Report No.353

epa Research
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Investigation into the Causes, Impacts and Measures to Deal with Algal Blooms in Vartry Reservoir

Authors: Yunhong Shi, Dunzhu Li, Laurence Gill, Bruce Misstear, Ian O'Donohue and Liwen Xiao

www.epa.ie

Rialtas na hÉireann
Government of Ireland

ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) is responsible for protecting and improving the environment as a valuable asset for the people of Ireland. We are committed to protecting people and the environment from the harmful effects of radiation and pollution.

The work of the EPA can be divided into three main areas:

Regulation: *We implement effective regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.*

Knowledge: *We provide high quality, targeted and timely environmental data, information and assessment to inform decision making at all levels.*

Advocacy: *We work with others to advocate for a clean, productive and well protected environment and for sustainable environmental behaviour.*

Our Responsibilities

Licensing

We regulate the following activities so that they do not endanger human health or harm the environment:

- waste facilities *(e.g. landfills, incinerators, waste transfer stations)*;
- large scale industrial activities (*e.g. pharmaceutical, cement manufacturing, power plants)*;
- intensive agriculture *(e.g. pigs, poultry)*;
- the contained use and controlled release of Genetically Modified Organisms *(GMOs)*;
- sources of ionising radiation *(e.g. x-ray and radiotherapy equipment, industrial sources)*;
- large petrol storage facilities;
- waste water discharges;
- dumping at sea activities.

National Environmental Enforcement

- Conducting an annual programme of audits and inspections of EPA licensed facilities.
- Overseeing local authorities' environmental protection responsibilities.
- Supervising the supply of drinking water by public water suppliers.
- Working with local authorities and other agencies to tackle environmental crime by co-ordinating a national enforcement network, targeting offenders and overseeing remediation.
- Enforcing Regulations such as Waste Electrical and Electronic Equipment (WEEE), Restriction of Hazardous Substances (RoHS) and substances that deplete the ozone layer.
- Prosecuting those who flout environmental law and damage the environment.

Water Management

- Monitoring and reporting on the quality of rivers, lakes, transitional and coastal waters of Ireland and groundwaters; measuring water levels and river flows.
- National coordination and oversight of the Water Framework Directive.
- Monitoring and reporting on Bathing Water Quality.

Monitoring, Analysing and Reporting on the Environment

- Monitoring air quality and implementing the EU Clean Air for Europe (CAFÉ) Directive.
- Independent reporting to inform decision making by national and local government *(e.g. periodic reporting on the State of Ireland's Environment and Indicator Reports)*.

Regulating Ireland's Greenhouse Gas Emissions

- Preparing Ireland's greenhouse gas inventories and projections.
- Implementing the Emissions Trading Directive, for over 100 of the largest producers of carbon dioxide in Ireland.

Environmental Research and Development

- Funding environmental research to identify pressures, inform policy and provide solutions in the areas of climate, water and sustainability.

Strategic Environmental Assessment

- Assessing the impact of proposed plans and programmes on the Irish environment *(e.g. major development plans)*.

Radiological Protection

- Monitoring radiation levels, assessing exposure of people in Ireland to ionising radiation.
- Assisting in developing national plans for emergencies arising from nuclear accidents.
- Monitoring developments abroad relating to nuclear installations and radiological safety.
- Providing, or overseeing the provision of, specialist radiation protection services.

Guidance, Accessible Information and Education

- Providing advice and guidance to industry and the public on environmental and radiological protection topics.
- Providing timely and easily accessible environmental information to encourage public participation in environmental decision-making *(e.g. My Local Environment, Radon Maps)*.
- Advising Government on matters relating to radiological safety and emergency response.
- Developing a National Hazardous Waste Management Plan to prevent and manage hazardous waste.

Awareness Raising and Behavioural Change

- Generating greater environmental awareness and influencing positive behavioural change by supporting businesses, communities and householders to become more resource efficient.
- Promoting radon testing in homes and workplaces and encouraging remediation where necessary.

Management and structure of the EPA

The EPA is managed by a full time Board, consisting of a Director General and five Directors. The work is carried out across five Offices:

- Office of Environmental Sustainability
- Office of Environmental Enforcement
- Office of Evidence and Assessment
- Office of Radiation Protection and Environmental Monitoring
- Office of Communications and Corporate Services

The EPA is assisted by an Advisory Committee of twelve members who meet regularly to discuss issues of concern and provide advice to the Board.

EPA RESEARCH PROGRAMME 2014–2020

Investigation into the Causes, Impacts and Measures to Deal with Algal Blooms in Vartry Reservoir

(2014-W-MS-18)

EPA Research Report

A copy of the end-of-project Technical Report is available on request from the EPA

Prepared for the Environmental Protection Agency

by

Trinity College Dublin

Authors:

Yunhong Shi, Dunzhu Li, Laurence Gill, Bruce Misstear, Ian O'Donohue and Liwen Xiao

ENVIRONMENTAL PROTECTION AGENCY
An Ghníomhaireacht um Chaomhnú Comhshaoil
PO Box 3000, Johnstown Castle, Co. Wexford, Ireland

Telephone: +353 53 916 0600 Fax: +353 53 916 0699
Email: info@epa.ie Website: www.epa.ie

ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2014–2020. The EPA Research Programme is a Government of Ireland initiative funded by the Department of the Environment, Climate and Communications. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

The authors would like to acknowledge the support from Mr Kevin Callanan from the Dublin City Council Central Laboratory and Mr Ned Fleming from Irish Water/Roundwood Water Treatment Plant; the contributions from the members of the project steering committee throughout the project, namely Wayne Trodd, Darragh Page and Michelle Roche (EPA), Brian Deegan (Irish Water) and Graham Mills (University of Portsmouth, UK), as well as Aisling O'Connor (EPA) and Rachel Clarke (Project Manager on behalf of the EPA) for their efficient management of the project.

DISCLAIMER

Although every effort has been made to ensure the accuracy of the material contained in this publication, complete accuracy cannot be guaranteed. The Environmental Protection Agency, the authors and the steering committee members do not accept any responsibility whatsoever for loss or damage occasioned, or claimed to have been occasioned, in part or in full, as a consequence of any person acting, or refraining from acting, as a result of a matter contained in this publication. All or part of this publication may be reproduced without further permission, provided the source is acknowledged.

This report is based on research carried out/data from September 2015 to August 2018. More recent data may have become available since the research was completed.

The EPA Research Programme addresses the need for research in Ireland to inform policymakers and other stakeholders on a range of questions in relation to environmental protection. These reports are intended as contributions to the necessary debate on the protection of the environment.

EPA RESEARCH PROGRAMME 2014–2020
Published by the Environmental Protection Agency, Ireland

ISBN: 978-1-84095-957-4 November 2020

Price: Free Online version

Project Partners

Liwen Xiao (Principal Investigator)
Department of Civil, Structural and
Environmental Engineering
Trinity College Dublin
Ireland
Tel.: +353 1 896 3741
Email: liwen.xiao@tcd.ie

Yunhong Shi
Department of Civil, Structural and
Environmental Engineering
Trinity College Dublin
Ireland
Email: yushi@tcd.ie

Dunzhu Li
Department of Civil, Structural and
Environmental Engineering
Trinity College Dublin
Ireland
Email: lidu@tcd.ie

Laurence Gill
Department of Civil, Structural and
Environmental Engineering
Trinity College Dublin
Ireland
Tel.: +353 1 896 1047
Email: laurence.gill@tcd.ie

Bruce Misstear
Department of Civil, Structural and
Environmental Engineering
Trinity College Dublin
Ireland
Tel.: +353 1 896 2800
Email: bruce.misstear@tcd.ie

Ian O'Donohue
School of Natural Sciences
Trinity College Dublin
Ireland
Tel.: +353 1 896 1356
Email: ian.donohue@tcd.ie

Contents

List of Figures

List of Tables

Executive Summary

Vartry Reservoir is a very important drinking water source in Ireland. It serves more than 220,000 customers and its supply area stretches from Roundwood, through north Wicklow and up to south Dublin. Since 2013, an *Asterionella*-dominated diatom bloom has occurred in the spring, leading to serious clogging of the slow sand filters in the Vartry water treatment plant. This results in a significant decrease in treatment capacity during the diatom bloom period, 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 3-year monitoring programme (from 2016 to 2018) and a series of laboratory experiments were carried out to (1) analyse the diatom growth trend in the Vartry Reservoir, (2) understand the change in nutrient concentrations in the Vartry Reservoir, (3) investigate the causes of the diatom bloom and (4) find measures to effectively mitigate the diatom bloom.

In the Vartry Reservoir, a diatom bloom occurs in spring and no obvious bloom is observed in autumn or winter. The diatom species include *Asterionella, Melosira, Navicula, Synedra* and *Tabellaria.* From 1996 to 2012 diatom concentrations in the lower lake were relatively low (averaging 430 counts/mL). Since 2013, the annual maximum diatom algae concentrations have been substantially higher, at 2457, 1754, 2054, 1878, 821 and 1120 counts/mL, in 2013, 2014, 2015, 2016, 2017 and 2018, respectively.

Each year, the silica concentration in the reservoir begins to fall as the diatom bloom starts to form, reaching its annual minimum value when the diatom bloom has finished, and then increases continuously until the next diatom bloom period begins. The nitrogen concentration in the reservoir also peaks at the beginning of diatom growth and then decreases, reaching its lowest point in the autumn before increasing again until the beginning of the next diatom bloom period. No significant year-to-year trend of increasing silica and nitrogen concentrations in the reservoir was detected during the study period.

The silica concentration in the reservoir is sufficient for the diatom bloom. The concentration of soluble reactive phosphorus affects the magnitude of the diatom bloom. In the upper lake, the mean soluble reactive phosphorus concentration before the diatom bloom season was 1 µg/L, 4 µg/L and 1 µg/L in 2016, 2017 and 2018, respectively, and the corresponding peak diatom concentrations were around 2000 counts/mL, 4940 counts/mL and 1762 counts/mL. The high diatom concentration in 2017 could be due to the relatively high concentration of soluble reactive phosphorus. Zooplankton is another factor that could influence diatom growth in the Vartry Reservoir. The dominant types of zooplankton in the Vartry Reservoir are rotifers, *Daphnia* and copepods. Zooplankton predation can reduce diatom concentrations. The impact of the zooplankton on diatom growth was found to be correlated with the ratio of diatom to zooplankton numbers (food to predator ratio). In laboratory experiments diatom growth was fully inhibited when the diatom to zooplankton ratio was less than 1.44×10^4 (count of diatom per head of zooplankton). When the ratio of diatom to zooplankton was more than 4.09×10^4, the influence of predation on diatom number was negligible. In the Vartry Reservoir, the ratio of diatom to zooplankton is always higher than 4.09×10^4, indicating that the low zooplankton population could contribute to the diatom algae bloom.

