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An investigation into the causes, impacts
and measures to deal with diatom bloom in
Vartry Reservoir

By

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Declaration

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Abstract

In Ireland, there are more than 12,000 lakes and lakes and reservoirs are the main source of drinking water for two million people. Consisting of upper lake and lower lake, Vartry Reservoir is a key drinking water source in Ireland. It serves more than 220,000 customers and the supply areas stretching from Roundwood, through north Wicklow up to south Dublin. However, since 2013 *Asterionella* dominated diatom bloom has been occurring in spring each year which has led to serious clogging of the slow sand filters in Vartry water treatment plant. As a result, the treatment capacity through the plant decreased significantly from 75 million litres per day to 40 million litres per day, creating a potential water shortage.

In this study, in addition to collecting and analysing historical water quality and ecology data, a three-year monitoring programme (from 2016 to 2018) and a series of laboratory experiments were carried out to (1) analyse the diatom growth trend in Vartry Reservoir; (2) understand the change of nutrient concentrations in Vartry Reservoir; (3) investigate the causes of diatom bloom and (4) recommend the measures to effectively mitigate diatom bloom.

In Vartry Reservoir, diatom bloom occurred in spring and no obvious bloom was observed in autumn or winter. The diatom species included *Melosira*, *Tabellaria*, *Asterionella*, *Synedra* and *Navicular*. In the lower lake from 1996 to 2018, *Asterionella*, *Melosira*, *Synedra* and *Tabellaria* dominated the diatom assemblages for 12 years, 7 years, 1 year and 1 year, respectively. Diatom growth in the lower lake from 1996 to 2012 was stable and the maximum diatom number was lower than 1000 counts/mL. From 2013 to 2016, diatom bloom in the lower lake was problematic and the peak diatom values was about 2000 counts/mL. The highest diatom number in the upper lake in 2017 and 2018 was 4940 counts/mL and 1762 counts/mL, respectively, which were much higher than that observed in the lower lake with the values of 821 counts/mL and 1120 counts/mL.

Nutrient monitoring showed that nutrient concentrations in the feeding rivers were higher than that in the reservoir. No diatom growth was observed in the feeding rivers. Feeding rivers with high silica concentrations (about 9 mg/L) flowing into the reservoir were silica sources in Vartry Reservoir. Every year, the silica concentrations in the reservoir started to decrease when diatom bloom started. It reduced to the annual minimum values when diatom bloom completed. The silica concentrations then increased continuously until the next diatom bloom period. The soluble reactive phosphorus (SRP) concentrations in the reservoir were lower than 9 µg/L in lower lake and 12 µg/L in the upper lake. Generally, the peak SRP concentration appeared before diatom bloom. The nitrogen concentration in the reservoir peaked at the beginning of diatom growth i.e. in spring, and then decreased to the lowest points in autumn. Then it increased again until the

beginning of next diatom bloom period. No significant increasing trend of nutrient concentrations in the reservoir were observed during the study period.

Nutrient and zooplankton were two major reasons for diatom bloom. The silica concentration in Vartry Reservoir was sufficient for diatom bloom. The soluble relative phosphorus could be a factor that leads to diatom bloom in Vartry Reservoir. The concentration of SRP determined the magnitude of diatom bloom. In the upper lake, the average SRP concentrations before diatom bloom season were 1.15 ug/L, 3.58 ug/L and 1.18 ug/L in 2016, 2017 and 2018, respectively, accordingly, the peak diatom concentrations were 2000 counts/mL, 4,900 counts/mL and 1762 counts/mL. The high diatom concentration in 2017 could be due to the relatively high SRP concentration. The low zooplankton number was another factor that could influence diatom growth in Vartry Reservoir. The dominant zooplankton species in Vartry Reservoir were Rotifer, Daphnia and Copepods. Zooplankton predation could reduce the diatom concentrations in the reservoir. The ratio of diatom number and zooplankton number (food to predator ratio) determined the extent of zooplankton limiting the diatom growth. Laboratory experiments indicated that diatom growth was fully inhibited when the diatom/zooplankton ratio was lower than 14.4×10^3 . When the ratio of diatom to zooplankton number was higher than 40.9×10^3 , the influence of predation on diatom number was negligible. However, in Vartry Reservoir, the ratio of diatom number to zooplankton number was always higher than 40.9×10^3 , indicating that the low zooplankton population could contribute to diatom algae bloom in Vartry Reservoir.

In Vartry Reservoir, the following measures could be considered to deal with diatom bloom. The limitation of nutrient especially phosphorus entering the reservoir was meaningful for the long-term protection of water quality in Vartry Reservoir. Increasing the number of zooplanktons in the reservoir could effectively control the diatom growth. In Vartry water treatment plant, coagulation and filtration could be considered for the removal of diatom before the raw water entering the slow sand filters.

This study provided diatom bloom pattern of Vartry Reservoir in 23 years and identified the factors that control diatom algae populations as well as the effective measures to deal with diatom issue. These results not only benefit the management of water supply in Ireland with more than 70 mesotrophic lakes used as water supply sources, but also deepen the understanding of diatom bloom causes and control, which is very important to tackle with the more and more frequent diatom bloom cases worldwide.

Key words: Diatom, *Asterionella*, Nutrients, Silica, Soluble relative phosphorus, Zooplankton.

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Table of Contents

Declaration	I
Abstract	II
Acknowledgements	IV
List of Figures	VIII
List of Tables	XII
List of Acronyms	XIII
1 Introduction	2
1.1 Background	2
1.2 Research objectives	3
1.3 The layout of this thesis	3
2 Literature Review	6
2.1 Sources of drinking water	6
2.2 Diatom bloom and the study of <i>Asterionella</i>	8
2.3 The cause of diatom bloom	12
2.3.1 <i>Nutrient availability</i>	12
2.3.2 <i>Water temperature and thermal stratification</i>	16
2.3.3 <i>Illumination condition</i>	18
2.3.4 <i>The effect of food chains</i>	19
2.4 Diatom bloom prevention and impact mitigation	20
2.4.1 <i>Reducing nutrient inputs</i>	20
2.4.2 <i>Altering hydraulic condition and reducing illumination</i>	20
2.4.3 <i>Removing diatoms, coagulation and flocculation</i>	21
2.5 Summary of the literature review	21
3 Methods	24
3.1 Study site	24
3.2 Data and samples collection	26
3.2.1 <i>Date collection</i>	26
3.2.2 <i>Samples collection</i>	27
3.3 Experiments in Vartry Reservoir and laboratory	32
3.3.1 <i>Diatom growth in bottles in the reservoir</i>	32
3.3.2 <i>Impact of zooplankton on diatom experiment in the lab</i>	32
3.3.3 <i>Coagulation and flocculation experiment</i>	33
3.4 Analytical methods	33
4 The growth of diatom in Vartry Reservoir from 1996 to 2018	39
4.1 Diatom growth in lower lake of Vartry Reservoir	39
4.1.1 <i>Diatom assemblages in lower lake from 1996 to 2012</i>	39

4.1.2	<i>Asterionella</i> dominated diatom bloom in lower lake from 2013 to 2018.....	45
4.2	The spatial change of diatom growth.....	50
4.2.1	<i>Diatom</i> bloom in upper lake in 2017 and 2018.....	50
4.2.2	The Spatial change of diatom along Vartry Reservoir in 2017.....	52
4.2.3	The growth of diatom in other lakes or reservoirs Ireland in 2018.....	53
4.3	Discussion.....	54
4.3.1	The magnitude of diatom bloom in lower lake from 1996 to 2018	54
4.3.2	The change of dominated diatom species in Vartry Reservoir.....	55
5	Nutrient concentrations.....	58
5.1	Feeding rivers of Vartry Reservoir	58
5.1.1	Long term monitoring of nutrient concentrations in the feeding rivers.....	58
5.1.2	24-hour monitoring of U3 and D5	63
5.2	The nutrient concentrations in boreholes.....	64
5.3	Nutrient concentrations in Vartry Reservoir.....	66
5.3.1	Long term monitoring of nutrient concentrations in Vartry Reservoir.....	66
5.3.2	Nutrient concentrations at different depths in Vartry Reservoir.....	71
5.3.3	The change of nutrient concentrations along Vartry Reservoir.....	74
5.4	Nutrient concentration in other lakes or reservoirs Ireland.....	76
5.5	Discussion.....	77
5.5.1	Nutrient concentrations in feeding rivers	77
5.5.2	Influence of nutrient concentrations on diatom growth.....	77
6	Zooplankton.....	81
6.1	Zooplankton in Vartry Reservoir	81
6.1.1	Zooplankton species and magnitude in Vartry Reservoir from 2016 to 2018	81
6.1.2	The Spatial change of zooplankton in 2017	84
6.1.3	The influence of water temperature on zooplankton number.....	86
6.2	The study of zooplankton and diatom growth in the laboratory	87
6.3	Discussion.....	91
6.3.1	Zooplankton in Vartry Reservoir	91
6.3.2	The influence of water temperature on zooplankton.....	91
6.3.3	The influence of zooplankton on diatom number	92
7	Hydrodynamic and weather effects.....	95
7.1	Hydrodynamic conditions in Vartry Reservoir.....	95
7.1.1	Water temperature and thermal stratification	95
7.1.2	Hydraulic effects in Vartry Reservoir	99
7.2	Weather conditions at Vartry Reservoir.....	101
7.2.1	Sunlight	101

7.2.2	<i>Rainfall</i>	106
7.2.3	<i>Air temperature</i>	107
7.3	Discussion	109
7.3.1	<i>Correlation analysis and model analysis</i>	109
7.3.2	<i>Water temperature</i>	112
7.3.3	<i>Thermal stratification</i>	112
7.3.4	<i>Hydraulic effects</i>	113
7.3.5	<i>Sunlight</i>	113
8	Impacts and measures to deal with diatom bloom in Vartry Reservoir	116
8.1	The impacts of diatom bloom	116
8.2	The measures to deal with diatom bloom.....	118
8.2.1	<i>Coagulation</i>	118
8.2.2	<i>Filtration</i>	122
8.3	Discussion	123
8.3.1	<i>The impact of diatom bloom</i>	123
8.3.2	<i>Measures to deal with diatom bloom</i>	124
9	Conclusions and recommendations	128
9.1	Conclusions	128
9.2	Recommendations	129
9.2.1	<i>Pilot-study for the practical control of diatom bloom</i>	129
9.2.2	<i>Disinfection by-product generation during chlorination of diatom</i>	130
	References.....	131

List of Figures

Figure 1.1 Vartry water treatment plant and the slow sand filter.....	2
Figure 1.2 Research overview of this thesis.	4
Figure 2.1 Ecological status of monitored lakes in Ireland during 2010-2015.....	7
Figure 2.2 Images of some common diatom species: (a) <i>Tabellaria</i> , (b) <i>Melosira</i> , (c) <i>Synedra</i> , (d) <i>Navicula</i>	8
Figure 2.3 Image of <i>Asterionella</i>	9
Figure 2.4 Image of zooplankton species a Daphnia; b Rotifer; c Copepods.	20
Figure 3.1 Location of Vartry Reservoir and long-term sampling sites.....	24
Figure 3.2 Location of feeding rivers/streams/pipes for upper lake (a) and lower lake (b).....	24
Figure 3.3 Catchment area of the extensive monitoring feeding rivers of the reservoir.	26
Figure 3.4 Locations of other sampling reservoirs in 2018.	27
Figure 3.5 Samples collecting in Vartry Reservoir.....	28
Figure 3.6 Water level sensors in the feeding rivers.....	29
Figure 3.7 Automatic water samplers.	29
Figure 3.8 Locations of four boreholes around the lower lake.	30
Figure 3.9 The boreholes.	30
Figure 3.10 Water bailer used for sampling underground water.	31
Figure 3.11 Locations of ten sampling sites along Vartry Reservoir.....	31
Figure 3.12 Locations of experiments in Vartry Reservoir.....	32
Figure 3.13 Secchi disk.....	33
Figure 3.14 Water temperature sensor.	34
Figure 3.15 Sedgewick-rafter counting cell slide.	34
Figure 4.1 Diatom assemblage in lower lake in 1996.....	39
Figure 4.2 Monthly peak diatom number in lower lake from 1997 to 2001.	40
Figure 4.3 The growth of diatom in lower lake in 2002.	41
Figure 4.4 The growth of diatom in lower lake in 2003.	41
Figure 4.5 The growth of diatom in lower lake in 2004.	42
Figure 4.6 The growth of diatom in lower lake from 2002 to 2007.....	43
Figure 4.7 The growth of diatom in lower lake in 2006.	44
Figure 4.8 The growth of diatom in lower lake from in 2007.....	44
Figure 4.9 The diatom number in lower lake from 2008-2012.....	45
Figure 4.10 Diatom bloom in lower lake in 2013.	46
Figure 4.11 Diatom bloom in lower lake in 2014.	47
Figure 4.12 Diatom bloom in lower lake in 2015.	48
Figure 4.13 Diatom bloom in lower lake in 2016.	49

Figure 4.14 Diatom bloom in lower lake in 2017.	49
Figure 4.15 Diatom bloom in lower lake in 2018.	50
Figure 4.16 The growth of diatom in upper lake in 2017.	51
Figure 4.17 The growth of diatom in upper lake in 2018.	52
Figure 4.18 Spatial change of diatom number along with the longitudinal axis of Vartry Reservoir during April-Jun 2017 in the upper and lower lakes.	53
Figure 4.19 The number of diatom in the lakes or reservoir in April 2018.	54
Figure 4.20 The recorded annual maximum diatom algae concentrations in lower lake 1996-2018.	55
Figure 5.1 Concentration of SRP in the feeding rivers.	58
Figure 5.2 Concentration of SiO ₂ in the feeding rivers.	59
Figure 5.3 Concentration of nitrogen in the feeding rivers.	61
Figure 5.4 Concentration of total organic carbon in the feeding rivers.	62
Figure 5.5 The concentration of nutrient in U3 and D5 within 24 hours.	63
Figure 5.6 TN concentrations in the boreholes.	64
Figure 5.7 Silica concentration in the boreholes.	65
Figure 5.8 TOC concentrations in the boreholes.	65
Figure 5.9 SRP concentrations in lower lake from 2016 to 2018.	66
Figure 5.10 SRP concentrations in upper lake from 2016 to 2018.	67
Figure 5.11 Silica concentrations in the lower lake from 2012 to 2018.	67
Figure 5.12 Silica concentrations in the upper lake from 2012 to 2018.	68
Figure 5.13 The change of DIN concentrations in lower lake from 2012 to 2018.	69
Figure 5.14 The DIN concentrations in upper lake from 2012 to 2018.	70
Figure 5.15 TOC concentrations in Vartry Reservoir from 2016 to 2018.	71
Figure 5.16 Concentration of nitrogen, silica and TOC at different depths in upper lake from April 2017 to June 2018.	72
Figure 5.17 The concentration of silica, nitrogen and TOC at different depths in lower lake from May 2016 to Jun 2018.	73
Figure 5.18 Spatial change of DIN concentrations along the longitudinal axis of Vartry Reservoir during April 2017-June 2017.	74
Figure 5.19 Spatial change of SiO ₂ concentration along the longitudinal axis of Vartry Reservoir during April-Jun 2017.	75
Figure 5.20 The diatom growth with low silica concentration.	78
Figure 6.1 Number of zooplankton in upper lake from Mach 2017 to Jun 2018.	81
Figure 6.2 The number of zooplankton in lower lake from April 2016 to Jun 2018.	82
Figure 6.3 Number of Daphnia and Copepods and diatom bloom in upper lake.	83
Figure 6.4 The number of Daphnia and Copepods and diatom bloom in lower lake.	84

Figure 6.5 Spatial change of zooplankton along the longitudinal axis of Vartry Reservoir during April-Jun 2017.	85
Figure 6.6 Impact of water temperature and the number of Daphnia, Copepods and Rotifer in Vartry Reservoir.....	86
Figure 6.7 The growth of diatom with zooplankton number of 40 counts/L.....	87
Figure 6.8 The growth of diatom with zooplankton number of 13 counts/L.....	88
Figure 6.9 Growth of diatom and the change of silica concentration with different number of zooplankton.....	89
Figure 6.10 Change of diatom number and the silica concentration with high zooplankton and initial diatom number.....	90
Figure 7.1 Surface and bottom water temperature in upper lake and lower lake from 2012 to 2014.	95
Figure 7.2 Surface and bottom water temperature in lower lake in 2016.....	96
Figure 7.3 Surface and bottom water temperature in lower lake in 2017.....	97
Figure 7.4 Surface and bottom water temperature in lower lake in 2018.....	98
Figure 7.5 Effect of water temperature on the diatom concentration in Vartry Reservoir.....	99
Figure 7.6 Location of free diatom bloom zone in upper lake in 2017.....	100
Figure 7.7 Diatom number and silica concentration in the diatom free zone of upper lake in 2017.	100
Figure 7.8 Daily sunshine hour at Vartry Reservoir during the diatom growth period from 2016 to 2018.	102
Figure 7.9 Diatom number and silica concentration at a depth of 0.5 m, 2 m, 4 m and 6 m in Site A in March to May 2017.....	103
Figure 7.10 Diatom number and silica concentration at a depth of 0.5 m, 2 m, 4 m and 6 m in Site B in March to May 2017.....	104
Figure 7.11 Diatom number and silica concentration at the depth of 1 m, 2 m, 3 m and 4 m in Vartry Reservoir in March to May 2017.....	105
Figure 7.12 Annual rainfall at Vartry Reservoir from 1996 to 2018.....	107
Figure 7.13 Monthly mean air temperature at Vartry Reservoir from 1996 to 2018.....	108
Figure 7.14 Principle component analysis of diatom growth with environmental variables in upper lake from 2016 to 2018.....	109
Figure 7.15 Principle component analysis of diatom growth with environmental variables in lower lake from 2016 to 2018.....	110
Figure 7.16 The result of model analysis.....	112
Figure 7.17 The growth rate of diatom at different depth in Vartry Reservoir.....	114
Figure 8.1 Water transparency in upper lake in 2017 and 2018.....	116
Figure 8.2 Water transparency in lower lake from 2016 to 2018.....	117

Figure 8.3 The relation between diatom number and VSS in the influent of Vartry water treatment plant.....	117
Figure 8.4 The slow sand filter in Vartry water treatment plant during the sand clearing phase.	118
Figure 8.5 Coagulation with $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$	118
Figure 8.6 Coagulation with $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$	119
Figure 8.7 Removal rate of coagulation with different dose (initial diatom number 3905 counts/mL).	120
Figure 8.8 Removal rate of coagulation with different dose (initial diatom number 1855 counts/ml).....	122
Figure 8.9 The removal efficiency of filtration.....	123
Figure 8.10 The colour of water during diatom bloom in Vartry reservoir.	123
Figure 8.11 Diatom number and silica concentration under different lighting condition.	125

List of Tables

Table 2.1 The ecological status of the monitored lakes in the periods of 2007-2009 and 2010-2015.	7
Table 2.2 <i>Asterionella</i> bloom and the nutrient concentrations.....	9
Table 2.3 The kinetics of <i>Asterionella</i>	10
Table 2.4 Silica content of diatoms.....	14
Table 2.5 Temperature ranges and diatom specific growth rates.....	16
Table 2.6 Diatom specific growth rates in different temperatures.....	17
Table 2.7 Variation in the specific growth rates with light intensity.	19
Table 3.1 Flow rates and nutrient concentrations at feeding rivers/streams of the upper lake on 21st Oct 2015.	25
Table 3.2 Flow rates and nutrient concentrations at feeding rivers/streams of the lower lake on 25th Oct 2015.....	25
Table 4.1 The annual maximum diatom concentration and predominant diatom species in lower lake since 1996.....	56
Table 5.1. The nutrient concentration in other lakes or reservoirs.	76
Table 5.2 The silica concentration before and after diatom growth and the silica concentration with peaked diatom number.	77
Table 5.3 Average SRP in Vartry Reservoir before diatom bloom.	79
Table 6.1 Maximum daphnia and copepods number and water temperature in Vartry Reservoir from 2016 to 2018.....	91
Table 6.2 The degree of limitation with different ratio of diatom and zooplankton.	93
Table 7.1 Monthly average daily sunshine hours (h) at Vartry Reservoir from 2012 to 2018.	101
Table 7.2 Monthly average rainfall (mm) at Vartry Reservoir from 1996 to 2018.	106
Table 7.3 Correlation analysis of diatom growth factors in upper lake (data from 2016 to 2018).	109
Table 7.4 Correlation analysis of diatom growth factors in lower lake (data from 2016 to 2018).	110
Table 8.1 The advantage and disadvantage of different measures.....	126

List of Acronyms

DIN	Dissolved inorganic nitrogen
DPBs	Disinfection by-products
EPA	Environmental Protection Agency
HRT	Hydraulic retention time
N	Nitrogen
NH ₄ -N	Ammonia nitrogen
NO ₃ -N	Nitrate nitrogen
NO ₂ -N	Nitrite nitrogen
NOM	Natural organic matter
P	Phosphorus
PCA	Principle component analysis
RC	Runoff coefficient
Si	Silica
SRP	Soluble reactive phosphorus
THMs	Trihalomethanes
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus
VSS	Volatile suspended solids

Chapter 1

Introduction

1 Introduction

1.1 Background

The total biomass and species composition of phytoplankton in a water body vary seasonally. The term “algal bloom” generally describes the planktonic algal biomass significantly higher than the water body’s average (Oliver and Ganf, 2002). Due to the increased anthropogenic nutrient inputs to the water system, the occurrences of algal blooms in lakes, reservoirs and recreational waters have become a significant worldwide issue in the last number of decades (Cao et al., 2011; Karadžić et al., 2010; Matthews et al., 2010; O’Neil et al., 2012). Depending on the dominant species, algal blooms may create low oxygen conditions, taste and odour problems, or even produce toxins harmful to humans and animals (Watson et al., 2007; Watson, 2004; Huisman et al., 2018). In addition, algal blooms can have serious consequences for drinking water supplies by physically blocking the filters in water treatment plants and causing serious economic losses to affected waters (Li et al., 2018; Watson, 2004; Joh et al., 2011). In the USA alone, it is estimated that algal blooms result in losses of recreational, drinking, and agricultural water resources worth \$2.2 billion annually (Paerl et al., 2011).

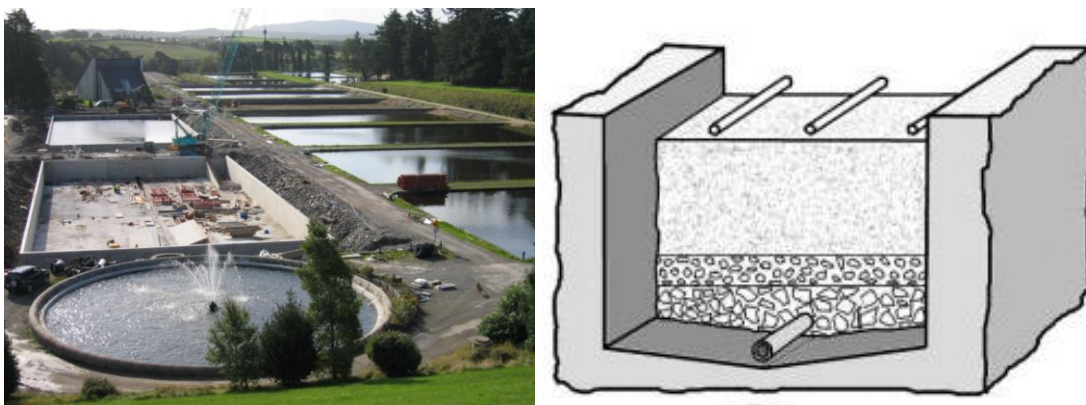


Figure 1.1 Vartry water treatment plant and the slow sand filter.

Vartry Reservoir located in Roundwood, Co. Wicklow is a very important drinking water source in Ireland. The water treatment plant (Figure 1.1) was constructed in the 1860’s. Slow sand filtration, chlorination and fluoridation are used in the water treatment plant for water treatment and purification. It serves more than 210,000 customers and produces approximately 75,000 – 80,000 cubic meters per day (m^3/day) and the supply area stretches from Roundwood, through north Wicklow and up to South Dublin (EPA, 2016). Though Vartry Reservoir was previously defined as oligotrophic during the period 2007 – 2009 in the EPA’s lake water abstraction dataset (McGarrigle et al., 2010), serious spring diatom algal blooms have been observed since 2013. Water production rates from the water treatment plant had been effected during the diatom algal bloom

periods because of the blocking of the sand filter. In these circumstances, a potential water shortage exists as the treatment capacity decreases.

1.2 Research objectives

The aims of this thesis are to investigate the cause, impact and potential mitigation measures to deal with diatom algal blooms in Vartry Reservoir. The specific objectives of this study are to:

- (1) collect historical data and analyse the diatom growth trend in Vartry Reservoir;
- (2) understand the change of nutrient concentrations in the reservoir by analysing the monitoring data of the nutrient concentrations in the feeding rivers and the reservoir;
- (3) investigate the potential factors (such as nutrient concentrations, zooplankton population, water temperature, thermal stratification and sunshine hours) that could cause diatom bloom in Vartry Reservoir;
- (4) undertake experiments to find the measures that could limit the growth of diatom or could relieve the clogging of slow sand filter in the water treatment plant during the spring diatom bloom.

1.3 The layout of this thesis

The research overview is shown in Figure 1.2. This thesis consists of nine chapters. Chapter 1 is an introduction to the topic. Chapter 2 presents the literature review on the factors that may affect the diatom growth and the measures to deal with diatom bloom. Chapter 3 describes the study sites, research methods and the monitoring equipment. Chapter 4 summarises the historical diatom blooms in Vartry Reservoir from 1996 to 2018 and the differences of diatom bloom in the upper lake and the lower lake is analysed. Chapter 5 investigates the nutrient balance in the reservoir which affects the growth of diatom bloom. The feeding rivers of the reservoir and the underground water are also analysed. Chapter 6 studies zooplankton in Vartry Reservoir through laboratory testing and analysis. The influence of hydrodynamic and weather on diatom growth is presented in Chapter 7. Chapter 8 assesses the impact of diatom bloom in Vartry Reservoir and investigates possible measures to deal with diatom bloom. Chapter 9 summarises the main findings of this study and recommendations for further work.

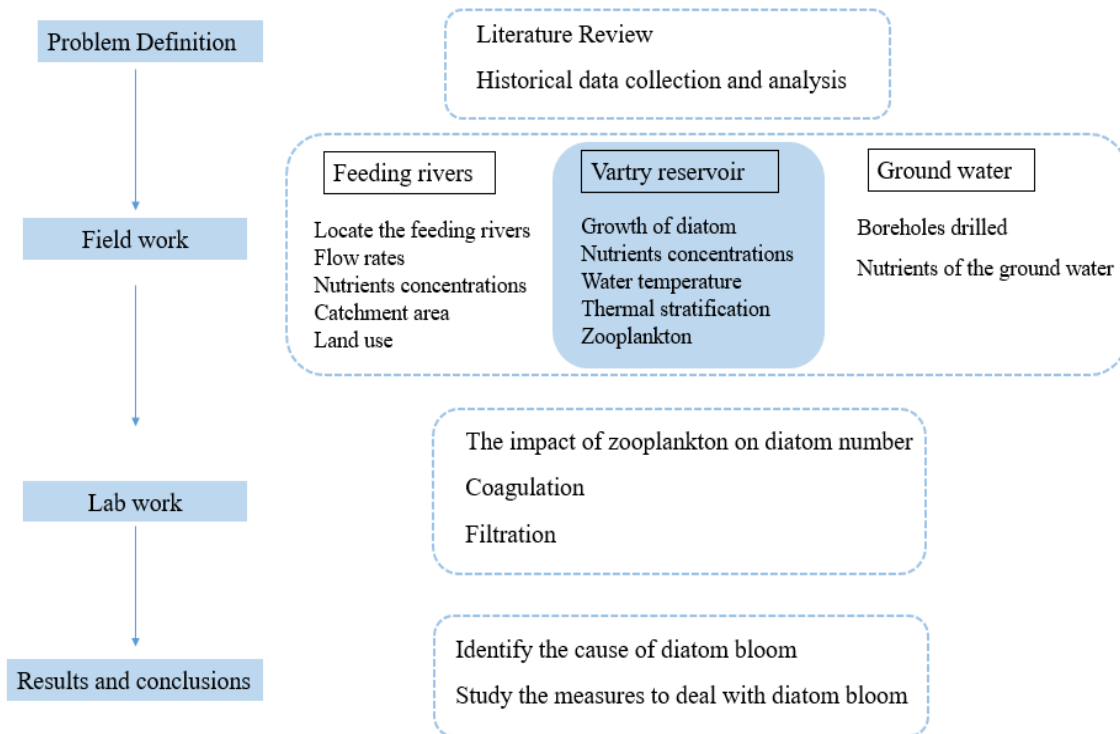


Figure 1.2 Research overview of this thesis.

Chapter 2

Literature Review

2 Literature Review

2.1 Sources of drinking water

The shortage of drinking water is a worldwide issue. The report released by the world health organization indicated that by 2025, half of the world's population would be living in water-stressed areas. Surface water such as lakes, reservoirs and rivers is one of the most important sources of drinking water. About 144 million people in the world are dependent on surface water (World Health Organization, 2019).

With the booming of world economy and the increasing of population, the impacts of human activities on surface water quality is becoming more and more serious. The discharge of wastewater and diffusion of runoff with agricultural fertilizer can increase the nutrient concentrations in the receiving water bodies which may lead to the eutrophication. The algal bloom in a drinking water source could not only produce bad taste and odour but also pose a threat to health by the production of organic matter during the algal decomposition process (Qin et al., 2011; Kraus et al., 2011). Natural organic matter (NOM) is precursor of the disinfection by-products (DPBs) such as Trihalomethanes (THMs). THMs are classified as a 'possible carcinogen' (Bacon and Saini, 2015). The eutrophication of drinking water sources can result in water shortages. The growth of cyanobacteria in Lake Taihu, China's third largest freshwater lake, lead to two million people without drinking water for a week in May 2007 (Qin et al., 2010). Slow sand filtration is widely used for drinking water treatment scheme (Guchi, 2015). Algae attached to the filter material shorten the filtration cycle and even block the filters (Shen et al., 2011). Due to the algae bloom in the raw water, the filter operation hours in the water treatment plant decreased from 24 h to 3-4 h and the frequency of back washing increased significantly (Yang, 2014).

In Ireland, there are more than 12,000 lakes and lakes and reservoirs are the main source of drinking water for two million people (Fanning et al., 2017). Eutrophication is recognised as a serious threat to lake water quality. Summer green or blue-green algal blooms were historically reported in eutrophic or hypertrophic lakes, such as Lough Leane (Killarney, County Kerry) and Lough Ree (County Westmeath) (O' Connor, 2004). Of the 222 lakes monitored by the Irish Environmental Protection Agency (EPA) during the period 2007-2009, 98, 82 and 42 lakes were defined as oligotrophic, mesotrophic and eutrophic/hypertrophic, respectively (McGarrigle et al., 2010). Following an analysis of the lake water abstraction dataset from Irish EPA, it was found that of the 100 lakes and reservoirs used as water supply sources, 71 were in mesotrophic status for at least one year of the three-year period 2007-2009 (McGarrigle et al., 2010).

During the period of 2010-2015, a total of 225 lakes were included as part of the national surface waters monitoring programme. Lakes are classified into five quality classes (status) under the European Union Water Framework Directive and the ecological status of monitored lakes during 2010-2015 is presented in Figure 2.1. As shown in Table 2.1, the percentage of lakes in high ecological status increased from 9% in 2007-2009 to 11% in 2010-2015. There is an 8.7% increase in the number of lakes in poor and bad ecological status compared to 2007-2009. From a chemical standpoint, nutrient condition has been the main driver of this status and total phosphorus was the dominant determinant (Fanning et al., 2017).

Table 2.1 The ecological status of the monitored lakes in the periods of 2007-2009 and 2010-2015.

Ecological status	2007-2009		2010-2015	
	Number	Percentage	Number	Percentage
High	20	9%	25	11%
Good	85	38.3%	78	35%
Moderate	92	41.4%	75	33%
Poor	19	8.6%	28	12%
Bad	6	2.7%	19	8%
Total number	222		225	

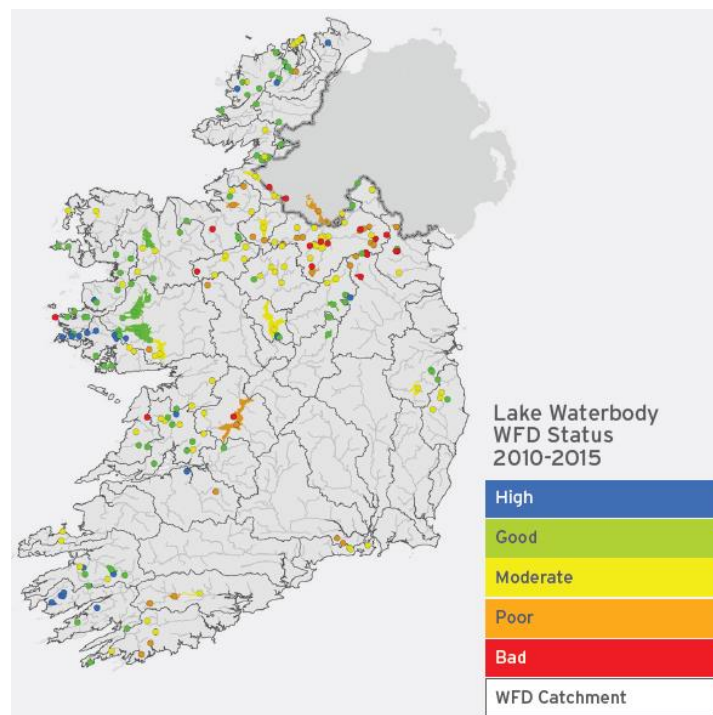


Figure 2.1 Ecological status of monitored lakes in Ireland during 2010-2015.

2.2 Diatom bloom and the study of *Asterionella*

Diatoms are a type of phytoplankton that are unicellular, microscopic and are classified taxonomically in the division *Bacillariophyta*. The major defining morphological characteristic of these algae is an exoskeletal structure composed of silica (Chapman, 1973; John et al., 2002). These structures, known as frustules, take the form of two overlapping valves (the epivalve and hypovalve) and have a wide variety of morphology (Round et al., 1990). The images of some common diatom species are shown in Figure 2.2.

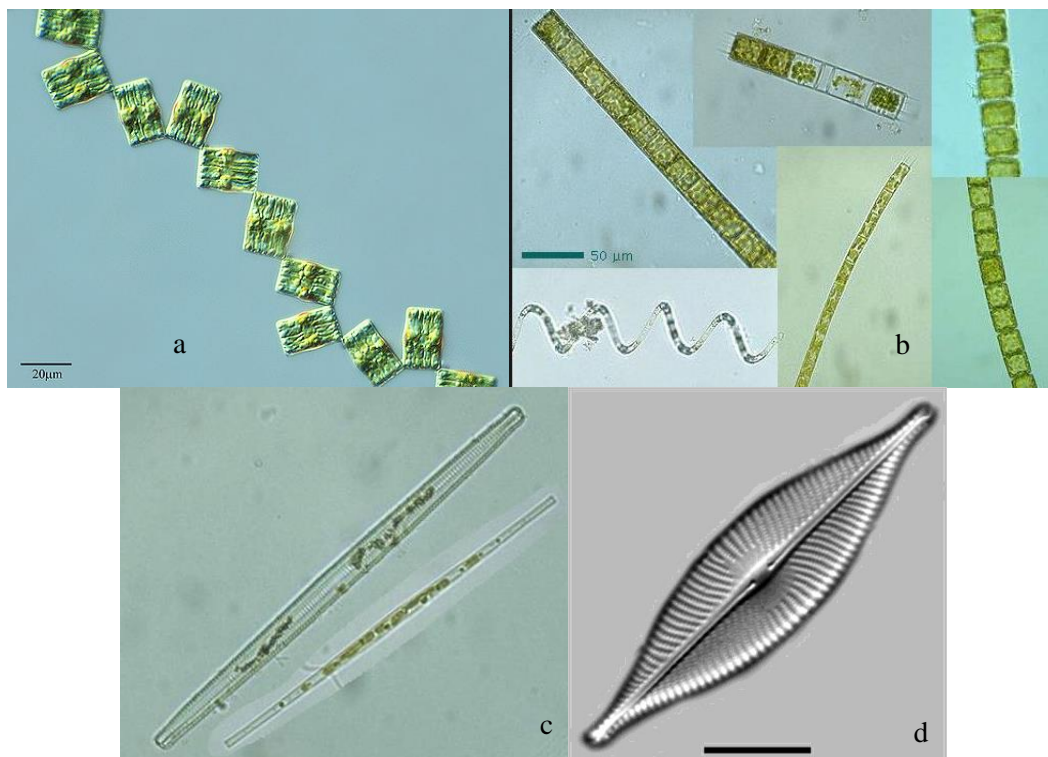


Figure 2.2 Images of some common diatom species: (a) *Tabellaria*, (b) *Melosira*, (c) *Synedra*, (d) *Navicula*.

Diatom plays an important role in the primary production of a water body and can also be used as an environmental pollution indicator (Nakanishi, 2004; Lei et al., 2018). It widely exists in many water bodies like lakes, rivers, reservoirs and ocean (Znachor et al., 2015). In contrast to summer green or blue-green algal blooms occurring in eutrophic and hypertrophic water bodies, spring/autumn diatom algal blooms can occur in oligotrophic and mesotrophic lakes (Edgar et al., 2016; Reid et al., 2012; Van et al., 2015). Diatoms are classified ecologically as r-strategists, which exhibits a high growth rate under the right environmental conditions. Though most of them do not produce toxins as blue-green algal do, they can threaten water supplies and increase the treatment cost in water treatment plant (Kang et al., 2012). Therefore, diatom algal blooms have attracted great attention. Ferris and Lehman (2007) studied the spring diatom bloom in Ford Lake, Michigan and

found that the main diatom species were *Asterionella*, *Cyclotella*, *Fragilaria*, *Aulacoseira* and *Synedra*. During diatom bloom period in 2004, the soluble reactive silica was almost depleted, indicating that silica could be the limiting nutrient in this lake. But in 2005 and 2006, the phosphorus (P) was found to be the limiting nutrient, while the lowest concentration of silica was about 40 μM in the lake (about 2.4mg/L as SiO_2). They also found that diatom bloom was affected by stratification.

Asterionella (Figure 2.3) is a common species found in many temperate lakes (Feuchtmayr et al., 2012; Saros et al., 2005; Bertrand et al., 2003). *Asterionella* was first studied in 1850 (Hassall, 1850). Since then many studies in relation to this diatom species have been carried out (Kain et al., 1958; Krivtsov et al., 2000; Villain et al., 2017). Table 2.2 summarises the studies relevant to *Asterionella* abundance and the nutrient concentrations.

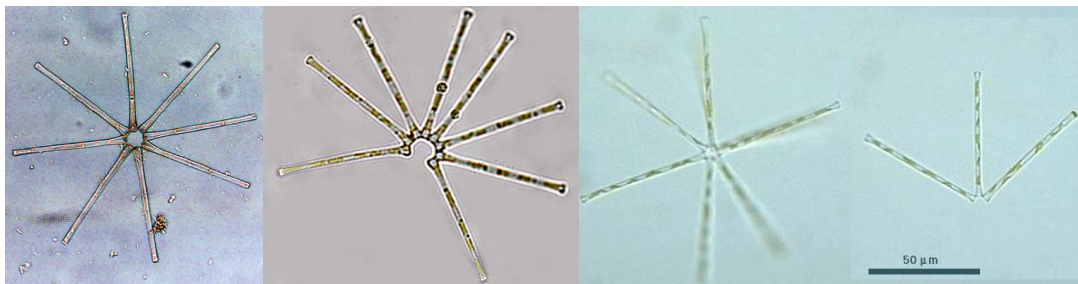


Figure 2.3 Image of *Asterionella*.

Table 2.2 *Asterionella* bloom and the nutrient concentrations.

Species	Location	Nitrogen (mg/L)	SRP ($\mu\text{g/L}$)	SiO_2 (mg/L)	Abundance (cell/ml)	Reference
<i>Asterionella</i>	North basin of Windermere UK	No data	<1	2	2000	Thackeray (2008)
<i>Asterionella</i>	North basin of Windermere UK	No data	8	1.8	4500	Thackeray (2008)
<i>Asterionella</i>	Rostherna mere (Cheshire,UK)	2.3	280	2.1	600	Krivtsov et al. (2000)
<i>Asterionella</i>	Durance-verdon France	0.7	<1	6.6	8	Bertrand et al. (2003)
<i>Asterionella</i>	Esthwaite water, UK	0.26-0.44	<1	2.5-3.5	8000	Lund (1950)
<i>Asterionella</i>	Windermere, UK	0.2-0.28	1	2.5-3.5	10000	Lund (1950)
<i>Asterionella</i>	Blelham Tarn,UK	No data	<10	5.25	14215	Feuchtmayr et al. (2012)
<i>Asterionella</i>	Sounth basin of Windermere, UK	No data	10-30	2.14	20669	Feuchtmayr et al. (2012)

Compared with other diatom species, *Asterionella* is a good competitor for phosphorus and the phosphorus requirement of *Asterionella* is quite low. The *Asterionella* can be abundant with phosphorus concentration of less than 1 µg/L (Saros et al., 2005; Bertrand et al., 2003). Theoretically, 1 µg/L of P can support the growth of 10⁶ cells/L of *Asterionella* (Mackereth, 1953). The requirement of silica for *Asterionella* is relatively high and high silica to phosphorus ratio is more suitable for the abundance of *Asterionella* (Kilham et al., 1996). The *Asterionella* bloom can occur with the ambient silica (Si) concentration of 0.1-4 mg/L (Kilham et al., 1971). The absence of silica could result in the change of elemental composition of diatom cell. The *Asterionella* cell silica concentration reduced significantly from 32% to 13% (dry weight for Si) when the Si in the lake was below 0.2 mg/L (Krivtsov 2000). Unlike *Fragilaria* and *Stephanodiscus*, the depletion of silica could lead to the death of *Asterionella* (Sommer, 1983). The impact of silica on the kinetics of *Asterionella* is shown in Table 2.3.

Table 2.3 The kinetics of *Asterionella*.

Species	Specific growth rate (/d)	Half-saturation constant K _s	Silicon required (µM Si/10 ⁶ cells)	Reference
<i>Asterionella</i>	1.1	13.8 µM Si	0.5-1.5	Kilham et al. (1975)
<i>Asterionella</i>	0.61	6.5 µM Si	0.6-1.9	Kilham et al. (1975)
<i>Asterionella</i>	0.107			Nicklisch (1999)
<i>Asterionella</i>	--	15 µM Si		Ferris and Lehman (2007)
<i>Asterionella</i>	--		1.67-3.17	Sommer and Stabel (1983)
<i>Asterionella</i>	--	1.83 µM Si		Tilman et al. (1976)
<i>Asterionella</i>	0.67-0.81	2.91 µM Si		Holm and Armstrong (1981)
<i>Asterionella</i>	0.285-0.971			Bruning (1991)
<i>Asterionella</i>	0.12	3.35 µM Si		Michel et al. (2006)
<i>Asterionella</i>	--		2.33	Mackereth (1953)

Lund (1950) studied the spring diatom bloom in lakes Windermere, Esthwaite Water and Blelham Tarn in the English Lake District and found that (1) the number of *Asterionella* started to decline when the dissolved silica had fallen to 0.5 mg/L, (2) the nitrate nitrogen concentrations did not appear to bear any definite relation to the changes in *Asterionella* numbers, (3) there was no detectable variation in phosphorus concentration during the *Asterionella* growth period, and (4) the seasonal variation population pattern of *Asterionella* was attributed to the effect of nutrient levels and environmental conditions. The study showed that with the correct environment and appropriate levels of nutrients, *Asterionella* can grow indefinitely. Mackereth (1953) studied the

relationship between the growth of *Asterionella* and the concentration of dissolved phosphorus in Lake Windermere in detail and found that *Asterionella* could take up and store reserve phosphorus at concentrations below 1 µg P/L, which would allow it to continue to grow in phosphorus-deficient media. Mackereth (1953) also determined that the limiting requirement per cell of phosphorus for *Asterionella* was very minute—about 0.06 µg P/10⁶ cells – meaning that initial concentrations as low as 1.0 µg P/L can theoretically produce a population of some 16 × 10⁶ cells/L before the phosphorus became deficiency. Holm and Armstrong (1981) investigated the effect of nutrition limitation on the cellular composition and morphology of *Asterionella* and found that *Asterionella* could take up more P (over an order of magnitude) when Si was limiting nutrient, and vice versa. Similar to that reported by Mackereth (1953), when nutrient levels are sufficient, *Asterionella* can store up to 28 times more P and 2 times more Si than needed. While few studies have focused on N as the limiting nutrient for *Asterionella*, Saros et al. (2005) found a positive correlation between *Asterionella* with C:P, Nitrogen (N):P, and Si:P ratios and concluded that the increase of *Asterionella* in oligotrophic alpine lakes since the 1950s was due to the result of N enrichment in these systems.

In addition to the availability of nutrients, the hydraulic condition of the water systems and the temperature have also been shown to affect the growth rates of *Asterionella*. Bertrand et al. (2003) studied the responses of *Asterionella* to environmental factors in a reservoir complex with 8 artificial reservoirs in south-eastern France and found that the population dynamics of this diatom depended strongly on the morphometric characteristics of the reservoirs. Warm monomictic reservoirs with long hydraulic retention times (126 to 280 days) appeared to favour the development of *Asterionella*. The reservoirs with short and variable hydraulic retention times had high turbidity which prevented light penetration and inhibited the growth of *Asterionella*. In the study of Sivarajah et al. (2016), the relative abundance of *Asterionella* increased with the decreasing of nutrient concentration in the Boreal Shield lake (George Lake, Killarney, Ontario).

In terms of *Asterionella* colonies, Lund et al. (1963) found that the natural populations of *Asterionella* had averaged 8 cells per colony during the period of maximum growth in the spring bloom of Windermere, England. Just after the bloom peaked with silicate limitation, colony size increased to 10 or more cells per colony. After the *Asterionella* population had fallen precipitously, the number of cells per colony decreased to 2-4. Tilman et al. (1976) published similar findings that at high growth rates the average cells per colony was 8. Under silicate limitation at very low growth rates it increased to over 20 cells per colony, while under phosphorus limitation, the number of cells per colony decreased. Holm and Armstrong (1981) also reported that the number of *Asterionella* cells per colony varied as a function of the Si to P and nutrient limitation, being usually less than or equal to 6 when P-limited, and greater than 10

when Si-limited. Wangner (2008) studied the influence of light on the morphological variations of *Asterionella* and found that the colony size was less than 5 with limited light. The average colony size of *Asterionella* was 8.02 when the light intensities exceeded $110 \mu\text{Em}^{-2}\text{s}^{-1}$. In addition, the predation of zooplankton also depends on the size of *Asterionella* colony. *Asterionella* with 8 cells or more was found to be inedible for zooplankton (Wangner, 2008).

2.3 The cause of diatom bloom

2.3.1 Nutrient availability

Nutrient such as phosphorus, nitrogen and silica are required for diatom growth and nutrient enrichment has been identified as the main driver for diatom blooms (Dong et al., 2012). When the concentrations of one or more of these required nutrient are low, the diatom will grow at a slower rate or stop growing completely. Such nutrient that limit the diatom growth in this way are called limiting-growth nutrients. On the other hand, when the required nutrient is sufficient, diatom can grow dramatically under appropriate conditions and this can result in diatom blooms.

One of the most efficient approaches to control diatom algal growth and prevent diatom algal blooms in water systems is to manage the growth-limiting nutrients. However, diatom's nutrient demand and the capacity for nutrient uptake differ among diatom species. Ammonia nitrogen ($\text{NH}_4\text{-N}$), nitrate nitrogen ($\text{NO}_3\text{-N}$) and phosphorus are the common nutrient and they are utilised by diatoms in varying amounts. Some diatoms known as oligotrophic diatoms seem to prefer very low amounts of nitrate or ammonia and phosphorus, whereas those that typically live in eutrophic and polysaprobic conditions seem to prefer higher amounts of these nutrient (Werner, 1977). The nutrient demand and the capacity for nutrient uptake by the diatom species can also be affected by the environmental conditions. Therefore, the most effective procedures to limit or control the algal blooms vary with the particular water body concerned and require an understanding of nutrient status and the microbial interactions in the water body (David, 2004).

