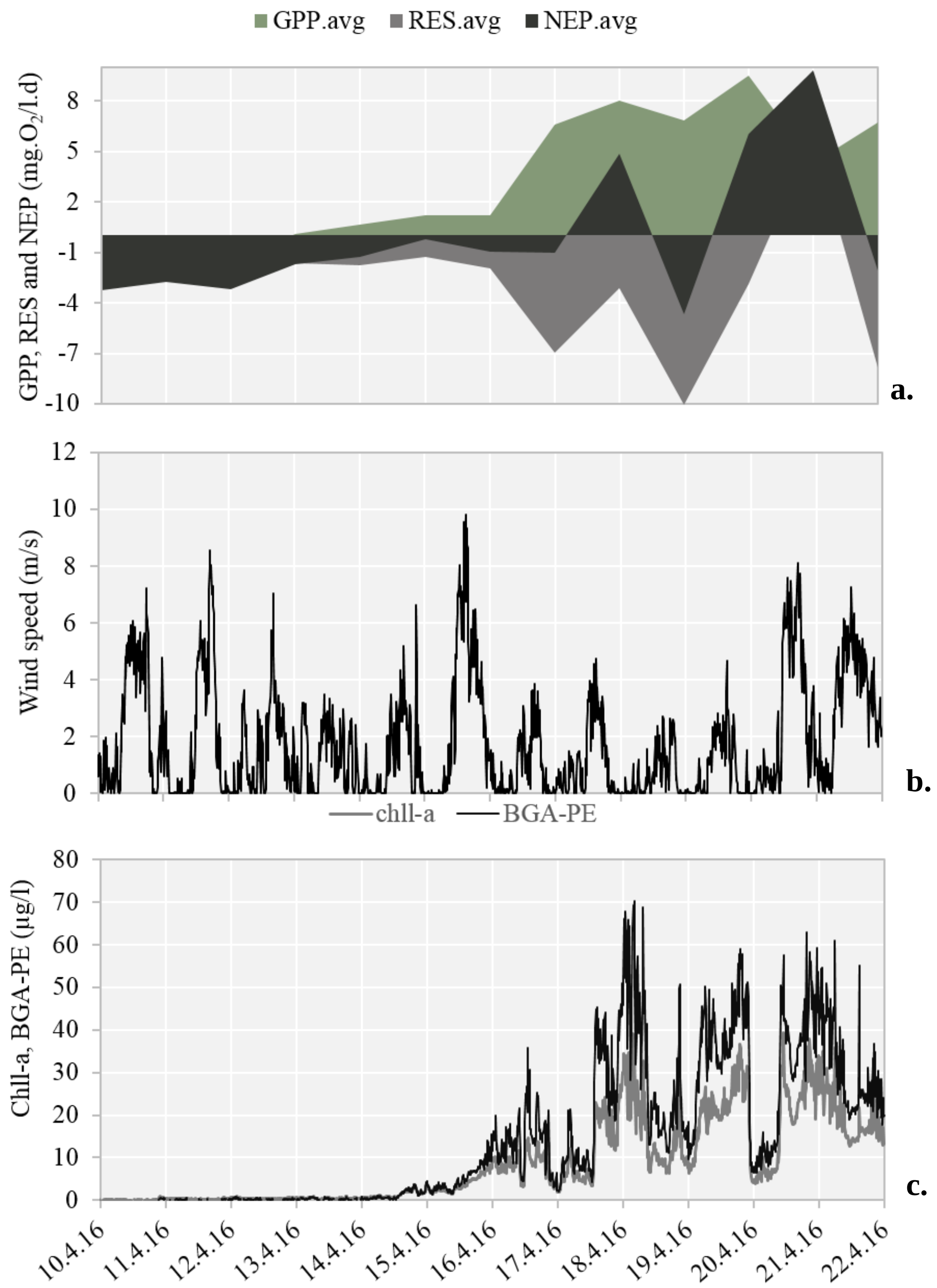


Figure 3.13 (a) Metabolism parameters, (b) Wind speed (m/s), (c) Primary producers concentration in Spring 2016

