epa Research

Report No. 474

Coastal Lagoons: Ecology and Restoration (CLEAR)

Authors: Brendan O’Connor, Geoff Oliver, Tony Cawley, Cilian Roden, Philip Perrin, Rutger de Witt, Kevin McCaffrey and Aisha O’Connor

www.epa.ie

Rialtas na hÉireann
Government of Ireland

Environmental Protection Agency

The 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: Implementing regulation and environmental compliance systems to deliver good environmental outcomes and target those who don't comply.

Knowledge: Providing high quality, targeted and timely environmental data, information and assessment to inform decision making.

Advocacy: Working with others to advocate for a clean, productive and well protected environment and for sustainable environmental practices.

Our Responsibilities Include:

Licensing

- Large-scale industrial, waste and petrol storage activities;
- Urban waste water discharges;
- The contained use and controlled release of Genetically Modified Organisms;
- Sources of ionising radiation;
- Greenhouse gas emissions from industry and aviation through the EU Emissions Trading Scheme.

National Environmental Enforcement

- Audit and inspection of EPA licensed facilities;
- Drive the implementation of best practice in regulated activities and facilities;
- Oversee local authority responsibilities for environmental protection;
- Regulate the quality of public drinking water and enforce urban waste water discharge authorisations;
- Assess and report on public and private drinking water quality;
- Coordinate a network of public service organisations to support action against environmental crime;
- Prosecute those who flout environmental law and damage the environment.

Waste Management and Chemicals in the Environment

- Implement and enforce waste regulations including national enforcement issues;
- Prepare and publish national waste statistics and the National Hazardous Waste Management Plan;
- Develop and implement the National Waste Prevention Programme;
- Implement and report on legislation on the control of chemicals in the environment.

Water Management

- Engage with national and regional governance and operational structures to implement the Water Framework Directive;
- Monitor, assess and report on the quality of rivers, lakes, transitional and coastal waters, bathing waters and groundwaters, and measurement of water levels and river flows.

Climate Science & Climate Change

- Publish Ireland's greenhouse gas emission inventories and projections;
- Provide the Secretariat to the Climate Change Advisory Council and support to the National Dialogue on Climate Action;
- Support National, EU and UN Climate Science and Policy development activities.

Environmental Monitoring & Assessment

- Design and implement national environmental monitoring systems: technology, data management, analysis and forecasting;
- Produce the State of Ireland's Environment and Indicator Reports;
- Monitor air quality and implement the EU Clean Air for Europe Directive, the Convention on Long Range Transboundary Air Pollution, and the National Emissions Ceiling Directive;
- Oversee the implementation of the Environmental Noise Directive;
- Assess the impact of proposed plans and programmes on the Irish environment.

Environmental Research and Development

- Coordinate and fund national environmental research activity to identify pressures, inform policy and provide solutions;
- Collaborate with national and EU environmental research activity.

Radiological Protection

- Monitoring radiation levels and assess public exposure to ionising radiation and electromagnetic fields;
- Assist in developing national plans for emergencies arising from nuclear accidents;
- Monitor developments abroad relating to nuclear installations and radiological safety;
- Provide, or oversee the provision of, specialist radiation protection services.

Guidance, Awareness Raising, and Accessible Information

- Provide independent evidence-based reporting, advice and guidance to Government, industry and the public on environmental and radiological protection topics;
- Promote the link between health and wellbeing, the economy and a clean environment;
- Promote environmental awareness including supporting behaviours for resource efficiency and climate transition;
- Promote radon testing in homes and workplaces and encourage remediation where necessary.

Partnership and Networking

- Work with international and national agencies, regional and local authorities, non-governmental organisations, representative bodies and government departments to deliver environmental and radiological protection, research coordination and science-based decision making.

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:

1. Office of Environmental Sustainability
2. Office of Environmental Enforcement
3. Office of Evidence and Assessment
4. Office of Radiation Protection and Environmental Monitoring
5. Office of Communications and Corporate Services

The EPA is assisted by advisory committees who meet regularly to discuss issues of concern and provide advice to the Board.

Coastal Lagoons: Ecology and Restoration (CLEAR)

Authors: Brendan O'Connor, Geoff Oliver, Tony Cawley, Cilian Roden, Philip Perrin, Rutger de Witt, Kevin McCaffrey and Aisha O'Connor

Lead organisation: AQUAFACT, part of the APEM Group

Identifying pressures

The CLEAR project addressed one of the most common problems impacting the quality of Ireland's aquatic environment which is the over-enrichment of surface waters with nutrients such as nitrogen and phosphorus. The focus of the CLEAR project was Lady's Island Lake located in the southeast of Ireland. Lady's Island Lake is a saline lagoon which is protected under the EU's Habitats Directive as a priority habitat. The ecology of this lagoon has been severely damaged by nutrient over-enrichment resulting in harmful algal blooms and fish kills. The purpose of the CLEAR project was to understand the extent to which Lady's Island Lake has been polluted by nutrients and the impact of this pollution on its ecology. This was achieved by comparing Lady's Island Lake to another saline lagoon known to be unimpacted by nutrient enrichment – Ballyteigue Channels. The shallow lake theory was used to compare the characteristics of both lagoons.

Informing policy

The continued decline of Lady's Island Lake and other saline lagoons in Ireland will result in the loss of many specialised species, the disappearance of feeding grounds for migratory birds and reduce the recreational and aesthetic value of these waters. The results of this research have shown that a 5 to 7-fold reduction in nitrogen and phosphorus inputs to Lady's Island Lake will be necessary to return the lagoon to its previous condition.

Developing solutions

The results of our research show that no improvement in the lake's ecology will be possible without a large reduction in nutrient run-off from land. Some amelioration may be possible by protecting the lake shoreline by tree planting, the use of artificial wetlands and the removal of nutrient rich sediments. Inevitably, society must address the conflict between the overuse of nutrients such as nitrogen and the impact this is having on our water resources.

EPA RESEARCH PROGRAMME 2021–2030

Coastal Lagoons: Ecology and Restoration (CLEAR)

(2018-W-MS-39)

EPA Research Report

Prepared for the Environmental Protection Agency

by

AQUAFACT, part of the APEM Group

Authors:

Brendan O’Connor, Geoff Oliver, Tony Cawley, Cilian Roden, Philip Perrin, Rutger de Witt, Kevin McCaffrey and Aisha O’Connor

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 2021–2030. 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 project was co-funded by the National Parks and Wildlife Service.

The authors would like to acknowledge the members of the project steering committee, namely Yvonne Leahy (Department of Arts, Heritage and the Gaeltacht), Trevor Harrison (Department of Agriculture, Environment and Rural Affairs of Northern Ireland), Michael Nugent (Local Authority Waters Programme), Joao Neto (Universidade De Coimbra), Robert Wilkes (Environmental Protection Agency), Brendan Cooney (Wexford County Council) and David Lyons (Department of Arts, Heritage and the Gaeltacht).

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 May 2019 to December 2021. 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 2021–2030
Published by the Environmental Protection Agency, Ireland

ISBN:978-1-80009-221-1 January 2025

Price: Free Online version

Project Partners

Brendan O'Connor
AQUAFACT International Services Ltd. (part of the APEM Group)
12 Kilkerrin Park
Galway
Tel.: (091) 756812
Email: boc@aquafact.ie

Geoff Oliver
Cape Clear
Skibbereen
Co. Cork
Tel.: (087) 6197817
Email: golivercape@gmail.com

Tony Cawley
Hydro Environmental
Clarinbridge
Co. Galway
Tel.: (087) 2061277
Email: tony@hydroe.ie

Cilian Roden
Gehy
Kinvara
Co. Galway
Tel.: (086) 1713795
Email: cilianroden@icloud.com

Philip Perrin
BEC
65 Holywell
Dundrum
Dublin
Tel.: (087) 2138499
Email: pperrin@botanicalenvironmental.com

Rutger de Witt
7 Rue Roc De Pezenas
34070 Montpellier
France
Tel.: (+33) 4671 43429
Email: rutger.de-wit@cnrs.fr

Contents

List of Figures

List of Tables

Executive Summary

One of the largest lagoons in Ireland, Lady's Island Lake in County Wexford, with a surface area of over 300 hectares, has also been shown to be one of the most eutrophic lagoons in the country. This state contrasts with the situation of Lady's Island Lake in the 1980s, when clear water was matched by a well-developed benthic sward of widgeon grass (*Ruppia* sp.) and charophytes (Healy, 1997). There is little doubt that the lagoon ecosystem switched from a benthos-dominated habitat to one dominated by plankton (largely cyanobacteria) some time between the 1980s and the first decade of the 21st century, probably due to excessive inputs of nitrogen and phosphorus from agriculture.

This project was structured around the concept that lagoons in good conservation status are dominated by benthic macrophytes rather than phytoplankton blooms. The Coastal Lagoons: Ecology and Restoration (CLEAR) research programme was designed to explain why and how Lady's Island Lake switched from a benthos-dominated habitat to one dominated by plankton. To do this the following suite of investigations were undertaken:

- Nutrient inputs from streams were studied over a 2-year period.
- Data on the flow of water to the lake from a secondary wastewater treatment plant at Lady's Island Lake were obtained from Irish Water.
- Nutrient cycling and phytoplankton growth were examined over a 2-year period.
- Sediment chemistry was studied at a number of locations within the lagoon.
- Shallow water and benthic samples were collected to describe those aspects of the lagoon.
- A sediment profile imagery survey was carried out at the same set of stations where benthic samples were taken.
- Current speed and direction measurements were taken over an extended period in the lagoon.
- A hydrodynamic model of the lagoon was developed.

A small saline pond at the neighbouring lagoon site of Ballyteige, which is in a less impacted, clear water state, was used as a comparison site, with the same suite of surveys being carried out there.

The research project was divided into seven work packages (WPs), as follows.

- WP 1: review of literature relating to lagoons, such as on ecology, water and sediment chemistry, shallow near-shore and deeper water biology, and hydrogeology;
- WP 2: nutrient inputs, impacts and processing;
- WP 3: lagoonal ecology and sediment chemistry;
- WP 4: hydrodynamic modelling;
- WP 5: remedial actions;
- WP 6: project management;
- WP 7: communications.

WP 1 has been submitted to the EPA as a separate document.

The main findings of WPs 2–5 are as follows:

- Winter values of chlorophyll *a* reached a maximum of *c.* 110 µg/l in Lady's Island Lake and were less than 10 µg/l in Ballyteige.
- A strong relationship was found between chlorophyll *a* levels and Secchi depths, with the highest chlorophyll *a* levels having shallow (< 1 m) Secchi depth.
- Such shallow Secchi depths compromise benthic macrophytic growth, with the result that such plants are limited to the shallower parts of the lagoon.
- Chlorophyll *a* levels of less than 10 µg/l are necessary for benthic vegetation to develop.
- The Secchi data suggest that total nitrogen concentration > 1.0 mg/l corresponds to a moderate/bad status for Lady's Island Lake.
- Lady's Island Lake's poor ecological condition is related to excess nitrogen input.
- To enable the lagoon to switch back to benthic macrophyte dominance would require at least a 10-fold reduction in nutrient input.
- Plankton-dominated lagoons are largely found in catchments with more than 60% farming or forestry. This suggests that run-off from agriculture and forestry is the source of the nutrients that

cause benthos plant dominance to give way to plankton dominance in Irish lagoons.

- The shallow water biological surveys of Lady’s Island Lake showed a fauna typical of lagoons.
- The results of both the sediment profile imagery and benthic surveys show very poor benthic sediment conditions with low redox values, low organism sediment indices, low successional stages and low numbers of infaunal species.
- These data were statistically compared with a similar dataset collected in 1977 in Lady’s Island Lake, and the results show that a very significant change occurred between 1977 and the present.

1 Introduction

1.1 Background

One of the largest lagoons in Ireland, Lady’s Island Lake in County Wexford (300 ha), has also been shown to be one of the most eutrophic lagoons in the country (see AQUAFACT and Roden Oliver Associates, 2017). This state contrasts with the situation of Lady’s Island Lake in the 1980s, when clear water was matched by a well-developed benthic sward of widgeon grass (*Ruppia* sp.) and charophytes (Healy, 1997). There is little doubt that the lagoon ecosystem switched from a benthos-dominated habitat to one dominated by plankton (largely cyanobacteria) some time between the 1980s and the first decade of the 21st century, probably due to excessive inputs of nitrogen and phosphorus from agriculture.

Lady’s Island Lake is a designated Special Protection Area and, as a coastal lagoon, also qualifies as a Special Area of Conservation under Annex I of the EU Habitats Directive. Coastal lagoons are listed as a priority habitat under the Habitats Directive and, as coastal waterbodies, they are also protected under the Water Framework Directive (WFD). The Irish government is obliged under EU law to restore the site to “favourable” conservation status under the Habitats Directive and to at least “good” water status under the WFD.

Nutrient inputs and cycling, phytoplankton growth and sediment chemistry were studied and a hydrodynamic model of the lagoon was developed. The results of these enabled the accurate description of the origin, quantities and fate of nitrogen and phosphorus in the lagoon and an investigation into how proposed management strategies would affect nutrient supply and salinity.

A small saline pond at the neighbouring lagoon site of Ballyteige, which is in a less impacted, clear water state, was used as a comparison site.

Benthic flora and fauna were surveyed at both Lady’s Island Lake and Ballyteige Lagoon using standard qualitative and semi-quantitative methods and also sediment profile imagery (SPI). The benthic data from the Coastal Lagoons: Ecology and Restoration (CLEAR) survey of Lady’s Island Lake were statistically compared with a dataset that was collected in 1977, and the results showed that differences between the two datasets were statistically highly significant. This project was structured around the concept that lagoons in good conservation status are dominated by benthic macrophytes rather than phytoplankton blooms.

In order to investigate what amount of nutrient loading results in a shift from macrophyte to phytoplankton dominance, existing lagoon data were used to redefine ecological quality ratios (EQRs) and nutrient loadings. An estimate of the reduction in nutrient loading needed to achieve the proposed values for good or high status, as defined by the WFD, was made based on current and proposed winter values of nitrogen and phosphorus in Lady’s Island Lake. A box model of nitrogen and phosphorus flows in Lady’s Island Lake was also developed and enabled the calculation of the relationship between nitrogen and phosphorus inputs and losses, and nitrogen and phosphorus available for plankton growth. A simple quantitative model was developed that relates plankton growth to reduction in light availability to macrophytes through shading. This model helped define the conditions that lead to a switch from macrophyte to phytoplankton dominance. Measures that are available to achieve these changes were reviewed and their effectiveness (such as artificial wetlands or nutrient buffer zones and the impact of agri-environment schemes that encourage reduced fertiliser inputs) assessed. Techniques used in other countries to manage lagoon eutrophication were also reviewed.

The initial outcome of the project was a plan to attempt to restore the Lady’s Island Lake site and produce a manual documenting methods to quantify excessive nutrient inputs and impacts of lagoon salinity change and flushing rates on conservation status for all Irish lagoons. The manual outlines a suite of techniques to restore environmentally degraded lagoons.

As part of the Environmental Protection Agency/National Parks and Wildlife Service (EPA/NPWS)-funded CLEAR project, AQUAFACT, part of the APEM Group, carried out benthic surveys at both Lady’s Island Lake and Ballyteige Lagoon, which included an SPI survey and a grab survey. This report presents the findings of these surveys.

2 Hydrodynamics – Lady's Island Lake

2.1 Catchment Hydrology and Hydrogeology

Lady's Island Lake is a small lagoonal lake of *c.*300 ha located in the southeastern corner of Ireland near Carnsore Point (Figure 2.1). The lake discharges through a sand dune cutting to the sea and has a relatively small contributing catchment area of 19.16 km^2. The lake surface area is currently mapped by the EPA at 300.3 ha and is classified by the EPA as a transitional waterbody. Historically, the first edition Ordnance Survey Ireland 25-inch map (*c.*1880s) shows a lagoon surface extent of 335.7 ha. The lake extent depends on the lake level, which can vary annually by over 2 m.

The lake discharges to the sea via a man-made cut in the sand dune barriers located at the southeast corner of the lake. This cut is based on the first edition Ordnance Survey Ireland 6-inch mapping and was opened in 1840 to relieve flooding in the lake. This cutting is opened each year to control flood levels

Figure 2.1. Lady's Island Lake and catchment extent.

and to empty the lake to a level of *c.*0.6 to 1.0 m ordnance datum (OD) Malin. In occasional years, a second cutting is required. The cut width can expand to over 100 m and eventually closes naturally through sediment deposition. Depending on rainfall patterns in a given year a second cutting may often be required to manage lake levels. The lake is elongated with the longitudinal orientation north-northeast (NNE) to south-southwest (SSW), measures 3.4 km in length, and the average width is 0.87 km, varying from 0.54 to1.5 km. The majority of catchment inflow occurs to the upper lake area near Lady's Island Lake village.

The lake's total upstream contributing catchment area is 19.16 km^2. There are seven EPA mapped streams discharging to the lake: the Kisha (4.2 km^2), the Coldblow (1.49 km^2), the Stonyford (1.16 km^2), the Racecourse (0.58 km^2), the Eardownes Little (0.34 km^2), the Trane (1.18 km^2) and the Strand (1.23 km^2). There are a number of other, smaller, unnamed streams/drainage channels discharging to the lake in the low-lying flood lands in the Ring townland area on the east side of the lake.

The underlying bedrock aquifer throughout the catchment is classified by Geological Survey Ireland as a poor aquifer that is generally unproductive except for local zones. The bedrock underlying the lower and middle lake sections and surrounding areas is a pink biotite granite with xenoliths referred to as the Carnsore Granite Formation. The bedrock underlying the upper lake section is described as a banded quartzo-feldspathic paragneisses, known as the Kilmore Quay Group, and the bedrock in the upper catchment is described as a foliated amphibolites with minor schists, known as the Greenore Point Group.

These bedrock groups have generally low permeability (primary and secondary), giving rise to generally low groundwater transmissivity and storativity and thus a poor aquifer yield, giving rise to a poor aquifer/non-aquifer classification. This results in a low groundwater baseflow contribution to the lake and to its contributing streams.

The quaternary geology is a till derived from granites overlying the granite bedrock to the southeast of the catchment; to the west and northwest the till is derived from metamorphic rocks and to the northeast the till is derived from Cambrian sandstones and shales. Windblown sands are deposited as a dune barrier system to the south between the shoreline and the lake. The windblown sands have high permeability, the tills to the west and northwest are classified as having low permeability, and the granite-, sandstone- and shale-derived tills to the east and northeast as having moderate to low permeability.

Generally, the soil group within the catchment is a deep, well-drained, acidic brown earth and brown podzolics. The estimated groundwater recharge rate is less than 51 mm per annum of effective rainfall for 36.5% of the catchment, primarily to the west and northwest, and between 51 and 100 mm per annum for the remainder. This free-draining topsoil gives rise to a risk of nitrates, particularly in the east of the catchment, percolating through the soil and subsoils to contribute to groundwater and interflow, eventually reaching surface watercourses and the lake as baseflow.

The land use within the catchment is categorised by the Coordination of Information on the Environment (Corine) land use database (Corine, 2018) as either agriculture pasture or arable land, at 81.3%, and the remaining 18.7% is classified as coastal lagoon and saltmarsh.

The long-term standard average annual rainfall (1981–2010) over the catchment[1] is 837.4 mm and the average annual evapotranspiration rate is 553.3 mm (EPA HydroTool[2]). The lake's annual average evaporation rate is estimated to be 800 mm. The mean annual water balance applied to the Lady's Island Lake river catchment gives an average inflow rate to the lake of 0.149 m^3/s (149.4 l/s or 7.8 l/s per km^2). The groundwater recharge rate, which supports baseflow in the streams and to the lake, is estimated to be 0.034 m^3/s (1.8 l/s per km^2), which is only 23% of effective rainfall over the catchment. Conversely, 77% of run-off is from quick surface and interflow run-off to the stream network and to the lake. This interflow source includes the subsurface flow in the unsaturated subsoil layer, which in the east of the catchment is 3–5 m deep in moderate-permeability subsoils. Based on the EPA HydroTool information for the hydrological estimation node on the Kisha Stream at its confluence

---

[1] https://gis.epa.ie/EPAMaps/

[2] https://gis.epa.ie/EPAMaps/

with the upper lake section, the following low-flow rates for the lake-contributing catchment can be estimated as 95% low flow (q_{95}) = 2.07 l/s per km^2 and 99% low flow (q_{99}) = 1.21 l/s per km^2. The annual average inflow to the lake is 4.715 million m^3, which represents a 1.57 m rise in lake level. From year to year, this inflow volume can vary by a factor of up to 2.

The aquifer vulnerability is a function of the overburden depth and varies from west to east in the catchment, with deep, low-vulnerability soils (> 10 m) to the west and high-vulnerability soils to the east, with overburden depths over bedrock of 3 to 5 m. The free-draining nature of the topsoil and the moderate permeability of subsoils in the east of the catchment suggest favourable conditions for the migration of nitrogen and phosphorus to the lake and inflowing streams via interflow and shallow groundwater flow in the subsoils. The bedrock aquifer itself is not very productive and does not represent a major source of recharge to the lake. The main transport of pollution to the contributing streams and to the lake is as quick flow by direct surface run-off from the land, as interflow through the unsaturated soil and as slower groundwater in the saturated subsoils and upper weathered section of the bedrock.

2.2 Lake Hydrological Regime

The Lady’s Island Lake is a shallow, artificially managed lagoon of some 300 ha with lakebed elevations varying from –2 to +2 m OD Malin (the barrier at the southern, seaward boundary is opened to prevent flooding but also serves to flush nutrients from the system). The bed levels used to define the lake and its riparian zone were obtained from a bathymetric survey commissioned by Malachy Walsh and Partners consulting engineers, and data on the riparian zone from the Office of Public Works (OPW) light detection and ranging (lidar), which is a 2 m grid digital terrain model (DTM) at ± 0.15 m vertical accuracy, flown in 2006 and available for download from the Open Topographic Data Viewer (GSI, 2018).

A hydrometric recorder on Lady’s Island Lake (station number 13070) has been operated by the EPA since 1998, and the gauge site is located near the village community hall at E310570, N107760. This recorder provides a gauged record of lake levels at 15-minute intervals. There are a number of gaps in the record due to recorder malfunction (February 2002 to April 2003, April 2011 to February 2013 and June 2013 to September 2014). The maximum recorded water level from the available record was 3.296 m OD Malin, which occurred on 29 January 2016. The recorded median (50th percentile) water level for the record period is 1.39 m OD Malin and the 99th percentile dry weather lake level is 0.70 m OD Malin (Table 2.1).

The recorded lake level time series profile reflects the management of lake levels, with lake levels continuing to rise each winter to between *c.*2.5 and 3.2 m OD until the cut in the sand barrier is carried out. Once the breach has been opened, the lake empties out to sea, with lake levels falling to a level typically between 0.7 and 1.2 m OD. There is a short period after the breaching, lasting a number of days, when a tidal signal can be observed in the lake levels during spring tides. Once the breach closes up and tides reduce to a neap cycle, this tidal signal is lost and the lake level gradually begins to rise from the freshwater inflow storing behind the sand barrier. The breach period is followed by a period of gradual rise and then a more rapid rise associated with the winter/autumn wet period.

The breach is generally carried out in late winter/early spring to combat flooding of agriculture lands, to protect flooding at Lady’s Island Lake village and to prevent flooding of the tern nesting site on the island. Periods of low lake levels can make nests prone to attack from predators crossing onto the island. In very wet years there may be a requirement to breach twice in order to protect against flooding. This breaching activity involves excavating a channel on the foreshore and through a lowered section of the dune. The breach site is kept to the same location, year in year out, with such breaching reported to have commenced in 1840.

Table 2.1. Lake level statistics in metres OD Malin

	Non-exceedance probability							
Min.	**1%**	**5%**	**10%**	**50%**	**90%**	**95%**	**99%**	**Max.**
0.572	0.7	0.958	1.037	1.391	2.47	2.748	3.1	3.296

Tidal records are available for the Rosslare Port gauge from the Marine Institute and from the Wexford Harbour tidal gauge. The Rosslare Port gauge is reasonably close to the breach location, at 7 km away along the coastline. The low- and highwater mean spring tides at the Rosslare Port gauge are –0.8 and 0.8 m OD Malin and the mean neap tides are –0.5 and 0.4 m OD. The tides off Lady's Island Lake are slightly higher, *c.*0.25 m higher than spring tides and 0.15 m higher than neap tides, giving a mean highwater level of 1.05 m at spring tides and of 0.55 m OD Malin at neap tides. The highest astronomical tide at Rosslare Port is estimated to be 1.2 m OD Malin and estimated to exceed 1.5 m OD Malin adjacent to Lady's Island Lake.

Without the human intervention of cutting the breach in the sand dune barrier each year, the lake would probably remain full, possibly in excess of 3.3 m OD, until sufficiently elevated so as to overtop the naturally forming sand barrier at its lowest point and/or percolate through the sand barrier under upstream freshwater head. Under such conditions, the difference between summer and winter lake levels would be much lower and the lagoon salinity would become virtually that of a freshwater lake. With the build-up of lake levels from fluvial freshwater inflow, there would be no positive hydraulic gradient for saltwater intrusion into the lake. Even after breaching in the current scenario, there is limited gradient for saltwater intrusion via percolation through the barrier and via the groundwater, as the spring highwater levels typically reach only 1 to 1.2 m OD Malin and the lake levels are generally above 1 m OD Malin for much of the year. The lake's main source of salinity is the breach channel, which, once cut, can widen out to over 100 m through erosion. This allows (during the period of high tides) saline coastal water to enter on the flooding tide into the lake, where it mixes with the lake freshwater. The mixed brackish water leaves on the subsequent ebbing tide repeating over spring tidal cycles. This process introduces significant salinity to the lower reaches of the lake. The breach eventually closes due to sediment deposition and wave/storm activity. This inflow and outflow tidal process introduces clean saline water into the lower section of Lady's Island Lake and represents an important flushing process for the lake.