Although the limitation of nutrients, especially phosphate, entering the reservoir is important for the protection of water quality in the Vartry Reservoir, increasing the population of zooplankton in the reservoir could effectively control the diatom growth. Coagulation and filtration could be considered short-term measures to mitigate the impact of the diatom bloom on the water treatment plant.

1 Introduction

1.1 Background

The total biomass and species composition of lake phytoplankton vary seasonally. The term "algal bloom" generally describes a planktonic algal biomass significantly higher than the water body's average (Oliver and Ganf, 2000). Owing to increasing anthropogenic nutrient inputs to water systems, the occurrence of algal blooms in lakes, reservoirs and recreational waters has become a significant worldwide issue in recent decades (Karadžić *et al*., 2010; Matthews *et al*., 2010; Cao *et al*., 2011; O'Neil *et al*., 2012). Depending on the dominant species, algal blooms may create low-oxygen conditions or taste and odour problems, or even produce toxins harmful to humans and animals (Watson, 2004; Watson *et al*., 2007). 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 (Watson, 2004; Li *et al*., 2010). 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).

In Ireland, eutrophication is recognised as the most serious threat to lake water quality (McGarrigle *et al*., 2010). 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). Summer green or blue–green algal blooms in eutrophic or hypertrophic lakes such as Lough Leane and Lough Derg have been reported (Lucey and Burns, 2018; Hayden, 2005).

In contrast to summer green or blue–green algal blooms occurring in eutrophic or hypertrophic water bodies, spring/autumn diatom algal blooms can occur in oligotrophic and mesotrophic lakes. Diatoms are a type of unicellular, microscopic phytoplankton classified taxonomically in the division Bacillariophyta. The major defining morphological characteristic of these algae is an exoskeletal structure composed of silica. These structures, known as frustules, take the form of two overlapping valves (the epivalve and hypovalve) and have a wide variety of morphology (Chapman, 1973; Round *et al*., 1990; John *et al*., 2002). Diatoms are classified ecologically as r-strategists, i.e. organisms that exhibit a high growth rate under the right environmental conditions. Although they do not produce toxins as blue–green algae do, such diatom algal blooms have attracted great attention, as they can threaten water supplies. In Ireland, drinking water mainly originates from surface water, with oligotrophic and mesotrophic lakes being the main sources. Following an analysis of the lake water abstraction dataset from the 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 1 year of the 3-year period 2007–2009 (McGarrigle *et al*., 2010).

Vartry Reservoir, located in County Wicklow (Figure 1.1), is one of the main drinking water sources in Ireland. The Vartry Reservoir water treatment plant, constructed in the 1860s with treatment technology of slow sand filtration, produces approximately 75,000–80,000 m^3/day and serves a population of approximately 210,000 (EPA, 2016). Although the Vartry Reservoir was 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 are affected during the diatom algal bloom periods because the sand filters become blocked. The treatment capacity decreases significantly during this period, from 75 million litres to 40 million litres per day, and therefore gives rise to a potential water shortage.

1.2 Research Objectives

This project aimed to investigate the cause and impact of diatom algal blooms in the Vartry Reservoir and potential mitigation measures to deal with these blooms. The detailed objectives of this study included:

1. identifying the nutrient sources of the reservoir by analysing historical data and monitoring the nutrient concentrations in the rivers feeding the reservoir;

Figure 1.1. Location of the Vartry Reservoir.

2. investigating the major reason(s) for diatom bloom in the Vartry Reservoir, including examining factors such as nutrients, water temperature and zooplankton;
3. examining measures that can limit the growth of diatoms or methods that can relieve the clogging of slow sand filters in the water treatment plant during the spring diatom bloom.

2 The Growth of Diatoms in the Vartry Reservoir from 1995 to 2018

Diatom growth (in terms of diatom assemblages, magnitudes and durations) in the Vartry Reservoir varies from year to year. To understand the cause of diatom blooms, data on diatoms in the Vartry Reservoir from 1995 to 2018 were collected and analysed.

The recorded annual maximum diatom algae concentrations in the Vartry Reservoir from 1995 to 2018 are presented in Figure 2.1. During the period 1995–2012, the annual maximum diatom concentrations followed a decrease–increase cycle pattern, with a mean annual maximum diatom concentration of 430 (±299) counts/mL. However, in 2013, 2014, 2015, 2016, 2017 and 2018, annual maximum diatom algae concentrations were substantially higher: 2457, 1754, 2054, 1878, 821 and 1120 counts/mL, respectively.

The predominant diatom species in the Vartry Reservoir since 1995 are shown in Table 2.1 and include *Asterionella*, *Melosira*, *Synedra* and *Tabellaria*. In 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 been the predominant diatom species since 2012 and is the main contributor to the diatom algal bloom. Therefore, studying *Asterionella* is critical for understanding and control of the diatom bloom in the Vartry Reservoir.

Compared with the previous year, the diatom bloom in 2013 was much more serious. The growth of diatoms occurred from March to May, with the highest number of total diatoms (2457 counts/mL) detected on 19 April. *Melosira*, *Tabellaria*, *Asterionella*, *Synedra*, *Navicula* and *Diatoma* were detected during the diatom bloom. *Melosira* and *Tabellaria* counts were lower than 100 counts/mL. The predominant species was *Asterionella*, with a peak concentration of 1375 counts/mL. The maximum number of *Synedra* and *Diatoma* was 550 and 515 counts/mL, respectively. In 2014, although *Melosira* was the major diatom species in January and February, by 17 April the dominant species was *Asterionella*. The diatom bloom ended in June when the total diatom concentration was 58 counts/mL. The diatom bloom period in 2015 occurred from March to May, with a maximum diatom concentration of 2054 counts/mL on 6 April. *Asterionella* and *Navicula* were the major diatom species, with a peak concentration of 1674

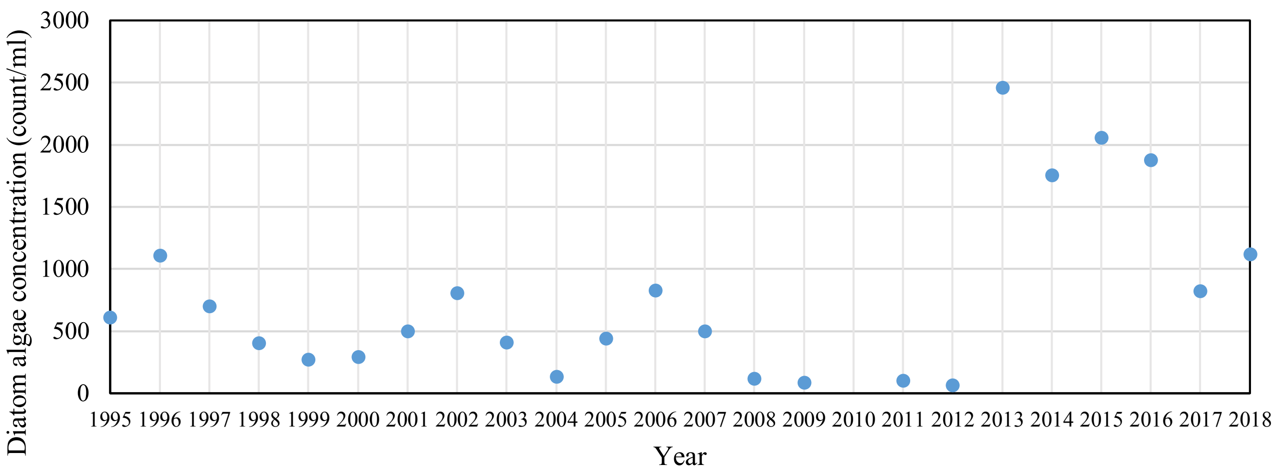

Figure 2.1. The recorded annual maximum diatom algae concentrations in the lower lake of Vartry Reservoir 1995–2018 (no data are provided for 2010 because the diatom algae concentration in that year was low).

Table 2.1. The annual maximum diatom concentration and predominant diatom species in the Vartry Reservoir since 1996

Year	Annual maximum concentration (counts/mL)	Sampling date	Predominant diatom species	Peak predominant species concentration (counts/mL)
1996	1107	02/05/1996	*Asterionella*	801
1997	671	02/1997	*Melosira*	638
1998	370	02/1998	*Asterionella*	187
1999	255	02/1999	*Melosira*	208
2000	277	03/2000	*Melosira*	174
2001	499	03/2001	*Asterionella*	284
2002	806	18/03/2002	*Tabellaria*	432
2003	406	07/04/2003	*Asterionella*	207
2004	135	24/03/2004	*Melosira*	128
2005	442	25/02/2005	*Melosira*	ND
2006	828	05/05/2006	*Synedra*	791
2007	498	25/03/2007	*Asterionella*	401
2008	118	01/02/2008	ND	ND
2009	86	03/03/2009	*Melosira*	78
2011	103	01/04/2011	*Melosira*	53
2012	102	29/01/2012	*Asterionella*	72
2013	2457	19/04/2013	*Asterionella*	1375
2014	1754	17/04/2014	*Asterionella*	1397
2015	2054	06/04/2015	*Asterionella*	1674
2016	1878	15/04/2016	*Asterionella*	1474
2017	821	10/05/2017	*Asterionella*	811
2018	1120	05/04/2018	*Asterionella*	902

Note, no data are provided for 2010 because the diatom algae concentration in that year was low.
ND, not determined.

and 736 counts/mL, respectively. In 2016, the highest diatom concentration was 1878 counts/mL on 15 April, and the bloom was dominated by *Asterionella* (1474 counts/mL). In addition, *Synedra* was present in much higher concentration than other species, peaking at 698 counts/mL on 3 May 2016. In 2017, the number of diatoms in the reservoir increased very slowly from 20 counts/mL on 6 January to 124 counts/mL on 10 April. Subsequently, the diatom concentration increased more rapidly, peaking at 821 counts/mL on 10 May, and was dominated by *Asterionella*. The diatom bloom finished at the end of May. In 2018, the diatom bloom period occurred from February to May. In the lower lake, the number of *Melosira* was higher than *Asterionella* in February. From March to May, *Asterionella* was the dominant diatom species. The maximum number of diatoms in the lower lake was 1120 counts/mL on 5 April 2018.

3 Nutrient Levels in the Vartry Reservoir

Nutrients are essential for the growth of diatoms, and diatom blooms can be limited by low nutrient concentrations. Therefore, assessing the level of nutrients entering and within the Vartry Reservoir is critical for diatom algae bloom control. In this project, nutrient levels in feeding rivers (Figure 3.1) and the Vartry Reservoir were monitored from 2015 to 2018.