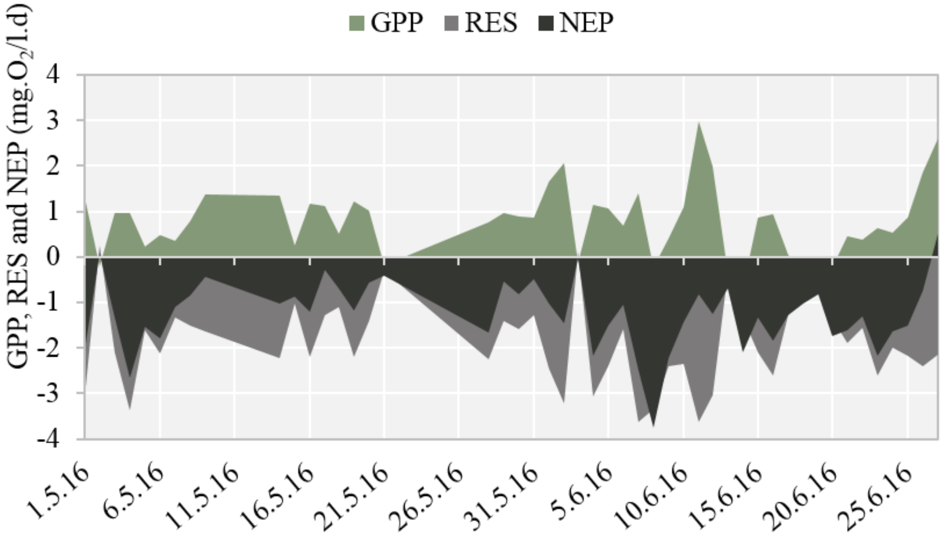


Figure 3.14 Metabolism parameters during late spring and begining of summer 2016

After the second episode, chlorophyll-*a* remained stable while respiration remained relatively high (Figure 3.15). This period concured with a period of an increase in large-sized zooplankton, which substantially contributed to the metabolic activity in the lake.

In late June 2016, water temperature of the lake got warmer and this stable environment created a suitable environment for an algal bloom. This bloom continued until the end of July, but was ended when wind speed increased after the 15th of August, when storms occurred. This reduced chlorophyll-*a* concentration and GPP but increased fDOM and RES (Figure 3.16). However, because the air temperature remained relatively high, a new algal bloom was induced, that could not be observed after first episode in September 2015.

