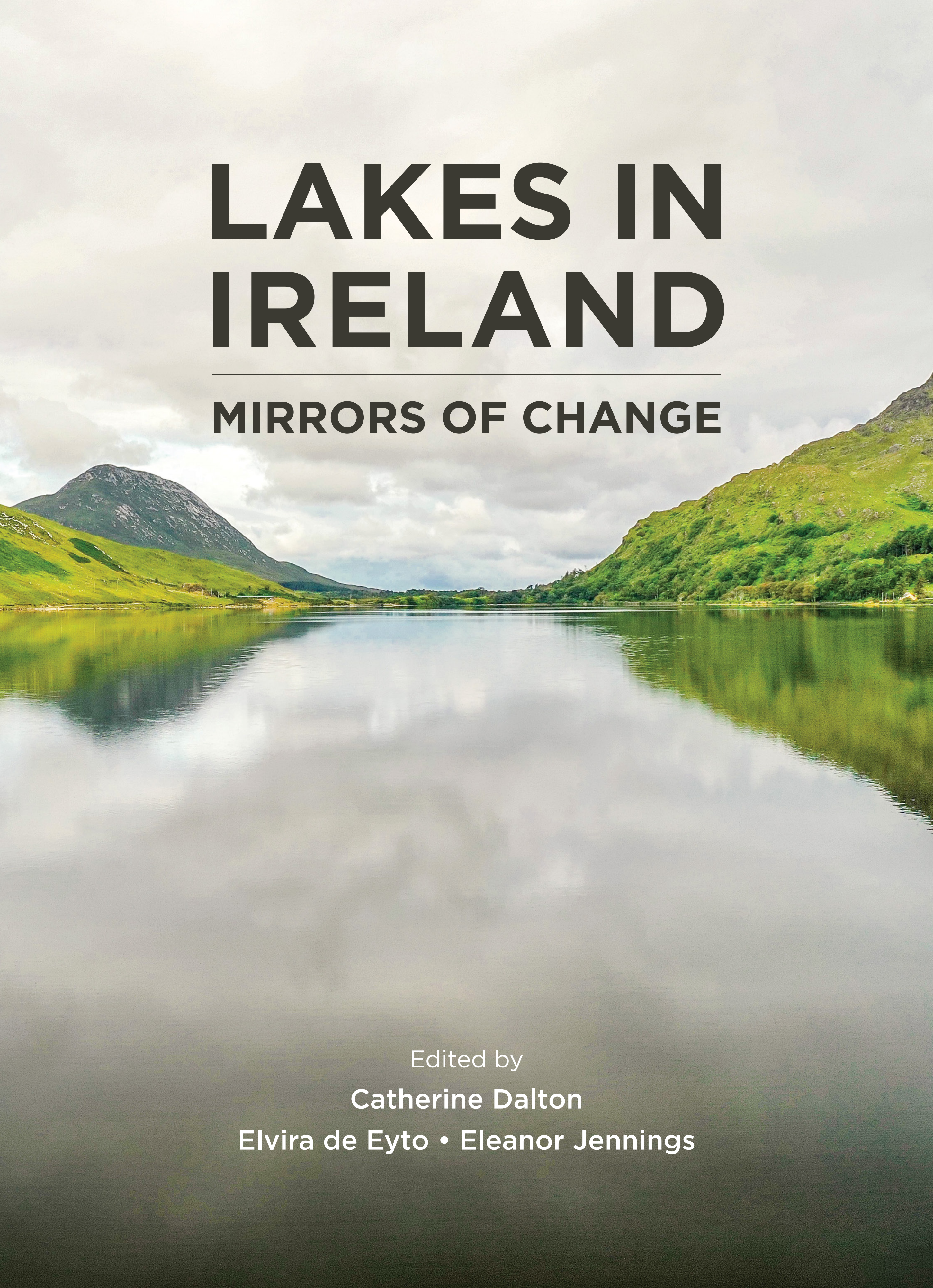

LAKES IN IRELAND

MIRRORS OF CHANGE

Edited by
Catherine Dalton
Elvira de Eyto • Eleanor Jennings

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with contributions from

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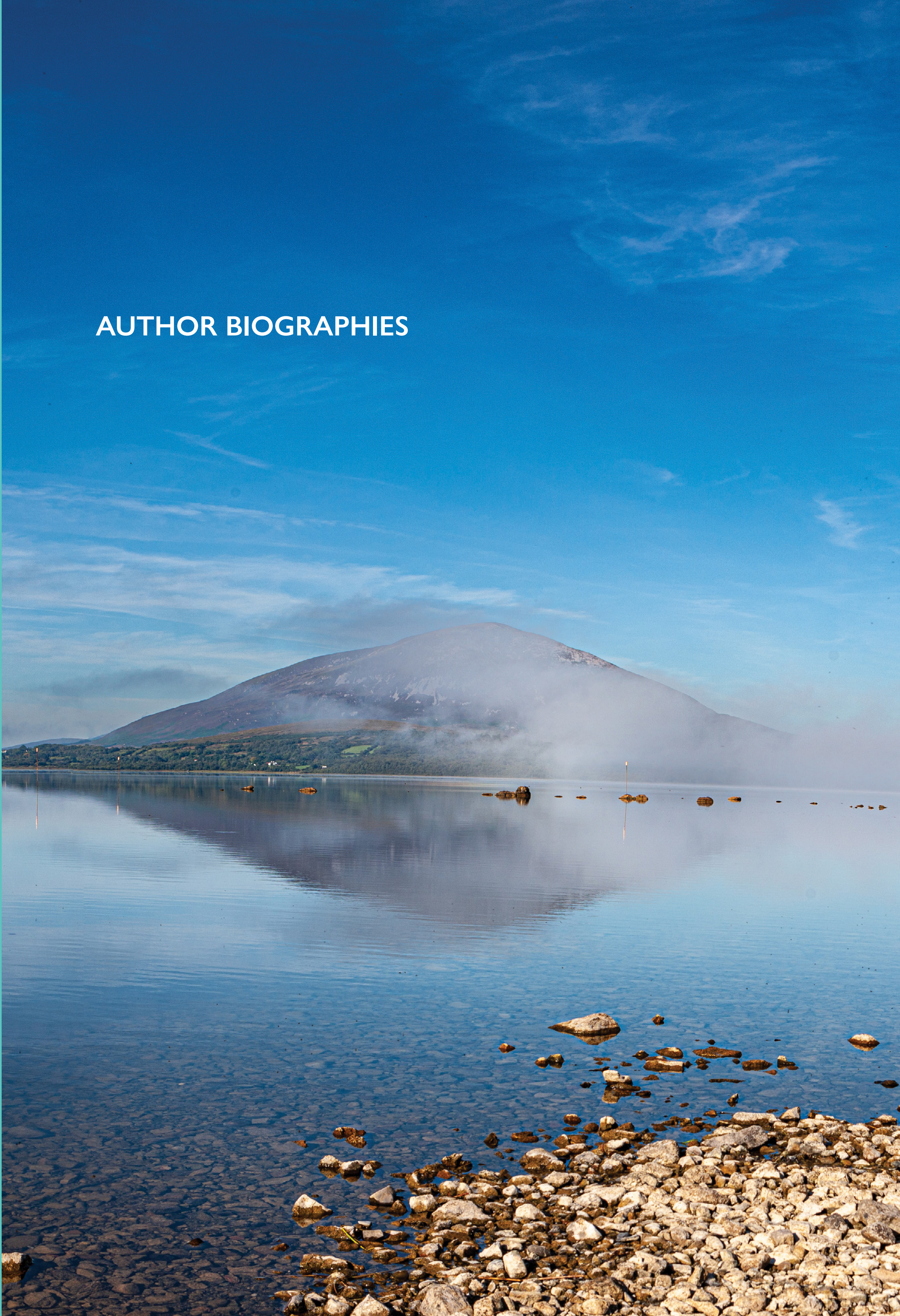

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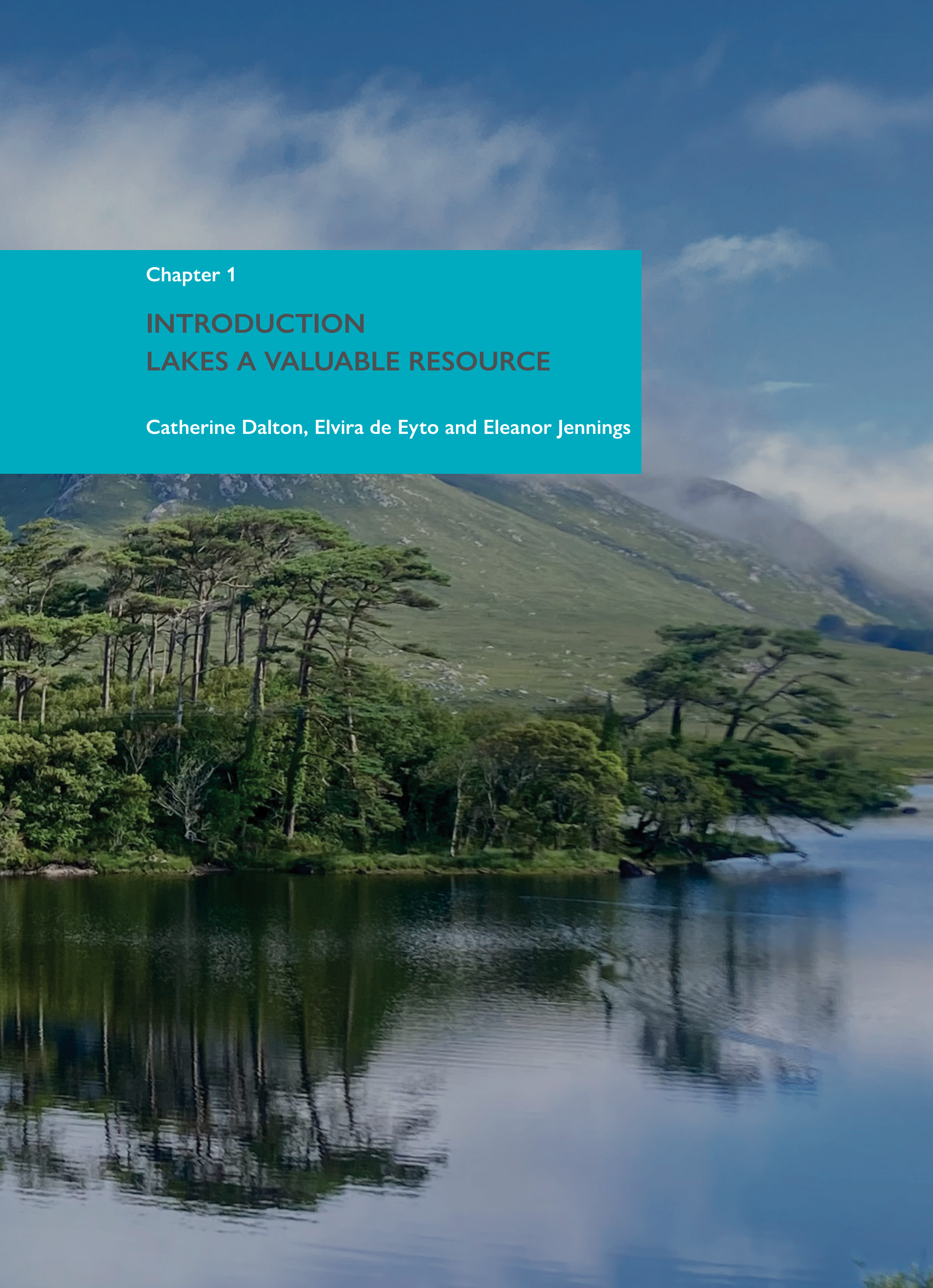
Chapter 1

INTRODUCTION
LAKES A VALUABLE RESOURCE

Catherine Dalton, Elvira de Eyto and Eleanor Jennings



Our lakes provide valued contributions to human life and society on the island of Ireland, contributions that enhance our society culturally, aesthetically, and economically. They are also key ecosystems in their own right and hotspots of biodiversity (Figure 1.1). We study them, fish in them, swim in them, paint them and write about them. Recently, however, lakes in Ireland have been in the news for all the wrong reasons. Lough Neagh was described worldwide as 'dying in plain sight' due to vast algal blooms following a satellite image provided by the European Space Agency (Reid and Emerson, 2023; O'Toole, 2023). With a headline: 'The ticking time bomb of environmental dereliction', similar issues were highlighted in Poulaphouca, Keeldra, Lein and Sheelin, and the lakes of Killarney (O'Connell, 2023). Coastal lake Lough Hyne was also in the news as a result of multiple pressures from disease, poaching, excess nutrients, wild swimmers, kayakers, and tourists (McSweeny, 2023). In contrast, an excerpt from one of the world's longest-running newspaper columns captures some of the essence of why we greatly value lakes.