3.1 Feeding Rivers of the Vartry Reservoir

The concentrations of nutrients [soluble reactive phosphorus (SRP), silica (SiO_2), total nitrogen (TN) and total organic carbon (TOC)] in 10 feeding rivers examined from 2015 to 2018 are shown in Table 3.1. The SRP concentration of U2 fluctuated between 1 and 152 µg/L, with the mean concentration of 33 (±34, standard deviation of the mean value) µg/L, which was much higher than in the other feeding rivers studied. The maximum recorded SRP concentrations in U3, U10 and U11 were 24 µg/L, 47 µg/L and 14 µg/L, respectively, with mean concentrations of 6 (±5) µg/L, 6 (±7) µg/L and 5 (±3) µg/L. The concentration of SRP in U8 remained at a low level, with a mean concentration of 1 µg/L. Except for U2, the concentrations of SRP in the feeding rivers for the upper lake were, in general, lower than in those rivers feeding the lower lake. The maximum SRP

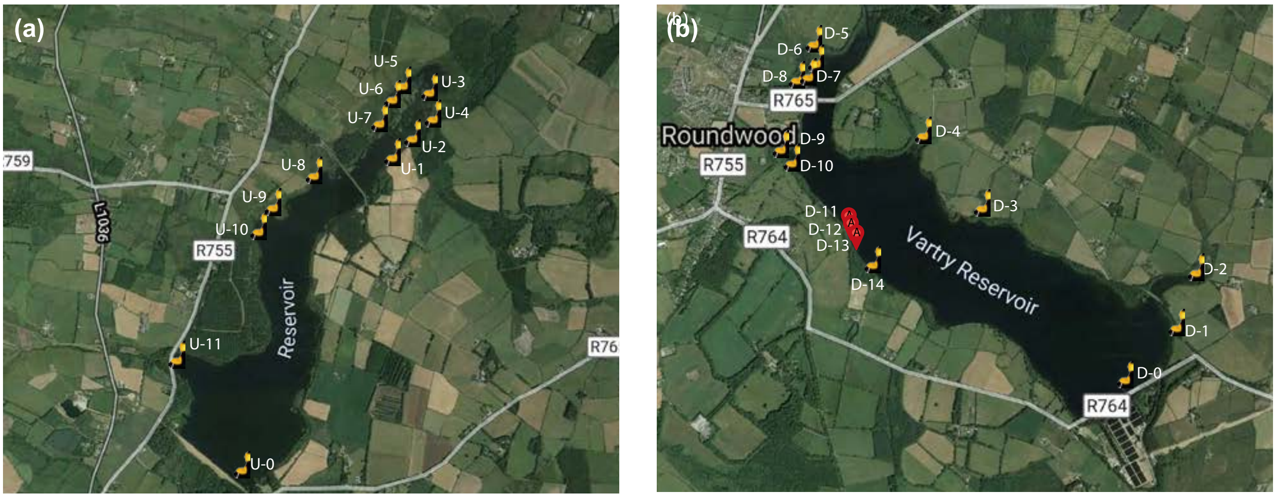

Figure 3.1. Location of feeding rivers, streams and pipes for (a) the upper lake and (b) the lower lake of the Vartry Reservoir. U, upstream; D, downstream; [pin icon], rivers and streams; [marker icon], pipes.

Table 3.1. The mean nutrient concentrations in feeding rivers from 2015 to 2018

Feeding rivers	SRP (µg/L)	SiO_2 (mg/L)	TN (mg/L)	TOC (mg/L)
U2	33 (±34)	7.7 (±2.6)	2.96 (±0.98)	4.12 (±1.66)
U3	6 (±5)	7.1 (±2.1)	1.44 (±0.36)	3.44 (±1.55)
U8	1 (±2)	5.8 (±1.2)	1.19 (±0.24)	1.42 (±0.85)
U10	6 (±7)	8.5 (±2.9)	1.60 (±0.35)	2.76 (±0.21)
U11	5 (±3)	10.0 (±3.1)	1.44 (±0.34)	2.98 (±1.43)
D1	14 (±11)	7.8 (±1.3)	2.33 (±0.77)	4.38 (±1.47)
D2	11 (±10)	8.3 (±1.9)	1.96 (±0.58)	4.54 (±1.42)
D4	11 (±14)	10.0 (±3.5)	2.71 (±0.98)	5.83 (±1.93)
D5	4 (±6)	6.9 (±2.1)	1.26 (±0.30)	2.35 (±1.16)
D9	15 (±15)	7.6 (±1.3)	2.43 (±0.90)	3.76 (±1.57)

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 mean concentration of 14 (±11) µg/L, 11 (±10) µg/L, 11 (±14) µg/L, 4 (±6) µg/L and 15 (±15) µg/L.

In the feeding rivers for the upper lake, silica concentrations in U2, U3, U8, U10 and U11 ranged from 4.7 to 10.4 mg/L, from 4.2 to 9.8 mg/L, from 4.5 to 7.4 mg/L, from 5.6 to 11.1 mg/L and from 6.0 to 13.3 mg/L, respectively, with mean 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 mean silica concentrations in the feeding rivers for the lower lake, 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.

In the upper lake catchment area, the mean TN concentration was 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. In the lower lake catchment area, the mean TN concentration was 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. In D4 and D9, the TN concentration fluctuated significantly, with a range of 0.64–5.36 mg/L and 0.47–5.13 mg/L, respectively. In D1 and D2, the maximum concentration was 4.27 mg/L and 3.16 mg/L, respectively. Compared with other feeding rivers in the lower lake, D5 had the lowest TN concentrations.

In U2, U3, U10 and U11, the TOC concentration ranges were 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 mean 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 mean TOC concentration in U8 was lower than in other feeding rivers, being 1.42 (±0.85) mg/L. The fluctuation in TOC concentrations in the feeding rivers for the lower lake was substantial. In D4, the TOC concentration varied between 2.93 mg/L and 9.91 mg/L and averaged 5.83 (±1.93) mg/L, which is higher than in the other rivers feeding the lower lake. TOC concentrations in D1, D2 and D9 ranged between 2.07 and 9.51 mg/L, between 2.56 and 8.68 mg/L and between 1.83 and 8.52 mg/L, respectively, and the mean TOC concentrations were 4.38 (±1.47) mg/L, 4.54 (±1.42) mg/L and 3.76 (±1.57) mg/L, respectively. The mean concentration of TOC in D5 was slightly lower than the other feeding rivers [2.35 (±1.16) mg/L].

3.2 The Study of Nutrients in the Vartry Reservoir

3.2.1 Long-term monitoring of nutrient concentrations in the reservoir from 2012 to 2018

Table 3.2 shows the mean nutrient concentrations in the upper and lower lakes of the Vartry Reservoir. The mean SRP concentration was approximately 2 µg/L during the period studied, and *Asterionella* was found to be abundant at low SRP levels. This agrees with the conclusion reached by various published studies that *Asterionella* is a good competitor for phosphorus (Lund, 1950; Bertrand *et al.,* 2003). Indeed, Nicklisch (1999) investigated the competition between different spring diatom species under phosphorus limitation and found that the specific growth rate of *Asterionella* was much higher than other species under phosphorus limitation at 10°C.

As shown in Figure 3.2, the silica concentrations in the lake started to decrease when the diatom blooms began and declined to the annual minimum values when the diatom bloom was complete. Silica concentrations then increased continuously until the next diatom bloom period. In the spring of 2012, a decrease in silica concentration was detected in the lower lake, although no significant diatom bloom was observed. In the lower lake, in 2013, 2014, 2015, 2016 and 2017, the annual maximum silica concentration was 5.99 mg/L, 4.80 mg/L, 5.03 mg/L, 6.73 mg/L and 7.74 mg/L, respectively, and the annual minimum silica concentration was 0.40 mg/L, 0.40 mg/L, 2.60 mg/L, 1.64 mg/L and 0.11 mg/L, respectively. The silica concentrations in the upper lake were similar to those in the lower lake.

Table 3.2. Mean nutrient concentrations in the upper and lower lakes

	SRP (µg/L)	SiO_2 (mg/L)	TN (mg/L)	TOC (mg/L)
Upper lake	2 (±3)	3.58 (±2.22)	1.13 (±0.38)	4.40 (±0.54)
Lower lake	2 (±3)	3.55 (±1.69)	1.04 (±0.32)	4.23 (±0.41)

Figure 3.3 shows the silica concentrations and diatom numbers in the upper lake from 2016 to 2018. The peak silica concentration was 7.58 mg/L on 5 February 2016. The concentration of silica then decreased to 2.18 mg/L on 11 June 2016, then increased steadily until the beginning of the next diatom bloom. In 2017, the maximum silica concentration in the upper lake was 8.48 mg/L on 10 January 2017. The silica levels declined gently, reaching 6.54 mg/L on 11 March 2017, when the diatom number was 280 counts/mL. Silica concentrations then decreased dramatically to less than 0.1 mg/L, and the diatom number reached the annual maximum value at the end of April 2017. The highest silica concentration in 2018 was 7.12 mg/L on 20 January 2018. The concentration of silica fell to 2.36 mg/L with the peak diatom number of

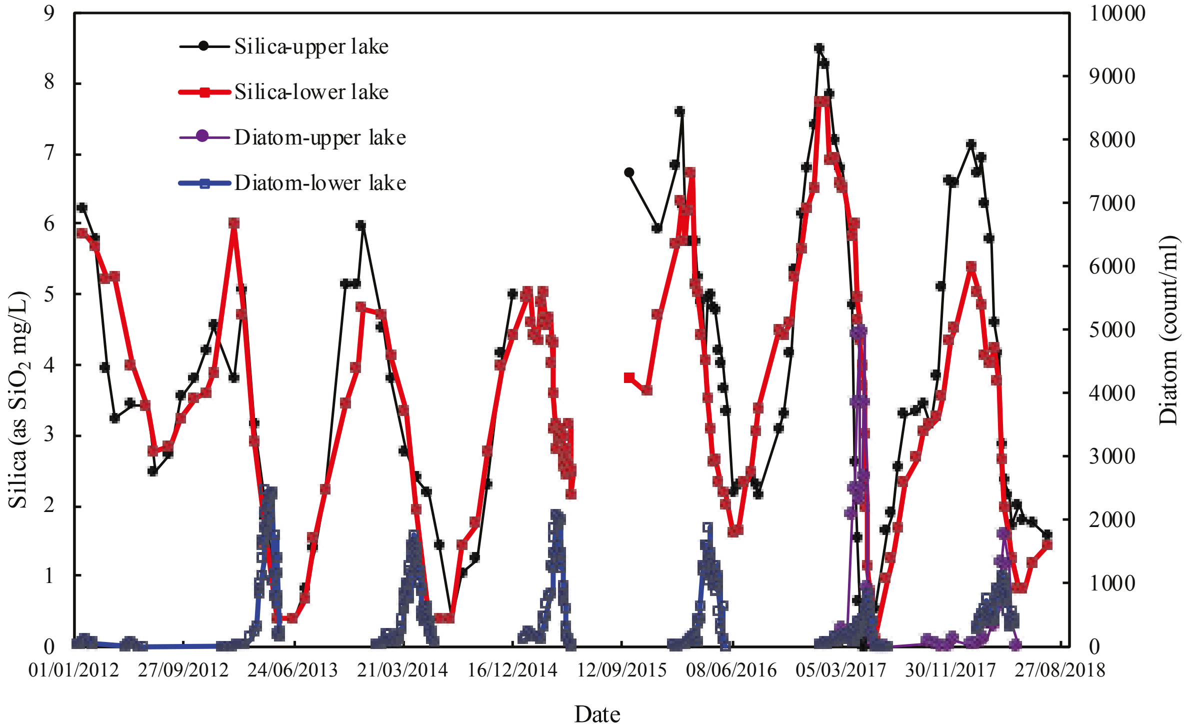

Figure 3.2. Silica concentrations and diatom numbers in the Vartry Reservoir from 2012 to 2017.