2.3 Lake Stage–Storage Relationship

A stage–storage relationship was developed for Lady's Island Lake based on the bathymetric survey and the lidar DTM 2 m grid levels. This relationship is presented in Figure 2.2 showing a storage of some 10 million m^3 at 3 m OD lake level. The figure shows that lake storage is 2.86 million m^3 at the low lake level of 0.6 m OD Malin, 4.79 million m^3 at the median lake level of 1.39 m OD and 11.01 million m^3 at the high flood level of 3.3 m OD. A typical annual range of 2 m in lake level represents a 6.1 million m^3 lake volume change.

2.4 Hydrodynamic Modelling

A Telemac two-dimensional (2D) hydrodynamic model (Figure 2.3) of Lady's Island Lake was developed using a variable triangular finite element mesh of

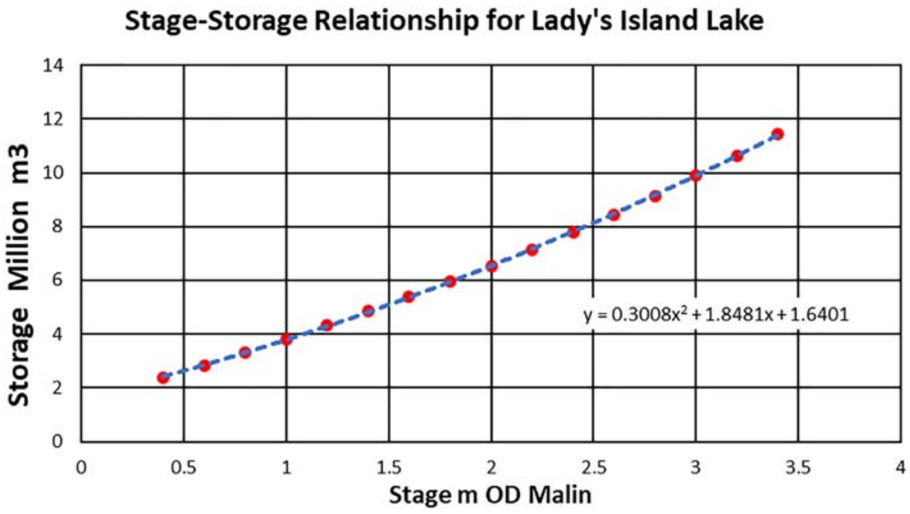

Figure 2.2. Stage–storage relationship for Lady's Island Lake.

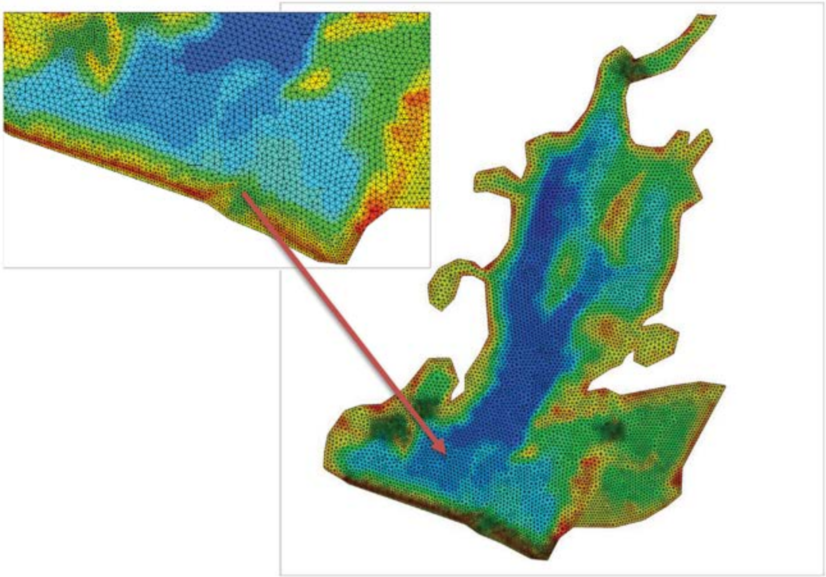

Figure 2.3. Lady's Island Lake finite element Telemac 2D model.

15 to 30 m element sizes. Given the very shallow nature of the lagoon, with the deepest depth at *c.*–2 m OD and maximum levels at 3.3 m OD, a 2D model was considered sufficient to model the hydrodynamics of the lake.

The boundary conditions to this model were:

- freshwater inflow condition at the head of the lagoon for the catchment freshwater stream inflows;
- breach outflow condition that was set to zero flux until the breach was opened.

The inflow and outflows were determined from linear reservoir routing using the stage–storage relationship. The breach period was isolated and the net inflow/outflow through the breach determined from the change in storage with respect to time relationship based on the gauge record from the Lady's Island Lake gauge and the stage–storage relationship.

2.5 Model Simulations and Findings

The Telemac 2D model simulation was performed for the period 1 September 2019 to 30 April 2020. This simulation period involved a wet winter, producing the second highest flooding event for the available record period (1998 to date), and involved breaching on two separate dates: 25 January 2020 and 19 March 2020. The peak flood level reached prior to the first breaching was 3.1 m OD and the lake level subsequently fell to 0.53 m. On the second breaching, a peak lake level reached prior to breaching was 2.44 m OD, with the lake level subsequently falling to 0.59 m OD.

The low level maintained in the lake after breaching is dictated by the subsequent spring tide levels and generally rebounds to between 0.8 and 1.0 m OD. The first breaching coincided with a period of high spring tides, producing a sustained period of tidal inflows and outflows through the breach over 13 tidal cycles (Figure 2.4). The second breach event at the end of March coincided with a period of mean tides, reducing to neap tides, and this resulted in no significant tidal inflow–outflow activity until spring tides returned, producing a jump in lake level of 0.3 m over two tidal cycles (Figure 2.5).

The lake level gauging and the hydrodynamic model simulations show that spring tides, once lake levels have been lowered through breaching, are important sources of introducing relatively low-nutrient saline waters into the lower reach of Lady's Island Lake. Mean and neap tide periods are too low to generate saline inflows to the lake, making the timing for breaching with respect to the lunar phase of the tide important. The optimum period for breaching with respect to lowering lake levels and flushing of the lower lake with coastal waters via tidal inflows is the cutting of the breach just prior to a high spring tide period.

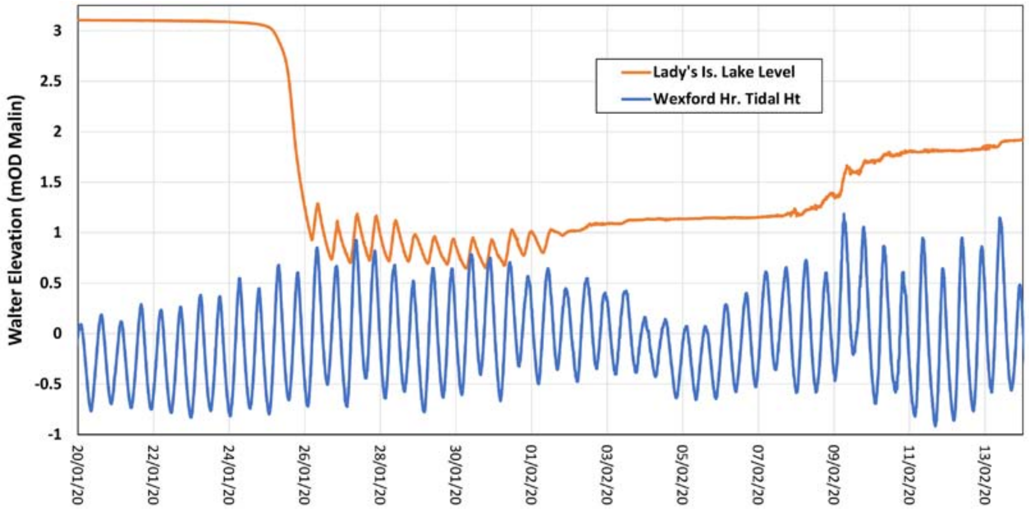

Figure 2.4. Tides and lake level during the first breach. Note: the Rosslare Port gauge was not recording and the Wexford Harbour gauging is *c*.0.35 m lower at spring highwaters than in the sea at Lady's Island Lake.

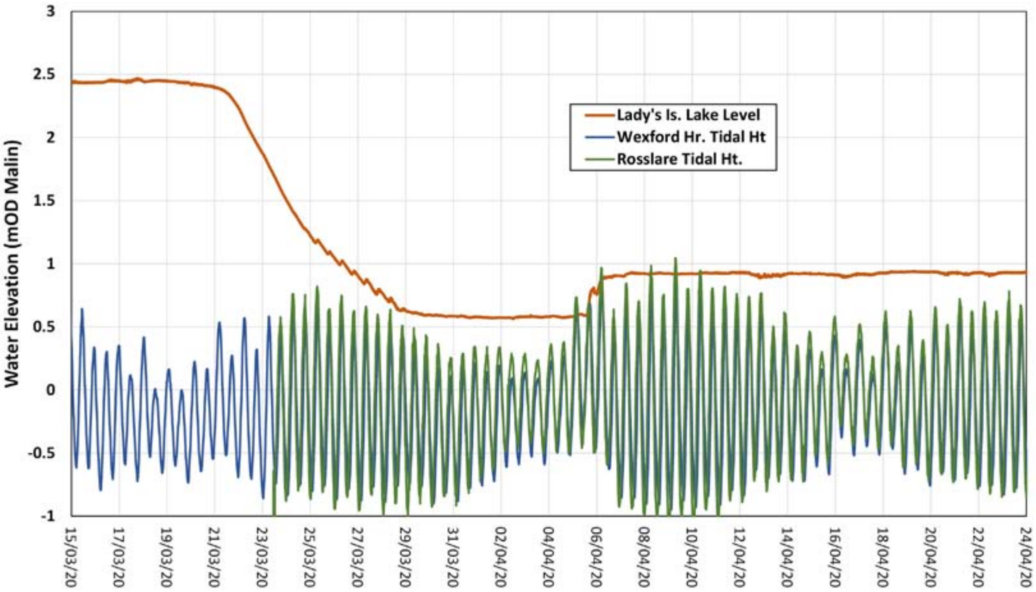

Figure 2.5. Tides and lake level during the second breach. Note: the Rosslare Port gauge was *c*.0.25 m lower at spring highwaters than in the sea at Lady's Island Lake.

Water quality simulations show that nutrients (nitrogen) build up in the lake system, with the higher concentrations remaining towards the head (north end) of the lake, and these are slowly transported downstream to the lower lake section, mainly through diffusion and dispersion. Wind shear is shown by the modelling to be an important process for mixing within the lake. The prevailing southerly winds tend to cause nutrients to be held in the upper, northerly, section of the lake, limiting their ability to disperse downstream. Sediments entering the lake from the fluvial inflows will generally settle out within the lake, with the finer sediments resuspending under wind shear and during breaching activities that induce increased flow velocities. The simulations show that the hydraulic gradient produced by the lowering effect at the breach pulls the water and pollutants in the upper lake section rapidly down into the lower, southern, section of the lake.

Nutrients (nitrogen and phosphorus) mainly enter the lake in autumn and winter, during the recharge period, via surface overland run-off and interflow and groundwater flow in the free-draining topsoils and subsoils. The groundwater flow from the bedrock aquifer within the catchment is low owing to the impervious nature of the underlying aquifer and therefore does not sustain streamflow during summer drought periods. Generally, in summer, the soil moisture deficit reduces catchment run-off and thereby can lower considerably the nutrient load on the lake during drought periods. Autumn produces a first flush effect once catchment soil moisture deficits have been met, mobilising nitrogen that accumulates within the topsoil layer.

The simulations show that the main source of dilution and flushing in the lake is the breaching activity, which first empties *c.*7 million m^3 of lake water (3.0 m OD Malin reduced to 0.6 m OD Malin) and then, over subsequent spring tidal cycles, allows coastal waters on the flooding tide to enter and mix in the lower lake section and then outflow on the subsequent ebbing tide. The model simulations indicate that some mixing of saline and lake waters takes place but that a high portion of the saline water entering from the previous flooding tide is discharged on the subsequent ebb flow, representing sluggish flow conditions as opposed to a well-mixed process. The storage calculations suggest that between 0.5 and 1 million m^3 of coastal seawater per tidal cycle is introduced into the lake during these high spring tides and that such tidal activity can last for up to 12 tidal cycles depending on the timing of the breach with the tide. The simulations show that the inflowing tidal waters after breaching are extremely important in maintaining a level of salinity within the lake and that, in the absence of breaching, the lake would tend essentially towards a freshwater lake system.

A proposal for a large pipeline (1.2 m diameter) to control lake flood levels and, in reverse, also under gravity, to introduce saline coastal waters into the lake to replace the breaching of the barrier, was examined. This pipeline option was found to be capable of gradually lowering the lake level from 3 to 0 m OD Malin over a 6-week period, requiring a non-return value to prevent reverse flow at high tides, which is considered feasible from a flood management perspective. However, using the pipeline to introduce saline water volume into the lake was only partly successful, and it took 6 weeks to increase the lake level from 0 to 0.5 m OD (1 million m^3 of saline water). In addition, this assumes that catchment fluvial inflow during that period is insignificant and requires the use of non-return valves. This saline volume is minor in comparison with the saline volume that can enter with the flood tide after breaching, which, from the modelling, is estimated at between 0.5 and 1 million m^3 per tidal cycle.

2.6 Climate Change

Increased variability in weather patterns due to projected climate change effects may give rise to greater flushing events, both in magnitude and frequency, in the catchment, which could, in turn, increase nutrient losses from agricultural lands, giving rise to increased nutrient loading on the lake if nutrient application rates in the catchment are not reduced.

The effect of potential climate change on Lady's Island Lake will be increased winter fluvial flooding and thus a requirement for more frequent breaching in any given year to manage lake flood levels. Sea level rise, predicted to be 0.5 to 1 m under various climate change emission scenarios, will ultimately cause lake levels to rise by a similar magnitude both during dry summer periods, when levels are low, and in winter, when in flood. Increased storminess will result in increased coastal erosion and could result in the existing sand dune barrier, which forms the southern boundary of the lake, retreating northwards into the lake. Such future conditions will make management of flood levels in the lake extremely difficult, particularly when combined with the projected increase in winter fluvial run-off.

2.7 Hydrodynamics Conclusion

The hydrodynamic simulations clearly show that the breaching arising from the lowering of the sand dune barrier that occurs each year is essential for the removal of nutrients from the lake, the introduction of saline water into the lower section of the lake and the maintenance of brackish conditions in the lake. Without breaching, the lake is likely to become a freshwater lake system, with increased build-up of nutrients and significant worsening of water quality and eutrophication. Wind shear dynamics play an important role in dispersing pollutants entering from the various stream inflows at the head of the lake into the lower and middle sections of the lake and in assisting the mixing of the cleaner saline water introduced during the breaching process.

The strategy of employing a pipeline to replace breaching would enable control of lake flood levels, but such a pipeline in reverse would not be capable of providing sufficient saline inflows to replicate the saline inflows currently achieved from the physical breaching process. A very serious additional problem is the control of lagoonal salinity. The hydrological model shows that even a large-diameter pipe replacing the present system of barrier breaching would radically reduce lagoonal salinity to the extent that the waterbody would be more of a shallow freshwater lake than a saline lagoon. As such, it would have little conservation value and could not be included in the priority habitat of lagoons, listed in the EU Habitats Directive.

The timing of breaching is shown to be important. Breaching should, where possible, take place just prior to high spring tides to maximise saline inflows, which have the dual purpose of maintaining salinity levels and, importantly, introducing cleaner coastal waters into the lake system. Climate change presents a difficulty for flood level management, particularly the projected sea level rise and increase in storm events, with lake levels, similarly to sea level, likely to rise by 0.5 to 1 m over the next 100 years. Increased coastal storms could result in the sand dune barrier retreating northwards into the lake and may at times be vulnerable to natural breaching.

3 The Impact and Fate of Nitrogen and Phosphorus on Lady's Island Lake and Other Irish Lagoons

3.1 Introduction

Irish lagoons were little studied until the work of Brenda Healy and co-workers on Lady's Island Lake from the 1980s onwards. Healy subsequently led two national surveys of lagoons, one in 1996 and one in 1998, for the NPWS (see Healy (1999a,b) for a summary of the results of these surveys). Ireland has nearly 100 lagoons, covering a total area of 2450 ha. These range in size from *c.*300 ha (Lady's Island Lake) to less than 1 ha. There are a variety of lagoon types, including shingle barrier lagoons, such as Tacumshin, silled rock basin types, as found in Connemara, and artificial dyked enclosures. The flora and fauna are diverse, with many lagoonal specialist species, including species protected under Irish law (e.g. *Lamprothamnion papulosum*). The EU Habitats Directive lists saline lagoons as a priority habitat, and many lagoons are threatened by eutrophication, land reclamation, urbanisation and other pressures.

Since 2005, the EPA and NPWS have organised several monitoring surveys of selected lagoons to establish their status under the WFD and the Habitats Directive (Oliver, 2005; Roden and Oliver, 2012; AQUAFACT and Roden Oliver Associates, 2017). These surveys have shown that, overall, Irish lagoons, like their continental counterparts, are under threat, especially from eutrophication in the short term and from sea level change in the long term.

In geographical terms, the most damaged lagoons occur along the south and east coasts of Ireland, a region that includes some of Ireland's largest lagoons (Tacumshin, 450 ha; Broadmeadow, 280 ha; Lady's Island Lake, *c.*300 ha) and a region where estuaries are very nutrient rich (O'Boyle *et al.*, 2015), probably reflecting intensive agriculture. Thus, all lagoons in Ireland > 200 ha are currently rated moderate to bad in terms of the WFD and unfavourable-bad in terms of the Habitats Directive, partly because of excess nitrogen and phosphorus inputs (AQUAFACT and Roden Oliver Associates, 2017). During previous EPA- and NPWS-funded surveys (Roden and Oliver, 2012), attempts were made to develop indicators of favourable or unfavourable conservation condition, based on water chemistry, phytoplankton, macrophytes and benthic invertebrates; these indicators are essentially empirical, without a developed ecological justification.

In the last 30 years, freshwater biologists have developed a theoretical analysis of ecosystem states in shallow freshwater lakes (e.g. Moss, 1994; Scheffer, 2004). They distinguish between turbid lakes with large phytoplankton biomass but little benthic macrophyte vegetation and clear water lakes with sparse phytoplankton but a well-developed macrophyte vegetation. They have shown that, as nutrient loading or other factors, including salinity, change, a lake can switch from benthos to plankton domination. This analysis has been applied to some lagoons (e.g. De Wit *et al.*, 2001; Hakanson and Bryhn, 2008; Viaroli, 2008). De Wit *et al.* (2017) report that lagoons on the French Mediterranean coast switched from benthic dominance in the 1960s to planktonic dominance in 2000, and then partially reverted to benthic dominance after sewage inputs were diverted in 2006. These changes were accompanied by changes in nitrogen and phosphorus concentration, phytoplankton abundance and composition, and macrophyte, fish and invertebrate diversity. As macrophyte dominance is associated with good conservation status, the biological and chemical characteristics of this ecosystem state could be proposed as indicators of favourable ecological status.

Part of the CLEAR project's purpose was to analyse the impact of nutrient enrichment on the ecological status of Irish lagoons and design methods to characterise ecological status. In the project, experimental design was based on a comparison of two lagoons, a eutrophicated and plankton-dominated site and a control site still dominated by macrophytes. The fate of nutrient inputs and biological responses were measured over a 12-month period (May 2019 to May 2020) and the data were combined with a hydrological model to construct nutrient budgets, determine limiting nutrients (if any) and calculate the nutrient reductions necessary to induce a switch from plankton to benthos dominance.

The overall purpose of this part of the project was to establish the current ecological condition of Lady's Island Lake, determine the factors controlling this state and estimate what changes are necessary to restore the site's conservation status. We attempted to do this through the following sequence of actions:

- We first established the ecological differences between lagoons dominated by plankton and those dominated by benthic vegetation and determined the concentrations of chlorophyll *a* that are obtained when the switch from one state to the other occurs.
- We then established whether nitrogen, phosphorus or light limitation determined plankton growth in the two sites.
- Using differences in biological and abiological factors between benthic and planktonic lagoons, we determined EQRs for brackish water lagoons by correlating nutrient levels and biota with changes from plankton to benthic vegetation dominance. The current status of Lady's Island Lake was then defined using these EQRs.
- We then calculated nutrient budgets for both sites and estimated the reduction in inputs necessary to change from plankton to benthos dominance.
- Finally, nutrient inputs were related to lagoon catchment land use.

This sequence of work was aimed at developing an estimate of the scale of nutrient reduction necessary to allow Lady's Island Lake (and other lagoons) to revert to benthic dominance and favourable conservation status, and to at least a "good" water status under the WFD. This account describes the results from work packages (WPs) 1 and 2, and parts of WPs 3, 4 and 5.

3.2 Materials and Methods

3.2.1 Experimental sites

Two sites were chosen: Lady's Island Lake in County Wexford and a small saline pond at Ballyteige, located about 15 km west of Lady's Island Lake. One of the largest lagoons in Ireland, Lady's Island Lake (*c.*300 ha)[3] has been shown to be one of the most eutrophic lagoons in the country. In 2016, the median chlorophyll *a* content of the water column was 46 µg/l, while winter dissolved inorganic nitrogen exceeded 0.5 mg/l. Water transparency (measured as Secchi disc) was less than 30 cm and benthic macrophytes grew to a depth of only 0.5–1 m. This state contrasts with the situation of Lady's Island Lake in the 1980s, when clear water was matched by a well-developed benthic sward of widgeon grass (*Ruppia* sp.) and charophytes (Healy, 1997). There is little doubt that the lagoon ecosystem switched from a benthos-dominated habitat to one dominated by plankton (largely cyanobacteria) some time between the 1980s and the first decade of the 21st century, probably due to excessive inputs of nitrogen and phosphorus; as early as 2003, massive fish kills were noted in the lagoon. The possibility of salinity change destroying grazing bivalve molluscs, such as *Cerastoderma glaucum*, also exists (Håkanson *et al*., 2007).

The control site at Ballyteige is a small pond about 0.5 ha in size, with a maximum depth of 3.5 m and a salinity of about 30 psu. It was chosen because it has a well-developed benthic vegetation dominated by *Ruppia* sp. and the uncommon lagoonal charophyte *Lamprothamnion papulosum*.

Additional data on Irish lagoons were obtained from a series of monitoring surveys covering over 40 sites between 2009 and 2017 (AQUAFACT and Roden Oliver Associates, 2017). These surveys were carried out by the current authors of this report for EPA Ireland.

3.2.2 Data collection

Both sites were sampled monthly between May 2019 and May 2020. The April 2020 sampling round was deferred to May 2020 owing to COVID-19 restrictions. Lady's Island Lake was sampled at four stations and the control site sampled at one station. At each station, temperature, salinity and conductivity were measured at 50 cm depth intervals. Secchi transparency was also measured at each station, except when the bottom was visible. Water for nutrient analyses, chlorophyll *a* and phytoplankton was collected from 50 cm below the surface. Zooplankton were sampled using a 100-µm

---

[3] The lagoon level and area fluctuate; for calculations we use the conservative area estimate of 284 ha.

mesh net. All six streams flowing into Lady's Island Lake were sampled monthly for total nitrogen (TN) and total phosphorus (TP). Meteorological data (rainfall, evaporation) were taken from Met Éireann's site at Johnstown Castle, located about 12 km from Lady's Island Lake.

3.2.3 *Chemical analyses of water samples*

All chemical analyses were carried out by Complete Laboratory Solutions Ltd., Galway, using standard methods.

3.2.4 *Growth experiments*

Experiments to test for growth-limiting nutrients were performed on alternate months. Four treatments were used: control with no added nutrients, phosphorus addition, nitrogen addition and nitrogen plus phosphorus addition. Each treatment was carried out in triplicate. Transparent plastic bottles of 1.5 l capacity were filled with test water from Lady's Island Lake and the control site, and nutrients added. Bottles were moored and positioned 20 cm below the water surface. After 48 hours, bottles were collected and water samples for the measurement of chlorophyll *a* taken. Trials were conducted in both Lady's Island Lake and the control site.

3.3 Chlorophyll *a* Concentration at Benthic–Planktonic Switching Points

The causal mechanism underlying the switch from benthic to planktonic dominance is light reduction: dense phytoplankton growth prevents the growth of rooted macrophytes on the lagoon bed (e.g. Scheffer, 2004). At some point, phytoplankton concentration (measured as chlorophyll *a*) prevents enough light reaching the lagoon bottom to enable benthic macrophyte growth. Beyond this point, macrophyte growth ceases and the lagoon is dominated by phytoplankton. We determined this point using three methods:

1. comparing lagoons with and without a developed benthic vegetation;
2. comparing chlorophyll *a* values between Lady's Island Lake and the control site;
3. modelling the relationship between water transparency, chlorophyll *a* concentration and the measured depth of benthic vegetation.