Numerous studies have been carried out to determine the growth-limiting nutrient for different diatoms species (Løvstad, 1983; Lee et al., 2014; Jansen et al., 2010; Muylaert et al., 2009; Wang et al., 2010). Løvstad (1983) studied five Norwegian lakes and found that phosphorus was the growth-limiting nutrient for both *Asterionella* and *Tabellaria* in the lakes with the total phosphorus (TP) of 4-12 $\mu\text{g/L}$ and soluble reactive phosphorus (SRP) of less than 1.4 $\mu\text{g/L}$. Silica with concentrations of 10-750 $\mu\text{g Si/L}$ limited the growth of both *Asterionella* and *Tabellaria*. The limitation of nitrogen might exist when the concentration of nitrogen was lower than 100 $\mu\text{g/L}$. *Asterionella* increased its growth rate from zero to probably the maximum with the SRP range of 0.6 to 1.2 $\mu\text{g P/L}$. Lee et al. (2014) assessed the seasonal algae variability in a reservoir

and the statistical analysis revealed that the growth of diatom was depended on total nitrogen (TN) concentration. The competitiveness of diatom and other algae was affected by the nutrient ratio and diatom species became the dominant phytoplankton when the ratio of TN and TP were greater than 30-40. The variation in diatom seasonally and spatially in the water column was found to be closely related to the chemistry of the water, changes in water chemistry due to seasonal temperature variations as well as the formation of a thermocline (Fonseca and Bicudo, 2008). The diatom was abundant with the silica dioxide (SiO₂), SRP, TP concentration of 1.7 mg/L, <4 ug/L, 1.68 mg/L.

A study carried out in Lough Neagh, Northern Ireland found that the annual spring diatom blooms were terminated by the depletion of available SiO₂ (Gibson et al., 2000). The population of *Asterionella formosa* decreased with decreasing levels of environmental silicon (Kilham et al., 1975). However, *Asterionella formosa* blooms could also be controlled by factors such as N, P, N:P ratio, Si:P ratio, Si:N ratio and predators such as Daphnia population (George, 2012; Saros et al., 2005). It is not only the concentration of nutrient in the environment that plays an important role in diatom growth and development, but also the ratios of these nutrient and the rate of supply of the nutrient to the water body (Holm and Armstrong, 1981).

Dissolved Si is an essential nutrient for diatom algal growth (Jansen et al., 2010; Muylaert et al., 2009; Wang et al., 2010) as diatoms use Si to develop cell walls. Studies have reported that diatom concentrations are controlled by the availability of Si. The uptake of Si during the bloom phase has been shown to result in a fall in the concentration of Si in the water body and this has been correlated with the mean concentration of silicon in the diatom cells decreasing during the bloom termination (Krivtsov et al., 2000).

The silica content of diatom cell walls varies among species. Even within a given species, silica content varies greatly – up to an order of magnitude (Conley et al., 1989). Table 2.4 shows the silica contents of different diatom species. Conley et al. (1989) found that silica content increases linearly with biovolume in freshwater diatoms, which can be described by the following equation:

$$\text{Log [silica content]} = 1.03 \text{ log [biovolume]} - 2.45;$$

Therefore, a first-order estimate of the amount of silica utilised by diatom production can be estimated from diatom biovolumes.

Diatom cell viability is dependent on the environmental availability of silicon (Znachor et al., 2015). Tessenow (1966) studied the silicon cycle in several lakes in Holstein and found 4-6 mg Si/L in soil water, 11-16 mg/L in spring waters and 0.02–12 mg Si/L in the waters leaving the

lakes; following blooms of diatoms in spring the concentration reduced to 0.02-0.05 mg /L. The release of SiO₂ from the sediment has also been shown to be an important factor in silicon availability (Gibson et al., 2000). The majority of Si in open water is coming from surface runoff and ground water.

Table 2.4 Silica content of diatoms.

Diatom species	pg SiO ₂ /cell mean (min-max)	Mean Biovolume μm ³	Size	Reference
<i>Asterionella formosa</i>	140 (90-170)	400	45-65 x 2-3	Einsele and Grim (1938)
	130 (120-140)		46-130 x 1-2	Lund (1950)
	160 (150-170)	754		Happey (1970)
	150	450		Bailey-Watts (1976)
	40 (20-70)	260		Holm and Armstrong (1981)
	130 (110-150)	516		Reynolds and Wiseman (1982)
	310 (210-410)	700		Sommer and Stabel (1983)
<i>Melosira granulate</i>	130	420		Einsele and Grim (1938)
	606	1030		Prowse and Talltnng (1958)
	214 (193-240)	500		Sommer and Stabel (1983)
	294	847		Reynolds (1984)
	581	5127		Sicko-Goad et al. (1984)
	84	283		Conley et al. (1989)
	114	611		Conley et al. (1989)
	516	1172		Conley et al. (1989)
<i>Melosira italic</i>	320 (257-386)	800	7 x 30	Einsele and Grim (1938)
	193	393		Gibson (1981)
<i>Navicula pelliculosa</i>	(2-3)		8-11 x 4-5	Busby and Lewin (1967)
<i>Synedra acus f.angustissima</i>	1200 (1100-1250)		420 x 3.5	Einsele and Grim (1938)
	1540			Sommer and Stabel (1983)
<i>Synedra delicatissima</i>	1572			Conley et al. (1989)
<i>Synedra ostenfeldii</i>	732			Conley et al. (1989)
<i>Tabellaria fenestrata</i>	390 (370-420)		57 x 6	Einsele and Grim (1938)

Hydrology, geology, topographical characteristics (such as relief and slope), land cover, land use and vegetation types of a catchment are the controlled mechanism for Si release (Jansen et al.,

2010; Tallberg et al., 2010). Soil erosion would increase Si flux. In terms of bedrock types, marls have higher silica weathering rates than sandstone (Bluth and Kump, 1994). Jansen et al. (2010) used land cover as a possibly significant predictor and successfully modelled Si fluxes for the conterminous USA. If the catchment area has high urbanization percentage, Si fluxes tend to be higher (Sferratore et al., 2006). Also, Si release appears to increase with an increase percentage of forest cover. Conversely, the extent of grassland has a negative impact on Si fluxes. The different impact of forest and grass land covers on Si release could be due to the different biochemical cycling of amorphous and dissolved silica in the soil-plant system. In forestry, roots could reach to the mineral layers and increase its weathering rates. In contrast, grasses have shorter roots (Conley, 2002; Jansen et al., 2010; Struyf et al., 2010).

Onderka et al. (2012) further examined the combined effects of hydrology, geology, topographical characteristics, land cover, land use and vegetation types on the export of Si in Luxembourg. They found that the runoff coefficient (RC) was the first-order control and main control for Si export fluxes. Si fluxes increase with runoff; the average topographic slope was the second most important variable for Si fluxes, followed by marls and sandstone, the areal percentage of grassland and urban areas. A negative relationship was found between the slope and Si, indicating lower Si fluxes in the steeper catchments. This could be due to lower contact time of water with soils and the bedrock on hill slopes (Jansen et al., 2010; Millot et al., 2002; West et al., 2005).

In another study which examined the impact of soil type, outwash and stream density on Si fluxes, Lin (2010) monitored Si fluxes on a weekly to bi-weekly basis in streams draining each of the 20 boreal catchments in Canada and developed a multivariate regression model to predict the silica flux. Lin (2010) found that the proportion of sand, outwash and peat were the most important factors determining Si levels in these streams. Both sand and outwash have a positive impact on Si fluxes. The sand with high Si content easily moves along the river bed, with the soil type peat, which is an indication of wetlands in a catchment, has a negative coefficient with Si fluxes. The same is true of the pond, which represents the extent of beaver ponds in the catchment. Stream density also has a negative impact on Si fluxes. These results indicated that water bodies in a catchment usually act as Si sinks, while soils act as Si sources. Within a water body, vegetation plays a significant role in the biological cycling of Si (Fulweiler and Nixon, 2005; Moulton et al., 2000). Lakes and reservoirs were found to act as Si sinks by reducing concentrations of Si mostly through biological uptake of diatoms (Friedl et al., 2004; Muylaert et al., 2009; Wang et al., 2010). In general, water contaminated with domestic and industrial wastewaters were found to have

higher Si concentrations. Depend on bedrock types, potable water from deep spring sources could also have higher Si concentration (Sferratore et al., 2006).

2.3.2 Water temperature and thermal stratification

In addition to nutrients, water temperature is also essential for diatom algal blooms and diatoms can survive in a large temperature range (Feuchtmayr et al., 2012; Lee et al., 2014). Table 2.5 shows the temperature ranges, optimum temperatures and the maximum specific growth rates of a number of common diatom species.

Table 2.5 Temperature ranges and diatom specific growth rates.

Species	Optimum temperature (T_{opt}), °C	Specific growth rate at T_{opt}	Temperature range, °C	Reference
<i>Asterionella formosa</i>	17-20	2.1	5 to 20	Talling (1955)
<i>Diatoma elongatum</i>	20	1.2	15 to 30	Muller (1972)
<i>Fragilaria crotonensis</i>	26	1.5	15 to 30	Muller (1972)
<i>Nitzschia actinastroides</i>	26	1.6	15 to 30	Muller (1972)
<i>Synedra acus</i> car. <i>Radians</i>	20	1.1	15 to 30	Muller (1972)
<i>Fragilaria sublinearis</i>	5-6	0.91	-2 to 8-9	Bunt (1968)
<i>Stauroneis membranacea</i>	5	0.57	-2 to 12	Bunt (1968)
<i>Synedra sp.</i>	4-6	1.0	-2 to 7	Bunt (1968)

Many diatom species can tolerate temperature from 0 to 35°C. Diatoms such as *Fragilaria sublinearis*, *Stauroneis membranacea* and *Synedra sp.* Isolated from Antarctic ice can tolerate temperatures as low as -2°C. For a diatom species, its optimum temperate for growth is close to its upper tolerated temperature limits. The optimum temperatures vary among diatom species and diatom species isolated from different areas have been found to display different optimum temperatures. For example, *Synedra sp.* From Antarctic ice has the optimum temperature of 4-6°C while *Asterionella formosa* from the boreal area has the optimum temperature of 17 – 20°C. In general, the diatom species with higher optimum temperature have higher maximum specific growth rate (Werner, 1977).

Table 2.6 shows the impact of temperature on specific growth rates of *Asterionella formosa* and *Tabellaria*. The specific growth rate of *Asterionella formosa* increases from 1/day at 10°C to 2/day at 20°C. At 13°C the specific growth rate of *Asterionella formosa* is 1.1 – 1.2/day, twice of that of *Tabellaria* at the same temperature.

Table 2.6 Diatom specific growth rates in different temperatures.

Temperature (°C)	Specific growth rate (divisions/day)	
	<i>Asterionella formosa</i>	<i>Tabellaria</i>
10	1.1	
	1	
13	1.1	0.6
	1.2	0.6
	1.1	
15	1.2	
	1.3	
20	2	
	1.9	

Water temperature has been found to have a statistically significant relationship to the overall biomass of the phytoplankton (Temponeras et al., 2000) with higher water temperatures found to be associated with earlier algal blooms (Winder et al., 2012). The review of planktonic diatoms undertaken by Willén (1991) illustrated that water temperature could be used to regulate the growth of diatom. A study into the diversity of benthic diatoms in relation to abiotic environmental factors found that the summer and autumn diatom distributions was affected by water temperature (Ognjanova-Rumenova et al., 2013). Similarly, Lv et al. (2014) found that seasonal shifts in diatom phytoplankton communities in a reservoir in subtropical China were strongly related to water temperature, as well as other factors such as nutrient availability. Other studies carried out by Lee et al. (2014) and Fonseca and Bicudo (2008) also indicated that diatom species were sensitive to water temperature changes.

The mixing regime of the water column can be one of the major factors that determine the phytoplankton community dynamics on a seasonal scale (Becker et al., 2009). The interplay between the various aspects of the hydrographic regime such as currents, thermal stratification, wind assisted mixing, water inflows have a direct effect on how the plankton are transported in the 3-dimensional space of the water column. Both of the interacting factors of water temperature and mixing depth were shown to affect the chronology and magnitude of occurrences to the phytoplankton spring time succession (Berger et al., 2007).

In addition, the mixing condition of water column influences the growth of diatom by affecting the diatom sedimentation loss, as well as nutrient distribution and the light intensity (Jäger, 2008). Compared with other algal, diatom is characterized with heavy frustule. As the density of diatom is heavy than the water and tend to sink in the water (Huisman et al., 2002). Turbulent mixing can keep the diatom suspend in the euphotic layer. The diatoms grow well in the fully mixed water system and the sedimentation caused by the stratification can end the diatom growth (George, 2012). The mixing of water column can also favour the process of nutrient transfer. Stratification contributes to the formation of microenvironment with low nutrient concentration which may lead to the decay of diatom (Winde et al., 2009). Fonseca and Bicudo (2008) studied the phytoplankton seasonal variation in the reservoir and diatom was only observed when the water was mixed during April to August. Fadel et al. (2015) studied the phytoplankton succession in the reservoir, the onset of stratification in spring limited the growth of diatom.

2.3.3 *Illumination condition*

Illumination is another essential factor affecting diatom algal blooms. Diatoms are photosynthetic organisms and changes in available incident solar radiation can affect diatom growth. The growth of diatoms in response to day length, as well as light intensity, has been studied since the mid-1900s (Werner, 1977). Lund (1950) found that the spring increase in division rate of *Asterionella formosa* was more closely correlated with increased illumination than with increased temperature. Similarly, Chandler (1944) showed that the spring diatom increase in Lake Erie was correlated with illumination. Winder et al. (2012) reported that the magnitude of diatom algal blooms was affected by the intensity of the incident light conditions, with decreased magnitude algal blooms corresponding to lower incident light intensity conditions. Diatoms had different optimistic light intensities for diatom bloom formation (Shi et al., 2016).

Table 2.7 shows the saturating light intensity and the corresponding specific growth rates for a number of diatom species. In general, when the temperature increases, the saturating light intensity increases, as well as the specific growth rates. In a study in White Clay Creek, Patrick (1971) found that with the average temperature of 2.8°C, artificial increases in the day length (by 1 hour 31 minutes) in a diatom community which naturally developed in January-February resulted in small increases in the number of species and total biomass; Artificial increase in the day length (by 3 hours and 16 minutes) of a diatom community which naturally developed in March with an average temperature of 5.7°C resulted in an increase in the number of species and a 28% increase in biomass. Species such as *N. palea* increased from 14.4% to 24.8% with the increased day length. A similar artificial increase in day length in the March diatom community

with an average temperature of 19°C resulted in little change in the number of species but it did produce a 38% increase in biomass. Patrick (1971) compared the diatom assemblages in White Clay Creek and found that the diatom biomass in March was 274% of that in February, though the average temperatures in February (10°C) and March (10.4°C) were similar. He attributed this biomass increase to the increase of day length from 10 hours 29 minutes in February to 11 hours 44 minutes in March.

Table 2.7 Variation in the specific growth rates with light intensity.

Species	Specific growth rate (divisions/day)	I _{sat} (cal.cm ⁻² .min ⁻¹)	Temperature (°C)	Reference
<i>Stephanodiscus hantzschil</i>		0.01	8	Swale (1963)
	0.67	0.01	14	Swale (1963)
		0.03	20	Swale (1963)
<i>Asterionella japonica</i>	1.0	0.006 – 0.024	18	Kain et al. (1958)
<i>Chaetoceros gracili</i> <i>Ignatiaders & Smaydas</i>	1.5	0.039	23-26	Thomas (1966)
<i>Detonula confervacea</i>	1.2	0.013-0.039	2	Smayda (1969)
	1.5	0.039-0.077	7	Smayda (1969)
	1.5	0.077 -0.116	12	Smayda (1969)

2.3.4 The effect of food chains

A food chain exists in every ecosystem including a freshwater ecosystem. Zooplankton such as copepods and daphnia (Figure 2.4) feed on phytoplankton and diatom may be the major food source of zooplankton especially when other kinds of food is scarce (Kleppel et al., 1991; Winder et al., 2012). As a result, grazing caused by the zooplankton could affect the abundance of phytoplankton. Vanni (1987) studied the relationship between zooplankton and phytoplankton in an oligo-mesotrophic lake and found that the increase of the phytoplankton biomass was associated with a decrease of zooplankton biomass. In the study of Conde-Porcuna (2002), the correlation of crustacean species and phytoplankton was obvious in a mesotrophic reservoir. The biomass of algal was suppressed by zooplankton in the study of McCarthy et al. (2006) with the maximum Daphnia amount associated with the low biomass of phytoplankton. However, Wagner (2008) studied the edibility of *Asterionella* for Daphnia in a reservoir in two consecutive years and found that the *Asterionella* was the main food source of daphnia in 1996 whereas *Asterionella* was inedible in 1995. By study the phytoplankton carbon dynamics in the marine ecosystem,

Keller and Riebesell (1989) obtained that grazing was only responsible for 11% of the loss of diatom.

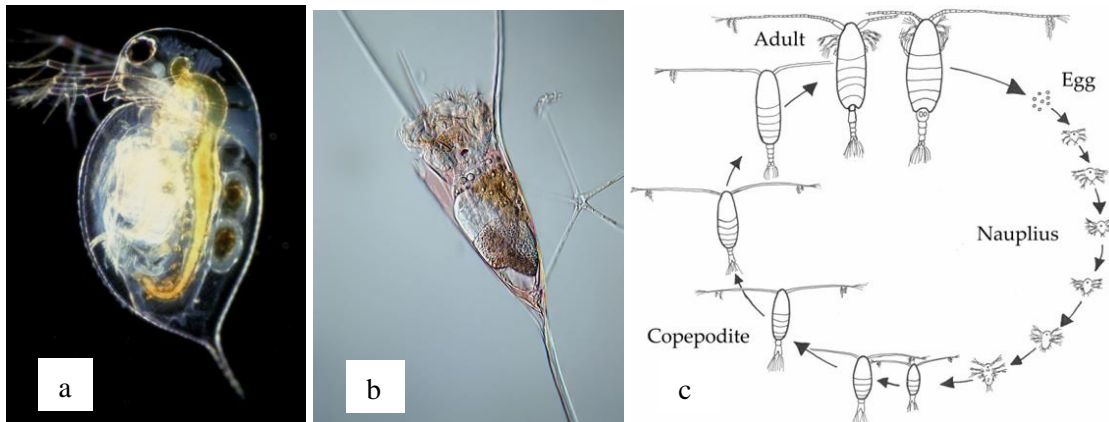


Figure 2.4 Image of zooplankton species a Daphnia; b Rotifer; c Copepods.

2.4 Diatom bloom prevention and impact mitigation

2.4.1 Reducing nutrient inputs

Nutrient enrichment has been identified as the main driver of diatom blooms (Dong et al., 2012). To prevent and control diatom blooms, identification of growth-limiting nutrient is critical. Once identified, reducing the external nutrient input is one of the measures employed to control diatom algal blooms. The first step of this approach is to elucidate the major point or diffuse sources of nutrient inflow. Following identification of the major pollution sources, best management practices could be proposed and implemented to reduce nutrient input.

2.4.2 Altering hydraulic condition and reducing illumination

Reducing nutrient entering water bodies is an essential solution for diatom algal bloom control. However, this approach is more long-term in nature. In drinking water sources where seasonal algal blooms can dramatically increase populations on relatively rapid timescales, water treatment process efficiency can be impaired, and short or medium-term approaches, such as temporarily managing the hydrodynamic conditions of the reservoir could be used to control diatom algal blooms. Mixing and high turbulence favour diatom growth because of their high density and the lack of planktonic motility. When there are initial signs of diatom algal blooms or even during the diatom algal blooms period, creating calm conditions and decreasing the depth of mixing layer by controlling water levels could prevent diatom algal blooms (Liu et al., 2012). In a study by Yang et al. (2012), a flushing strategy was used to prevent diatom bloom in the river.

2.4.3 Removing diatoms, coagulation and flocculation

Once diatom algal blooms occur, removal of diatoms from water is the last approach to mitigate its impact on the water treatment plant. The types of algae and their characteristics can have an impact on removal treatment. External morphological features, density and surface charge can all have an effect (Henderson et al., 2008). There are a variety of methods for removing algae from water, with a number of reviews available in the literature detailing treatment options ranging from various filtration hardware to processes such as ozonisation (Mouchet and Bonnelye, 1998).

Treatment of drinking water with ultrasound has been shown to be effective in removal of diatom algae. It was found that both higher frequencies and higher power facilitated the removal of a bloom forming cyanobacteria *Microcystis aeruginosa* (Zhang et al., 2006).

Technologies such as coagulation and flocculation are also solutions employed for removal of diatom algal blooms. Before the water is introduced to the slow sand filters, mixing the water with a coagulant allows the diatom to settle. Flocculation and coagulation processes have been widely used to remove diatom algae in water treatment plants. Coagulants with charges opposite the diatom algae could neutralise the charge. Once the charge is neutralised, the diatoms are capable of sticking together and form higher density microflocs and suspended particles which subsequently settle quicker. Coagulants such as aluminium and iron salts and polymers have been widely used to remove diatoms (Henderson et al., 2010). In the study of Jun et al. (2001), polyaluminium hydrogen chloride silicate was used for the removal of *Synedra* in the source water of the CheongJu water treatment plant (South Korea) and the *Synedra* removal efficiency in jar test reached 88%. However, coagulants alone may not sufficient to remove diatoms. To enhance algae removal in the coagulation process, traditionally, a pre-oxidation process is added and ozone, chlorine dioxide, chlorine or permanganate is usually employed. A number of coagulants have been successfully used to remove algae (Henderson et al., 2008; Shen et al., 2011) and numerous studies have demonstrated that a pre-oxidation process can significantly improve algae removal (Fitzgerald, 1966; Petrusevski et al., 1996; Steynberg et al., 1996; Sukenik et al., 1987) due to deactivating algal cells and reducing cell stability.

2.5 Summary of the literature review

In the literature review, the current situation of drinking water, diatom bloom, the causes of diatom bloom and the measures to deal with diatom bloom are included.

Drinking water is vital important for our daily life and eutrophication mainly caused by human activities influences the quality of drinking water sources. Although the lake water quality in

Ireland is better than the European average, efforts are still required to maintain the good ecological status of the water quality (Fanning et al., 2017).

Developing an understanding of the characteristics of *Asterionella* and its response to the changes of environmental factors are essential for this study. The growth of diatom is affected by many factors such as nutrient concentrations, water temperature, thermal stratification, light intensity and the predation of zooplankton.

To prevent the diatom growth, reducing the nutrient concentration, changing the hydraulic condition and limiting the illumination could be considered. Furthermore, to deal with the impact of diatom bloom in the water treatment plant, filtration and coagulation can be effectively used to remove the diatom in the influent.

Chapter 3

Methods

3 Methods

3.1 Study site

Vartry Reservoir (53°03'N, 6°12'W) is located at Roundwood in County Wicklow, Ireland (Figure 3.1). The reservoir includes the upper lake and the lower lake. The upper lake has a capacity of 5.6 million cubic meters of water with a maximum depth of 13.4 m. The lower lake has a capacity of 11.3 million cubic meters of water and a maximum water depth is 18.3 metres. Water is piped from the lower lake to the Vartry water treatment plant for future purification.

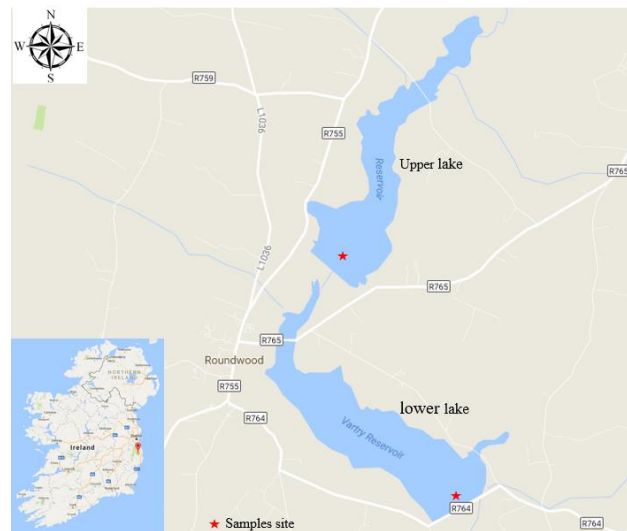


Figure 3.1 Location of Vartry Reservoir and long-term sampling sites.

The combined catchment area of the two reservoirs is 57 square kilometres. Principal land uses within the catchment are: pasture (58%), wet bog & heath (25%), forest (12%) and arable (5%). At the beginning of this study, site surveys were carried out to identify the location and number of the feeding rivers. There are 11 and 14 feeding rivers/streams/pipes into the upper lake and the lower lake, respectively. The locations of the feeding rivers/streams/pipes are shown in Figure 3.2.



Figure 3.2 Location of feeding rivers/streams/pipes for upper lake (a) and lower lake (b).

The flow rates and nutrient concentrations of the feeding rivers/streams/pipes were measured during the survey and this information is presented in Table 3.1 and Table 3.2.

Table 3.1 Flow rates and nutrient concentrations at feeding rivers/streams of the upper lake on 21st Oct 2015.

No.	Flow (L/s)	PO ₄ -P (µg/L)	TON (mg/L)	NH ₄ -N (mg/L)	SiO ₂ (mg/L)	Main land use
U1	<5	30	0.28	1.89	14.09	Pasture
U2	84	61	1.93	0.19	25.03	Pasture with forest
U3	907	19	1.25	0.08	20.39	Pasture with wet bog and heath
U4	<5	16	0.38	1.47	14.28	Pasture with wet bog and heath
U5	<5	7	0.91	0.97	25.39	Pasture with wet bog and heath
U6	<5	<5	0.50	1.35	44.09	Pasture with wet bog and heath
U7	<5	13	0.75	0.05	36.99	Pasture with wet bog and heath
U8	281	28	1.26	0.08	13.98	Pasture with forest
U9	12	36	1.36	0.06	30.68	Pasture with forest
U10	132	15	1.32	0.05	28.84	Pasture with forest
U11	83	20	1.35	0.06	30.76	Pasture with forest

Table 3.2 Flow rates and nutrient concentrations at feeding rivers/streams of the lower lake on 25th Oct 2015.

No.	Flow (L/s)	PO ₄ -P (µg/L)	TON (mg/L)	NH ₄ -N (mg/L)	SiO ₂ (mg/L)	Main land use
D1	190	<5	1.60	0.00	10.90	Pasture
D2	125	<5	1.55	0.03	12.71	Pasture
D3	<5	<5	0.15	0.01	12.27	Pasture
D4	39	39	1.45	0.04	16.78	Pasture
D5	237	31	0.67	3.73	22.71	Pasture with wet bog and heath
D6	5	<5	1.78	2.25	21.09	Pasture
D7	<5	<5	0.44	1.58	16.32	Pasture
D8	<5	<5	0.32	0.97	22.13	Pasture
D9	89	85	1.76	0.47	8.73	Urban
D10	9	<5	4.53	0.02	9.21	Pasture
D11	<5	<5	3.40	0.05	6.55	Pasture
D12	<5	<5	3.27	0.03	7.03	Pasture
D13	<5	<5	2.12	0.02	7.71	Pasture
D14	<5	<5	1.93	0.08	7.78	Pasture

Drained area land use types and the flow rates were considered when the feeding rivers/streams/pipes were selected for detail monitoring in this study. Based on the data (Table 3.1 and Table 3.2), U2, U3, U8, U10, U11 and D1, D2, D4, D5, D9 were chosen for extensive monitoring. These rivers contribute to 78% and 63% of surface water feeding to the upper reservoir and lower reservoir, respectively. The running areas of each river are shown in Figure 3.3.

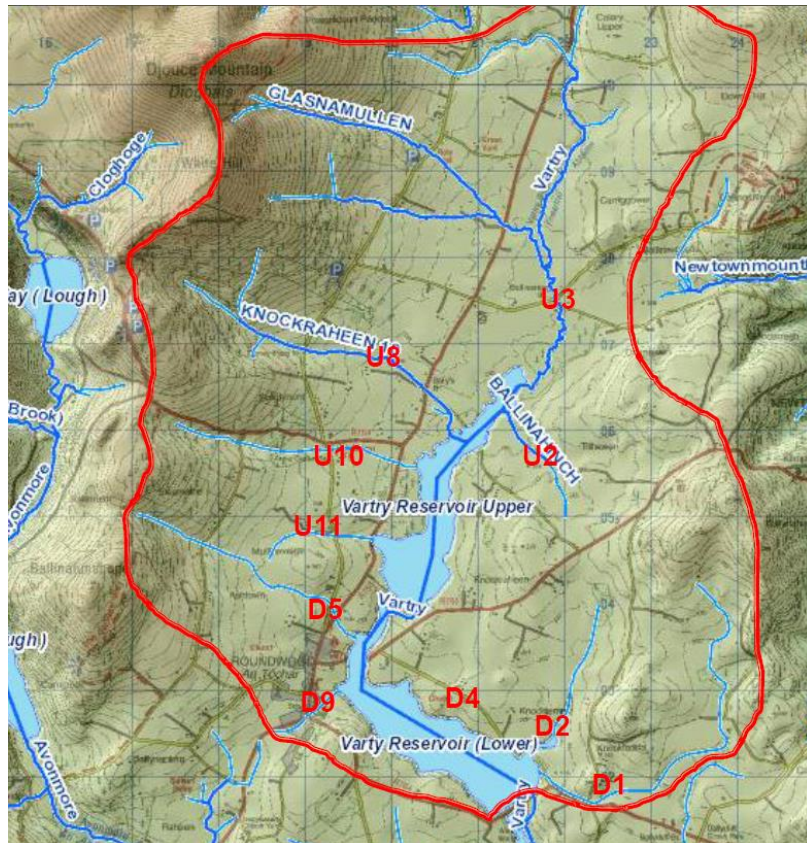


Figure 3.3 Catchment area of the extensive monitoring feeding rivers of the reservoir.

Water samples and phytoplankton samples were also collected in other lakes or reservoirs in spring 2018 and the location is shown in Figure 3.4.

3.2 Data and samples collection

3.2.1 Date collection

Historical data including diatom number in the lower lake, the concentrations of silica and nitrogen in Varty Reservoir and water temperature in Varty Reservoir from 2012 to 2014 was collected from Varty water treatment plant.

Meteorological data such as sunlight condition in Vartry Reservoir, rainfall, air temperature was collected from the Irish Meteorological Service.

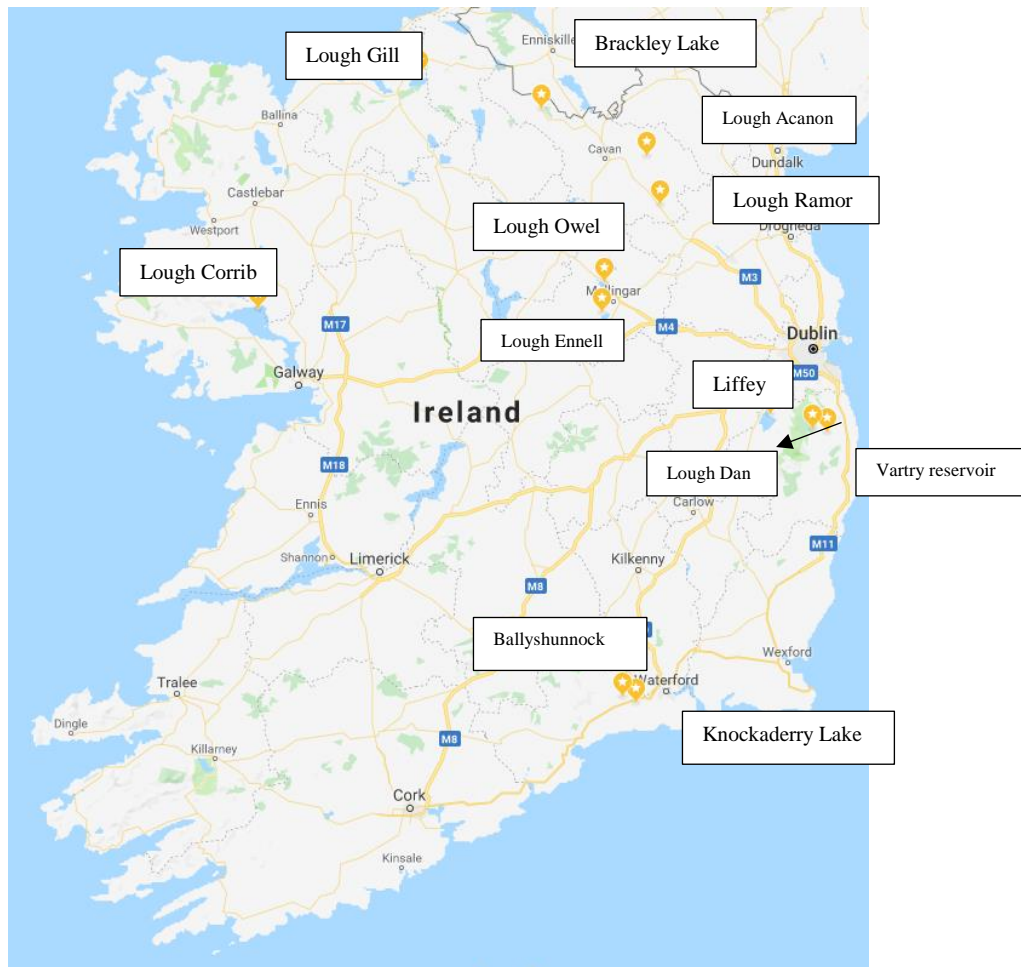


Figure 3.4 Locations of other sampling reservoirs in 2018.

3.2.2 Samples collection

3.2.2.1 Sampling in the reservoir

From 2016 to 2018, water samples and the zooplankton samples in the reservoir were typically collected every two weeks. During diatom bloom period in spring (March to May), the frequency of samples collected was every 3 or 4 days. The sample locations for long term monitoring in the upper lake and the lower lake is shown in Figure 3.1.



Figure 3.5 Samples collecting in Vartry Reservoir.

In the reservoir, 20 ml water samples were taken at a depth of 0.5 m. $\text{NH}_4\text{-N}$, SRP, $\text{NO}_3\text{-N}$, nitrite ($\text{NO}_2\text{-N}$), total organic carbon (TOC) and SiO_2 were tested. Water samples used for the counting of diatom was preserved with Acidified Lugol's Iodine. Acidified Lugol's Iodine was made by adding 20g of Potassium iodide, 10 g Crystal Iodine and 20ml of Glacial Acetic Acid to 100 ml deionised water and then making up the total volume to 200 ml by adding more deionised water. This solution was stored in bottles wrapped in tin foil to prevent light penetration at a temperature of $5 \pm 3^\circ\text{C}$.

Zooplanktons were collected by using a net with a mesh size of $63 \mu\text{m}$. The screened sample bucket was attached to the bottom of the net. The tow is taken from two meters above the bottom of the lake to the surface at a speed of 0.5 meters per second to collect the zooplankton. Zooplankton samples were concentrated and then transferred to the sample bottle. Soda was added to narcotize the zooplankton and the samples were preserved with Acidified Lugol's Iodine. In order to preserve the zooplankton samples, 0.7 ml of Acidified Lugol's Iodine per 100ml of sample was used.

3.2.2.2 Sampling in the feeding rivers

About 20 ml water samples in the 10 feeding rivers (U2, U3, U8, U10, U11 and D1, D2, D4, D5, D9) were collected every two weeks from 2015 to 2018. Water level sensors (OTT Orpheus mini water level logger) were placed in D1, D9, U3 and U8 (Figure 3.6) and the water levels were recorded every hour.



Figure 3.6 Water level sensors in the feeding rivers.

The automatic samplers (Figure 3.7) were used to collect the water samples every hour over a 24-hour period. The concentration of $\text{NH}_4\text{-N}$, SRP , $\text{NO}_3\text{-N}$, $\text{NO}_2\text{-N}$, TOC and SiO_2 were measured in the laboratory.



Figure 3.7 Automatic water samplers.

3.2.2.3 The sampling of underground water

Four boreholes W-1, W-2, W-3, W-4 with the diameter of 10 cm were drilled in February 2017 (Figure 3.8 and Figure 3.9). Both W-1 and W-2 are near to the feeding river D2 and the depth is 3.5 m and 2.2 m. Both W-3 and W-4 are near to the feeding river D9 and the depths are 4 m and 2 m, respectively. The water biobailer (ESP INC, Figure 3.10) was used to collect the water samples and the sampling frequency was once every two weeks.



Figure 3.8 Locations of four boreholes around the lower lake.



Figure 3.9 The boreholes.



Figure 3.10 Water bailer used for sampling underground water.

3.2.2.4 Sampling along the longitudinal axis of the reservoir

During diatom bloom period from April 2017 to May 2017, water samples and zooplankton samples were collected along the longitudinal axis of the reservoir every 3-4 days and the sampling sites are shown in Figure 3.11.

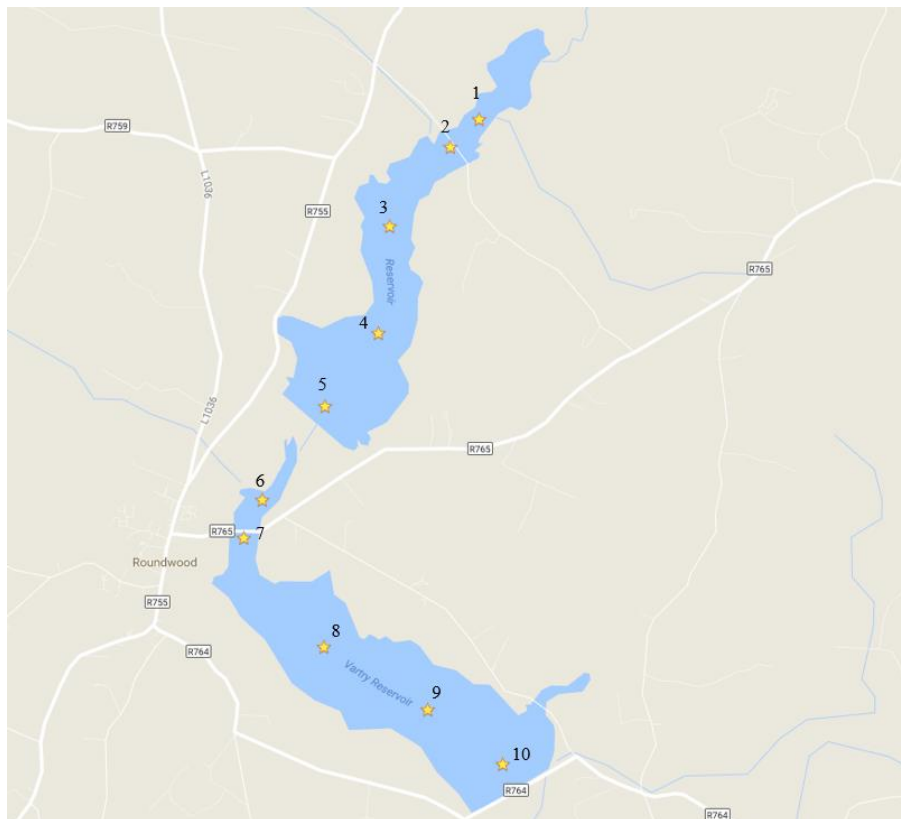


Figure 3.11 Locations of ten sampling sites along Vartry Reservoir.

3.3 Experiments in Vartry Reservoir and laboratory

3.3.1 *Diatom growth in bottles in the reservoir*

In April 2017, glass bottles with the volume of 200 ml were filled with water samples taken from the reservoir. Four bottles were suspended at a depth of 0.5 m, 2 m, 4 m and 6 m on the rope attached to the buoy. Two locations were chosen for this experiment and the locations (Site A and Site B) are shown in Figure 3.12. Every four or five days, 3 ml water samples were taken from the bottles and the number of diatom and nutrient concentrations were measured. During this period, the water temperature was about 12 °C.



Figure 3.12 Locations of experiments in Vartry Reservoir.

3.3.2 *Impact of zooplankton on diatom experiment in the lab*

During diatom bloom period in 2018, water samples and zooplankton samples were collected from the lower lake and transport to the lab immediately. Flasks with the volume of 500 ml were used as the culture vessels and each flask was filled with 500 ml water. Different number of individual zooplanktons were placed in the flasks and the initial diatom and zooplankton concentration was recorded.

The diatom was cultured at room temperature (about 20 °C) and 4000 lux illumination provided by cool white fluorescent on a 14-hour light and 10-hour dark cycle. Every two days, 3ml water samples were taken and the number of diatom and the concentration of silica was tested.

3.3.3 Coagulation and flocculation experiment

In May 2018, water samples were taken from Vartry Reservoir for the coagulation and flocculation experiment in the laboratory. Flocculation testing apparatus, 5 beakers (1000 ml), pH meter, Aluminium sulphate ($\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$) solution and Ferric chloride ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) solution are prepared.

The water samples were fully mixed and placed in 5 beakers with the water volume of 1L each. The pH of the water samples was tested. Coagulant was added to the beakers and the concentration of coagulate was 0, 5 mg/L, 10 mg/L, 20 mg/L and 30 mg/L. The paddle of the flocculation apparatus was inserted to the beakers. The mixing speed was 250 r/min for 2 min (rapid mix), then reduced to 40 r/min for 15 min. Then, the mixing was stopped and the beakers were allowed to settle down for 20 min. 2-3 ml samples were then collected at 2-3 cm below the water surface and the number of diatoms was counted.

3.4 Analytical methods

Nutrient concentrations were tested using the Konelab 20i (Thermo, Finland). A TOC analyser was used to test TOC and TN. Water transparency was measured by Secchi disk (Figure 3.13).

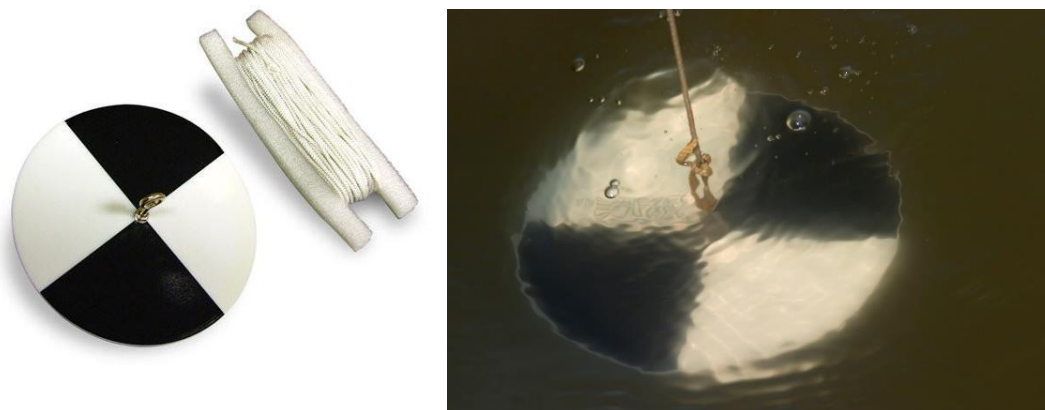


Figure 3.13 Secchi disk.

A thermistor string (GeoPrecision, German, Figure 3.14) with 7 temperature sensors at 1.5-meter intervals was attached to the buoy to record the water temperature every hour at different depths in the lower lake.



Figure 3.14 Water temperature sensor.

Sedgewick-rafter counting cell slide (Figure 3.15) and microscope (Leica, Germany) were used for the identification and enumeration of the diatoms and zooplankton. The Sedgewick Rafter Counting Cell Slide was constructed as a flat slide (76mm ×40mm) onto which was cemented a 'wall' to form a chamber or cell. This chamber is 50mm long ×20mm wide and 1mm deep at its base. This chamber is marked with a grid of 100 ×1mm squares. When filled with liquid and with a cover glass placed over the chamber a 1ml volume of liquid is retained. When used under a low magnification light microscope, each of the grid squares equates to 1microlitre of liquid.

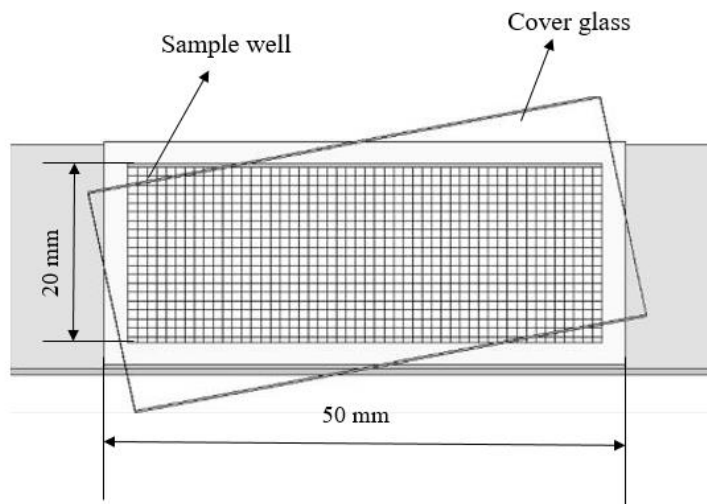


Figure 3.15 Sedgewick-rafter counting cell slide.

The procedure of enumeration is followed:

- (1) Samples must be fully mixed before counting the number of diatom or zooplankton by gently inverting water samples 5 times;

- (2) The cover glass should be placed carefully onto the counting slide, perpendicular to the long axis of the slide, so one corner is left open for filling and another for the escape of air. The 1 ml sample is then dispensed into the counting chamber using a Pasteur pipette;
- (3) Slowly swing the cover glass so that it completely covers the sample;
- (4) Carefully align the cover slip to prevent air bubbles from being introduced into the sample. If a bubble develops, refill the counting cell;
- (5) Preserved samples should be left to settle for 3-5 minutes before enumeration;
- (6) The sample is then examined using the microscope;
- (7) The slide should first be scanned under low magnification to estimate the concentration of cells. Where the concentration of phytoplankton is too dense to allow identification and enumeration, a dilution step should be performed using filtered water. Once an appropriate concentration has been made, examine the contents of the cell and record densities of taxa present;
- (8) Plankton units overlapping on the right hand / top boundary of cell line are included in a count. Those on the left hand /lower boundary are not. This is done to avoid counting the same plankton twice;
- (9) After completing the count, remove the cover glass and clean the counting chamber with water or a mild cleaning solution (10% solution of bleach). Rinse with acetone and allow to dry in the fume hood.

After the analysis is completed (or between samples) the slide is thoroughly rinsed with deionised water, cleaned with 70% Alcohol and dried.

The diatom growth rates (u) were calculated with the following equation:

$$U = \frac{\ln N_{t2} - \ln N_{t1}}{t2 - t1}$$

(1)

Where u is the specific growth rate (per day), N_{t1} (counts/mL) is the number of diatoms on day t1, N_{t2} (counts/mL) is the number of diatoms on day t2

Similar to a previous study by Ferris and Lehman (2007), the diatom number and silica concentrations in the lower reservoir was simulated by following model.

$$Q_{in} = \sum_i^{n=14} Q_{Ri, i} \quad (2)$$

$$Q_{out} = Q_{of} + Q_{WTP} \quad (3)$$

$$Q_{of} = 86.4 \cdot \left(\frac{h \cdot d^{0.7}}{9.87}\right)^{1.368} \quad (4)$$

$$V_{Re} = 11.4 + h \cdot 0.00166 \quad (5)$$

Where Q_{in} is total flow rate into reservoir, Q_{Ri} is flow rate of each feeding river, monitoring by flow sensors, Q_{out} is flow rate out reservoir, Q_{of} is flow rate of overflow, calculating by equation, Q_{WTP} is flow rate of water treatment plant, 70000 m³/d. All flow rate units are m³/d; h is the water rising level of overflow, mm, d is the effective diameter of overflow pipe, assumed as 5000 mm. V_{Re} the total volume in reservoir, million m³.

The growth of diatom was described by following equation:

$$U_{[Dia]} = ([SiO_2]_{Re} - [SiO_2]_0)u_g / (K + [SiO_2]_{Re} - [SiO_2]_0) \cdot [Dia]_{Re} \quad (6)$$

Where $U_{[Dia]}$ is diatom growth rate in reservoir, count/(mL • d), $[SiO_2]_{Re}$ is the silica concentration in reservoir (mg/L), $[SiO_2]_0$ is the the minimum threshold silica concentration for diatom growth, assuming as 0.3 mg/L. K is the half-saturation constant, (mg/L). u_g is the maximum intrinsic growth rate, (d⁻¹). $[Dia]_{Re}$ is the diatom count in reservoir, counts/mL.