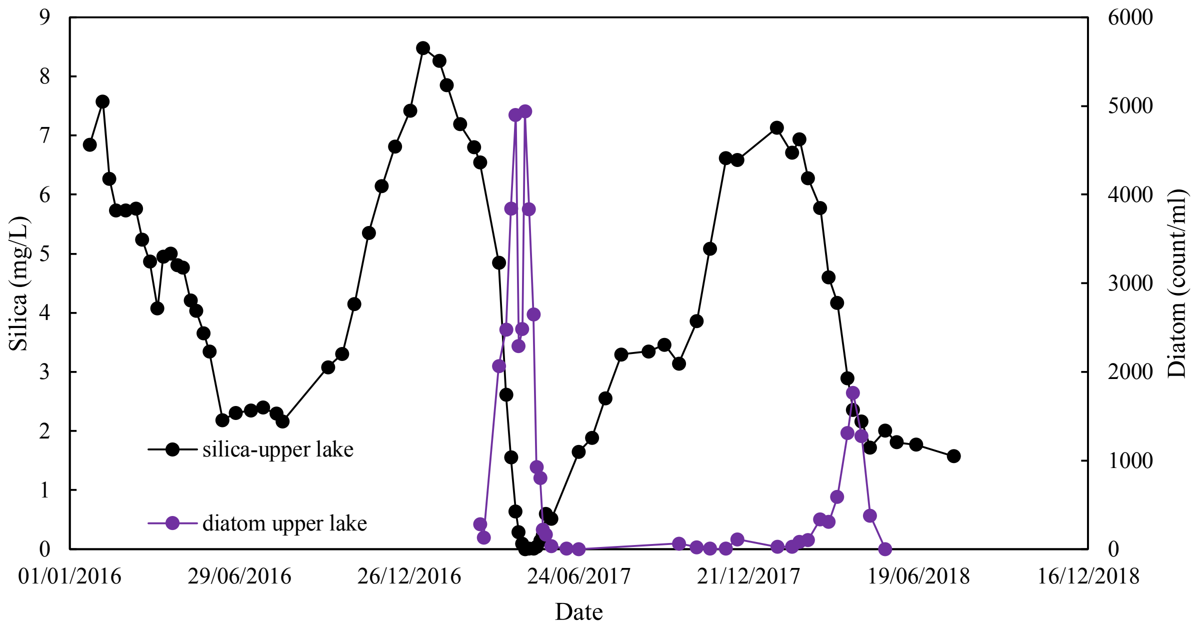

Figure 3.3. Silica concentrations and diatom numbers in the upper lake from 2016 to 2018.

1762 counts/mL on 11 April 2018. The lowest silica concentration was 1.72 mg/L on 29 April 2018.

Unlike other algae, diatoms require silica for the formation of frustules. As a result, the concentrations of silica in the reservoir decreased during the diatom bloom. Feeding rivers with high silica concentrations (about 9 mg/L) flowing into the reservoir were sources of silica for the reservoir. Lund (1950) studied the *Asterionella* bloom in the Esthwaite Water (Ambleside, UK) and found that the maximum diatom number was 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 (Lund, 1950). From 2013 to 2015, in the lower lake, the maximum biomass of diatoms was observed at silica concentrations of 1.48 mg/L, 1.92 mg/L and 2.94 mg/L, respectively, much higher than concentrations found to be limiting in previous studies, indicating that the growth of diatoms in the lower lake was not limited by silica from 2013 to 2015. In the upper lake in 2017, the concentration of silica was lower than 0.1 mg/L when the diatom number peaked, indicating that the lack of silica prevented the further growth of diatoms.

The TN and diatom concentrations in the reservoir from 2012 to 2014 are shown in Figure 3.4. In general, the TN concentration peaked at the beginning of diatom growth and then decreased to the lowest points in autumn. TN then increased again until the beginning of the next diatom bloom period. The annual maximum TN concentration was 1.47 mg/L, 1.34 mg/L, 0.92 mg/L, 1.50 mg/L and 1.60 mg/L in 2013, 2014, 2015, 2016 and 2017, respectively, with annual minimum TN concentrations of 0.65 mg/L, 0.54 mg/L, 0.45 mg/L, 0.4 mg/L and 0.72 mg/L, respectively. Similar results were found in the upper lake.

The TN concentrations detected in the upper lake from 2016 to 2018 are presented in Figure 3.5. In 2016, the TN concentration decreased from 1.42 mg/L on 5 February to 0.33 mg/L on 1 October. Thereafter, the concentration of nitrogen increased, reaching a maximum of 1.96 mg/L on 18 February 2017. In 2017, the lowest TN concentration was observed on 8 October (0.74 mg/L). This was followed by a maximum TN concentration of 2.14 mg/L, detected on 13 February 2018, before the diatom bloom. By 27 July 2018, the TN level had declined to 1.08 mg/L.

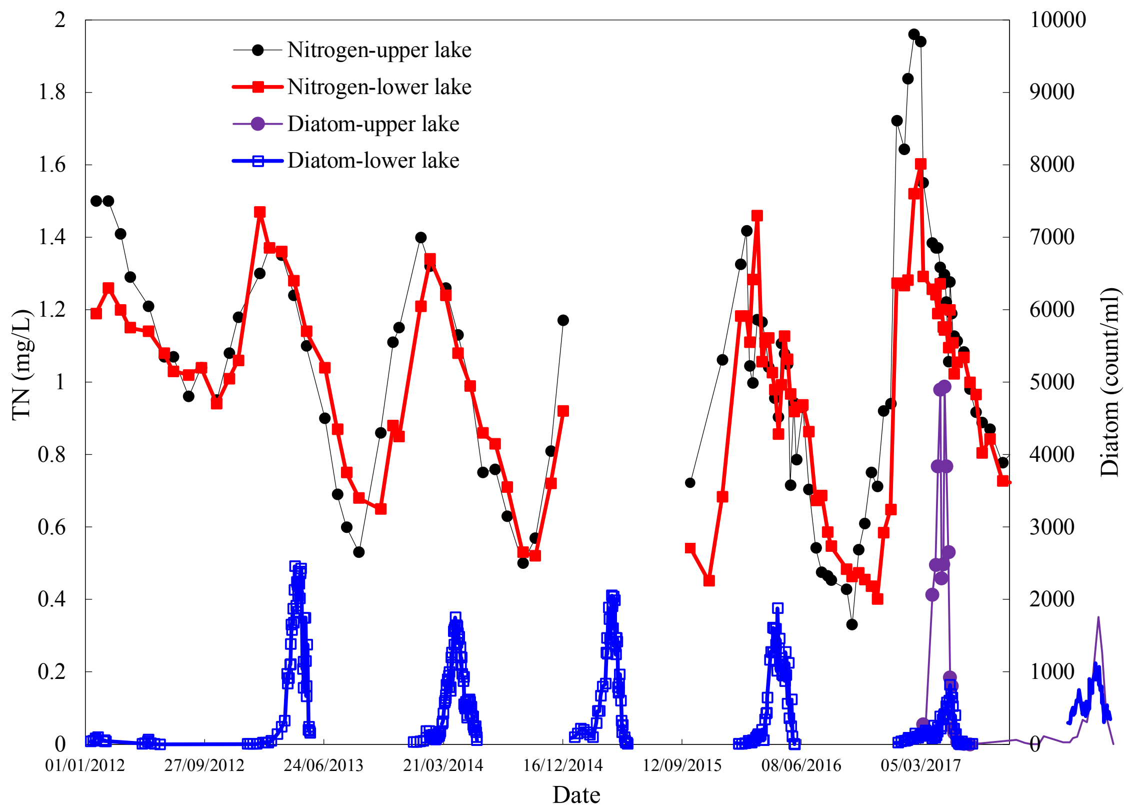

Figure 3.4. Change in TN concentrations and diatom numbers in the Vartry Reservoir from 2012 to 2014.

As shown in Figure 3.6, the concentrations of TOC in the reservoir fluctuated within a small range of 3.44 to 5.74 mg/L. No substantial change in TOC concentrations was observed during the diatom bloom period. In 2016, the mean concentration of TOC in the upper and lower lakes was 4.16 mg/L and 3.85 mg/L, respectively, with the range of 3.49 to 5.40 mg/L and 3.44 to 4.47 mg/L, respectively. In 2017, the TOC concentrations ranged between 3.51 and 5.47 mg/L in the upper lake and between 3.75 and 4.88 mg/L in the lower lake, with mean values of 4.37 mg/L and 4.26 mg/L, respectively. In 2018, the TOC concentrations ranged from 3.64 to 5.58 mg/L and from 4.09 to 5.74 mg/L in the upper and lower lake, respectively, with mean concentrations of 4.78 mg/L in the upper lake and 4.63 mg/L in the lower lake. It appears from these data that the diatom bloom did not have a significant impact on TOC concentrations.