3.4 Comparing Lagoons with or without a Developed Benthic Vegetation

Data from previous lagoon surveys between 2009 and 2017 are presented in Figure 3.1. The lagoons are grouped into three categories: lagoons with a developed benthic flora, lagoons without a benthic flora and a smaller group of lagoons with some benthic vegetation. A developed benthic flora was defined as extensive beds of species including *Ruppia* sp., *Stuckenia pectinata*, *Zostera* sp. or charophytes. Lagoons lacking benthic vegetation included those with no areas of dense macrophyte cover (defined as cover exceeding 50%). Intermediate sites were difficult to assign to either category. A more objective categorisation would require detailed vegetation mapping. It can be seen that lagoons without a developed macrophyte vegetation have significantly higher contents of both chlorophyll *a* and nutrients. These differences are listed in Table 3.1.

These data show large differences in chlorophyll *a* and nutrient concentration between the two states, with values for macrophyte-dominant lagoons lower than those for plankton-dominated lagoons, with a threshold between the two states of 6.5 µg/l chlorophyll *a*.

3.5 Comparing Chlorophyll *a* Values Between Lady's Island Lake and the Control Site

Figure 3.2 shows the annual chlorophyll *a* cycle of both sites.

Average chlorophyll *a* in the control site is 4.9 µg/l, while it is 28.1 µg/l for Lady's Island Lake. Both values are comparable to the values derived from the 2009–2017 dataset, discussed above. The large winter maximum in Lady's Island Lake is an unusual feature in Irish waterbodies but has been noted in other eutrophicated Irish lagoons (2009–2017 dataset).

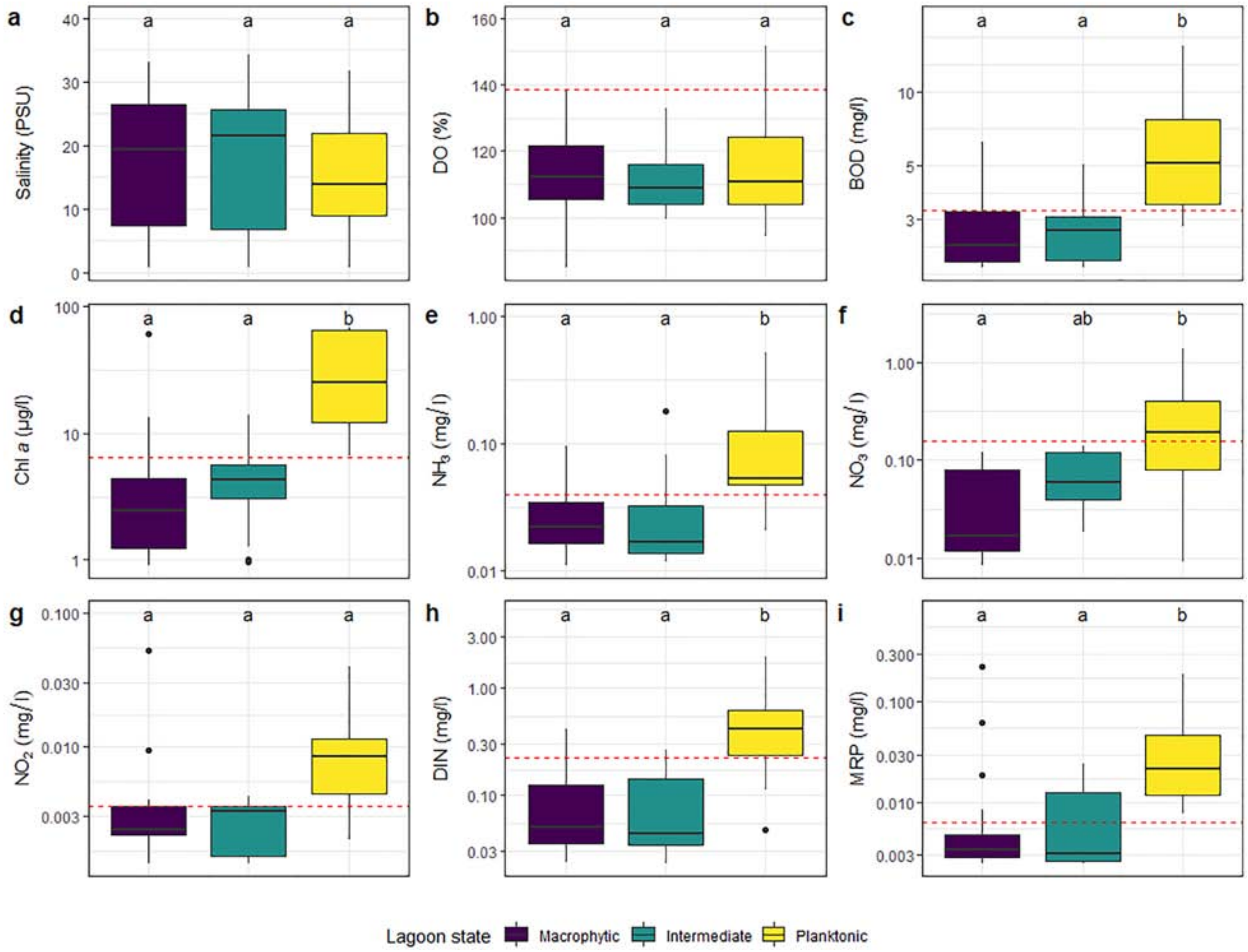

Figure 3.1. Comparison of hydrochemistry in Irish lagoons dominated by macrophytic flora, planktonic flora and those in an intermediate state. For each parameter, lagoon states with different lower-case letters are significantly different ($p < 0.05$) according to post-hoc pairwise comparisons. Red dashed lines indicate thresholds between macrophytic and planktonic states, as determined by a single split with recursive partitioning for individual variables. Except in (a) and (b), the *y*-axis is log transformed to improve clarity. BOD, biological oxygen demand; Chl *a*, chlorophyll *a*; DIN, dissolved inorganic nitrogen; DO, dissolved oxygen; MRP, molybdate-reactive phosphorus; NH_3, ammonia; NO_2, nitrogen dioxide; NO_3, nitrate.

3.6 Modelling the Relationship Between Water Transparency, Chlorophyll *a* Concentration and the Measured Depth of Benthic Vegetation

Both previous estimates of chlorophyll *a* values for benthic and planktonic states were derived from empirical data; in this section a simple model is derived to estimate these values. Figure 3.3 shows the relationship between chlorophyll *a* concentration and water transparency, measured as Secchi depth based on data collected from Lady's Island Lake in 2019–2020. Unsurprisingly, there is a strong inverse correlation between the amount of chlorophyll *a* and the depth of light penetration. The data are fitted to a power equation ($r = 0.727$; $n = 48$). Data published by Pérez-Ruzafa *et al*. (2019) are comparable.

Secchi depth can be related to the depth at which vegetation ceases to grow due to light shortage – the euphotic depth. Here we use data derived from recent surveys of Irish lakes (Roden *et al*., 2021, 2022) in which the vegetation limit was accurately measured using a diver's depth gauge (Figure 3.4). At Secchi depths less than 4 m, Secchi depth and vegetation depth are roughly comparable, but note that data for very shallow depths are not available. The data are fitted to a power equation with $r = 0.734$ ($n = 42$).

Table 3.1. (a) Kruskal–Wallis rank sum tests for differences in hydrochemical parameters between lagoonal states. (b) Threshold values between macrophytic and planktonic states as determined by a single split with recursive partitioning for individual variables

	(a) Kruskal–Wallis tests		(b) Recursive partitioning	
Parameter	χ^2	p	**Threshold**	**Accuracy (%)**
Salinity	0.72	0.70	Not found	NA
DO	0.98	0.61	138%	63.6
BOD	17.93	<0.01	3.28 mg/l	66.7
Chlorophyll *a*	22.20	<0.01	6.48 µg/l	75.0
NH_3	14.95	<0.01	0.04 mg/l	78.8
NO_3	8.08	0.02	0.16 mg/l	81.0
NO_2	7.47	0.02	0.0036 mg/l	76.2
DIN	16.41	<0.01	0.22 mg/l	72.7
MRP	15.68	<0.01	0.064 mg/l	81.8

BOD, biological oxygen demand; DIN, dissolved inorganic nitrogen; DO, dissolved oxygen; MRP, molybdate-reactive phosphorus; NA, not applicable; NH_3, ammonia; NO_2, nitrogen dioxide; NO_3, nitrate.

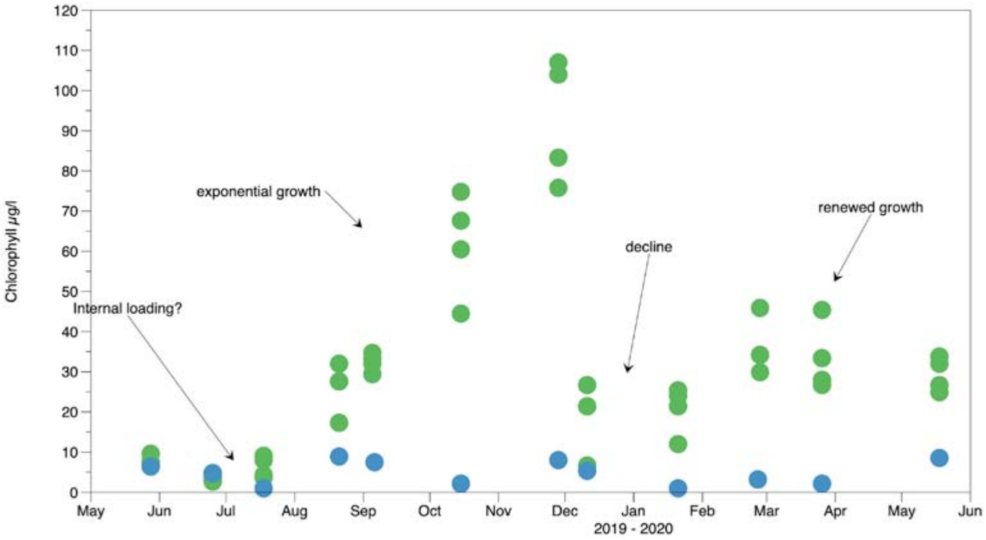

Figure 3.2. The 2019–2020 annual cycle in planktonic chlorophyll *a* in Lady's Island Lake (green) and the control site (blue). Note the consistent low values in the control site and the winter maximum in Lady's Island Lake.

Combining the two power equations, it is possible to relate lagoon chlorophyll *a* to maximum vegetation depth using the following equations:

- Secchi depth = 1.96 (chlorophyll a)$^{-0.33}$;
- vegetation depth = 1.566 (Secchi depth)$^{0.8}$.

In Figure 3.5, the predicted relationship between chlorophyll *a* concentration and maximum vegetation depth is plotted.

The model suggests that, at chlorophyll *a* concentrations ≥ 10 µg/l, vegetation depth approaches a minimum of less than 1 m, while vegetation depths greater than 2 m require chlorophyll *a* concentrations less than 5 µg/l.

Data on chlorophyll *a* and vegetation depth collected in the 2009–2017 surveys are plotted for comparison, and it appears that the model reasonably predicts maximum recorded vegetation depths, although in many lagoons even shallower vegetation depths were recorded. It should be noted that the data used to construct the model (CLEAR project data and data from freshwater lake surveys) did not include data

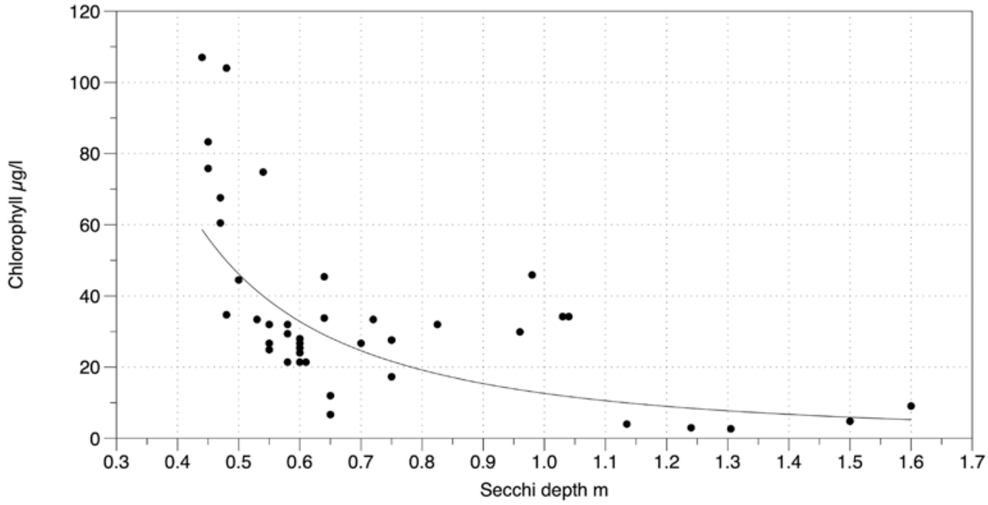

Figure 3.3. The relationship between Secchi depth and chlorophyll *a* using data from Lady's Island Lake.

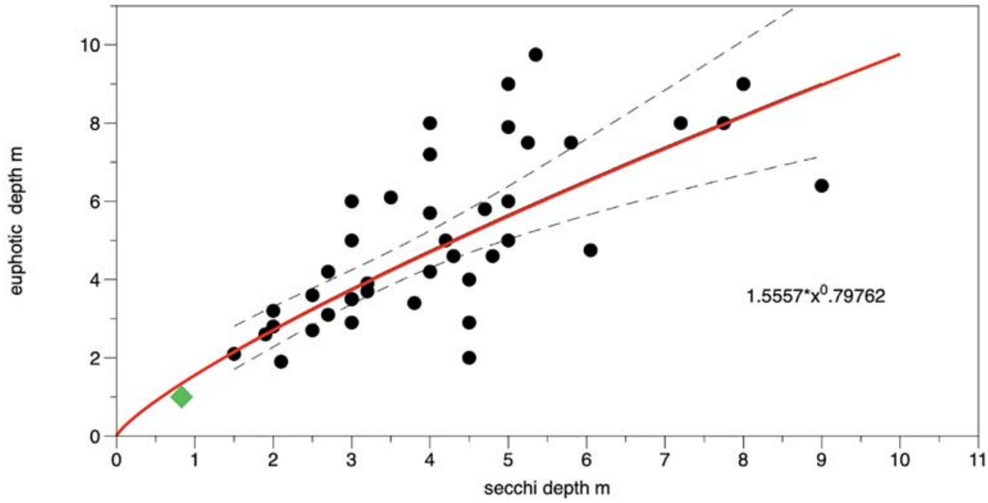

Figure 3.4. The relationship between Secchi depth and euphotic depth (maximum depth of vegetation) based on recent Irish lake surveys (Roden *et al.*, 2020, 2021). The average value derived from the CLEAR project for Lady's Island Lake is shown for comparison (green diamond).

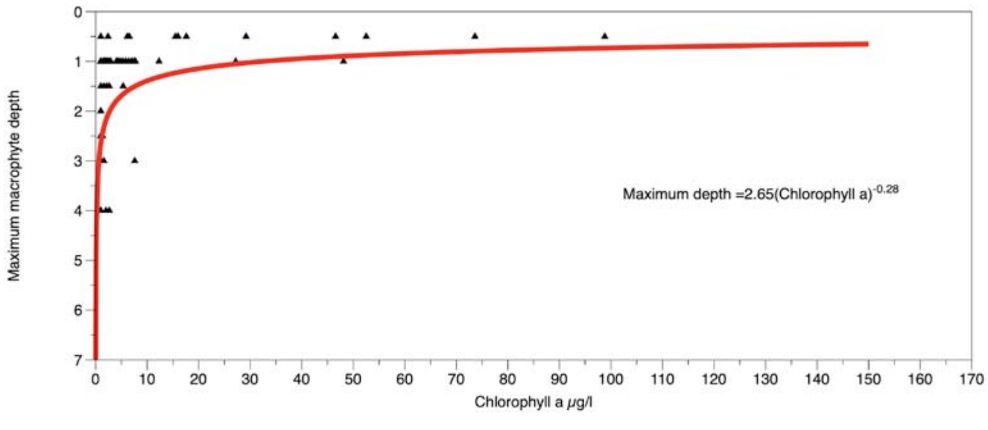

Figure 3.5. The modelled relationship between chlorophyll *a* concentration and maximum macrophyte depth (red line). Black triangles show data from the 2016–2017 survey. Each triangle represents a single lagoon. Note: vegetation depth is very sensitive to chlorophyll *a* concentration up to about 10 µg/l; greater concentrations have a much smaller effect.

from the 2009–2017 surveys; therefore, these data are an independent test of the model.

If lake depth is greater than maximum vegetation depth, then benthic macrophytes cannot grow owing to light shortage. Therefore, if chlorophyll *a* is too dense, benthic vegetation will disappear. Nearly all Irish lagoons are between 2 and 4 m deep (Healy, 2003); Figure 3.5 shows that, at chlorophyll *a* levels > 10 µg/l, benthic vegetation does not occur, except in very shallow sites (< 1 m). Wave disturbance will inhibit vegetation at such very shallow depths.

3.7 Establishing Switching Point Concentration of Chlorophyll *a*

Three separate approaches to determining the chlorophyll *a* level at which macrophyte dominance switches to plankton dominance have been described. An analysis of 2009–2017 survey data suggests a threshold value of about 6.5 µg/l; the control site has an average of about 4.9 µg/l, which indicates that the switching point concentration must be greater than this concentration. The model suggests that values of less than 10 µg/l are necessary if benthic vegetation is to develop in most Irish lagoons.

Combining these approaches (see Table 3.2), the switching point is between 5 and 10 µg/l. Here we propose a concentration of 7.5 µg/l. These figures are, as indicated by the model, dependent on lagoon depth. In very shallow lagoons (< 2 m), benthic macrophytes might grow at higher chlorophyll *a* concentrations; conversely, even lower figures would apply to deeper lagoons. Lady's Island Lake is an unusual example of a lagoon, as depth can vary by as much as 2 m, depending on rainfall and when breaching occurs. Analysis of the distribution of macrophytes in Lady's Island Lake in September 2020 shows that *Ruppia* sp. and *Lamprothamnion* occurred only at stations about 1 m deep or less. Some *Ruppia* sp. also grows close to the shore in shallower water (< 0.5 m), possibly getting sufficient light in summer, when lake level is low.

Table 3.2. Different estimates of lagoon chlorophyll *a* concentration associated with a switch from the benthic to planktonic state

Test	Result
Analysis of 2009–2017 lagoon data	Switch is 6.5 µg/l
Control site	Switch occurs when the chlorophyll *a* level is > 4.9 µg/l
Model	Switch occurs when the chlorophyll *a* level is < 10 µg/l

As the switching point is a function of light intensity, one would not expect salinity variation to result in changes in switching point of chlorophyll *a*; however, high water colour might reduce light intensity at lower salinities and thus indirectly reduce the chlorophyll *a* concentrations that result in plankton dominance. In the absence of data, we do not propose to adjust the value to take account of salinity.

3.8 Nitrogen and Phosphorus Concentrations at Benthic–Planktonic Switching Points

The preceding section has established likely levels of chlorophyll *a* in plankton- and benthos-dominated lagoons. In this section, associated values of nitrogen and phosphorus are established and the probable limiting factors governing plankton growth investigated.

Associated values of nitrogen and phosphorus are determined using three different methods:

1. comparing values in Lady's Island Lake and the control site;
2. using Secchi transparency in Lady's Island Lake to predict nitrogen and phosphorus levels;
3. examining data from 2009–2017 lagoon surveys.

Limiting factors are determined using growth enrichment experiments and analysis of the nitrogen–phosphorus (N/P) ratios relative to the Redfield ratio. This ratio of 16:1 is the ratio of nitrogen to phosphorus in growing phytoplankton when neither element limits growth. N/P values higher than 16:1 are taken to indicate phosphorus limitation of growth, whereas values lower than 16:1 indicate nitrogen limitation.

3.8.1 Comparison of values in Lady's Island Lake and the control site

Figures 3.2 and 3.6 show annual variation in chlorophyll *a* and TN in Lady's Island Lake and the control site. The average value at the control site is 0.5 mg/l TN, while the Lady's Island Lake value

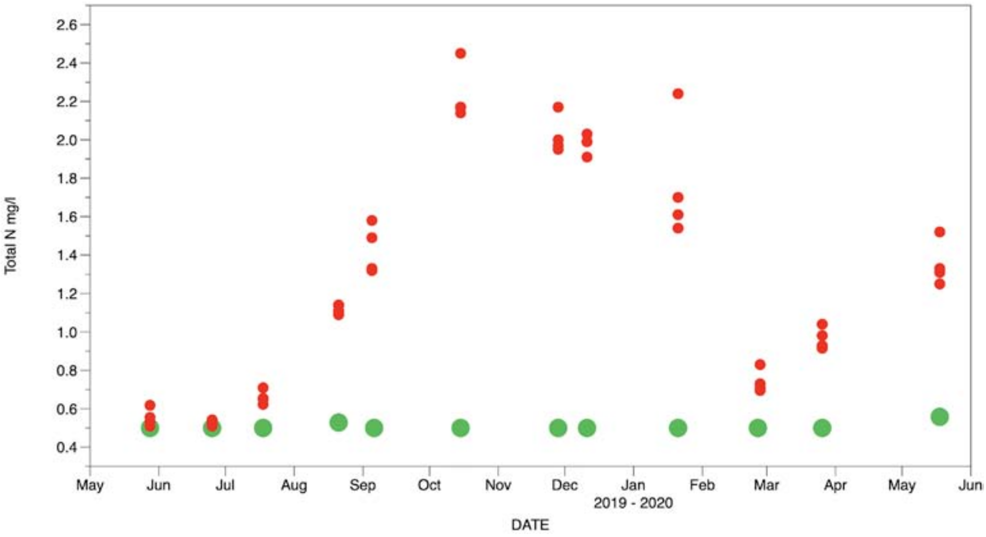

Figure 3.6. Annual cycle in TN in Lady's Island Lake (red) and the control site (green). Note the consistent low values (average 0.5 mg/l) in the control site and the winter maximum in Lady's Island Lake.

is 1.2 mg/l TN. While chlorophyll *a* is much higher in Lady's Island Lake on average (Figure 3.3), it is noticeable that, in summer 2019, levels were very similar in Lady's Island Lake and the control site. The reason for this appears to be that there was no net inflow of nutrients during this period (owing to little rainfall; see section 3.9 for further detail). Consequently, Lady's Island Lake summer 2019 nutrient values may indicate nutrient levels in the absence of external nutrient enrichment; the average values recorded in this period, 0.58 mg/l TN and 0.054 mg/l TP, approach those recorded at the control site (0.5 and 0.047 mg/l, respectively).

3.8.2 Secchi disc transparency depths used to predict nitrogen and phosphorus levels

There is a strong correlation between Lady's Island Lake Secchi depth and TN in the water column (see Figure 3.7), possibly because most N is contained in the phytoplankton population and measured as chlorophyll *a*. In the previous section, it was shown that the switch from benthic to planktonic dominance occurred at Secchi transparency between 1 and 2 m in lagoons. Figure 3.7 shows that this equates to a TN value of about 0.5 mg/l or less. A plot of TP against Secchi depth indicates that the equivalent TP value is

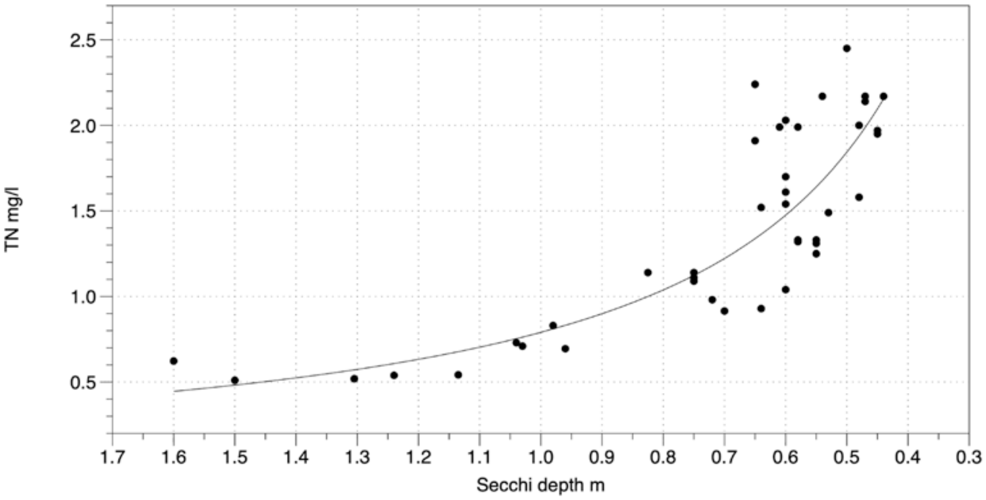

Figure 3.7. The relationship between total N and Secchi depth in Lady's Island Lake during the period 2019–2020.

c.0.05 mg/l, but the regression of TP versus Secchi is not as strong as the regression of TN versus Secchi.

3.8.3 Data examined from 2009–2017 lagoon surveys

Unfortunately, no data on TN and only a limited number of measurements are available for TP in this dataset. The median figure of TP for macrophyte-dominated lagoons is 0.006 mg/l, while the median value for plankton-dominated lagoons is 0.064 mg/l. In comparison, even the Ballyteige site has TP that is almost 10-fold higher (0.05 mg/l) than the median figure for macrophyte-dominated sites from the 2009–2017 results. This may reflect the smaller number of observations ($n = 170$) or the fact that phosphorus may not be limiting in either the control site or the Lady's Island Lake site.