The sinking loss of diatom due to thermal stratification and capture loss due to zooplankton was described by following equation:

$$SK_{[Dia]} = u_{sk} \cdot [Dia]_{Re} \quad (7)$$

$$ZP_{[Dia]} = [ZP] \cdot 2 \cdot \frac{[Dia]_{Re}}{1000} \quad (8)$$

Where $SK_{[Dia]}$ is diatom sinking rate in reservoir, count/(mL•d), u_{sk} is the specific sinking rate (d⁻¹). $SK_{[Dia]}$ is diatom decrease rate due to zooplankton capture in reservoir, count/(mL•d). $[ZP]$ is number of zooplanktons in reservoir. In terms of capture ability, it was assumed 2000 count diatom captured by zooplankton when diatom number is 1000 counts/mL.

The concentration of diatom at N day could be calculated as follow:

$$[Dia]_{Re,N} = \frac{[Dia]_{Re,N-1}(V_{Re,N-1} - 1 \cdot Q_{out,N-1})}{(V_{Re,N-1} + 1 \cdot Q_{in,N-1} - 1 \cdot Q_{out,N-1})} + 1 \cdot U_{[Dia],N-1} - 1 \cdot SK_{[Dia],N-1} - 1 \cdot ZP_{[Dia],N-1} \quad (9)$$

The concentration of silica at N day could be calculated as follow:

$$[SiO_2]_{Re,N} = \frac{[SiO_2]_{Re,N-1}(V_{Re,N-1} - 1 \cdot Q_{out,N-1}) + [SiO_2]_{Ri,N-1} \cdot 1 \cdot Q_{in,N-1}}{(V_{Re,N-1} + 1 \cdot Q_{in,N-1} - 1 \cdot Q_{out,N-1})} - 1 \cdot U_{[Dia],N-1} \cdot C_v \quad (10)$$

Where C_v is coefficient of diatom growth requirement of silica, 1 million diatom growth was found require 1.1 mg silica. At the numerical study, the start day (0 day) was picked according to the starting point of each year. Then the diatom growth and silica concentration change tendency

was calculated via above equations. Finally, the simulated results of diatom number and silica concentration were compared with experimental results.

Principal component analysis (PCA) was carried out to investigate the potential factors for diatom growth by using the SPSS 20.0 software.

Chapter 4

The growth of diatom in Vartry Reservoir
from 1996 to 2018

4 The growth of diatom in Vartry Reservoir from 1996 to 2018

The diatom growth trends (diatom assemblages, magnitudes and durations) in Vartry Reservoir were different every year. Diatom growth is affected by numerous factors. To understand the cause of diatom bloom, the diatom data from 1996 to 2018 in Vartry Reservoir was collected and analysed.

4.1 Diatom growth in lower lake of Vartry Reservoir

4.1.1 Diatom assemblages in lower lake from 1996 to 2012

The growth of diatom in the lower lake in 1996 is shown in Figure 4.1. Diatom bloom occurred from April to June, with the maximum diatom concentration of 1107 counts/mL on the 2nd May. *Asterionella* and *Tabellaria* were the major dominant species in 1996. The number of *Asterionella* increased significantly from 325 counts/mL on 15th April to 801 counts/mL on 2nd May. The concentration of *Tabellaria* ranged between 122 counts/mL and 290 counts/mL during 15th April and 13th June.

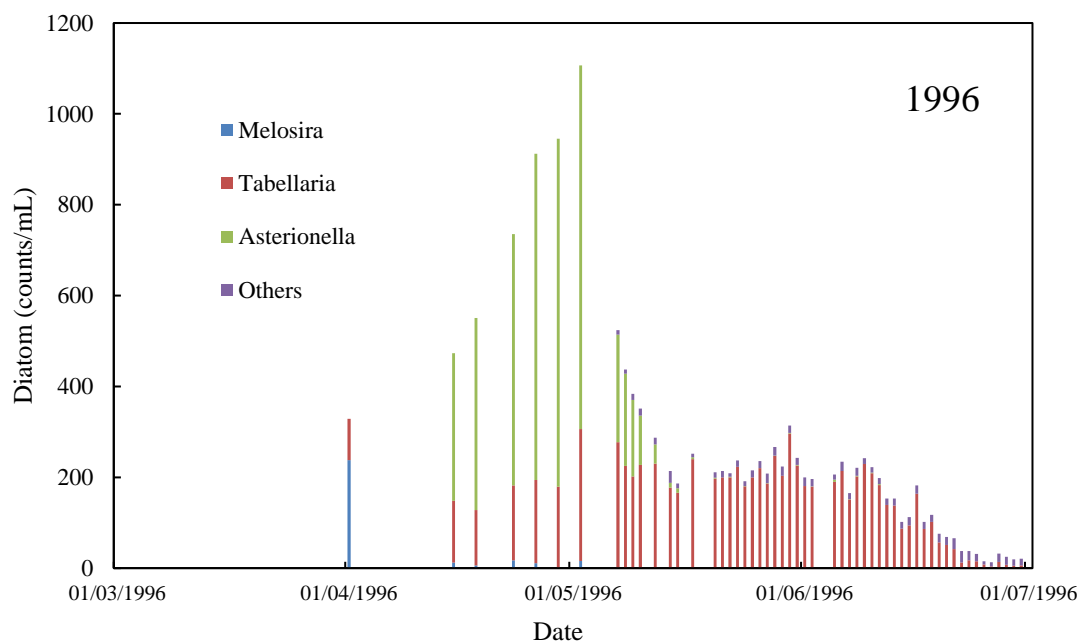


Figure 4.1 Diatom assemblage in lower lake in 1996.

Figure 4.2 shows the monthly peak diatom number in lower lake from 1997-2001. The predominated diatom species in 1997, 1999 and 2000 were *Melosira* and the maximum diatom concentrations were observed in February with the values of 701 counts/mL, 270 counts/mL and 291 counts/mL, respectively. The major diatom species in 1998 and 2001 was *Asterionella*. The peaked diatom number was 403 counts/mL in March 1998 and 499 counts/mL in March 2001. In

1998 and 2001, diatom growth was also observed in autumn and the diatom concentration remained lower than 200 counts/mL.

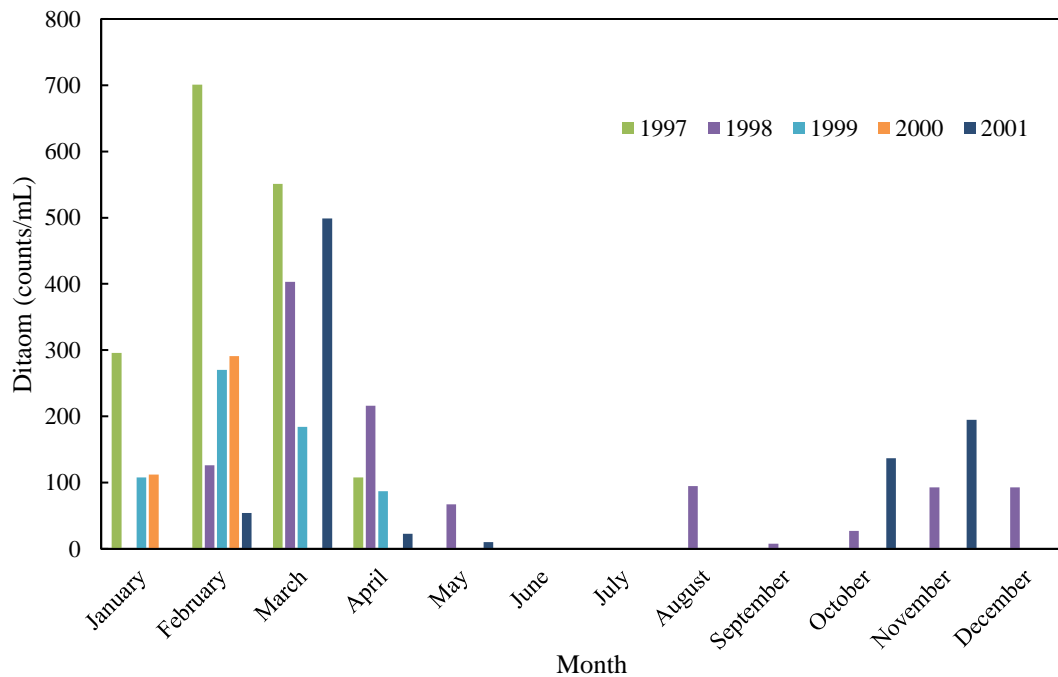


Figure 4.2 Monthly peak diatom number in lower lake from 1997 to 2001.

The diatom assemblage in 2002 is presented in Figure 4.3. The number of diatoms increased from 56 counts/mL on 6th February 2002 to the peaked concentration of 806 counts/mL on 18th March 2002. After that, the number decreased slowly to 40 counts/ml on 22nd May. The major diatom species were *Tabellaria* and *Melosira* with the maximum values of 432 counts/mL and 234 counts/mL, respectively. During diatom bloom period, the number *Synedra* and *Asterionella* remained lower than 100 counts/mL.

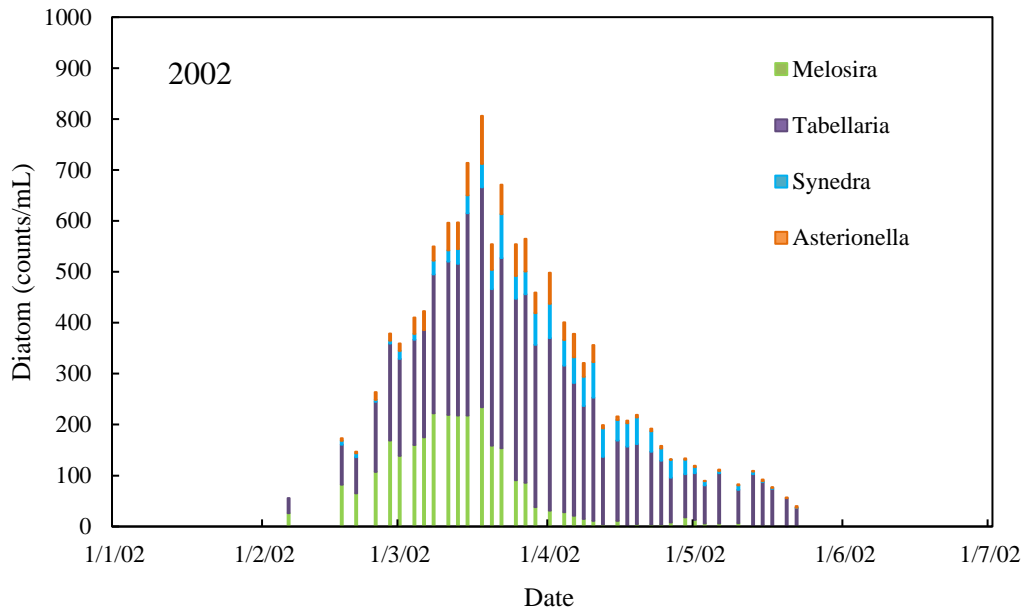


Figure 4.3 The growth of diatom in lower lake in 2002.

In 2003 (Figure 4.4), diatom bloom period was from 7th February 2003 to 28th April 2003 and the maximum diatom number was 406 counts/mL on 7th April 2003. At the beginning of diatom bloom, *Melosira* was the major species with the highest concentration of 138 counts/mL on 15th March 2003. At the end of March (from 20th March to 26th March), *Tabellaria* dominated diatom bloom with the value of 144 counts/mL. Since April, the number of *Asterionella* was higher than other species and the maximum values was 207 counts/mL on 7th April 2003.

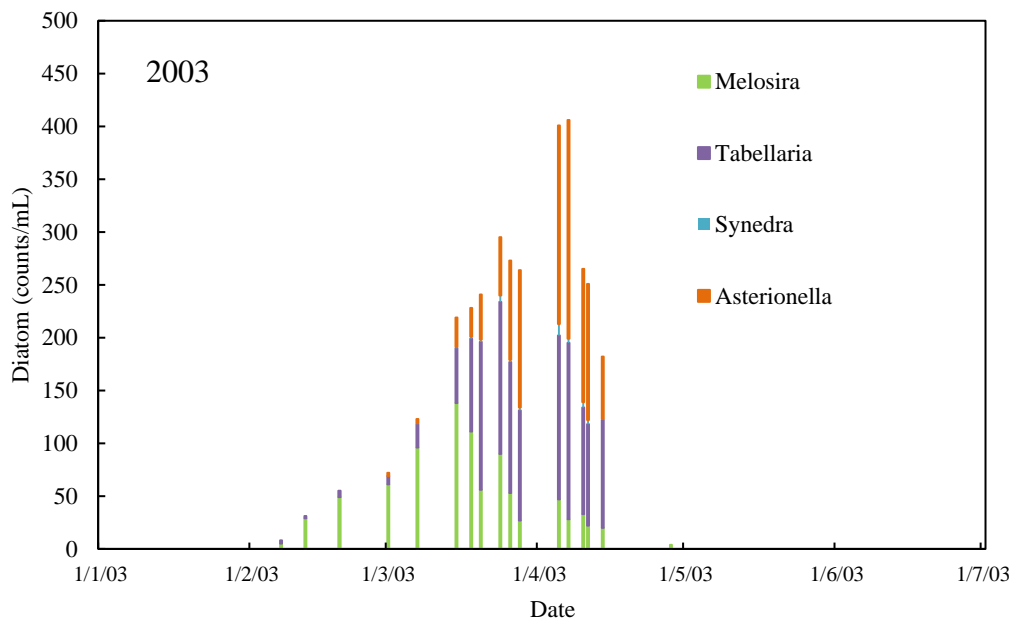


Figure 4.4 The growth of diatom in lower lake in 2003.

The change of diatom number in the lower lake in 2004 is presented in Figure 4.5.

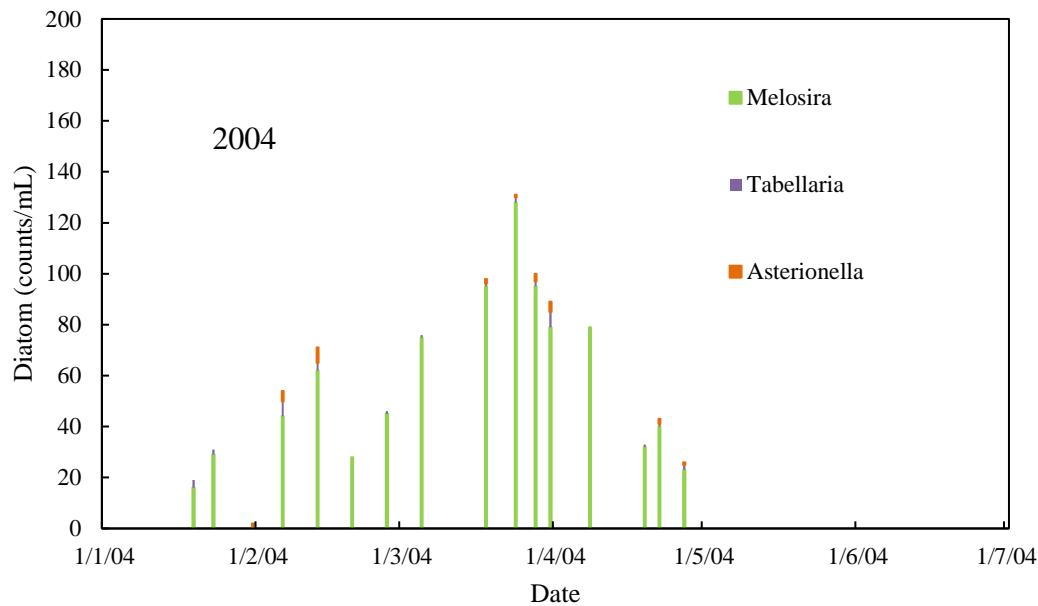


Figure 4.5 The growth of diatom in lower lake in 2004.

In 2004, the amount of diatom in Vartry reservoir remained at low number with the maximum concentration of 135 counts/mL on 24th March. The diatom species was *Melosira*, *Tabellaria* and *Asterionella*. The number of *Melosira* increased from 16 counts/mL on 19th January 2004 to 128 counts/mL on 24th March 2004. The values of *Tabellaria* and *Asterionella* was lower than 10 counts/mL during diatom bloom period.

The total diatom number in the lower lake in 2005 is shown in Figure 4.6. During diatom bloom period, the predominated species was *Melosira*. The total diatom number was 79 counts/mL on 2nd February 2005 and the highest concentration was 442 counts/mL on 25th February 2005. After that, the diatom number reduced to 75 counts/mL on 28th May 2005.

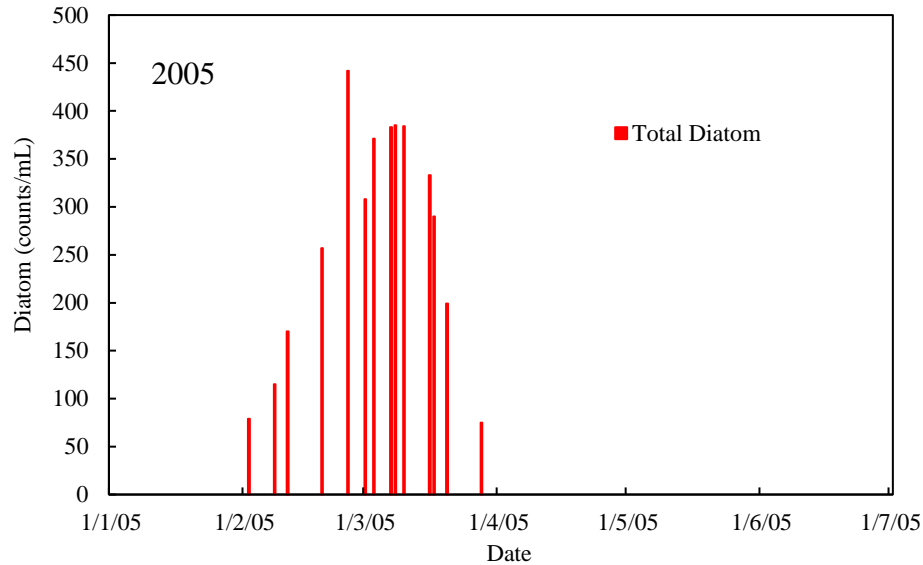


Figure 4.6 The growth of diatom in lower lake from 2002 to 2007.

In 2006, diatom bloom period was from 30th March to 26th May and the maximum diatom number was 828 counts/mL on 5th May (Figure 4.7). Compared with other years, diatom bloom occurred in 2006 was much later. *Synedra* was the major species during the whole diatom growth period. The number of *Synedra* increased from 8 counts/mL on 30th March to 791 counts/mL on 5th May and then decreased to 22 counts/mL. The number of *Melosira*, *Tabellaria* and *Asterionella* was lower than 40 counts/mL.

Diatom bloom in the lower lake in 2007 is shown in Figure 4.8. The amount of diatom raised from 30 counts/mL on 31st January to 498 counts/mL on 26th March and then the value reduced to 4 counts/mL on 27th April. *Asterionella* and *Melosira* were the major diatom species during diatom bloom period. The maximum number of *Asterionella* and *Melosira* was 401 counts/mL on 28th March and 157 counts/mL on 14th March, respectively. The concentration of *Tabellaria* was lower than 20 counts/mL.

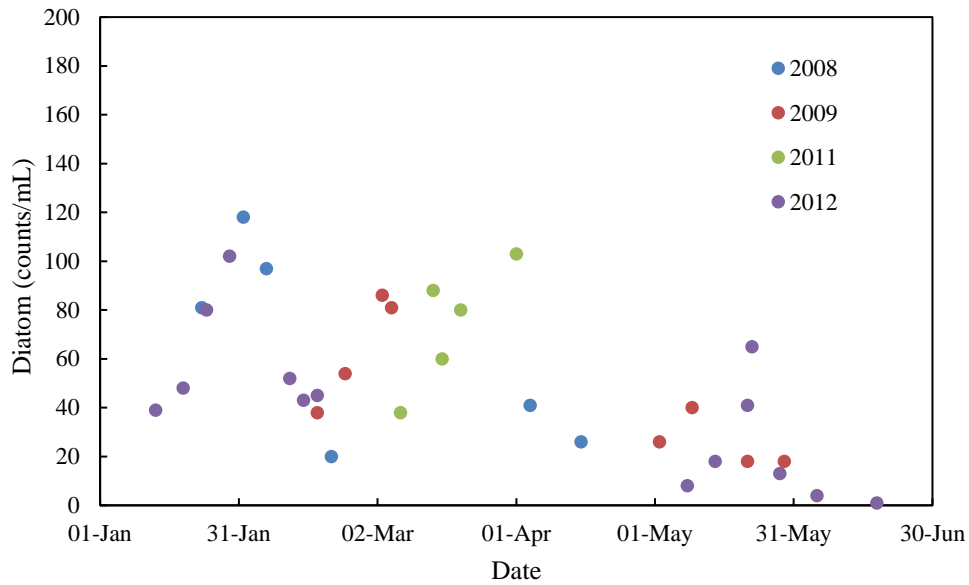


Figure 4.9 The diatom number in lower lake from 2008-2012.

4.1.2 *Asterionella* dominated diatom bloom in lower lake from 2013 to 2018

Diatom bloom in the lower lake from 2013 to 2018 is shown in Figure 4.10-Figure 4.15. Compared with the previous years, diatom bloom in 2013 was much more serious. Diatom bloom occurred from March to May and the highest number of total diatom was 2457 counts/mL on 19th April. *Melosira*, *Tabellaria*, *Asterionella*, *Synedra*, *Navicula* and *Diatoma* were observed during diatom bloom period. The numbers of *Melosira* and *Tabellaria* were lower than 100 counts/mL. The predominated species was *Asterionella* with the peaked amount of 1375 counts/mL on 19th April. The maximum number of *Synedra* and *Diatoma* was 550 counts/mL on 13th May and 515 counts/mL on 2nd May, respectively.

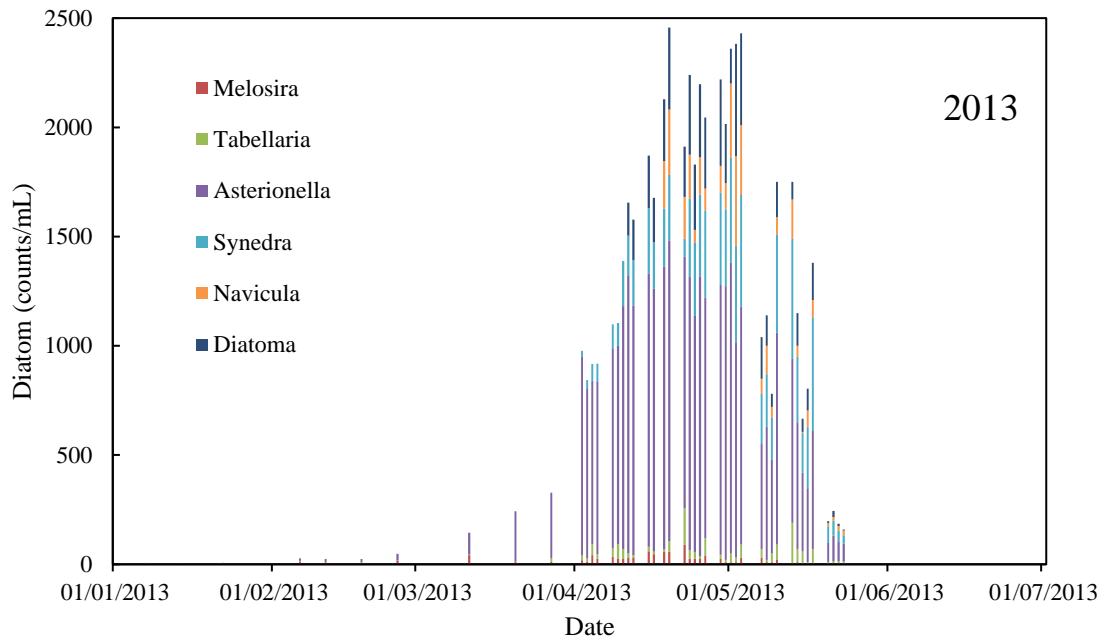


Figure 4.10 Diatom bloom in lower lake in 2013.

As shown in Figure 4.11, in 2014, *Melosira* was the major diatom species in January and February with the maximum *Melosira* number of 165 counts/mL on 17th February. In March and April, *Asterionella* was the dominate species and the number of diatoms increased significantly from 281 counts/mL on 18th March to 1754 counts/mL on 17th April. In April, the amount of *Navicula* remained around 200 counts/mL. Diatom bloom ended in June with a total diatom concentration of 58 counts/mL. During diatom bloom period, the number of *Tabellaria* was lower than 20 counts/mL and the amount of *Synedra* was less than 70 counts/mL.

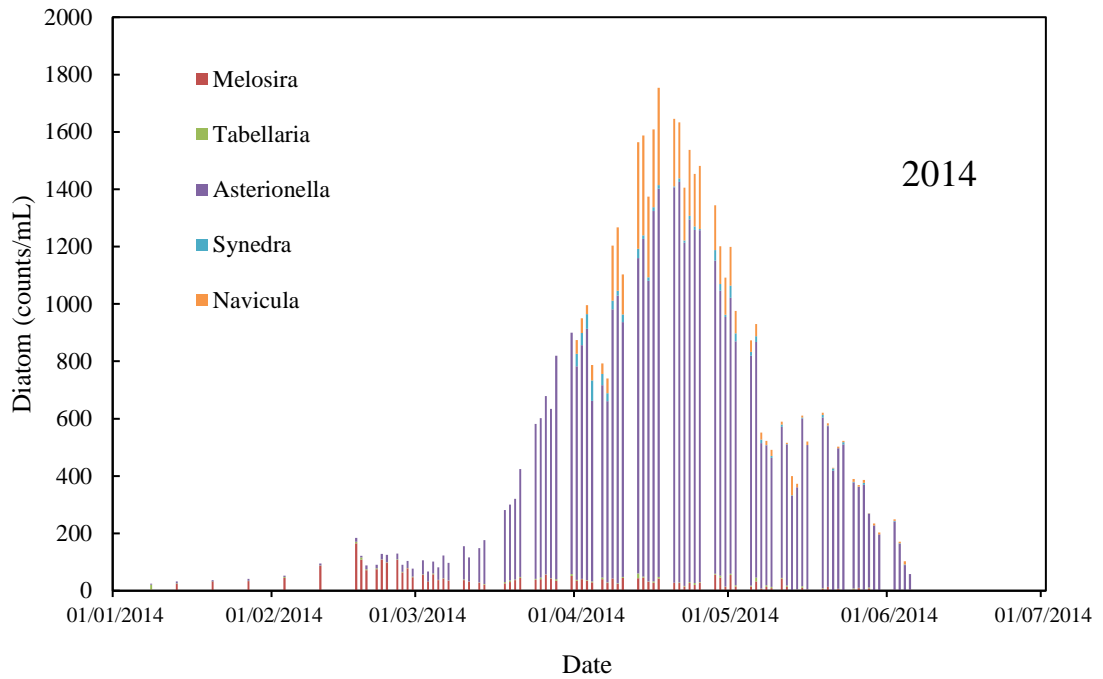


Figure 4.11 Diatom bloom in lower lake in 2014.

The growth of diatom in the lower lake in 2015 is presented in Figure 4.12. In January 2015, the number of *Melosira* was higher than other diatom species with the value of 159 counts/mL on 26th January. Diatom bloom period was from March to May and the maximum diatom number was 2054 counts/mL on 6th April. *Asterionella* and *Navicula* were the major diatom species with the peaked amount of 1674 counts/mL on 6th April and 736 counts/mL on 16th April. During the diatom growth period, the amount of *Tabellaria* and *Synedra* was less than 40 counts/mL.

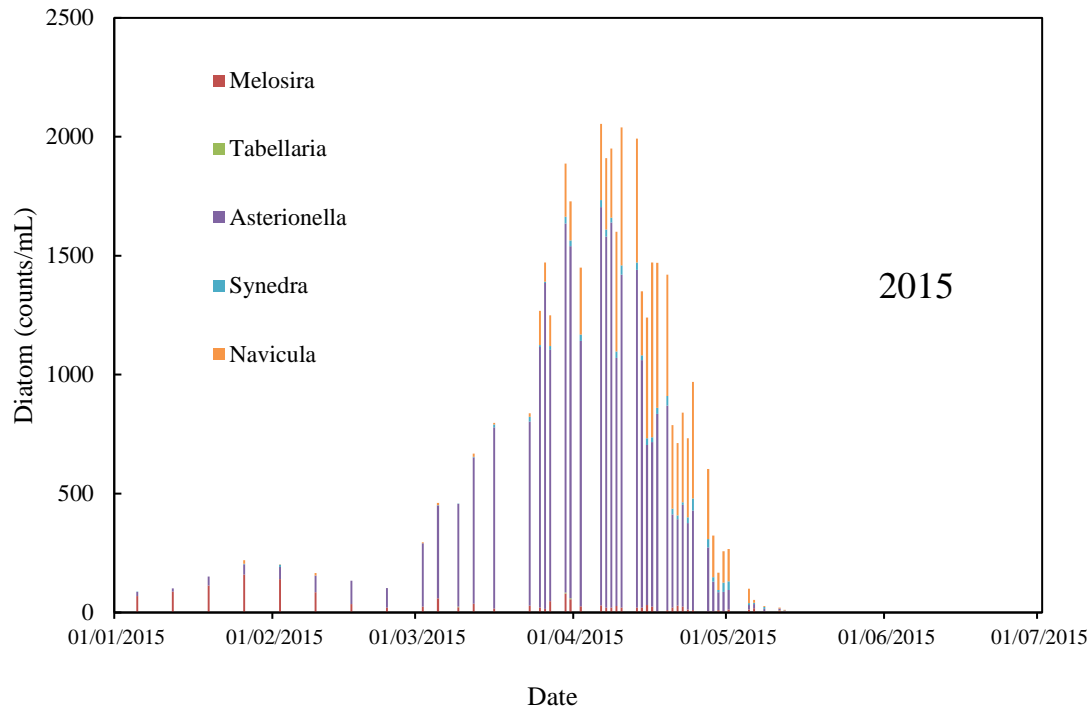


Figure 4.12 Diatom bloom in lower lake in 2015.

In 2016 (Figure 4.13), the highest diatom amount was 1878 counts/mL on 15th April with the *Asterionella* number of 1474 counts/mL. In addition to *Asterionella*, the number of *Navicula* was much higher than other species with the peaked concentration of 698 counts/mL on 3rd May. The diatom number reduced to 8 counts/mL on 23rd May. The maximum number of *Tabellaria* and *Synedra* was 164 counts/mL on 7th April and 116 counts/mL on 19th April. During diatom bloom period, the amount of *Melosira* remained lower than 50 counts/mL.

The change of diatom in lower lake in 2017 is shown in Figure 4.14 and *Asterionella* was the dominated species. The number of diatom in the reservoir increased very slowly from 20 counts/mL on 6th January to 124 counts/mL on 10th April. After that, the diatom concentration went up to the peaked number 821 counts/mL on 10th May. Diatom bloom finished at the end of May.

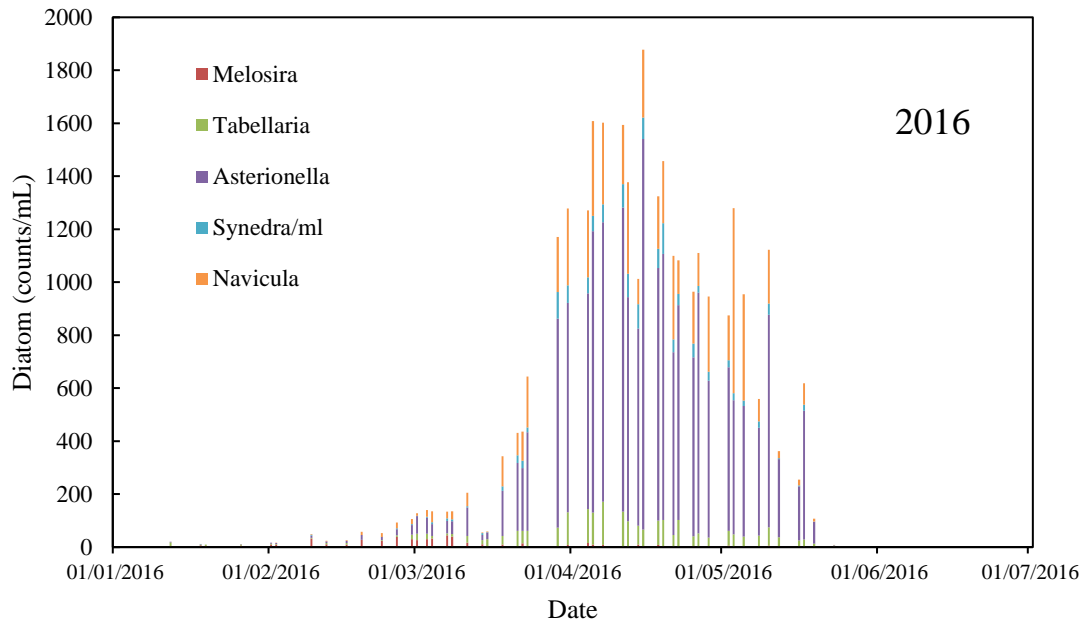


Figure 4.13 Diatom bloom in lower lake in 2016.

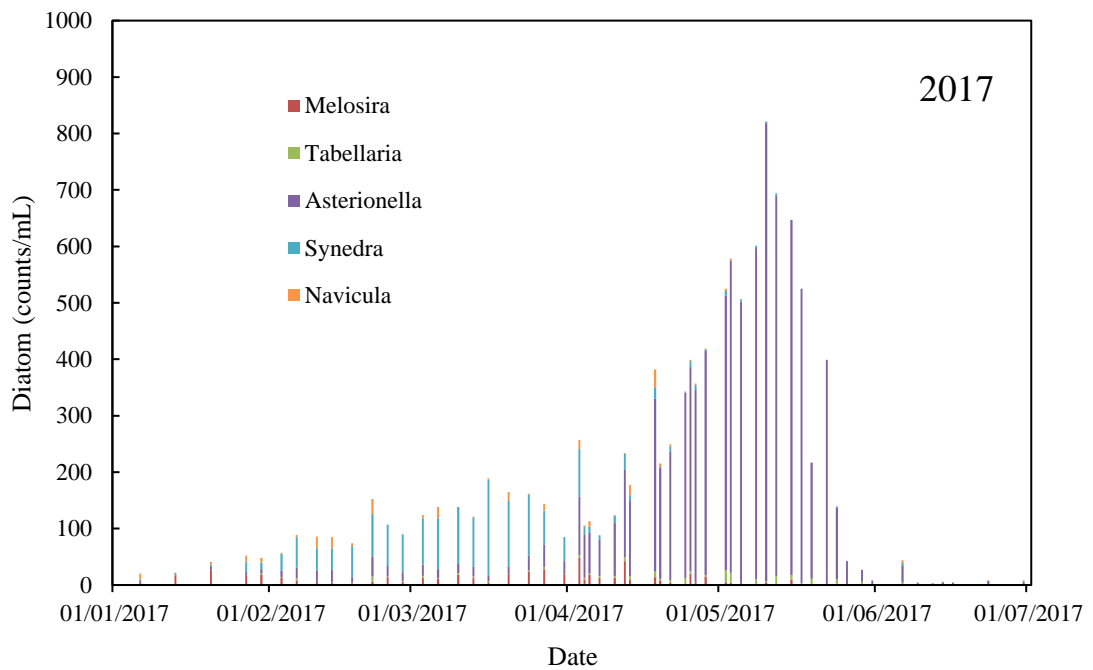


Figure 4.14 Diatom bloom in lower lake in 2017.

In 2018, diatom bloom period was from February to May (Figure 4.15) and the maximum number of diatom in the lower lake was 1120 counts/mL on 5th April 2018. In February, the number of *Melosira* was higher than *Asterionella*. The peaked amount of *Melosira* was 464 counts/mL on 26th February. Since March, *Asterionella* became the dominant diatom species and the highest number of *Asterionella* was 894 counts/mL on 9th April. The peaked number of *Synedra* was

recorded on 29th March with the values of 192 counts/mL. The number of *Navivula* and *Tabellaria* was low during diatom bloom period.

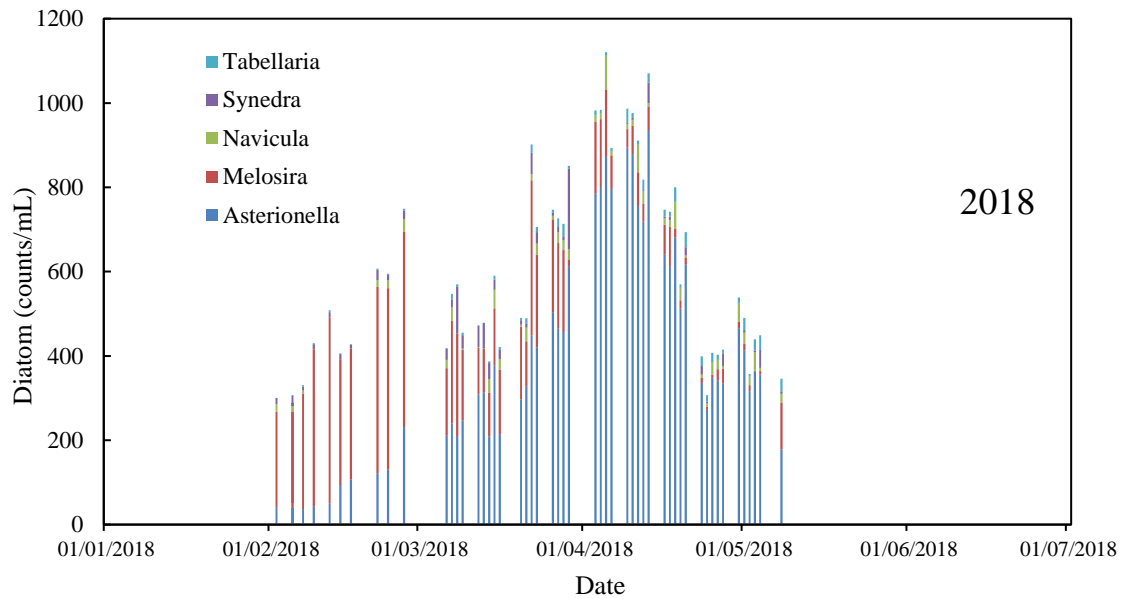


Figure 4.15 Diatom bloom in lower lake in 2018.

4.2 The spatial change of diatom growth

4.2.1 Diatom bloom in upper lake in 2017 and 2018

Since 2017, the diatom samples were also taken from the upper lake. The total diatom concentrations in the upper lake and lower lake in 2017 and 2018 were presented in Figure 4.16 and Figure 4.17.

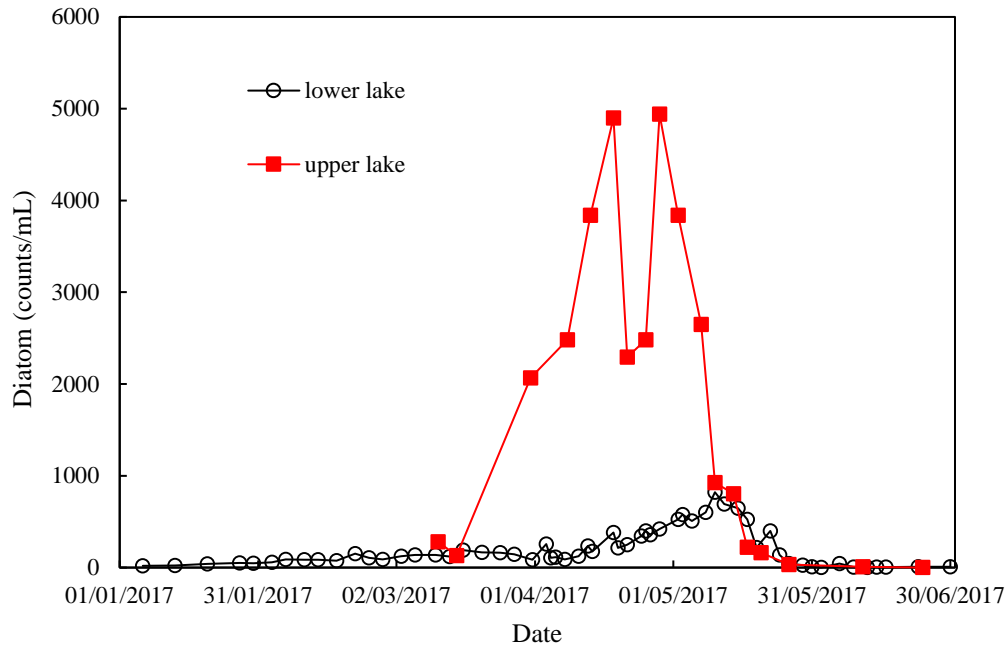


Figure 4.16 The growth of diatom in upper lake in 2017.

In 2017, *Asterionella* was the dominated species in the upper lake. Diatom bloom occurred from March to May. The diatom number increased from 132 counts/mL 15th March 2017 to 4900 counts/mL on 18th April 2017. The recorded maximum diatom concentration was 4940 counts/mL on 28th April 2017, which was higher than that the value of 821 counts/mL in the lower lake. After that, the number of diatom decreased to 223 counts/mL on 22nd May 2017.

In 2018, diatom bloom period was from February to May and the major species was *Asterionella*. In the upper lake, the number of diatom increased obviously from 106 counts/mL on 22nd February to the peaked amount of 1762 counts/mL on 11th April. Then a significant reduction of diatom number was observed. The peak diatom concentration was higher than the peak value of 1120 counts/mL in the lower lake.

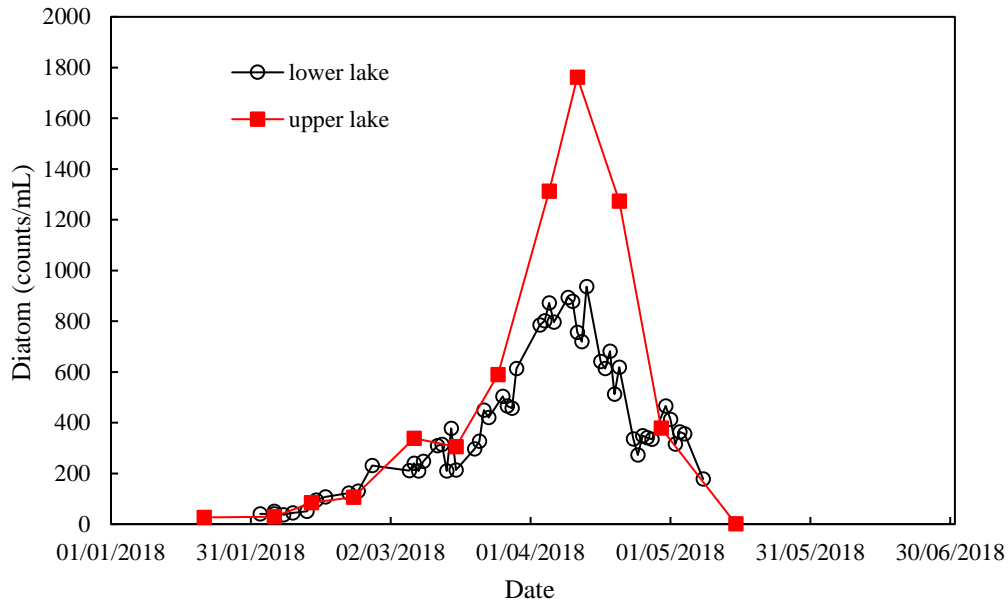


Figure 4.17 The growth of diatom in upper lake in 2018.

4.2.2 The Spatial change of diatom along Vartry Reservoir in 2017

In 2017, diatom samples were taken along the reservoirs from the upper lake to the lower lake and the sampling locations were shown in Figure 3.11. The change of diatom along the reservoir was presented in Figure 4.18. Diatom bloom in the upper lake was much more serious than the lower lake. The growth of diatom at Site 1 was not obvious with the maximum amount of 397 counts/mL on 7th May. The peaked number of diatom at Site 2 to Site 5 was 4288 counts/mL, 5030 counts/mL, 4828 counts/mL and 4940 counts/mL, respectively. In lower lake, the number of diatom in Site 6 and Site 7 was higher than that in the other part and the highest amount of diatom was 2434 counts/mL and 2049 counts/mL, respectively. The growth of diatom in Site 8, Site 9 and Site 10 was the same with the maximum concentration of 1251 counts/mL, 965 counts/mL and 978 counts/mL.

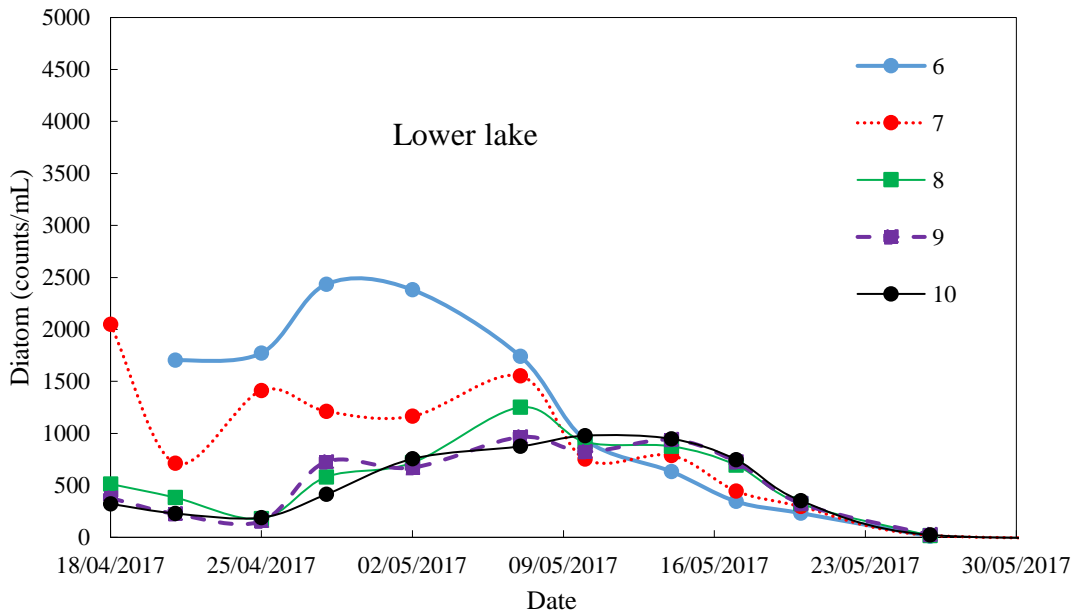
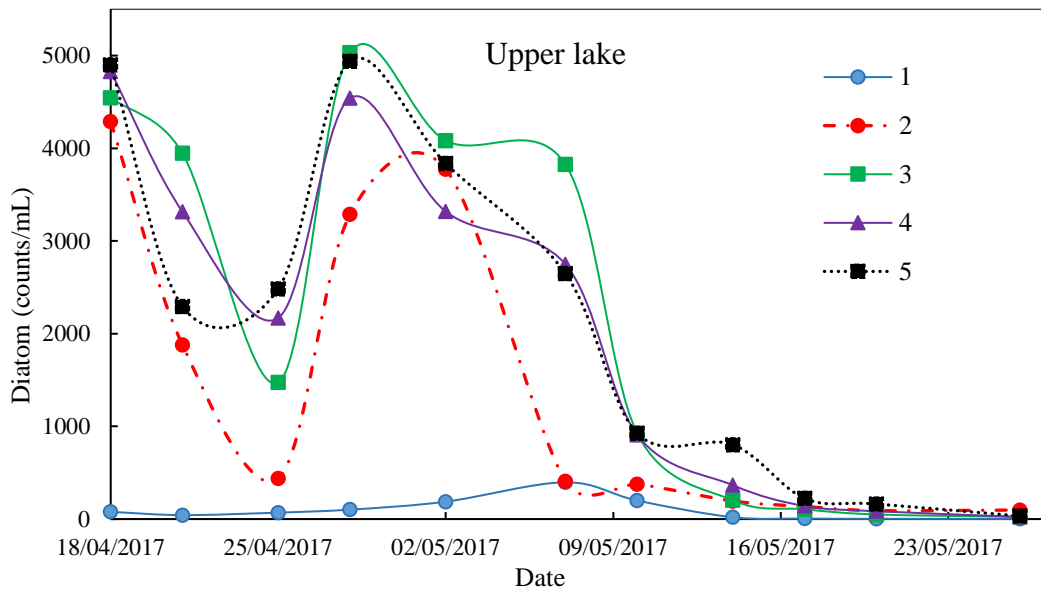


Figure 4.18 Spatial change of diatom number along with the longitudinal axis of Vartry Reservoir during April-Jun 2017 in the upper and lower lakes.