> On a crisp January morning the sun glows in the reeds and gleams, perhaps, on a pair of mute swans, taking refuge from the whoopers bugling on the big lagoon [Corragaun Lough] next door. Or the peace may yield to a squealing swoop of choughs, bouncing between heights, each beak a bright flash of vermilion. In this remote corner sea-feeding otters come to rinse the salt and fish scales from their fur. Their pawprints begin at the edge of the tide, print a line on the sand before disappearing into a watery ravine in the dunes, then furrow up through mosses and liverworts to the lake [Dooaghtry Lough]. At its moist margins, too, a hand lens finds tiny snails, *Vertigo*-somethings, rare survivors from a chilly antiquity (Viney, 2015).

The divergence between this poetic description of a coastal lake and lagoon and the challenges highlighted in the media in some of our most iconic lakes is poignant. This conundrum is a core feature of this well-timed book

Figure 1.1 Pine Island, Derryclare Lough, Galway. Photo: Ruth Little

which examines how lakes on the island of Ireland are reflections, mirrors, and windows of environmental change. Moreover, lakes are under-researched compared to rivers in scientific exploration and thus this book will help redress the balance.

SO WHY THIS BOOK?

The principal aim of this book is to collect, document and present the findings of, and lessons learnt from lake studies across different geographical settings in Ireland. The book reviews, highlights and celebrates the nature of lakes in Ireland through geography, science, history, ecology, biodiversity, climate, and sustainability. Irish academics and professionals share knowledge and research experiences in twenty-two chapters. The book provides a timely summary of knowledge, takes stock of these valuable resources, and reflects on where we go from here to help respond to uncertain water futures and extreme events projected with climate warming.

The last analogous books with some focus on lake water bodies were published by the Marine Institute in 1998 (Studies of Irish Rivers and Lakes (Moriarty, 1998); Studies in Irish Limnology (Giller, 1998)) as part of the SIL (Society of Limnology) Conference in Dublin. More recently a book on

Irish Rivers was published (Kelly-Quinn and Reynolds, 2020) so a volume on lakes is opportune.

The book is aimed towards practitioners, undergraduates, postgraduates, decision-makers and the general public. The editors were particularly focussed on producing an open access volume to ensure the widest possible reach and impact. This authoritative, peer-reviewed, independently published, open access E-format book is freely downloadable on the Marine Institute Open Access Repository, thanks to our generous sponsors, in particular the National Parks and Wildlife Service, Environment Protection Agency, and Marine Institute. We have included data, accessible text, and plenty of colour illustrations and have opted to include common and scientific names for plants and animals. Each chapter is followed by a list of references should readers wish to follow up on particular topics.

Complacency

Lakes hold a special place in the hearts of many, as most people love the serene beauty they offer. On the island of Ireland, we are fortunate to have numerous lakes, large and small, dotting the landscape. Relative to the rest of Europe, Ireland's waterbodies were considered pristine due to low population and the lack of industry. This could suggest a complacency of sorts. The unfortunate reality is that we have actively contributed to the pollution of these cherished bodies of water both in the past and today. Flanagan and Toner (1972) were already highlighting the nutrient enrichment of lakes in the early 1970s. Allott et al. (1998) noted that water quality was in decline in regions associated with intensive livestock (cattle, pig, and poultry) but that other areas are generally of high quality. Wood (1998) highlighted the conflicting demands on Lough Neagh in terms of waste disposal, fertiliser runoff, angling, water sports and sand extraction, topics which are still central to current water quality problems today. The problems that have been highlighted in the media and their causes, therefore, are not new.

In the realm of research, rivers have often taken precedence over lakes in Ireland, leaving lakes in relative obscurity. Allott et al. (1998), for example, describe data on lakes as less comprehensive than for rivers. All the authors in this book have worked on lakes in Ireland over the last two to three decades. Each can pinpoint a point in our careers when we recognised that our lakes have unique scientific properties but were under-researched and warranted further examination.

Figure 1.2 Clonee Lough Upper, Kerry. Photo: Ruth Little

LAKE CHARACTERISTICS

Nearly 14,000 lakes and ponds are scattered across the island of Ireland, predominantly along the western Atlantic seaboard (Dalton, 2018) (Table 1.1). They range from tranquil ponds on peatland (Figure 1.2) to large rich limestone lakes and include Lough Neagh, the most expansive area of fresh water in Ireland and Britain. The majority of the world's lentic or still waterbodies are small: over 95% are less than 10 ha (0.1 km^2) and this is true also for the island of Ireland. Small lakes or ponds can be defined as those with a surface area of <0.05 km^2 or 5 ha (Richardson et al., 2022). Less than 2% of lakes exceed 0.5 km^2 or 50 hectares (which must be monitored according to EU regulations) thus smaller lakes (or 98% of the population of lakes and ponds) are excluded from statutory monitoring. Small lakes and ponds dominate the western regions, yet their quality is not known and thus the overall value and the contribution of these bodies of water to biodiversity and ecosystem services is potentially being underestimated (Figure 1.3).

Figure 1.3 Lough Formal, Derrygonnelly Co. Fermanagh. Photo: Robert Rosell

Table 1.1 Number of lakes in Ireland (after Dalton 2018)

Area km²	All-Island	Republic of Ireland (RoI)	Northern Ireland (NI)
0.0001	3640	3003	637
0.001	5854	5404	450
0.01	3443	2885	558
0.1	799	799	0
1	97	94	3
10	17	14	3
100	5	3	2
Total no. Lakes	**13855**	**12205**	**1653**

Most people possess a rudimentary understanding of lake geography, recognizing their surface area, shallow (littoral) waters, and deep (profundal) regions. Lakes vary greatly in their physical dimensions, from circular shapes to intricate dendritic (branched) formations. Furthermore, the duration water resides within lakes spans a wide time spectrum, ranging from mere days to enduring years, contingent upon a multitude of factors, including but not limited to climatic patterns, hydrological dynamics, and size. Lake typology (types) refers to the categorization of lakes based on various characteristics such as their size, shape, depth, water chemistry, ecological features, and geographical location (and specifically alkalinity, area, and depth in Ireland). This classification system helps in identifying common patterns, trends, and relationships among lakes, facilitating comparisons between different bodies of water, and aiding in the formulation of general principles about lake ecology, hydrology, and dynamics.

LAKE STRUCTURE

Most people are not familiar with the fact that lakes themselves have an internal structure. This structure is based on layers of different water temperature and density, and the seasonal mixing of these layers. Traditional views on the physical or hydrological structure of lakes have been strongly influenced by a northern hemisphere continental paradigm of summer layering or stratification, winter mixing, and isolation of the water column during periods of winter ice. This simple model does not work as well for lakes in Ireland where there is seldom ice cover, and the water column is subject to frequent mixing through the force of prevailing winds (Figure 1.4). The water column in lakes can stratify thermally during warmer calm conditions. A stratified lake is considered to have three well-defined layers: 1. a turbulent upper layer (the epilimnion), 2. a middle layer that is stable (the metalimnion), and 3. quiescent (dormant) lower waters (the hypolimnion) (Wüest and Lorke, 2009). The thermocline is the depth of the maximum change in temperature or density over a one-metre depth.

Mixing events, whether seasonal such as in winter, or during the stratified period in summer due to storms, have a major effect on the lake's thermal structure, with depth of stratification between the upper epilimnion and deeper hypolimnion in even the deeper lakes subject to disruption at any time. The depth and periodicity of mixing are highly variable. On the other hand, even shallow Irish lakes can stratify in the summer after only a few days with low wind speeds. Short periods of stratification can have profound effects on the biogeochemical and productivity cycles, especially if these lead to low oxygen (anoxia) at the interface of the lake bed and water. This can then lead to the release of nutrients from the lake sediment. When combined with saltwater influxes in coastal areas this introduces a denser layer of water into the lake, disrupting this stratification. This denser

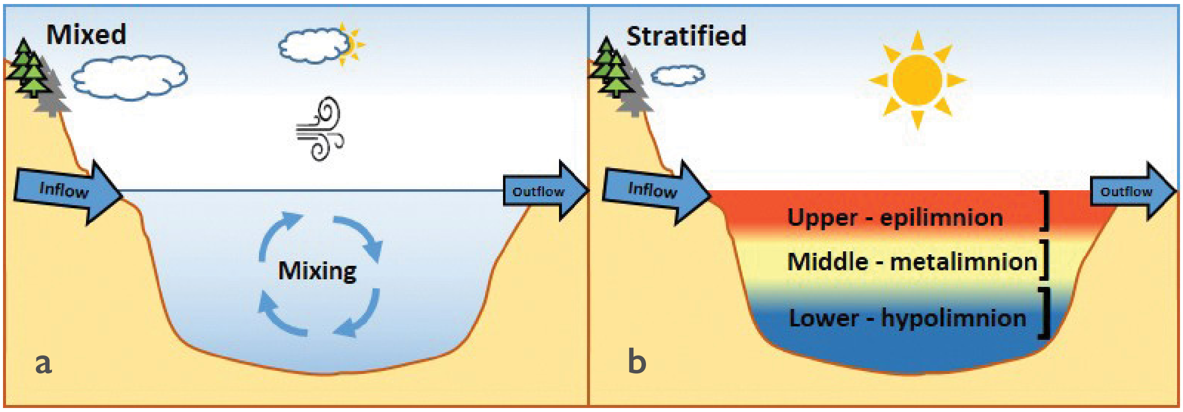


Figure 1.4 (a) Lake fully mixed in winter, with no ice cover; (b) Lake stratified in summer during warm calm conditions into three layers: the upper epilimnion, the middle metalimnion and the lower hypolimnion.

saltwater layer tends to sink below the freshwater layers altering the thermal stratification of the lake.

The interaction between nutrient status and physical structure has significant implications for the ecological status of lakes (Jeppesen et al., 2007). Reduced oxygen concentrations in the deeper profundal water of lakes have a direct impact on the organisms that live there (Bazzanti et al., 2012). The influence of physical structure is not, however, confined to the open water of a lake, but also to the physical attributes of the shallower, littoral, areas.

LAKE LIFE

Lakes exhibit a fascinating blend of physical, chemical, and biological traits facilitating natural biodiversity, nutrient, and water cycling, and providing cultural services. Lake waters are complemented by fringing (riparian) vegetation that plays a crucial role in maintaining their delicate balance (Figure 1.5).