Regarding proposed values of nitrogen and phosphorus, allowing that the control site is in at least "good" condition, its values of TN and TP (0.5 and 0.047 mg/l, respectively) are treated as "good". The Secchi data suggest that TN = 1.0 mg/l corresponds to the moderate/poor boundary. We propose a TN moderate/poor boundary of 1.0 mg/l and moderate/good boundary of 0.5 mg/l. As phosphorus may not be a limiting nutrient, measured phosphorus values may not be closely correlated with lagoon state in our data; we therefore have less confidence in our proposed phosphorus value of 0.04–0.05 mg/l for the moderate/good boundary.

3.8.4 Factors limiting algal growth in Lady's Island Lake

Limiting factors were determined using growth enrichment experiments and analysis of N/P ratios relative to the Redfield ratio (Redfield, 1934). This ratio of 16:1 is the ratio of nitrogen to phosphorus in growing phytoplankton when neither element limits growth. Values higher or lower than 16:1 are taken to indicate phosphorus or nitrogen limitation of growth, respectively.

The basic driver behind the switch from benthic macrophyte dominance to plankton dominance is rapid growth of phytoplankton (measured as chlorophyll *a*). In turn, plankton growth is controlled by supplies of nutrients (essentially nitrogen and phosphorus) and light. The factors that control growth in Lady's Island Lake are discussed here. Enrichment experiments in which extra nitrogen and phosphorus are added to lagoon water may indicate what combination of nutrients best promote growth. Figures 3.8 and 3.9 summarise plankton growth response to additions of nitrogen, phosphorus or nitrogen plus phosphorus in Lady's Island Lake and the control site, respectively.

In Lady's Island Lake, three summer experiments show a much larger response to nitrogen or nitrogen

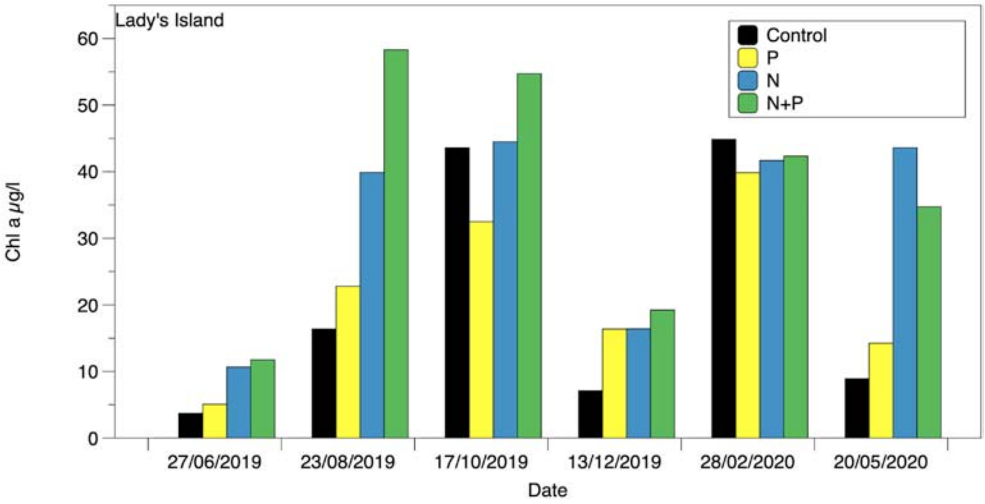

Figure 3.8. Nutrient addition experiments conducted in Lady's Island Lake on six occasions in 2019–2020. In each experiment, four treatments were used: no addition (control), P addition, nitrogen addition and nitrogen plus phosphorus addition. Each bar is the average of three replicates. Values show measured chlorophyll *a* after 48 hours.

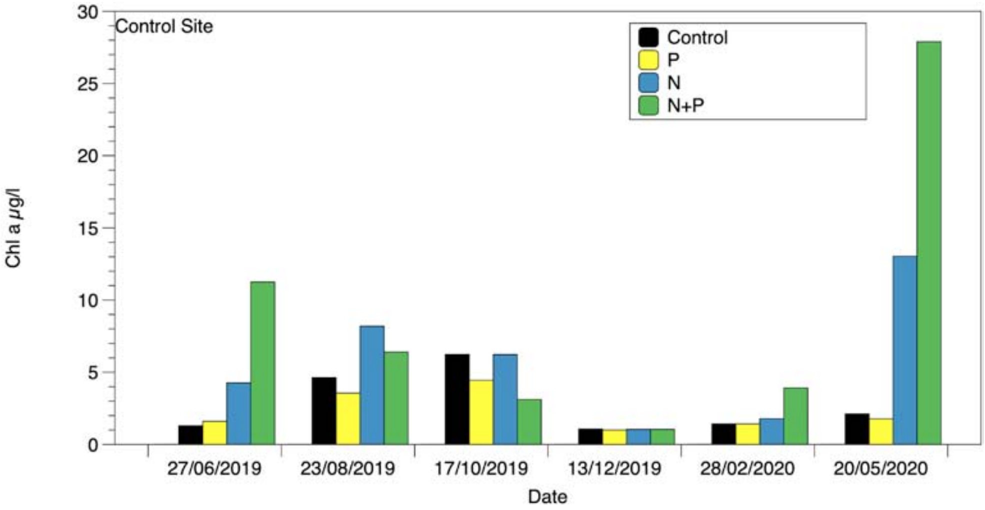

Figure 3.9. Nutrient addition experiments conducted in the control site at Ballyteige. See Figure 3.8 for explanation.

plus phosphorus than to phosphorus alone, which is barely greater than the response to the control treatment. Winter and autumn experiments show a less clear response, with either no response to nutrients or, in December, no obvious preferred nutrient.

In the control site series, nitrogen and nitrogen plus phosphorus again produce the largest responses, while the response to phosphorus is no greater than the response to the control treatment. In winter, no treatment response differs from the control treatment response. An initial analysis would suggest that, in summer, nitrogen, more than phosphorus, limits growth, while in winter the lack of response to nutrient addition compared with the control suggests that light limits growth.

It is accepted that growing phytoplankton, with a balanced nutrient supply, consume nitrogen and phosphorus in a ratio of 16:1 (the Redfield ratio), with higher values indicating phosphorus shortage and lower values indicating nitrogen shortage. As is explained below, the nutrient ratio in streams flowing into Lady's Island Lake is about 63:1, which indicates a large surplus of nitrogen relative to phosphorus. One might therefore expect that phosphorus shortage would limit phytoplankton growth, the opposite of the results from the growth experiments shown above.

However, the N/P ratios in Lady's Island Lake show a complex pattern (Figure 3.10 and Table 3.3). When water column nitrogen and phosphorus are partitioned into dissolved and particulate factions, it appears that the range of particulate N/P ratios contracts and N/P approaches the Redfield ratio as chlorophyll *a* concentration declines. Thus, large N/P ratios are associated with very high planktonic biomass. The large biomass is itself a product of very large nitrogen inputs, especially in winter. In other words, when nitrogen is low in the lagoon, N/P ratios do not show severe phosphorus shortage. Only when high chlorophyll *a* values occur (implying an abundant supply of nutrients) do high N/P values occur. These values may suggest some form of planktonic storage of excess nitrogen. A provisional interpretation of nutrient limitation is that at low nutrient levels, nitrogen shortage, more than phosphorus shortage, limits growth, as indicated by the growth experiments; at high nutrient levels. growth is not greatly restricted by nutrients but more likely by light shortage due to self-shading. The limited data on TP from the 2009–2017 surveys suggest that far lower TP concentrations occur in some lagoons, and the TP concentrations recorded in both the control and Lady's Island Lake sites are close to switching point concentrations of TP. There is a possibility that phosphorus is recycled faster than nitrogen from sediments, thus providing an internal source of phosphorus, which complements the inflow of very large quantities of nitrogen from the streams surrounding Lady's Island Lake.

Other studies show that plant growth in brackish lagoons is mainly nitrogen limited, even when N/P ratios suggest otherwise. Berthold and Schumann

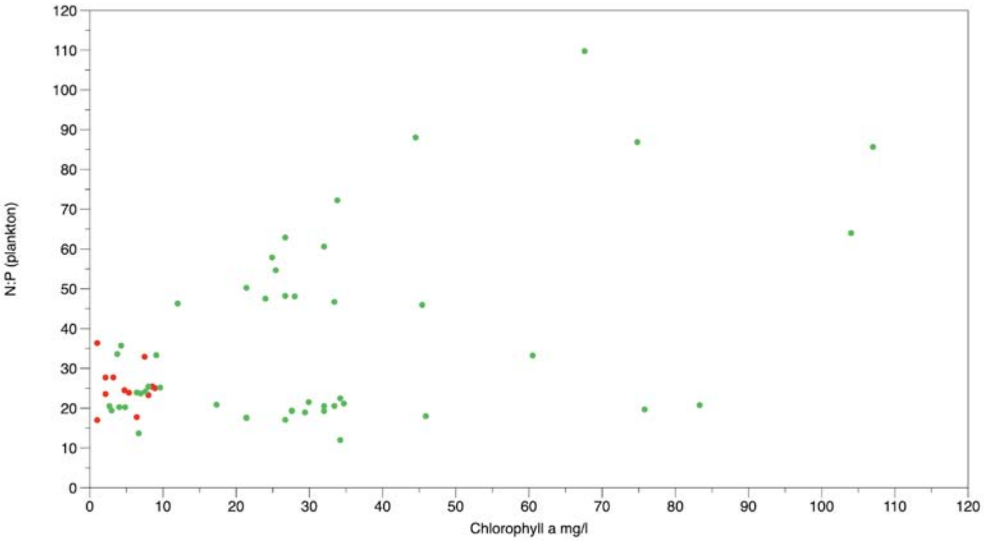

Figure 3.10. N/P ratio of particulate nitrogen and phosphorus (calculated as TN or TP minus dissolved nitrogen or phosphorus) as a function of planktonic chlorophyll *a*. Green dots are Lady's Island Lake; red dots are the control site. At low planktonic chlorophyll *a*, N/P approaches the Redfield ratio of 16:1.

Table 3.3. Estimates of lagoon parameters at which switching from benthic to planktonic dominance occurs, based on 2009–2017 survey data and 2019–2020 data from Lady's Island Lake and the control site

Parameter	Min., 2009–17	Max., 2009–17	Switch point	Control site (median)	Lady's Island Lake (median)
DO (%)	11	174	138	105	104.5
BOD (mg/l)	2	22	3.28	NA	3
Chlorophyll *a* (µg/l)	1	112	7.5	5.03	27.17
NH_3 (mg/l)	0.01	0.862	0.04	0.013	0.013
DIN (mg/l)	0.014	6.332	0.22	0.024	0.0295
MRP (mg/l)	0.0033	0.083	0.0064	0.005	0.005
TN (mg/l)	NA	NA	1.0	0.5	1.195
TP (mg/l)	0.003	NA	0.06	0.05	0.0565
Depth of colonisation (m)	NA	NA	1.5	3.5	< 1
Vegetation cover (%)	NA	NA	50	> 80	< 20

Switching point values in red are based on 2009–2017 data (see Figure 3.1); values in blue are from the Lady's Island Lake 2019–2020 data.

BOD, biological oxygen demand; DIN, dissolved inorganic nitrogen; DO, dissolved oxygen; MRP, molybdate-reactive phosphorus; NA, not available; NH_3, ammonia.

(2020), in a study of plant growth in Baltic lagoons, found that growth was not increased by the addition of phosphorus unless nitrogen was also added, even though they showed that phytoplankton appeared to be phosphorus limited based on expression of phosphatase enzymes and N/P ratios. They noted that rapid recycling of phosphorus may be relevant. Many studies (see, for example, Schallenberg *et al.*, 2012) found plankton dominance was related to N loading more than P.

3.8.5 Proposing EQRs for Irish lagoons

By combining the results of the 2009–2017 lagoon surveys and the differences between Lady's Island Lake and the control site, the EQRs for non-biological and biological elements can be proposed for Irish lagoons. Rooted macrophyte dominance is designated high or good, while planktonic dominance is designated poor or bad, and values at or near the macrophyte/plankton switching point are designated moderate. These ecological states and corresponding classification categories are consistent with the normative definitions used in the WFD.

The first two parameters in Table 3.4 refer to biological elements. Chlorophyll *a* is a measure of phytoplankton abundance, and in both Lady's Island Lake and the control site species composition was dominated by very small species of phytoplankton (*μ* flagellates and picoplankton) so species comparisons are not possible as species identification is unreliable for such very small organisms. We therefore propose only chlorophyll *a* levels as useful EQR for phytoplankton at present.

Biological oxygen demand (BOD), a measure of organic matter in the water column, results from the 2009–2017 surveys indicate higher levels for plankton-dominated sites. Comparable data for the CLEAR project were not obtained but the parameter appears to be a useful EQR.

The remaining non-biological parameters listed in Table 3.4 above also show significant differences between plankton and macrophyte dominance and therefore of use as EQRs. Two further parameters, TN and TP, were measured in the CLEAR project and significant differences between control and Lady's Island Lake were recorded for TN, but not for TP. Switching point values in red are based on 2009–17 data (see Table 3.3) while values in blue are from the Lady's Island Lake 2019–20 data.

Three measures of macrophyte condition are available: species composition and abundance, depth of colonisation and area of lagoon colonised. The first two factors can be determined from shore transects, but total vegetation cover requires a comprehensive boat survey; consequently, these data are rarely available. Previous surveys have shown that in most lagoons, *Ruppia maritima* and *R. cirrhosa* (widgeon grass) are almost universal, while in some lagoons *Zostera marina* (eel grass) and charophytes (*L. papulosum* and *Chara canescens*) occur. These results are confirmed in the CLEAR project, but species abundance is very different, with *Ruppia* sp. and *L. papulosum* abundant in the Ballyteige control site but restricted to small patches in water < 1 m deep in Lady's Island Lake.

As explained previously, depth of colonisation is a measure of macrophyte dominance. Figure 3.5 indicates that, at a chlorophyll *a* concentration of 7.5 μg/l (the switching point between plankton and benthos dominance) depth of colonisation is 1.5 m. As most lagoons are > 2 m in depth, a concentration of

Table 3.4. Proposed EQRs for Irish lagoons compared with existing EQRs for transitional and coastal water

	Proposed EQR					Existing EQR (S.I. 272 of 2009 as amended) (median)	
Parameter	High	Good	Moderate	Poor	Bad	Transitional water; good/moderate boundary	Coastal water; good/moderate boundary
DO (%)	NA	NA	> 138	NA	NA	70–130 80–120	80–120
BOD (mg/l)	NA	NA	< 4.0	NA	NA	< 4.0	NA
Chlorophyll *a* (μg/l)	< 2.5	< 5	< 10	< 20	> 20	NA	10
NH_3 (mg/l)	NA	NA	NA	NA	NA	NA	NA
DIN (mg/l)	NA	< 0.22	> 0.22	NA	NA	NA	< 2.6 < 0.25
MRP (mg/l)	NA	NA	0.0064	NA	NA	< 0.06 < 0.04	NA
TN (mg/l)	NA	< 0.5	> 0.5	> 1.0	NA	NA	NA
TP (mg/l)	NA	NA	NA	NA	NA	NA	NA
Depth of colonisation (m)	> 4	> 2	> 1.5	> 1	< 1.0	NA	NA
Vegetation cover (%)	100	NA	50	NA	0	NA	NA

We lack sufficient data to say if EQRs for oligohaline lagoons should be modified. For transitional and coastal waters, the upper and lower figures refer to low and high salinity values.

DIN, dissolved inorganic nitrogen; DO, dissolved oxygen; MRP, molybdate-reactive phosphorus; NH_3, ammonia.

7.5 µg/l implies little or no macrophyte growth and is taken as the colonisation depth switching point.

Area of colonisation is a function of both colonisation depth and lagoon basin shape. For the control site, vegetation cover was > 80%, while for Lady's Island Lake, vegetation was recorded at only 2 of 10 sampling points, and only in water < 1 m deep. As data are lacking from other lagoons, it is not possible to estimate the minimum percentage vegetation cover consistent with macrophyte dominance.

3.8.6 EQRs and ecological state of Lady's Island Lake

Other studies have proposed nitrogen loading and chlorophyll *a* concentrations that indicate a switch from macrophyte to plankton dominance. Boynton *et al*. (1996), in a study of a Chesapeake Bay lagoon, found that sea grasses collapsed at chlorophyll *a* concentrations of 15 µg/l and TN of 0.14 mg/l. Grillas *et al*. (2016) proposed values for use in assessing Mediterranean lagoons in France (Table 3.5).

Table 3.2 (section 3.7) shows that a shift from benthic to planktonic dominance occurs at a chlorophyll *a* concentration between 6.5 and 10 µg/l in Irish lagoons. These figures are used to propose a good/moderate boundary value of 5 µg/l and a moderate/poor boundary value of 10 µg/l, for the chlorophyll *a* EQR, These figures are comparable to the values of Grillas *et al*. (2016). Comparing Grillas *et al*.'s values, shown in Table 3.5, with the annual median values for Lady's Island Lake and the control site (Table 3.4), chlorophyll *a* in Lady's Island Lake exceeds the poor/bad and TN exceeds the good/moderate boundary values used by Grillas *et al*. All other parameters are lower than the good/moderate boundary. Annual medians, however, mask the much higher winter figures of chlorophyll *a* for Lady's Island Lake. From October onwards, many readings exceed the poor/bad boundary level. Lower summer figures reflect the lack of nutrient inputs owing to low rainfall.

The figures for France suggest that the proposed values based on Irish lagoon studies are comparable to other European studies, which rest on much larger databases. Using these metrics, Lady's Island Lake would be rated bad, while the control site would be rated good. While a salinity adjustment for these figures may be necessary, we lack sufficient data to know the effect of salinity variations on the response of lagoons to eutrophication. As noted previously, however, light penetration appears to be the most important variable controlling the switch from benthos to plankton dominance, and it appears not to be altered by changing salinity.

3.9 A Nutrient Budget for Lady's Island Lake

The purpose of the budget is to establish the input and fate of nitrogen and phosphorus in Lady's Island Lake. The budget is based on monthly measurements of nitrogen and phosphorus in inflowing streams, in the lagoon water column and in water exported to sea, and measurements of nitrogen and phosphorus stored in bottom sediments. Inputs and exports of both freshwater and saline water are derived from the hydrological model described in WP 4.

The hydrology of Lady's Island Lake is simple: the lake is fed by six small streams (some of which have reduced or extremely low summer flows), but water can leave the lake only when the barrier is breached, which may be annually or more often. Consequently, lake level increases with increasing rainfall. Lake levels are measured accurately by the OPW, and thus input of water is easily measured as increasing lake levels. Loss of water through breaching is also measured as a fall in lake levels. Nutrient concentrations in the six inflowing streams

Table 3.5. EQRs derived from French lagoon studies by Grillas *et al.* (2016)

Parameter	Very good	Good	Moderate	Poor	Bad
Chlorophyll *a* (µg/l)	< 5	< 7	< 10	< 20	> 20
TN (mg/l)	< 0.7	< 1.05	< 1.4	< 1.68	> 1.68
DIN (mg/l)	< 0.028	< 0.084	< 0.14	< 0.28	> 0.28
MRP (mg/l)	< 0.0093	< 0.031	< 0.047	< 0.124	> 0.124
TP (mg/l)	< 0.068	< 0.093	< 0.124	< 0.155	> 0.155

DIN, dissolved inorganic nitrogen; MRP, molybdate-reactive phosphorus.

were measured monthly; thus, increase in lake volume multiplied by stream nutrient concentration indicates nutrient input into the lake, providing that stream nitrogen and phosphorus concentrations are close to groundwater concentrations. Loss due to breaching can be calculated similarly using lake nutrient concentration and decline in lake level. The budget includes inputs from the small sewerage treatment plant, aerial deposition of nitrogen and the role of evaporation, but these constitute less than 15% of the total nutrient budget. The role of lagoon sediment is assessed by measuring sediment nitrogen and phosphorus.

Figures 3.11 and 3.12 show the relationship between rainfall and evaporation, lagoon volume and movements of nitrogen and phosphorus in the lagoon in 2019–2020. The diagrams show that only between September and April does rainfall exceed evaporation; consequently, the lagoon expands in volume in winter but reaches a minimum size during summer. Breaching the barrier in January and March reduced the lagoon to its minimum volume, but heavy rainfall in winter rapidly replenished it. Its volume did not increase after the March breach.

Inflowing freshwater is the major source of nitrogen and phosphorus input: in summer, nutrient addition to the lagoon is low, while in winter large quantities of nutrients are added. The amount of nitrogen and phosphorus added each month is calculated as change in lagoon volume compared with previous month × weighted average stream nutrient concentration. Cumulative nitrogen or phosphorus is the total amount of nitrogen or phosphorus added to date. Monthly changes in lagoon water column and plankton (TN or TP) nutrient content are calculated as change in lagoon volume compared with previous month × lagoon nutrient concentration. In months when breaching occurred, changes in lagoon volume include water exported to sea. Differences between cumulative nutrient input and lagoon nutrient content indicate loss to sediment or other sinks, such as benthic macrophytes.

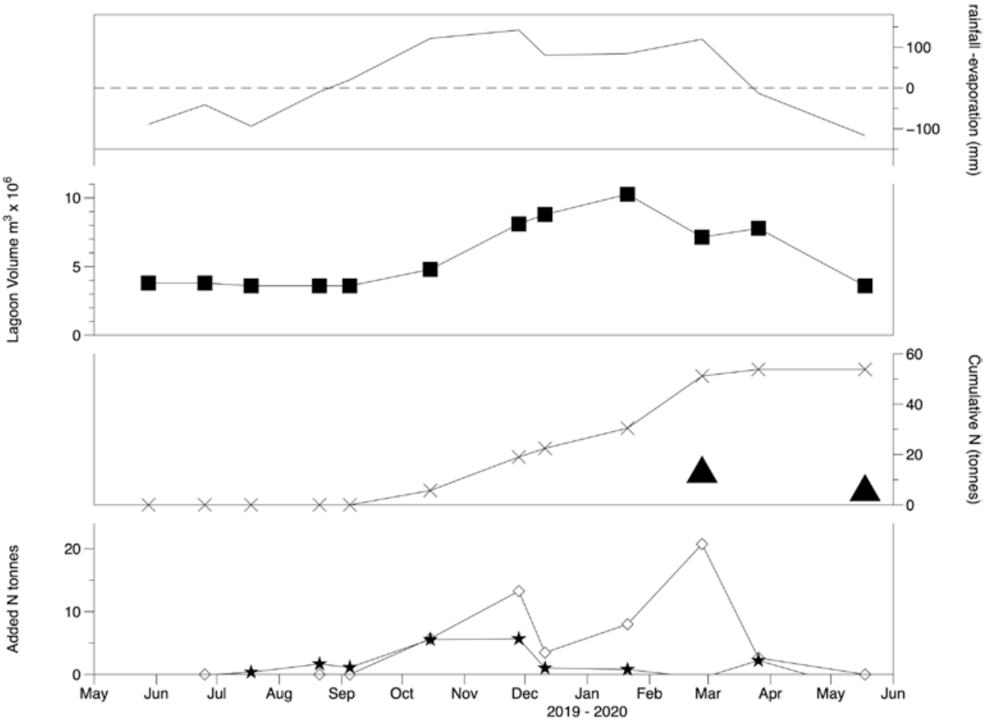

Figure 3.11. Nitrogen movement in Lady's Island Lake. From top: difference between rainfall and evaporation; change in lagoon volume; cumulative input of nitrogen into the lagoon; monthly additions of nitrogen to the lagoon calculated from stream inputs (diamonds) and from changes in water column TN (stars). The difference between stream input estimates and water column estimates indicates the loss of nitrogen to sediment or other sinks. Black triangles represent nitrogen lost through breaching in January and late March.

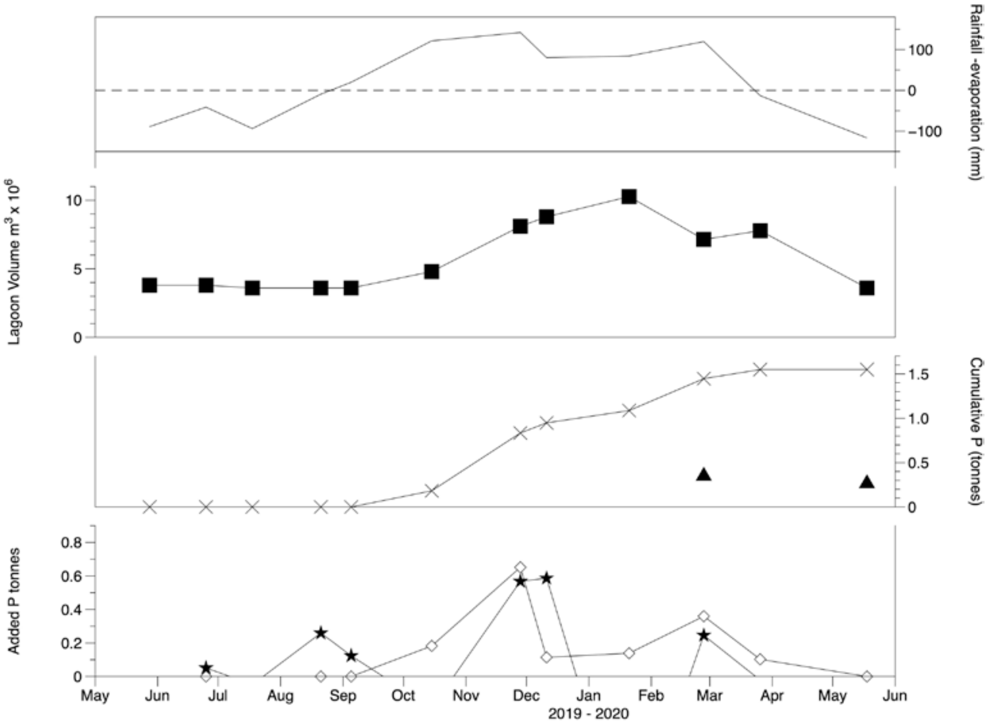

Figure 3.12. Phosphorus movement in Lady's Island Lake. From top: difference between rainfall and evaporation; change in lagoon volume; cumulative input of phosphorus into the lagoon; monthly additions of phosphorus to the lagoon calculated from stream inputs (diamonds) and from changes in water column TP (stars). Black triangles represent phosphorus lost through breaching in January and late March.