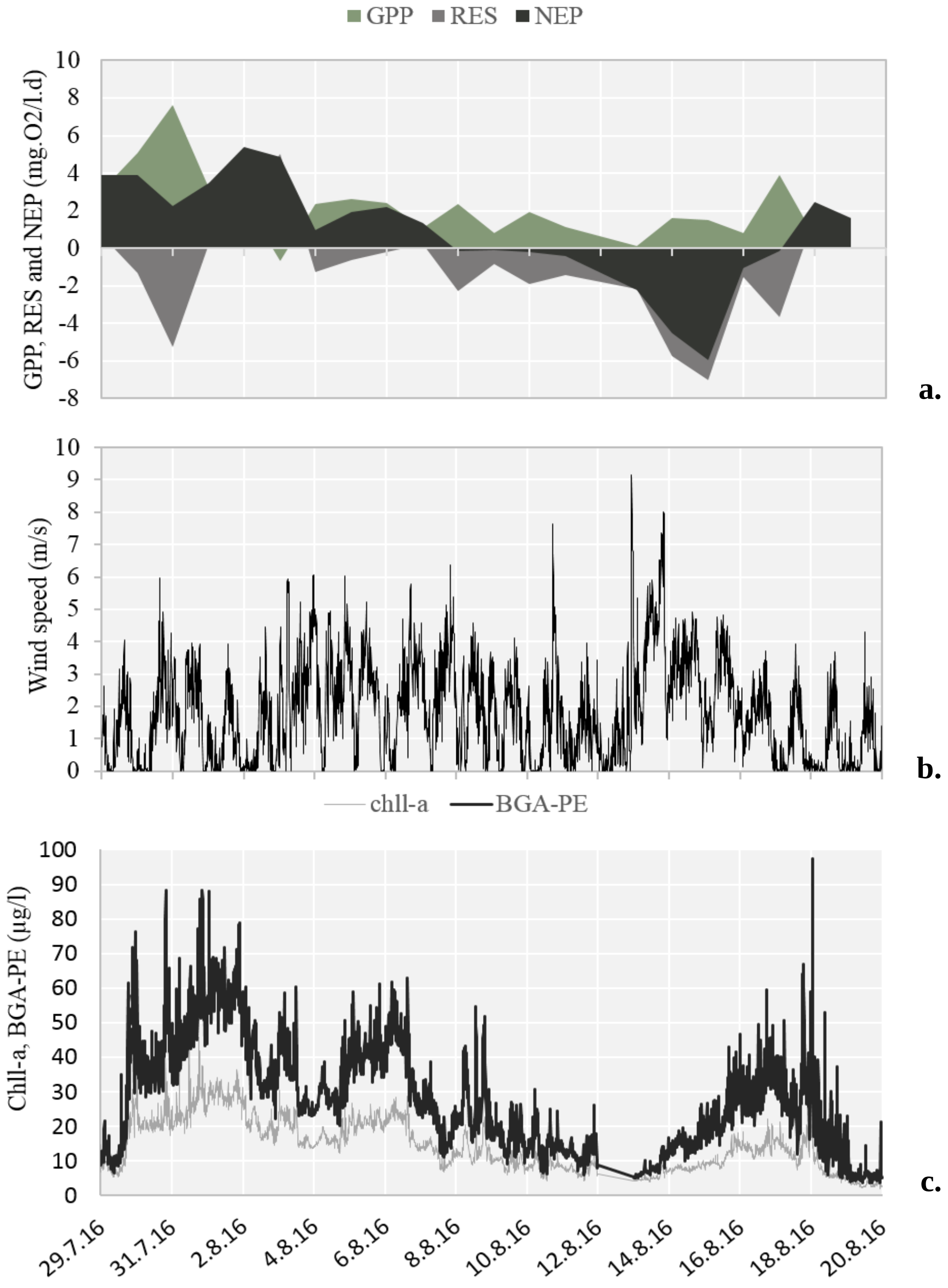


Figure 3.15 (a) Metabolism parameters, (b) Wind speed (m/s), (c) Primary producers concentrations in August 2016

CHAPTER 4

DISCUSSION

Traditional ecosystem monitoring relies on discrete sampling that may cause overlooking the effects envirionemental changes including meterological e.g. short term wind on lake ecosystem (Marcé et al., 2016). By means of advanced technology, automated high frequency measurements in hours, minutes and seconds have been becoming common way to estimate lake metabolism (Cole et al., 2000; Gelda and Effler, 2002; Laas et al., 2012; Lauster, Hanson, and Kratz, 2006; Staehr and Sand-Jensen, 2007). Lake metabolism is one of the powerful metrics for understanding formation and utilization of organic matter by looking diel oxygen changes and estimating gross primary production (GPP), respiration (RES) and net ecosystem production (NEP) (Hoellein et al., 2013; Staehr et al., 2012(a)).

Basic model for estimating metabolism called *Bookkeep* is based on basic algebra. On the other hand, in advanced models, GPP is explained by irradiance data and RES is a function of water temperature. In addition, piston velocity, which explains how fast the exchange of O_2 between water and air, is also estimated by using various methods (Winslow et al., 2016). However, the effects of using different methods and models on metabolism results has not been fully studied. For this purpose, In Lake Eymir, seven different methods to estimate piston velocity and five metabolism models were compared.

4.1 Comparisons of Piston Velocity Methods and Metabolism Models

In this study, seven methods for piston velocity which explains fluxes of O_2 between water and air were used. While *Cole* and *Crusius* methods explained k_{gas} based on wind speed only (Cole and Caraco, 1998; Crusius and Wanninkhof, 2003), *Vachon* adds lake area into the equation. Surface renewal gas exchange methods *MacIntyre, Heiskanen, Read* and *Soloviev,* on the other hand, were developed by adding more parameters like relative humidity, air temperature, latitude and atmospheric pressure (Heiskanen et al., 2014; MacIntyre et al., 2010; Read and Rose, 2013; Soloviev et al., 2007).