In this book, we delve into the principal features of these water bodies which provide essential roles as biodiversity repositories, fish spawning, nursery, nesting and migration spaces (Figure 1.6) and carbon-rich ecosystems. Lakes, with their varied characteristics and ecosystem services, play a pivotal role in the Irish environment. They are not merely physical bodies of water and biodiversity sanctuaries; they are islands within the landscape, each possessing a unique identity and significance. They are also inspirational and mysterious

Figure 1.5 Dromore Lough, Clare. Photo: Ruth Little

entities that add value to surrounding landscapes. The calming stillness of ponds and lakes is relaxing and for many therapeutic. Beyond their habitat value and aesthetic allure, however, lakes face ongoing challenges such as pollution, and fluctuating water levels.

MANAGEMENT OF LAKES

Catchment or drainage areas can be an ambiguous geographical entity for many people to contemplate, yet many of us inhabit, work within, and exert an impact on drainage water, thereby affecting lakes themselves. Catchments are complex hydrological, biophysical, chemical, environmental, and ecological entities and interact with political, socioeconomic, and cultural influences. Nature, including water, knows no boundaries, and the island of Ireland is essentially one biogeographical unit.

Common challenges are faced in the Republic of Ireland (RoI) and Northern Ireland (NI) in relation to shared river catchments, lakes, and water sources. The RoI and NI share 11 cross-border river basins (Newry, Fane,

Figure 1.6 Great crested grebe nesting in emergent vegetation. Photo: Thomas O'Flynn

Glyde, Dee, Neagh, Lower Bann, Erne, Foyle, Swilly, and Donagh-Moville), and the international border traverses at least 57 lakes and ponds. This adds complexity in terms of water governance, particularly in the border regions. The only cross-border agencies are Waterways Ireland and the Loughs Agency which partly manage shared water resources. There is existing collaboration on surface waters under the EU Water Framework Directive (WFD), however, there are no shared policies on groundwater and the supply of treated water and disposal of waste water (NESC, 2021),

The significance of water bodies, including lakes, is central to river basin management planning. EU member states implement the WFD through River Basin Management Plans in six-year cycles (1st cycle 2009-2015, 2nd cycle 2018-2021, and 3rd cycle 2022-2027). Consultations on the third cycle took place in 2021-22 north and south of the border and have just been published in the south (DHLGH, 2024b).

The current biodiversity and climate crises that are affecting our planet have led to calls for EU member states to restore degraded habitats, prioritise high nature value areas, and develop new protected areas to help nature on a path to recovery (EC 2020). The European Union's regulation on nature restoration (Nature Restoration Law) as part of the Biodiversity Strategy for 2030, requires member states to establish and implement measures to restore at least 20% of the EU's land and sea areas by 2030 (DHLGH, 2024a). Aquatic ecosystems play an important role in ecological connectivity and could qualify for strict protection thus adding a layer of importance to our understanding of Ireland's lakes. Additionally, consideration of Ireland as a single river basin district (NESC, 2021) would serve to further integrate collaboration and productive partnerships for water and nature.

LAKE NAMES

Lakes are islands in terrestrial landscapes and before we embark on this journey exploring lakes in Ireland, it is important to appreciate the diversity of lake terminology; pond, pool, tarn, reservoir, lagoon, waterhole, inland sea, loch, lochan, linn, lough, meres, and turlough. From the familiar lough to the less-known mere, each term adds a unique nuance to the rich lexicon of lakes in Ireland. From Loch Cliabháin to Loughanaveeny, the positioning of Lough in lake names reflects historical and linguistic nuances, while the names themselves reflect the connection between language and landscape. Lough is how the Gaelic word Loch was written when the English came to Ireland. They incorporated the 'gh' sound to match how it was pronounced and lough became the standard representation of Loch in English in Ireland. In Gaelic, Loch generally precedes the lake name (Loch Abhainn Fhia), however, Lough is often found in compound form (e.g., Loughanaveeny, Doolough), before and after lake names (e.g. Lough Cleevaun, Dromore Lough). In the case of Loughanaveeny, the form is closest to the anglicisation of the Irish original while Doolough/Dúloch represents a closed compound category made up of an adjective and noun. Interestingly lough and lake are not interchangeable, lough does not mean lake, it is simply derived from a word that means lake in another language.

CHAPTER OVERVIEW

As we unfold the chapters ahead, the contributing authors delve into specific facets of Ireland's lakes. From glacial lake origins and invisible lake sediment archives to biodiversity conservation efforts and cultural history, this book aims to be a comprehensive exploration of these aquatic wonders.

Catherine Delaney invites readers on a journey through the frosty annals of Irish lake formation in Chapter 2. This chapter unravels the mysteries of how glaciers sculpted the landscape creating voids which filled with glacial sediments and water, and detailing key lake types such as proglacial and moraine-dammed lakes and now extinct palaeo (ancient) lakes. The influences of glaciers, geomorphology, and fluvial processes are explored, providing a comprehensive understanding of the icy histories that shaped Ireland's lakes.

In Chapter 3, **Catherine Dalton** and co-authors unearth the research trajectory of the silent narratives hidden within lake sediments. Revealing the process of environmental reconstruction, this chapter delves into Holocene (11.7 K years) and more recent Industrial and Anthropocene (post-1850 AD) reconstructions, showcasing the important role of lake sediments. From sediment signals (proxies) to the phases of research, readers gain insights into scientific advances and the information preserved in these invisible lake archives.

Ken Irvine and **Konstantina Katsanou** guide us through the pathways of lake hydrology in Chapter 4. From drainage areas and catchments to surface/groundwater connections, this chapter outlines the dynamic interplay of lake water levels and flow. Hydrological and morphological status, along with key hydromorphological pressures, are detailed, providing a holistic view of these interconnected water systems.

Emma Gray and **Heather Lally** immerse readers in the dynamic world of biodiversity in Ireland's lakes in Chapter 5. The chapter dives into the trophic dynamics, food webs, and the significance of small ponds. Highlighting species from the micro- to macro-scopic scale underscores the importance of lakes in Ireland for biodiversity and demonstrates how some species are under threat due to habitat loss, disease, catchment modifications and climate change.

In Chapter 6, **Fiona Kelly** and her co-authors explore the balance of lake fish populations and the delicate equilibrium they maintain. Since the 12th century, native and introduced species have coexisted under human control. Yet, this balance is under threat from pollution, barriers, and invasive species. The chapter includes new fish distribution maps. The diverse methods of monitoring fish, the categories of angling, and the regulations that govern lake fish are outlined.

When is a turlough a lake? **Owen Naughton** and co-authors unravel the unique tale of turloughs in Chapter 7. These internationally significant ephemeral freshwater habitats, face pressures from pollutant pathways and eutrophication. From defining their distribution to exploring hydrogeology and ecology, this chapter sheds light on the disappearing act of turloughs amid limestone landscapes.

Geoff Oliver and co-authors lead readers to the edge of the land in Chapter 8. Coastal lakes and lagoons, with their brackish waters, are shaped by coastal weather conditions and human modifications. The chapter provides details on their distribution, unique flora and fauna and insights into their conservation value.

Mary Kelly-Quinn explores remote upland lake habitats in Chapter 9. Positioned above 150m in moorland or heathland, these lakes face threats from sheep grazing and afforestation. This chapter navigates through the challenging water chemistry environment, exploring the unique biota and emphasizing the importance of conservation in these isolated settings.

Cilian Roden and **Áine O'Connor** guide readers through Ireland's most unique lakes designated under the EU Habitats Directive Annex I in Chapter 10. Spanning oligotrophic, mesotrophic, and naturally eutrophic and dystrophic waters, the chapter delves into the distribution of these distinctive lakes, some of the best-known examples, their conservation status, and scrutinizes their challenges.

Join **Deirdre Tierney** in Chapter 11 as she navigates the health of lake waters and the historical journey of Irish lake monitoring, from the 1970s to preparing for the WFD in 2000. Lakes, exceeding 50 hectares or associated with protected areas or drinking water abstraction, undergo assessment and reporting. The chapter outlines lake assessment tools, trophic status, phosphorus levels, and key issues from lake characterisation to nutrient enrichment.

Discover the role of lakes as environmental sentinels in Chapter 12, where **Elvira de Eyto** and co-authors reveal the capacity of lakes to capture signals of change. Data from six lakes (Sheelin, Leane, Neagh, Lower Erne, Carra, and Feeagh) integrate impacts from land use modification, climate warming, and pollution. Long-term data, collected consistently over decades, offers a unique appreciation of environmental changes.

Frances Lucey and co-authors shed light on the vulnerability of Ireland's aquatic environments to Invasive Alien Species (IAS) in Chapter 13. Framed within the EU IAS risk assessment/regulation approach, the chapter traverses the history, geography, and establishment of IAS. Explore their spread in Irish lakes, the impacts they pose, and the ongoing management efforts.

In Chapter 14, **Eleanor Jennings** and co-authors evaluate the consequences of climate warming on lakes. From flooding and droughts to sediment erosion and pollutant transport, lakes face the brunt of more frequent extreme events. The chapter explores projected impacts on lake physics, biogeochemistry, and biota and paves the way for understanding the future of lakes in a changing climate.

Michal Potterton unveils the historical use of lakes in Chapters 15 and 16, from prehistory to medieval times where lakeshores have been hubs of human settlement. These chapters explore extensive evidence of lakeshore habitations through archaeological studies and underwater archaeology, offering a comprehensive understanding of early human-water interactions.

In Chapter 17, **Catherine Dalton** and **Paul O'Brien** dip into some of the tangible and intangible cultural histories of lakes. Acting as natural focal points, lakes inspire and sometimes provoke fear. The chapter explores a range of cultural snapshots through archival records, folklore commissions, and news media, illuminating the multifaceted nature of links between people and lakes.

Embark on a journey with **Catherine Dalton** and co-authors as they delve into the role of lakes as natural amenities in Chapter 18. The natural habitats of lakes offer physical as well as emotional health benefits to people who engage with them. This chapter reviews recreation provision and services and considers the consequences for lake habitats, wildlife, and water quality.

In chapter 19, **Triona McGrath** and co-authors provide a panoramic view of water governance in Ireland. Framed by the WFD, lakes and rivers fall under a three-tiered governance structure involving government departments, national agencies, and local authorities. The chapter explores the roles, responsibilities, and challenges of these governance structures, emphasizing the need for policy coherence in environment and lake management.

Fran Igoe and **Bernie O'Flaherty** outline efforts to foster community engagement in water stewardship in Chapter 20. The chapter showcases examples of voluntary community water groups, water steward roles, and citizen science initiatives illustrating the positive impact of community involvement.

Micheál Ó Cinnéide profiles a community catchment group focused on safeguarding Lough Corrib and ensuring sustainable development in the catchment in Chapter 21. The progression of the group since 2019, its efforts in communication, education, environment, heritage, and recreation are detailed as well as the challenges encountered.

The chapters additionally include a range of case studies and topic highlight boxes, notably birdlife provided by **Tom Cooney** and remote sensing of lakes from **Gary Free**.

In the closing chapter (Chapter 22) the book editors **Catherine Dalton**, **Elvira de Eyto** and **Eleanor Jennings** summarise some of the significant learnings and issues identified by chapter authors. Research gaps are highlighted, and key questions and recommendations identified in earlier chapters are collated.

In summary, lakes and ponds play a vital role in the Irish landscape but are often overlooked relative to rivers. This book summarises the progress made in understanding lakes in Ireland thus far. The optimist might characterize the condition of lakes in Ireland as generally pristine, noting that nearly half of the monitored lakes are in good condition. Conversely, the pessimist directs attention to the 50% that fall short of expectations. By sharing data, research experience, insights, and recommendations on all-island lakes we hope that this book provides readers with an informed summary of current knowledge, and identifies knowledge gaps and recommendations to adequately address future biodiversity and climate challenges.