In summer, some water is lost by evaporation, and, if the lagoon level did not fall, some stream replenishment must have occurred; the nutrients added through this process are calculated as volume lost by evaporation × weighted average stream nutrient concentration. Data on treatment plant input are derived from Wexford County Council. Aerial nitrogen deposition is calculated using the figures in Kellegan *et al.* (2021).

The annual budget is summarised in Figure 3.13. About 60 tonnes of nitrogen and 1.5 tonnes of phosphorus enter the lake. About 17 tonnes of nitrogen and 0.5 tonnes of phosphorus are discharged to sea. On average, 7 tonnes of nitrogen and 0.5 tonnes of phosphorus are retained in the plankton and water column. About 35 tonnes of nitrogen and 1 tonne of phosphorus are added to the lake sediment or taken up by the sparse macrophytes or the expanding reed beds.

In order to test the accumulation of nutrient in the sediment, sediments were analysed for nutrient content. In the first 10 cm of sediment, 5.4 g of nitrogen and 0.448 g of phosphorus were present per dry kilogram. Assuming a density of sediment of 1.0 (a figure that will underestimate nutrient deposition) and a lake area of 284 ha, there are 1505 tonnes of nitrogen in the first 10 cm of sediment and 127.2 tonnes of phosphorus.

A deposition rate of 35 tonnes of nitrogen per annum corresponds to a sediment accumulation of 0.23 cm per annum, which is a credible figure. Denitrification, however, may be occurring (Berthold and Schumann, 2020; Berthold and Campbell, 2021), and, if so, less nitrogen will accumulate in sediments. Phosphorus accumulation is much slower – only 0.078 cm per annum. Figure 3.11 shows a substantial loss of incoming nitrogen in winter but little loss in summer. Phosphorus loss from the water column appears far smaller except in mid-winter. This may indicate that phosphorus is recycled from the sediment more rapidly than nitrogen.

A possible source of error in this budget is in the calculation of the contribution of groundwater nutrients. In the hydrology section (section 2.1), it is estimated that groundwater accounts for 23% of

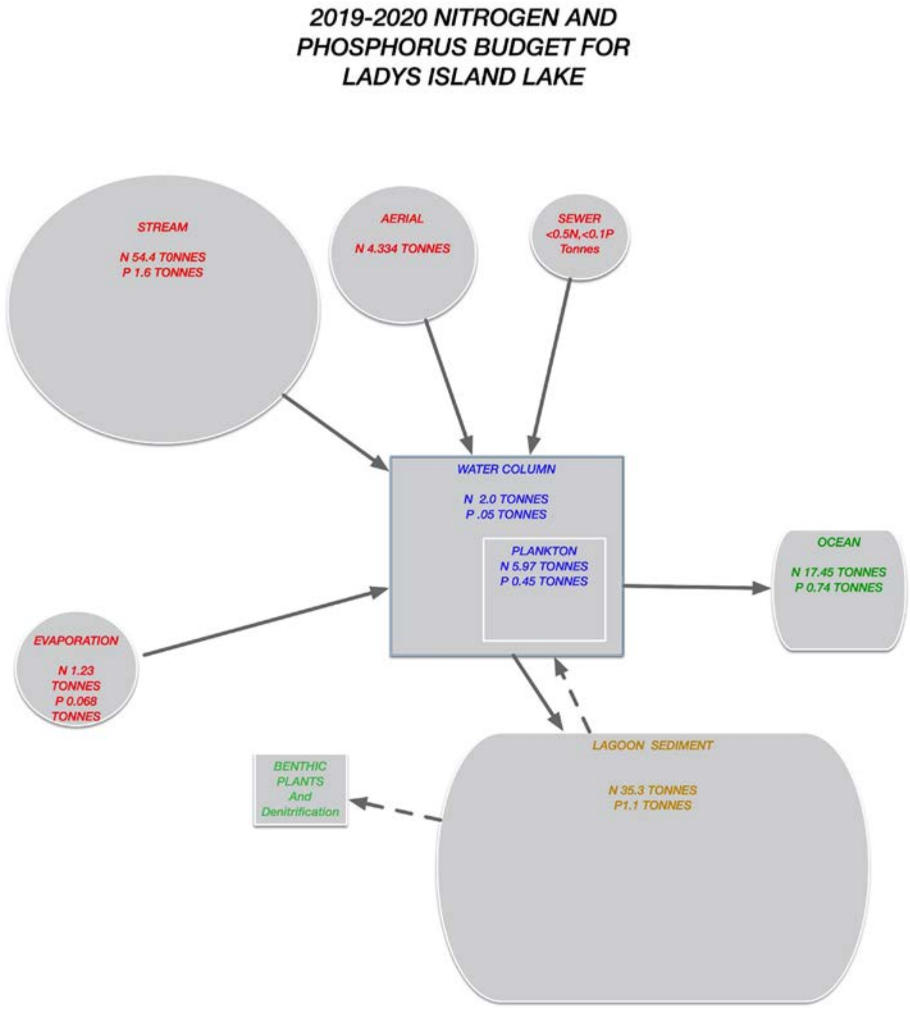

Figure 3.13. A nutrient budget for Lady's Island Lake. While some inputs are poorly constrained, major nutrient flows calculated from stream inputs, changes in water level and sediment nutrient content are based on accurate measurement. Dashed lines are inferred processes.

water flow. If nutrient concentrations in groundwater were similar to those of the inflowing streams, the proportion of groundwater input would not affect the final calculations. The reason for this is that nutrient input is calculated as the *total increase in lagoon water volume* × *nutrient concentration*; whether that increase is due to groundwater or surface flow is immaterial. No direct data on groundwater nutrient concentration in the Lady's Island Lake catchment are available, but an estimate can be derived from stream nutrients measured in May, June, July and August. In this period, stream flow is close to baseflow rate and rainfall is too low to allow lagoon levels to increase. In this condition the streams are largely fed from groundwater, so stream nutrient levels reflect those of groundwater. In the May–August period, stream nitrogen is 82% the concentration of the annual average concentration, while stream phosphorus is 88% of this figure. Using this figure for nutrient concentration and allowing groundwater to contribute 23% of the total input into the lagoon, nutrient input would be calculated as (stream nutrient concentration × 77 + (0.82 stream nutrient concentration × 23))/100, or 0.96 stream nutrient concentration. This difference is too small to affect the budget, and stream nutrient is taken to include the groundwater fraction.

Another possible error is related to the fact that no streams occur on the east shore of the lagoon. Thus, some groundwater may enter directly and might contain additional nitrogen and phosphorus. Such nutrients will be measured within the lagoon as part of overall nutrient levels and increase in lagoon volume, but some errors in inflowing nutrient estimates are possible.

3.10 The Control Site Nutrient Budget

It is more difficult to construct an accurate budget for the Ballyteige control site, as nutrient inputs must come from groundwater and water loss is largely due to evaporation. On the assumption that nutrient concentration in the water column reflects that of surrounding groundwater and that water movement into the site is a function of rainfall and evaporation, a tentative budget can be constructed. Increase in salinity is assumed to indicate net water loss by evaporation and its replacement by groundwater. Nitrogen or phosphorus added per month is then calculated as the percentage change in salinity per month × lagoon volume × TN or TP. Conversely, a decline in salinity indicates dilution of the lagoon, a reduction in salinity and export of water. As the lagoon level and volume remains stable, then inputs and export of water must balance. There are no data on export of nutrients, but incoming groundwater, it is assumed, also brings in nutrients. If groundwater nutrients are absorbed by macrophytes before entering the water column, nutrient flows are underestimated, but, as Figure 3.14 shows, changes in salinity and consequent nutrient movements do not exceed 6% in any month. Using figures for aerial nitrogen deposition given in Kelleghan *et al*. (2021), aerial deposition is at least three times greater than assumed groundwater inflow.

Some nitrogen and phosphorus are exported to the sediment. The figures for phosphorus suggest very small inputs, and, consequently, recycling of the nutrient is important. No measurable surplus for export to sediment was detected, even though some phosphorus is stored in the sediment. Table 3.6 summarises the control site budget.

Table 3.6. A provisional annual nutrient budget

Nutrient source	Nitrogen (kg)	Phosphorus (kg)
Input from ground water	3.3	0.328
Input from aerial deposition	8.93	–
Nutrient in water column	5.09	0.45
Exported to sediment	6.4	Unknown
Amount in upper 10 cm of sediment	512	152

The pond is 0.64 ha and 2 m deep. Nutrient input is calculated based on pond nutrient concentration and change in salinity; nutrient in sediment is measured directly. Notice the much smaller quantities (shown as kilograms, not tonnes) compared with Lady's Island Lake.

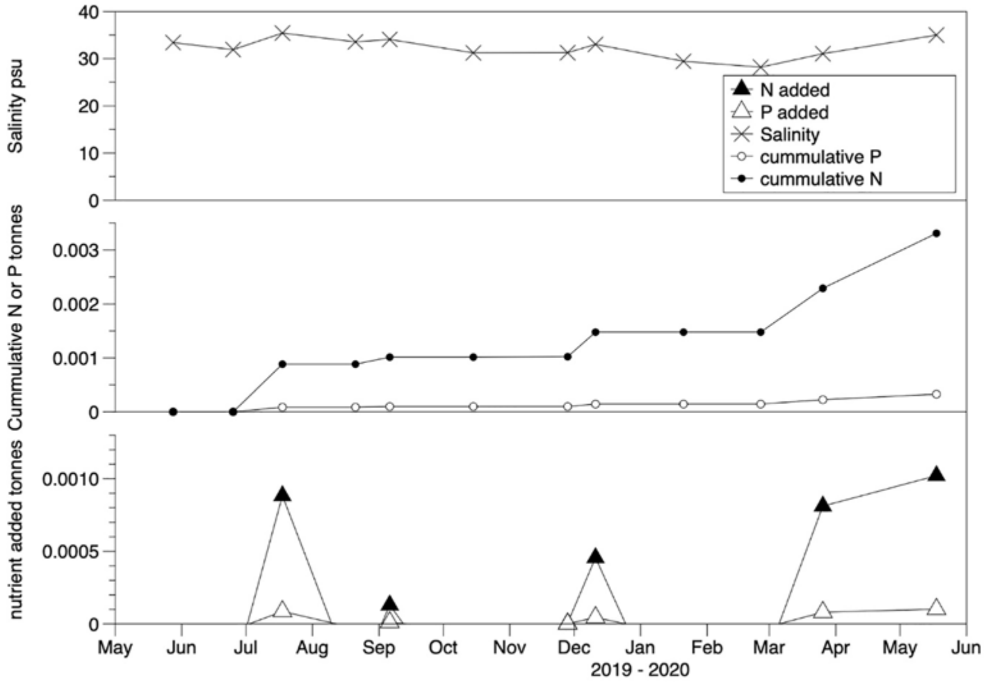

Figure 3.14. Nitrogen and phosphorus movement in the Ballyteige control site. From top: salinity; cumulative input of nitrogen and phosphorus into the lagoon; monthly additions of nitrogen and phosphorus to the lagoon calculated from changes in salinity.

3.11 A Comparison Between the Two Sites

In Table 3.7, nutrient flows for the lagoon and control site are compared, having first adjusted control values for lagoon area (the control site is 0.64 ha or 1/443.75 of Lady's Island Lake).

Table 3.7 indicates that nitrogen input would need to fall 12-fold to reach the input levels of the control site. This figure is of course approximate, but other measures, such as chlorophyll *a* or sediment nutrients, also need to be reduced sixfold if Lady's Island Lake nutrient flows are to approach those of the control site.

Schallenberg *et al.* (2012) reviewed a number of studies on lagoons and reported that nitrogen loadings of 20–100 kg N ha^{-1} yr^{-1} were associated with macrophyte collapse. For example, an Australian lagoon lost its sea grasses at a loading of 30 kg N $ha^{-1}yr^{-1}$, and east coast American studies suggest that loadings of 12 kg N ha^{-1} yr^{-1} allow sea grass dominance, while loadings of 400 kg N ha^{-1} yr^{-1} result in plankton dominance. Viaroli (2008) calculated that loadings > 100 kg N ha^{-1} yr^{-1} led to replacement of sea grasses (*Ruppia* and *Zostera*) by macroalgae. These figures are consistent with CLEAR project estimates of a loading of about 200 kg N ha^{-1} yr^{-1} in Lady's Island Lake compared with 18 kg N ha^{-1} yr^{-1} at the control site. Derolez *et al.* (2019) reported that, depending on site, a minimum 50–80% reduction in nitrogen and phosphorus loading was necessary to reverse plankton dominance in French lagoons, a figure comparable to CLEAR project estimates.

3.12 Relationship Between Nutrient Inputs and Lagoon Catchment Management Practices

The CLEAR project shows that Lady's Island Lake's poor ecological condition is attributable to excess nitrogen input. The source and quantity of the input can be calculated based on the size of the catchment and published figures for nutrient run-off from different types of land use and sewage discharge. According to Tannian (2013), who carried out a desk study of Lady's Island Lake:

- If all the land was under pasture, nitrogen input would amount to 14.4 tonnes per year, largely from inorganic fertiliser. Tannian, however, assumes that all slurry nitrogen is recycled and not included in his calculations, but, as much of the slurry nitrogen comes from imported fodder, it should be treated as a nitrogen input. If allowance is made for nitrogen imported as fodder, then a maximum of 170 tonnes of nitrogen could be available for export to the lagoon.
- Alternatively, if all the land was under arable (wheat) rather than grass, 62 tonnes of nitrogen would be available.

Tannian's (2013) estimated nitrogen input under wheat of 62 tonnes is close to the CLEAR estimate. However, 14.4 tonnes under livestock farming is probably too low, as it does not take account of the fact that nitrogen imported in fodder is also an external input. Lacking precise data on the actual quantity of feed imported in 2019–2020 into the catchment or the

Table 3.7. Measured (in red) or estimated nutrient flows in Lady's Island Lake and Ballyteige control site

Process	Lady's Island Lake	Control site	Comparison
Nitrogen input (t)	60.5	5.1 (of which 4 t is aerial deposition)	11.9
Phosphorus input (t)	1.8	0.049	49
Nitrogen in water column (t)	7.97	2.26	3.52
Phosphorus in water column (t)	0.5	0.2	2.5
Nitrogen sediment deposition (t)	35.3	2.84	12.42
Phosphorus sediment deposition (t)	1.1	0 (measurable t)	Unknown
Sediment nitrogen (g/kg dry wt)	5.4	0.8	6.75
Sediment phosphorus (g/kg dry wt)	0.544	0.22	2.47
Chlorophyll *a* (μg/l)	30.7	4.9	6.26

The comparison column shows the factor by which Lady's Island Lake flows exceed the control site.

percentage retained by the soil, the actual amount discharged into the lagoon cannot be accurately estimated. A ceiling figure of 140 tonnes, however, suggests, if anything, that the CLEAR estimate may be too low.

3.12.1 Land use and benthic/planktonic dominance

An alternative approach is to relate lagoon conservation status to land use in the lagoon catchment. Using data derived from the Local Authorities Water Programme (LAWPRO) and Corine land use database maps (Corine, 2018), the catchment of each of the lagoons surveyed in 2009–2017 was divided into areas of farming and forestry, semi-natural habitats and developed land. In Figure 3.15 planktonic or benthic dominance of these lagoons is related to land use types. Plankton-dominated lagoons are largely found in catchments with more than 60% farming or forestry. Both approaches suggest that run-off from agriculture and forestry is the source of the nutrients that cause benthos plant dominance to give way to plankton dominance in Irish lagoons.

3.13 Conclusion of Impact and Fate of Nitrogen and Phosphorus

Irish lagoons can be classified as macrobenthos or plankton dominated. The former are in acceptable conservation condition; the latter are not. Our data suggest that an average annual chlorophyll *a* concentration of about 7.5 µg/l marks the boundary between benthic and planktonic dominance. Corresponding TN and TP concentrations are about 0.5 and 0.05 mg/l. Lady's Island Lake, with a chlorophyll *a* concentration of 27 µg/l, is in extremely poor conservation condition. At low nutrient values, plankton growth appears limited by nitrogen shortage; at higher nitrogen concentrations, plankton growth is limited by light due to self-shading. About 60 tonnes of nitrogen and 1.8 tonnes of phosphorus enter Lady's Island Lake each year. These figures are 11 times

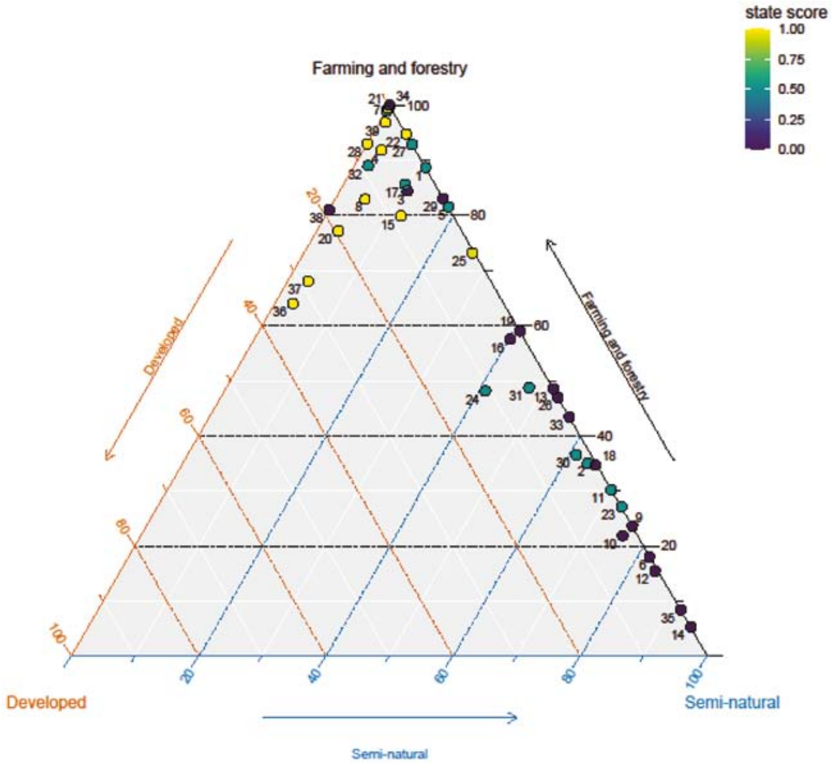

Figure 3.15. The relationship between land use and lagoon state for lagoons surveyed in 2009–2017. State 0 (purple) is benthic dominance, state 0.5 (blue) is intermediate/uncertain and state 1 (yellow) is planktonic dominance. Three benthic sites at the apex are lagoons occurring on small islands without intensive farming. Note that nearly all planktonic lagoons occur in catchments with > 60% farming or forestry.

the nitrogen input and 49 times the phosphorus input of lagoons in good conservation condition. For the lagoon to switch back to benthic dominance, nutrient input would need to fall at least 10-fold. Very large reserves of nitrogen and phosphorus (1505 tonnes and 127 tonnes, respectively) are retained in the lagoonal sediments; in the absence of further nutrient inputs, this nutrient store will probably continue to allow excessive algal growth and delay a return to the macrophytic dominance noted in the 1980s.

4 Surveys: Sediment Profile Imagery and Benthic Infaunal Surveys

4.1 Sediment Profile Imagery

SPI was first proposed by Rhoads and Cande (1971) as an efficient *in situ* technique for documenting organism–sediment relations on the sea floor. The intervening years have seen refinements of the methodology and the development of a successional framework in the context of benthic community development. Experimental and direct field investigations (e.g. Pearson and Rosenberg, 1977; Rhoads *et al.* 1977; Rhoads and Germano, 1986) have helped to redefine what we know of organism–sediment relationships. Sediments in grossly polluted or polluted sediments are black in colour, whereas those in transitory or normal conditions are pale olive. This succession framework has proved to be a major key to interpreting SPI.

The mapping of successional stages follows a predictable sequence after a major perturbation (see Pearson and Rosenberg, 1977). Their theory states that primary succession results in the predictable appearance of macrobenthic invertebrates belonging to specific functional types following a benthic disturbance.

Pioneering assemblages (stage I assemblages) usually consist of dense aggregations of near-surface-living, free-living and tube-dwelling polychaetes and some molluscan species, and are usually associated with a shallow redox boundary. Bioturbation depths are shallow, particularly in the earliest stages of colonisation. In the absence of further disturbance, these early successional assemblages are replaced by infaunal deposit feeders, and the start of this succession process is designated arbitrarily a stage II sere.

Typical stage II species are shallow-dwelling bivalves or tubicolous amphipods. Stage III taxa, in turn, represent high-order successional stages typically found in low-disturbance regimes. These invertebrates are infaunal and many feed at depth in a head-down orientation; they include holothurians and ophiuroids. The bioturbational activities of these infaunal deposit-feeders are responsible for aerating the sediment and causing the redox horizon to be located several centimetres below the sediment–water interface. These end-member stages (stages I and III) are easily recognised in SPI images by the presence of dense assemblages of near-surface oligochaetes and/or the presence of subsurface feeding voids. Both types of assemblages may be present in the same image.

A multi-parameter SPI organism–sediment index (OSI) has been constructed to characterise habitat quality (see sections 4.1.2.1 and 4.1.2.2).

4.1.1 Materials and methods

A diver-operated sediment profile camera was used to obtain *in situ* digital profile images of up to 20 cm of the top layers of sediment on the sea floor at the same set of stations as used for the grab surveys (Figures 4.1 and 4.2).

4.1.2 Image analysis

Images were downloaded to a computer for image analysis. The image analysis system analysed 21 of the physical, chemical and biological parameters in each image.

A multi-parameter benthic habitat quality (BHQ) index was calculated based on the measured physical and biological parameters. This index characterises habitat quality and has been found to be an excellent parameter for mapping disturbance gradients and the health status of the seabed.

4.1.2.1 Organism–sediment index

This OSI was constructed to characterise habitat quality based on the information returned by the SPI images. Habitat quality is defined relative to two end-member standards, i.e. from a lower standard of –10 to an upper standard of +11. The lowest value is given to those sediments that have low dissolved oxygen in the overlying bottom water, no apparent macrofaunal life and methane pockets. Aerobic sediment with a deep redox potential discontinuity, mature macrofaunal

Figure 4.1. Location of the sites (B1–10) at which the SPI diver-operated camera was deployed in Lady's Island Lake.

Figure 4.2. Ballyteige Lagoon showing the locations of the stations (Ballyteige 1–3) where SPI images were collected.

assemblages and no methane voids is given an OSI value of +11.

4.1.2.2 Benthic habitat quality

This multivariate index of BHQ is described in Nilsson and Rosenberg (1997). This index reduces the subjectivity of the OSI and provides a greater sensitivity to the collective meaning of the SPI-generated data. The index ranges from 0 (poor) to a maximum of 15 (excellent). The BHQ places an emphasis on the presence or absence of infauna. It considers the presence of faecal pellets, tubes, burrows, feeding mounds and/or pits, oxic voids and visible fauna, as well as the apparent redox potential discontinuity.

4.1.3 SPI results

4.1.3.1 Lady's Island Lake

SPI analyses of images taken at the 10 sites in Lady's Island Lake showed that most of the sites generally have a low successional stage (OSI) score of 1.

B1a, B1b and B1c (Figure 4.3). The three SPI images show shallow (*c.*2–3 cm) but variable (0–3 cm) redox depths indicating large amounts of organic carbon bound into the sediment. Image B1a has one small specimen of *Ruppia* sp. No other macrophytes or macrofauna are visible on any of the three SPI images. Successional stage (OSI) is scored at 1. Sediment boundary roughness in images a and b is more even than in image c, but none of the images show bioturbation.

B2a, B2b and B2c. In comparison with B1, redox depths at station B2 are deeper, extending down to *c.*5 cm. Sediment colour is less dark than at station B1, and this indicates that less organic material is bound into the sediment. (As this station is relatively close to the location in the barrier that is cut to allow ingress of the sea, this might explain the deeper redox conditions.) There are no signs of any biology in any of the images. Successional stage (OSI) is scored at 1. Sediment boundary roughness is similar in each image, i.e. even sediment surface levels indicate that there is no biological activity in the sediments.

B3a, B3b and B3c. The three SPI images taken at station B3 show no redox discontinuities, meaning that the sediment is anoxic to the surface. This indicates high levels of organic carbon in the sediment. Not surprisingly, therefore, no signs of biology are present in the images. Successional stage (OSI) is scored at 1. Sediment boundary roughness is similar in each image, i.e. even sediment surface levels indicate that there is no biological activity in the sediments.