In Lake Eymir, seven methods for k_{gas} estimation gave significant results but when they ran into five metabolism models, five methods (*Cole, Crusius, Vachon, Read and Soloviev*) over seven gave similar results for both RES and GPP when non-aggregated data were used. Since results from *Read* and S*oloviev* were not significantly different, wave effects on diffusion of O_2 added by *Soloviev* may not contribute to metabolism of Lake Eymir. Also, similar results with *Cole, Crusius* and *Vachon* may indicate measuring wind speed is enough to estimate piston velocity that reduce cost as well. In spite of these results, two surface renewal gas exchange methods *Heiskanen* and *MacIntyre* were significantly different than all other methods in non-aggregated data. Even two methods have similar logic with *Read* and *Soloviev* methods, formulation of parameters is different (Heiskanen et al., 2014; MacIntyre et al., 2010). Also, *Heiskanen* and *MacIntyre* did not include lake area and latitude. The reason for significant differences may also explained by coefficients. Two methods use bigger constants comparing with *Read* and *Soloviev*. In despite of these differences, when aggregated data were used, only *MacIntyre* method stayed significant. However, in *Kalman* model the *Heiskanen* was different than other methods. Big variation in *MacIntyre* and *Heiskanen* methods may indicate two approaches do not provide reliable results. The other possible answer for this, since k_{gas} estimation for *MacIntyre* and *Heiskanen* are various than the other methods, metabolism models could not be able to smooth the data. Even the real reason for this difference is unknown, the results indicate piston velocity has substantial proportion on metabolism of Lake Eymir like found in the study was conducted by *Gilling* et. al. (2017).

When results of metabolism models were compared, no significant differences except *Bookkeep* model were obtained. *Bookkeep* estimated higher mGPP and hGPP may due to approach of estimating primary production. In *Bookkeep* model, GPP are not calculated with irradiance data (Winslow et al., 2016). Instead, it separates a day into dark and light and keeps GPP constant during daylight. In spite of this difference, distinct statistical approaches in metabolism models did not change the metabolism significantly which similar results were revealed by Hanson et al. 2008 as well.

Since estimation of metabolism relies on certain assumptions, unrealistic values for GPP and RES became inevitable and are needed to be examined (Staehr et al., 2012 (b); Staehr et al., 2010; Winslow et al., 2016). Models assume RES at night is equal to RES during daylight. This omits effects of environmental changes on living organism. For instance, strong winds may disrupt the algal bloom during day and may reduce abundance of phytoplankton that can alter respiration at night. Also, flow from catchment area may change with meteorological events that can alter balance of dissolved oxygen in lake. As a result, estimation of respiration during daylight or night would be inaccurate. This problem can be overcome at some level by using statistical approach like *Kalman* filter (smoothing) or *Bayesian* regression (replacing noisy observed data with model estimation) (Batt and Carpenter, 2012; Cremona et al., 2014). Also, results showed that using aggregated data reduce noisy observation for RES as well. However, still errors were observed even these approaches were used. Other assumption in the models, all parameter except GPP, RES and F are neglected that ignores the effects like ground water or horizontal and vertical advection (Giling et al., 2017; Obrador, Staehr, and Christensen, 2014). Generally unrealistic values were recorded when the extreme meteorological events occurred that disrupted thermal stratification in the lake also obtained from previous study explained by poor fitting the model (Honti et al., 2016). Thermal stratification influences distribution of organic and inorganic cycling within lakes (Coloso, Cole, and Pace, 2011; Matthew et al., 2012). Since metabolism was estimated only for epilimnion, during mixing periods, entrainment of organic matter and anoxic water from bottom layers may develop unrealistic results (Giling et al., 2016; Jennings et al., 2012). According to our results since thermal stratification changes very fast during day and within days, estimating metabolism with single sonde at one point may not represent true metabolic processes. Instead, depth integrated approaches can be used which set up with more sondes at different depths and includes advection between layers. On the other hand, it will not be cost effective (Coloso et al., 2008; Sadro et al., 2011; Staehr et al., 2012(a)).