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Chapter 2

GLACIAL LAKE ORIGINS
ICY HISTORIES

Catherine A. Delaney

SUMMARY

It has been over 11,000 years since a glacier last existed on the island of Ireland. Nevertheless, the impact of former glaciations on our lakes is inescapable and almost every lake in Ireland has a glacial legacy. During the last glaciation, ice covered the entire island. As the ice retreated onshore, vast quantities of meltwater were released, forming lakes along the ice margin wherever bedrock, ice or moraines formed a barrier. Some of these lakes have vanished completely, but many remain. Glacial lakes with dams formed largely of bedrock continue to exist in both upland and lowland glaciated landscapes today, whereas lakes dammed by moraines and ice drained more easily and have mostly disappeared or are much smaller than in the past. As the last ice sheet melted, the meltwater carried sediments from the glacier that were then deposited in the lakes and these glacial lake deposits continue to affect our environment and society today. Sand and gravel deposited where meltwater streams entered the glacial lake form groundwater aquifers in many areas, while the finer silt and clay carried further into deeper parts of the lake basins controls local hydrology by acting as an impermeable seal, causing waterlogging and the growth of peat in raised bogs across lowland Ireland. Glacial lake sediments can provide a record of meltwater discharge and ice sheet retreat, useful for understanding future retreat patterns in modern ice sheets. Deltas and outwash fans deposited in glacial lakes are an important source of aggregates for the construction industry. This chapter examines the glacial origins of modern and ancient lakes in Ireland.

Keywords ice-dammed lake, palaeolake, varve, moraine-dammed lake, corrie lake, trough lake

WHAT IS A GLACIAL LAKE?

Defining modern glacial lakes is relatively straightforward. A glacial lake, also termed a pro-glacial lake, is one that receives glacially derived meltwater, i.e., melt from a glacier, ice cap or ice sheet (Ashley, 2002; Carrivick and Tweed, 2013). A further division can be made between those lakes that are in direct contact with the glacier or ice sheet (i.e., the ice margin terminates in water), known as ice-proximal, ice-contact or ice-marginal lakes, and those that are not in direct contact but are fed by water from a glacial system, known as ice-distal lakes (Ashley, 2002). This classification is useful because there are significant differences in lake characteristics, including sediment input and water circulation, depending on the presence or absence of an ice margin. Other classifications refer to the type of barrier that holds the lake in place. This can be one or a combination of ice, bedrock, glacial moraine, or landslide debris (Carrivick and Tweed, 2013). This latter classification is useful because ice, moraine and landslide barriers are much more likely to fail, causing sudden lake drainage and often catastrophic floods downstream (Carrivick and Tweed, 2016).

Definition and classification are a little less straightforward for former glacial lakes, including Ireland's lakes. As for modern lakes, classifying former lakes based on how glacially derived meltwater arrived in the lake can be done, but the division into ice-proximal and ice-distal lakes is not helpful, as in a formerly glaciated area such as Ireland all lakes will have moved from an ice-proximal to an ice-distal position as the glacier or ice cap retreated.

There are several other ways to classify former glacial lakes. One approach is to consider how the lake basin formed. Using this approach, it is possible to identify three main ways these lakes were created. These are: lake basins formed primarily by glacial erosion, such as corrie lakes or lakes in glacial troughs and glacial overdeepenings; lakes formed primarily due to glacial deposition, such as lakes formed between drumlins or ribbed moraine, in hollows left by buried ice melting (kettle holes), or between glacial moraines; and lakes formed within a pre-glacial basin that was occupied by ice and then a glacial lake during ice retreat. The latter are often modified by glacial erosion and deposition but retain evidence that indicates a lake probably existed prior to the start of the Quaternary period (2.6 million years). Lakes in this last group can be very large in area but are often surprisingly shallow compared to their size.

Another way to classify former glacial lakes is to consider the type of barrier or dam that creates, or created, the glacial lake basin, and the time span for which that barrier existed. There are three basic types of dams, although all three commonly form part of a glacial lake margin at some point during its existence. These are bedrock dams, unconsolidated glacial debris or moraine dams, and the ice itself. Of these, a bedrock dam is the most stable, although the elevation of the dam can shift through time due to the rebounding of the Earth's surface after the weight of ice has been removed and rock channels can be cut and deepened by streams discharging from the lake, slowly altering the lake level. Dams formed of unconsolidated material are much less stable and can be breached easily and in modern lakes often result in glacial lake outburst floods (Carrivick and Tweed, 2016).

In all cases, as ice retreats across a lake basin, the ice margin forms at least one margin of the lake, damming the lake water. As with moraines, this ice barrier can be breached relatively easily, especially as it thins due to melting (e.g. Veh et al., 2023). As the ice barrier retreats, water escapes from the lake as lower outlets emerge, from under the ice sheet, and water levels in the lake fall. The lake may shrink considerably or disappear completely as the ice retreats further and the water can escape from the basin created by the ice dam.

A further consideration when classifying former glacial lakes is time. In many cases, ice-dammed lakes are ephemeral in nature. In modern glacial settings some lakes form and disappear within a few years (e.g. Rick et al., 2022). Records from formerly glaciated areas indicate that other lakes can last for much longer periods (100s-1000s years), before disappearing completely (e.g. Dyke, 2004; Hughes et al., 2016; Davies et al., 2020). Ancient lakes that have disappeared completely, or that have a much smaller modern equivalent are referred to as palaeolakes and there are many examples of such lakes in Ireland.

Finally, glacial lakes can also be formed indirectly by ice, where the weight of the ice cap presses down on the Earth's surface, forming a depression below the ice cap. As the ice sheet melts, the ice cap retreats into the depression created by its weight and a glacial lake forms around the margin, ponded by the ice and higher ground outside the depression. Even after the ice has completely melted, the depression remains for many thousands of years, as does the lake. Through time, the Earth's surface slowly rebounds, gradually lifting the depression and reducing the lake size. In Ireland, ice was thickest in the north of the island and thinned southward, so the north of the island is rebounding more than the south. This means that large lakes in Ireland are still changing in size many thousands of years after the removal of the last ice sheet, as the northern end of the lake closest to the centre of the ice sheet rebounds more quickly compared to the end far from the ice sheet centre (e.g. Delaney, 2022).

These lake types are discussed further below. However, before that, it is worth considering two things: the unique characteristics of glacial lakes; and the evidence used to identify former glacial lakes.

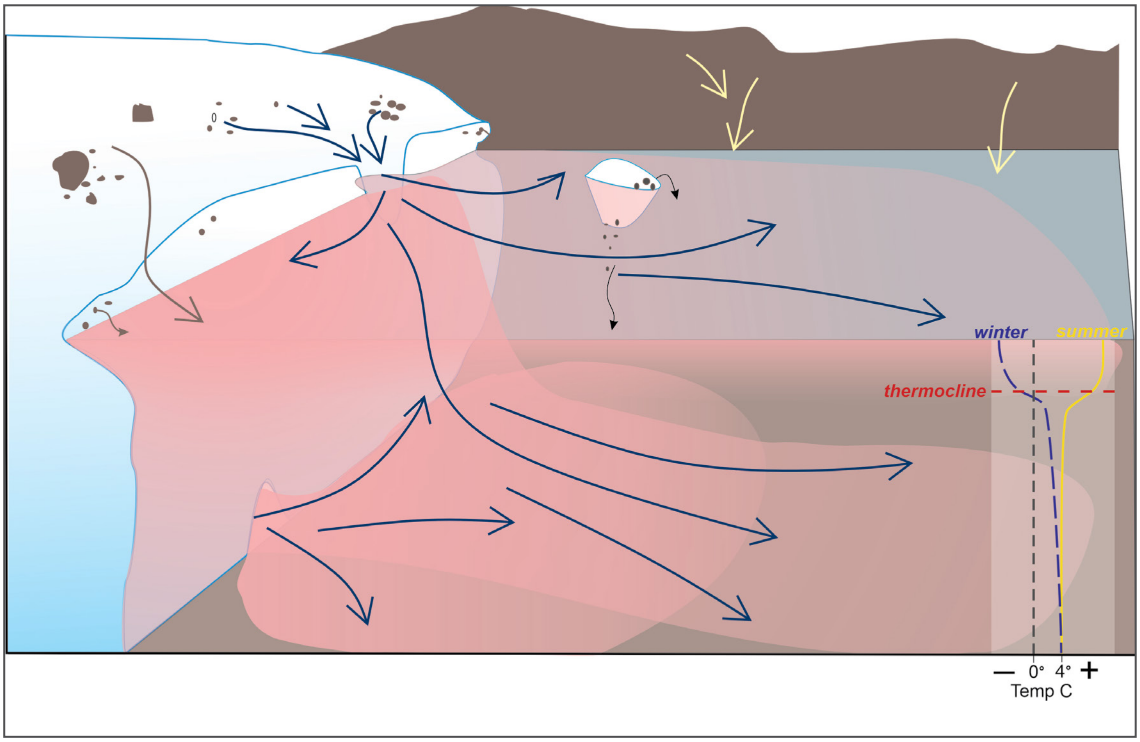
GLACIAL LAKE LIMNOLOGY

Modern glacial lakes have several distinct limnological characteristics that impact on the sediments and landforms left behind, so can also be identified in palaeolake deposits and landforms in Ireland.

Lake water stratification and circulation

In modern glacial lakes, well-developed vertical stratification of the water column is a common feature (Figure 2.1; Smith and Ashley, 1985; Ashley, 2002). This can be both temperature (see Chapter 1) and sediment-driven density stratification, as its development reflects vertical and seasonal changes in both temperature and suspended sediment concentrations in the lake water.

Figure 2.1 Schematic block diagram showing thermal stratification and interflows in an ice-contact glacial lake.



Thermal stratification is controlled by both solar radiation and meltwater input (e.g. Smith and Ashley, 1985; Sugiyama et al., 2016). Solar radiation in summer creates a less dense, warmer layer at the top of the lake water column, overlying a colder, denser bottom layer. These two layers are separated by the thermocline, an area of rapid temperature change (Figure 2.1). In autumn, as temperatures drop, the cooling surface waters become increasingly dense and as they reach 4°C (H_2O is at its densest at 4°C), the thermocline breaks down and vertical mixing (overturning) occurs. Thermal stratification then re-establishes with the warmest water (4°C) now at the base of the water column and colder water above. In spring, as waters warm, overturning occurs again, and re-establishes the summer stratification. Such lakes are termed 'dimictic' and are often ice-covered throughout the winter, effectively creating a closed system.

Density stratification also occurs due to the input of cold meltwater and suspended sediment. In ice-contact lakes, water temperatures near the ice margin are often very low, as meltwater near 0°C in temperature is discharged from the ice sheet/glacier into the lake and icebergs calve from the ice margin and add further meltwater. This water sinks to the bottom. Away from the ice margin or in ice-distal lakes, temperatures rise and may be above 4°C throughout the water column (Sugiyama et al., 2016 and references therein). However, the water columns of such lakes are still commonly stratified because sediment carried in suspension increases the density of the inflowing water (e.g. Gustavson, 1975a, b; Smith and Ashley, 1985; Gilbert and Desloges, 1987). These dense inflows sink downward on entry into the lake, forming underflows and increasing the density of the bottom lake waters further. Meltwater discharges with lower sediment content tend to form overflows at the lake water surface or move down toward the thermocline, forming interflows (Figure 2.1). These occur in summer but cease in winter as the lake surface freezes over.