4.2.3 The growth of diatom in other lakes or reservoirs Ireland in 2018

The number of diatom in the sampling lakes or reservoirs is shown in Figure 4.19. No significant diatom bloom was observed in all sampling sites. The highest diatom number was 216 counts/mL with the dominated species of *Asterionella* in Ballyshannocy Lake. The diatom concentration in Lough Gill and Lough Corrib were 124 counts/mL and the major species was *Synedra*. The number of diatom in Brackley, Lough Ramor, Lough Ennell, Lough Acanon, Knockaderry and Liffey remained lower than 100 counts/mL. No diatom was observed in Lough Dan.

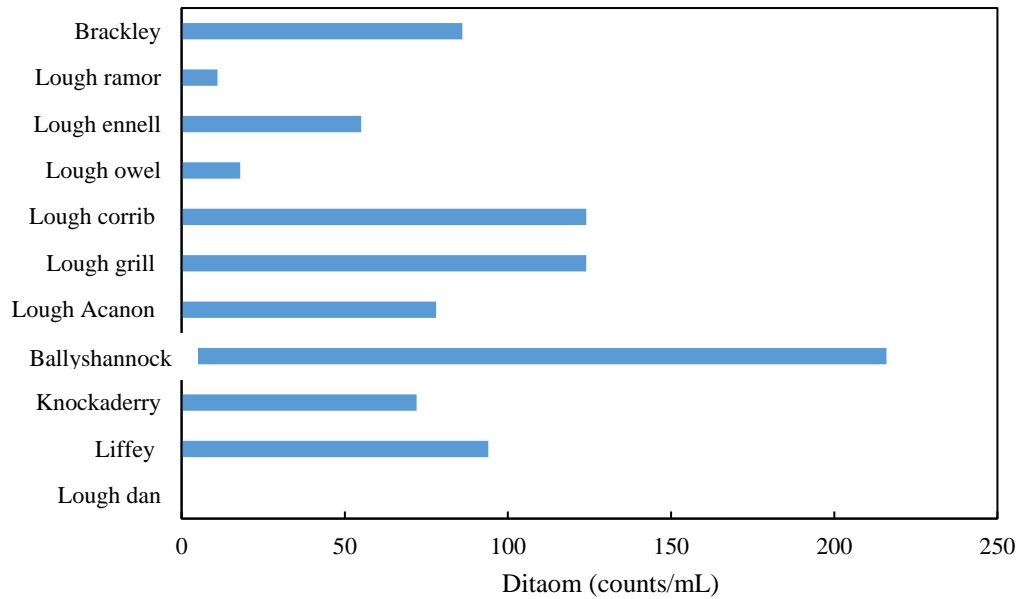


Figure 4.19 The number of diatom in the lakes or reservoir in April 2018.

4.3 Discussion

4.3.1 *The magnitude of diatom bloom in lower lake from 1996 to 2018*

The recorded annual maximum diatom algae concentrations in lower lake from 1996 to 2018 is presented in Figure 4.20. For the period 1996 to 2012, the annual maximum diatom concentrations had a decrease-increase cycle pattern. It decreased from 1107 counts/mL in 1996 to 270 counts/mL in 1999 and increased to 806 counts/mL in 2002, then decreased to 135 counts/ml in 2004 and increased to 828 counts/mL in 2006 and decreased again to 118 counts/mL in 2008, then kept in values of lower than 100 counts/mL until 2013. In 2013, 2014, 2015 and 2016, the annual maximum diatom algae concentrations were 2457 counts/mL, 1754 counts/mL, 2054 counts/mL and 1878 counts/mL, respectively, which were much higher than previous years (1996-2012).

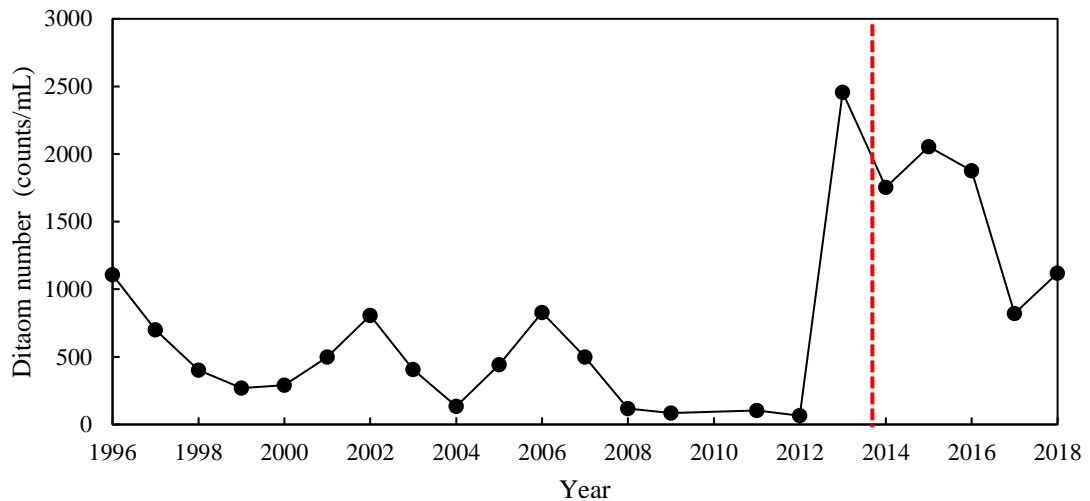


Figure 4.20 The recorded annual maximum diatom algae concentrations in lower lake 1996-2018.

4.3.2 The change of dominated diatom species in Vartry Reservoir

Table 4.1 shows the predominant diatom species in lower lake since 1996. The predominant diatom species includes *Asterionella*, *Melosira*, *Synedra* and *Tabellaria*.

Each year, the predominant diatom species always accounted for more than 50% of the total diatom counts. Over the period, *Asterionella*, *Melosira*, *Synedra* and *Tabellaria* dominated the diatom assemblages for 12 years, 7 years, 1 year and 1 year, respectively. *Asterionella* has become the predominant diatom species since 2012 and is the main contributor to the diatom algae bloom. Therefore, studying the *Asterionella* is critical for understanding and control of diatom bloom in Vartry Reservoir.

Asterionella was also the major diatom species in the upper lake of Vartry Reservoir. Diatom bloom in the upper lake was much more serious than that in the lower lake in 2017 and 2018. During diatom bloom in 2017, a small part of upper lake was characterized with no diatom bloom. In other lakes or reservoir Ireland, no diatom bloom was observed in 2018.

Table 4.1 The annual maximum diatom concentration and predominant diatom species in lower lake since 1996.

Year	Annual maximum diatom concentration (counts/mL)	Date	Predominant diatom species	Peak predominant species concentration (counts/mL)
1996	1107	2/5/1996	<i>Asterionella</i>	801
1997	701	Feb-97	<i>Melosira</i>	638
1998	403	Mar-98	<i>Asterionella</i>	187
1999	270	Feb-99	<i>Melosira</i>	208
2000	291	Feb-00	<i>Melosira</i>	174
2001	499	Mar-01	<i>Asterionella</i>	284
2002	806	18/03/2002	<i>Tabellaria</i>	432
2003	406	07/04/2003	<i>Asterionella</i>	207
2004	135	24/03/2004	<i>Melosira</i>	128
2005	442	25/02/2005	<i>Melosira</i>	
2006	828	05/05/2006	<i>Synedra</i>	791
2007	498	25/03/2007	<i>Asterionella</i>	401
2008	118	01/02/2008		
2009	86	03/03/2009	<i>Melosira</i>	78
2011	103	01/04/2011	<i>Melosira</i>	53
2012	102	29/1/2012	<i>Asterionella</i>	72
2013	2457	19/4/2013	<i>Asterionella</i>	1375
2014	1754	17/4/2014	<i>Asterionella</i>	1397
2015	2054	6/4/2015	<i>Asterionella</i>	1674
2016	1878	15/4/2016	<i>Asterionella</i>	1474
2017	821	10/5/2017	<i>Asterionella</i>	811
2018	1120	5/4/2018	<i>Asterionella</i>	902

Chapter 5

Nutrient concentrations

5 Nutrient concentrations

Nutrient is the precondition for the growth of diatom and diatom bloom can be limited with low nutrient concentrations. Therefore, assessing the nutrient entering Vartry Reservoir and within the Reservoir is critical for diatom algae bloom control.

5.1 Feeding rivers of Vartry Reservoir

5.1.1 Long term monitoring of nutrient concentrations in the feeding rivers

The concentrations of SRP, SiO₂, TON and TOC in the ten feeding rivers were measured between 2015 to 2018 and are shown in Figures 5.1-5.4.

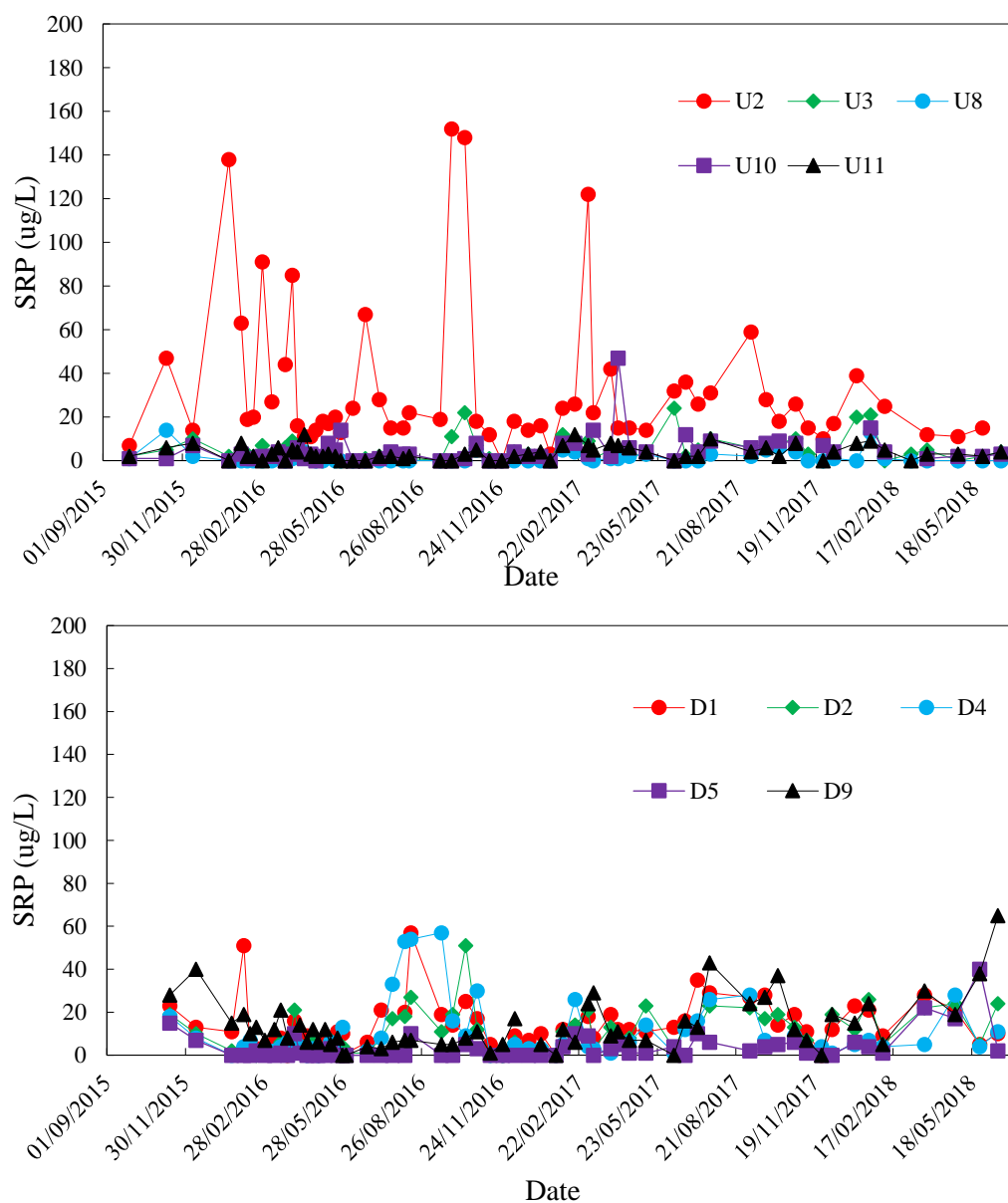


Figure 5.1 Concentration of SRP in the feeding rivers.

The change of SRP concentration in the feeding rivers is presented in Figure 5.1. In the three years studied period, no annual change of SRP concentrations was observed. The SRP concentration of U2 fluctuated between 1 and 152 $\mu\text{g/L}$, with an average concentration of 33 $\mu\text{g/L}$ which was much higher than other feeding rivers. The maximum recorded SRP concentrations in U3, U10 and U11 were 24 $\mu\text{g/L}$, 47 $\mu\text{g/L}$ and 14 $\mu\text{g/L}$, respectively, with the average concentrations of 6 $\mu\text{g/L}$, 6 $\mu\text{g/L}$ and 5 $\mu\text{g/L}$. The concentration of SRP in U8 remained at a low level with an average concentration of 1 $\mu\text{g/L}$.

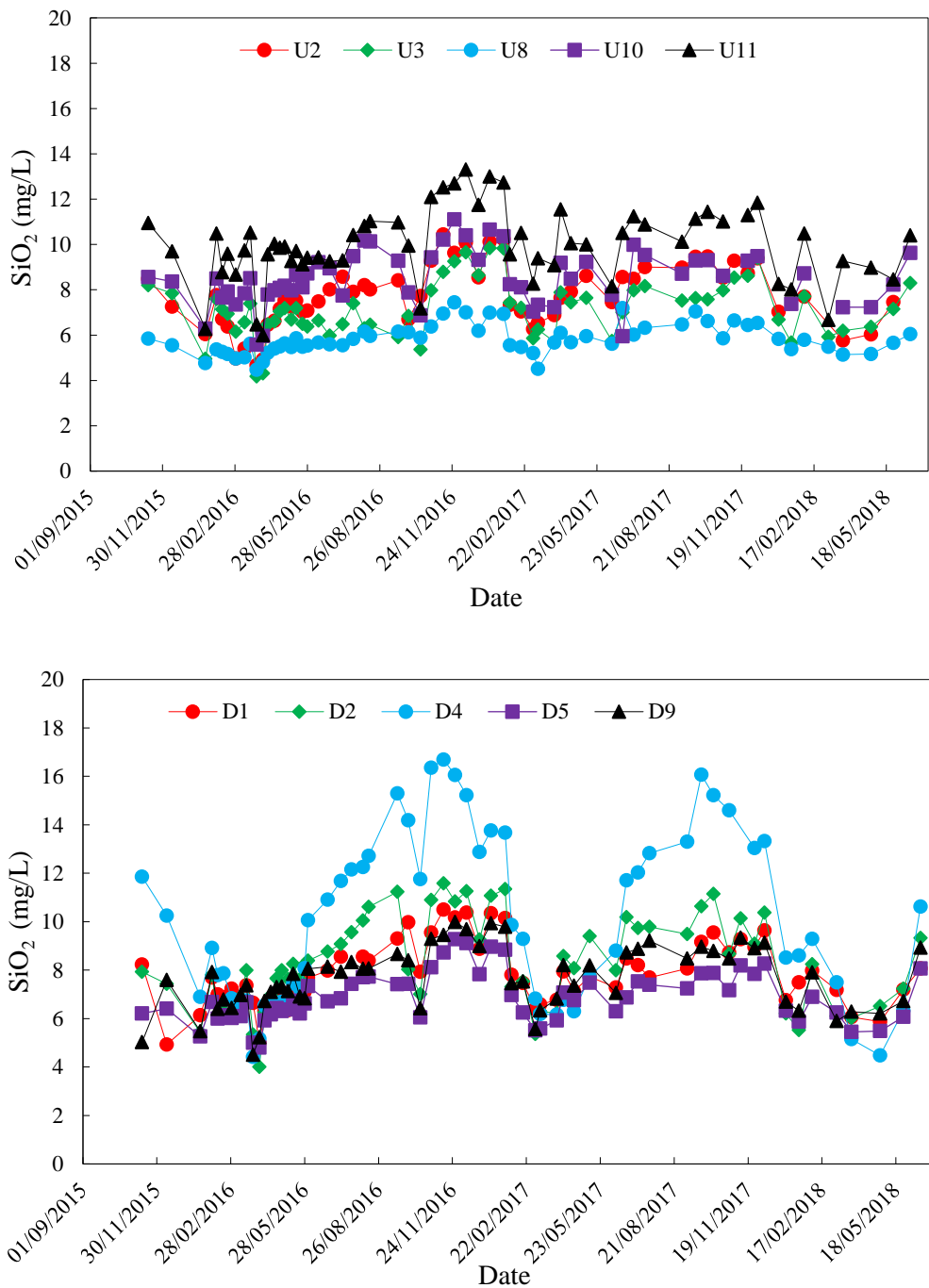


Figure 5.2 Concentration of SiO₂ in the feeding rivers.

Except for U2, the concentrations of SRP in the feeding rivers for the upper lake, in general, were lower than that in the lower lake. The highest SRP concentrations in D1, D2, D4, D5 and D9 were 57 µg/L, 51 µg/L, 57 µg/L, 40 µg/L and 65 µg/L, respectively, with the average concentration of 14 µg/L, 11 µg/L, 11 µg/L, 4 µg/L and 15 µg/L.

The silica concentrations in the feeding rivers are shown in Figure 5.2. In the feeding rivers for upper lake, the concentrations of silica in U2, U3, U8, U10 and U11 varied between 4.7-10.4 mg/L, 4.2-9.8 mg/L, 4.5-7.4 mg/L, 5.6-11.1 mg/L and 6.0-13.3 mg/L, respectively, with the average concentrations of 7.7 (± 2.6) mg/L, 7.1 (± 2.1) mg/L, 5.8 (± 1.2) mg/L, 8.5 (± 2.9) mg/L and 10.0 (± 3.1) mg/L, respectively.

The average silica concentrations in D1, D2, D4, D5 and D9 were 7.8 (± 1.3) mg/L, 8.3 (± 1.9) mg/L, 10.0 (± 3.5) mg/L, 6.9 (± 2.1) mg/L and 7.6 (± 1.3) mg/L, respectively. The fluctuation of silica concentrations in D4 was significant with the range of 4.4 mg/L-16.7 mg/L, with the annual minimum concentrations achieved in March or April. In 2016 and 2017, the annual maximum silica concentrations in D4 were 16.7 mg/L in November 2016 and 16.1 mg/L in September 2017, respectively. The silica concentrations in D1 and D2 were with the range of 4.93-10.49 mg/L and 4.01-11.58 mg/L, respectively. The silica concentrations in D5 were slightly lower than other feeding rivers.

The nitrogen concentrations in the feeding rivers are shown in Figure 5.3. In the upper lake catchment area, the average TN concentrations were 2.96 (± 0.98) mg/L, 1.44 (± 0.36) mg/L, 1.19 (± 0.24) mg/L, 1.60 (± 0.35) mg/L and 1.44 (± 0.34) mg/L in U2, U3, U8, U10 and U11, respectively. U2 had higher TN concentrations than other feeding rivers, with a range between 0.66-4.47 mg/L. The highest and lowest nitrogen concentrations in U3, U10 and U11 were 2.22 mg/L, 2.57 mg/L, 2.24 mg/L and 0.52 mg/L, 0.72 mg/L, 0.53 mg/L, respectively. In U8, the nitrogen concentration was the lowest.

In the lower lake catchment area, the average TN concentrations were 2.33 (± 0.77) mg/L, 1.96 (± 0.58) mg/L, 2.71 (± 0.98) mg/L, 1.26 (± 0.30) mg/L and 2.43 (± 0.91) mg/L in D1, D2, D4, D5 and D9, respectively. The change of nitrogen in D4 and D9 was evident in the range of 0.64-5.36 mg/L and 0.47-5.13 mg/L, respectively. In D1 and D2, the maximum concentrations were 4.27 mg/L and 3.16 mg/L, respectively. Compared with other feeding rivers for the lower lake, D5 had the lowest TN concentrations.

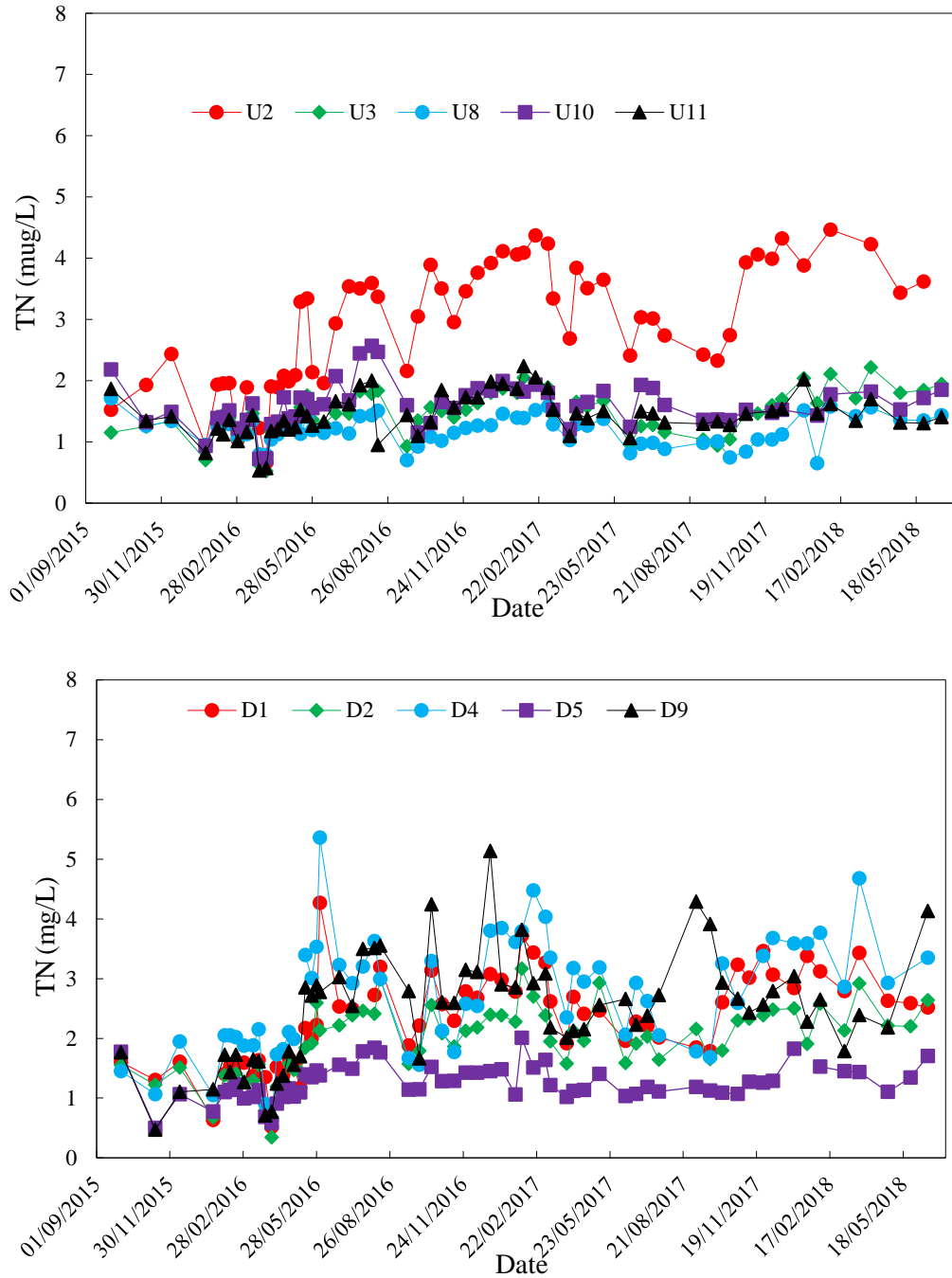


Figure 5.3 Concentration of nitrogen in the feeding rivers.

The concentration of TOC in the feeding rivers from 2016 to 2018 are shown in Figure 5.4. In U2, U3, U10 and U11, the TOC concentrations ranged between 2.04-8.66 mg/L, 1.29-8.34 mg/L, 1.19-5.92 mg/L and 1.47-7.05 mg/L, respectively, with the average concentrations of 4.12 (± 1.66) mg/L, 3.44 (± 1.55) mg/L, 2.76 (± 0.21) mg/L and 2.98 (± 1.43) mg/L. The average TOC concentrations in U8 were lower than other feeding rivers with an average value of 1.42 (± 0.85) mg/L. The fluctuation of TOC concentrations in the feeding rivers for the lower lake was significant. In D4, the concentrations of TOC changed between 2.93 mg/L and 9.91 mg/L and the

average concentration was $5.83 (\pm 0.193)$ mg/L which was higher than other feeding rivers for the lower lake. The TOC concentrations in D1, D2 and D9 ranged between 2.07-9.51 mg/L, 2.56-8.68 mg/L, 1.83-8.52 mg/L and the average TOC concentrations were $4.38 (\pm 1.47)$ mg/L, $4.54 (\pm 1.42)$ mg/L and $3.76 (\pm 1.57)$ mg/L, respectively. Compared with other rivers, the concentrations of TOC in D5 were slightly lower with the average number of $2.35 (\pm 1.16)$ mg/L.

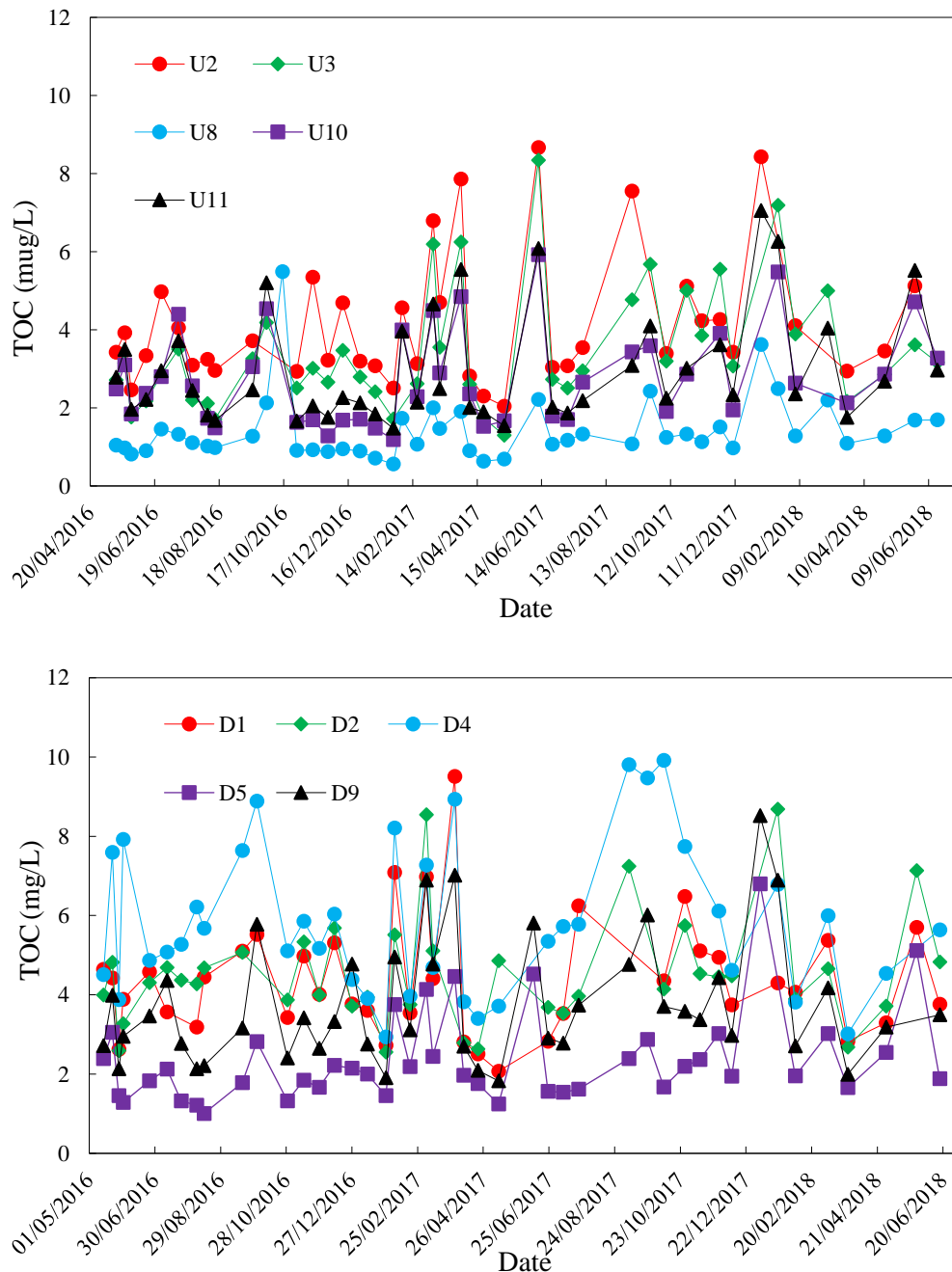


Figure 5.4 Concentration of total organic carbon in the feeding rivers.

5.1.2 24-hour monitoring of U3 and D5

The change of nutrient concentration in U3 and D5 within 24 hours is shown in Figure 5.5. The silica concentration in U3 and D5 was 7.2 mg/L and 5.5 mg/L and the nitrogen concentration was 1.8 mg/L and 0.8 mg/L. The silica and nitrogen concentration were almost the same during the full day. The concentration of PO₄-P in U3 and D5 fluctuated between 0-3 ug/L and 0-4 ug/L.

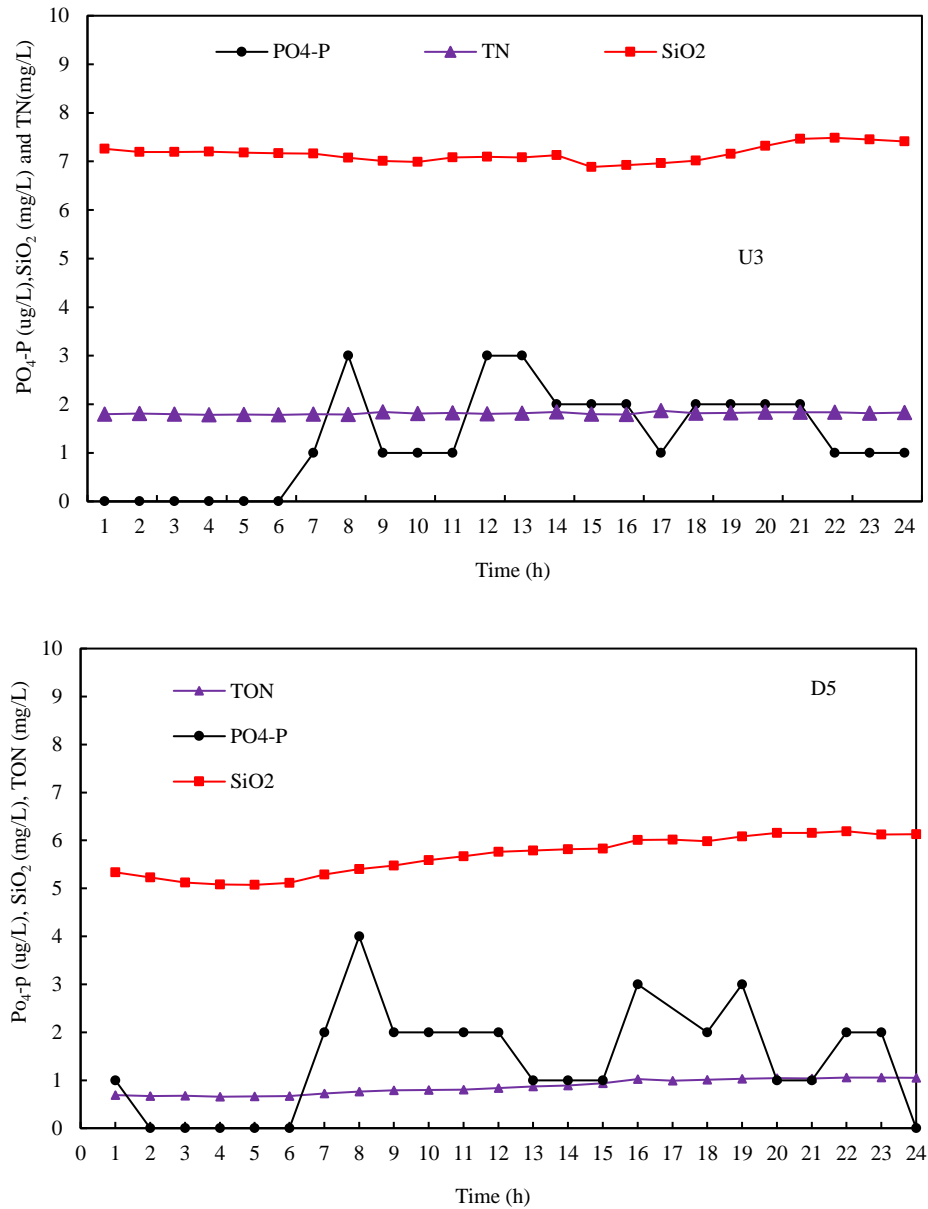


Figure 5.5 The concentration of nutrient in U3 and D5 within 24 hours.

5.2 The nutrient concentrations in boreholes

Water samples were taken from four boreholes from February 2017 to April 2018 and the location of the boreholes are shown in Figure 3.8. The nutrient concentrations in the boreholes are shown in Figure 5.6-5.8.

The concentrations of SRP in W-1, W-2, W-3 and W-4 were 1-13 $\mu\text{g/L}$, 1-7 $\mu\text{g/L}$, 1-15 $\mu\text{g/L}$, 1-6 $\mu\text{g/L}$ with the average concentration of 3 $\mu\text{g/L}$, 3 $\mu\text{g/L}$, 3 $\mu\text{g/L}$ and 2 $\mu\text{g/L}$, respectively.

The TN concentrations are shown in Figure 5.6. The TN in W-1 and W-3 were higher than that in W-2 and W-4 with an average concentration of 1.64 mg/L and 1.45 mg/L. The average TN concentrations in W-2 and W-4 were 0.90 mg/L and 0.75 mg/L, respectively. The major form of nitrogen of the groundwater was nitrate. The average concentration of $\text{NH}_4\text{-N}$ was 17 $\mu\text{g/L}$, 44 $\mu\text{g/L}$, 17 $\mu\text{g/L}$ and 34 $\mu\text{g/L}$ in the W1-4, respectively.

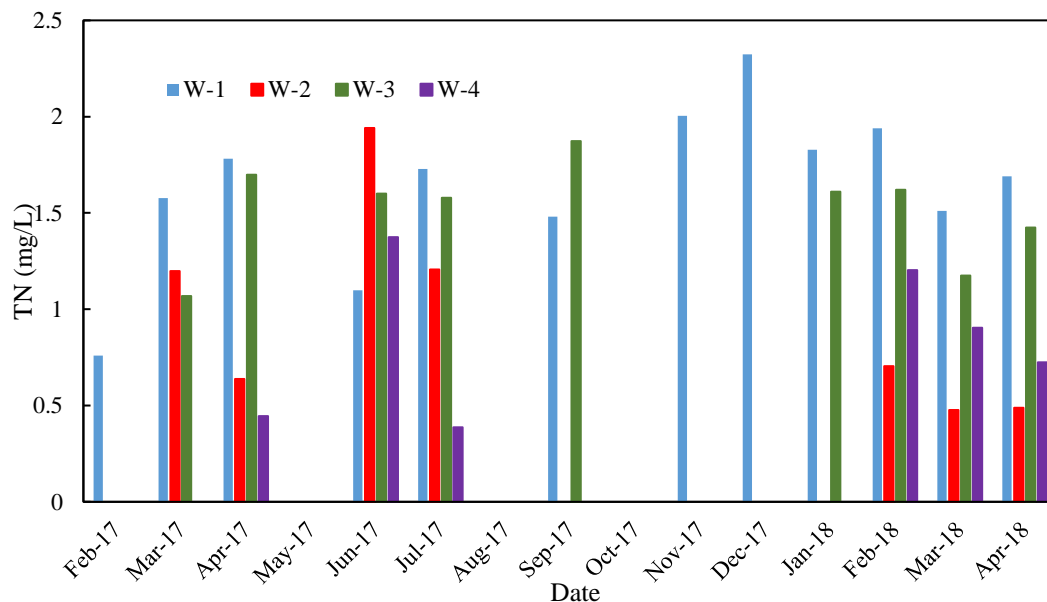


Figure 5.6 TN concentrations in the boreholes.

The silica concentrations in the boreholes are shown in Figure 5.7. The average SiO_2 concentrations in W-1 and W-3 were 5.66 mg/L and 5.57 mg/L, respectively, which were much higher than that in W-2 and W-4 (3.15 mg/L and 3.21 mg/L).

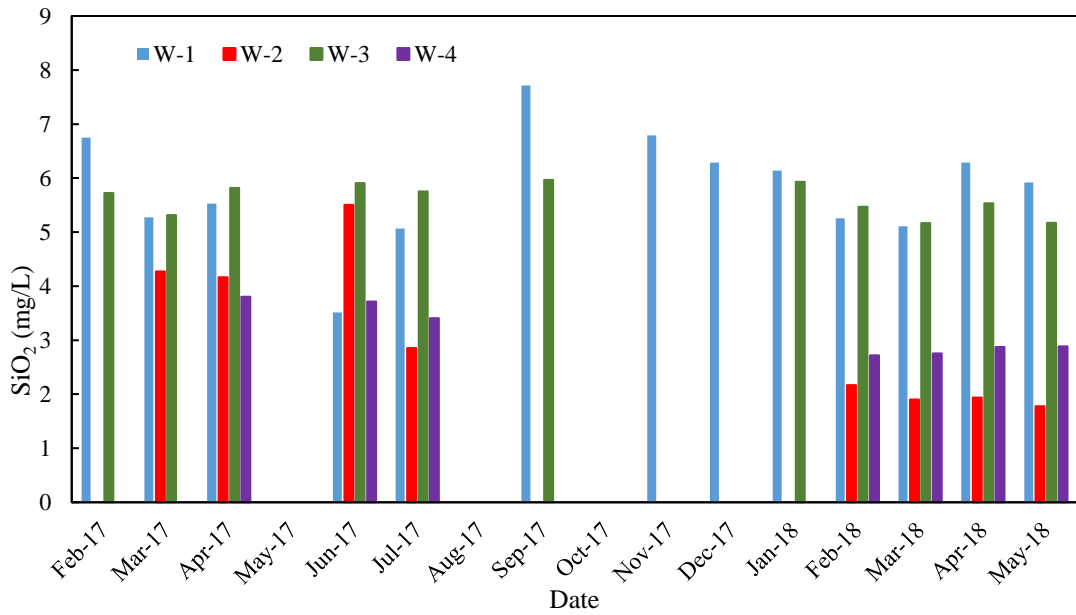


Figure 5.7 Silica concentration in the boreholes.

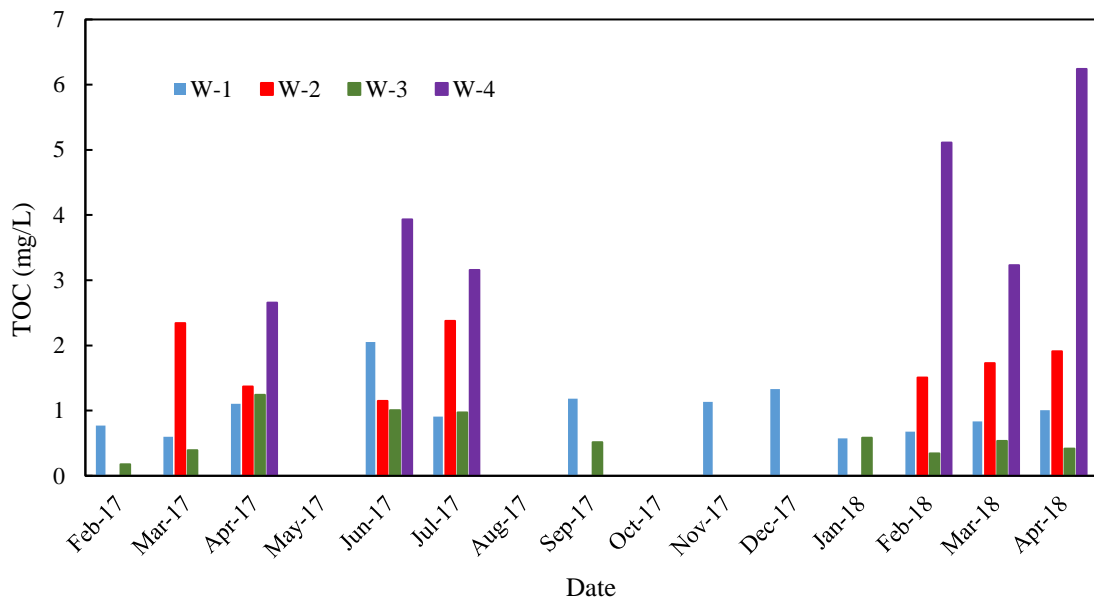


Figure 5.8 TOC concentrations in the boreholes.

Figure 5.8 shows the TOC concentrations in the boreholes. The TOC concentration in W-4 was much higher than the other boreholes and the average concentration was 3.71 mg/L. The average concentrations in W-1, W-2 and W-3 were 1.79 mg/L, 0.95 mg/L and 0.65 mg/L, respectively.

5.3 Nutrient concentrations in Vartry Reservoir

5.3.1 Long term monitoring of nutrient concentrations in Vartry Reservoir

The concentrations of SRP in the lower lake and upper lake from 2016 to 2018 are shown in Figure 5.9 and Figure 5.10.

In Vartry Reservoir, the SRP concentrations fluctuated significantly with the range of 0-9 $\mu\text{g/L}$ in lower lake and 0-12 $\mu\text{g/L}$ in the upper lake. Generally, the peak SRP concentration appeared before diatom bloom every year. The average SRP concentrations before diatom bloom in the lower lake were 1.76 $\mu\text{g/L}$ in 2016, 3.00 $\mu\text{g/L}$ in 2017 and lower than 1 $\mu\text{g/L}$ in 2018. This values in the upper lake were 1.15 $\mu\text{g/L}$, 3.58 $\mu\text{g/L}$ and 1.18 $\mu\text{g/L}$ in 2016, 2017 and 2018, respectively. In the lower lake, the highest SRP concentrations in 2016, 2017 and 2018 were 7 $\mu\text{g/L}$, 9 $\mu\text{g/L}$ and 1 $\mu\text{g/L}$, respectively. The maximum SRP concentrations for the upper lake from 2016 to 2018 was 4 $\mu\text{g/L}$, 12 $\mu\text{g/L}$ and 4 $\mu\text{g/L}$. In 2017 and 2018, the SRP in the upper lake was higher than that in the lower lake. However, the average and maximum concentration of SRP in 2016 in the lower lake was higher than the upper lake.

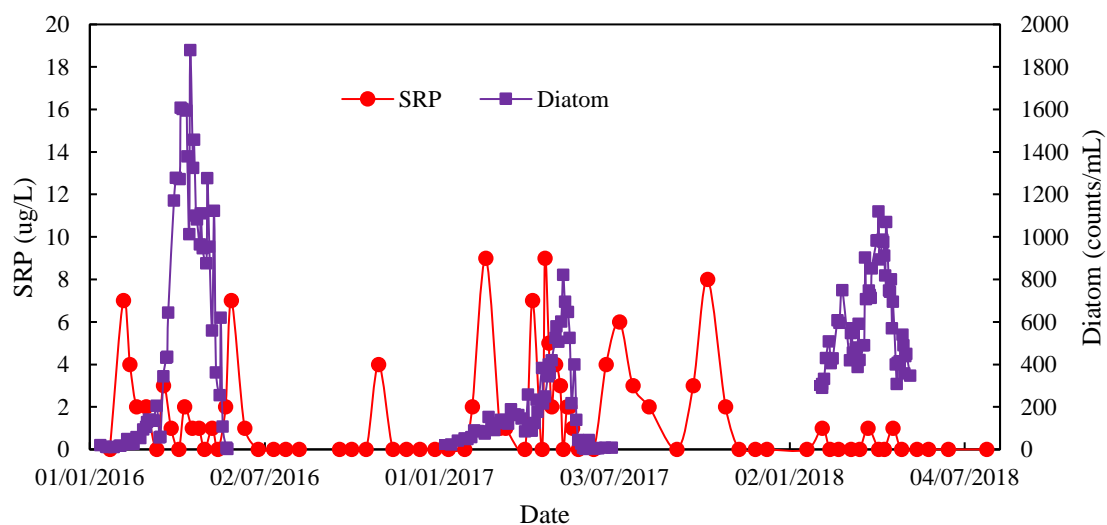


Figure 5.9 SRP concentrations in lower lake from 2016 to 2018.

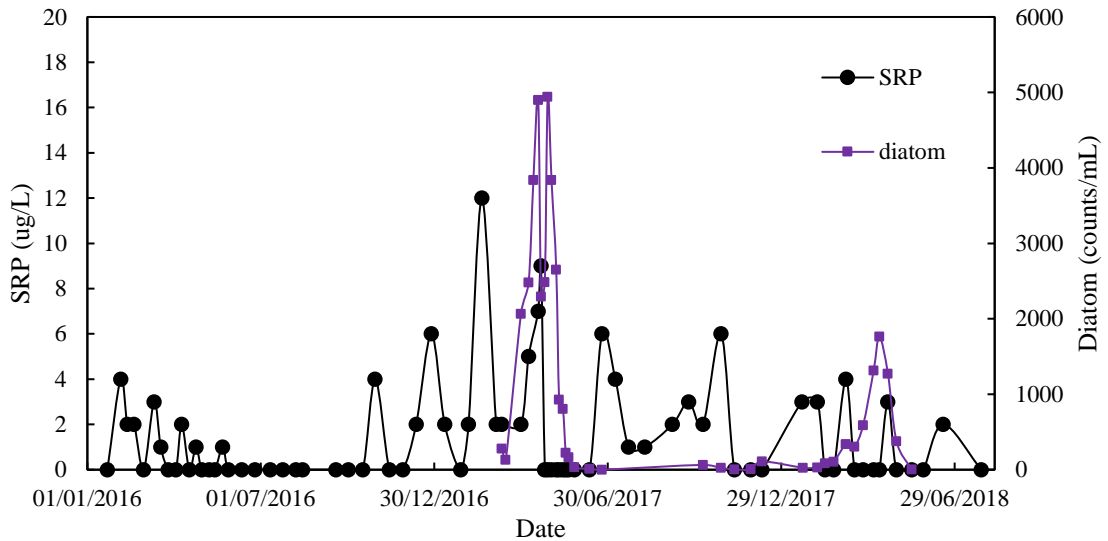


Figure 5.10 SRP concentrations in upper lake from 2016 to 2018.

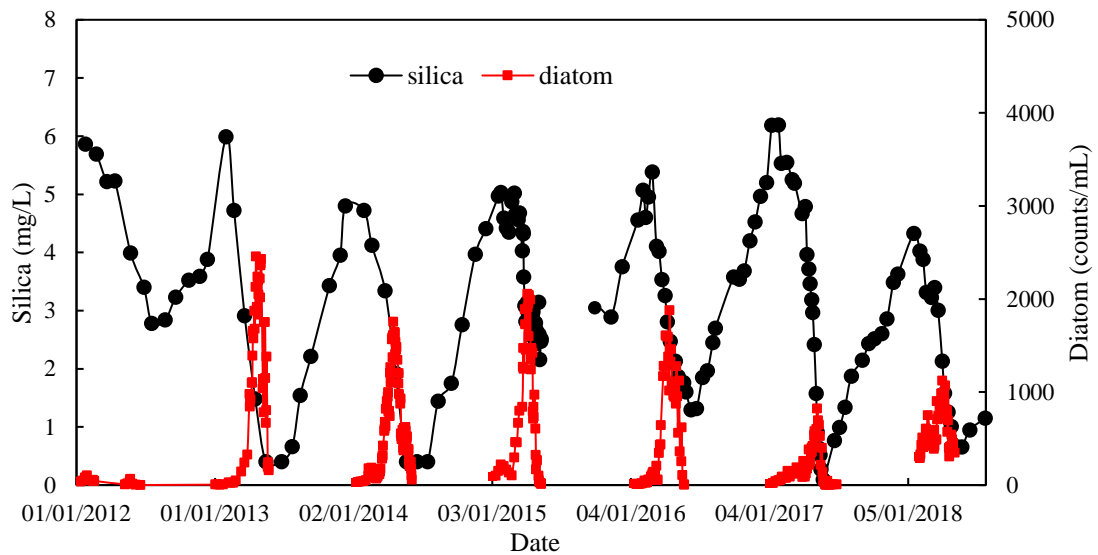


Figure 5.11 Silica concentrations in the lower lake from 2012 to 2018.