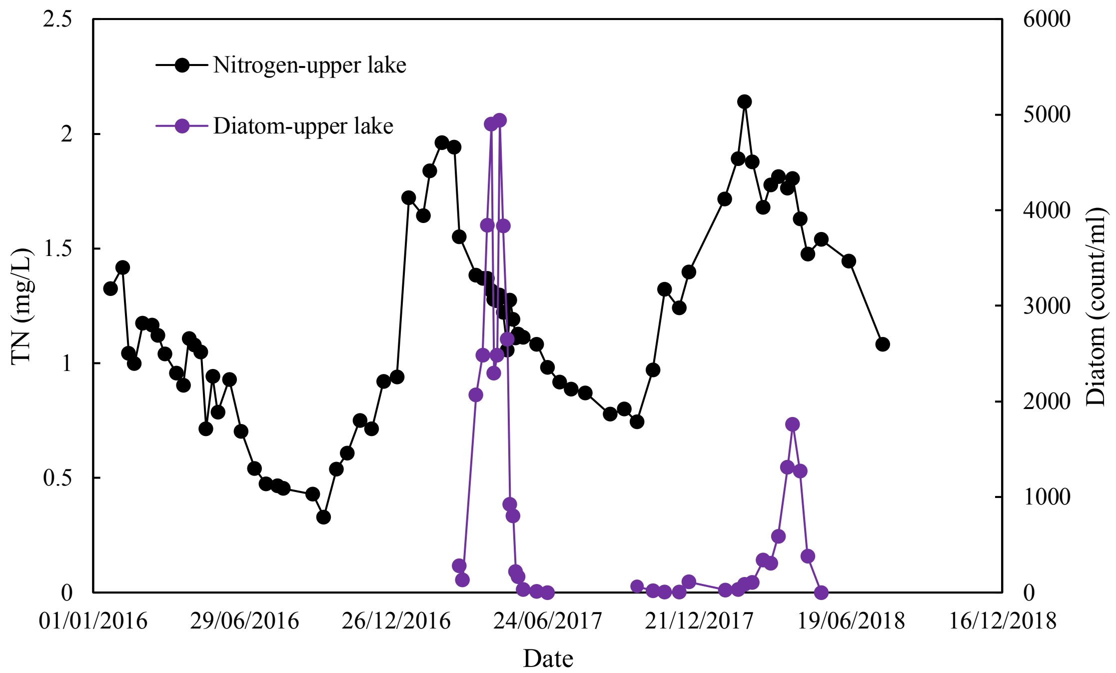

Figure 3.5. Changes in TN concentrations and diatom numbers in the upper lake from 2016 to 2018.

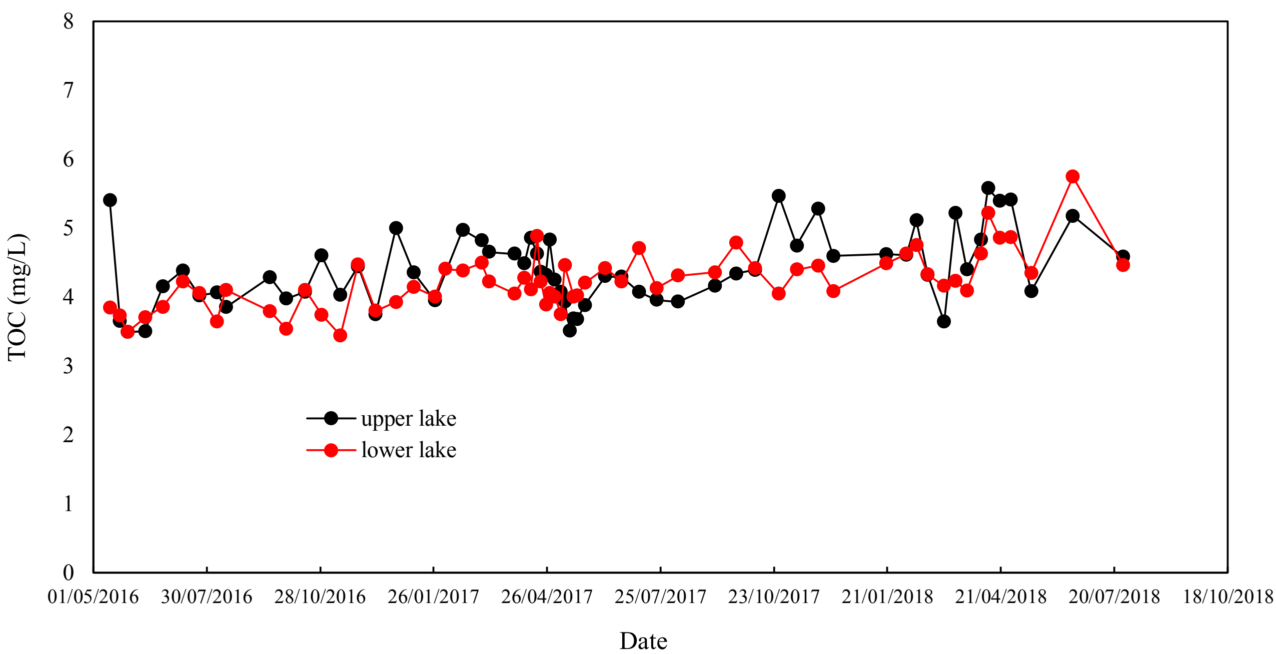

Figure 3.6. TOC concentrations in the Vartry Reservoir from 2016 to 2018.

3.3 Conclusion

Nutrient concentrations in the feeding rivers were higher than those in the reservoir. No significant increasing trends in nutrients in the feeding rivers and the reservoir were observed during the study period (from 2016 to 2018). During the diatom bloom periods, the concentration of both silica and nitrogen fell considerably in the Vartry Reservoir. 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, 0.91 mg/L and 2.13 mg/L, indicating that the growth of diatom in the lower lake was not limited by silica during 2013–2018. In 2017, the availability of silica was limited in the upper lake, with a concentration of less than 0.1 mg/L when the diatom density peaked at 4940 counts/mL.

4 Other Factors Affecting Diatom Bloom

In addition to nutrients, water temperature and thermal conditions can also affect the growth of diatoms. In 2017, the reduction in nutrient concentration was similar in both the upper and lower lake during the diatom bloom period. However, the diatom concentrations in the lower lake were much lower than those detected in the upper lake, which could be due to the predation of diatoms by zooplankton in the lower lake.

4.1 Water Temperature and Thermal Stratification

In general, diatom blooms occurred in spring, when the temperature was low. In the studies by Lund (1950) and Bertrand *et al.* (2003), *Asterionella* was the dominant species when the water temperature was lower than 10°C. The maximum abundance of diatoms was reached in the study of Lee *et al.* (2014) when the water temperature was 7°C, with the dominant species *Aulacoseira ambigua*. Thermal stratification, the phenomenon in which lakes form two discrete layers of water with different temperatures, has been found to lead to a serious reduction in diatom density. Kilham *et al.* (1996) observed that the population of *Asterionella* decreased when thermal stratification occurred in Yellowstone Lake. Mixing of the water column is vital for the growth of diatoms; the density of the diatom bloom is slightly higher than that of water and so the diatom bloom sinks out of the euphotic zone when thermal stratification is established in the reservoir. Similar results were obtained in studies by Ferris *et al.* (2007) and Fadel *et al.* (2015).

4.2 Zooplankton

4.2.1 Zooplankton in the Vartry Reservoir

In the Vartry Reservoir, the major zooplankton species include *Daphnia*, rotifers, copepods, *Kellicottia* and *Keratella*; the numbers of each zooplankton type over the study period are shown in Figure 4.1. The numbers of zooplankton remained at a low level in autumn and winter.

The spring diatom bloom could be the major food source for zooplankton in the Vartry Reservoir. The lack of food sources could be the main reason for the low density of zooplankton from July until the following February. A similar trend was observed in a marl lake in Ireland (McCarthy *et al.,* 2006), where the maximum biomass of zooplankton occurred in spring, and the biomass was very low in summer and autumn.

In 2017, the consumption of nitrogen and silica in the upper and lower lakes were similar, as shown in Figures 3.2 and 3.4. However, the peak number of diatoms was six times higher in the upper lake than that in the lower lake. Considering the number of zooplankton in the reservoir, it seems that the grazing pressure caused by the zooplankton limited the growth of diatoms in the lower lake. Zooplankton mainly feed on diatoms, so a time lag exists between the growth of diatoms and zooplankton numbers. In the upper lake in 2017 and in the lower lake in 2016, the largest zooplankton population occurred at the end of the diatom bloom. However, in 2017 the increase in diatom and zooplankton numbers began at the same time in the lower lake. As the peak diatom population was reached much later in 2017 than in previous years, it seems possible that the diatom bloom may have been delayed by zooplankton predation. Jewson *et al.* (1981) reached a similar conclusion, i.e. that grazing contributed to a delay in the increase of the diatom population.

4.3 Conclusion

In the Vartry Reservoir, the diatom bloom occurs when the water temperature is between 4°C and 12°C. Thermal stratification normally occurs when the water temperature is higher than 10°C, which subsequently leads to a discontinuation of diatom growth. Zooplankton (*Daphnia* and copepods) appear to affect the growth of diatoms; the diatom bloom can apparently be suppressed and delayed by zooplankton predation.

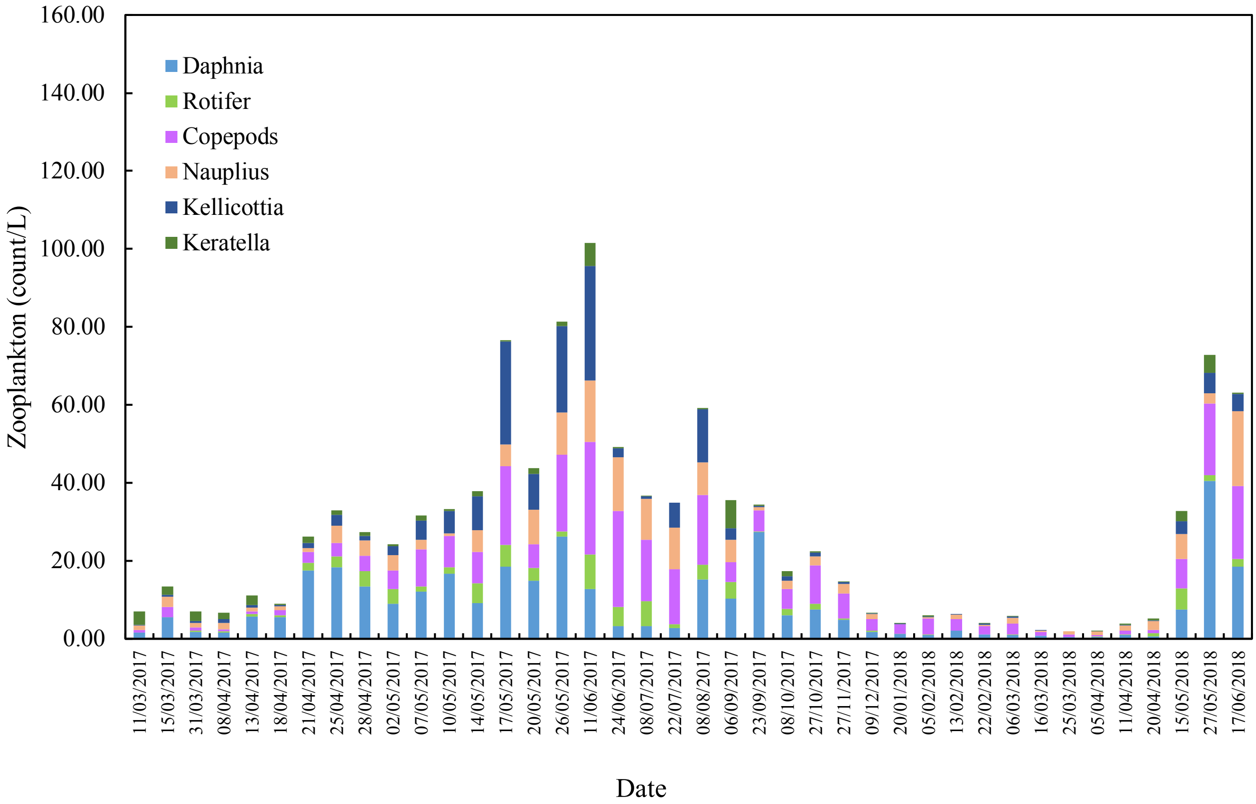

Figure 4.1. The number of zooplankton detected in the upper lake from March 2017 to June 2018.