Not all glacial lakes are dimictic, and polymictic (mixing occurs several times a year), monomictic (mixing occurs once a year) and non-stratified lakes also occur, depending on water temperatures and bathymetry. A further control on lake stratification is wind. Strong, katabatic winds are a common feature of ice sheets and glaciers, as cold, dense air formed above the ice cap moves downward and outward toward the ice margin; these winds are often funnelled down glacial troughs. Wind-driven circulation of the surface waters of a glacial lake mixes the surface layer and increases its thickness (e.g. Smith, 1978). In shallow lakes, the entire water body may be mixed, removing stratification. Wind can also drive overflows across the lake, changing where sediment is deposited.

Sedimentation in glacial lakes

The patterns of water circulation and stratification in glacially fed lakes have a profound influence on sediment deposition within the lake. Firstly, seasonal variation in sediment input is marked. In winter, meltwater and sediment input to the lake is almost non-existent, as ice cover forms in the autumn and seals the lake surface. In contrast, large amounts of meltwater and sediment are input in the relatively short summer period (Smith and Ashley, 1985). Initially, sediment transport is by melt from snow. Later in the season, glacial melt becomes more important. Rainfall events during summer also contribute to sediment movement, both from land and adjacent ice (e.g. Cockburn and Lamoureux, 2007). Most of this sediment (both bedload and suspended load) is rapidly deposited close to the discharge point, as the dense inflow sinks downward, forming a rapidly thinning wedge of sediment. Where sediment builds up to the level of the lake water surface, a delta forms. This is termed an ice-contact delta, or glaciodelta, when the discharge is directly from the ice. Deltas formed in this way are commonly Gilbert-type deltas, exhibiting a tripartite sedimentary sequence of flat or gently dipping bottomset beds composed of sand and silt, deposited distal to the sediment discharge point, overlain by steeply dipping foresets that have aggraded across the bottomsets as sediment is added, and then by topsets, consisting of fluvial sediments deposited on the delta surface (Figure 2.2A). Sometimes at the ice margin, discharges from the base of the ice do not build up to the surface and instead form a fan of sediment, termed a subaqueous outwash fan (Delaney, 2019; Figure 2.2B), that decreases in particle size rapidly down the fan surface. These deposits are important for identifying past glacial lakes and reconstructing past ice margins.

Further away from discharge points, toward the centre of the lake basin, finer-grained sediment, mostly silt and clay, is deposited (Figure 2.2C, D). In these areas, the silt grains are deposited quite quickly, as the inflowing water spreads out across the lake. This means that silt deposition primarily occurs in summer when meltwater is entering the lake. However, due to both their very small size and platy shape, many clay grains remain auto-suspended toward the top of the lake water column throughout the summer, kept in motion by surface winds currents. It is only when full mixing occurs in the autumn that these very small grains are transported downward. Once the lake surface

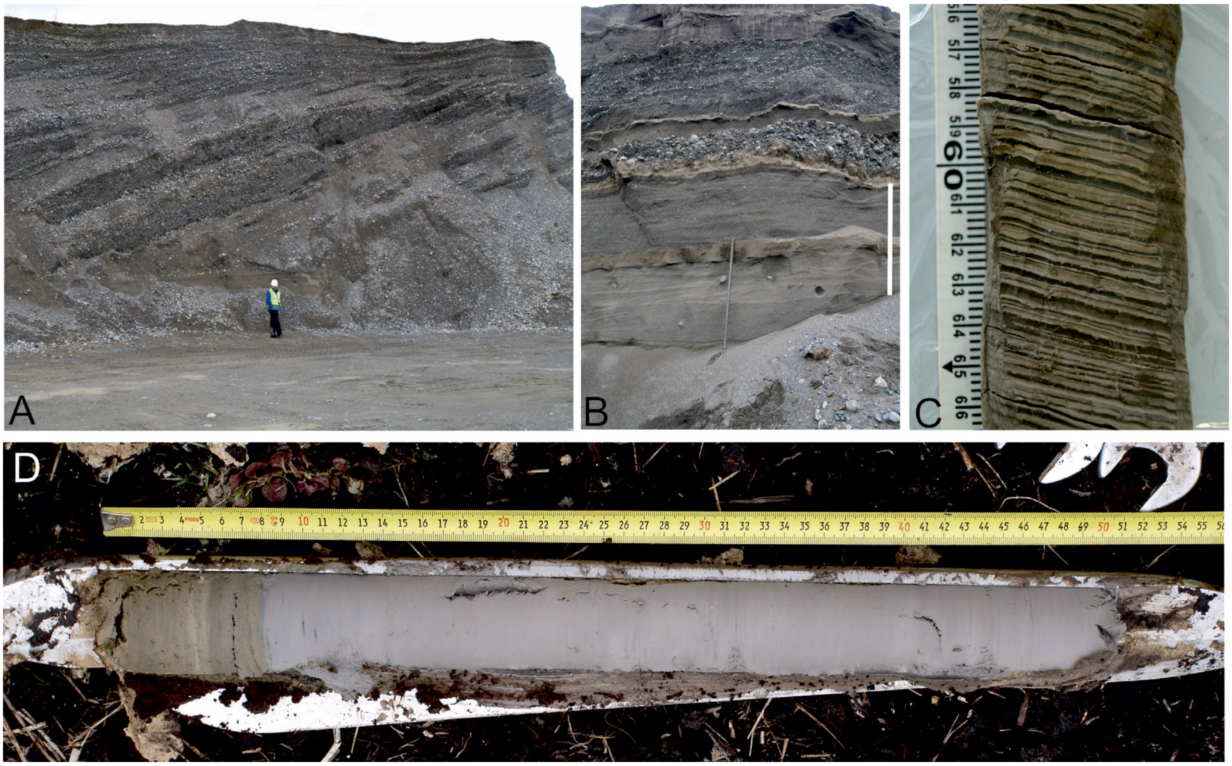


Figure 2.2 A. Blackwood glaciodelta, Co. Offaly, person for scale. The tilted foresets were formed by material avalanching down the delta front. B. Birr outwash fan. Beds of sand and gravel deposited rapidly from high energy underflows are separated by drapes of fine sand and silt deposited at low flow. C. Dried core from Carriganachtan bog, south of Athlone, Co. Roscommon, containing glacial varves. The paler layers are coarse to fine silt deposited in summer; the darker layers are fine silt and clay deposited when the lake is frozen in winter. D. Fresh core from Carriganachtan Bog, Co. Roscommon, showing an abrupt transition from glaciolacustrine silt and clay on the right to organic Holocene (after 11,700 BP) lake sediments (left). The glacial lake sediments appear massive (homogeneous), but when dried the fine laminations visible in photo C appear.

waters are frozen, the still water allows the deposition of a very fine silt and clay layer during winter (Smith and Ashley, 1985).

This highly seasonal variation in sedimentation in stratified glacial lakes leads to distinctive laminated patterns in the resulting deposits (Figure 2.2C). The pattern is rhythmic, in that it is repeated from year to year, and consists of a lower layer composed of one or more silt-dominated laminae, representing the summer/melt season, capped by a distinct lamination of clay and very fine silt deposited from suspension when the lake surface is frozen in winter.

The winter lamination is commonly graded, with the finest particles at the top. The coarse-fine rhythmite formed in this way is called a varve. Varve is a Swedish word applied by Gerhard De Geer at the end of the nineteenth century to annually laminated sediments deposited in Swedish palaeolakes during deglaciation (De Geer, 1940).

The formation of clastic varves, composed of mineral sediments, in glacial lakes is a hugely important feature for palaeo-environmental reconstruction in formerly glaciated areas like Ireland. By measuring varve thickness, sequences of varves can be matched across long distances, allowing stratigraphic correlation of lake sediments across vast areas, provided suitable sediments fed by the same ice sheet can be found. Where large palaeolakes formed along the ice margin, varve-matching in the direction of ice retreat has been used to reconstruct the retreat rate of the ice margin (De Geer, 1940; Ridge et al., 2012). Varved sediments also provide a continuous, high-resolution record that can be used to examine changes in climate-related parameters including temperature and rainfall, as well as records of changing ice margin position and meltwater discharge (e.g. Loso et al., 2006; Palmer et al., 2012). These records also formed during the last glaciation in Ireland.

GLACIAL LAKES IN IRELAND: ICE-DAMMED PALAEOLAKES

The recession of the last major ice sheets was marked by the development of large ice-contact lakes along their margins during retreat (Dyke, 2004; Murton and Murton, 2012; Hughes et al., 2016; Davies et al., 2020). That such lakes also formed along the margins of the last Irish ice sheet has been known since the 1920s (Charlesworth, 1928, Farrington, 1934). Despite this, the number and extent of ice-dammed palaeolakes in Ireland is unknown, and the existence or extent of many of these lakes is debated. Palaeolakes continue to be identified (e.g. Synge, 1950; Van der Meer and Warren, 1997; Meehan, 1999) and it is likely that evidence for further, as yet unidentified, ice-dammed lakes will be found in the future, and the size and extent of those already known will continue to be revised. The location of ice-contact palaeolakes is shown in Figure 2.3 (letters in blue) and named in the text. While some palaeolakes have entirely disappeared, in other cases a modern remnant exists. Modern lakes in glacially formed basins are numbered in red in Figure 2.3. Evidence for ice-dammed palaeolakes can be recognised from a combination of erosional and depositional features in the Irish landscape.

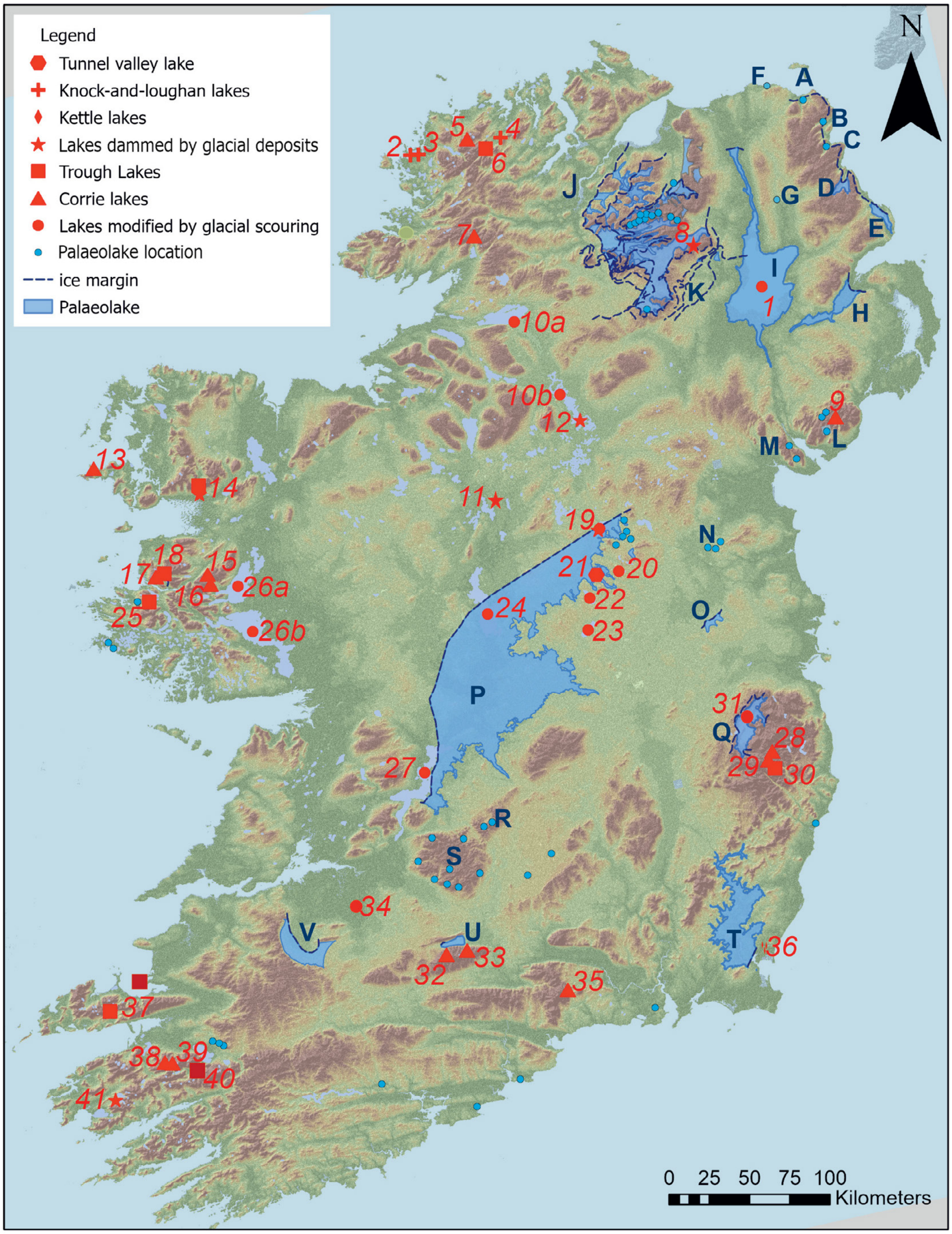


Figure 2.3 Glacial lakes in Ireland. Palaeolake locations, where the lake has disappeared or only a remnant remains, are shown as blue dots where the lake is too small or the evidence too little to show extent. Paleolakes named in the text are indicated by a blue letter. Lakes in glacially formed basins are numbered in red.