As shown in Figure 5.11, the silica concentrations started to decrease when diatom bloom started. It reduced to the annual minimum values when diatom bloom completed. The silica concentrations then increased continuously until the next diatom bloom period. In 2012, the silica concentration decreased in the spring in the lower lake, though no significant diatom bloom was recorded. In the lower lake, in 2013, 2014, 2015, 2016, 2017 and 2018, the annual maximum silica concentrations were 5.99 mg/L, 4.80 mg/L, 5.03 mg/L, 5.38 mg/L, 6.19 mg/L and 4.32 mg/L, and the annual minimum silica concentrations were <0.40 mg/L, <0.40 mg/L, 2.16 mg/L, 1.31 mg/L, 0.11 mg/L and 0.65 mg/L, respectively. The change of silica concentrations in the upper lake were similar to those in the lower lake.

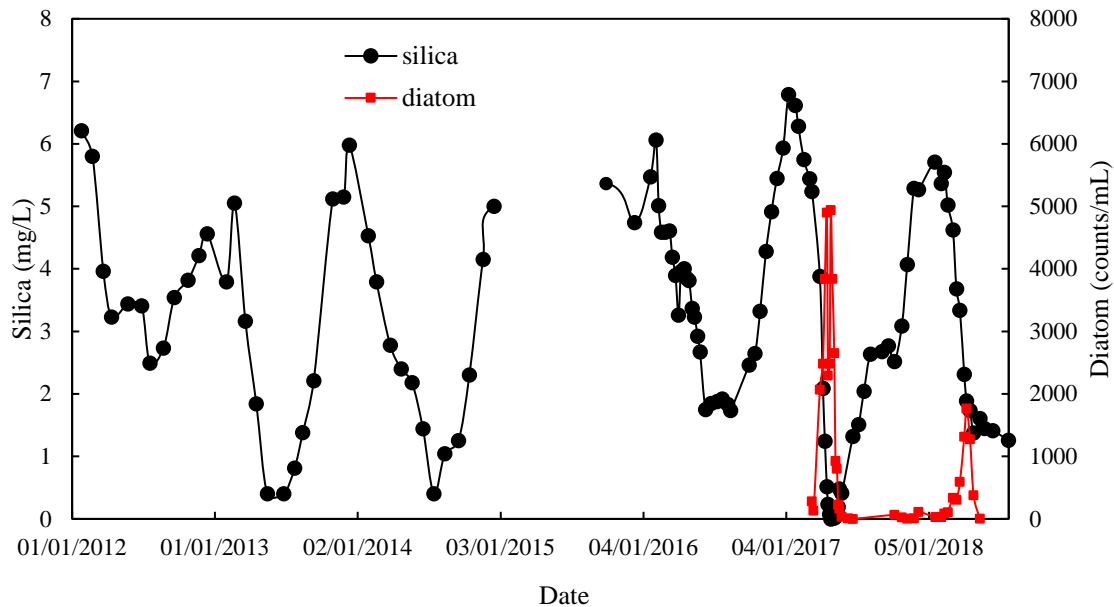


Figure 5.12 Silica concentrations in the upper lake from 2012 to 2018.

Figure 5.12 shows the silica concentrations in the upper lake from 2012 to 2018. In 2012, the concentration of silica decreased from 6.21 mg/L in January 2012 to 2.49 mg/L in July 2012. The maximum silica concentration in 2013 and 2014 was 5.05 mg/L and 5.98 mg/L respectively and the minimum silica concentration in 2013 and 2014 was less than 0.4 mg/L. The peaked silica concentration was 6.06 mg/L on 5th February 2016. Since then, the concentration of silica decreased continually to 1.74 mg/L on 11th Jun 2016. It increased significantly until the beginning of next diatom bloom. In 2017, the maximum silica concentration in the upper lake was 6.79 mg/L on 10th January 2017 and the silica reduced gently to 5.23 mg/L on 11th March 2017 with the diatom number of 280 counts/mL. Then it decreased dramatically to below than 0.1 mg/L and the diatom amount reached the annual maximum value at the end of April 2017. The highest silica concentration in 2018 was 5.70 mg/L on 20th January 2018. The concentration of silica reduced to 1.88 mg/L with the peaked diatom number of 1762 counts/mL. The lowest silica concentration was 1.38 mg/L on 29th April 2018.

The Dissolved Inorganic Nitrogen (DIN) concentrations and the diatom concentrations in the lower lake and upper lake are shown in Figure 5.13 and Figure 5.14, respectively. In general, the nitrogen concentration peaked at the beginning of diatom growth and then decreased to the lowest points in autumn. Then it increased again until the beginning of next diatom bloom period.

In the lower lake, the annual maximum DIN concentrations were 1.47 mg/L, 1.34 mg/L, 1.46 mg/L, 0.94 mg/L and 1.03 mg/L in 2013, 2014, 2016, 2017 and 2018, respectively, with the

annual minimum DIN concentrations of 0.65 mg/L, 0.52 mg/L, 0.40 mg/L, 0.40 mg/L and 0.65 mg/L.

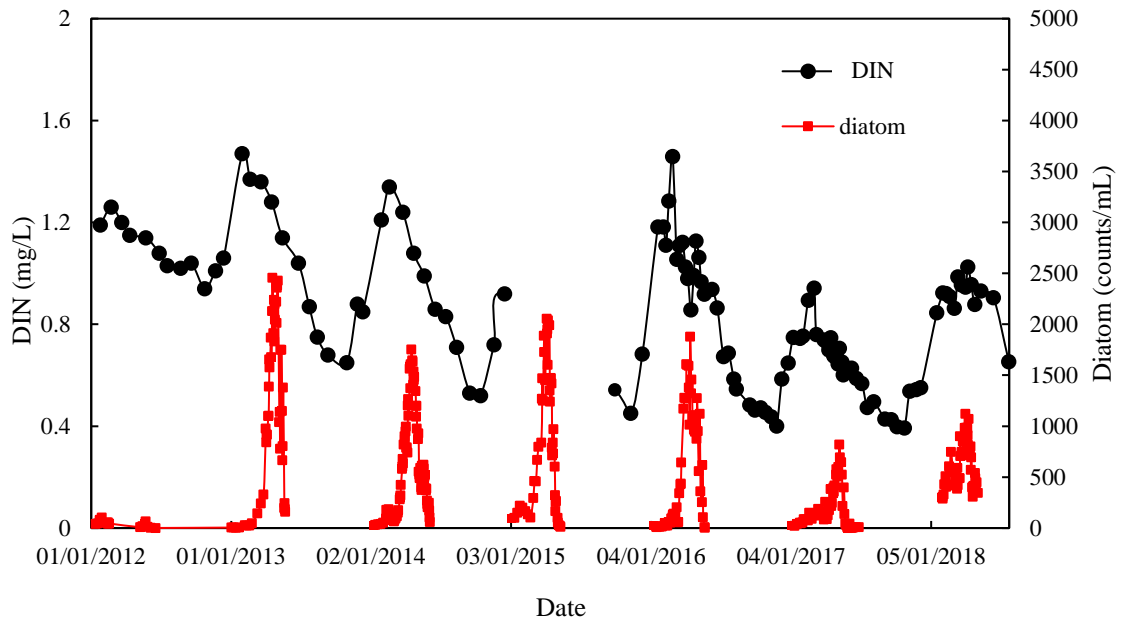


Figure 5.13 The change of DIN concentrations in lower lake from 2012 to 2018.

As is presented in Figure 5.14, the maximum DIN concentration in the upper lake in 2012, 2013 and 2014 was 1.50 mg/L, 1.47 mg/L and 1.40 mg/L with the minimal concentration of 0.96 mg/L, 0.53 mg/L and 0.50 mg/L, respectively. In 2016, the nitrogen concentration decreased from a maximum of 1.42 mg/L on the 5th February to a minimum of 0.33 mg/L on the 1st October. After that, the concentration of nitrogen increased continually to 1.16 mg/L on 18th February 2017. In 2017, the lowest nitrogen concentration was observed on 8th October with the number of 0.44 mg/L. The maximum concentration of nitrogen was 1.27 mg/L on 13th February before diatom bloom in 2018 and the nitrogen reduced to 0.64 mg/L on 27th July.

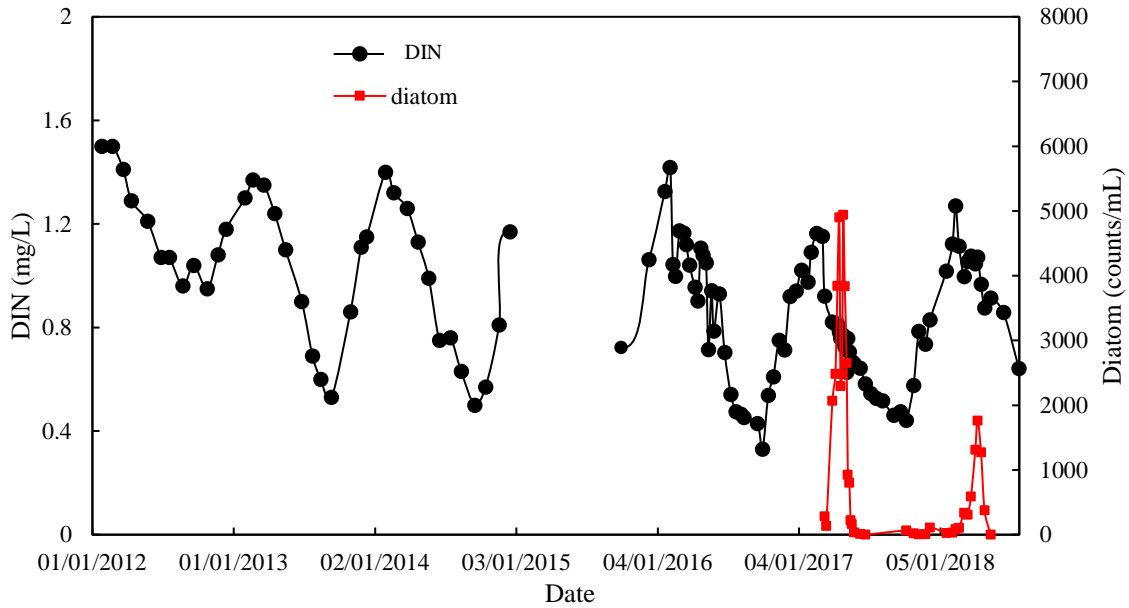


Figure 5.14 The DIN concentrations in upper lake from 2012 to 2018.

As shown in Figure 5.15, the concentrations of TOC in the reservoir fluctuated within a small range. While no significant change of TOC concentrations was observed during diatom bloom period, TOC concentrations in both upper and lower lakes were increasing from 2016 to 2018. In 2016, the average concentrations of TOC in the upper lake and lower lake were 4.16 mg/L and 3.85 mg/L, respectively. In 2017, the TOC concentrations ranged between 3.51-5.47 mg/L in the upper lake and 3.75-4.88 mg/L in the lower lake with the average values of 4.37 mg/L and 4.26 mg/L, respectively. In 2018, the maximum and minimum TOC concentrations in the upper and lower lake were 5.58 mg/L, 3.64 mg/L and 4.09 mg/L, 5.74 mg/L, respectively, with the average concentrations of 4.78 mg/L in the upper lake and 4.63 mg/L in the lower lake. It seemed diatom bloom didn't have a significant impact on TOC concentrations.

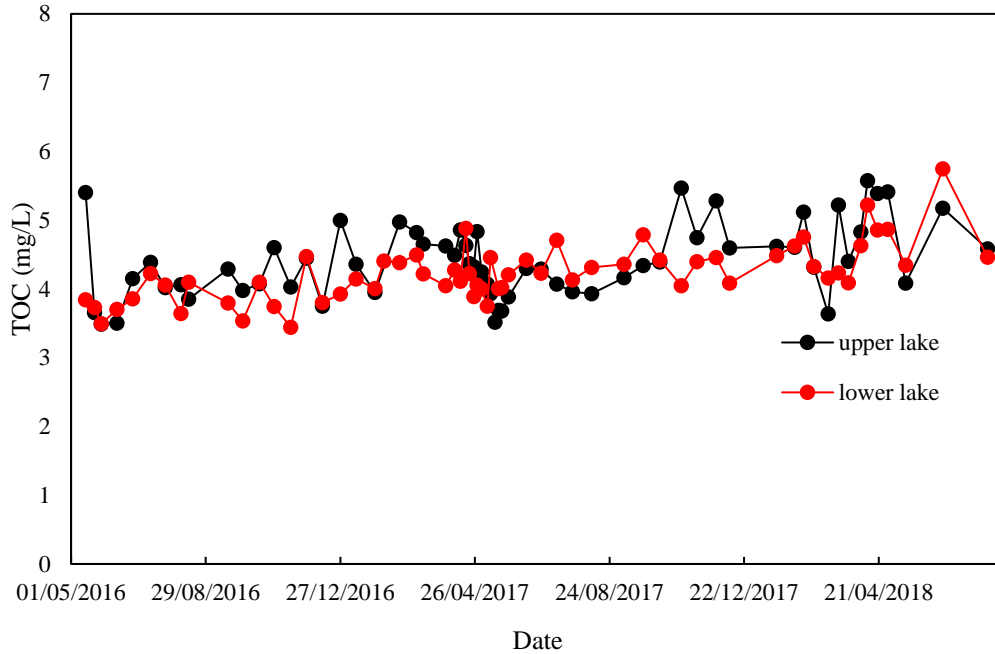


Figure 5.15 TOC concentrations in Vartry Reservoir from 2016 to 2018.

5.3.2 Nutrient concentrations at different depths in Vartry Reservoir

Water samples at different water depths (0.75 m, 3 m, 6 m and 9 m) were taken in the reservoir and the sampling locations are shown in Figure 3.1.

The nutrient concentrations in the upper lake from April 2017 to June 2018 are presented in Figure 5.16. The nutrient concentration gap between different depths in the upper lake was negligible in most cases. The nitrogen concentration at 0.75 m on 13th February 2018 was 2.2 mg/L which was higher than other layers (1.9 mg/L). On 25th March 2018, the concentration of nitrogen at a depth of 9 m was the lowest.

The concentration of TOC in the surface layer on 13th February and 16th March 2018 was 5.12 mg/L and 5.22 mg/L which was higher than that in the other water layers.

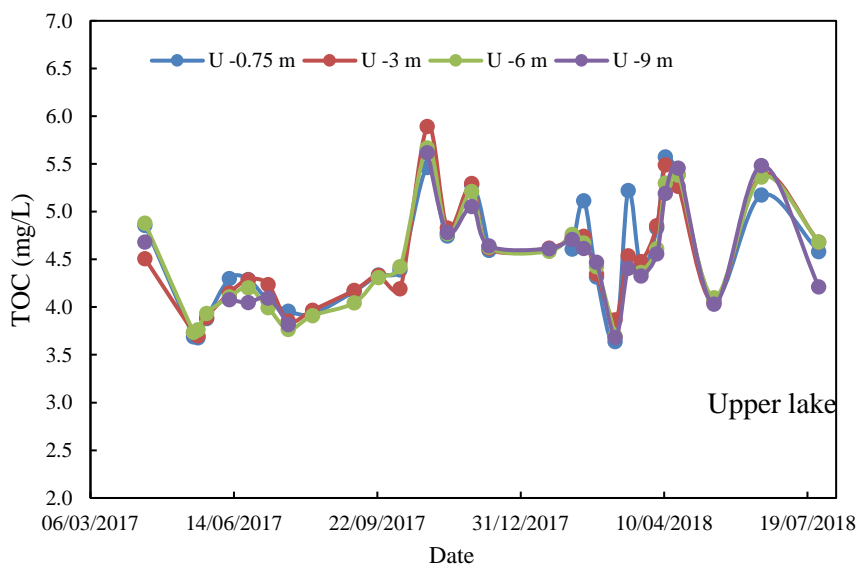
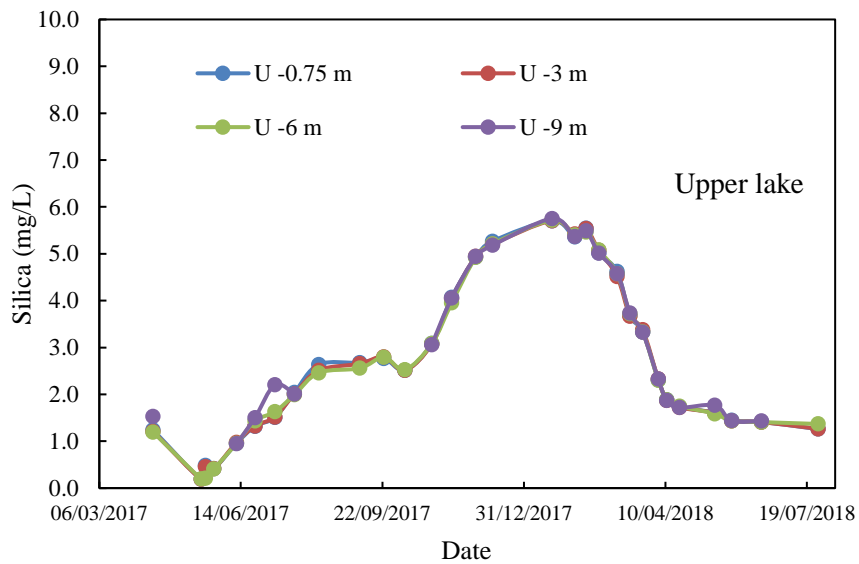
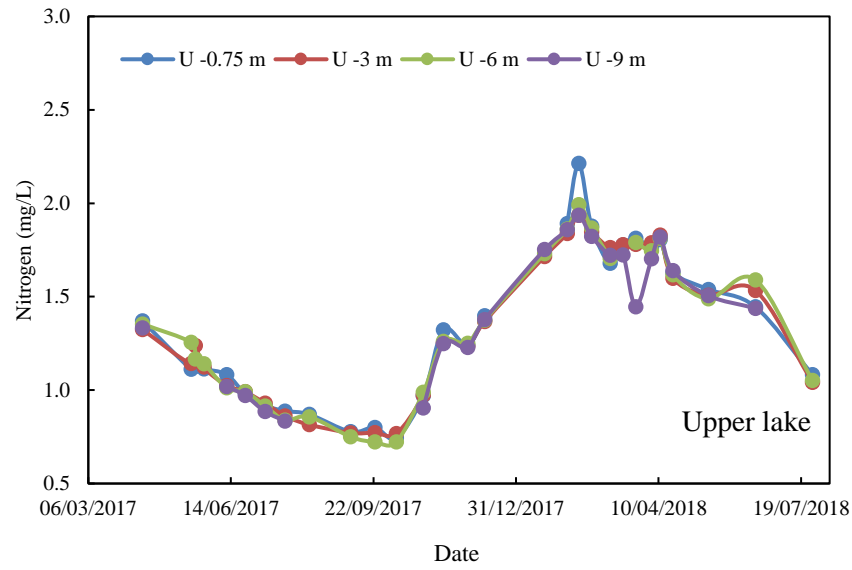


Figure 5.16 Concentration of nitrogen, silica and TOC at different depths in upper lake from April 2017 to June 2018.

The concentrations of silica, nitrogen and TOC at different depth in lower lake are shown in Figure 5.17. No significant difference in nutrient concentration existed between different water layers.

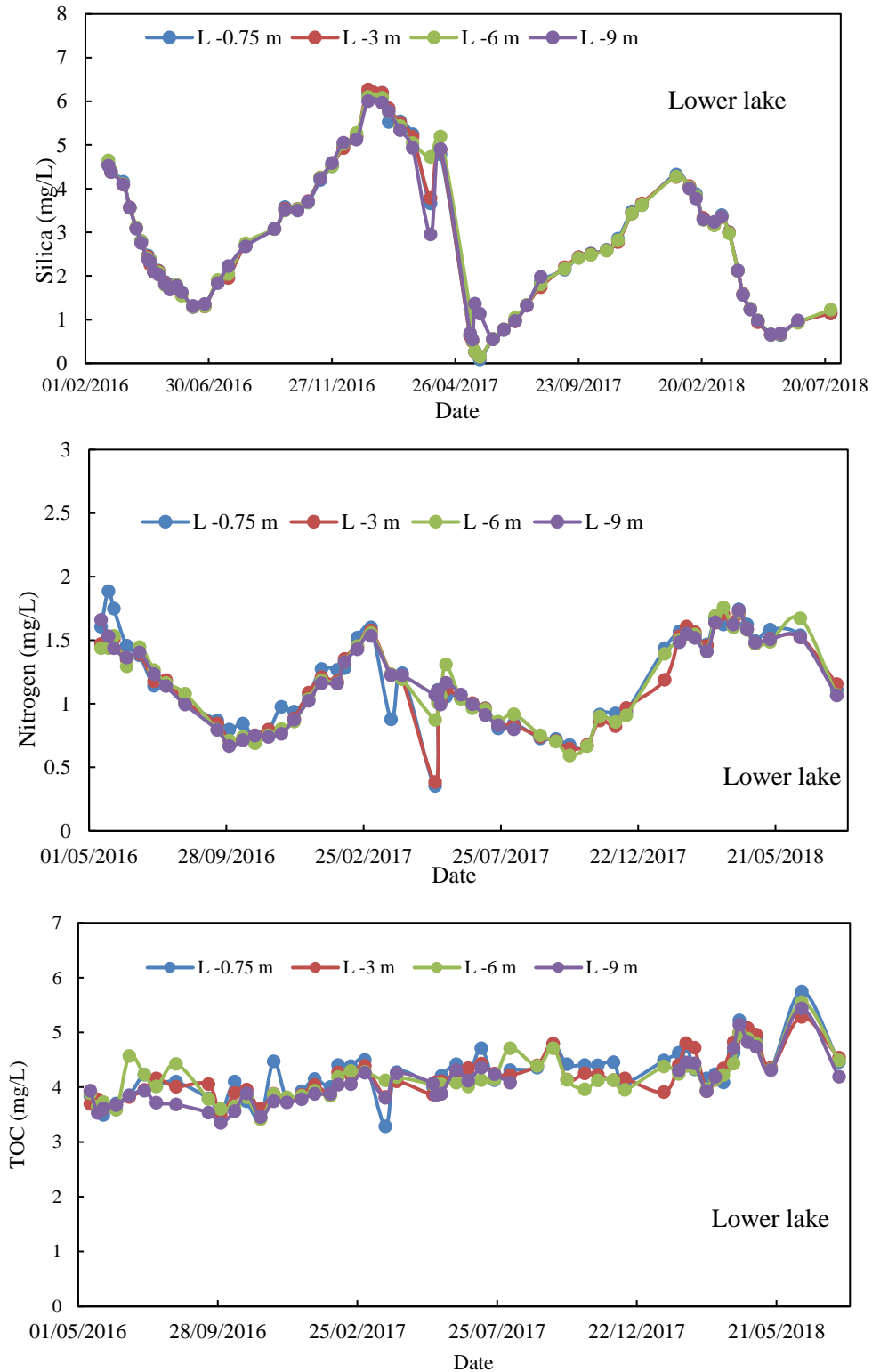


Figure 5.17 The concentration of silica, nitrogen and TOC at different depths in lower lake from May 2016 to Jun 2018.

5.3.3 The change of nutrient concentrations along Vartry Reservoir

The concentrations of SRP in Vartry Reservoir remained at a low level (2-3 ug/L) during diatom bloom period in 2017. No obvious difference in SRP concentration at different sites was observed.

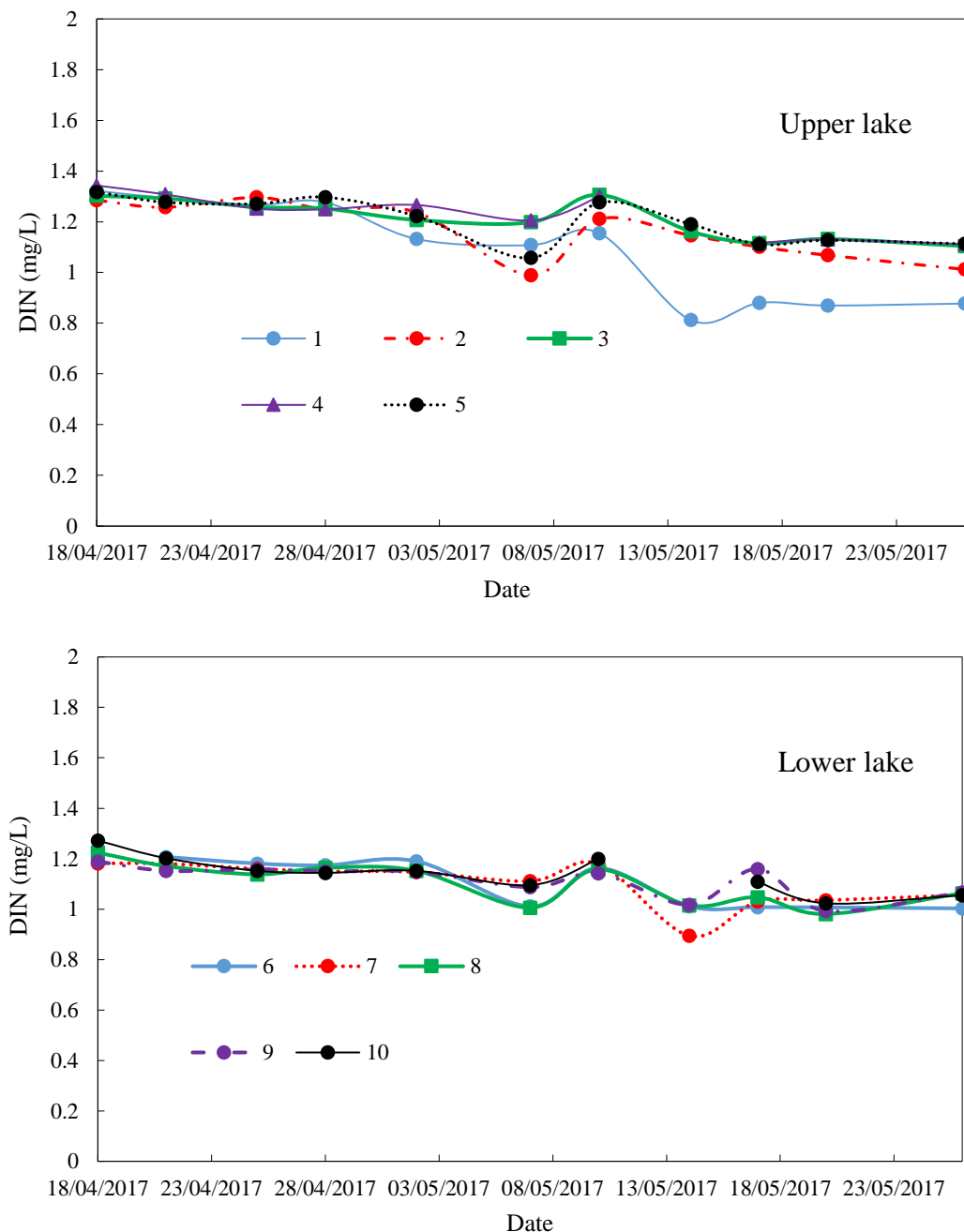


Figure 5.18 Spatial change of DIN concentrations along the longitudinal axis of Vartry Reservoir during April 2017-June 2017.

The concentrations of nitrogen along the reservoir in 2017 is shown in Figure 5.18. The nitrogen concentrations fluctuated between 0.88-1.34 mg/L in the upper lake and 0.98-1.21 mg/L in the lower lake. A slight reduction of nitrogen concentrations was observed during the studied period.

In the upper lake, the concentrations of nitrogen decreased from 1.32 mg/L to 0.88 mg/L in Site 1, 1.29 mg/L to 1.01 mg/L in Site 2, 1.32 mg/L to 1.11 mg/L in Site 3-5.

The silica concentrations along the reservoir during diatom bloom period in 2017 are presented in Figure 5.19. The concentration of SiO₂ was negatively correlated with the number of diatom directly. In Site 1, the SiO₂ concentration was 4.09 mg/L on 21st April 2017 and then slightly decreased to 2.69 mg/L on 10th May 2017.

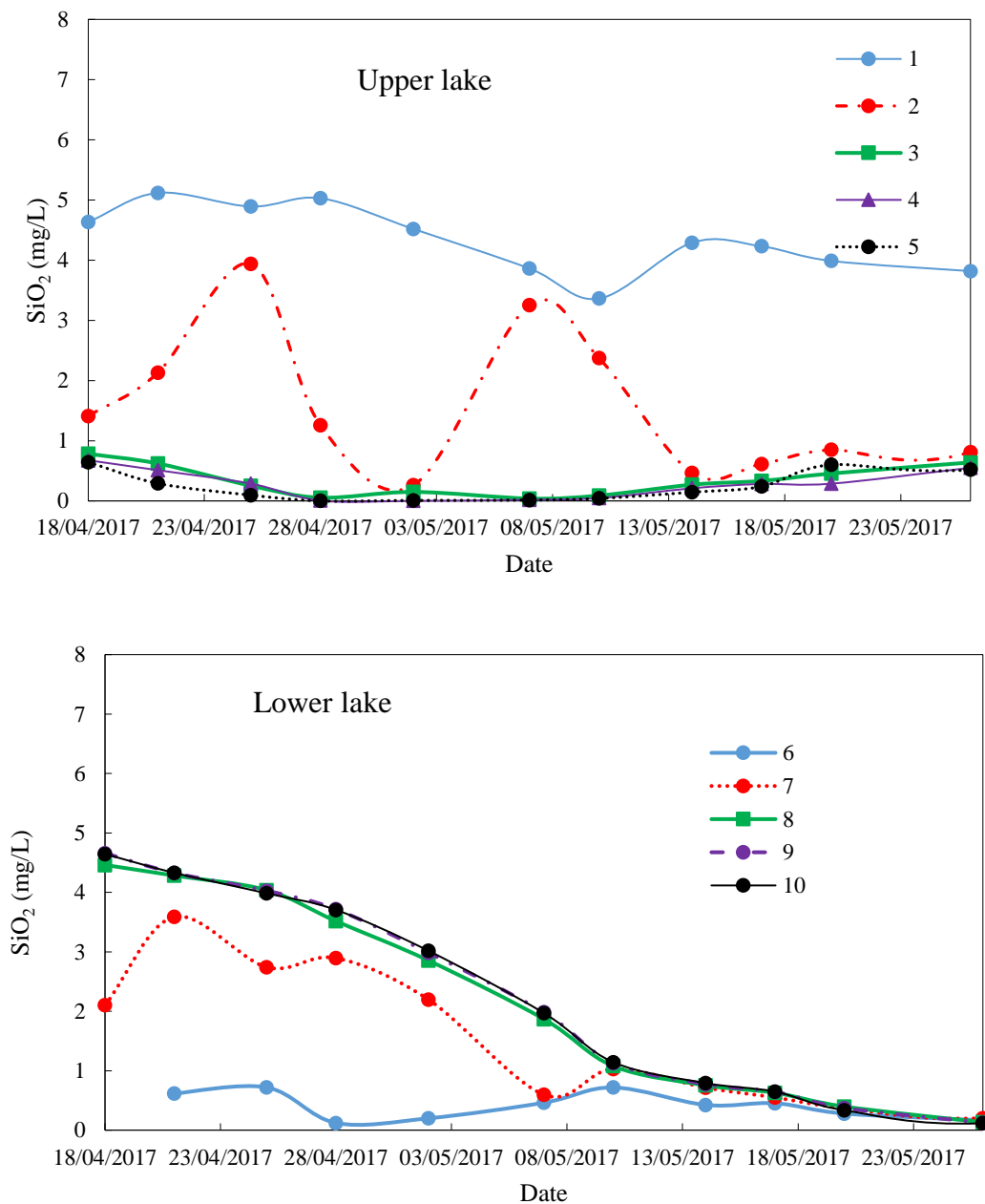


Figure 5.19 Spatial change of SiO₂ concentration along the longitudinal axis of Vartry Reservoir during April-Jun 2017.

The concentrations of SiO₂ at Site 2 fluctuated between 0.21 mg/L and 3.15 mg/L which was higher than the Site 3-5 and lower than that in Site 1. In Site 3, Site 4 and Site 5, the concentration of silica on 18th April 2017 was 0.62 mg/L, 0.54 mg/L, 0.51 mg/L, and reduced to the minimum concentrations of 0.039 mg/L, 0 (lower than the testing limitation), 0, respectively.

The water in Site 6 was mainly from the upper lake so the SiO₂ concentration in Site 6 was much lower than other parts of the lower lake. During the study period, the concentration of SiO₂ in Site 8-10 decreased from 3.57 mg/L, 3.73 mg/L, 3.72 mg/L on 18th April to 0.10 mg/L, 0.10 mg/L, 0.096 mg/L on 26th May 2017.

5.4 Nutrient concentration in other lakes or reservoirs Ireland

The nutrient concentration in the sampling lakes or reservoir are illustrated in Table 5.1. The PO₄-P concentration in Ballyshannock was 29 ug/L which was much higher than other lakes. The concentrations of NH₄-N in Ballyshannock, Lough Grill, Lough Ennell and Brackley were 122 ug/L, 147 ug/L, 146 ug/L and 141 ug/L, respectively. The NH₄-N concentration in other lakes remained lower than 100 ug/L. The silica concentration in Knockaderry Lake was the highest with the number of 5.32 mg/L, followed by 3.69 mg/L in Lough Ennell, 3.31 mg/L in Liffey, 2.69 mg/L in Lough Dan and 2.33 mg/L in Lough Ramor. The lowest silica concentration was 0.19 mg/L in Lough Owel. The maximum and minimum TOC concentration was 8.80 mg/L in Brackley Lake and 4.28 mg/L in Lough Ennell.

Table 5.1. The nutrient concentration in other lakes or reservoirs.

Name	PO ₄ -P (ug/L)	NH ₄ -N (ug/L)	SiO ₂ (mg/L)	TON (mg/L)	TOC (mg/L)	TN (mg/L)	Drinking water source (Y/N)
Lough Dan	<1	27	2.69	0.082	7.98	0.35	Y
Liffey	<1	21	3.31	0.36	7.63	0.73	
Knockaderry	<1	58	5.32	1.92	6.93	3.05	Y
Ballyshannock	29	122	0.89	1.97	5.56	2.96	N
Lough Acanon	<1	27	0.37	0.21	8.67	0.77	Y
Lough Grill	<1	147	0.35	0.011	7.00	0.34	Y
Lough Corrib	<1	20	0.72	0.12	4.90	0.42	Y
Lough Owel	3	54	0.19	0.14	5.22	0.57	Y
Lough Ennell	<1	146	3.69	0.80	4.28	1.95	Y
Lough Ramor	1	46	2.33	0.47	8.16	1.11	N
Brackley Lake	<1	141	0.60	<0.01	8.80	0.44	N

5.5 Discussion

5.5.1 Nutrient concentrations in feeding rivers

The nutrient concentrations in the feeding rivers were higher than that in the reservoir. No significant increasing trend of silica and nitrogen concentration in the feeding rivers were observed during the study period. Based on the 24 hours monitoring of the feeding rivers, the nutrient concentrations in the feeding rivers was stable. No diatom was observed in the feeding rivers.

5.5.2 Influence of nutrient concentrations on diatom growth

Feeding rivers with high silica concentrations (about 9 mg/L) flowing into the reservoir were silica sources in the reservoir. Unlike other alga, diatom requires silica for the formation of frustule. As a result, the concentrations of silica in the reservoir decreased during diatom bloom. Lund (1950) studied the *Asterionella* bloom in the lake and maximum diatom number reached when the silica concentration fell to 0.5 mg/L. The growth of *Asterionella* was limited when the concentration of silica was lower than 0.5 mg/L. In the study of Jewson et al. (1981), the population of diatom achieved the maximum with the silica concentration of 0.66 mg/L.

As shown in Table 5.2, in the lower lake from 2013 to 2018, the maximum biomass of diatom was achieved with the silica concentration of 1.48 mg/L, 1.92 mg/L, 3.14 mg/L, 2.83 mg/L, 0.91mg/L and 2.13 mg/L which was higher than the limited concentration in previous studies, indicating that the growth of diatom in the lower lake was not limited by silica during 2013-2018. In the upper lake, the concentration of silica was lower than 0.1 mg/L in 2017 when the diatom number peaked indicating that the lack of silica prevented the further growth of diatom.

Table 5.2 The silica concentration before and after diatom growth and the silica concentration with peaked diatom number.

Year	Silica before diatom bloom (mg/L)	Silica with the max diatom number (mg/L)	Silica after diatom bloom (mg/L)
2013	5.99	1.48	<0.4
2014	4.72	1.92	<0.4
2015	5.03	3.14	
2016	5.24	2.83	1.29
2017	6.19	0.91	0.094
2018	4.32	2.13	0.65
2017 upper lake	6.78	<0.1	<0.1
2018 upper lake	5.70	1.88	1.34

As is presented in Figure 5.20, the laboratory work was carried out with the initial silica concentration of 0.88 mg/L. The number of diatom raised up from 1940 counts/mL to 2403 counts/mL on the 3rd day and the concentration of silica decreased to 0.52 mg/L. The diatom concentration peaked on the 5th day with the number of 3254 counts/mL and the silica concentration was 0.12 mg/L. After that, the diatom number decreased to 862 counts/mL on the 11th day and the concentration of silica was lower than the testing limitation since the 7th day.

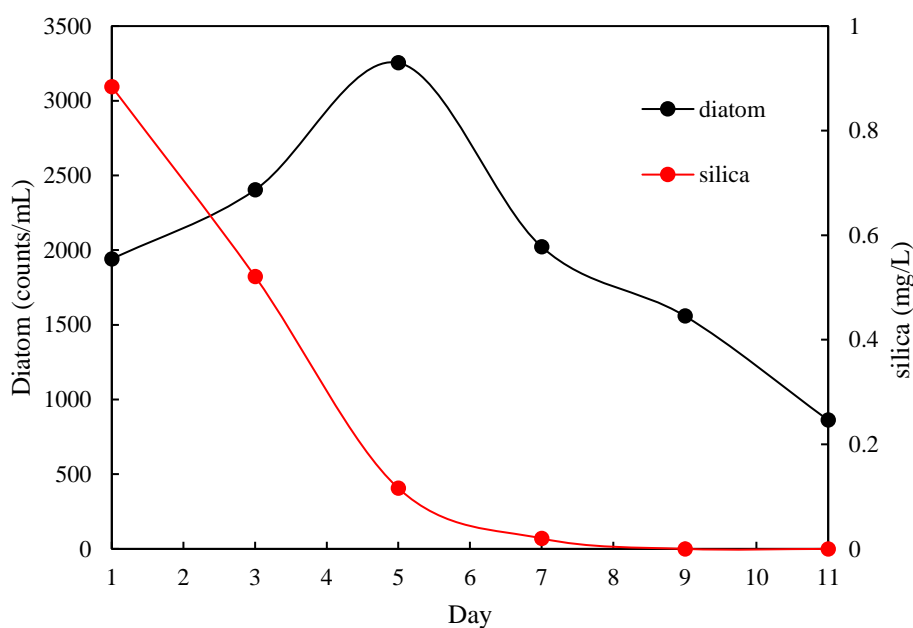


Figure 5.20 The diatom growth with low silica concentration.

In Vartry Reservoir, the concentration of silica was always sufficient for the growth of diatom. The limitation of silica might exist when the diatom number reached a relative high level (more than 4500 counts/mL in this study). The silica concentration could influence the magnitude of a diatom bloom.

The SRP requirement of *Asterionella* was very low. In theoretically, the consumption of SRP was 0.06 ug/10⁶ cell. In Vartry Reservoir, *Asterionella* could be abundant with low SRP level. This coincides with the conclusion reached in many studies that the *Asterionella* is a good competitor for phosphorus (Bertrand 2003; Lund 1950). Nicklisch (1999) investigated the competitive of different spring diatom species and found that the specific growth rate of *Asterionella* was much higher than other species under the limitation of phosphorus at 10°C. The lack of SRP is recognised as the limiting factor for the growth of diatom in many water systems especially in some static lake (Litchman, 2003; Wang et al., 2012).

As shown in Table 5.3, the concentration of SRP in Vartry Reservoir remained at a low level. It is noticeable that the SRP concentration in 2017 was much higher than that in other years. Coincidentally, the number of diatom in the upper lake in 2017 was the highest on record in Vartry Reservoir.

Table 5.3 Average SRP in Vartry Reservoir before diatom bloom.

	Upper lake		Lower lake	
	SRP (ug/L)	Peaked diatom number (counts/mL)	SRP (ug/L)	Peaked diatom number (counts/mL)
2016	1.15(±1.29)	<2000	1.76(±1.93)	1878
2017	3.58(±3.71)	4940	3.00(±3.39)	821
2018	1.18(±1.59)	1762	<1	1120

The reason for the low diatom number in the lower lake in 2017 was discussed in Chapter 6. Except for the lower lake in 2017, the correlation between the magnitude of diatom bloom and the SRP concentration was apparent. High concentration of SRP leads to serious diatom bloom such as the upper lake in 2017. In 2018 in the lower lake, the SRP was lower than 1 ug/L as a result the magnitude of diatom bloom was low.

Chapter 6

Zooplankton

6 Zooplankton

As shown in Chapter 4, in 2017, the reduction in nutrient concentrations was similar in both the upper lake and the lower lake during diatom bloom period. However, the diatom number in the lower lake were much less than that in the upper lake, which could be due to the predation diatom by zooplankton in the lower lake.

6.1 Zooplankton in Vartry Reservoir

6.1.1 Zooplankton species and magnitude in Vartry Reservoir from 2016 to 2018

In Vartry Reservoir, the major zooplankton species included Daphnia, Rotifer (Keratella and Kellicottia) and Copepods, and the number of zooplankton in the upper lake and lower lake are shown in Figure 6.1 and Figure 6.2, respectively. The number of zooplankton remained at a low level in autumn and winter. Normally the growth of zooplankton occurred in April.

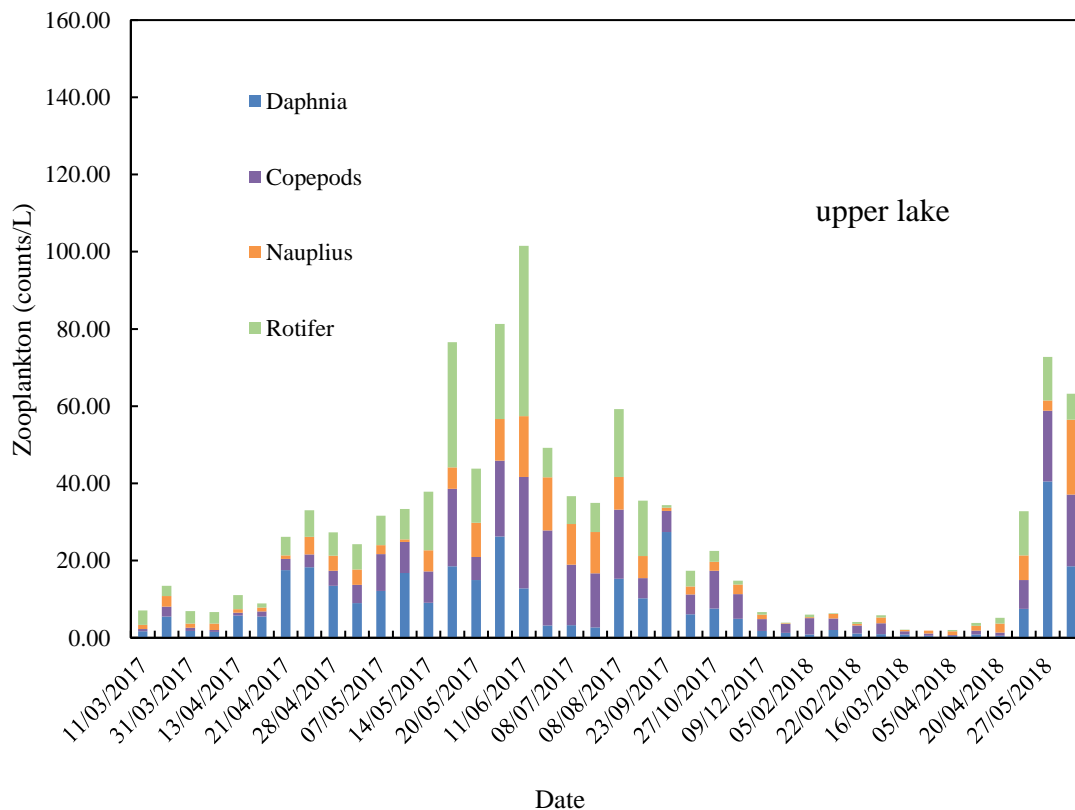


Figure 6.1 Number of zooplankton in upper lake from March 2017 to June 2018.

In the upper lake, the total number of zooplankton was about 10 counts/L in March 2017 and the number increased significantly to the maximum amount of 102 counts/L on 11th Jun 2017. The

concentration of zooplankton reduced to 15 counts/L on 27th November 2017. The zooplankton number was lower than 5 counts/L in the spring of 2018 in the upper lake. It reached to 73 counts/L on 27th May. In the upper lake, Daphnia, Copepods and Rotifer account for 32% ($\pm 16\%$), 28% ($\pm 15\%$) and 22% ($\pm 14\%$) of the total values.

As shown in Figure 6.2, zooplankton population in the lower lake increased from 8 counts/L on 17th April 2016 to the highest number of 57 counts/L on 22nd May 2016 and the major zooplankton species were Daphnia and Rotifer during this period. The total zooplankton amount ranged between 5 counts/L to 16 counts/L from October 2016 to November 2016 with Copepods as the dominated zooplankton species. In 2017, the zooplankton number was about 8 counts/L in January and February. In March 2017, the total zooplankton values ranged between 34 counts/L to 84 counts/L and Rotifer accounted for more than 80% of this. From 18th April 2017 to 26th May 2017, the number of zooplankton in the lower lake was above 60 counts/L with the major zooplankton species of Daphnia. The peaked amount of zooplankton was 126 counts/L on 28th April 2017. The zooplankton number remained lower than 20 counts/L from June 2017 to December 2017. Rotifer predominated in the lower lake from January to May in 2018. The peaked total zooplankton number was 145 counts/L on 15th May 2018.

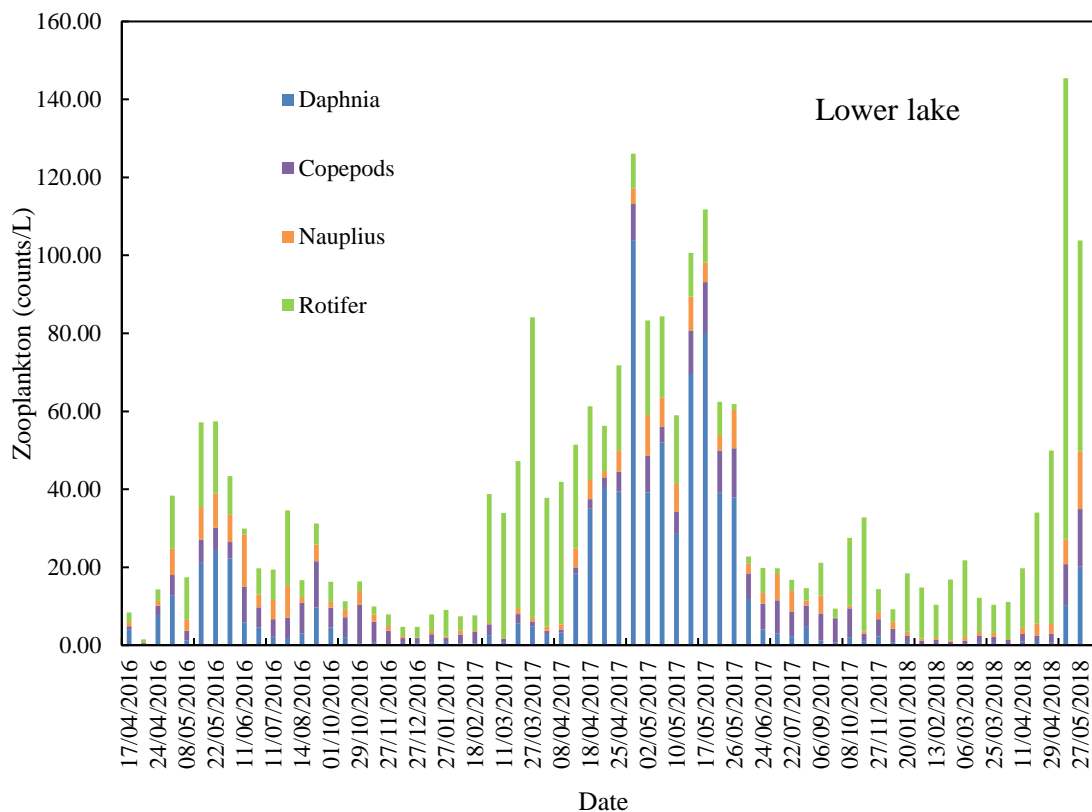


Figure 6.2 The number of zooplankton in lower lake from April 2016 to Jun 2018.