Even there was no accurate one model to avoid errors, two methods are suggested to deal with errors (Winslow et al., 2016): Removing the unrealistic values from the dataset or force to models until get the realistic results. However, both have missing points. Former acts like there were no measurements in those days but most of the unrealistic values are obtained during extreme meteorological events. This will cause missing the effects of environmental changes which was our one of the main objectives. On the other hand, even true values obtained by forcing models, these values will also unrealistic and affect data quality.

Diel oxygen changes approach is less expensive and less labor intensive so that it gives us quick information about the lake ecosystem. However, it seems the metabolism estimation by dissolved oxygen approach has several missing points that shows improving of the equation is needed and crucial. Nowadays, even it is expensive, C^{13} stable isotope approach is used to gather information about the lakes. The stable isotope analysis provides both organic and inorganic carbon changes within the lake (Kluijver et al., 2015).

4.2 Environmental Parameters and Lake Metabolism

The contribution of lakes to global carbon cycle has become hotspot even lakes constitute small portion (4%) of Earth surface area (Downing and Duarte, 2006). Today, it is known that lakes can store or release CO_2 depending on both metabolic processes and environmental variables (Jeppesen et al., 2014; Raymond et al., 2013; Tranvik et al., 2009). Even the major role of lakes in global scale is still unclear, most of the time lakes are oversaturated with CO_2 (Kosten et al., 2010). The balance of CO_2 fluxes is managed by primary producers (Jeppesen et al., 2015). Therefore, increase in primary production especially through aquatic plants causes sink of CO_2 in lakes that change the ecosystem functions and services (Wetzel, 2001).

One of the most threatened problem in lakes is eutrophication. By means of anthropogenic disturbance, increment of nutrient loading combining with climate change induces primary production (Cole et al., 2007; Einsele, Yan, and Hinderer, 2001; Schallenberg et al., 2013). It is clear that climate warming provoke eutrophication but the consequences depend on initial conditions and location (Jeppesen et al., 2015;2011; Özen et al., 2010; Rigosi et al., 2014). Since primary production is higher in eutrophic lakes, sink of CO_2 largely though it is more temporary is monitored (Wetzel, 2001). Therefore, it is expected that eutrophic lakes should act as sites of carbon storage (Alfonso et al., 2015; Cole et al., 2007; Dunalska et al., 2014).

Although Lake Eymir has been experiencing eutrophic conditions for long time, the results have shown net heterotrophy (NEP<0) most of the time in a year. In most cases, the autotrophic days (NEP>0) were limited with algal bloom periods. After 1997, in order to increase water clarity and to control algal bloom in Lake Eymir, two biomanipulation studies were applied by reducing the number of benthi-planktivorous fish, thus resulting with a reduction of the predation pressure on zooplankton which expose limitation of algal growth (Beklioglu, Burnak, and Ince, 2000; Beklioglu and Tan, 2008; Søndergaard et al., 2017; Caraco et al., 1997; Jeppesen et al., 1990). In addition, zooplankton community in spring composed of big-sized daphnids and copepods which may support respiration more as well as reduce NEP through grazing down phytoplankton (Elser et al., 2000; Elser et al. 1996). These could be the main reason to observe net heterotrophy in the lake though it is tricky as primary prouduction was more burried in lake through zooplankton excreation. Previous study related to biomanipulation effects on lake metabolism were evaluated and found removal of zooplankton pressures induces net heterotrophy in the lake (Jeppesen et al., 2016). The lake is not biomanimulated but also not eutrophic showed that The other reason could be the nitrogen limitation in the lake may control the reproduction of the phytoplankton throughout the year. Increase in phytoplankton biomass after mixing of the lake is a good evidence that resuspension of the nitrogen from sediment may triggers the reproduction. Similar metabolism results were obtained in Yeniçağ Lake in Bolu (Karakaya et. al., 2011). Even the lake is not eutrophic and biomanipulated, the lake shows similar metabolism pattern like in Lake Eymir which is a good evidence that although Lake Eymir is experiencing algal bloom periods, it can compensate the effects of human disturbance at a certain point. Also, RES and GPP were positively correlated in epilimnion which is similar with many studies (Laas et al., 2012; Solomon et al., 2013; Staehr and Sand-Jensen, 2007) that implies RES in the epilimnion is mostly supported by primary producers.