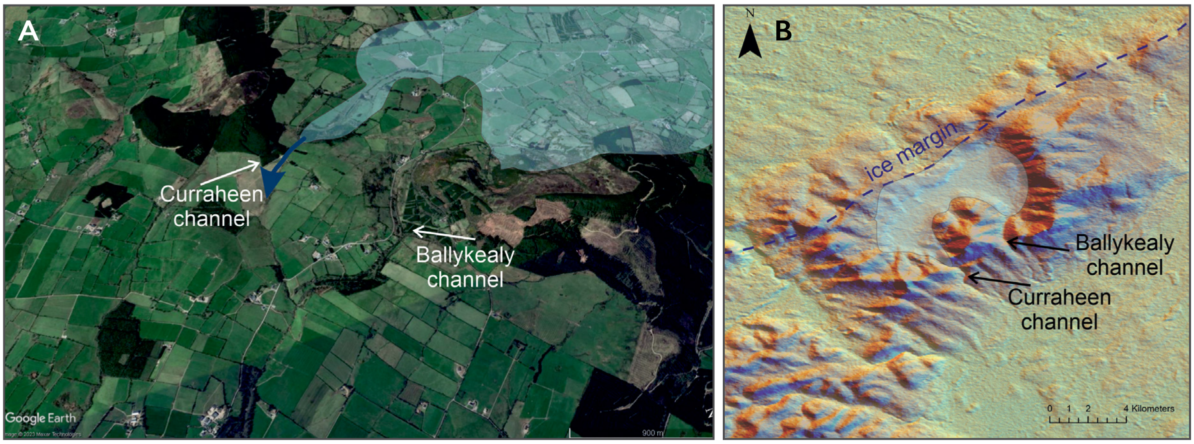


Figure 2.4 A. Google Earth image showing the meltwater channels at Curraheen and Ballykealy, Co. Tipperary, formed by outflows from ice-dammed palaeolake Ollatrim (R; Figure 2.3). The area shaded blue shows the likely extent of the lake when water was exiting through the Curraheen channel. B. 12.5 m resolution hillshaded digital elevation model (DEM) created from radar (ALOS-PALSAR) showing a reconstruction of Palaeolake Ollatrim and the meltwater channels pictured in 2.4A.

Erosional Features

The most commonly found erosional features are the outflow channels through which the former lakes drained. These are usually perched on the watershed across which the lake drained, away from the ice margin. They are often (but not always) without a modern stream and may terminate at a fan of sediment deposited by the outflowing meltwater. The elevation of the channel floor indicates the water level height of the lake when the outflow was active.

Examples of such channels can be seen around the Devil's Bit Mountains in Co. Tipperary. Here, the last ice sheet margin receded westward; once across the NE-SW oriented Devil's Bit ridge, water was ponded on the reverse slope between the ice and the ridge, forming Palaeolake Ollatrim (R on Figure 2.3; Charlesworth, 1928). Two major outlet channels developed, one at c. 245 m above sea level at Ballykealy and a lower channel at Curraheen as the ice retreated further across the Ollatrim river basin (Figure 2.4). Once the ice margin retreated beyond the northwest margin of the ridge, the lake drained westward down the path of the modern Ollatrim River.

Less commonly identified features are wave-cut shoreline notches and wave-planed surfaces, formed by erosion of bedrock and previously deposited glacial features. Such features can only develop when the palaeolake was large enough

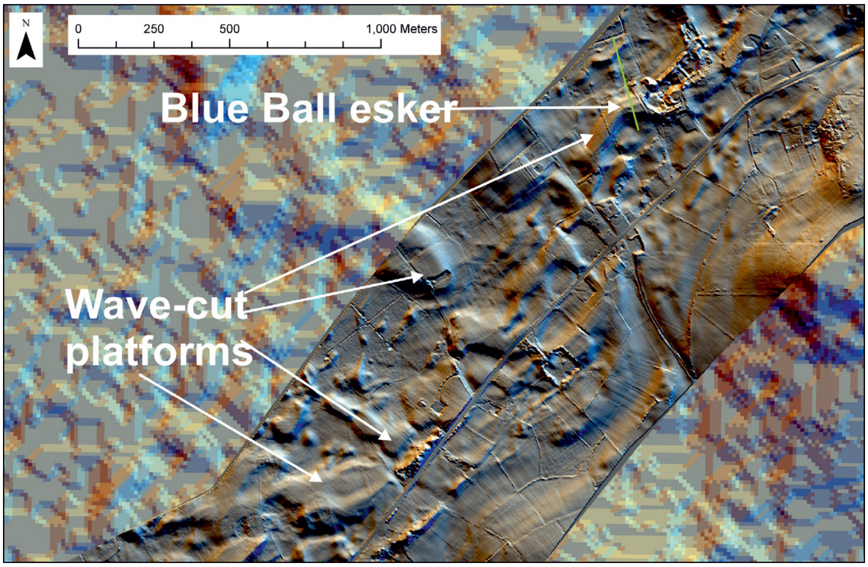


Figure 2.5 Hillshaded digital elevation model created from 1 m resolution airborne LiDAR (data from Transport Ireland, available for download through GSI.ie), showing terraces cut by wave erosion in Palaeolake Riada (P) into the Blue Ball-Kilcormac esker, Co. Offaly. Reprinted from Delaney (2022).

to have a significant wave fetch. A good example of a wave-planed surface can be seen along the northwestern margin of the Blue Ball-Kilcormac esker in Co. Offaly, where the northern side of the esker and adjacent glaciofluvial features have been truncated to form a flat surface, cut by wave erosion in Palaeolake Riada (P; Figure 2.5; Delaney, 2022). Terraces and shoreline notches are also recorded at several locations in Co. Tyrone, formed by extensive lakes ponded on south central Ulster between multiple ice lobes during the final stages of ice sheet decay (K; Doughty and Enlander, 2019).

Depositional features

Many palaeolake depositional features are relatively common and easily identified. Most important are ice-contact subaqueous outwash fans and deltas, formed at a point discharge into the former lake, either at the ice margin (where they are often at the downstream end of eskers) or at inflows from the surrounding land. Their flat surfaces are similar in appearance to wave-cut terraces, but they often have shallow channels cut into their surface, as seen in the Blackwood delta west of Tullamore (Figure 2.6). Ice-contact deltas were first described in Ireland in Co. Meath, where they formed in now-vanished Palaeolake Summerhill (O) at the mouth of a

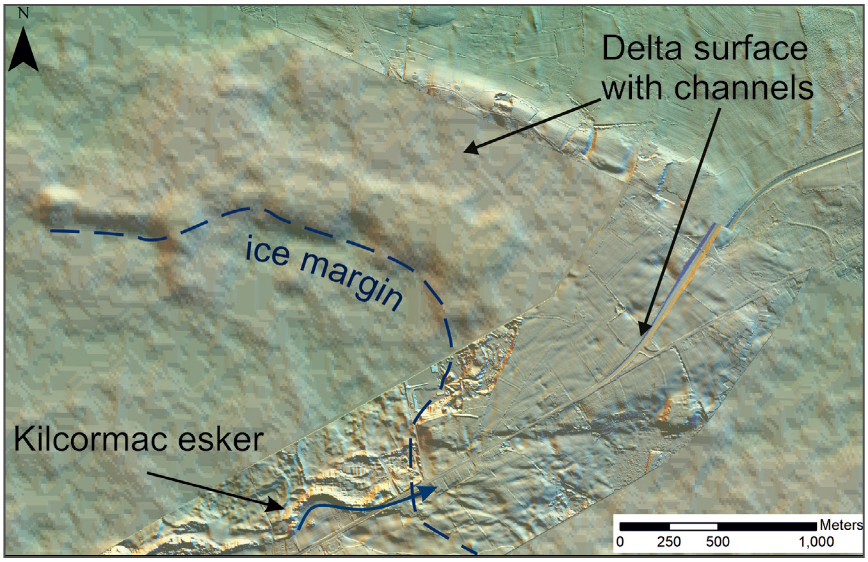


Figure 2.6 Hillshaded digital elevation model created from combined 1 m resolution airborne LiDAR (Transport Ireland) and 12.5 m radar data (ALOS-PALSAR) showing the Screggan-Blackwood delta complex at the north end of the Blue Ball esker, Co. Offaly. A faint network of braided channels can still be seen in the 1 m resolution image on the upper part of the fan. The Kilcormac esker marks the path of the subglacial stream that fed the delta. Image reprinted from Delaney (2019).

tunnel in the ice sheet through which meltwater discharged each summer; as the ice margin retreated each year, a new delta formed (Synge, 1950).

Ice-contact deltas can reach a considerable size and, in many cases, act as an important source of building aggregates. One of the largest examples in Ireland lies north of Blessington, Co. Wicklow, where a delta complex formed in Palaeolake Blessington (Q) covering over 10 km^2 and reaching vertical thicknesses of over 80 m, has been used as a source of aggregates for building for over 40 years (Philcox, 2019). The delta was fed by meltwater streams discharging from an ice margin that lay against the Slievethoul bedrock ridge to the northwest of the delta. Sedimentary sequences indicate multiple changes in water level during the existence of the ice-dammed lake; at its highest level the lake surface was over 100 m above modern Lake Blessington

Shoreline deposits have rarely been described in relation to palaeolakes in Ireland. However, some evidence of beach and shoreface deposition is found on top of deltas that formed in the largest known ice-contact lake, Palaeolake Riada (P; see below and Delaney, 2022). Around smaller lakes in mountainous areas, boulder shorelines may be found, such as that described around the modern Lough Nahanagan, Co. Wicklow (number 29 on Figure 2.3), associated with a wavecut notch indicating a higher past water level at the end of the last glaciation (Colhoun and Synge, 1980). More shoreline sediments will likely be recognised in the future, as palaeolakes are more closely investigated.