B4a, B4b and B4c. Images B4a and B4b show a lens of pale-coloured sediment on the surface (*c.*2 cm deep) and a variable redox depth below this of up to 7 cm. B4c differs in that the sediment is anoxic right up to the surface, but for a small patch of lighter coloured, and therefore more oxic in nature, sediment. There are no signs of any biological material in any of the images. Successional stage (OSI) is scored at 1. However, surface boundary roughness in B4a is uneven and may indicate some infaunal biological activity.

B5a, B5b and B5c. The three SPI images taken at station B5 are somewhat similar to B4a and B4b in that

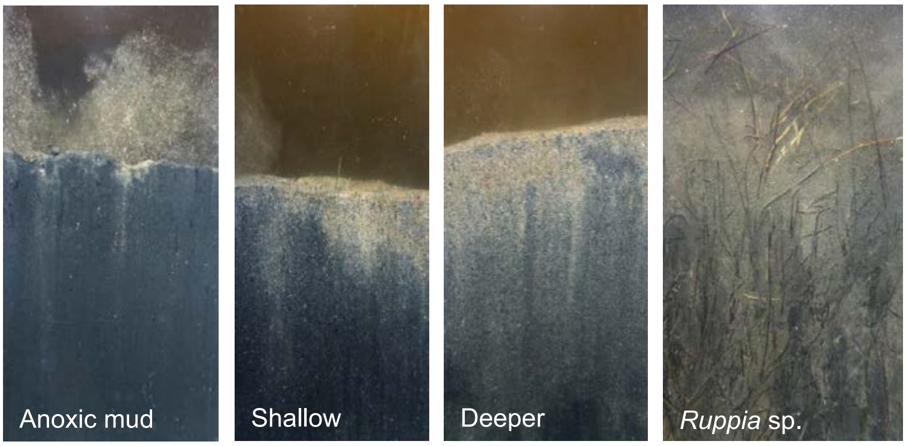

Figure 4.3. SPI showing anoxic mud, shallow redox, deeper redox and *Ruppia* sp.

the upper sediment layer of *c.*5 cm is oxic, and, below this, sediments are anoxic. There are no signs of biological activity. Successional stage (OSI) is scored at 1. Surface boundary roughness in all three images is variable, indicating the potential for some biological infaunal activity.

B6a, B6b and B6c. Redox depths at B6 are variable, with a clear upper grey/brown layer of sediment in the upper *c.*5 cm overlying deeper, darker and more organically enriched sediments. There are signs of some biology (i.e. orange flecks in B6a and B6b). Successional stage (OSI) is scored at 1/2. Surface boundary roughness is indicative of bioturbation.

B7a, B7b and B7c. The SPI images from station B7 all show *Ruppia* sp. growing in sediments with variable redox depths. The dark, hypoxic sediments are unlikely to support any macrofaunal species. Successional stage (OSI) is scored at 1.

B8a, B8b and B8c. Redox depths at station B8 are variable, with a clear pale-coloured upper layer of oxygenated sediment in the upper *c.*5 cm overlying deeper, darker and more organically enriched sediments. Although there are no signs of biology, surface boundary roughness conditions are indicative of bioturbation. Successional stage (OSI) is scored at 1.

B9. No SPI images were returned for this site.

B10a. Like the images from station B7, the SPI image from station B10 shows *Ruppia* sp. growing in sediments with variable redox depths. The dark, hypoxic sediments are unlikely to support any macrofaunal species. Successional stage (OSI) is scored at 1.

4.1.3.2 Ballyteige Lagoon

Ballyteige 1a, 1b and 1c (Figure 4.4). The three SPI images indicate a well-oxygenated sediment low in organic carbon and no sign of a significant redox discontinuity. The brittle star, *Amphipholis squamata*, was imaged at this station. Successional stage (OSI) is scored at 2.

Ballyteige 2a, 2b and 2c. At station 2 redox conditions are poorer than at station 1, with hypoxic conditions close to or at the surface. Some *Ruppia* sp. was imaged at this location. Successional stage (OSI) is scored at 1.

Figure 4.4. SPI from Ballyteige Lagoon.

Ballyteige 3a, 3b and 3c. Similarly to station 2, redox conditions at station 3 are poorer than at station 1, with hypoxic conditions close to or at the surface. Some *Ruppia* sp. was imaged at this location. Successional stage (OSI) is scored at 1. Relict redox layers were visible at depth.

4.1.4 SPI discussion

4.1.4.1 Lady's Island Lake

Except for the presence of *Ruppia* sp. in some of the SPI images collected in Lady's Island Lake, sedimentary conditions in terms of redox depth and successional stage are poor throughout the lagoon and indicate high levels of organic carbon in the sediment. Except for a small number of polychaetes, e.g. *Capitella capitata* and *Malacoceros fuliginosus*, such sediment chemistry conditions are too hostile for most infaunal taxa and the area is largely devoid of macrofauna. There was little evidence in any of the SPI images taken in Lady's Island Lake of the presence of infauna or infaunal activity.

In conclusion, the SPI survey of Lady's Island Lake indicates that the seabed ecology is in an extremely poor state due to excessive organic enrichment.

4.1.4.2 Ballyteige

The SPI images collected at Ballyteige 1 indicate a well-oxygenated sediment low in organic carbon and no sign of a significant redox discontinuity. A brittle star, *Amphipholis squamata*, a taxon known to be intolerant of hypoxic/anoxic conditions, was imaged at this location. Because of these two findings, successional stage (OSI) was scored at 2.

However, at both stations 2 and 3, redox conditions were shallower than at station 1, with hypoxic conditions close to or at the surface. Some *Ruppia* sp. was imaged at station 3. Successional stage (OSI) was scored at 1 in both these locations, indicating that at least parts of this lagoon are organically stressed.

The physical oceanographic conditions of lagoons (with or without barriers), i.e. asymmetrical tides (e.g. only 3 hours of flood tides), mostly shallow water and low tidal velocities (except at mouths, if present), are all features that give rise to systems acting as sinks for organic matter. Therefore, increased levels of sedimentary organic carbon occur in the inner, more quiescent, areas of such waterbodies. These characteristics suggest that, by their nature, benthic communities in shallow lagoons are faunistically depauperate. However, a spatially broadscale survey of benthic conditions of lagoons is required to substantiate this.

4.2 Benthic Infaunal Surveys

4.2.1 Sampling procedure

An assessment of the benthic conditions in Lady's Island Lake and Ballyteige Lagoon was carried out by collecting three replicate faunal samples from each of the same 10 stations in Lady's Island Lake as were used for the SPI survey (Figure 4.1) and from two stations in Ballyteige Lagoon (Figure 4.5). A 0.025-m^2 Van Veen grab was used to collect the samples and these were washed through a 1-mm mesh sieve. A fourth sample was collected for analysis of grain size and organic carbon content. The faunal material was identified to species level where possible and enumerated using a binocular microscope, a compound microscope and all relevant taxonomic keys.

4.2.2 Faunal data analysis

Uni- and multivariate statistical analyses of the faunal data were undertaken using PRIMER v. 6 (Clark and Warwick, 2001).

4.2.3 Univariate indices

Using PRIMER v. 6, the faunal data were used to produce the following univariate indices: number of taxa (S) in the samples, number of individuals (N) in the samples, Margalef's species richness index (d), Pielou's evenness index (J), the Shannon–Wiener diversity index (H') and effective number of species ($\exp(H')$).

4.2.4 Multivariate analysis

The PRIMER programme (Clarke and Warwick, 2001) was used to carry out multivariate analyses on the faunal data station by station. All species abundance data from the grab surveys were fourth-root

Figure 4.5. Locations of two grab stations in Ballyteige Lagoon.

transformed and used to prepare a Bray–Curtis similarity matrix.

Each stress value must be interpreted in terms of both its absolute value and the number of data points. In the case of this study, the moderate number of data points indicates that the stress value can be interpreted more or less directly. While the above classification is arbitrary, it does provide a framework that has proved effective in this type of analysis.

Hierarchical agglomerative clustering (HAC) was used to cluster samples based on between-sample similarities into groups in dendrograms, while similarity profiling (SIMPROF) was used to test if differences between HAC-derived similarity-based clusters were significant. Similarity percentages (SIMPER) analysis can be used to determine the characterising species of each cluster of stations identified either arbitrarily (by eye) from HAC dendrograms or statistically using SIMPROF testing. The species that were responsible for the grouping of samples in cluster analyses were identified using the PRIMER programme SIMPER. This programme determined the percentage contribution of each species to the dissimilarity/similarity within and between each sample group.

4.2.5 AZTI Marine Biotic Index analysis

To assess the benthic ecological quality of the communities in Lady's Island Lake and Ballyteige Lagoon, the AZTI Marine Biotic Index (AMBI) was calculated on the survey results. AMBI offers a pollution or disturbance classification that represents the benthic community health. Individuals are allocated to one of five ecological sensitivity groups, and the

AMBI score is calculated as a weighted average of the sensitivity scores of each replicate sample:

- group I – very sensitive to disturbance/pollution;
- group II – indifferent to disturbance/pollution;
- group III – tolerant of disturbance/pollution;
- group IV – second-order opportunists;
- group V – first-order opportunists.

Assemblages with high proportions of sensitive taxa are indicative of areas with low levels of disturbance, and stations dominated by opportunistic taxa are impacted areas.

4.2.6 Results and discussion

4.2.6.1 Faunal results

The 36 grabs yielded a total of 74 taxa, which were ascribed to eight phyla. The 74 taxa consisted of 24,018 individuals. Of the 74 taxa recorded, 45 were identified to species level. The remaining 29 could not be identified to species level, as they were juveniles, partial/damaged or indeterminate. A full faunal list is available from the authors upon request.

4.2.6.2 Univariate indices

The processed and pooled data were used to calculate primary and derived biological univariate indices for each station (Figure 4.6).

The number of individuals ranged from 7119 (B1) to 33 (L3), the number of taxa ranged from 32 (L10) to 3 (L3), richness ranged from 3.88 (L1) to 1.13 (L3), evenness values varied from 0.64 (L3) to 0.44 (L4) and Shannon–Wiener ranged from a high of 2.15 (L1) down to 1.03 (L3), while effective number of species was highest at L1 (8.61) and lowest at L3 (2.81).

Numbers of individuals and numbers of taxa are low in comparison with open-water benthic communities surveyed in Irish waters, and these low values are reflected in low values for richness, evenness and Shannon–Weiner diversity.

4.2.6.3 Multivariate analysis

Multivariate analysis showed that there are only four faunal assemblages in Lady’s Island Lake and Ballyteige Lagoon and that the assemblage in Ballyteige is unique to that location. A HAC dendrogram and the multi-dimensional scaling (MDS) plot of the stations (B1 and 2 and L1–3) based on faunal similarity can be seen in Figures 4.7 and 4.8, respectively.

Across the 12 stations, SIMPROF analysis revealed four statistically significant groupings. These groupings are group a to group d in the HAC dendrogram presented in Figure 4.7. Stations connected by black lines are significantly different, while stations

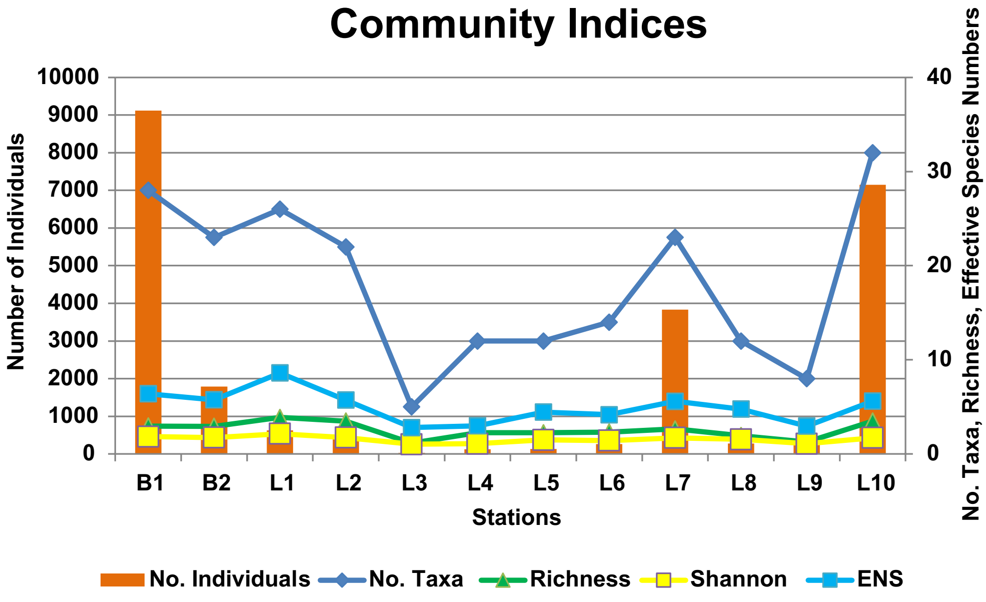

Figure 4.6. Plot of primary and derived univariate indices for sampling stations in Lady’s Island Lake (L1–10) and Ballyteige Lagoon (B1 and B2). ENS, effective number of species.

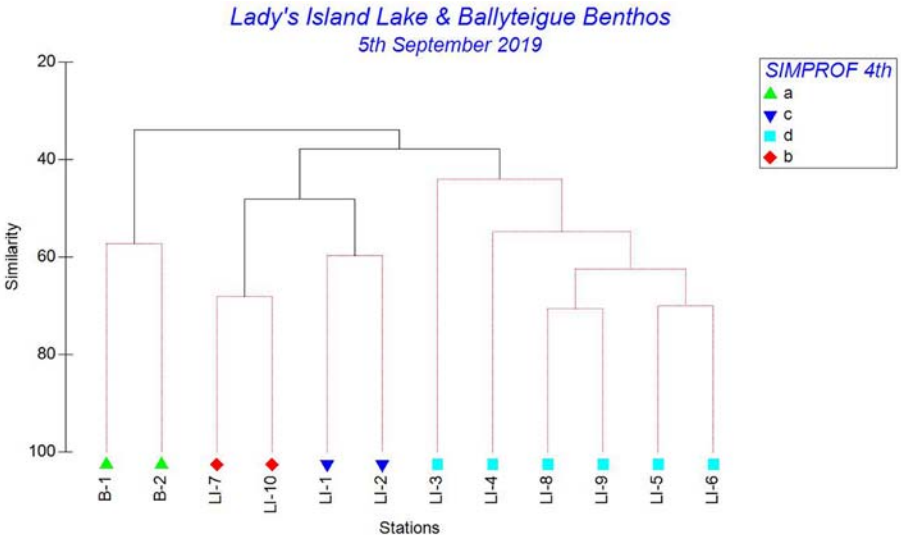

Figure 4.7. HAC dendrogram of stations.

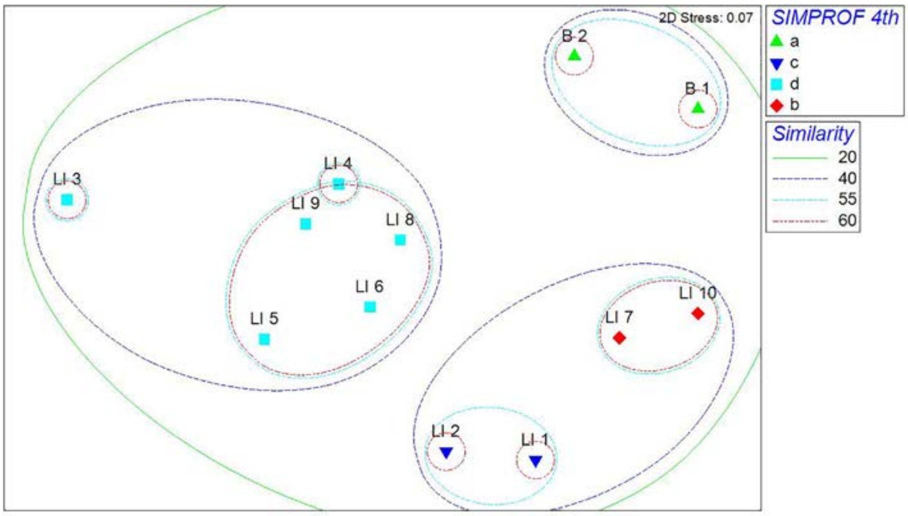

Figure 4.8. MDS plot of stations. Stress level for the MDS plot is <0.07. SIMPROF group labels have been superimposed.

connected by red lines cannot be statistically differentiated.

The grouping of stations is also illustrated in the MDS plot (Figure 4.8). In the MDS plot, the SIMPROF groups to which the stations have been assigned are shown. The stress level of the MDS plot is 0.07, indicating that the MDS is a "good representation of the data with no real prospect of misinterpretation" (Clarke and Warwick, 2001).

4.2.6.4 Sedimentology

Regarding sedimentology, based on the particle size analysis, the sediments of both waterbodies are defined as muddy sands. Organic carbon levels in Lady's Island Lake ranged from 1.02% to 25.4% (mean 12.17%; median 9.6%). In Ballyteige Lagoon, two values were recorded: 1.21% and 1.57%.

4.2.6.5 AMBI

Figure 4.9 presents the results of the AMBI analyses. In Ballyteige, one station (B1) was classified as slightly disturbed and one station (B2) was described as moderately disturbed. In Lady's Island Lake, two stations (L1 and L2) were moderately disturbed, while eight stations (L3–10) were described as slightly disturbed.

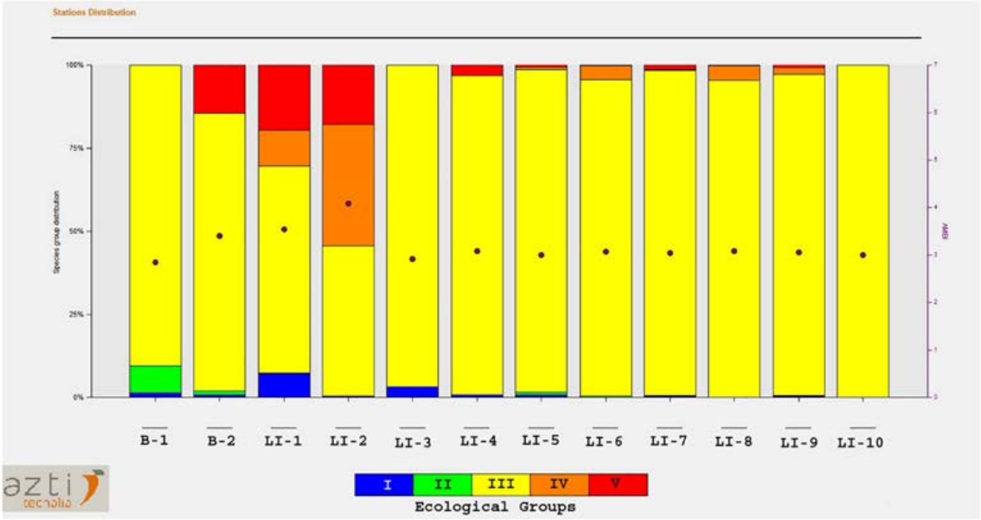

Figure 4.9. AMBI results for Ballyteige and Lady's Island Lake.

These AMBI results are in line with the results of the SPI successional stage, with both locations returning scores of 1 of 2 that reflect moderate to slight levels of disturbance.

4.3 SPI/Grab Conclusion

Given the results of the SPI survey, it is not surprising that the number of taxa in the organically enriched sediments in Lady's Island Lake is low and that the other univariate statistics and the AMBI analysis reflect this. These low faunal returns are also reflected in a low diversity of faunal assemblages.

The benthos of Lady's Island Lake was the focus of a BSc thesis (Bates, 1977). The faunal data recorded by him were compared with the 2019 data using the statistical methods presented earlier. Figure 4.10 presents the results of the cluster analysis of these two datasets. Clearly, the datasets split at a high level of *c.*25% similarity, which indicates a very low level of similarity between the two datasets. From this result, it is possible to state definitively that benthic conditions of the lagoon changed significantly between 1977 and 2019.

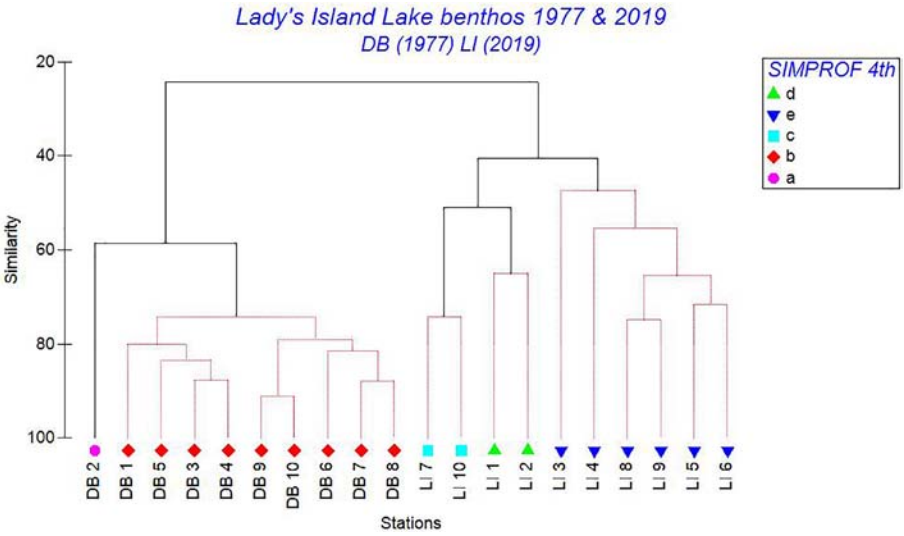

Figure 4.10. Dendrogram of combined 1977 and 2019 Lady's Island Lake benthic datasets. DB, Dick Bates 1977 data; LI, 2019 data.

5 Remedial Techniques

It is clear from the nutrient studies carried out as part of this research project that the biggest threat to Lady's Island Lake, and many other lagoons in the country and Europe (see later), is the inflow of excessive nutrients to the lagoon. The literature survey has shown that this has been recognised since at least 1983 and, although it has been recommended that steps are taken to reduce the inflow of excessive nutrients, this has not yet been achieved, but the inflow has continued since that date. The nutrient modelling has estimated that 60 tonnes of nitrogen enters the lake annually.

Various relatively easy remedial actions can be taken to address this threat, the most obvious of which is to enforce the regulations. This may appear to be difficult to achieve, but it seems unfair to place all the blame on farmers. The EU Nitrates Directive went a long way towards improving water quality in Irish waters, but the Irish government applied for a derogation. The European Commission granted the derogation and did so five times consecutively. There are other, relatively easy, actions that could be taken, such as changes to farming practices to reduce the loss of nutrients from the land and the creation of integrated constructed wetlands (ICWs) and buffer zones around the lagoon and feeder streams to reduce nutrient inputs. It might also be possible to use some areas for commercial forestry rather than marginal farmland.

A number of other potential solutions, involving biomanipulation, such as reseeding the lagoon with *Ruppia* sp. and reintroducing bivalves, have been suggested and could be considered. However, even if nutrient inputs are reduced to zero, the build-up of nutrients within the lagoon may be so great that more extreme methods, such as dredging, may need to be considered. Another proposed solution is to divert the inflow streams to a sea outfall, but this is associated with other problems. Traditionally, the barrier of the lagoon has been breached almost annually in order to control water levels; now there is a plan to install a permanent pipe in the barrier. However, it seems that the design of this permanent pipe may not allow enough saltwater to enter the lagoon and thereby maintain the brackish nature of the lagoon, which is listed as a priority habitat under the Habitats Directive and which also happens to be the biggest and best example of a coastal lagoon in Ireland.

The following remedial techniques are suggested for immediate consideration:

- enforce the regulations;
- change farming practices;
- introduce buffer zones and modifications to drainage areas;
- create ICWs;
- convert land to forestry;
- install a permanent pipeline through the barrier;
- divert inflow streams to a sea outfall;
- use biochar;
- develop a restoration plan.

The following are suggested for future consideration:

- biomanipulation;
- dredging.

5.1 Enforcing the Regulations

Nutrient modelling (WP 2) has estimated that 60 tonnes of nitrogen enters the lake annually. Much of this is in the form of slurry entering through feeder streams. At the workshop in Wexford in March 2022, a Teagasc representative refuted the suggestion that farmers are still allowing this, but the contrary was quite obvious when some of the outlets of the streams were visited during the sampling procedure.

A representative from An Taisce provided the information in the remainder of this section.

The Nitrates Directive came into force in 1991. Its objective is to protect water quality from agricultural pollution and to promote the use of good farming practices. All EU Member States are required to produce a Nitrates Action Plan (NAP) every 4 years, which then sets the rules and regulations for farm management, including the application of slurry and fertilisers. These rules are encapsulated in the

Good Agricultural Practice regulations, which are updated whenever the NAP is updated to reflect any changes.

This is the 5th NAP and it comes amid an ever-worsening water quality crisis. Nearly half of our rivers (47%) and a third of our lakes are failing to meet their environmental quality standards for nutrients, with serious consequences for the health of Irish waters. Rather than meeting our obligations under EU law to halt and reverse water pollution, it is actually on the rise; more than one third of river sites (38%) have increasing rates of nitrate pollution.

Several rivers in the south and southeast such as the Barrow, the Slaney and the Lee are of particular concern, with the majority (85%) of the nitrogen in these rivers coming from agriculture. Clearly, radical changes are necessary in the management of nitrogen inputs to agricultural land to comply with the Nitrates and Water Framework Directives.

There are a number of reasons why plans have failed to date, but the most recent NAP consultation documents highlight one of the key reasons for this failure.

In short, the NAP measures are currently failing to protect water quality from agriculture, as required under Article1 of the Directive. This is in part as a result of the industry expansion, but poor enforcement and compliance is also hindering progress in implementation. A significant change in future enforcement and greater compliance is a prerequisite before any further consideration of what additional measures are required to protect water quality.