The negative correlation between air/water temperature and chlorophyll-*a*/BGA concentrations was observed. It has been justified that increase in air temperature induces primary production in lakes (Deng et al., 2014; Rigosi et al., 2014; Yang et al., 2008). It was also observed in Lake Eymir. Algal blooms concurred with higher air temperatures. The reason to obtain negative relation may that measurements were recorded at 1.5 meter. When algal bloom occurred, it covers the surface of lake and may reduce algal production at lower depths. When air temperature decreases with rising of wind speed, chlorophyll-*a* concentration more evenly distributed. Therefore, measurements from 1.5 meter also increased. The other possible reason could be zooplankton grazing effect. In spring, even temperature rose, chlorophyll-*a* concentration remained lower values because of grazing pressure of big-sized zooplankton. This makes arduous to detect water temperature effect on chlorophyll-*a* concentration. However, when the data were segregated into small datasets, positive correlation both for water and air temperature were noticed. This may also due to nitrogen limitation which limits reproduction of the phytoplankton even the temperature increases.

Environmental parameters other than air temperature have also effects on lake ecosystem. Wind is one of the main drivers of ecosystem of Lake Eymir even no strong correlation with other physico-chemical or metabolism parameters was obtained. The reason for this could be duration of winds is often short but its effect is crucial and only detect with long term high frequency monitoring (Jennings et al., 2012). During windy periods, thermal stratification is broken down and cause abrupt changes like entrainment of organic matters from bottom layers that was observed at 1.5 meter with the incline of fDOM measurements. In addition, heavy rainfalls in autumn could provoke flow of organic matter from catchment area (Hoellein et al., 2013; Nõges et al., 2016).

Since nutrient concentrations have great influence on growth of phytoplankton, TN:TP ratio is lower than 10 most of the times indicates nitrogen is the limiting nutrient for growth of algae (Meybeck et al. 1989, Chapman 1996). Therefore, when nitrogen is available in the environment, they may consume it for growing and resulted with negative correlation. SRP is also one of the main source for primary producers that reduces with increment of chlorophyll-*a* concentration.

4.3 Extreme Meteorological Events

According to climate change scenario, less precipitation and higher air temperatures are expected in Tukey that may change the precipitation type from snow to rain during winter. In addition, number of extreme weather events has been increasing since 1997 (Demircan et al., 2017). According to report of State of the Climate in Turkey (SCT2015), heavy precipitation (26%), wind storm (25%) and heat wave (11%) were the most monitored extremes during 2015. Such changes in the environment will affect the hydrology of shallow lakes like Lake Eymir. As reported by previous studies, Lake Eymir has been experiencing water fluctuation more than one meter within a year that affects primary production (Özen, 2006). Also, it is claimed that increase in atmospheric CO_2 will affect fresh water CO_2 dynamics either directly by reducing plankton nutrient quality, community and food web structure or indirectly by influencing soil respiration, terrestrial productivity and climate regime (Hasler et al., 2016).

In order to assess effects of extreme meteorological events, high frequency data were examined and three distinct periods with abrupt changes were spotted in a year. First episode was breaking down of long term summer thermal stratification in September 2015. While decreasing in temperature, more storm events were monitored with heavy rainfall. Meanwhile, the lake has been experiencing algal bloom conditions. Therefore, mixing disturbed environment by reducing the chlorophyll-*a* concentration sharply unlike the mesocosm experiment conducted by Blottière and colleagues (2017). After first storm, incline in O_2 concentration with wind may due to atmospheric fluxes and evenly distribution of dissolved oxygen, then depletion of O_2 concentration were recorded may owing to death of phytoplankton and entrainment of deoxygenated water from lower layers. Additionally, fDOM increased after first mixing event that may be explained by increment of bacterial function after death of phytoplankton or entrainment of organic matters from bottom layers or from catchment area (Jennings et al., 2012; Sadro and Melack, 2012). Unstable environment resulted reduction both in GPP and RES but respiration exceeded to gross primary production after mixing that led CO_2 emission in the Lake (NEP <0).