The populations of Daphnia and Copepods and the diatom number in the upper lake are shown in Figure 6.3. In the upper lake, the amount of Daphnia and Copepods was very low at the beginning of diatom bloom and increased gradually with the growth of diatom. The number of Daphnia and Copepods remained at a high level at the end period of diatom growth. In 2017, the sum of Daphnia and Copepods was lower than 10 counts/L at the early stage of diatom growth (11/3/2017-18/4/2017). In the later stage of a diatom bloom, the amount of Daphnia and Copepods increased to about 20 counts/L. During diatom bloom period, the number of Daphnia was higher than Copepods. After diatom bloom finished, the peaked amount of Daphnia and Copepods achieved with the number of 46 counts/L on 26th May 2017. From Jun to September, the number of Daphnia and Copepods ranged between 18 individual/ to 42 counts/L. During diatom bloom in 2018, the number of Daphnia and Copepods was lower than 5 counts/L. It increased from 15 counts/L on 15th May 2018 to 59 counts/L on 27th May 2018.

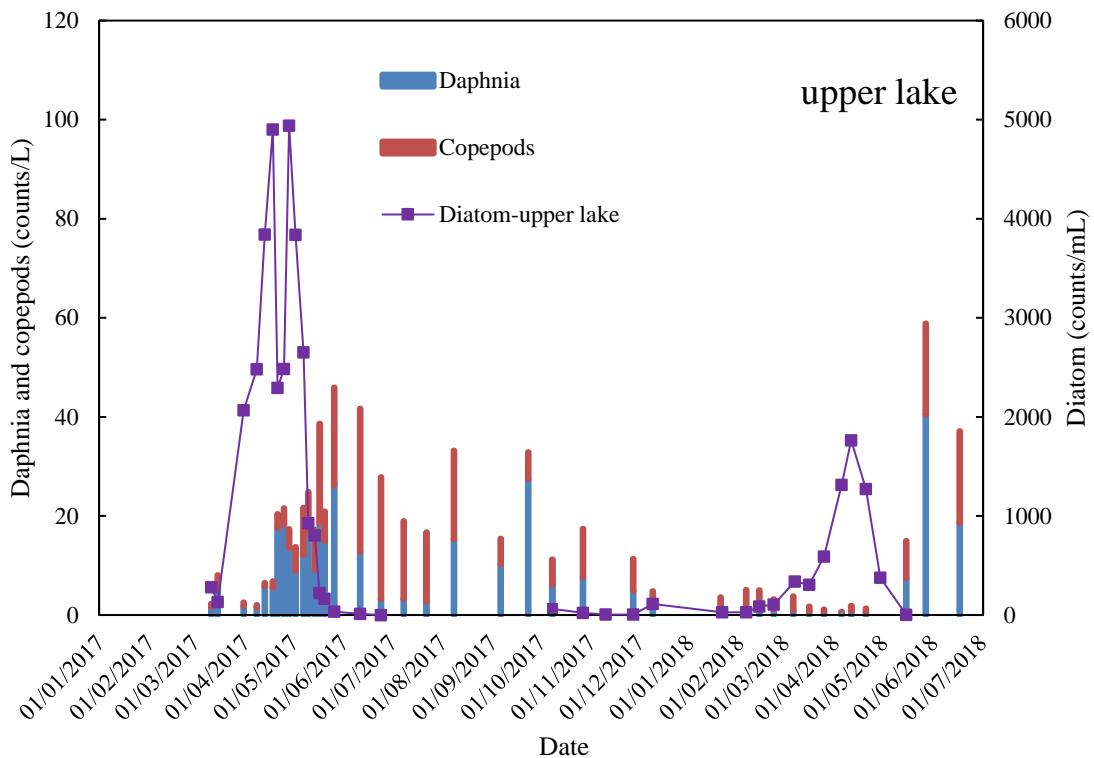


Figure 6.3 Number of Daphnia and Copepods and diatom bloom in upper lake.

The populations of Daphnia and Copepods and diatom bloom in the lower lake from 2016 to 2018 are shown in Figure 6.4. Compared with Copepods, the fluctuation of the Daphnia number in the lower lake was very significant, especially in the year of 2017. The Daphnia and Copepods populations in 2016 and 2018 had a similar trend with that in the upper lake. The amount of Daphnia and Copepods started to increase at the end of diatom growth. The total peaked number of Daphnia and Copepods were 30 counts/L on 22nd May 2016 and 35 counts/L on 27th May 2018,

respectively. In 2017, the growth of Daphnia coincided with diatom bloom. The number of Daphnia increased from 3 counts/L on 8th April 2017 to the maximum number of 104 counts/L on 28th April 2017 and the Daphnia amount maintained at relative high lever from 21st April 2017 to 26th May 2017 (diatom bloom period). The Daphnia number dropped down from 38 counts/L on 26th May 2017 to 4 counts/L on 24th June 2017.

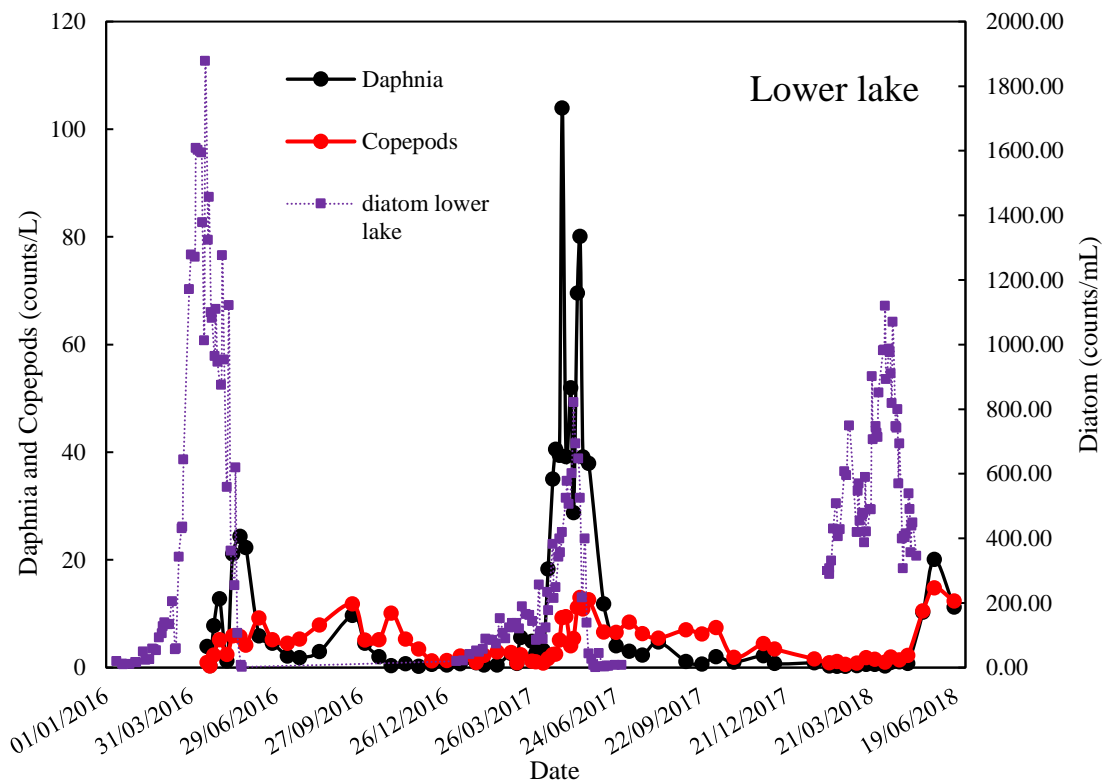


Figure 6.4 The number of Daphnia and Copepods and diatom bloom in lower lake.

6.1.2 The Spatial change of zooplankton in 2017

The zooplankton populations in different sites are present in Figure 6.5. The number of zooplankton in Sites 1-4 were lower than 20 counts/L from 25th April to 2nd May. The zooplankton population then raised significantly, especially in Site 1. The maximum zooplankton numbers in Sites 1-3 were 558 counts/L, 166 counts/L and 128 counts/L, respectively. The dominated zooplankton species was Daphnia. In Site 4, the amount of zooplankton increased gradually from 11 counts/L to 61 counts/L during the studied period. Compared with other sites in the upper lake, the number of zooplankton in Site 5 remained at a relatively stable level during the studied period with the range of 18 counts/L on 2nd May to 47 counts/L on 26th May.

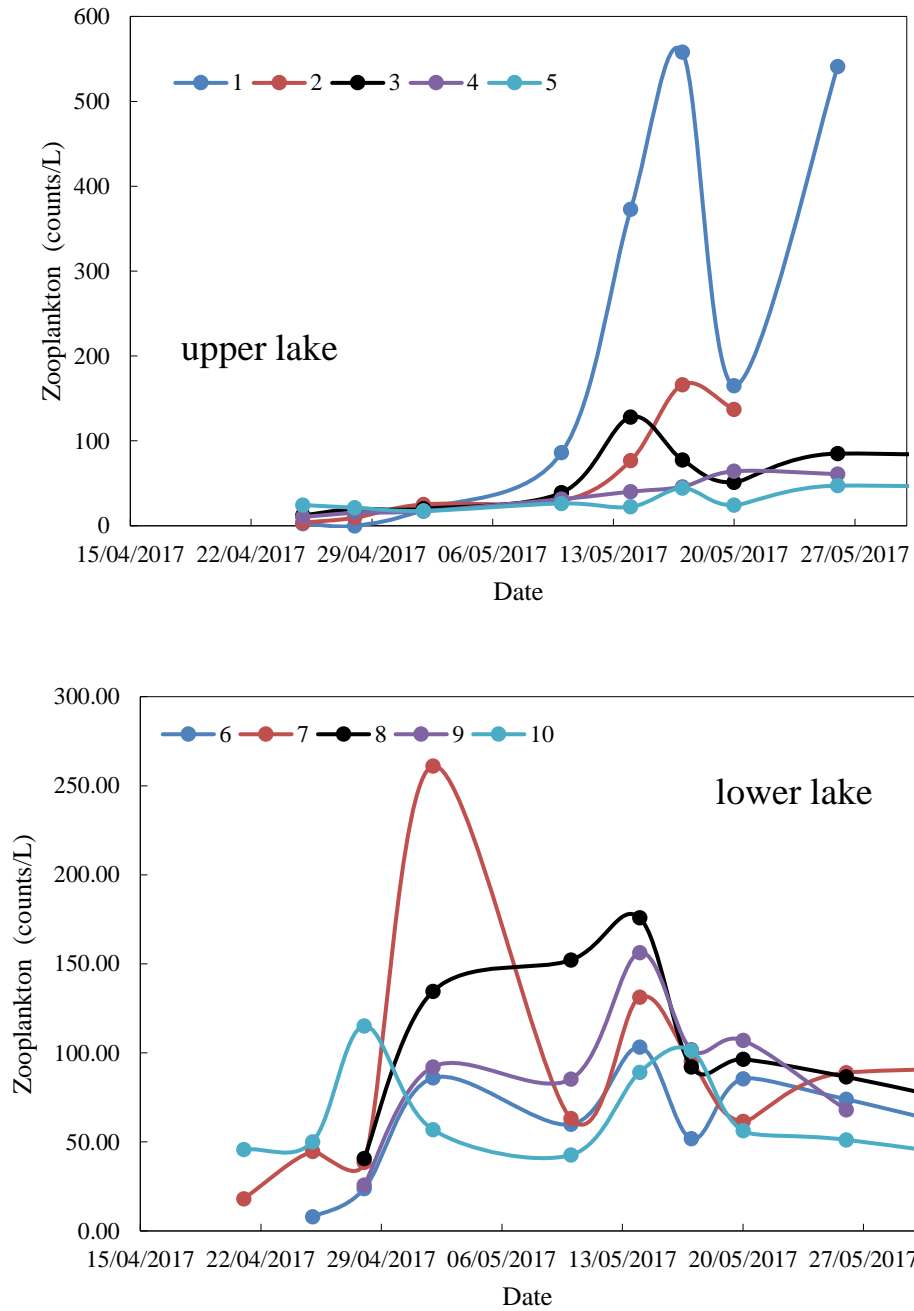


Figure 6.5 Spatial change of zooplankton along the longitudinal axis of Varray Reservoir during April-Jun 2017.

In the lower lake, the zooplankton population maintained at a relatively high level during diatom bloom period. In Site 6, the number of zooplankton was 8 counts/L on 25th April and then increased to 103 counts/L on 14th May. In Sites 7-9, the ranges of zooplankton quantity were 18-261 counts/L, 41-176 counts/L, 26-156 counts/L with the average number of 89 counts/L, 92 counts/L and 91 counts/L, respectively. The number of zooplankton in Site 10 was higher than 40 counts/L during the studied period and the average zooplankton quantity was 68 counts/L.

6.1.3 The influence of water temperature on zooplankton number

The influence of water temperature on the number of Daphnia, Copepods and Rotifer is presented in Figure 6.6.

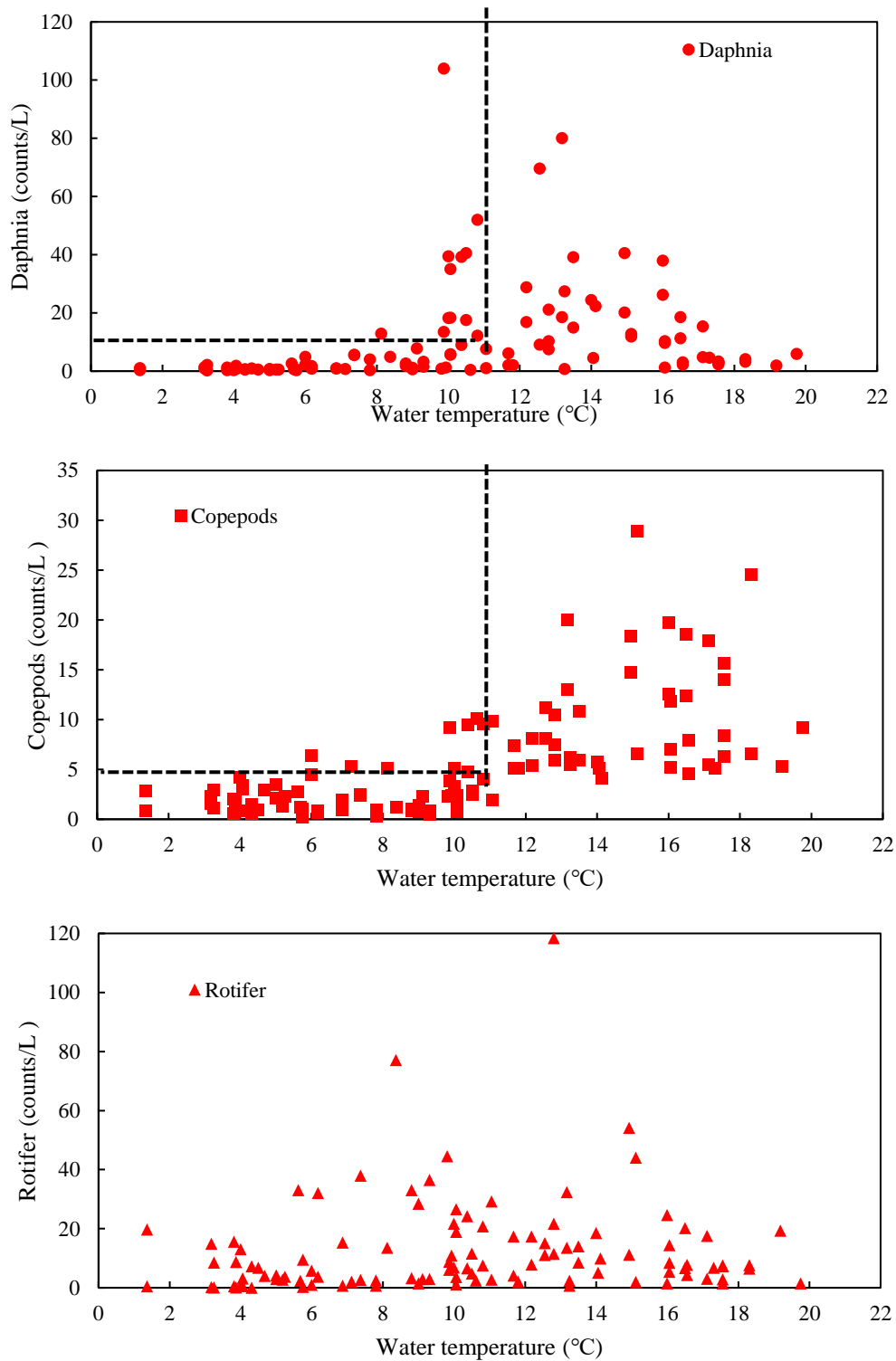


Figure 6.6 Impact of water temperature and the number of Daphnia, Copepods and Rotifer in Vartry Reservoir.

As shown in the figure, that the amount of Daphnia and Copepods was affected by the water temperature. The number of Daphnia and Copepods was below 10 counts/L and 5 counts/L when the water temperature was lower than 9 °C. With the increase of water temperature, the amount of Daphnia and Copepods fluctuated within wide range. However, the growth of Rotifer was unsusceptible to water temperature. The values of Rotifer could reach 33 counts/L with the water temperature of 5.6 °C

6.2 The study of zooplankton and diatom growth in the laboratory

Figure 6.7 shows the impact of zooplankton (with a population of 40 counts/L) on the diatom growth. The initial *Asterionella* concentrations in containers No A-0 and No A-1 were 109 counts/mL and 96 counts/mL, respectively, with the zooplankton in No A-0 and No A-1 of 0 and 40 counts/L. The *Asterionella* concentration in No A-0 increased to 2712 counts/mL on Day 17 and the diatom number remained at 2000 counts/mL until Day 22, then decreased to 473 counts/ml on Day 33. However, no *Asterionella* growth was observed in No A-1, indicating that the zooplankton population of 40 counts/L could prevent diatom bloom.

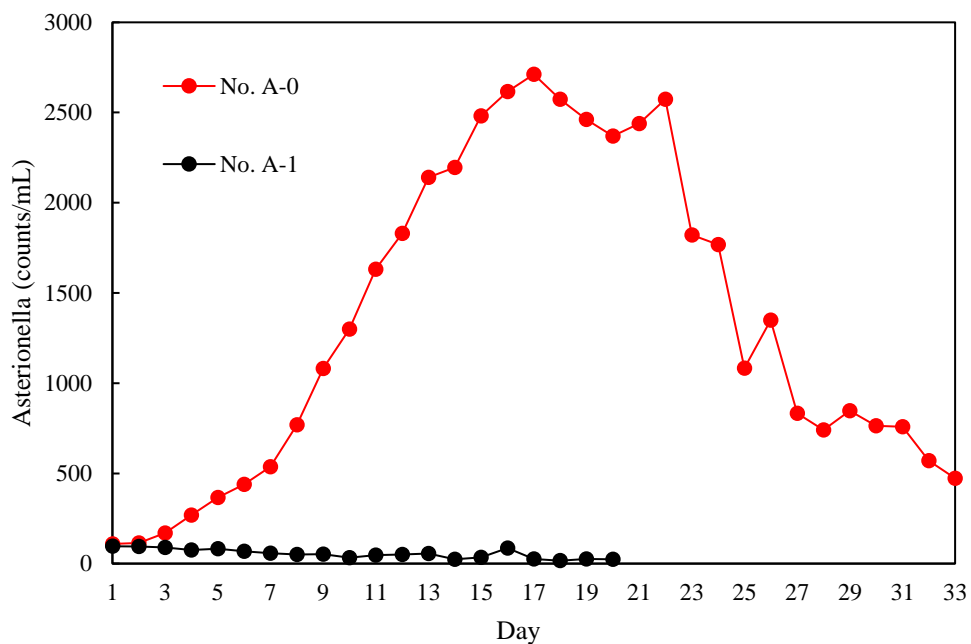


Figure 6.7 The growth of diatom with zooplankton number of 40 counts/L.

Figure 6.8 shows the impact of zooplankton (with a population of 13 counts/L) on the diatom growth with different initial concentrations. Both containers No B-0 and No C-0 had no zooplankton while in both No B-1 and No C-1 the zooplankton population were 13 counts/L. The initial *Asterionella* concentrations were about 780 counts/mL in No B-0 and No B-1 and 460 counts/mL in No C-0 and No C-1. In No B-0, the *Asterionella* concentration increased to 6214

counts/mL on Day 14 and then dropped down to 570 counts/mL on Day 18. In No B-1, the *Asterionella* concentration increased to 6877 counts/mL on Day 11. In No C-0, the *Asterionella* concentration went up to 5596 counts/mL on Day 12. In No C-1, the *Asterionella* concentration increased to 7024 counts/mL on Day 10. The zooplankton population of 13 counts/L is not enough to suppress the diatom growth.

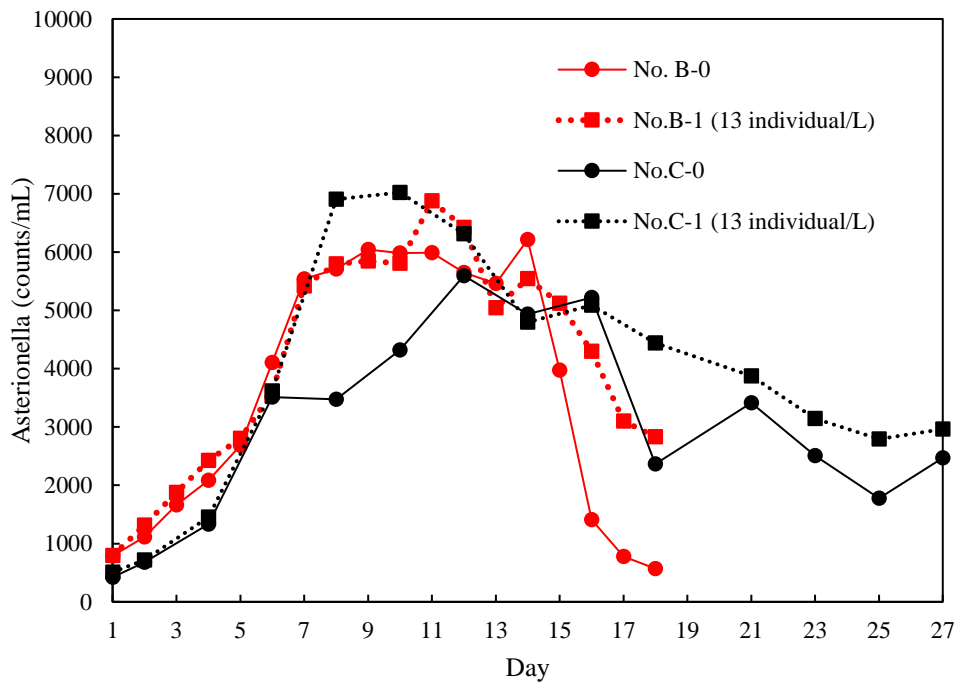


Figure 6.8 The growth of diatom with zooplankton number of 13 counts/L.

The impact of zooplankton populations on diatom growth and silica concentrations is shown in Figure 6.9. The initial diatom concentrations were about 600 counts/mL and the silica concentration was about 3.7 mg/L in all the containers. The zooplankton populations in No D-0, No D-1, No D-2, No D-3 and No D-4 were 0, 12 counts/L, 14 counts/L, 30 counts/L and 64 counts/L, respectively.

In the No D-0, the diatom increased to 10521 counts/mL on Day 15 and the concentration of silica decreases from 3.70 mg/L to 0.57 mg/L. Similar results were also observed in No D-1 (zooplankton 12 counts/L) and No D-2 (zooplankton 14 counts/L). In No D-3 (zooplankton 30 counts/L), the diatom increased from 560 counts/mL to 4936 counts/mL on Day 9 and concentration of silica decreased to 0.65 mg/L. Then the diatom concentration reduced significantly. In No D-4 (zooplankton 64 counts/L), no diatom growth was observed during the experiment while the concentrations of silica decreased continually. On Day 7, the number of diatom decreased from 613 counts/mL to 180 counts/mL and the silica concentration decreased

from 3.78 mg/l to 0.01 mg/l. In all five containers, the concentrations of silica decreased since the beginning of the experiment. However, the diatom concentrations were very different. The experiment indicated that increase the zooplankton to 64 counts/L could prevent diatom bloom.

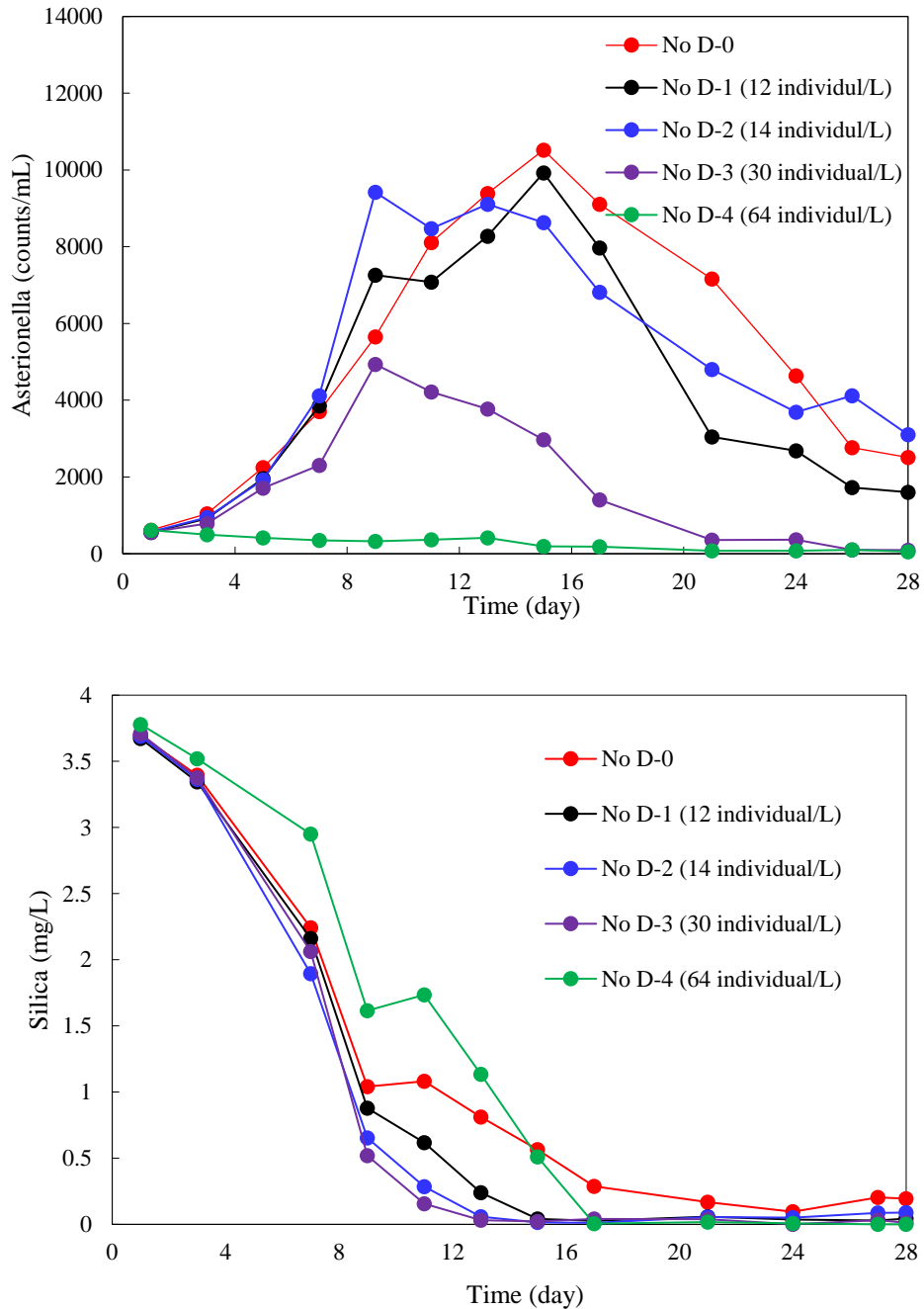


Figure 6.9 Growth of diatom and the change of silica concentration with different number of zooplankton.

The impact of zooplankton populations on the diatom growth with high initial concentrations is shown in Figure 6.10. The initial diatom concentrations were about 1800 counts/mL in all the

containers, with the silica concentration of about 0.8 mg/L. The zooplankton populations in No E-0, No E-1, No E-2 and No E-3 were 0, 72 counts/L, 100 counts/L and 202 counts/L, respectively.

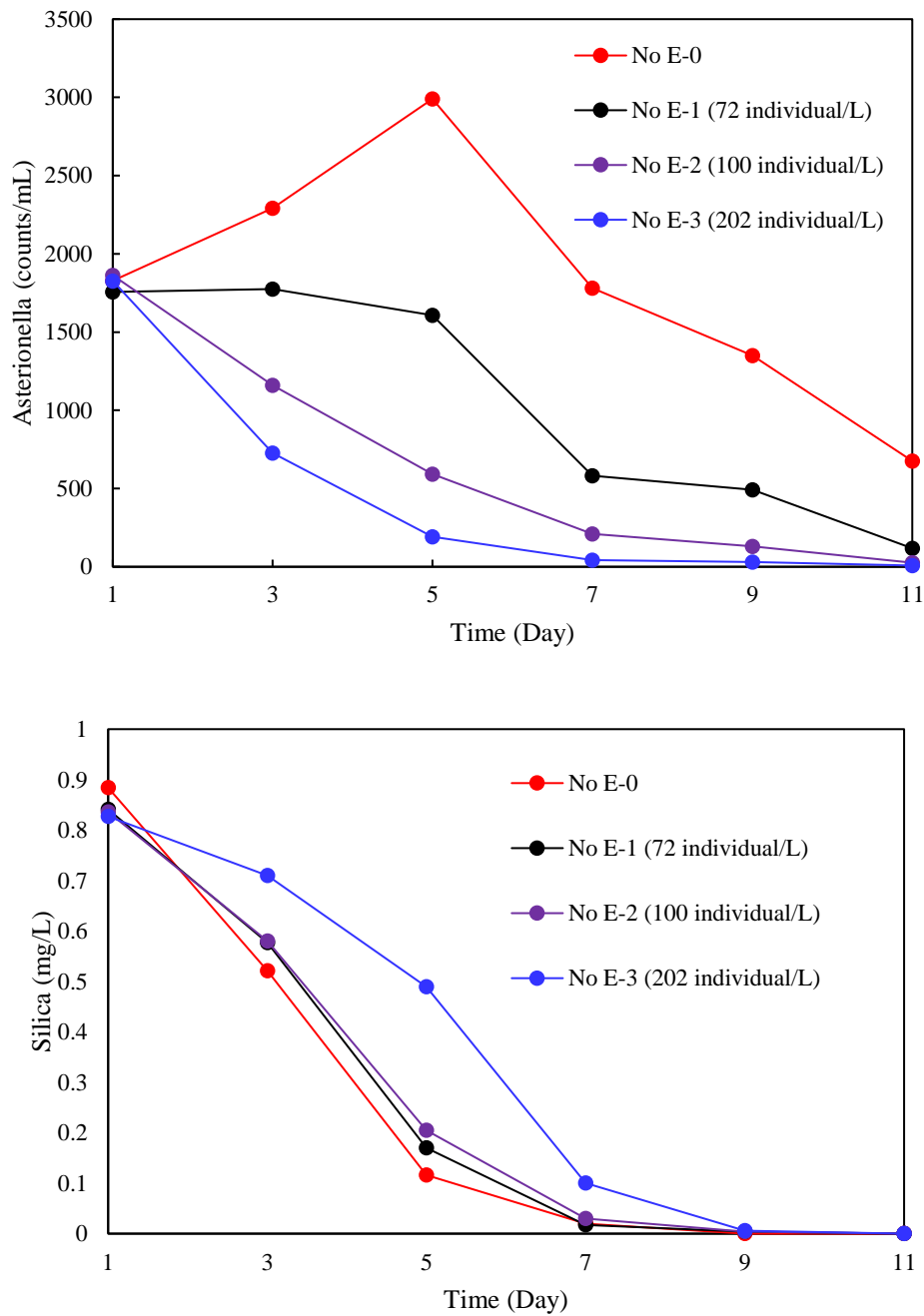


Figure 6.10 Change of diatom number and the silica concentration with high zooplankton and initial diatom number.

In No E-0, the number of *Asterionella* increased from 1829 counts/mL to 2990 counts/mL on Day 5; then declined gradually to 676 counts/mL on Day 11. In No E-1 (zooplankton 72 counts/L), the amount of *Asterionella* dropped down slowly from 1827 counts/mL to 1608 counts/mL on Day 5, then reduced to 118 counts/mL on Day 11. The number of *Asterionella*

decreased significantly from 1863 counts/mL to 210 counts/mL in No E-2 and from 1827 counts/mL to 43 counts/mL in No E-2 on Day 7. The concentrations of silica in No E-0, No E-1, No E-2 and No E-3 decreased from 0.88 mg/L, 0.84 mg/L, 0.84 mg/L and 0.83 mg/L to 0.12 mg/L, 0.17 mg/L, 0.21 mg/L and 0.49 mg/L, respectively, on Day 5. This experiment indicated that increasing the zooplankton population to 72 counts/L during diatom bloom period could stop the bloom.

6.3 Discussion

6.3.1 Zooplankton in Vartry Reservoir

In Vartry reservoir, the number of zooplankton remained at a low level in autumn and winter. The predation of Daphnia and Copepods on diatom existed in the reservoir. The diatom could be the major food sources for Daphnia and Copepods in Vartry Reservoir due to the absence of other phytoplankton. The lack of food sources could be the main reason for the low density of Daphnia and Copepods from July to the next February. The similar trend was also observed in a marl lake in Ireland (McCarthy et al., 2006). The maximum biomass of zooplankton occurred in spring. Daphnia and copepods mainly feed on diatoms, so the time lag exists between the growth of diatom and zooplankton. As observed in the upper lake in 2017 and the lower lake in 2016, the largest Daphnia and Copepods population occurred at the end of a diatom bloom.

6.3.2 The influence of water temperature on zooplankton

As shown in Table 6.1, the growth of zooplankton normally occurred at the end of April and the peaked amount reached in May.

Table 6.1 Maximum daphnia and copepods number and water temperature in Vartry Reservoir from 2016 to 2018.

lower lake	Maximum number (counts/L)	Peaked date	Fasting growing period	Water temperature (°C)
2016	30	22/5	20/04-22/05	7.80-14.00
2017	113	28/4	08/04-07/05	9.31-10.80
2018	35	27/5	49/04-27/05	9.87-14.93
Upper lake				
2017	46	26/5	08/04-26/05	9.31-16.00
2018	59	27/5	20/04-27/05	9.00-14.93

Compared with the growth in 2016 and 2018, the zooplankton growth took place much early in 2017. Higher water temperature in 2017 contributed to the early start-up of zooplankton. A similar result was also achieved in other studies (Berger et al., 2007; Winder et al., 2012). Berger

et al. (2007) studied the influence of water temperature on the time of zooplankton growth with man-made enclosure experiment. The peaked Daphnia number was achieved one week early in the warmer water temperature than the cold-water condition. In Vartry reservoir, the magnitude of zooplankton was independent to the water temperature.

6.3.3 *The influence of zooplankton on diatom number*

The diatom growth in the lower lake in 2017 was characterised with delayed occurring and low diatom number with high nutrient consumption. In 2017, the consumption of nitrogen and silica in the upper lake and the lower lake was similar. However, the peaked amount of diatom in the upper lake (4940 counts/mL) was 6 times as much as that of the lower lake (821 counts/mL). This could be caused by zooplankton. Due to difference feeding habit of zooplankton species, the influence of zooplankton on the diatom growth was different.

Rotifer normally feeds on organic particles, dead bacteria and small size algae. Rotifer can also direct take up phosphorus from water (Jensen et al., 2004). Conde-Porcuna (2000) studied the correlations between rotifer and nutrient concentration in the mesotrophic reservoir. The result suggested that the SRP concentration influenced the biomass of rotifer and the rotifer abundance was not affected by algae. In Vartry reservoir, the fast growing of diatom normally began in March. However, in the lower lake in 2017, the diatom growth started from April. As shown in Figure 6.2, the population of rotifer increased significantly in March from 5 counts/L to 77 counts/L. The competition of SRP between rotifer and diatom affected the growth of diatom.

Unlike rotifer, the predation of Daphnia and Copepods on diatom could also directly limit the diatom number. As shown in Table 6.2, the degree of limitation was directly correlated with the ratio of diatom number and zooplankton number. The limitation was intensive with the decreasing of diatom and zooplankton ratio. No diatom growth was observed when the ratio was lower than 14.4×10^3 . The limitation of zooplankton was not apparent with the ratio higher than 40.9×10^3 .

The average ratio of diatom and zooplankton in 2017 was 460×10^3 in upper lake and 17×10^3 in the lower lake during the diatom growth period. In 2018, this ratio was 725×10^3 and 381×10^3 in the upper and lower lake, respectively. Based on the conclusion obtained in the lab work, predation of Daphnia and Copepods limited the diatom number in the lower lake in 2017. However, Daphnia and Copepods exhibited almost no influence on diatom bloom in upper lake in 2017, the whole reservoir in 2018. McCarthy (2007) studied zooplankton population in the lake of Ireland. The result showed that the biomass of zooplankton in Lough Carra and Lough

Talt was higher than 3×10^5 ug DW/m² in February and March with Daphnia and Copepods dominated.

In Vartry Reservoir, this value was lower than 1.5×10^5 ug DW/m² except for the lower lake in 2017. The low amount of zooplankton exacerbated diatom bloom.

Table 6.2 The degree of limitation with different ratio of diatom and zooplankton.

Diatom (counts/mL)	Zooplankton (counts/L)	Ratio (diatom:zooplankton)	Degree of limitation
96	40	2.4×10^3	Fully limited
1827	202	9.0×10^3	
613	64	9.6×10^3	
504	48	10.5×10^3	
1443	100	14.4×10^3	
454	26	17.5×10^3	Medium limitation
560	30	18.6×10^3	
1757	72	24.4×10^3	
526	14	37.6×10^3	Minor limitation
573	14	40.9×10^3	No obvious limitation
786	18	43.6×10^3	
554	12	46.2×10^3	
792	13	60.9×10^3	

Chapter 7

Hydrodynamic and weather effects

7 Hydrodynamic and weather effects

Besides nutrient and zooplankton, hydrodynamic elements such as water temperature, thermal stratification, hydraulic dynamic time and weather includes sunshine, rainfall, air temperature also influence the time and magnitude of diatom growth.

7.1 Hydrodynamic conditions in Vartry Reservoir

7.1.1 Water temperature and thermal stratification

The water temperature in the upper lake and lower lake from 2012 to 2014 is shown in Figure 7.1.

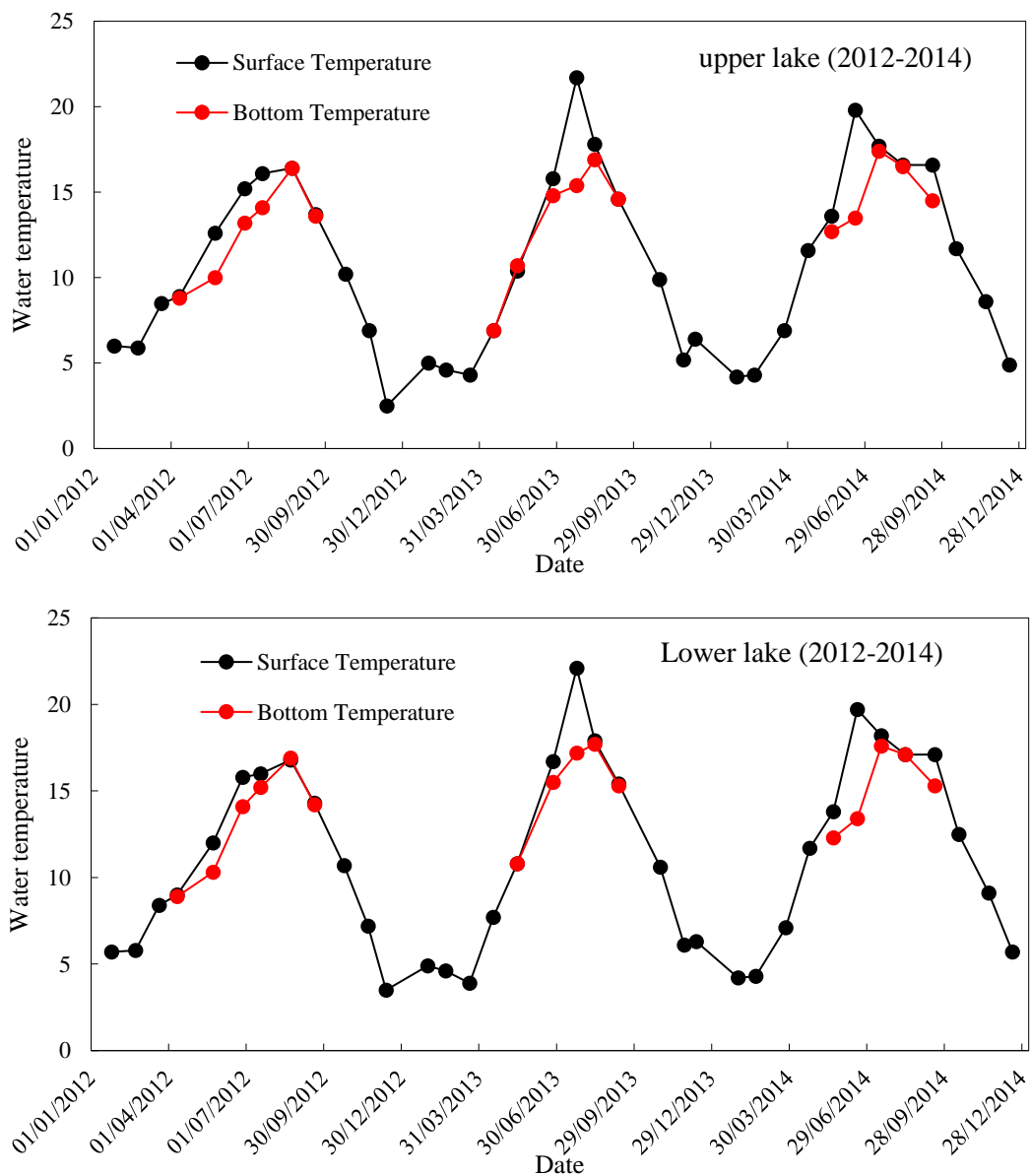


Figure 7.1 Surface and bottom water temperature in upper lake and lower lake from 2012 to 2014.

The change of water temperature in the upper lake and lower lake was similar. In 2012, the lowest water temperature in the upper lake and lower lake was 2.5 °C and 3.5 °C in 12th December 2012, respectively. The highest water temperature was 17 °C in 22nd August 2012 in the reservoir. In 2013, the highest and lowest water temperature in Vartry reservoir was 22 °C in 24th July 2013 and 4 °C in 20th March 2013. In 2014, the water temperature in Vartry reservoir increased from 4 °C in 29th January 2014 to 20 °C in 18th Jun 2014.

Water temperature gap between the surface and bottom water layer generally existed from May to August. In 2012, the surface water temperature was about 2 °C higher than the bottom water temperature from 11th April 2012 to 22nd August 2012. In 2013, the maximum water temperature gap was 5 °C in 24th July 2013. In 2014, the surface water temperature was higher than the bottom water temperature during 21st May 2014 and 16th July 2014. The water temperature gap also existed from 13th August 2014 to 17th September 2014.

The water temperature and the diatom concentration in the lower lake in 2016 are shown in Figure 7.2. The water temperature in the lake fluctuated between 4.4 °C and 20.3 °C.

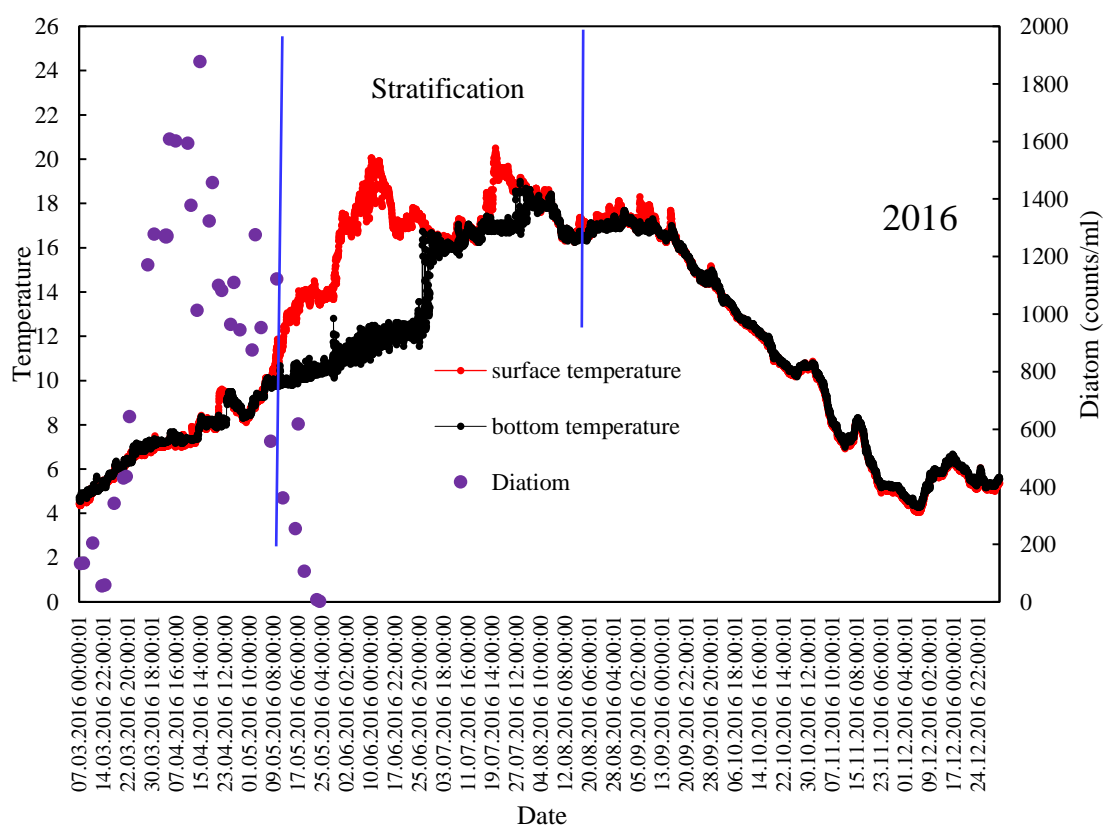


Figure 7.2 Surface and bottom water temperature in lower lake in 2016.

During diatom bloom period, the water temperature was 4°C -14°C. From May to August, the surface water temperature was obviously higher than the bottom water layer. On 12th Jun 2016, the surface water temperature was 8.6 °C higher than that in the bottom area. Thermal stratification occurred on 9th May with the surface water temperature and a bottom temperature of 10.75 °C and 9.75 °C, respectively. The diatom concentrations on 10th May 2016 was 1122 counts/mL. After the stratification formed, the density of diatom dramatically decreased to 8 counts/mL on 24th May 2016.

As presented in Figure 7.3, the highest water temperature in the lower lake was 20.4 °C in 21st Jun and the lowest water temperature was 2.8 °C on 16th December. The range of water temperature was 5°C-17°C during the growth of diatom in 2017. The stratification started to establish in the lower lake on 8th May with the temperature gap between the surface and bottom lay of 1°C, and the diatom concentration decreased from 821 counts/mL on 10th May 2017 to 8 counts/mL on 20th May. The thermal stratification disappeared at the end of July.