Dairy cow numbers have increased significantly in recent years to 1.6 million cows in 2020, an increase of 50% from 2010. Simultaneously, fertiliser imports have increased 35% in a similar period.

EPA data indicate that in some catchments in the south and east over a 50% reduction in nitrogen load will be necessary. Enforcement is required to address the issue of where slurry is being spread. At the very least, mapping exercises should be carried out to ensure that unsuitable land is clearly identified, as some will clearly be inaccessible to slurry spreading machinery, particularly the larger low emission slurry spreading (LESS) equipment. This land should be zoned ineligible for land spreading and removed from land holding calculation. Additionally, land calculations should be based on land parcels within a given distance to the home farm.

5.2 Changes in Farming Practices

Much of the following information in this section was supplied by Mr Paul Moore who attended the workshop and is a tillage and beef farmer in County Cork who understands farmers' problems well. He has been involved in nature conservation for over 30 years and is a former board member of BirdWatch Ireland. He was one of the founders of The BRIDE Project, an EU-funded biodiversity project on intensive dairy farms, and is on the steering committee of Harper's Island Wetlands, a nature reserve near Cork city.

Traditionally, farmers have looked on agri-environment schemes as income supplement for small farmers or only for areas where the land is not suitable for more profitable enterprises. To overcome this mindset the best strategy is for a local and locally led scheme where it becomes "personal" and local pride or peer pressure can play a role in encouraging farmers to participate in a scheme they might otherwise not have any interest in.

The main impediments to joining such a scheme are perceptions around (1) loss of earnings, i.e. taking good land out of production, (2) inconvenience to the main farming enterprise and (3) the possibility of extra inspections or audits.

Whether a local scheme or national scheme is felt to be the best source of funding, it will need to be sold to potential participants by someone. This could be a project manager for a locally led scheme or a local advisory representative or a local development company.

The issues around farming at this site (Lady's Island Lake) revolve around slurry and fertilisers entering waterways, and there are a number of on-farm measures that can address this situation:

- constructed wetlands to treat water run-off;
- buffer strips along the edge of waterways;
- multi-species swards, which require far less fertiliser than standard perennial ryegrass;
- liquid fertilisers sprayed onto arable crops, which have a quicker uptake than standard pelleted fertiliser;

- slurry spreading techniques such as injection systems or trailing shoes – LESS rather than the standard splash plate, which can reduce run-off;
- winter cover crops in an arable cropping situation, which will maintain a green cover over winter and will reduce leaching of nutrients and soil erosion;
- reduction in the use of fertilisers, especially N.

Potential sources of funding for measures to address the pollution issues follow.

5.2.1 European Innovation Partnership scheme

There are a number of such schemes around the country at present, such as The Pearl Mussel Project, Protecting Farmland Pollinators, Enable Conservation Tillage Ireland and The BRIDE Project. The European Innovation Partnership scheme funds projects that allow farmers, scientists and other experts to develop innovation partnerships that road-test new ideas and practices, which can then be rolled out countrywide.

5.2.2 LEADER funding

LEADER is an EU-funded scheme to help rural communities develop in many different ways. It funds schemes for tourism, protection and sustainable use of water resources, local biodiversity and environmental protection. It is administered at a local level (see https://www.wld.ie/ for funding in Wexford).

5.2.3 Community Water Development Fund, provided by LAWPRO

This fund supports communities seeking to progress projects aimed at protecting or improving the water quality of a local waterbody. Any group seeking funding has to start by contacting its local community water officer.

5.2.4 Agri-Climate Rural Environmental Scheme (formerly the GLAS (Global Loan Agency Services) scheme)

This is the national agri-environment scheme funded by the EU's Common Agricultural Policy (CAP). There are elements of it that would be applicable here; however, the GLAS scheme has officially ended; it is being rolled over for 1–2 years and is not accepting any new applicants. It will be replaced with a new agri-environment scheme, the Agri-Climate Rural Environmental Scheme (ACRES), the details of which have not yet been decided. The funding and timing of this new scheme will be dependent on the outcome of the CAP negotiations at European Commission/European Parliament level.

5.2.5 NPWS Farm Plan Scheme

This scheme, run by the NPWS, draws up tailored plans for each farm accepted into the scheme, so would be suitable for Lady's Island Lake. Applications are closed for 2021, but presumably will reopen next year.

5.2.6 LIFE funding

This EU scheme funds projects to safeguard nature and biodiversity. The funding for the 2021–2027 programme has been agreed at an elevated figure of €5.45 billion. Nature and biodiversity is one of the four subprogrammes within LIFE.

5.2.7 Targeted Agriculture Modernisation Schemes

These schemes provide grants to farmers to build and/or improve a specified range of farm buildings and equipment. Slurry storage, slurry treatment and slurry spreading equipment would all be covered under these schemes.

5.3 Buffer Zones and Modifications to Drainage Areas

The information in this section was provided by Féidhlim Harty, a participant at the workshop. Féidhlim Harty is a Director at FH Wetland Systems with over two decades of experience in designing and planting constructed wetland systems and reed bed treatment treatment systems. FH Wetland Systems' latest endeavour is the development of zero-discharge willow systems for sites with poor percolation characteristics.

5.3.1 Grassed riparian buffer strips

Fencing along streams and drains allows an ungrazed strip of grasses and forbs to grow as a filter strip to catch silt and nutrients from the adjacent field. These strips may vary in width from 2 m to 10 m (from the top of the drain to the grazed land) depending on the field gradient and adjacent land use. It is, however, of limited value in well-drained soils.

- Fencing costs: €2/m for post and single-strand electric wire, including material and labour.
- Typical system section of 100 m length = €200.

5.3.2 Wooded riparian buffer strips

Buffer strips are useful where additional uptake of nutrients is desired, particularly on more steeply sloping ground or in areas where groundwater movement is a source of nutrients. The deeper rooting of trees compared with grasses allows a curtain of roots to mop up nutrients beneath the soil as the water migrates towards the watercourse. These are of more benefit than grass buffers. These strips are typically 2 m to 20 m in width but may be wider on steeply sloping ground.

- Fencing costs: €2/m for post and single-strand electric wire, including material and labour.
- Planting costs: €1/m^2 for mixed deciduous tree planting, inclusive of both native and edible species (e.g. hawthorn, alder, birch, hazel, crab apple, willow, walnut, sweet chestnut, cobnut).
- Typical system section of 5 m width × 100 m of stream length = €900 for fencing, and supply and planting of trees plus follow-up maintenance. Maintenance is crucially important in the first 3 years to ensure the success of plant establishment.

5.3.3 Wetland buffer zones and ponds

These may resemble constructed wetland systems but are designed for improvement of field run-off rather than yard areas and are not covered by the ICW guidelines in terms of sizing or design layout. Rather they are more typically relatively shallow and narrow marsh channels that open out into ponds at the low part of the field, where contours permit, and are created prior to reintroduction of the existing stream. These may have some use in shallower flow in the west but will not intercept flow at 3–5 m depth on the eastern side.

- **Size.** Wetland marsh should be 1–3 m wide at the wetland channel base and run the full length of the field parallel to the stream or river. Ponds may vary in size and depth. For example, a relatively deep pond measuring 3 m × 3 m might be created at the base of the wetland channel while larger ponds, over an acre in area, could be created where gradients are suitable and the land is available.
- **Costs.** A digger and driver costs €350/day. One day is sufficient time to create a parallel wetland channel of 2 m × 100 m on shallow sloping ground plus one 10 m × 10 m pond at the end of the channel run. Plant supply and planting for 200 m^2 of wetland buffer zone channel = €500. Plant supply and planting for 100 m^2 pond = €100. See fencing costs above if required.

5.3.4 In-channel wetland filters

If seasonal drains are already present on the farm, these may be planted directly as a wetland buffer zone without the need to construct a separate channel parallel to the watercourse. Such filters may be beneficial in deeper drains that intercept wetlands. For zero cost and zero resource inputs, use old piping rather than buying new.

- **Size.** Follow the existing drain base width, typically 0.5 to 1.5 m in width × the full drain length within the field or land holding. Compacted earthen dams to be 300 mm high × 1 m of channel length for structural strength.
- **Costs.** The cost of constructing a dam by hand or machine is €50. Plant supply and planting of 100 m^2 of channel base area (1 m × 100 m) = €250. See fencing costs above if required.

5.3.5 In-channel settlement pond

Allows for greater settlement volume per unit area than the shallow wetland planted channel and may be of some use in the deeper drains that intercept the wet land.

- **Size.** Assume that 0.3% of the catchment drains into the pond. Thus, for a farm drain below a catchment area of 10 ha, allow an in-channel pond area of 300 m^2.
- **Costs.** For a 300 m^2 pond, allow 2 days of machine time at €350/day = €700. Perimeter fencing = 50 m × €2/day for post and single-strand

electric wire = €100. Perimeter planting of 80 m length = €250.

5.3.6 Brash dams

These are typically dams of twiggy brash, heather or rushes, baled and staked into position to fill the entire channel width in farm drains or small streams. Alternatively, leaky log dams can be used to regulate peak flows from hillside catchments. However, these are typically more suited to more steeply sloping catchments subject to flash flood events and therefore may be of limited use in Lady's Island Lake.

- **Costs.** €100/unit supplied and installed for 10 units.

5.3.7 In-field contour swale and planted ditch combination

This is a shallow channel plus planted mound to form a hedgerow within a field, created parallel with the contour (level) for maximum capture of run-off water from the upslope field. It is known to be ineffective in well-drained soils.

- **Size.** Shallow swale width of 1 m and mounded ditch of 1 m × full width of field.
- **Costs.** For 100 m of swale/mound creation allow €500, inclusive of machine time plus planting. Fencing above and below the area is €2/m for each side. Thus, the total cost is €900 for 100 m to include construction, planting and fencing.

5.3.8 In-field mound/recontouring

This is used to route direct down-gradient run-off away from a lake or river and back towards planted ditches or ponds. The recontoured area may be reseeded and grazed and remains wet in wet weather but does not remove land from grazing. Like the method described in section 5.3.7, this solution is known to be ineffective in well-drained soils.

- **Size.** Typically 2 m to 5 m wide, depending on the slope of the land, × the full length of the field.
- **Costs.** Allow €5/m for a 3-m-wide recontouring requirement. Thus, for 100 m of swale length allow €500 for machine time and reseeding. No fencing needed. The mound becomes part of the original grazing land once the grass regrows.

5.3.9 Woodland habitat reinstatement

Woodland habitat is an excellent water filter and hydrodynamic buffer zone, particularly if planted along the bottom edge of a sloping field or alongside watercourses as a wide riparian buffer zone. This method is useful in addressing subsurface pathways.

- **Size.** As an example, assume an area of 1 ha.
- **Costs.** Allow €5000/ha for planting and maintenance.

5.3.10 Willow biocoppice plantation

Willows can be planted as a biomass crop, but where used as a water filtration measure they must not be fertilised or have slurry applied. The principle is to derive a crop from the land at the same time as mopping up residual nitrogen and phosphorus run-off from the field. Uptake rates for willow as a biomass crop have been measured at 8.2 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$ for phosphorus and 57.6 $\mathrm{kg\,ha^{-1}\,yr^{-1}}$ for nitrogen (Larsen *et al.*, 2018). Like woodland reinstatement (see section 5.3.9, above), this method is useful in addressing subsurface pathways.

- **Costs.** Allow €7000/ha for modest in-field contouring plus planting.

5.3.11 Willow filtration of lake water

An extension to the above approach is to plant a willow filter area specifically for receiving pumped inputs from the lake itself. This will permit ongoing stripping of the lake nutrient levels over time. Willow filters have been used in Denmark for removal of nutrients from fishing lakes, allowing pumped lake water to flow through a sand layer and back into the lake once more. In Wexford there is unlikely to be free-draining soil, so careful loose bunding of lower edges will be needed to permit flow of water back into the lake with some lateral percolation.

- **Size.** This may also be many hectares and be managed on a 3-year rotation basis in the same way as a standard biocoppice plantation.
- **Costs.** The typical cost for field-scale effluent-irrigated willow plantations is €20,000/ha, inclusive of pumping, irrigation piping, contouring, bunding and planting.

5.3.12 Regenerative farming methods and techniques

There are many techniques that can be adopted for farm practice that actively enhance the soil depth, soil quality and humus levels and thus directly improve the capacity of the soil to act as a store for both nutrients and water.

- **Farm-scale composting.** This is the use of dry composting rather than wet slurry infrastructure for recycling of both biomass and nutrients. This approach is advocated in Northern Ireland (Department of Agriculture, Environment and Rural Affairs) and Greece and by the Danish Environmental Protection Agency and the Danish Ministry of the Environment.
- **Holistic planned grazing.** This technique uses a planned grazing pattern similar to strip grazing or mob grazing, and grass recovery time between grazing events is maximised to enhance overall biomass production and forage value for livestock.
- **Conservation agriculture.** A range of methods and techniques are designed to maximise nutrient availability for plants, minimise chemical inputs to keep costs down and maximise soil health.
- **Agroforestry and silvopasture**. These techniques involve the use of trees on cropland or grazing land, respectively, to provide shelter, carbon sequestration, wildlife habitat, water quality benefits and multiple yields from the farm.

In summary, the use of any or a combination of these waterway protection and nutrient uptake measures on the farmland within the Lady's Island Lake catchment would enable a reduction in and/or reversal of the ongoing nutrient input challenges for the lake. In this way the lake quality may be restored, and the habitat of the wider area enhanced and enriched for wildlife.

5.4 Integrated Constructed Wetlands

Rory Harrington, a participant at the workshop, provided the information in this section. Dr Rory Harrington is a senior scientist at Vesi Environmental Ltd, a company based in Dunhill, Waterford, which specialises in constructed wetlands for the treatment of waste water and other ecosystem-based services. He is a graduate of University College Dublin, Ireland, and Yale University, USA, with degrees in Forestry and Evolutionary Biology.

ICWs have been used in various parts of the world to treat eutrophic waters, often with great success. The ICW working framework deployed to improve the water quality of the watershed is similar to that of the small watershed technique and associated ecosystem studies developed by Bormann and Likens (1981) at Hubbard Brook, New Hampshire, USA (Scholz *et al*., 2007). The ICW initiative therefore endeavours to promote the advantages of restoring some of the wetlands' key environmental services and their associated lost habitats (Harrington and Ryder, 2002).

There are many examples throughout Europe and the USA of these ICWs. There are over 120 in Ireland alone, and one of the main contractors for these is Dr Rory Harrington, senior scientist at Vesi Environmental (for more information see Harrington and Ryder, 2002; Harrington *et al*., 2005; Scholtz *et al*., 2007).

The proportion of phosphorus removed by surface flow constructed wetland treatment of agricultural dirty water currently varies from 30% to almost 100% depending on the type of treatment/source of phosphorus/something else (e.g. Newman *et al*., 2000; Reddy *et al*., 2001; Braskerud, 2002).

The most relevant work related to the current ICW database has been published by Carroll *et al*. (2005), Dunne *et al*. (2005a,b) and Harrington *et al*. (2005), providing evidence that phosphorus removal correlates positively with an increase in wetland area. Although the quality and quantity of farmyard dirty water may be similar throughout the year, phosphorus removal varies from 5% in winter to 84% in summer (Dunne *et al*., 2005a,b). However, these figures refer to relatively undersized ICW systems. A study in Ireland (Costello, 1989) reported on a dairy farm with a large constructed wetland of 12 ha and found a mean reduction in orthophosphate of up to 91%. In general, the ICW treatment performance improves with an increase in both wetland area and retention time (Harrington and Ryder, 2002; Harrington *et al*., 2005).

A recent study of the Mississippi, by Hansen *et al*. (2021), revealed that fluvial wetlands (i.e. wide, slow-flowing, vegetated waterbodies within the riverine corridor) are the single most cost-effective management action to reduce both nitrate and sediment loads, and will be essential for meeting moderate to aggressive water quality targets.
The study concludes that extensive interagency cooperation and coordination at a watershed scale is

required to achieve substantial, economically viable improvements in water quality under intensive row crop agricultural production.

The Anne River Project in Waterford was supported by the county's LEADER Programme, NPWS, OPW, the EU Interreg Programme, Irish Water and, most importantly, the majority of the landowners of the area.

As part of the workshop in Wexford we looked at two of the feeder streams at the north end of the lagoon. Based on very approximate flow rates supplied by Dr Cilian Roden for the eastern side of these streams, Dr Harrington estimated that to treat water entering from this one stream would require a wetland of approximately 5 ha.

- **Costs.** Allow approximately €25,000–35,000 for machine hire and landscaping and €50,000–100,000 for planting (principally *Typha latifolia*, *Glyceria fluitans*, *Carex riparia*).

In these cases, an ICW is used as an "end of pipe" measure to treat water from the stream before it enters the lake. The ICW will have little effect on nitrogen levels in the lake water that originates on the eastern side and travels to the lake through subsurface pathways.

5.5 Converting Land to Forestry

Dr Harrington is also very keen that, in addition to creating an ICW, some of the land bordering the lagoon that often floods and is not very productive could be converted to commercial forestry. This concept is partly based on the Hubbard Brook experiment by Borman and Likens (1979), which showed the importance of forestry within the catchment of a river course in maintaining water quality.

5.6 Permanent Pipeline Through the Lagoon Barrier

Another suggestion is to construct a permanent concrete channel through the lagoon barrier, similar to the one under construction at Lough Donnell, County Clare.

5.7 Sea Outfall

Sea outfalls to the Mediterranean were one of the remedial actions taken to improve water quality lagoons near Montpelier and have been used in many other places as a quick solution. However, this can solution simply shift the problem to a different area. Concern has been expressed recently about the eutrophication of coastal marine waters, the proliferation of green algal blooms in estuaries and even the encouragement of toxic cyanobacterial blooms.

The creation of a sea outfall has been suggested as a solution to the problem in Lady's Island Lake because the installation of a permanent structure in the mobile sediments of the lagoon barrier was considered impractical. At one time the OPW was asked to investigate the possibility of pumping the water to an outfall by the pier at Carne (Figure 5.1), but this was considered to be too expensive.

The OPW stated that this solution presents two issues in particular:

1. "Any solution, therefore, which removes the excess water without breaching the dunes is likely to lead to the lake becoming a low salinity lake in a short period."
2. A suggestion to "deepen the channel between the mainland shore and the islands. This would require major dredging works and suitable dumping sites and has not been costed at present."

5.8 Biochar

The word biochar derives from the Greek words βίος, *bios*, meaning "life", and "char" (charcoal produced by carbonisation of biomass). It is a high-carbon residue that is produced via pyrolysis (i.e. the heating of an organic material in the absence of oxygen) and results from the thermal decomposition of biomass in the absence of oxygen, which prevents the combustion of solids. Common crops used for making biochar include various tree species, as well as various energy crops. For example, low-cost materials such as coconut husk, gorse, olive stones, pine, etc., can all be pyrolysed. Some of these energy crops can store much more carbon on a shorter timespan than trees do.

Biochar offers multiple soil health benefits in degraded tropical soils but is less beneficial in temperate regions. Its porous nature means that it is effective at retaining both water and water-soluble nutrients. Biochar also improves water quality, reduces soil

Figure 5.1. Map of Lady's Island Lake showing possible solutions for controlling water levels. Reproduced with kind permission of Malachy Walsh.

emissions of greenhouse gases, reduces nutrient leaching and soil acidity (i.e. increases soil fertility) and reduces irrigation and fertiliser requirements. It is known to raise agricultural productivity and reduce pressure on old-growth forests. It can also sequester carbon in soil for hundreds to thousands of years. Modest additions of biochar reduce nitrous oxide emissions by up to 80% and eliminate methane emissions (both nitrous oxide and methane are more potent greenhouse gases than carbon dioxide).

In recent years, biochar has attracted interest as a wastewater filtration medium, as well as for its capacity to adsorb wastewater pollutants, and it is known to be highly effective to adsorb wastewater pollutants, and many other solutes. A recent review by Xiaoqing *et al.* (2020) describes the physicochemical properties of biochar, e.g. surface area, porosity and acid–base behaviour. Surface functional groups and element composition depend on pyrolysis temperatures and have vital implications for the suitability of biochar for the removal from wastewater of target contaminants (e.g. heavy metals, nitrate, ammonium, phosphate and fluoride) and the efficiency of removal. The review also gives a systematic overview of the broad application of biochar in water and wastewater treatment to remove organic and inorganic contaminants. Based on the mechanisms, attention has been given to biochar modification to improve its performance with the aims of increasing:

- surface area;
- porosity;
- surface sorption sites of the biochar.

New frontiers of magnetic biochar and biochar–biofilm combination are being explored. Existing environmental concerns of biochar application are discussed in the aspects of cost, performance, stability, co-contaminant and sustainability. Future research directions are put forward to facilitate the practical application of biochar.

5.9 Restoration Plan/Demonstration Site

Before a restoration plan can be presented it will be necessary to hold a public meeting to present the slurry findings to the stakeholders and local residents, to discuss the various options and to decide on a demonstration site.

Any restoration plan will have to be site specific but it will be difficult to predict the effectiveness of any plan and the resulting improvement in water quality and conservation status of the lagoon. It is strongly suggested that a demonstration site is first designed and tested.

A suitable site will need to be found, with receptive landowners. The two sites that we visited following the workshop, each of which has a feeder stream entering the northern end of the lagoon, would appear to be good candidates. The larger of the two streams certainly appeared to have very low water quality, based on appearance alone, and a combination of techniques could be applied in order to improve the water quality of this stream. In particular, it would appear to be a good candidate for an ICW and associated buffer zones. The farms in the catchment could be visited (perhaps by LAWPRO) and advised about "environmentally friendly" farming practices. Eventually, the restoration plan would have to be a locally led group scheme, similar to the Anne River Project, and speakers at the workshop, such as Jim Hurley, Paul Moore, Rory Harrington and Féidhlim Harty, would make very good committee members for the demonstration site.

Ideally, this demonstration site would be open to the public and become a local amenity, education centre and tourist attraction, similar to the Harper's Island bird reserve in Cork Harbour. There are extensive areas of shoreline around Lady's Island Lake where this would be possible (Figure 5.2).

5.10 Bioremediation

Bioremediation is a developing technology that can be used with other physical and chemical treatment methods for the management of a diverse group of environmental pollutants. It is a sustainable approach for the management of environmental pollution. In the marine environment, capitellid polychaetes (*Capitella*)

Figure 5.2. Aerial photograph of Lady's Island Lake showing the intensive agriculture along the shoreline of the lake and the great potential for ICWs and for amenity and conservation areas. Photo credit: Riccardo Conway.

have been used to break down organic matter in sewage treatment plants in Japan. This is because capitellids are capable of existing in highly anoxic sediments.

Gulati (1990) manipulated freshwater fish species and developed a top down–bottom up approach, but this is probably not appropriate for Lady’s Island Lake owing to its salinity. It might be possible to introduce filter-feeding shellfish, such as mussels, that would filter out phytoplankton in the water column. However, this would require float systems and extensive longlines to effectively filter sufficient volumes of water. Owing to low levels of off-bottom oxygen, bottom-dwelling species such as *Cerastoderma* and oysters would not be successful, as they would die.

5.11 Dredging

Some stakeholders may consider dredging extreme, but it may be necessary: even if fertiliser inputs can be reduced to zero, nutrients may continue to build up in the lake. This situation has occurred in several countries. For example, at the Eurolag Conference in Venice, in 2020, it was reported that zero fertiliser inputs was achieved in Kucukcekmece Lagoon, Turkey, but was not sufficient to prevent nutrient build-up, and now they have decided to resort to dredging. There are also many examples of the need for dredging in the Netherlands and in Mediterranean countries (Van der Does *et al*., 1992).

There is anecdotal evidence that Lady’s Island Lake is silting up, becoming shallower and could eventually turn into a freshwater marsh. Reeds are encroaching from the north and at Scallan’s pool. Dredging around the islands would help prevent terrestrial predators accessing the tern nests. Dredging at the southern end of the lagoon would help to drain the lagoon and allow more saltwater to enter.

It is estimated that dredging 0.5 m of sediment from the 350-ha lake would produce 6 million tons of sand, which would have to be disposed of. A Dutch colleague of Billy Bates (owner of Inish Pebble gravel pit) estimates that dredging would cost €2.7/tonne, but the machine would have to be transported from the Netherlands. Smaller dredgers, such as the “mud-cat” used in Texas, can dredge 76 m^3/day.

The following are possible solutions for the disposal of the material:

- Sell it. It has been estimated that the removal of 0.5 m of sediment from Lady’s Island Lake, with an area of 350 ha, would result in 6 million tonnes of good fine sand that might have a market value. Granulometry of Lady’s Island Lake suggests that the sediment is mostly good sand, but it would need to be washed and transported.
- Pump the sand offshore for beach nourishment. This would reduce erosion at Tacumshin.
- Build islands for terns to nest on.
- Build a bank along the shoreline and create treatment ponds behind bank.
- Spread it on the land (already fertilised). This would raise the level of the shoreline and reduce the risk of flooding farmland.

6 Conclusions and Policy Recommendations

6.1 Conclusions

This work has shown that Lady's Island Lake is severely degraded due to excess inputs of nitrogen and possibly phosphorus. To return the lagoon to its ecological state of 40 years ago would require a reduction in inputs of over 80%. Whether such a reduction can be achieved by means such as artificial wetlands, better nutrient management on farms or watercourse management remains to be seen. An additional problem is the large reserve of nutrients accumulated in the lagoon sediments, which may, as in some French lagoons, continue to determine lagoon ecology long after excess inputs have been reduced. Should this be the case, only sediment removal could remedy the situation.