5 Control of Diatom Blooms Using Zooplankton in the Vartry Reservoir

In the Vartry Reservoir, the number of zooplankton remained at a low level during autumn and winter. Diatom predation by *Daphnia* and copepods occurred in the reservoir, and diatoms could represent the major food sources for *Daphnia* and copepods in the Vartry Reservoir owing to the absence of other phytoplankton. From July to the following February, low density of *Daphnia* and copepods was caused by the lack of food source. This trend was also detected in a marl lake in Ireland and the maximum biomass of zooplankton occurred in spring (McCarthy *et al*., 2006). *Daphnia* and copepods mainly feed on diatoms, so a time lag exists between the growth of diatoms and the zooplankton. As detected in the upper lake in 2017 and the lower lake in 2016, the largest *Daphnia* and copepod populations occurred at the end of a diatom bloom.

As shown in Table 5.1, the growth of zooplankton normally occurred at the end of April and peaked in May. Compared with 2016 and 2018, zooplankton growth took place much earlier in 2017. Higher water temperatures in 2017 contributed to the early start of zooplankton growth. Similar results were observed in other studies (e.g. Berger *et al*., 2007; Winder *et al*., 2012). Berger *et al*. (2007) studied the influence of water temperature on the timing of zooplankton growth in a man-made enclosure experiment and found that the peak number of *Daphnia* occurred 1 week earlier in warm water than in cold water conditions. In the Vartry Reservoir, the number of zooplankton was independent of the water temperature.

The diatom growth in the lower lake in 2017 was characterised by a delayed start, low diatom numbers and high nitrogen and silica consumption. In 2017, the consumption of nitrogen and silica in the upper lake and the lower lake was similar. However, the peak diatom concentration in the upper lake (4940 counts/mL) was six times higher than that of the lower lake (821 counts/mL). This disparity could be caused by zooplankton. As different zooplankton species have different feeding habits, the influence of zooplankton on diatom growth varies.

Rotifers normally feed on organic particles, dead bacteria and small algae. Rotifers can also directly take up phosphorus from water (Jensen *et al*., 2004). Conde-Porcuna (2000) studied the correlations between rotifers and nutrient concentrations in a mesotrophic reservoir. Their results suggested that the SRP concentration influenced the biomass of rotifers and that rotifer abundance was not affected by algae. In the Vartry Reservoir, the period of rapid diatom growth normally begins in March. However, in 2017, diatom growth started in April in the lower lake, whereas the population of rotifers increased substantially in March, from 5 to 77 counts/L. The competition for SRP between rotifers and diatoms affected the growth of diatoms.

Table 5.1. Maximum *Daphnia* and copepod numbers and water temperature in the Vartry Reservoir from 2016 to 2018

	Maximum number (counts/L)	Peak date	Fast growing period	Water temperature (°C)
Lower lake				
2016	30	22/05	20/04–22/05	7.80–14.00
2017	113	28/04	08/04–07/05	9.31–10.80
2018	35	27/05	29/04–27/05	9.87–14.93
Upper lake				
2017	46	26/05	08/04–26/05	9.31–16.00
2018	59	27/05	20/04–27/05	9.00–14.93

Unlike rotifers, the predation of *Daphnia* and copepods on diatoms could also directly limit the diatom number. As shown in Table 5.2, the degree of limitation was directly correlated with the ratio of diatom to zooplankton number. The limitation was more intense with a decreasing diatom to zooplankton ratio. No diatom growth was observed when the ratio was lower than 1.44×10^4. The limitation of zooplankton was not apparent when the ratio was greater than 4.09×10^4.

The mean diatom to zooplankton ratio in 2017 was 4.6×10^5 in the upper lake and 1.7×10^4 in the lower lake during the diatom growth period. In 2018, this ratio was 7.25×10^5 and 3.81×10^5 in the upper and lower lake, respectively. Based on laboratory work, it was concluded that predation by *Daphnia* and copepods limited the diatom number in the lower lake in 2017. However, *Daphnia* and copepods exerted almost no influence on the diatom bloom in either the upper lake in 2017 or the whole reservoir in 2018. McCarthy (2007) studied the zooplankton population in the lakes of Ireland and showed that the biomass (dry weight) of zooplankton in Lough Carra and Lough Talt was higher than 3×10^5 µg/m^2 in February and March and was dominated by *Daphnia* and copepods. In the Vartry Reservoir, this value was lower than 1.5×10^5 µg/m^2 except in the lower lake in 2017. The low numbers of zooplankton exacerbated the diatom bloom in the Vartry Reservoir.

Table 5.2. The degree of diatom population limitation with different ratios of diatoms and zooplankton

Diatom (counts/mL)	Zooplankton (counts/L)	Diatom to zooplankton ratio	Degree of diatom population limitation
96	40	2.4×10^3	Fully limited
1827	202	9.0×10^3	
613	64	9.6×10^3	
504	48	1.05×10^4	
1443	100	1.44×10^4	
454	26	1.75×10^4	Medium limitation
560	30	1.86×10^4	
1757	72	2.44×10^4	
526	14	3.76×10^4	Minor limitation
573	14	4.09×10^4	No obvious limitation
786	18	4.36×10^4	
554	12	4.62×10^4	
792	13	6.09×10^4	

6 Impacts of and Measures to Deal with Diatom Bloom in the Vartry Reservoir

6.1 Impacts of Diatom Blooms

Algal blooms can have significant impacts on water quality. However, in the Vartry Reservoir, diatom algae growth reduces silica levels, and impacts on pH, dissolved oxygen (DO) and TOC were not detected. The diatom algal bloom in Vartry Reservoir decreased the water transparency and increased the volatile suspended solid (VSS) concentrations (Figure 6.1), which reduced the water production rates of the slow sand filters in the Vartry water treatment plant. In 2016, the capacity of the water treatment plant decreased significantly, from 75 million litres per day to 40 million litres per day, when the diatom algal bloom occurred.

6.2 Measures to Deal with Diatom Blooms

Although the impact on water quality is not a main concern in the Vartry Reservoir, diatom blooms pose a great challenge to the Vartry water treatment plant, resulting in a significant decrease in water production rates. Therefore, measures are urgently needed to deal with the diatom bloom.

One measure that can mitigate the impact of diatom blooms on the Vartry water treatment plant is coagulation, removing the diatom before the influent enters the sand filters. Jar tests were carried out in the laboratory to assess the performance of different coagulants on diatom removal. Aluminium sulfate ($Al_2(SO_4)_3{\cdot}18H_2O$) and ferric chloride ($FeCl_3{\cdot}6H_2O$) were chosen in this study because of their safety and low cost. At a dose of 10 mg/L, $Al_2(SO_4)_3{\cdot}18H_2O$ and $FeCl_3{\cdot}6H_2O$ removed 58.00% and 50.14% of the total diatoms, respectively. Increasing the dose of $Al_2(SO_4)_3{\cdot}18H_2O$ and $FeCl_3{\cdot}6H_2O$ to 30 mg/L increased the proportion of total diatoms removed to 96.90% and 99.49%. $Al_2(SO_4)_3{\cdot}18H_2O$ at a dose of 10 mg/L removed 85% of *Synedra* and 54.51% of *Asterionella*. At a dose of 10 mg/L, $FeCl_3{\cdot}6H_2O$ removed 64.04% of *Synedra* and 45.99% of *Asterionella*. The removal rate of both *Asterionella* and *Synedra* was greater than 95% when the dose of $Al_2(SO_4)_3{\cdot}18H_2O$ or $FeCl_3{\cdot}6H_2O$ was 30 mg/L.

Filtration can also be used for the removal of diatoms. In this study, denim and filter nets were tested as filter materials. Water can flow by gravity through these materials. With the initial total diatom concentration of 1432 counts/mL, a filter net with a mesh size of 150 µm or 63 µm could remove 18.09% and 19.27% of diatoms, respectively. When the initial diatom concentration was 456 counts/mL (*Asterionella* 438 counts/mL), denim removed 78.95% of the

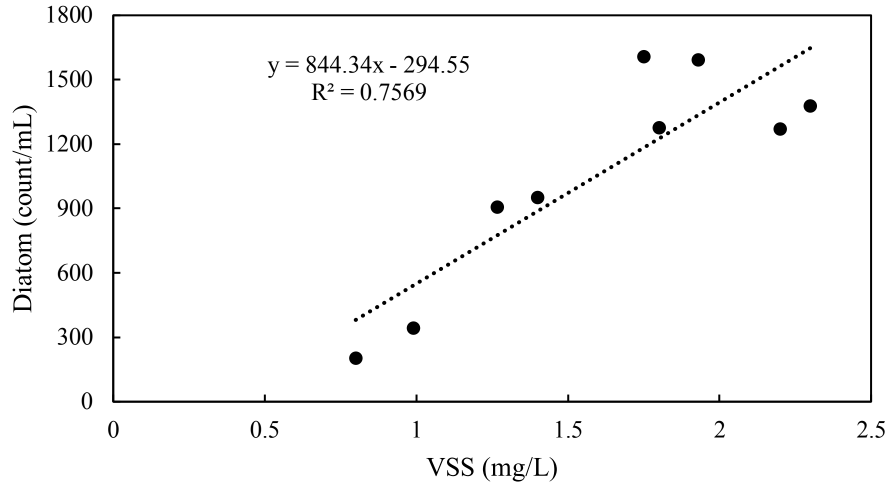

Figure 6.1. The relation correlation between diatom number and VSS in the influent of the Vartry water treatment plant.

diatoms. Filter nets with a mesh size of 150 µm and 63 µm removed 8.33% and 29.82% of the diatoms, respectively. When four layers of filter nets were used, the removal efficiencies of nets with mesh size of 150 µm and 63 µm increased to 41.67% and 77.19%, respectively.