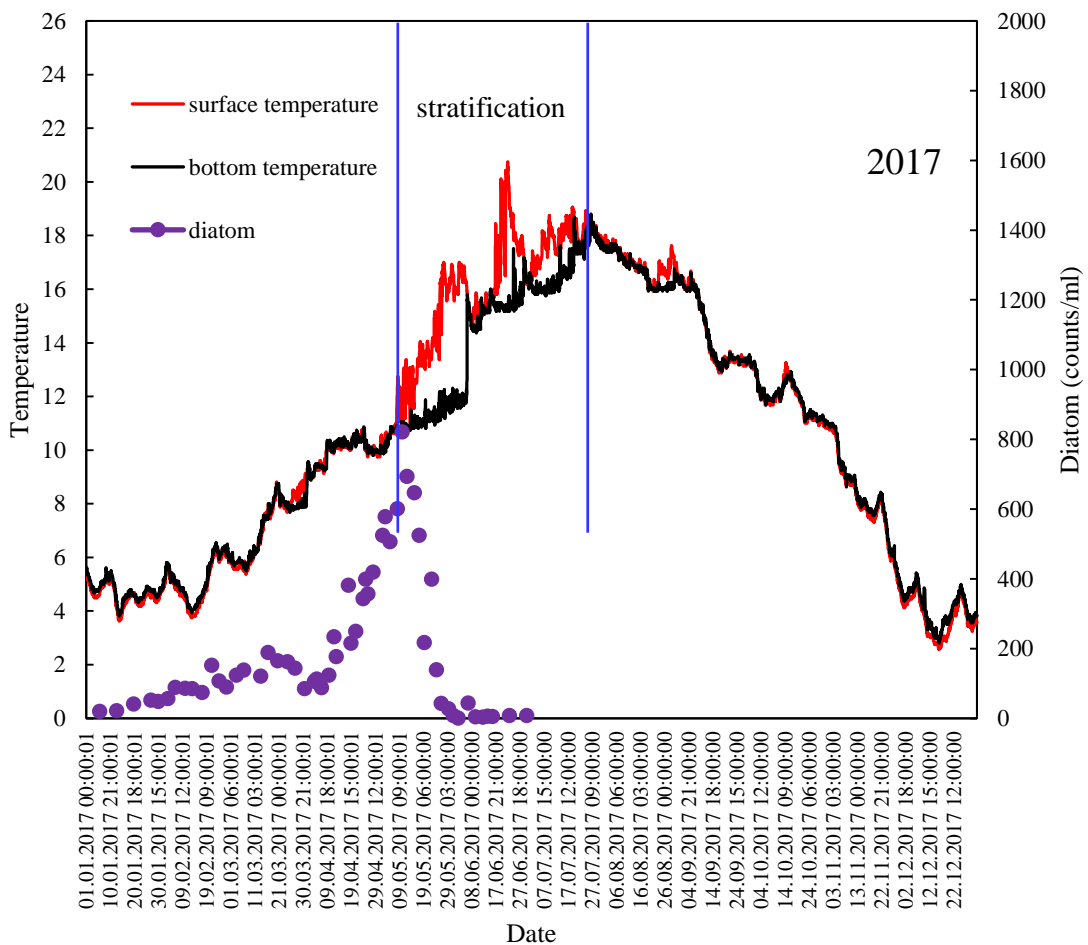


Figure 7.3 Surface and bottom water temperature in lower lake in 2017.

The water temperature and the growth of diatom in the lower lake in 2018 are presented in Figure 7.4. The lowest water temperature was 1.7 °C in 4th March. The water temperature in the lake was lower than 5 °C from January to March which was much lower than in previous years. During diatom bloom period, the water temperature ranged between 1.7 °C and 12°C. The short period thermal stratification formed between 20th April and 24th April. After that, the regular stratification established since 5th May with the surface water temperature of 10.9 °C. The largest temperature gap existed on 10th Jun with the surface and bottom layer of 20.7 °C and 11.7 °C, respectively.

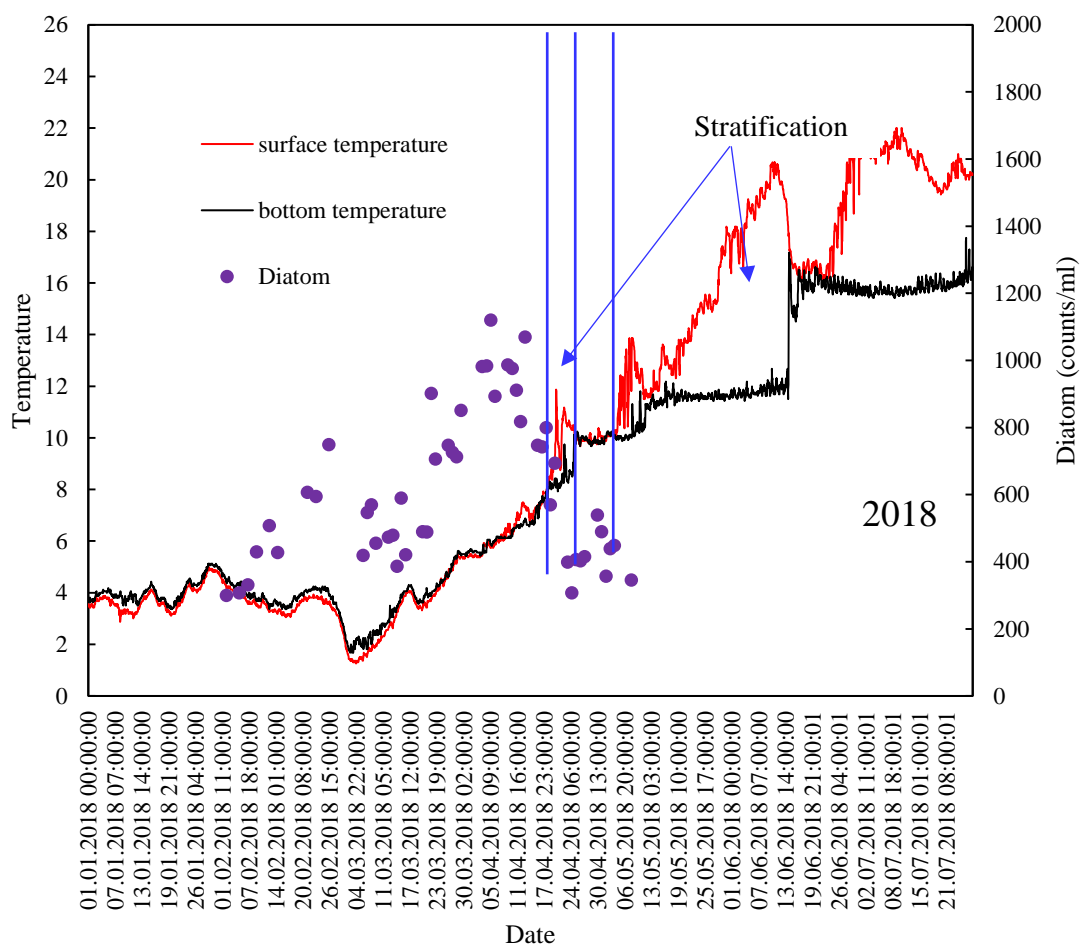


Figure 7.4 Surface and bottom water temperature in lower lake in 2018.

The influence of water temperature on the number of the diatom is shown in Figure 7.5. The diatom number was lower than 1000 counts/mL when the water temperature was higher than 11 °C. The formation of thermal stratification in the reservoir was responsible for this phenomenon. The amount of diatom also less than 1000 counts/mL when the water temperature was lower than 6.5 °C.

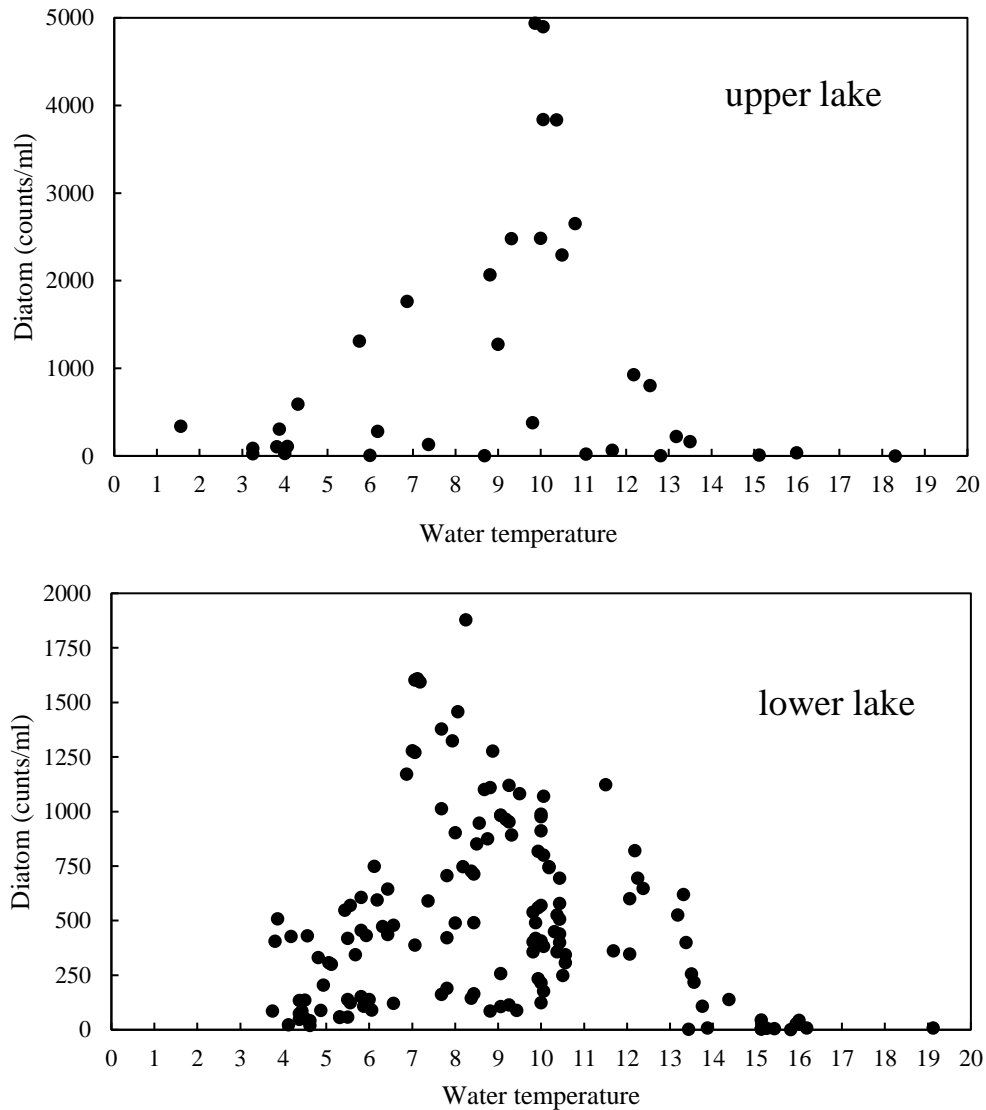


Figure 7.5 Effect of water temperature on the diatom concentration in Vartry Reservoir.

7.1.2 Hydraulic effects in Vartry Reservoir

During diatom bloom in 2017, water samples were taken along Vartry Reservoir. As presented in Figure 7.6, a small part of the upper lake was free of diatom bloom. The water surface area was about 53,000 m² with an average depth of 1.87 m. The diatom number and the silica concentration is shown in Figure 7.7.

Compared with the significant diatom bloom in the major part of the upper lake, the diatom concentration remained at a low level with a maximum number of 397 counts/mL. The silica concentration of these diatom free areas fluctuated within a small range and the minimum concentration of silica was 3.36 mg/L on 10th May. At the same time, the silica concentration was lower than 0.1 mg/L in other part of the upper lake.



Figure 7.6 Location of free diatom bloom zone in upper lake in 2017.

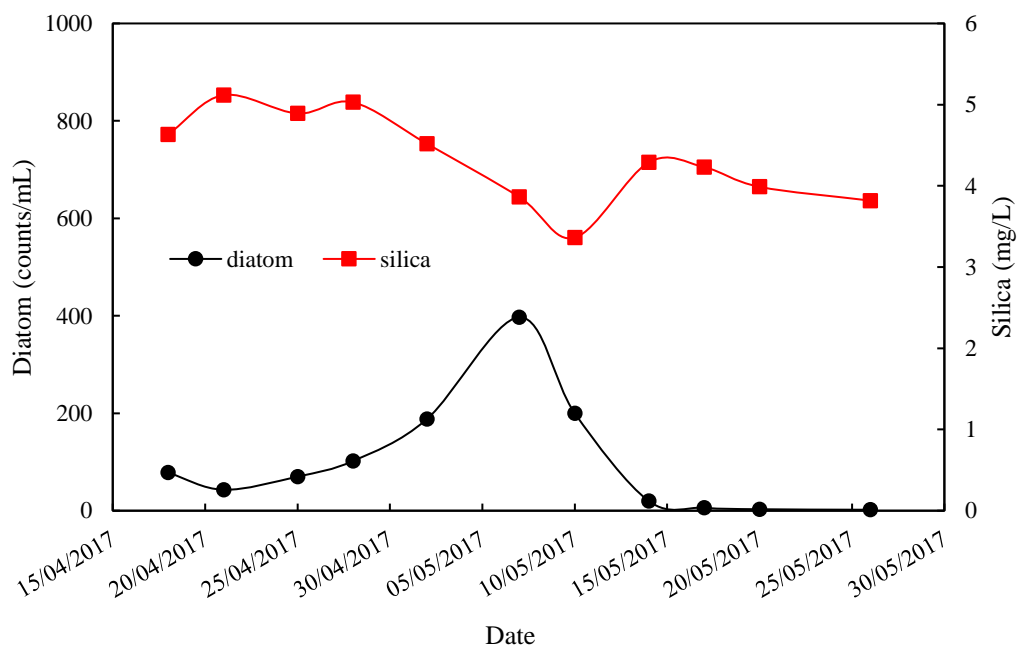


Figure 7.7 Diatom number and silica concentration in the diatom free zone of upper lake in 2017.

7.2 Weather conditions at Vartry Reservoir

7.2.1 Sunlight

7.2.1.1 Sunshine at Vartry Reservoir

The monthly average daily sunshine hours from 2012 to 2018 is shown in Table 7.1. At Vartry Reservoir, the minimum sunshine hours were recorded either in January or February every year. The average daily sunshine hour in April and May was much higher than that in January, February and March. As mentioned above, diatom bloom was serious since 2013. However, the average sunshine hour in 2013 was very low, especially in January and March.

Table 7.1 Monthly average daily sunshine hours (h) at Vartry Reservoir from 2012 to 2018.

	Jan	Feb	Mar	Apr	May
2012	2.0	2.1	4.5	5.5	6.2
2013	1.2	2.6	2.1	5.5	6.3
2014	2.1	3.5	4.0	6.2	3.8
2015	3.0	2.8	5.0	7.7	5.4
2016	2.1	2.7	3.9	4.7	6.8
2017	1.8	1.8	4.0	3.3	7.3
2018	2.3	3.9	2.6	4.9	7.2
Ave	2.1	2.8	3.7	5.4	6.1

As presented in Figure 7.8, the daily sunshine hour in January and February in 2017 was much lower than that in 2016 and 2018. In 2016, the average daily sunshine hour was 3.6 h during the diatom growth period (15/3/2016-15/4/2016). The values in 2017 and 2018 was 5.3 h and 2.9 h, respectively. The diatom growth in 2018 occurred from 5/3/2018 to 5/4/2018, which was much earlier than that in 2016 and 2017. As a result, the sunshine hours were very low.

Opposite phenomenon was observed in 2017--relatively high daily sunshine hour with delayed diatom growth period. During the diatom growth period in 2018, the sunshine hour was lower than 2 h in eight consecutive days from 26th February to 5th March. As a result, the diatom concentration declined from 749 counts/mL to 419 counts/mL.

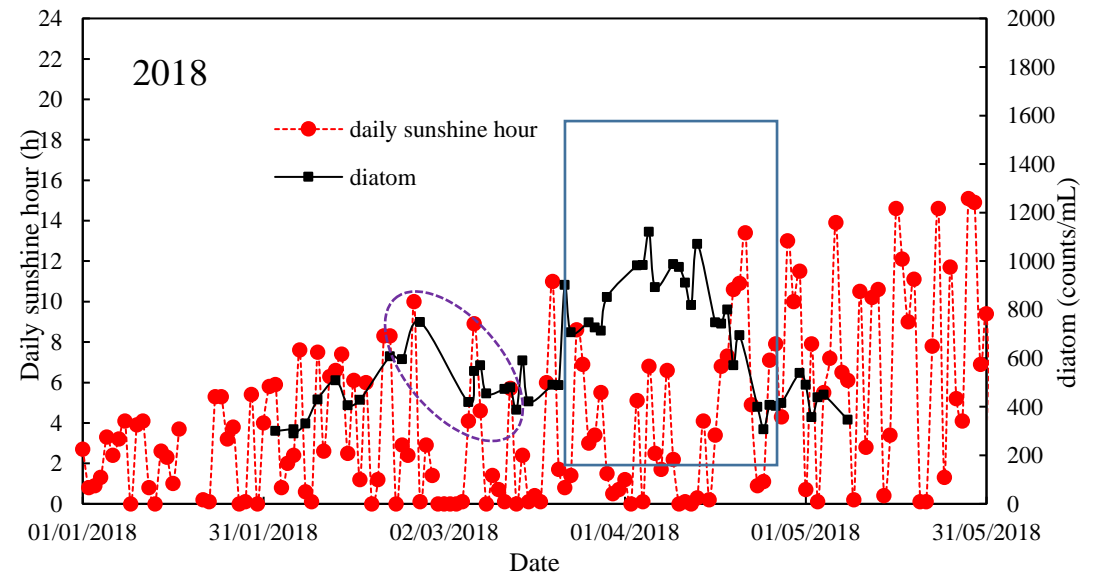
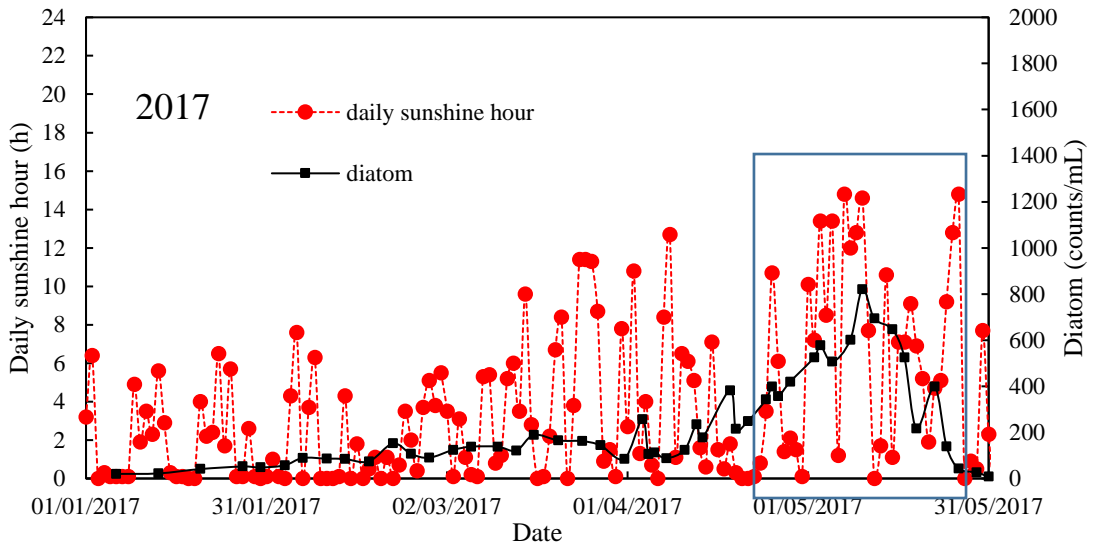
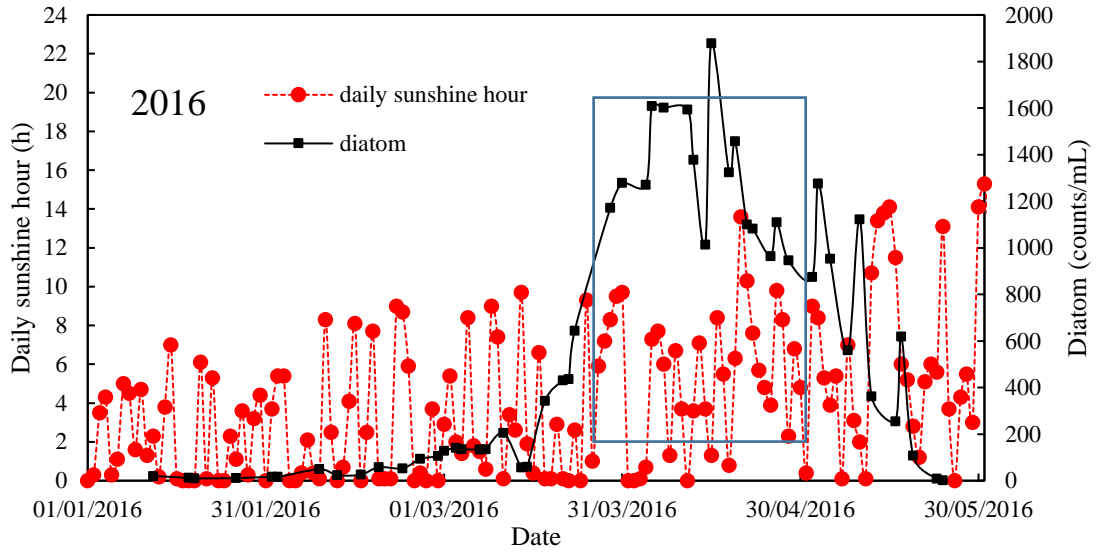


Figure 7.8 Daily sunshine hour at Vartry Reservoir during the diatom growth period from 2016 to 2018.

7.2.1.2 Effect of lighting conditions on diatom growth

The diatom number and the change of silica concentration at a depth of 0.5 m, 2 m, 4 m and 6 m in site A and site B in Vartry Reservoir are presented in Figure 7.9. The initial diatom number and silica concentration in Site A and Site B was 313 counts/mL, 5.99 mg/L and 209 counts/mL, 6.49 mg/L.

As shown in Figure 7.9, obvious diatom growth was observed in A-2 m. The number of diatom in A-2 m increased from 313 counts/mL to 5030 counts/mL on the 30th day and the silica concentration decreased from 5.99 mg/L to 1.54 mg/L during this period. Slight diatom growth existed in A-4 m with the number of diatom increased to 371 counts/mL. The concentration of silica in A-4 m dropped to 4.11 mg/L on the 30th day. In A-0.5 m and A-6 m, no diatom growth was observed and the silica concentration remained stable.

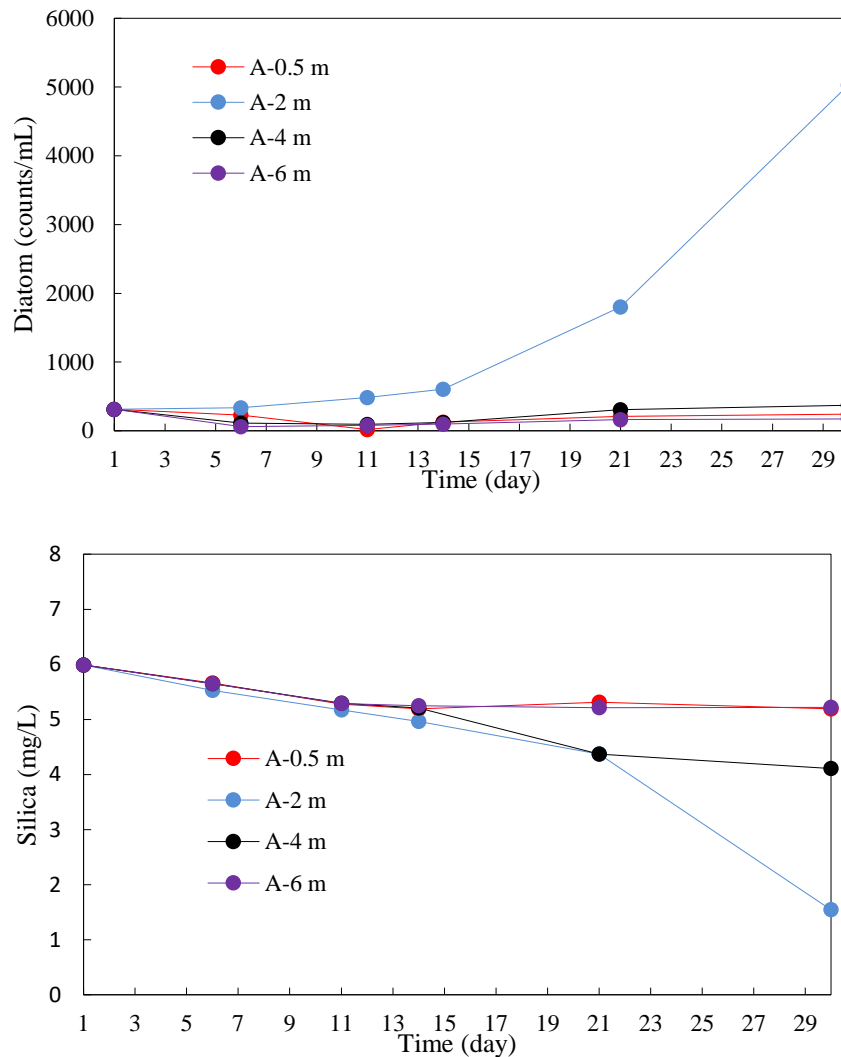


Figure 7.9 Diatom number and silica concentration at a depth of 0.5 m, 2 m, 4 m and 6 m in Site A in March to May 2017.

As shown in Figure 7.10, a similar change was also observed in site B. In B-2 m, the diatom amount raised from 209 counts/mL to 5151 counts/mL on the 34th day with the reduction of silica concentration from 6.49 mg/L to 1.65 mg/L. Compared with B-2 m, declination of diatom number was observed in B-0.5 m, B-4 m, B-6 m.

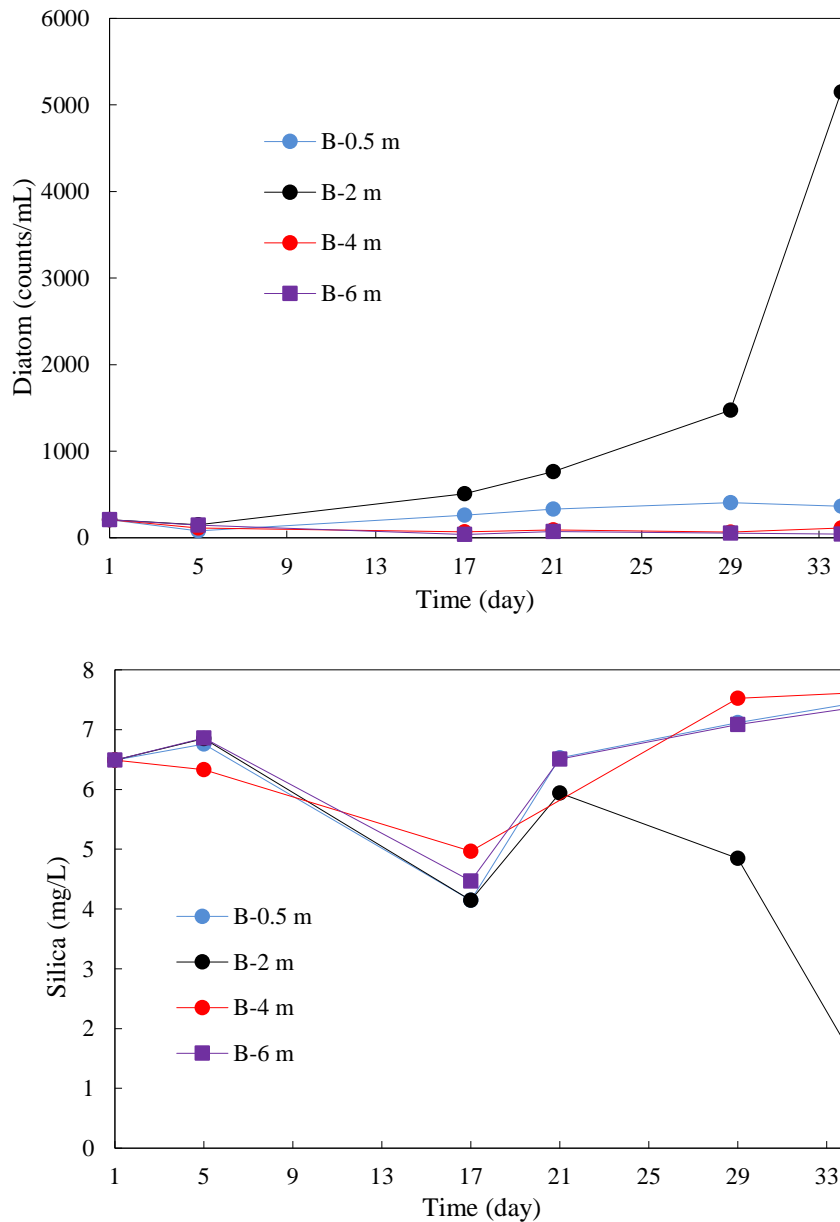


Figure 7.10 Diatom number and silica concentration at a depth of 0.5 m, 2 m, 4 m and 6 m in Site B in March to May 2017.

The diatom growth and the change of silica concentration at a depth of 1 m, 2 m, 3 m and 4 m is presented in Figure 7.11. The initial diatom number and silica concentration was 755 counts/mL and 3.02 mg/L.

The change of diatom and silica in C-1 m was similar to that in A-0.5 m and B-0.5 m. No diatom growth occurred and the concentration of silica remained stable. In C-2 m, the diatom number increased to 2528 counts/mL and the concentration of silica fell to 0.02 mg/L on the 13th day. In C-3 m, the silica concentration decreased from 3.02 mg/L to 1.13 mg/L on the 19th day. During this period, the amount of diatom raised up to 2770 counts/mL. Compared with C-2 m and C-3 m, the reduction of silica in C-4 m was less with the concentration of 2.33 mg/L on the 19th day. The diatom number increased from 755 counts/mL to 3103 counts/mL.

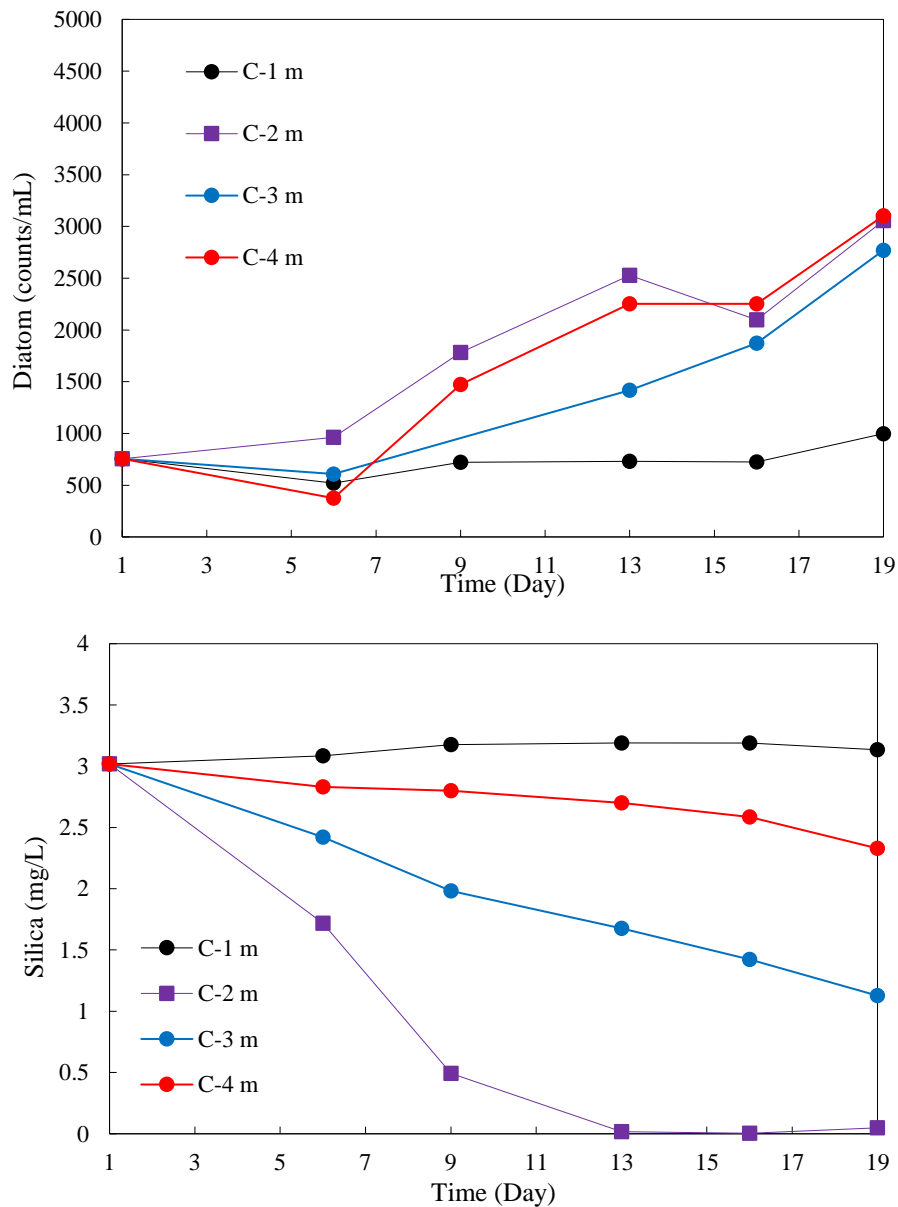


Figure 7.11 Diatom number and silica concentration at the depth of 1 m, 2 m, 3 m and 4 m in Vartry Reservoir in March to May 2017.

7.2.2 Rainfall

The annual and monthly rainfall at Vartry Reservoir from 1996 to 2018 is presented in Figure 7.12 and Table 7.2.

Table 7.2 Monthly average rainfall (mm) at Vartry Reservoir from 1996 to 2018.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996	305.7	101.4	143.5	81	98.4	28.6	43.5	83.9	43.7	180.6	204.4	76.6
1997	27.8	120.7	14.8	34.8	69.7	192.3	31.4	169.2	31.7	120	317.4	171.1
1998	162.5	16	81.8	198.9	47.6	156.4	50.2	35.3	148.6	156.8	135.8	151.1
1999	124.1	45.9	42.6	141.9	78.2	48.7	16.7	133.2	237.2	94.6	79.4	140.4
2000	56.4	78.6	18	146.1	61.5	40.5	32.8	76.9	153.4	136.4	281	252.8
2001	102.6	87.2	165.4	90.5	32.5	42.1	62.9	93.3	52.6	167.5	29.8	66.6
2002	161.9	164.9	78.7	102.9	199.5	58.1	42.2	74.5	12.7	258.1	301.9	180.4
2003	110.8	86.7	62.3	106.4	117.2	143	75.7	10.6	46.4	160.7	135.4	115.4
2004	136	44.4	130	65.6	61.6	92	43	149.7	76.8	187.1	51.5	60.9
2005	122.7	69.3	88.5	117	90.8	26.3	91.7	41	64.6	245.9	106.7	89.3
2006	64.8	59.1	181.6	29.3	124.7	33.3	71	50.9	159.5	166	162.6	167.9
2007	97.7	122.5	85.6	20.4	44.1	140.9	107	86.9	52	34.2	75.8	92.1
2008	160	45.2	142	36.9	56.6	93.2	199.1	156	151.3	146.9	69.5	51.4
2009	201.9	75.9	28.1	146.5	83.6	111.5	211.7	96.8	39.4	193.6	315.1	190.2
2010	139	71.1	93.4	38.4	67.2	59.4	107.6	33.5	137.9	82.9	191.1	91.8
2011	57.1	172.2	26.1	27.6	104.6	104.7	50.8	27.1	85.5	160.2	131.6	79.2
2012	104.9	30.6	24.2	161.8	69.7	273.9	111.9	239.4	79.8	95.8	164	125.7
2013	187.4	50.9	191.2	59.1	92.4	53	30.2	33.9	45.6	264.5	35.6	184
2014	223.9	261.4	74.5	78.2	131.3	47.4	63.9	187.1	25	202.2	247.8	58.3
2015											121.5	193.5
2016	118.4	59.7	36.3	88.2	46.8	58.5	43.7	61.9	56.6	60	36.9	46.6
2017	21.9	41.6	67.2	10	43.5	86.4	42.2	73.2	82.3	47.8	81.5	63.1
2018	93.1	36.9	100	68.9	19.1	4.8	40	48	43.8	42.6	131.2	81
Ave	126.4	83.7	85.3	84.1	79.1	86.1	71.3	89.2	83.0	145.7	148.2	118.7

The annual mean rainfall in Vartry Reservoir was 1199 ± 272 mm. The highest rainfall was recorded in 2002 and 2009 with the values of 1636 mm and 1694 mm. Compared with the previous year, the rainfall in 2016, 2017 and 2018 was low with the values of 714 mm, 661 mm and 709 mm, respectively. Normally, the rainfall in Oct, Nov, Dec and Jan was higher than other months. Flood could lead to serious reduction of diatom number (Lund 1950). In this study, the influence of rainfall for diatom growth was not obvious.

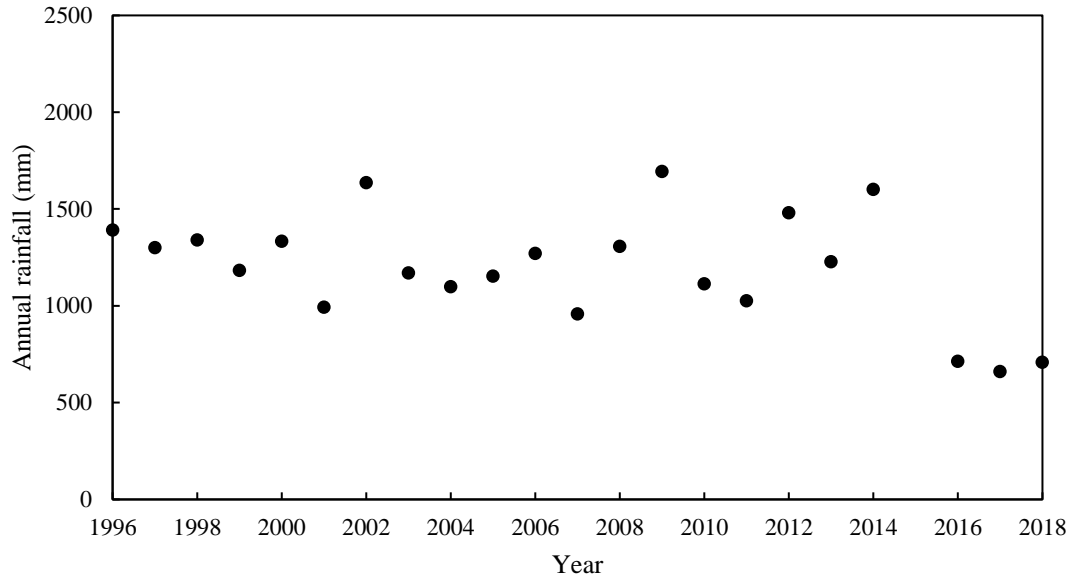


Figure 7.12 Annual rainfall at Vartry Reservoir from 1996 to 2018.

7.2.3 Air temperature

The monthly mean air temperature at Vartry Reservoir from 1996 to 2018 is shown in Figure 7.13. At Vartry Reservoir area, air temperature in December, January and February was much colder than other month. The highest air temperature normally recorded in July and August. From 1996 to 2018, the average air temperature was 5.22 ± 1.16 °C in Jan, 5.23 ± 1.25 °C in Feb, 6.30 ± 1.24 °C in Mar, 8.01 ± 1.08 °C in Apr, 10.69 ± 0.79 °C in May and 13.35 ± 0.80 °C in Jun. The average air temperature form July to December was 15.13 ± 0.87 °C, 14.92 ± 0.64 °C, 13.10 ± 0.73 °C, 10.40 ± 1.04 °C, 7.29 ± 1.11 °C and 5.54 ± 1.64 °C.

The lowest temperature recorded in January and February occurred in 2010 with the values of 1.7 °C and 2.3 °C. The coldest March was observed in 2013 and the average temperature was 3.1 °C. The March in 2012 and 2017 was mild with the temperature of 8.0 °C and 7.7 °C. The highest and lowest temperature in April was 10.6 °C in 2007 and 6.2 °C in 2016, respectively.

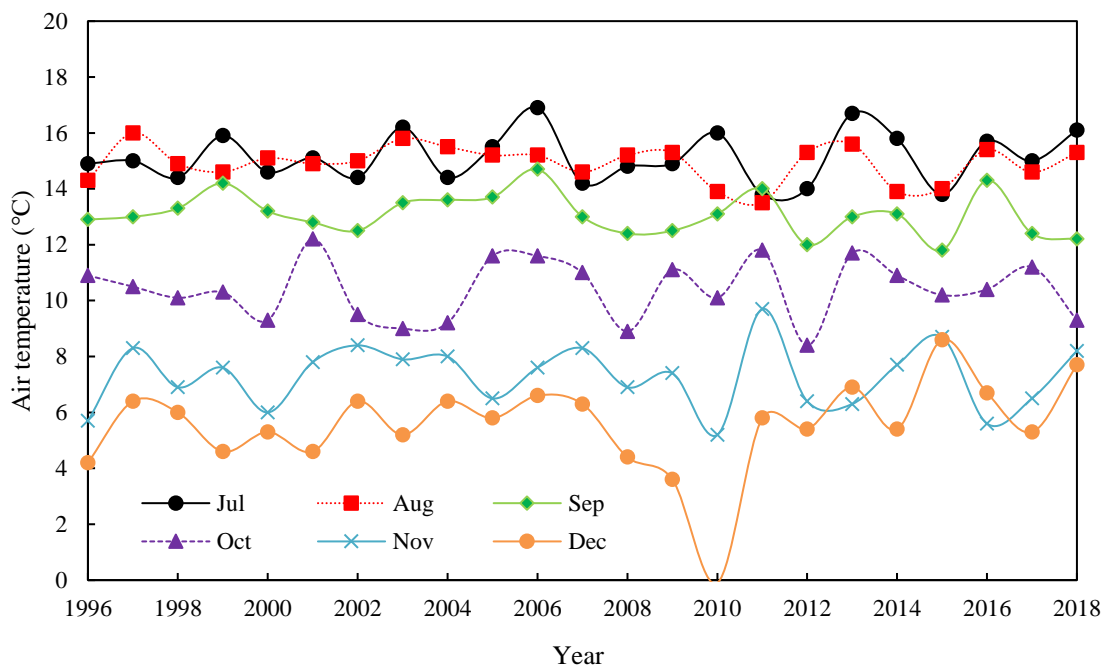
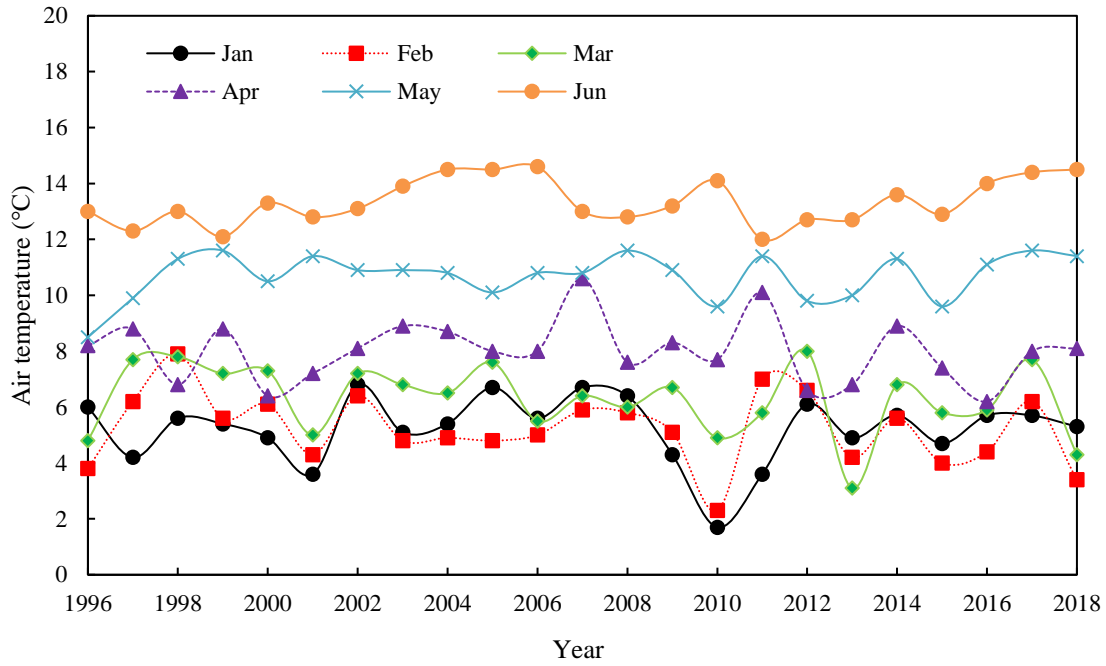


Figure 7.13 Monthly mean air temperature at Vартry Reservoir from 1996 to 2018.

7.3 Discussion

7.3.1 Correlation analysis and model analysis

7.3.1.1 Correlation analysis of diatom growth factors

The correlation analysis of diatom growth factors in the upper lake and lower lake is illustrated in Table 7.3 and Table 7.4 and the result of a principle component analysis is shown in Figure 7.14 and Figure 7.14.

Table 7.3 Correlation analysis of diatom growth factors in upper lake (data from 2016 to 2018).

	diatom	SiO ₂	TON	zooplankton	sunshine	rainfall	water temperature
diatom	1						
SiO ₂	-0.520	1					
TON	-0.119	0.571	1				
zooplankton	-0.109	-0.611	-0.662	1			
sunshine	0.0844	-0.451	-0.135	0.347	1		
rainfall	-0.231	0.325	0.243	-0.167	-0.231	1	
water temperature	0.107	-0.765	-0.790	0.792	0.316	-0.276	1

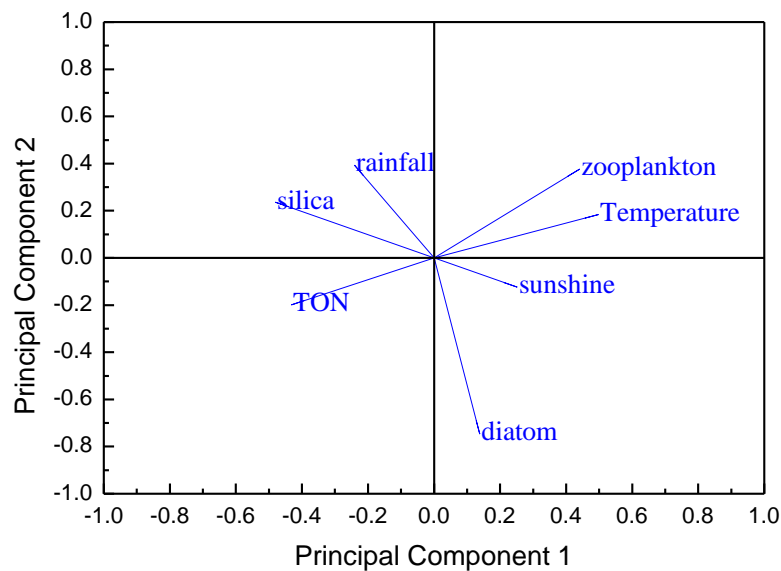


Figure 7.14 Principle component analysis of diatom growth with environmental variables in upper lake from 2016 to 2018.