One of the most widespread, but least described, indicators of the existence of glacial palaeolakes in Ireland are deposits of fine-grained silt and clay (Figure 2.2 C, D). These are very widespread in the central lowlands, where they underlie many of the extensive raised bogs (Van der Meer and Warren, 1997; Delaney, 2007, 2022) and can create a considerable challenge for road and bridge construction (Long, 2020). They also commonly underlie Holocene sediments in both lowland and upland lakes throughout Ireland (see Chapter 3). As these deposits are generally overlain by Holocene wetland and lake sediments, they are hard to spot. Nevertheless, significant thicknesses of glacial lake sediments associated with the larger palaeolakes have been identified in borehole records and exposures. For example, north of Lake Ennell, Co. Westmeath (23), a series of boreholes drilled to support construction of the Joe Dolan Bridge revealed more than 14 m of glacial lake sediments that were originally deposited in Palaeolake Riada (P; Long, 2020).

While sedimentary records extending into the Late Glacial (Younger Dryas) cold period (12,900-11,700 BP (Before Present)) have been studied at multiple sites, the underlying glacial sediments are rarely studied, as such studies tend to focus on bio-indicators and geochemistry rather than physical sediment characteristics. This is a pity, as varved (annually laminated) deposits are known to occur, although they are difficult to recognise without drying core samples (see Figure 2.2 C, D). Such high-resolution sediments are useful for examining rapid changes in climate and environment, such as happened during the last glacial termination.

Varves in glacial lake sediments can also shed light on the duration of a glacial lake's existence. Modern glacial lakes are very variable in age. At modern, rapidly retreating ice margins, ice-dammed lakes can appear, expand, and then drain completely in less than ten years (e.g. Rick et al., 2022). This timescale order is likely to apply to many smaller former lakes, as minor shifts in the margin are likely to have resulted in new outflows opening. However, some lakes can persist over 100s and even 1,000s of years. Attempts have been made to estimate the duration of just two ice-dammed palaeolakes, using the record of varved sediments. Charlesworth (1938) counted 137 varves from glaciolacustrine sediments associated with Palaeolake Lagan (H), which formed in inner Belfast Lough and the Lagan Valley during the latter stages of ice retreat across Ireland, dammed by ice from Scotland. However, it is unclear how much of the glaciolacustrine deposit was exposed, so this is a minimum estimate.

In central Ireland, varve counts for Palaeolake Riada (P) from sites west of the River Shannon give a minimum age of 262 years for the palaeolake's existence (Delaney, 2007 and unpublished data). As the varve sites are located close to the most westerly, and youngest, ice margin position, this is a minimum estimate of the lake duration and, given the extent of the lake to the east, suggests that a duration of more than 1,000 years is not unlikely. Similar extensive lowland lakes are also likely to have existed for several 100 years.

The longest varved record comes from modern Lough Nagirra at Tory Hill, Co. Limerick (34), where partly varved glacial lake silt and clay underlies Late-Glacial and Holocene lake sediments (O'Connell et al., 1999). Counting of varved clays, combined with interpolation of the sediment accumulation rate for unlaminated sections, indicates that cold conditions continued at the site for c. 1,870 years after ice was initially removed from the basin.

DISTRIBUTION OF PALAEOLAKES

Ice-dammed lakes from the last glaciation (and probably older glaciations) formed in a wide variety of settings (Figure 2.3). A division is made here into upland and lowland lakes, as these tend to have somewhat different characteristics. However, in reality, a continuum exists, depending on the height and steepness of the bedrock against which the lake was dammed. Where the ground rose steeply and reached significant heights, relatively small, deep lakes formed that rapidly changed configuration and dropped in level as minor ice margin retreat allowed water to escape. Where the ground surface sloped gently toward the ice margin, then larger, but shallower, lakes formed that existed for longer periods.

Upland ice-dammed lakes generally formed in relation to regional ice retreat away from higher ground, rather than the recession of local glaciers that originated within the upland area. This is because local glaciers receded to higher areas, whereas regional ice retreated downslope, damming water between the ice margin and the bedrock. For many upland areas, the result was the damming of multiple small lakes in valleys and lower areas within the upland area. These lakes tended to evolve rapidly as the ice retreated and new outlet routes were exposed, dropping in height and merging with adjacent lakes. Evidence for such lakes has been found around the Antrim Plateau (A-H on Figure 2.3), the Sperrin Mountains (J, K), the Mourne Mountains and Cooley Peninsula (L, M), Wicklow Mountains (Q), the Keeper Hills (S), and associated Devils Bit Ridge (R), and on the northern margin of the Galtee Mountains (U), but similar lakes almost certainly formed around other mountains and hills, especially where upland ridges were elongated across the path of ice flow.

A particularly large cluster of such lakes occurred during ice retreat from the Sperrin Mountains in Cos. Tyrone and Londonderry (J; Charlesworth, 1921; Dardis, 1986a; McCarron, 2013). This is because, during the last deglaciation, the ice retreated from both the northwest and southeast side of the mountains. Initially, the entire upland area was covered by ice. Ice retreated more quickly on the northern side first, so that lakes formed on the southern side of the watershed and drained north and northwestward across the cols (saddle between two ridges), leaving delta terraces and outflow channels suspended above the modern drainage system when the ice retreated. As ice thinned vertically, these lakes merged into larger lakes to the north and south of the mountains, the largest of which was probably Palaeolake Gortin (K), which covered almost 52 km^2 and was over 150 m deep (Charlesworth, 1921). As the ice receded into lowland areas the ice cap broke down into multiple separate domes, damming more water, although the exact configuration of the lake is unknown. Today, the only lake in the area is the 0.47 km2 Lough Fea (8).

One of the largest examples of a lake dammed against an upland massif (or group of mountains) is Palaeolake Blessington (Q; Charlesworth, 1928; Farrington, 1934; 1957, Synge et al., 1975; Warren, 1993; Philcox, 2019). This palaeolake formed in the upper part of the Liffey valley in the Blessington basin, in and around the area occupied by the modern Blessington Lake (31; currently dammed at a lower level than the original glacial lake by the Pollaphuca dam), as ice retreated from the western and northern slopes of the Wicklow massif.

The outflows from Palaeolake Blessington lie south of the modern outlet from the Blessington Reservoir at Pollaphuca and consist of a group of meltwater channels around Hollywood, West Wicklow. Some of these meltwater channels have undulating long profiles, indicating that initially, water flowed out of the lake through the ice sheet, flowing upslope across the underlying bedrock, under pressure from the weight of ice above (Farrington and Mitchell, 1973; Synge et al., 1975). As the ice sheet thinned, channels developed at lower levels down the hillside, forming between the ice margin and the bedrock. In modern glacial systems, lakes with similar subglacial outlets often drain suddenly, as the ice dam tends to lift when water pressure against it is higher, releasing water in an outburst flood (e.g. Roberts et al., 2005). South of Palaeolake Blessington, coarse gravels exposed at the base of the Whitestown terrace are thought to have been deposited by these outburst floods (Farrington and Mitchell, 1973; Philcox, 2019).

Lowland ice-dammed lakes were widespread during retreat of the last ice sheet and included the largest palaeolakes by area, although many much smaller lakes also existed. These lakes developed in relatively shallow depressions, many of which were probably pre-glacial in origin, but were modified by glacial erosion during the Quaternary. The largest known examples include Palaeolake Newcastlewest in Co. Limerick (V), Palaeolake Mulmontry in Co. Wexford (T), Palaeolake Riada, which extended across parts of Counties Offaly, Westmeath, Tipperary and Longford and included modern Loughs Sheelin (19), Derravaragh, Owel, Ennell, Ree (21-24 on Figure 2.3) and part of Derg (27) and areas between (P), Palaeolake Summerhill in Co. Meath (O), and Palaeolake Neagh (I), whose surface lay approximately 30 m above modern Lough Neagh (Dardis, 1986b). Other large modern lakes, including Corrib, Mask (26) and the upper and lower Lough Ernes (10), are also likely to have been larger during the last glacial period.

Where detailed mapping has been undertaken, many smaller lakes have also been identified. For example, Meehan (1999) has mapped multiple small lakes in Cos. Meath and Cavan, that shifted position and drained as the ice margin retreated downslope to the northwest (N).

The largest of the ice-contact lakes was Palaeolake Riada, which reached over 2,300 km2 in size (P; Figure 2.3) greatly exceeding Ireland's largest modern lake, Lough Neagh, at 383 km2 (see Chapter 12). The westward and north-westward retreat of ice across the Irish midlands north of the Slieve Bloom massif caused damming of meltwater between the ice margin, the Slieve Blooms, and the rising topography to the east prevented water from escaping. The lake outflow position changed as the ice margin retreated northwest and west toward the Shannon River. Initially, the lake drained eastward into the Barrow catchment, but then the outflow switched to the northern end of the Inny River catchment between Derravaragh and Lene

(21, 20), draining into the Boyne catchment. Finally, as ice retreated west beyond the western margin of the Slieve Bloom mountains, the lake drained into the lower Shannon through an outlet south of Nenagh, Co. Tipperary. As ice retreated west, the modern drainage path through the Shannon Gorge at the base of Lough Derg (27) was established. This gorge may have initially formed subglacially and been subsequently modified by glacial meltwater discharge or may date from earlier glaciations.

EROSIONAL GLACIAL LAKES

Subglacial erosion has played an important part in creating lake basins in Ireland. The largest lake basins, including Neagh, Upper and Lower Erne (10), Ree (24), Derg (27), Corrib (26), and Owel and Ennell (22, 23; Figures 2.3, 2.7), are all thought to have been partly eroded by glaciers and contain evidence of glacial action, including rock drumlins, channels and overdeepenings in their bed. However, many much smaller lakes on bedrock throughout Ireland also owe their origin to glacial erosion. This is because the processes of glacial erosion tend to create an irregular surface, even where the topography is relatively flat. Minor irregularities, often reflecting bedrock structures such as bedding planes, cause minor changes in subglacial pressure as ice moves across the landscape, and this, in turn, leads to variable erosion and the creation of ridges and hollows. The hollows then become areas of low pressure where water tends to accumulate beneath the ice, enhancing weathering and breakdown of bedrock. The resulting basins vary considerably in size, depending on the interaction between ice and variable bedrock lithology. Very small lakes are widespread on areas of formerly glaciated bedrock known as knock-and-lochan topography. Examples include the lakes explored by Fossitt (1994) and Watson et al. (2010) in Co. Donegal, Loughs Mullaghalan and Altar Lough (2, 3), and Lough Nadourcan (4) which contain glacial lake sediments deposited before 14,500-13,100 BP, indicating that they filled with water as ice retreated. Many examples of similar lake basins exist.

In mountainous areas, larger glacial erosion features such as corries and glacial troughs are thought to have formed over several glacial cycles and the lakes that presently occur in these features have likely reformed in multiple interglacials, of which the modern lakes in these basins are just the latest examples. Different types of basins, including some compound forms, are described below.

Cirque lakes

In mountainous areas during glaciations, snow accumulates in depressions on north- and east-facing slopes, where it is protected from solar radiation. Melting and refreezing of the snow enhances the weathering of bedrock below so that depressions expand due to periglacial frost action. As these depressions deepen, the perennial snow infill thickens and is transformed into ice, eventually deforming under its own weight and moving, becoming a glacier. These glaciers erode by quarrying and plucking bedrock; the rotational movement of the ice body within the hollow causes overdeepening of the hollow and forms a rock lip at the ice terminus where erosion is reduced, forming the amphitheatre morphology characteristic of cirques (or corries, as they are termed in Ireland; Figure 2.7A). There are hundreds of such corries in the Irish mountains (Geological Survey of Ireland, 2021), many of which contain lakes, or wetland areas underlain by lake sediments. Well-known examples include Callee and Alohart in the Macgillycuddy's Reeks, Co. Kerry (38, 39); Coumshingaun in the Comeragh Mountains, Co. Waterford (35), Curra and Muskry in the Galtee Mountains, Co. Tipperary (32, 33), Bellawaum in the Mweelrea Mountains (17; Figure 2.7), Glenawough and Loch na Deirce Móire in the Partry Mountains (15, 16), and Acorrymore on Achill Island, Co. Mayo (13), Belshade in the Bluestack Mountains and Feeane in the Derryveagh Mountains, Co. Donegal (7, 5), Shannagh in the Mourne Mountains, Co. Down (9), and Ouler and Nahanagan in the Wicklow Mountains (28, 29).