Second episode was observed in early spring with unexpected high phytoplankton abundance may due to sudden increase in air temperature but also big-size zooplankton has not peaked yet. Therefore, GPP increased after 15th of April. However, then suddenly air temperature drops 11 Celsius degrees. After 21th of the April, even the air temperature increase enough to growth of primary producers, GPP was lower than RES. This may be explained by grazing pressures on phytoplankton. High abundance of zooplankton may be main control in phytoplankton community, especially in spring (Lampert et al., 1986; Meerhoff et al., 2012). Also, great amount of big size zooplankton may contribute to metabolic processes (NEP <0) more than small-sized zooplankton observed during summer (Elser et al., 2000, 1996)

Last episode, at the end of July, algal bloom occurred with high air temperature and low wind period. However, wind speed increased after 2nd week of August and storm occurred in 15th of August. This reduced chlorophyll-*a* concentration increased fDOM and RES. Despite of similar behavior with first episode, after storm, the lake reverted to previous conditions with high chlorophyll-*a* concentration may because of continuation of higher air temperatures. Even wind induced CO_2 efflux, higher temperatures reinforced autotrophy (storage of carbon). Also, in this period, cyanobacteria with diatoms which use extensive of CO_2 (John et.al. 2002) dominated the lake that may keep system autotrophic after storm.

Within three extreme events, only in the last episode the metabolism models did not fail. At the first episode, model couldn't explain the RES for two days where the two strongest wind occured. In the second episode, after heatwave, sudden drop in the air temperature led faulty assumption in RES estimation. However, in the last period strong heterotrophy were detected during storm. This shows that when the lake is mixed by external factors, models fail to explain metabolism. This could be because of the assumptions of the equation. Entrainment from the other layer causes faulty assumptions. Therfore, for future work the equation should be improved.

To sum up, according to results, estimating piston velocity correctly has more influence on metabolism of Lake Eymir than metabolism models. In addition, obtaining less unrealistic values can be overcome by using depth integrated approach even it is costly. Moreover, it was observed that thermal stratification of Lake Eymir is vulnerable to meteorological changes that affects the lake metabolism. Besides, meteorological events and grazing pressure of zooplankton may induce heterotrophy in the lake even Lake Eymir is at eutrophic conditions that contradicts with many studies (Alfonso et al., 2015; Brighenti et al., 2015; Jeppesen et al., 2016; Laas et al., 2012).

CHAPTER 5

CONCLUSION

One of the objectives of the thesis was to monitor behavior of metabolism in biomanipulated eutrophic lake and to assess how extreme weathers induce metabolic activity of autotrophs and heterotrophs. To quantify this, we used diel oxygen changes. This objective was included to monitor and understand CO_2 fluxes in Lake Eymir. Since there were many distinct methods for estimating piston velocity and models for metabolism estimation, different methods and models were run to identify whether variation in approaches may result significantly different for lake Eymir. As a result, the evaluation of methods and models constitutes of other objective of the thesis.

Results showed that piston velocity methods have more important effects on metabolism results than metabolism estimation. High frequency measurements are necessary to understand shifts in lake ecosystems. By using high frequency measurements, we were able to observe effects of short term weather-related events on lake ecosystem. In Lake Eymir, wind was main agent that leads abrupt change in ecosystem functioning. In addition, air temperature was shown to induce algal blooms. On the other hand, zooplankton grazing had great influence on primary producers which plays an active role in CO_2 fluxes. Eymir acts as carbon sources (heterotrophic) to atmosphere even it has been experiencing eutrophication for long time.

In continuation to this study, first of all, we would like to recommend improving metabolism models to explain the effects of extreme events on lake ecosystem since during extremes the models failed. Secondly, since each lake is like individuals that responses differently to similar changes, monitoring more lakes will give more information to develop sustainable management strategies for lakes. Such monitoring has to be conducted using high frequency monitoring. Besides, to understand how climate change affects lakes, long term high frequency monitoring should also be continued.

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APPENDIX A

METHODS AND MODELS FLOW CHART

GPP, RES and NEP estimation by using different k_{gas} methods and metabolism models from aggregated and non-aggregated data