Table 7.4 Correlation analysis of diatom growth factors in lower lake (data from 2016 to 2018).

	diatom	SiO ₂	TON	zooplankton	sunshine	rainfall	water temperature
diatom	1						
SiO ₂	-0.428	1					
TON	-	0.284	1				
zooplankton	-	-0.387	-0.461	1			
sunshine	0.109	-0.257	-	0.162	1		
rainfall	0.158	0.0036	0.273	-0.0945	-0.273	1	
water temperature	-	-0.653	-0.399	0.505	0.286	-0.0575	1

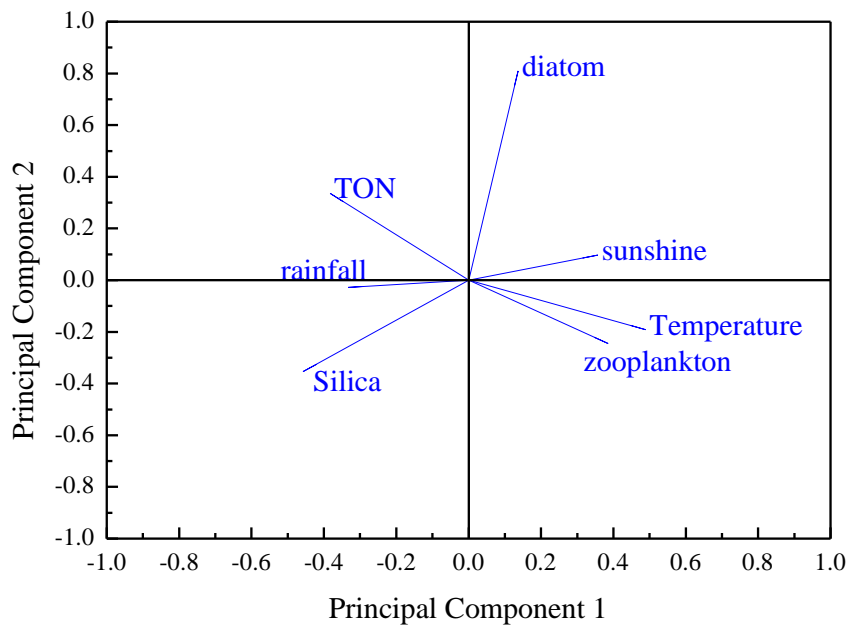


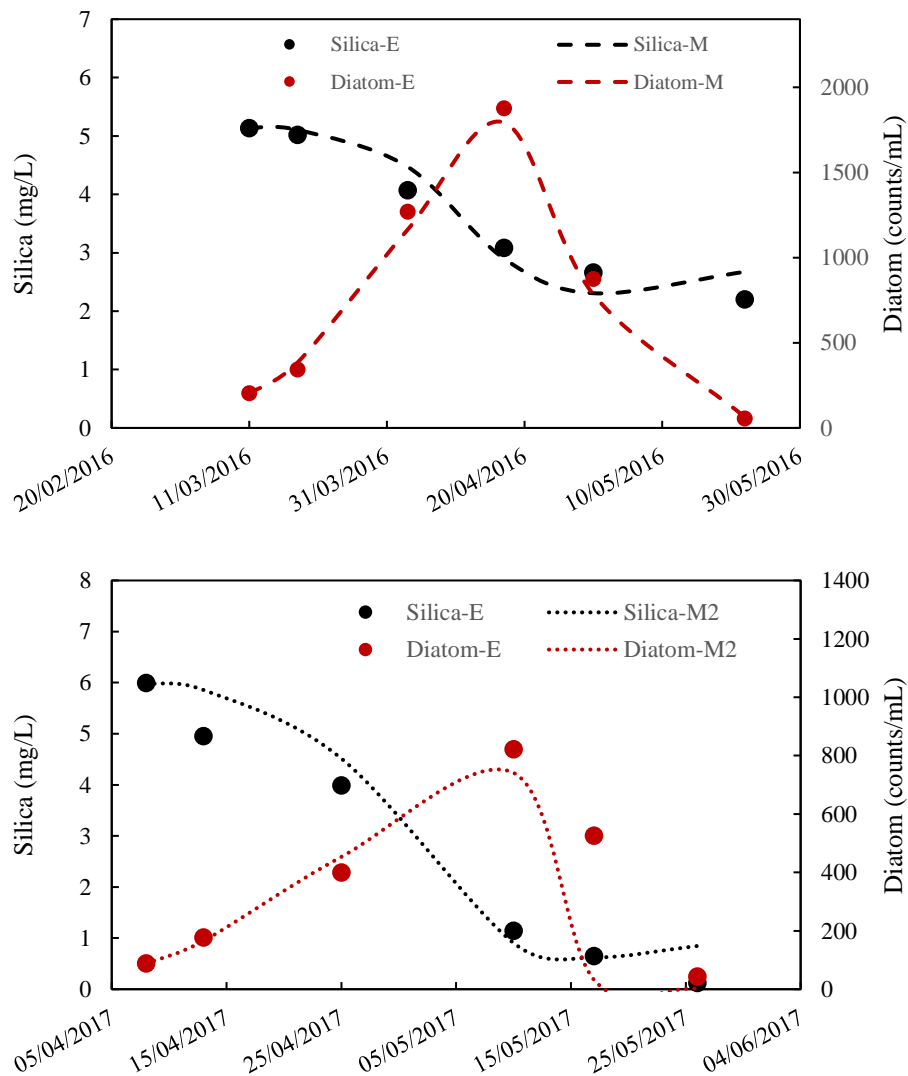
Figure 7.15 Principle component analysis of diatom growth with environmental variables in lower lake from 2016 to 2018.

There was a significant negative correlation between diatom and silica with the coefficient of -0.520 in the upper lake and -0.428 in the lower lake, which suggested that the diatom growth with the consumption of silica. However, other factors include nitrogen, zooplankton, sunshine, rainfall and water temperature exhibited no correlation with diatom bloom neither in the upper lake nor the lower lake.

As shown in Table 7.3 and Table 7.4, water temperature exhibited positive correlation with the amount of zooplankton. The correlation coefficient in the upper lake and the lower lake were 0.792 and 0.505, respectively.

7.3.1.2 Model analysis

Based on the data collected in Vartry Reservoir from 2016 to 2018, we used the equation in Chapter 3.4 to monitor the change of diatom number and silica concentration and the result of model analysis is presented in Figure 7.16. Combined field work result with model analysis, it is deduced that sinking loss and the predation of zooplankton should be the major contractor for the collapse of diatom bloom.



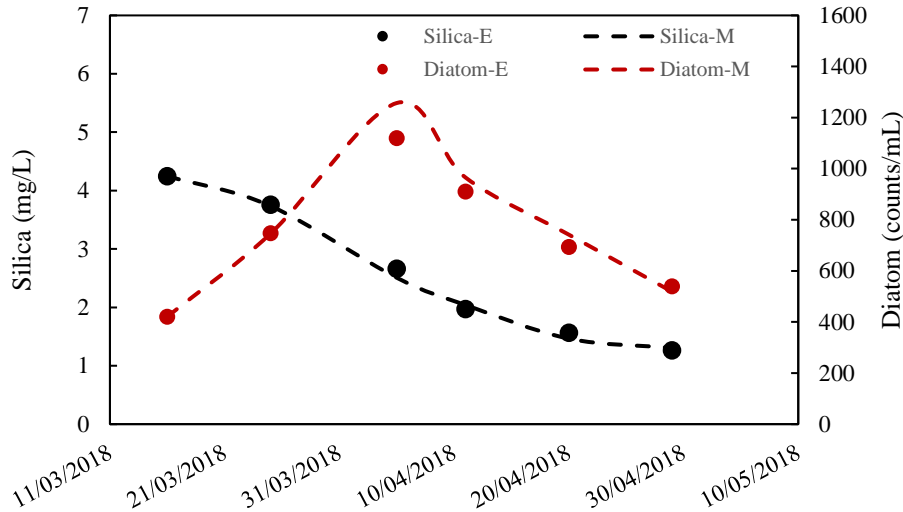


Figure 7.16 The result of model analysis.

7.3.2 Water temperature

Unlike other algal, diatom bloom occurred in spring with low temperature. In Vartry Reservoir, the suitable water temperature for diatom growth was about 6.5 °C to 11 °C. In the study of Bertrand (2003), Lund (1950), *Asterionella* was the dominant species with the water temperature lower than 10°C. The maximum abundance of diatom was reached in the study of Lee et al. (2014) with a water temperature of 7 °C.

Water temperature may affect the time of diatom growth. In the study of Winder et al. (2012), diatom bloom time was advanced with higher water temperature. However, in Vartry Reservoir, the time of diatom bloom was not influenced by the water temperature. The average water temperature in 2017 from Jan to April was 4.58 °C, 5.05 °C, 7.16 °C and 9.94 °C, which was higher than the water temperature in 2018 (Jan 3.79 °C, Feb 3.63 °C, Mar 3.31°C and Apr 7.89 °C). But diatom bloom in 2018 was not postponed by the low water temperature.

7.3.3 Thermal stratification

Thermal stratification normally formed in Vartry Reservoir at the beginning of May with the water temperature of 11 °C. The thermal stratification can lead to serious reduction of diatom number. In the study of Kilham et al. (1996), the decreasing population of *Asterionella* was observed when stratification occurred in Yellowstone Lake. The mixing of the water column is vital for the growth of diatom. As the density of the diatom is slightly higher than water, the diatom sinks out the euphotic area when the thermal stratification established in the reservoir. Similar results were obtained in the study of Fadel et al. (2015) and Ferris and Lehman (2007). As is presented in Figure 7.4, the diatom concentration decreased from 618 counts/mL to 272

counts/mL due to the 4-day stratification. The value of diatom went back to 466 counts/mL when the water remixed. This phenomenon may also occurred in the upper lake in 2017 (Figure 4.6). The number of diatom decreased from 4900 counts/mL in 18th April to 2293 counts/mL in 21st April and 2484 counts/mL in 25th April. Then the value increased to 4940 counts/mL in 28th April. The sudden water temperature rise was recorded by the sensor in the lower lake from 19th April to 24th April which could result in that short-term stratification occurred in the upper lake. During this period, the diatom tends to sink in the water column when the short-term stratification ended the diatom re-suspended in the mixing water.

7.3.4 Hydraulic effects

In Vartry Reservoir, a diatom free zone existed in the upper lake in 2017. The formation of this diatom free area was due to the short hydraulic dynamic time (HRT). U3 was the major feeding river of this area with the flow rate of 1500 m³/h. The water capacity (V) of the area was about 99000 m³ so the HRT of this area was less than 3 days. The HRT of the reservoir was about 180 days which was much higher than that of the diatom free area. Ferris and Lehman (2007) studied diatom bloom dynamics in Ford Lake, Michigan. It has been found that diatom bloom was serious with almost depleted silica in the lake when the flushing time was higher than 20 d. The decreasing of silica concentration in the lake was not obvious when the flushing time was lower than 10 days.

7.3.5 Sunlight

The growth rate of diatom at different water depth in the reservoir is shown in Figure 7.17. The growth of diatom was prohibited at a depth of 0.5 m and 1 m. The maximum growth rate was achieved at a depth of 2 m and the growth rate declined with the increasing of depth. A similar result was also obtained in the study of Talling et al. (1955). Light saturation point existed in the surface water layer, so the diatom growth was inhibited. In the study of, Cao et al. (2011), the strong light intensive was unfavourable for the growth of algae. Kain et al. (1958) studied the growth rate of *Asterionella* with different light intensity. The growth rate increased when the light intensity strengthens from 2000 lux to 6000 lux. No inhibition of diatom growth was observed with the light intensity of 10000 lux.

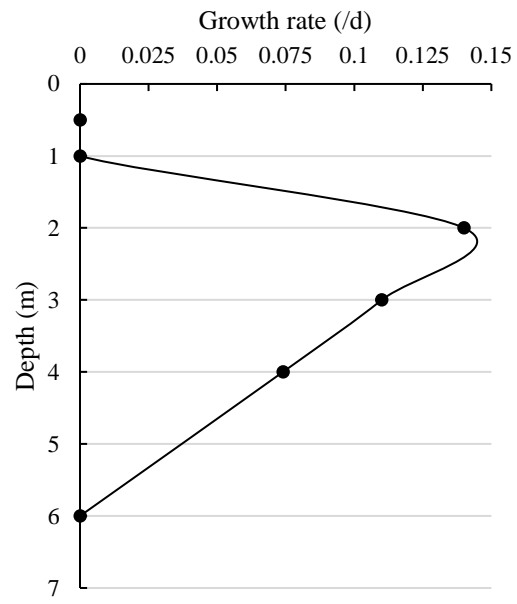


Figure 7.17 The growth rate of diatom at different depth in Vartry Reservoir.

Chapter 8

Impacts and measures to deal with diatom bloom in Vartry Reservoir

8 Impacts and measures to deal with diatom bloom in Vartry Reservoir

8.1 The impacts of diatom bloom

As shown in Figure 8.1 and Figure 8.2, the growth of diatom in the reservoir affected the water transparency directly. In the upper lake, the average transparency was 2.34 (± 0.3) m without the influence of diatom. In 2017, the transparency reached as low as 1.20 m during diatom bloom period. Compared with diatom bloom in 2017, the peaked diatom values were much lower. Therefore, the transparency was 1.62 m during diatom bloom in 2018.

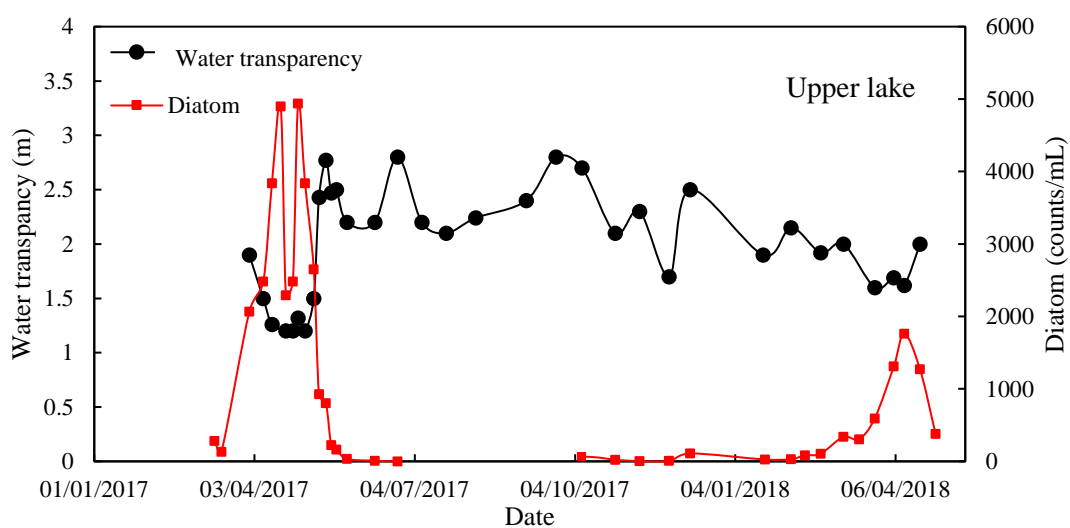


Figure 8.1 Water transparency in upper lake in 2017 and 2018.

As presented in Figure 8.2, the transparency in the lower lake fluctuated between 4.00 m to 1.97 m with the average values of 2.46 m during the water clear water phase (no diatom). The lowest transparency observed during diatom bloom was 1.8 m in 2016, 1.5 m in 2017 and 1.66 m in 2018, respectively.

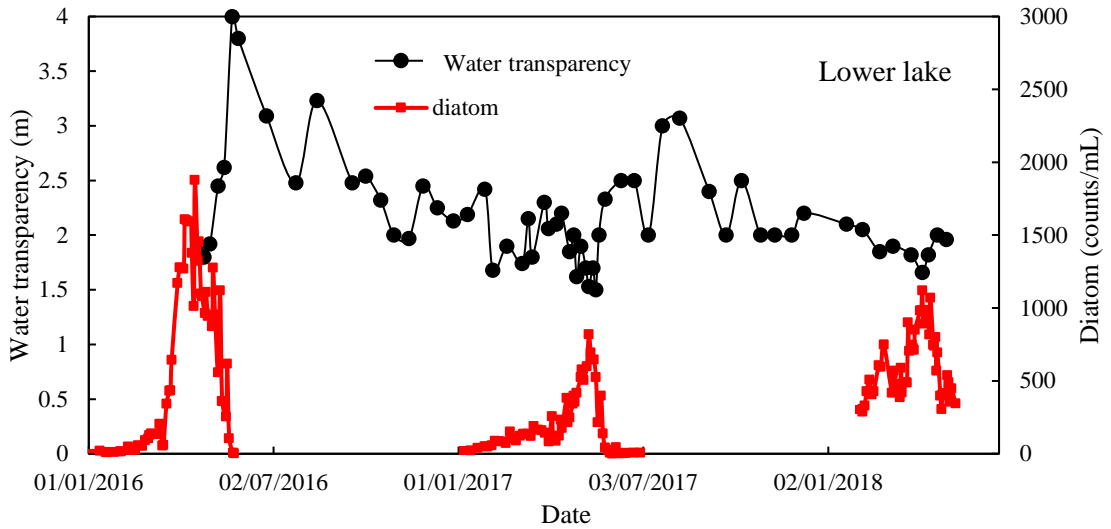


Figure 8.2 Water transparency in lower lake from 2016 to 2018.

In Vartry water treatment plant, slow sand filters are used for the water purification. As shown in Figure 8.3, the values of volatile suspended solids (VSS) in the influent increased with the growth of diatom. The particles filtered by the sand bed majorly originated from the influent with the values of 79.42%. So, more particulate was filtered by the sand (Figure 8.4) during diatom bloom period. As a result, increasing clearing frequency of the surface sand bed was required in order to ensure the smooth operation of water treatment.

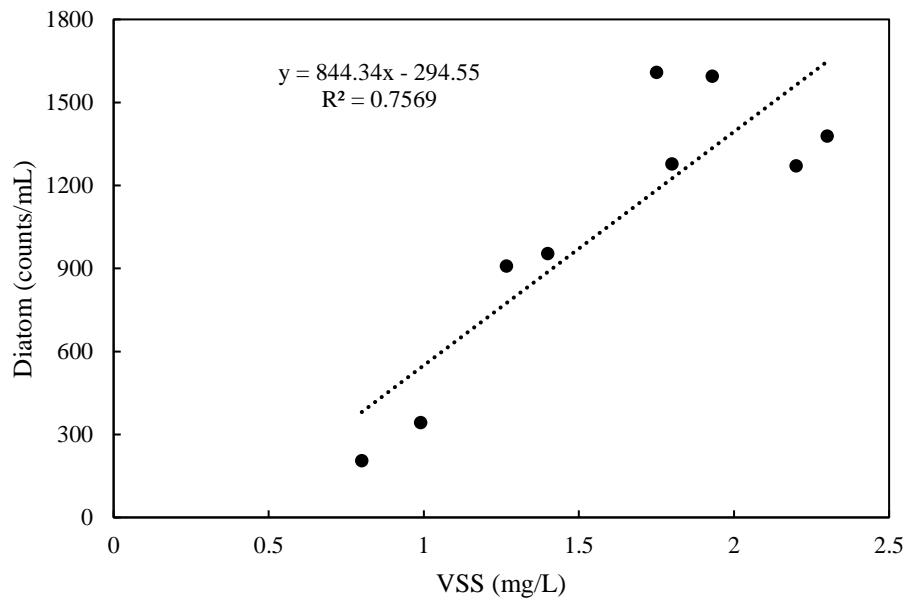


Figure 8.3 The relation between diatom number and VSS in the influent of Vartry water treatment plant.

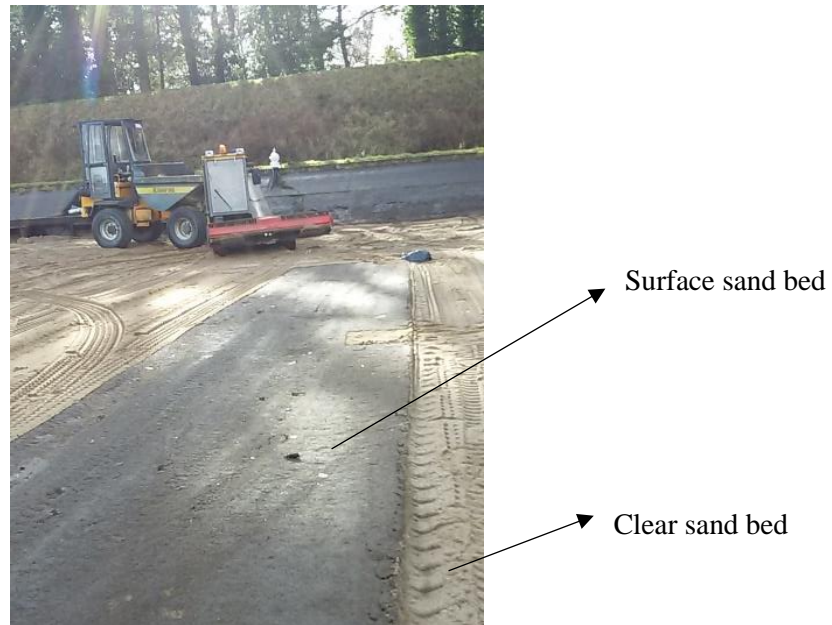


Figure 8.4 The slow sand filter in Vartry water treatment plant during the sand clearing phase.

8.2 The measures to deal with diatom bloom

8.2.1 Coagulation

Jar test (Figure 8.5 and Figure 8.6) were carried out in the lab. Aluminium sulphate ($\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$) and Ferric chloride ($\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$) were used as the coagulant to remove the diatom.

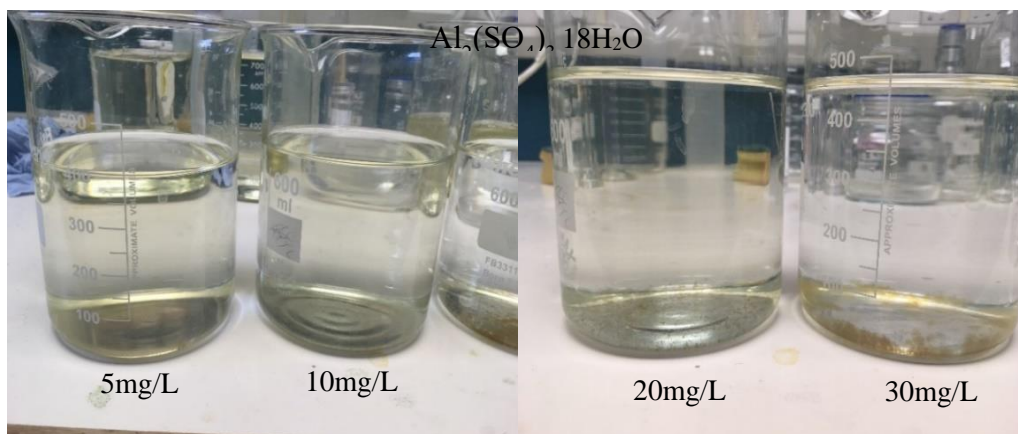


Figure 8.5 Coagulation with $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$.

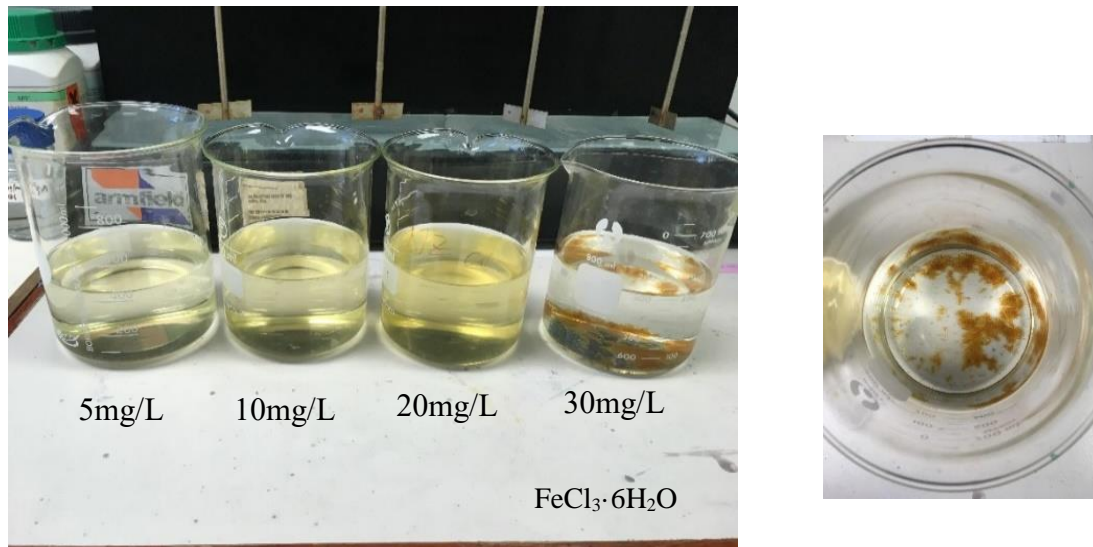


Figure 8.6 Coagulation with $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$.

The initial diatom concentration was 3905 counts/mL and the dominant diatom species were *Asterionella* (3605 counts/mL) and *Synedra* (220 counts/mL). The dose of coagulant was 0, 10 mg/L and 30 mg/L. The total diatom removal rate is shown in Figure 8.7 (a) and the removal rate of *Asterionella* and *Synedra* is in Figure 8.7 (b).

The total diatom removal efficiencies of $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ and $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ were 58.00%, 96.90% and 50.14%, 99.49% with the concentrations of 10 mg/L and 30 mg/L. The removal rate of *Synedra* and *Asterionella* was 85% and 54.51% when the dose of $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ was 10 mg/L. For $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$, the removal efficiency of *Synedra* and *Asterionella* was 64.04% and 45.99% with the dose of 10 mg/L. The removal rate of *Asterionella* and *Synedra* was higher than 95% when the dose of coagulant was 30 mg/L.

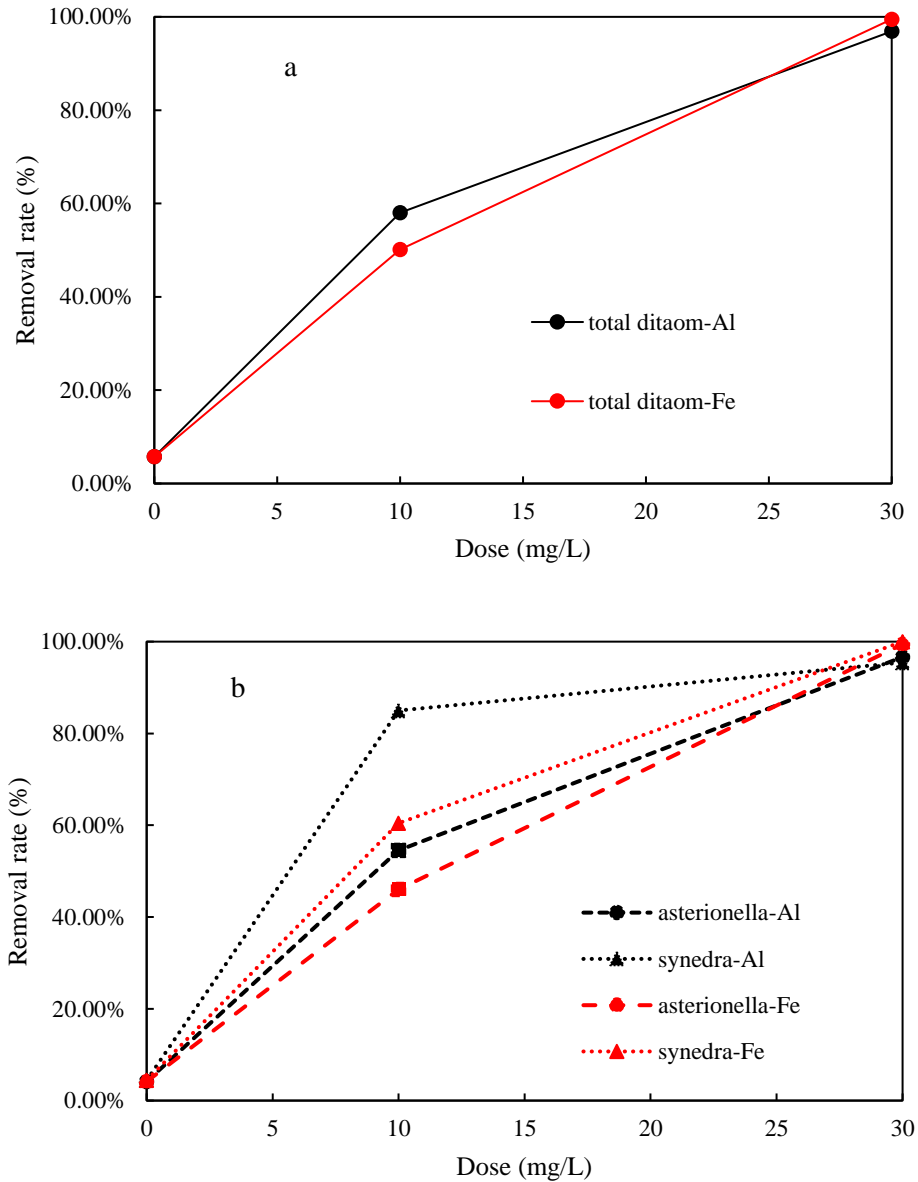
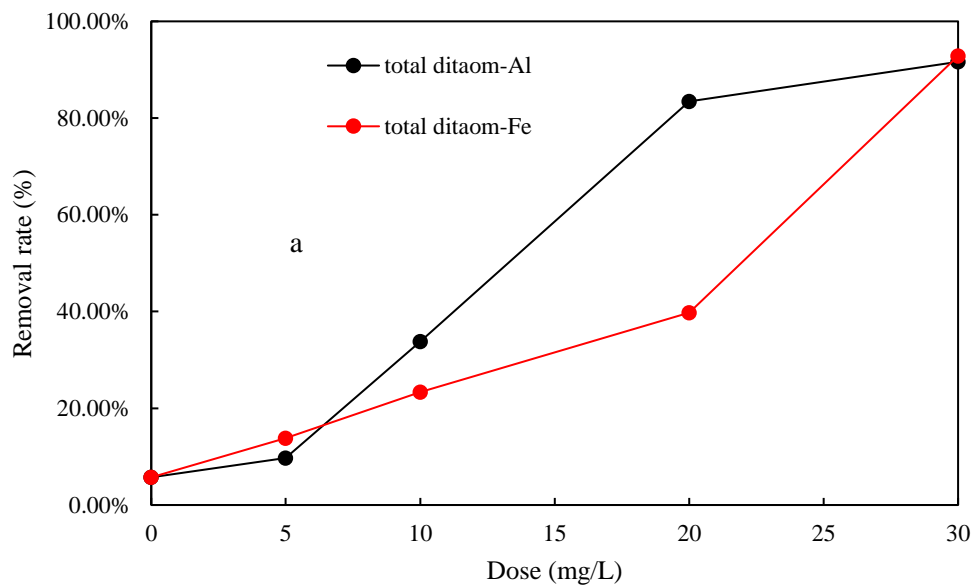


Figure 8.7 Removal rate of coagulation with different dose (initial diatom number 3905 counts/mL).

The total diatom removal rate of coagulant with different dose are shown in Figure 8.8 (a) and the initial diatom concentration was 1855 counts/mL. The removal efficiencies of $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ were 9.74% and 33.79% with the concentrations of 5 mg/L and 10 mg/L. The removal rates increased significantly to 83.42% when the dose was increased to 20 mg/L. The removal rate of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ was lower than 40% with a dose of less than 20 mg/L. It increased from 39.8% to 92.84% when the dose concentration of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ increased from 20 mg/L to 30 mg/L.

The removal efficiency of *Asterionella* and *Synedra* with different doses are shown in Figure 8.8 (b) and the initial number of *Asterionella* and *Synedra* was 1558 counts/mL and 262 counts/mL. For $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$, the removal efficiency of *Asterionella* and *Synedra* was 9.41% and 10.00% with the dose of 5 mg/L. This value increased to 36.87% and 20.00% when the dose of $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ was 10 mg/L. Increasing the dose of $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ to 20 mg/L and 30 mg/L, the removal efficiency of *Asterionella* and *Synedra* was 83.66%, 80.75% and 91.74%, 93.25%, respectively. The removal rate of *Asterionella* and *Synedra* was 15.29%, 10.57% and 24.24% 16.26% with the $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ dose of 5 mg/L and 10 mg/L. When the dose of $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ was 20 mg/L, the removal efficiency of *Asterionella* and *Synedra* was 39.53% and 43.09%, which was much lower than that of $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$. The removal rate of *Asterionella* and *Synedra* was 92.87% and 91.87% with the $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ dose of 30 mg/L.



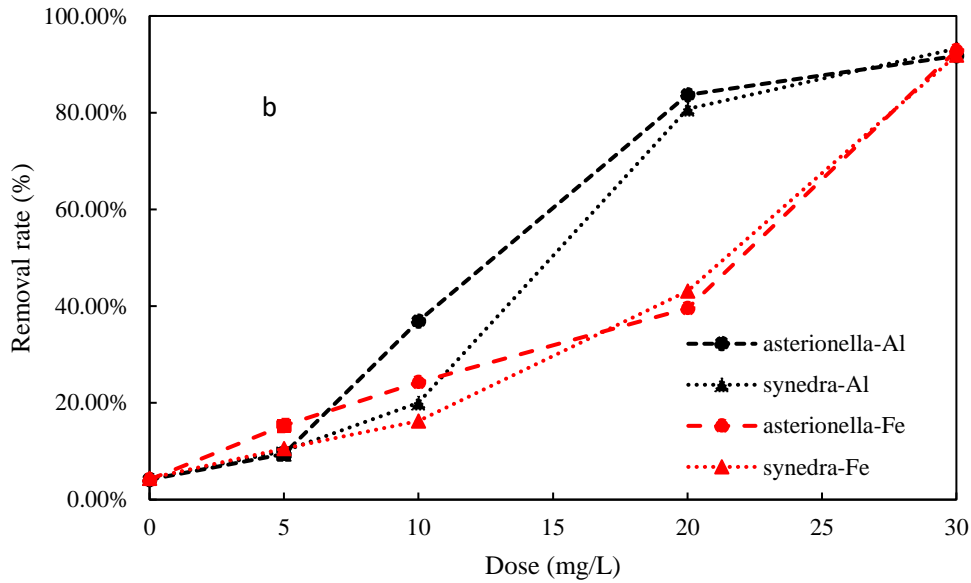


Figure 8.8 Removal rate of coagulation with different dose (initial diatom number 1855 counts/ml).

8.2.2 Filtration

Filtration can also be used for the removal of diatom. The initial total diatom concentration was 1432 counts/mL and the number of *Asterionella*, *Melsoria*, *Synedra* and *Tabellaria* were 1319 counts/mL, 10 counts/mL, 83 counts/mL and 20 counts/mL, respectively. The removal rates of the filter net with mesh size of 150 μ m and 63 μ m were 18.09% and 19.27%, respectively.

The results of denim and filter net with different mesh size are shown in Figure 8.9. The initial diatom concentration was 456 counts/mL and the dominant diatom species were *Asterionella* (438 counts/mL). The removal rate of denim was the highest (78.95%). It is obvious that the larger the mesh size the lower the removal rate. The removal efficiency of the filter net with the mesh size of 150 μ m and 63 μ m was 8.33% and 29.82%, respectively. After repeating the filtration process four times, the removal rate increased to 41.67% and 77.19%, respectively.

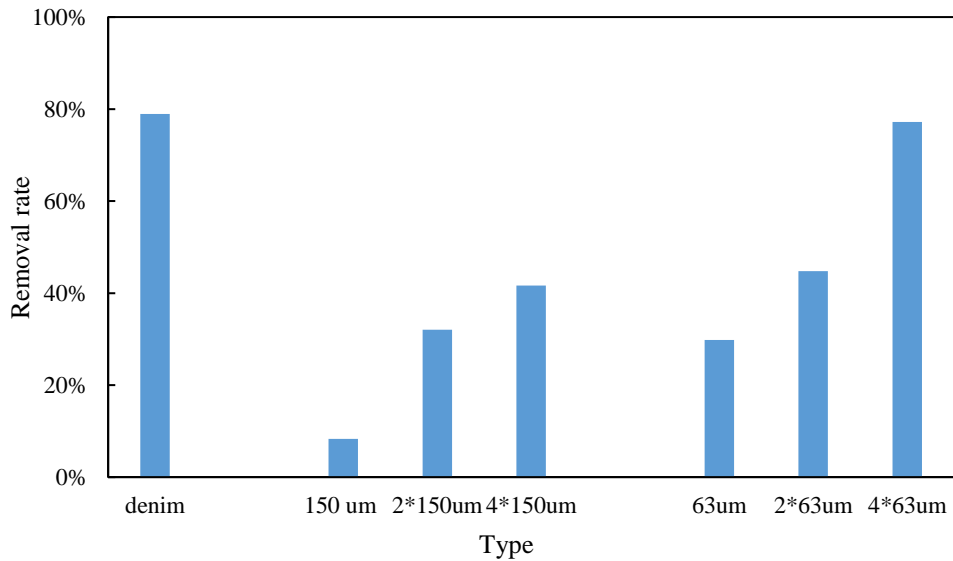


Figure 8.9 The removal efficiency of filtration.

8.3 Discussion

8.3.1 *The impact of diatom bloom*

Diatom bloom influenced the colour of water. During diatom bloom period, the colour of water in Vartry Reservoir turned to light olive (Figure 8.10).

In Vartry water treatment plant, the slow sand filters were blocked within a short time during diatom bloom period and the surface sand bed were required washing very often. As a result, the treatment capacity of the water treatment plant decreased significantly from 75 million litres per day to 40 million litres per day.

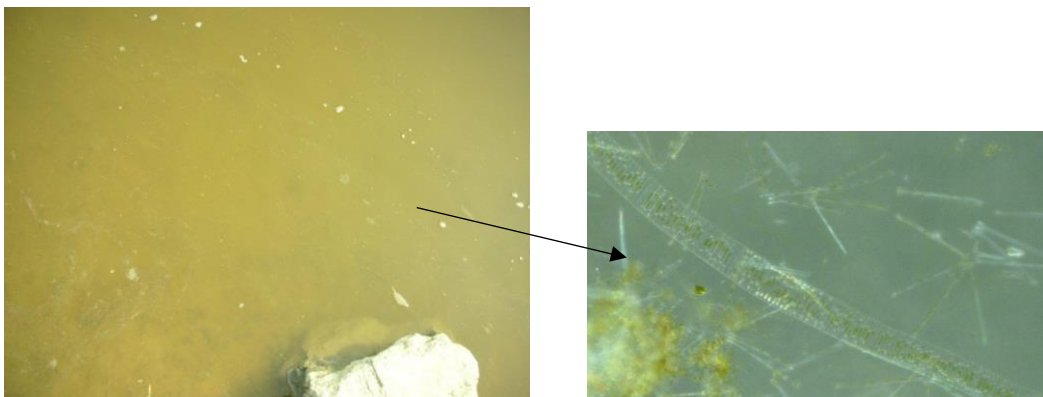


Figure 8.10 The colour of water during diatom bloom in Vartry reservoir.

8.3.2 *Measures to deal with diatom bloom*

Diatom bloom occurred in specific conditions. It was affected by conditions such as nutrient, weather, as well as biological and hydrodynamic factors. To control any of these factors could limit the growth of diatom. The following measures could be considered to mitigate diatom bloom. The advantages and disadvantages of different measures is shown in Table 8.1.

- (1) The limitation of nutrient entering the reservoir was meaningful for the long-term protection of water quality in Vartry reservoir. Reducing the concentration of phosphorus could lower the magnitude of diatom bloom in Vartry Reservoir.

- (2) Reducing the illumination can also limit the growth of diatom. As shown in Figure 8.11, no diatom growth was observed in dark condition. The initial diatom number in the blank and dark one was 634 counts/mL and 560 counts/mL and the silica concentration was 4.17 mg/L and 4.15 mg/L, respectively. In the blank one, the number of diatom increased to 2756 counts/mL at the 11th day and then decreased to 1589 counts/mL at the 17th day. The silica concentration dropped down to 1.98 mg/L during this period. In the dark one, the number of diatom declined to 238 counts/mL at the 17th day and the silica concentration remained at around 4 mg/L.

Covering a small portion of the reservoir may not benefit diatom algae control because during the algae bloom period Vartry Reservoir is well mixed and the diatoms are evenly distributed around the reservoir. Covering the whole Vartry Reservoir with membrane/black balls would have a negative impact on the ecosystem of the reservoir.

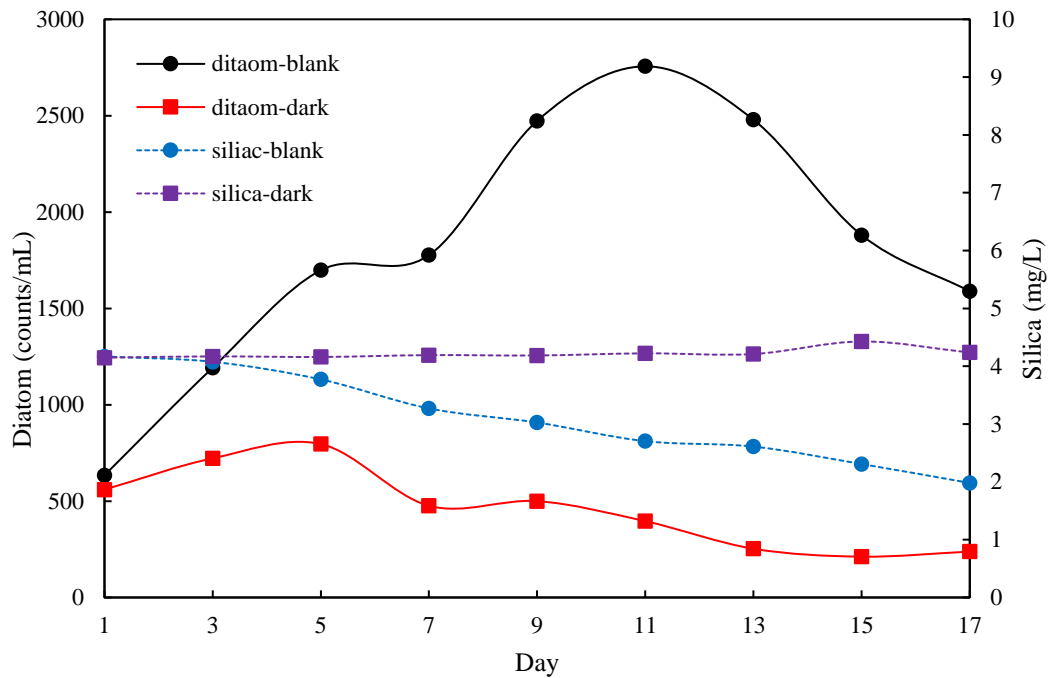


Figure 8.11 Diatom number and silica concentration under different lighting condition.

- (3) Altering the hydraulic condition in Vartry Reservoir could affect the growth of diatom. Light saturation point existed in the surface water layer, so the diatom growth was inhibited. But it is not practical in Vartry Reservoir to reduce the water depth to 1 m. Thermal stratification will end diatom algae bloom. Stratification forms when the water temperature increase to around 11 °C. Reducing the water level in lower reservoir may facilitate the formation of stratification earlier.
- (4) Increasing the number of zooplankton especially daphnia and copepods in the reservoir could effectively control the diatom growth. Based on lab work results, the growth of diatom could be fully limited when the ratio of diatom number and zooplankton number lower than 14.4×10^3 . Reducing the population of fish might also contribute to the augment of zooplankton but future investigation is required.
- (5) In Vartry water treatment plant, coagulation could be used to mitigate the impacts of diatom bloom on the slow sand filters. The diatom removal efficiency could reach 83% with the $\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$ dosage of 20 mg/L. Using $\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$ as the coagulant, the removal rate of diatom was 93% with the dosage of 30 mg/L.

(6) Denim and filter nets could be used for filtration, as experimental results demonstrated that the diatom removal rate was 79% with denim. The filter net can be installed in the feeding streams of the sand filters.

Table 8.1 The advantage and disadvantage of different measures.

Measures	Advantage	Disadvantage
Nutrient limitation	Meaningful for the protection of drinking water quality	Long term is required for this method to come into effect
Reducing illumination	The growth of diatom can be prohibited in dark condition	Other species in the reservoir will be impacted once covering the whole reservoir
Altering hydraulic condition	Thermal stratification can end diatom bloom	It is difficult to induce the thermal stratification in Vartry Reservoir
Increasing zooplankton population	Increasing zooplankton population is an efficient and effective approach to control diatom number and reducing fish population may increase the zooplankton population	Further investigation is needed
Coagulation and filtration	Once diatom bloom, coagulation and filtration can remove the diatom in the influent of the Vartry water treatment plant.	Pilot-scale experiments are required in Vartry water treatment plant

Chapter 9

Conclusions and Recommendations

9 Conclusions and recommendations

9.1 Conclusions

Focusing on Vartry Reservoir, this study summarized and analysed the historical data of water quality and ecology situation, conducted the intensive monitoring from 2016 to 2018 and undertook the simulated lab-scale study to unravel the reason of diatom bloom and screen out the effective control methods as well as recommend the potential management in long term. The main conclusions were summarized as following:

Diatom bloom pattern in Vartry Reservoir was obtained. From 1996 to 2012, the diatom concentration in lower lake was consistently lower than 1000 counts/mL while in the past 6 years (2013-2018) this number significantly increased, with maximum concentration of 2457 counts/mL observed in 2013. In 2017 and 2018, the diatom concentration of upper lake overtook that of lower lake. In 2017, the concentration of diatom in upper lake reached the highest number in all observed years, reaching as high as 4940 counts/mL. In terms of species analysis, *Asterionella* was found as the dominated one in both lakes since 2013.

The analysis of factors that affected diatom growth showed that nutrient concentrations, especially phosphorus affected the extent of diatom bloom in Vartry Reservoir while silica was not the limit factor of diatom growth. The concentration of phosphorus determined the magnitude of diatom bloom. In the upper lake, the average soluble relative phosphorus concentrations before diatom bloom season were 1.15 ug/L, 3.58 ug/L and 1.18 ug/L in 2016, 2017 and 2018, respectively. Due to the relatively high SRP concentration in 2017, diatom bloom was much more serious with the peak diatom concentration of up to 4900 counts/mL compared with the peak value of 2000 counts/mL in 2016 and 2018. By contrast, the silica concentration in Vartry reservoir was sufficient for diatom bloom. In the upper lake, the silica concentration was always higher than 5.0 mg/L before the diatom growth every year. In the lower lake, the concentration of silica was 5.24 mg/L, 6.19 mg/L and 4.32 mg/L in 2016, 2017 and 2018, respectively. These values were much higher than the half saturation concentrations of dominated diatom species (*Asterionella*). In 2017, the low silica level in the upper lake with the concentration of lower than 0.1 mg/L might contribute to the collapse of diatom bloom event with a peak concentration of 4940 counts/mL.

Food chain analysis found diatom predator (zooplankton) was another key factor determining diatom growth in Vartry reservoir. The major zooplankton species in Vartry Reservoir were Rotifer, Daphnia and Copepods. Rotifer could take up phosphorus directly from water. In addition, competition for phosphorus may exist between Rotifer and diatom which can restrain

the diatom growth. In the lower lake in March 2017, the diatom number remained lower than 300 counts/mL with the rotifer number above 30 counts/L. Predation could reduce the diatom number in Vartry Reservoir. The ratio of diatom number and zooplankton number (food to predator ratio) determined the extent of zooplankton limiting diatom growth. Laboratory experiments indicated that diatom growth was fully inhibited when the diatom/zooplankton ratio was lower than 14.4×10^3 . When the ratio of diatom and zooplankton number was higher than 40.9×10^3 , the influence of predation on diatom number was negligible.

Thermal stratification was the major factor for quick reduction of diatom concentration. Thermal stratification normally formed in Vartry Reservoir at the beginning of May when the surface water temperature reached 11 °C. At that point, the significant reduction of diatom number was always observed and the diatom number never bounced back in the rest of the year. Furthermore, a short-term (normally few days) stratification occurred during February to May could also lead to the significant decrease of diatom concentration, though the number bounced back after the disappearance of thermal stratification. This is because thermal stratification could cause the deposition of diatom dramatically while the diatom could re-suspend to the water column after the end of this stratification.

Overall, sufficient nutrient and the relative low zooplankton number could be the key factors for diatom bloom in Vartry Reservoir. Combined field work result with model analysis, it is deduced that sinking loss and the predation of zooplankton should be the major contributor for the collapse of diatom bloom.

9.2 Recommendations

The research has completed the objectives listed in Section 1.2. However, further studies are needed to better control diatom bloom and benefit drinking water management. We recommend continuing the study through the following two aspects.

9.2.1 Pilot-study for the practical control of diatom bloom

It was found that the limitation of nutrient especially phosphorus entering the water body was meaningful for the long-term protection of water quality in reservoirs. Increasing the number of zooplankton especially daphnia and copepods in the reservoir could effectively control diatom growth. Furthermore, reducing the population of fish might contribute to the augment of zooplankton. Relating to policy establishment, appropriate fishing could be encouraged. In terms of water treatment plant, coagulation and filtration could be used to deal with the impacts of diatom bloom on the slow sand filters.

However, most of the results are obtained via lab-scale study and field monitoring. To practically control diatom bloom, the pilot-scale study is necessary. In addition, food chain control method may cause other unexpected influences on other species. Pilot-study could be very helpful to have a more comprehensive assessment of each control method.

9.2.2 Disinfection by-product generation during chlorination of diatom

Chlorination is commonly used in water treatment plants. When diatom bloom occurs, there is a high potential of by-product generation (such as THM). This could be risky to human health. It is especially true considering the significant increase extent of diatom bloom in recent years. Hence, it is needed to continue the study about the disinfection by-product generation and protect public health.

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