A very serious additional problem is the control of lagoonal salinity; the hydrological model shows that replacing the present system of barrier breaching with even a large-diameter pipe would radically reduce lagoonal salinity to the extent that the waterbody would be more of a shallow freshwater lake than a saline lagoon. As such, it would have little conservation value and could not be included in the priority habitat of lagoons listed in the EU Habitats Directive.

Lady's Island Lake is not the only Irish lagoon in ecological decline; analyses show that most lagoons in agricultural catchments are also eutrophicated. Lady's Island Lake exemplifies the problems involved in managing Irish lagoons. A number of problems must be solved before habitat restoration is possible. These will require the following measures:

- reducing the use of imported nitrogen on farmland;
- increasing measures designed to retain nutrients on farmland and forestry;
- removing or capping nutrient-rich bottom sediments;
- maintaining or restoring the salinity regime of Irish lagoons.

These problems are very similar to those confronting the management of other waterbodies such as lakes or estuaries, except that the scale of the problems may be larger for lagoons than for other waterbodies with greater water exchange. Given the difficulties in lagoon restoration, some attention should also be given to the creation of new lagoon habitat, as was inadvertently achieved in the case of the Ballyteige control site.

6.1.1 Fauna

Despite the deterioration in water quality in Lady's Island Lake, this lagoon is among the largest lagoons in Ireland, and the conservation value based on the shallow water fauna recorded from the sweep nets is still good. However, the benthic fauna is impoverished and is of very low conservation value.

Lagoonal specialist fauna is highly tolerant of fluctuations in many environmental variables, such as salinity, temperature, pH, turbidity and nutrient levels. Many animals cannot withstand these fluctuations, which is why they are outcompeted by the lagoonal specialists.

Past variations in the fauna of the lagoon have largely been explained by variations in salinity caused by breaching of the barrier. More recent changes may be the result of the deterioration in water quality, but it is hard to distinguish between the effects of water quality and the frequent changes in salinity due to current management practices in the lake.

6.1.2 Remedial techniques

It is clear from the nutrient studies carried out as part of this research project that the biggest threat to Lady's Island Lake, and many other lagoons in the country and throughout Europe, is the inflow of excessive nutrients to these waterbodies. The literature survey has shown that this has been recognised since at least 1983, and has been advised against, but the inflow has continued since that date.

Various relatively easy remedial actions can be taken to address this threat (see Chapter 5), the most obvious of which is to enforce the regulations. This seems to be difficult to achieve, but it seems unfair to place all the blame on farmers. The EU Nitrates Directive went a long way towards improving water quality in Irish waters, but the Irish government applied for a derogation. The European Commission granted the derogation and did so five times consecutively. Traditionally, the barrier of the lagoon has been breached almost annually,in order to control water levels; now there is a plan to install a permanent pipe in the barrier.

However, it seems that the design of this permanent pipe may not allow enough saltwater to enter the lagoon and thereby maintain the "brackish nature" of the lagoon,which is listed as a priority habitat under the Habitats Directive and which also happens to be the biggest and best example of a coastal lagoon in Ireland.

6.1.3 Restoration plan

Any restoration plan will have to be site specific, but it will be difficult to predict the effectiveness of any plan and the resulting improvement in water quality and conservation status of the lagoon. It is strongly suggested that a demonstration site is first designed and tested.

A suitable site will need to be found, with receptive landowners. The two sites that we visited (following the workshop), each of which has a feeder stream entering the northern end of the lagoon, would appear to be good candidates. The larger of the two streams certainly appeared to have very low water quality, based on appearance alone, and a combination of techniques could be applied in order to improve the water quality of this stream. In particular, it would appear to be a good candidate for an ICW and associated buffer zones. The farms in the catchment could be visited and advised about environmentally friendly farming practices. Eventually, the restoration plan would have to be a locally led group scheme, similar to the Anne River Project, and speakers at the workshop, such as Jim Hurley, Paul Moore, Rory Harrington and Féidhlim Harty, would make very good committee members for the demonstration site. Ideally, this demonstration site would be open to the public and become a local amenity, education centre and tourist attraction, similar to the Harper's Island bird reserve in Cork Harbour.

References

AQUAFACT and Roden Oliver Associates, 2017. *Coastal Lagoon Monitoring Programme 2016–2017. Volume II. Monitoring and Assessment of Irish Lagoons for the purpose of the EU Water Framework Directive*. Unpublished report on behalf of the Environmental Protection Agency, Johnstown Castle, Ireland.

Bates, R., 1977. *An Ecological Survey of a Brackish Lagoon. Our Lady's Lake, Co. Wexford.* Unpublished BSc Thesis, Department of Zoology, University College Dublin, Ireland.

Berthold, M. and Campbell, D.A., 2021. Restoration, conservation and phytoplankton hysteresis. *Conservation Physiology* 9: p.coab062.

Berthold, M. and Schumann, R., 2020. Phosphorus dynamics in a eutrophic lagoon: uptake and utilization of nutrient pulses by phytoplankton. *Frontiers in Marine Science* 7: 1–15.

Bormann, F.H. and Likens, G.E., 1979. Catastrophic disturbance and the steady state in northern hardwood forests: a new look at the role of disturbance in the development of forest ecosystems suggests important implications for land-use policies. *American Scientist* 67: 660–69.

Bormann, F.H. and Likens, G.E., 1981. *Pattern and Process in a Forested Ecosystem*. Springer, New York, NY.

Boynton, W., Murray, L., Hagy, J. and Stokes, C., 1996. A comparative analysis of eutrophication patterns in a temperate coastal lagoon. *Estuaries* 19: 408–421.

Braskerud, B.C., 2002. Factors affecting phosphorus retention in small, constructed wetlands treating agricultural non-point source pollution. *Ecological Engineering* 1: 41–61.

Carroll, P., Harrington, R., Keohane, J. and Ryder, C., 2005. Water treatment performance and environmental impact of integrated constructed wetlands in the Anne Valley watershed, Ireland. In Dunne, E.J., Reddy, K.R. and Carton, O.T. (eds), *Nutrient Management in Agricultural Watersheds: A Wetlands Solution*. Wageningen Academic Publishers, Wageningen, Netherlands, pp. 207–217.

Clarke, K.R. and Warwick, R.M., 2001. *Change in Marine Communities: An Approach to Statistical Analysis and Interpretation*. Second edition. Primer-E Ltd, Plymouth, UK.

Corine, 2018. European Corine land use mapping. Available online: https://land.copernicus.eu/en/products/corine-land-cover/clc2018 (accessed 14 March 2024).

Costello, C.J., 1989. Wetlands treatment of dairy animal wastes in Irish drumlin landscape. In Hammer, D.A. (ed), *Constructed Wetlands for Wastewater Treatment: Municipal, Industrial, and Agricultural*. Lewis Publishers, Chelsea, UK, p. 702.

Derolez, V., Bec, B., Munaron, D., Fiandrino, A., Pete, R., Simier, M., Souchu, P., Laugier, T., Aliaume, C. and Malet, N., 2019. Recovery trajectories following the reduction of urban nutrient inputs along the eutrophication gradient in French Mediterranean lagoons. *Ocean and Coastal Management* 171: 1–10.

De Wit, R., Rey-Valette, H., Balavoine, J., Oisse, V. and Lifran, R., 2017. Restoration ecology of coastal lagoons: new methods for the prediction of ecological trajectories and economic valuation. *Aquatic Conservation: Marine and Freshwater Ecosystems* 27: 137–157.

De Wit, R., Stal, L.J., Lomstein, B.A., Herbert, R.A., van Gemerden, H., Viaroli, P., *et al*., 2001. ROBUST: the role of buffering capacities in stabilising coastal lagoon ecosystems. *Continental Shelf Research* 21: 2021–2041.

Dunne, E.J., Culleton, N., O'Donovan, G., Harrington, R. and Daly, K., 2005a. Phosphorus retention and sorption by constructed wetland soils in Southeast Ireland. *Water Research* 39: 4355–4362.

Dunne, E.J., Culleton, N., O'Donovan, G., Harrington, R. and Olsen, A.E., 2005b. An integrated constructed wetland to treat contaminants and nutrients from diary farmyard dirty water. *Ecological Engineering* 24: 221–234.

Grillas, P., Derolez, V., Bec, B., Ximenes, M.C. and Giraud, A., 2016. *Adaptation des Grilles DCE de Qualité Nutriments et Phytoplancton (Abondance et Biomasse) pour les Lagunes Oligo et Mésohalines*. French National Agency for Water and Aquatic Environments (ONEMA), Paris.

GSI (Geological Survey Ireland), 2018. Open topographic lidar data. Available online: https://data.gov.ie/dataset/open-topographic-lidar-data (accessed 30 January 2024).

Gulati, R., 1990. Structural and grazing responses of zooplankton community to biomanipulation of some Dutch water bodies. *Hydrobiologia* 200: 99–118.

Håkanson, L. and Bryhn, A.C., 2008. Goals and remedial strategies for water quality and wildlife management in a coastal lagoon – A case study of Ringøbing Fjord, Denmark. *Journal of Environmental Management* 86: 498–519.

Håkanson , L., Bryhn, A. and Eklund, J., 2007. Modelling phosphorus and suspended particulate matter in Ringkøbing Fjord in order to understand regime shifts. *Journal of Marine Systems* 68: 65–90.

Hansen, A.T., Campbell, T., Cho, S.J. and Wilcock, P., 2021. Integrated assessment modelling reveals near-channel management as cost-effective to improve water quality in agricultural watersheds. *Proceedings of the National Academy of Sciences of the USA* 118: e2024912118.

Harrington, R. and Ryder, C., 2002. The use of integrated constructed wetlands in the management of farmyard runoff and wastewater. *Proceedings of the National Hydrology Seminar on Water Resources Management Sustainable Supply and Demand*, Tullamore, 19 November, Co. Offaly, pp. 5–63.

Harrington, R., Dunne, E.J., Carroll, P., Keohane, J. and Ryder, C., 2005. The concept, design and performance of integrated constructed wetlands for the treatment of farmyard dirty water. In Dunne, E.J., Reddy, K.R. and Carton, O.T. (eds), *Nutrient Management in Agricultural Watersheds: A Wetlands Solution*. Wageningen Academic Publishers, Wageningen, Netherlands, pp. 179–188.

Healy, B., 1997. Long-term changes in a brackish lagoon, Lady’s Island Lake, south-east Ireland. *Proceedings of the Royal Irish Academy* 97B: 33–51.

Healy, B., 1999a. *Survey of Irish coastal lagoons 1996 and 1998*. Vol. 1 Part 1. Background, description and summary of the surveys. Dúchas, Dublin.

Healy, B., 1999b. *Survey of Irish Coastal Lagoons 1996 and 1998*. Vol. 1 Part 2. Lagoons surveyed in 1998. Dúchas, Dublin.

Healy, B., 2003. Coastal lagoons. In Otte, M.L. (ed), *Wetlands of Ireland: Distribution, Ecology, Uses and Economic Value*. University College Dublin Press, Dublin, pp. 44–78.

Kelleghan, D.B., Hayes, E.T., Everard, M., Keating, P., Lesniak-Podsiadlo, A. and Curran, T.P., 2021. Atmospheric ammonia and nitrogen deposition on Irish Natura 2000 sites: implications for Irish agriculture. *Atmospheric Environment* 261: 118611.

Larsen, S.U., Jørgensen, U. and Lærke, P.E., 2018. Biomass yield, nutrient concentration and nutrient uptake by SRC willow cultivars grown on different sites in Denmark. *Biomass and Bioenergy*. 116: 161–170.

Moss, B., 1994. Brackish and freshwater shallow lakes – different systems or variations on the same theme? *Hydrobiologia* 275: 1–14. https://doi.org/10.1007/BF00026695.

Newman, J.M., Clausen, J.C. and Neafsey, J.A., 2000. Seasonal performance of a wetland constructed to process dairy milkhouse wastewater in Connecticut. *Ecological Engineering* 14: 181–198.

Nilsson, H.C. and Rosenberg, R., 1997. Benthic habitat quality assessment of an oxygen stressed fjord by surface and sediment profile images. *Journal of Marine Systems* 11: 249–264.

O’Boyle, S., Wilkes, R., McDermott, G., Longphuirt, S.N. and Murray, C., 2015. Factors affecting the accumulation of phytoplankton biomass in Irish estuaries and nearshore coastal waters: a conceptual model. *Estuarine, Coastal and Shelf Science* 155: 75–88.

Oliver, G.A., 2005. Seasonal changes and Biological classification of Irish coastal lagoons. PhD Thesis. University College Dublin, Dublin. Available online: www.irishlagoons.com/wp-content/uploads/2019/07/PhD-Seasonal-Changes-and-Biological-Classification-of-Irish-Coastal-Lagoons.pdf (accessed 4 January 2024).

Pearson, T.H. and Rosenberg, R., 1978. Macrobenthic succession in relation to organic enrichment and pollution of the marine environment. *Oceanography and Marine Biology – An Annual Review* 16: 229–311.

Pérez-Ruzafa, A., Campillo, S., Fernández-Palacios, J.M., García-Lacunza, A., García-Oliva, M., Ibañez, H., Navarro-Martínez, P.C., Pérez-Marcos, M., Pérez-Ruzafa, I.M., Quispe-Becerra, J.I., Sala-Mirete, A., Sánchez, O. and Marcos, C., 2019. Long-term dynamic in nutrients, chlorophyll *a*, and water quality parameters in a coastal lagoon during a process of eutrophication for decades, a sudden break and a relatively rapid recovery. *Frontiers in Marine Science* 6: 26.

Reddy, G.B., Hunt, P.G., Phillips, R., Stone, K. and Grubbs, A., 2001. Treatment of swine wastewater in marsh-pond-marsh constructed wetlands. *Water Science and Technology* 44: 545–550.

Redfield, A.C., 1934. On the proportions of organic derivatives in sea water and their relation to the composition of plankton. In *James Johnstone Memorial Volume*. Liverpool University Press, Liverpool, UK, pp. 176–192.

Rhoads, D.C. and Cande, S., 1971. Sediment profile camera for in situ study of organism-sediment relations. *Limnology and Oceanography* 16: 110–114.

Rhoads, D.C. and Germano, J.D., 1986. Interpreting long-term changes in benthic community structure: a new protocol. *Hydrobiologia* 142: 291–308.

Rhoads, D.C., Aller, R.C. and Goldhaber, M., 1977. The influence of colonising benthos on physical properties and chemical diagenesis of the estuarine seafloor. In Coull, B.C. (ed), *Ecology of Marine Benthos*. University of South Carolina Press, Columbia, SC, pp. 113–138.

Roden, C.M. and Oliver, G.A., 2012. *Monitoring and Assessment of Irish Lagoons for the Purpose of the EU Water Framework Directive, 2011.* Parts 1 and 2. Unpublished report on behalf of the Environmental Protection Agency, Johnstown, Ireland.

Roden, C., Murphy, P. and Ryan, J., 2020. *Benthic Vegetation in Irish Marl Lakes: Monitoring Habitat 3140 Condition 2011 to 2018. Irish Wildlife Manuals, No. 124*. National Parks and Wildlife Service, Department of Housing, Local Government and Heritage, Ireland.

Roden, C., Murphy, P. and Ryan, J.B., 2021. *A Study of Lakes With Slender Naiad (Najas flexilis). Irish Wildlife Manuals, No. 132*. National Parks and Wildlife Service, Department of Housing, Local Government and Heritage, Ireland.

Schallenberg, M., Goff, J. and Harper, M.A., 2012. Gradual, catastrophic and human induced environmental changes from a coastal lake, southern New Zealand. *Sedimentary Geology* 273: 48–57.

Scheffer, M., 2004. *Ecology of Shallow Lakes*. Kluwer Academic Publishers, Amsterdam.

Scholz, M., Harrington, R., Carroll, P. and Mustafa, A., 2007. The integrated constructed wetlands (ICW) concept. *Wetlands* 27: 337–354.

Tannian, C., 2013. Will the Water Framework Directive protect Lady's Island Lake, a lagoon in Co. Wexford? MSc Thesis. Galway-Mayo Institute of Technology, Galway, Ireland.

Van der Does, J., Verstraelen, P., Boers, P., Van Roestel, J., Roijackers, R. and Moser, G., 1992. Lake restoration with and without dredging of phosphorus-enriched upper sediment layers. *Hydrobiologia* 233: 197–210.

Viaroli, P., Bartoli, M., Giordani, G., Naldi, M., Orfanidis, S. and Zaldivar, J.M., 2008. Community shifts, alternative stable states, biogeochemical controls and feedbacks in eutrophic coastal lagoons: a brief overview. *Aquatic Conservation: Marine and Freshwater Ecosystems* 18(S1): S105–S117.

Xiaoqing, W., Zizhang, G., Zhen, H. and Jian, Z., 2020. Recent advances in biochar application for water and wastewater treatment: a review. *PeerJ* 8: e9164. https://doi.org/10.7717/peerj.9164.

Abbreviations

AMBI	AZTI Marine Biotic Index
BHQ	Benthic habitat quality
BOD	Biological oxygen demand
CAP	Common Agricultural Policy
CLEAR	Coastal Lagoons: Ecology and Restoration
Corine	Coordination of Information on the Environment
DTM	Digital terrain model
EQR	Ecological quality ratio
EU	European Union
GLAS	Global Loan Agency Services
HAC	Hierarchical agglomerative clustering
ICW	Integrated constructed wetland
LAWPRO	Local Authorities Water Programme
LESS	Low emission slurry spreading
lidar	Light detection and ranging
MDS	Multi-dimensional scaling
NAP	Nitrates Action Plan
NPWS	National Parks and Wildlife Service
OD	Ordnance datum
OPW	Office of Public Works
OSI	Organism–sediment index
SIMPER	Similarity percentages
SIMPROF	Similarity profiling
SPI	Sediment profile imagery
2D	Two dimensional
TN	Total nitrogen
TP	Total phosphorus
WFD	Water Framework Directive
WP	Work package

An Ghníomhaireacht Um Chaomhnú Comhshaoil

Tá an GCC freagrach as an gcomhshaol a chosaint agus a fheabhsú, mar shócmhainn luachmhar do mhuintir na hÉireann. Táimid tiomanta do dhaoine agus don chomhshaol a chosaint ar thionchar díobhálach na radaíochta agus an truaillithe.

Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

Rialáil: Rialáil agus córais chomhlíonta comhshaoil éifeachtacha a chur i bhfeidhm, chun dea-thorthaí comhshaoil a bhaint amach agus díriú orthu siúd nach mbíonn ag cloí leo.

Eolas: Sonraí, eolas agus measúnú ardchaighdeáin, spriocdhírithe agus tráthúil a chur ar fáil i leith an chomhshaoil chun bonn eolais a chur faoin gcinnteoireacht.

Abhcóideacht: Ag obair le daoine eile ar son timpeallachta glaine, táirgiúla agus dea-chosanta agus ar son cleachtas inbhuanaithe i dtaobh an chomhshaoil.

I measc ár gcuid freagrachtaí tá:

Ceadúnú

- Gníomhaíochtaí tionscail, dramhaíola agus stórála peitril ar scála mór;
- Sceitheadh fuíolluisce uirbigh;
- Úsáid shrianta agus scaoileadh rialaithe Orgánach Géinmhodhnaithe;
- Foinsí radaíochta ianúcháin;
- Astaíochtaí gás ceaptha teasa ó thionscal agus ón eitlíocht trí Scéim an AE um Thrádáil Astaíochtaí.

Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

- Iniúchadh agus cigireacht ar shaoráidí a bhfuil ceadúnas acu ón GCC;
- Cur i bhfeidhm an dea-chleachtais a stiúradh i ngníomhaíochtaí agus i saoráidí rialáilte;
- Maoirseacht a dhéanamh ar fhreagrachtaí an údaráis áitiúil as cosaint an chomhshaoil;
- Caighdeán an uisce óil phoiblí a rialáil agus údaruithe um sceitheadh fuíolluisce uirbigh a fhorfheidhmiú
- Caighdeán an uisce óil phoiblí agus phríobháidigh a mheasúnú agus tuairisciú air;
- Comhordú a dhéanamh ar líonra d'eagraíochtaí seirbhíse poiblí chun tacú le gníomhú i gcoinne coireachta comhshaoil;
- An dlí a chur orthu siúd a bhriseann dlí an chomhshaoil agus a dhéanann dochar don chomhshaol.

Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

- Rialacháin dramhaíola a chur i bhfeidhm agus a fhorfheidhmiú lena n-áirítear saincheisteanna forfheidhmithe náisiúnta;
- Staitisticí dramhaíola náisiúnta a ullmhú agus a fhoilsiú chomh maith leis an bPlean Náisiúnta um Bainistíocht Dramhaíola Guaisí;
- An Clár Náisiúnta um Chosc Dramhaíola a fhorbairt agus a chur i bhfeidhm;
- Reachtaíocht ar rialú ceimiceán sa timpeallacht a chur i bhfeidhm agus tuairisciú ar an reachtaíocht sin.

Bainistíocht Uisce

- Plé le struchtúir náisiúnta agus réigiúnacha rialachais agus oibriúcháin chun an Chreat-treoir Uisce a chur i bhfeidhm;
- Monatóireacht, measúnú agus tuairisciú a dhéanamh ar chaighdeán aibhneacha, lochanna, uiscí idirchreasa agus cósta, uiscí snámha agus screamhuisce chomh maith le tomhas ar leibhéil uisce agus sreabhadh abhann.

Eolaíocht Aeráide & Athrú Aeráide

- Fardail agus réamh-mheastacháin a fhoilsiú um astaíochtaí gás ceaptha teasa na hÉireann;
- Rúnaíocht a chur ar fáil don Chomhairle Chomhairleach ar Athrú Aeráide agus tacaíocht a thabhairt don Idirphlé Náisiúnta ar Ghníomhú ar son na hAeráide;
- Tacú le gníomhaíochtaí forbartha Náisiúnta, AE agus NA um Eolaíocht agus Beartas Aeráide.

Monatóireacht & Measúnú ar an gComhshaol

- Córais náisiúnta um monatóireacht an chomhshaoil a cheapadh agus a chur i bhfeidhm: teicneolaíocht, bainistíocht sonraí, anailís agus réamhaisnéisiú;
- Tuairiscí ar Staid Thimpeallacht na hÉireann agus ar Tháscairí a chur ar fáil;
- Monatóireacht a dhéanamh ar chaighdeán an aeir agus Treoir an AE i leith Aeir Ghlain don Eoraip a chur i bhfeidhm chomh maith leis an gCoinbhinsiún ar Aerthruailliú Fadraoin Trasteorann, agus an Treoir i leith na Teorann Náisiúnta Astaíochtaí;
- Maoirseacht a dhéanamh ar chur i bhfeidhm na Treorach i leith Torainn Timpeallachta;
- Measúnú a dhéanamh ar thionchar pleananna agus clár beartaithe ar chomhshaol na hÉireann.

Taighde agus Forbairt Comhshaoil

- Comhordú a dhéanamh ar ghníomhaíochtaí taighde comhshaoil agus iad a mhaoiniú chun brú a aithint, bonn eolais a chur faoin mbeartas agus réitigh a chur ar fáil;
- Comhoibriú le gníomhaíocht náisiúnta agus AE um thaighde comhshaoil.

Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- 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 um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

Treoir, Ardú Feasachta agus Faisnéis Inrochtana

- Tuairisciú, comhairle agus treoir neamhspleách, fianaise-bhunaithe a chur ar fáil don Rialtas, don tionscal agus don phobal ar ábhair maidir le cosaint comhshaoil agus raideolaíoch;
- An nasc idir sláinte agus folláine, an geilleagar agus timpeallacht ghlan a chur chun cinn;
- Feasacht comhshaoil a chur chun cinn lena n-áirítear tacú le hiompraíocht um éifeachtúlacht acmhainní agus aistriú aeráide;
- Tástáil radóin a chur chun cinn i dtithe agus in ionaid oibre agus feabhsúchán a mholadh áit is gá.

Comhpháirtíocht agus Líonrú

- Oibriú le gníomhaireachtaí idirnáisiúnta agus náisiúnta, údaráis réigiúnacha agus áitiúla, eagraíochtaí neamhrialtais, comhlachtaí ionadaíocha agus ranna rialtais chun cosaint chomhshaoil agus raideolaíoch a chur ar fáil, chomh maith le taighde, comhordú agus cinnteoireacht bunaithe ar an eolaíocht.

Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

Tá an GCC á bainistiú ag Bord lánaimseartha, ar a bhfuil Ard-Stiúrthóir agus cúigear Stiúrthóir. Déantar an obair ar fud cúig cinn d'Oifigí:

1. An Oifig um Inbhunaitheacht i leith Cúrsaí Comhshaoil
2. An Oifig Forfheidhmithe i leith Cúrsaí Comhshaoil
3. An Oifig um Fhianaise agus Measúnú
4. An Oifig um Chosaint ar Radaíocht agus Monatóireacht Comhshaoil
5. An Oifig Cumarsáide agus Seirbhísí Corparáideacha

Tugann coistí comhairleacha cabhair don Ghníomhaireacht agus tagann siad le chéile go rialta le plé a dhéanamh ar ábhair imní agus le comhairle a chur ar an mBord.

EPA Research

Webpages: www.epa.ie/our-services/research/
LinkedIn: www.linkedin.com/showcase/eparesearch/
Twitter: @EPAResearchNews
Email: research@epa.ie

www.epa.ie