7 Conclusions and Recommendations

7.1 Conclusions

In the Vartry Reservoir, a diatom bloom occurs in the spring. From 1996 to 2012, diatom concentration in the lower lake was below 1000 counts/mL, with the mean annual maximum diatom concentration of 430 counts/mL. Since 2013, the diatom bloom in the reservoir has become significant and is dominated by *Asterionella* species. The mean annual maximum diatom concentration detected in the lower lake was 2457, 1754, 2054, 1878, 821 and 1120 counts/mL in 2013, 2014, 2015, 2016, 2017 and 2018, respectively. In 2017 and 2018, the annual maximum diatom concentration in the upper lake was 4940 and 1762 counts/mL, respectively – much higher than in the lower lake.

Phosphorus and nitrogen levels in the reservoir were much higher than *Asterionella*'s half-saturation concentrations for these nutrients. The level of SRP determined the magnitude of the diatom bloom. In the upper lake, the mean SRP concentration before the diatom bloom was about 1 µg/L, 4 µg/L and 1 µg/L in 2016, 2017 and 2018, respectively. Owing to the higher SRP concentration in 2017, the diatom bloom was more significant in 2017.

The silica concentration in the reservoir was sufficient for the diatom bloom. In the upper lake, the silica concentration was always higher than 5.0 mg/L before the spring season. In the lower lake, the silica concentration before the diatom bloom occurred was 5.24 mg/L, 6.19 mg/L and 4.32 mg/L in 2016, 2017 and 2018, respectively. These values are much higher than the half-saturation concentrations of diatoms such as *Asterionella*. In 2017, the low silica level in the upper lake (less than 0.1 mg/L) may have contributed to the collapse of the diatom bloom event, which had a peak concentration of 4940 counts/mL.

Zooplankton is another factor that could influence diatom growth in the reservoir. Zooplankton predation can reduce diatom numbers. The major types of zooplankton found in the Vartry Reservoir are rotifers, *Daphnia* and copepods. In the lower lake in March 2017, the diatom number remained below 300 counts/mL at rotifer numbers above 30 counts/L. The degree to which diatom growth was limited was correlated with the ratio of diatom to zooplankton numbers, that is, the food to predator ratio. Laboratory experiments showed that diatom growth was fully inhibited when the diatom to zooplankton ratio was lower than 1.44×10^4. When the ratio of diatoms to zooplankton was higher than 4.09×10^4, the influence of predation on diatom numbers was negligible.

Thermal stratification normally occurs in the Vartry Reservoir at the beginning of May, when the water temperature increases to 11°C, and can lead to considerable reductions in diatom numbers. Sometimes short-term stratification occurred during the diatom bloom period, resulting in a dramatic decrease in diatom concentration. However, the diatoms started to bloom again once this short-term stratification ended.

Nutrient levels higher than the half-saturation concentrations of *Asterionella*, combined with relatively low zooplankton numbers, could be the causes of diatom blooms in the Vartry Reservoir.

In the Vartry Reservoir, diatom algae growth reduced silica levels, but impacts on pH, DO and TOC were not detected. The diatom algae bloom in the Vartry Reservoir reduced the water transparency and increased the VSS concentrations, which reduced the water production rates of the slow sand filters in the Vartry water treatment plant.

Chemicals such as aluminium sulfate ($Al_2(SO_4)_3 \cdot 18H_2O$) and ferric chloride ($FeCl_3 \cdot 6H_2O$) can be used as coagulants to remove diatoms. More than 90% of diatoms can be removed by a dose of 30 mg/L.

Denim and filter nets with a mesh size of 63 µm can be used as filter materials to remove more than 77% of diatoms.

7.2 Recommendations

The limitation of nutrients, especially phosphorus, entering the reservoir is important for the protection of water quality in the Vartry Reservoir. In this study, nutrient levels in the main feeding rivers and streams were monitored and the nutrient release hotspots

(U2, D1, D4 and D9) were identified. In the future, studies should be carried out to (1) investigate the cause and mechanisms of nutrients released in these hotspots and (2) develop the best land management practices to mitigate the impact of nutrients released, by combining the data collected in this study with the catchment management tools developed in the EPA-funded Pathways Project (Mockler *et al*., 2014).

In this study it was found that the ratio of diatoms to zooplankton in the Vartry Reservoir was high compared with other lakes in Ireland and that an increase in the population of zooplankton, especially *Daphnia* and copepods, could effectively control diatom growth. The study also found that stratification occurs when the water temperature increases to around 11°C and that thermal stratification can end the diatom algae bloom. In the future, predator–prey and nutrients–food chain interactions in the reservoir should be investigated and a reservoir model including nutrients, food chains and hydrological elements (such as water temperature, thermal stratification condition) should be developed and calibrated for the Vartry Reservoir. A Vartry Reservoir catchment management tool should be developed by integrating the reservoir model with the catchment management tools developed in the Pathways Project.

In this study, preliminary laboratory experiments indicated that coagulants such as $Al_2(SO_4)_3{\cdot}18H_2O$ and $FeCl_3{\cdot}6H_2O$, and filter materials such as denim and filter nets with mesh sizes of 63 µm, could be used to remove diatoms and mitigate the impacts of the diatom bloom on the slow sand filters. In the future, pilot-scale studies should be carried out to assess the feasibility of these practices.

References

Berger, S.A., Diehl, S., Stibor, H., Trommer, G., Ruhenstroth, M., Wild, A., Weigert, A., Jäger, C.G. and Striebel, M., 2007. Water temperature and mixing depth affect timing and magnitude of events during spring succession of the plankton. *Oecologia* 150(4): 643–654.

Bertrand, C., Fayolle, S., Franquet, E. and Cazaubon, A., 2003. Responses of the planktonic diatom Asterionella formosa Hassall to abiotic environmental factors in a reservoir complex (south-eastern France). *Hydrobiologia* 501(1–3): 45–58.

Cao, C., Zheng, B., Chen, Z., Huang, M. and Zhang, J., 2011. Eutrophication and algal blooms in channel type reservoirs: a novel enclosure experiment by changing light intensity. *Journal of Environmental Sciences* 23(10): 1660–1670.

Chapman, D.,1973. *The Algae*. Palgrave Macmillan, London, UK.

Conde-Porcuna, J.M., 2000. Relative importance of competition with Daphnia (Cladocera) and nutrient limitation on Anuraeopsis (Rotifera) population dynamics in a laboratory study. *Freshwater Biology* 44(3): 423–430.

EPA (Environmental Protection Agency), 2016. Drinking water audit report. Available online: https://www.epa.ie/pubs/advice/drinkingwater/epadrinkingwaterauditreports/vartrydwaudit12052016.html (accessed 21 October 2020).

Fadel, A., Atoui, A., Lemaire, B.J., Vinçon-Leite, B. and Slim, K., 2015. Environmental factors associated with phytoplankton succession in a Mediterranean reservoir with a highly fluctuating water level. *Environmental Monitoring and Assessment* 187(10): 1–14.

Ferris, J.A. and Lehman, J.T., 2007. Interannual variation in diatom bloom dynamics: roles of hydrology, nutrient limitation, sinking, and whole lake manipulation. *Water Research* 41(12): 2551–2562.

Jensen, T.C. and Verschoor, A.M., 2004. Effects of food quality on life history of the rotifer Brachionus calyciflorus Pallas. *Freshwater Biology* 49(9): 1138–1151.

Jewson, D.H., Rippey, B.H. and Gilmore, W.K., 1981. Loss rates from sedimentation, parasitism, and grazing during the growth, nutrient limitation, and dormancy of a diatom crop. *Limnology and Oceanography* 26(6): 1045–1056.

John, D.M., Brook, A.J. and Whitton, B.A. (eds), 2002. *The Freshwater Algal Flora of the British Isles: An Identification Guide to Freshwater and Terrestrial Algae*. Cambridge University Press, Cambridge, UK.

Hayden J., 2005. Blue-green algae killed two dogs at Lough Derg. *Irish Times,* 13 July 2005.

Karadžić, V., Subakov-Simić, G., Krizmanić, J. and Natić, D., 2010. Phytoplankton and eutrophication development in the water supply reservoirs Garaši and Bukulja (Serbia). *Desalination* 255(1): 91–96.

Kilham, S.S., Theriot, E.C. and Fritz, S.C.,1996. Linking planktonic diatoms and climate change in the large lakes of the Yellowstone ecosystem using resource theory. *Limnology and Oceanography* 41(5): 1052–1062.

Lee, J.Y., Han, M. and Kim, T., 2014. Assessment of seasonal algae variability in a reservoir. *Environmental Engineering Research* 19(3): 223–228.

Li, Z., Yu, J., Yang, M., Zhang, J., Burch, M.D. and Han, W., 2010. Cyanobacterial population and harmful metabolites dynamics during a bloom in Yanghe Reservoir, North China. *Harmful Algae* 9(5): 481–488.

Lucey A. and Burns S., 2018. Killarney's largest lake contaminated with toxic "algae". *Irish Times*, 24 July 2018.

Lund, J.,1950. Studies on Asterionella formosa hass: II. Nutrient depletion and the spring maximum. *Journal of Ecology* 38: 15–35.

McCarthy, V., Donohue, I. and Irvine, K., 2006. Field evidence for stoichiometric relationships between zooplankton and N and P availability in a shallow calcareous lake. *Freshwater Biology* 51(9): 1589–1604.

McCarthy, V., 2007. The relationship between resource elemental deficiencies and zooplankton community structure and dynamics. Thesis. Trinity College Dublin.

McGarrigle, M., Lucey, J. and Cinnéide, M.Ó., 2010. *Water Quality in Ireland 2007–2009*. Environmental Protection Agency, Johnstown Castle, Ireland.

Matthews, M.W., Bernard, S. and Winter, K., 2010. Remote sensing of cyanobacteria-dominant algal blooms and water quality parameters in Zeekoevlei, a small hypertrophic lake, using MERIS. *Remote Sensing of Environment* 114(9): 2070–2087.

Mockler, E., Bruen, M., Desta, M. and Misstear, B., 2014. *Pathways Project Final Report Volume 4: Catchment Modelling Tool*. Report No. 2007-WQ-CD-1-S1. Environmental Protection Agency, Johnstown Castle, Ireland.

Nicklisch, A., 1999. Competition between the Cyanobacterium Limnothrix redekei and some spring species of diatoms under P-limitation. *International Review of Hydrobiology* 84(3): 233–241.

Oliver, R.L. and Ganf, G.G., 2000. Freshwater blooms. In Whitton, B.A. and Pitts, M. (eds), *The Ecology of Cyanobacteria. Their Diversity in Time and Space*. Kluwer, Dordrecht, Netherlands, pp. 149–194.

O'Neil, J., Davis, T.W., Burford, M.A. and Gobler, C., 2012. The rise of harmful cyanobacteria blooms: the potential roles of eutrophication and climate change. *Harmful Algae* 14: 313–334.

Paerl, H.W., Hall, N.S. and Calandrino, E.S., 2011. Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. *Science of the Total Environment* 409(10): 1739–1745.

Round, F.E., Crawford, R.M. and Mann, D.G. (eds), 1990. *The Diatoms. Biology and Morphology of the Genera*. Cambridge University Press, Cambridge, UK.

Watson, S.B., 2004. Aquatic taste and odor: a primary signal of drinking-water integrity. *Journal of Toxicology and Environmental Health, Part A* 67(20–22): 1779–1795.

Watson, S., Charlton, M., Rao, Y., Howell, T., Ridal, J., Brownlee, B., Marvin, C. and Millard, S., 2007. Off flavours in large waterbodies: physics, chemistry and biology in synchrony. *Water Science and Technology* 55(5): 1–8.

Winder, M., Berger, S.A., Lewandowska, A., Aberle, N., Lengfellner, K., Sommer, U. and Diehl, S., 2012. Spring phenological responses of marine and freshwater plankton to changing temperature and light conditions. *Marine Biology* 159(11): 2491–2501.

Abbreviations

DO	Dissolved oxygen
EPA	Environmental Protection Agency
SRP	Soluble reactive phosphorus
TN	Total nitrogen
TOC	Total organic carbon
VSS	Volatile suspended solid

AN GHNÍOMHAIREACHT UM CHAOMHNÚ COMHSHAOIL
Tá an Ghníomhaireacht um Chaomhnú Comhshaoil (GCC) freagrach as an gcomhshaol a chaomhnú agus a fheabhsú mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ó éifeachtaí díobhálacha na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialú: *Déanaimid córais éifeachtacha rialaithe agus comhlíonta comhshaoil a chur i bhfeidhm chun torthaí maithe comhshaoil a sholáthar agus chun díriú orthu siúd nach gcloíonn leis na córais sin.*

Eolas: *Soláthraímid sonraí, faisnéis agus measúnú comhshaoil atá ar ardchaighdeán, spriocdhírithe agus tráthúil chun bonn eolais a chur faoin gcinnteoireacht ar gach leibhéal.*

Tacaíocht: *Bímid ag saothrú i gcomhar le grúpaí eile chun tacú le comhshaol atá glan, táirgiúil agus cosanta go maith, agus le hiompar a chuirfidh le comhshaol inbhuanaithe.*

Ár bhFreagrachtaí

Ceadúnú

Déanaimid na gníomhaíochtaí seo a leanas a rialú ionas nach ndéanann siad dochar do shláinte an phobail ná don chomhshaol:
- saoráidí dramhaíola *(m.sh. láithreáin líonta talún, loisceoirí, stáisiúin aistrithe dramhaíola)*;
- gníomhaíochtaí tionsclaíocha ar scála mór *(m.sh. déantúsaíocht cógaisíochta, déantúsaíocht stroighne, stáisiúin chumhachta)*;
- an diantalmhaíocht *(m.sh. muca, éanlaith)*;
- úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe *(OGM)*;
- foinsí radaíochta ianúcháin *(m.sh. trealamh x-gha agus radaiteiripe, foinsí tionsclaíocha)*;
- áiseanna móra stórála peitril;
- scardadh dramhuisce;
- gníomhaíochtaí dumpála ar farraige.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Clár náisiúnta iniúchtaí agus cigireachtaí a dhéanamh gach bliain ar shaoráidí a bhfuil ceadúnas ón nGníomhaireacht acu.
- Maoirseacht a dhéanamh ar fhreagrachtaí cosanta comhshaoil na n-údarás áitiúil.
- Caighdeán an uisce óil, arna sholáthar ag soláthraithe uisce phoiblí, a mhaoirsiú.
- Obair le húdaráis áitiúla agus le gníomhaireachtaí eile chun dul i ngleic le coireanna comhshaoil trí chomhordú a dhéanamh ar líonra forfheidhmiúcháin náisiúnta, trí dhíriú ar chiontóirí, agus trí mhaoirsiú a dhéanamh ar leasúchán.
- Cur i bhfeidhm rialachán ar nós na Rialachán um Dhramhthrealamh Leictreach agus Leictreonach (DTLL), um Shrian ar Shubstaintí Guaiseacha agus na Rialachán um rialú ar shubstaintí a ídíonn an ciseal ózóin.
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Uisce

- Monatóireacht agus tuairisciú a dhéanamh ar cháilíocht aibhneacha, lochanna, uiscí idirchriosacha agus cósta na hÉireann, agus screamhuiscí; leibhéil uisce agus sruthanna aibhneacha a thomhas.
- Comhordú náisiúnta agus maoirsiú a dhéanamh ar an gCreat-Treoir Uisce.
- Monatóireacht agus tuairisciú a dhéanamh ar Cháilíocht an Uisce Snámha.

Monatóireacht, Anailís agus Tuairisciú ar an gComhshaol

- Monatóireacht a dhéanamh ar cháilíocht an aeir agus Treoir an AE maidir le hAer Glan don Eoraip (CAFÉ) a chur chun feidhme.
- Tuairisciú neamhspleách le cabhrú le cinnteoireacht an rialtais náisiúnta agus na n-údarás áitiúil *(m.sh. tuairisciú tréimhsiúil ar staid Chomhshaol na hÉireann agus Tuarascálacha ar Tháscairí)*.

Rialú Astaíochtaí na nGás Ceaptha Teasa in Éirinn

- Fardail agus réamh-mheastacháin na hÉireann maidir le gáis cheaptha teasa a ullmhú.
- An Treoir maidir le Trádáil Astaíochtaí a chur chun feidhme i gcomhair breis agus 100 de na táirgeoirí dé-ocsaíde carbóin is mó in Éirinn.

Taighde agus Forbairt Comhshaoil

- Taighde comhshaoil a chistiú chun brúnna a shainaithint, bonn eolais a chur faoi bheartais, agus réitigh a sholáthar i réimsí na haeráide, an uisce agus na hinbhuanaitheachta.

Measúnacht Straitéiseach Timpeallachta

- Measúnacht a dhéanamh ar thionchar pleananna agus clár beartaithe ar an gcomhshaol in Éirinn *(m.sh. mórphleananna forbartha)*.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta, measúnacht a dhéanamh ar nochtadh mhuintir na hÉireann don radaíocht ianúcháin.
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha.
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta.
- Sainseirbhísí cosanta ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Faisnéis Inrochtana agus Oideachas

- Comhairle agus treoir a chur ar fáil d'earnáil na tionsclaíochta agus don phobal maidir le hábhair a bhaineann le caomhnú an chomhshaoil agus leis an gcosaint raideolaíoch.
- Faisnéis thráthúil ar an gcomhshaol ar a bhfuil fáil éasca a chur ar fáil chun rannpháirtíocht an phobail a spreagadh sa chinnteoireacht i ndáil leis an gcomhshaol *(m.sh. Timpeall an Tí, léarscáileanna radóin)*.
- Comhairle a chur ar fáil don Rialtas maidir le hábhair a bhaineann leis an tsábháilteacht raideolaíoch agus le cúrsaí práinnfhreagartha.
- Plean Náisiúnta Bainistíochta Dramhaíola Guaisí a fhorbairt chun dramhaíl ghuaiseach a chosc agus a bhainistiú.

Múscailt Feasachta agus Athrú Iompraíochta

- Feasacht chomhshaoil níos fearr a ghiniúint agus dul i bhfeidhm ar athrú iompraíochta dearfach trí thacú le gnóthais, le pobail agus le teaghlaigh a bheith níos éifeachtúla ar acmhainní.
- Tástáil le haghaidh radóin a chur chun cinn i dtithe agus in ionaid oibre, agus gníomhartha leasúcháin a spreagadh nuair is gá.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an ghníomhaíocht á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóirí. Déantar an obair ar fud cúig cinn d'Oifigí:
- An Oifig um Inmharthanacht Comhshaoil
- An Oifig Forfheidhmithe i leith cúrsaí Comhshaoil
- An Oifig um Fianaise is Measúnú
- Oifig um Chosaint Radaíochta agus Monatóireachta Comhshaoil
- An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tá Coiste Comhairleach ag an nGníomhaireacht le cabhrú léi. Tá dáréag comhaltaí air agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research Report 353

Investigation into the Causes, Impacts and Measures to Deal with Algal Blooms in Vartry Reservoir

Authors: Yunhong Shi, Dunzhu Li, Laurence Gill, Bruce Misstear, Ian O'Donohue and Liwen Xiao

epaResearch
Climate - Water - Sustainability
Identifying pressures • Informing policy • Developing solutions

Identifying pressures

Vartry Reservoir is a very important drinking water source in Ireland. Since 2013, spring diatom algae blooms have been occurring in the Vartry Reservoir. In this project, in addition to collecting and analysing historical water quality and ecology data, a 3-year monitoring programme (from 2016 to 2018) and a series of laboratory experiments were carried out to investigate the causes of diatom blooms and identify the pressures. The study monitored nutrient levels in both the feeding rivers and the reservoir. It was found that, although the silica and nutrient concentrations in the reservoir were sufficient for diatom growth, the concentration of soluble reactive phosphorus affected the magnitude of the diatom bloom. The study also found that the ratio of diatom to zooplankton in the Vartry Reservoir was high compared with other lakes in Ireland.

Informing policy

In Ireland, drinking water mainly originates from surface water, with lakes being the main sources. Of the 224 lakes monitored by the Irish Environmental Protection Agency, 113 lakes, including the Vartry Reservoir, were in high or good ecological status during the period 2013 to 2018. The findings of this project have implications for managing these lakes. Although the impact on the water quality is not a main concern in the Vartry Reservoir, diatom blooms pose great challenges to the Vartry water treatment plant, resulting in a significant decrease in water production rates. The data collected in this project will benefit stakeholder decision making in terms of the management of the Vartry Reservoir.

Developing solutions

Vartry Reservoir serves more than 220,000 customers and its supply area stretches from Roundwood, through north Wicklow up to south Dublin. The spring diatom algae bloom results in serious clogging of the downstream slow sand filters in the Vartry water treatment plant. This project provides solutions to (1) prevent the diatom algae bloom in the reservoir and (2) mitigate the impact of diatom algae bloom on the water treatment plant. The project found that, by increasing the zooplankton population to a threshold level, the diatom algae bloom could be inhibited. Coagulation and filtration could be considered as short-term measures to mitigate the impact of diatom blooms on the water treatment plant. Using aluminium sulfate and ferric chloride as coagulants can remove more than 90% of the diatoms. Denim and filter nets with a mesh size of 63 µm can also be used as filter materials to remove more than 77% of diatoms.

EPA Research: McCumiskey House, Richiew, Clonskeagh, Dublin 14.

Phone: 01 268 0100
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie

EPA Research Webpages
www.epa.ie/researchandeducation/research/