Dating of the most recent phase of lake formation relies on two approaches: dating the moraines damming the lake, which formed during the last stage of glaciation; and dating sediments deposited within the lakes, which can give the age of lake formation after ice left the basin. Such dates do not give the age at which the corrie started to form, but rather the end of the last phase of glacial activity. Dating of glacial moraines commonly relies on surface exposure dating of glacial boulders on the moraines, using terrestrial cosmogenic nuclides such as 10Be or 36Cl, produced within crystals in the rock by exposure to cosmic rays (see Davies, 2023 for further explanation). The concentration of nuclides depends on the duration of exposure to light, so an age can be derived for the uncovering of the boulder. A few corries containing lakes have been dated in Ireland, and indicate that most corries were exposed, and presumably lakes formed, as ice retreated after the most recent glacial maximum. For example, at Lough Alohart in the Macgillycuddy's Reeks, Co. Kerry (39) terrestrial cosmogenic nuclide dates suggest that moraines formed

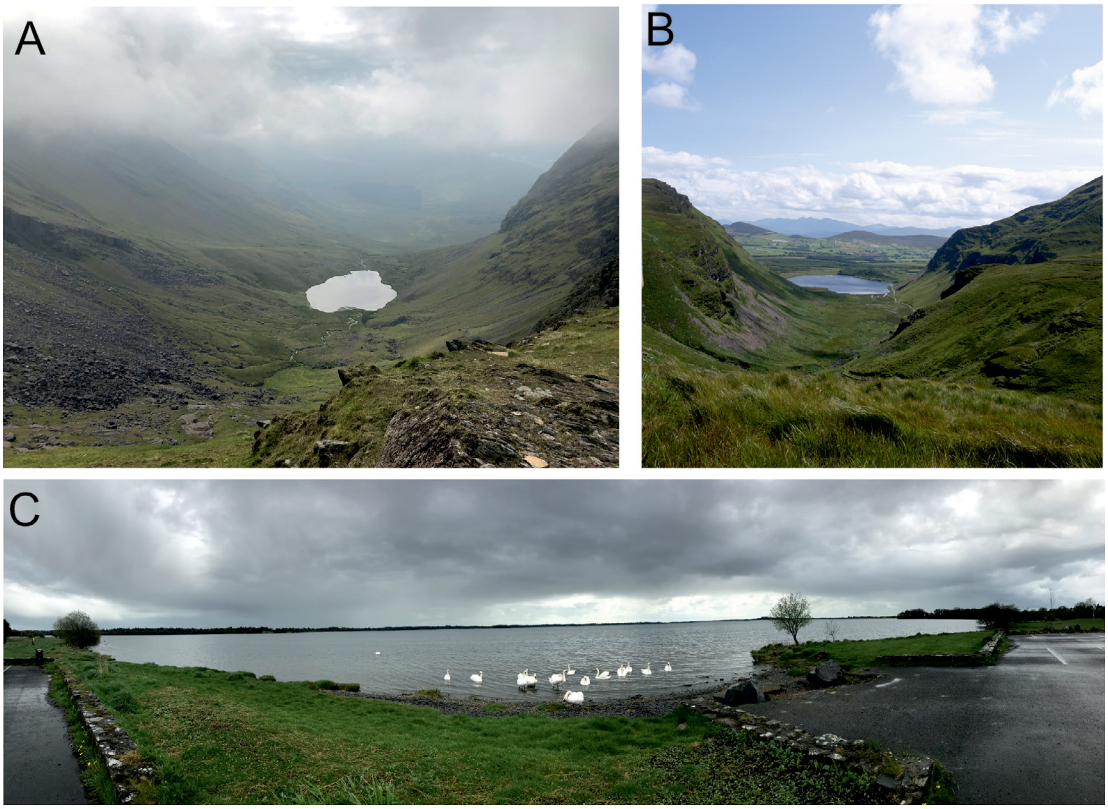


Figure 2.7 Types of erosional glacial lakes. A. Corrie lake: Lough Bellawaum, Mweelrea Mountain, Co. Mayo (17). Photo taken from back wall of corrie. The lake is primarily dammed by the bedrock lip of the corrie beyond the far edge of the lake, on top of which moraines are visible. B. Glacial Trough lake: Lough Annascaul, Dingle Peninsula, Co. Kerry (37), looking south from above the trough. The lake extends to the lowland beyond the glacial trough, where it is dammed by terminal moraines. C. Basin overdeepened by glacial erosion: Lough Ennell, Co. Westmeath (23).

at the mouth of the corrie lake at around 20,400 BP, during the early stages of ice retreat (Barth et al., 2018).

One corrie lake, Lough Nahanagan in Co. Wicklow, is of particular interest as it is the typesite for the Younger Dryas stadial within Ireland, known as the Nahanagan stadial (27; Watts et al., 1977; Colhoun and Synge, 1980). This was a short cold period, lasting c. 1,000 years, that occurred after the initial climate warming at the end of the last glaciation. At Lough Nahanagan, this climate warming led to the melting of ice and formation of a lake in which organic sediments were deposited. After this, a return to cold conditions led to the reforming of a small glacier in the corrie, partly displacing the lake. The ice ploughed up the lake sediments, which were incorporated into small moraine ridges within the corrie. These moraine ridges are visible today because the surface of the lake lies approximately 38 m below its natural elevation, exposed by partial drainage of the lake to drive the turbines of the Turlough hydroelectric power scheme. It is likely that similar moraines and disturbed lake sediment lie within other corrie lakes in upland areas but have not yet been identified.

Glacial trough lakes

During multiple glaciations, selective linear erosion occurred along pre-existing valleys in Ireland, resulting in the creation of glacial troughs (Figure 2.7B). These large valleys commonly have undulating long profiles, as overdeepenings developed where ice discharge through the trough is relatively high, for example at the junction with tributary valleys (Benn and Evans, 2010). As the ice retreated, moraines formed at the glacier terminus, creating further barriers to water movement, and the overdeepenings filled with water, forming elongated lakes. Dramatic, classic examples of such lakes exist in many of the longer glaciated valleys in upland areas. These include Glendalough in the Wicklow Mountains (Upper and Lower lakes; 30), Black Valley/Cummeenduff Glen in the Magillycuddy's Reeks (Reagh and upper and lower parts of Cummeenduff; 40), Kylemore Valley in the Twelve Bens Mountains (Kylemore, Pollacappul and Maladrolaun; 25), Doolough Valley, Mweelrea Mountains (Glenullin, Doo, and Fin; 18), Glenveagh in the Derryveagh mountains (Beagh and Glen; 6), and Silent Valley, Mourne Mountains (L).

Lakes in glacial meltwater features

As the last ice sheet melted it generated a large amount of meltwater, which drained either along the margins of the ice sheet or flowed downward to the ice sheet bed and then toward the margin, flowing under pressure. This pressurized subglacial meltwater cut channels into the ice sheet bed that, on a reverse slope, led upward toward the ice margin, against the slope gradient. Often the path of these subglacial tunnel channels undulated. Today, many such tunnel channels contain small lakes. An exceptionally large example is Lough Derravaragh (21), the southern end of which lies within a tunnel channel which drained subglacially through the Knockeyon chert and limestone ridge.

LAKES FORMED BY GLACIAL DEPOSITS

Many of the lakes lying within corrie and trough basins in mountainous areas of Ireland are dammed partly by glacial moraines, in addition to bedrock. These moraines formed at the glacier terminus at a time when the ice margin was relatively stable. Today many of these moraines do not form a part of the lake dam, as the outflow channel through the moraine has usually cut down to bedrock in the thousands of years since the lake first formed. However, when the ice extended beyond the trough or corrie to lowland areas beyond, very large moraines are often present that continue to form part of the lake barrier. Examples of such lakes include Lough Namona on the Iveragh Peninsula (41) and Lough Annascaul on the Dingle Peninsula (37; Figure 2.7B), both in Co. Kerry.

Other large lakes are partly or fully dammed by glacial deposits, particularly subglacially formed landforms such as ribbed moraines and drumlins. Both these landforms are a major glacial feature of the northern half of the island. Drumlins are small hills (500-4000 m in length, generally around 10 m high) that are elongated parallel to the direction of former ice flow. Ribbed moraine are much larger ridges (up to 70 km long), that are aligned at right angles to the direction of ice flow. The surfaces of ribbed moraine are reshaped into drumlins, so lakes dammed by these ridges often appear to be drumlin-dammed lakes. Lakes where ribbed moraines form part or all of the dams include Loughs Feeagh and Furnace in Co. Mayo (14), dammed by ribbed moraine that form part of the Clew Bay drumlin field, and the complex of lakes that include Loughs Oughter, Corglass, Inchin and Farnham (12) in Co. Cavan. Lakes dammed solely by drumlins are much smaller. An example is the cluster of small lakes north of Drumod, Co. Leitrim, that includes Gubagraffy, Roosky, Cloonturk, Bog and Cloonboniagh Loughs (11). These lakes are all less than 500 m in length.

The smallest lakes in glacial depositional settings are kettle hole lakes that occur in kame-and-kettle topography. Kettle holes form when ice buried within glacial sediments melts, leaving a depression that infills with water, while kames are elevated mounds. Kettle hole lakes occur very commonly in deposits that formed at or near the ice margin, where sediment is often moved onto the glacier surface by upward ice flow, or by water transport, burying the glacier ice, which later melts. The best-known examples are the many very small lakes and ponds found between Curracloe and Blackwater, Co. Wexford, which formed within the Screen Hills kame-and-kettle moraine during the retreat of ice up the Irish Sea Basin. These are almost entirely unnamed and are mostly less than 5000 m^2 in area and less than 100 m in width, although larger examples occur, including Lough Ballyroe, Lough Na Beist and Doo Lough (36; Mitchell, 1950; Heuff, 1984). They are usually steep-sided and can be surprisingly deep; for example, Lough Na Beist is less than 200 m long, but has a maximum depth of 15 m (Heuff, 1984), while cores from Doo Lough show that over 12 m of sediments have infilled the basin since its formation (Mitchell, 1950).

CONCLUSIONS

The history of almost all lakes in Ireland includes a significant phase of glacial activity, and this is reflected in both lake basin morphology, including size, shape, and bathymetry, and the deposits underlying these lakes. The geomorphology and depositional record from these lakes are of considerable use in reconstructing the last glacial period but also mask evidence of the pre-glacial history of many lakes. In many cases, it is difficult to distinguish between the impact of ice and of other erosional processes, particularly in coastal and limestone areas where solution has played a role in lake basin development.

The impact of now-vanished glacial palaeolakes on many aspects of modern Irish landscape development is almost certainly underestimated. In the Irish lowlands, there are many areas where the former existence of glacial lakes is indicated by the presence of blue-grey silt and clay deposits underlying raised bogs, and by sand and gravel mounds underlain by deltaic deposits. Given the extent of raised bogs through the Irish midlands these unmapped lakes may have been very large, on a similar scale to Palaeolake Riada.

These glacial lake deposits have the potential to provide highly detailed information on glacial retreat patterns and meltwater discharge and interactions between the last Irish ice sheet and climate during ice sheet retreat, information that contributes to understanding how modern ice sheets will react to the ongoing climate crisis.

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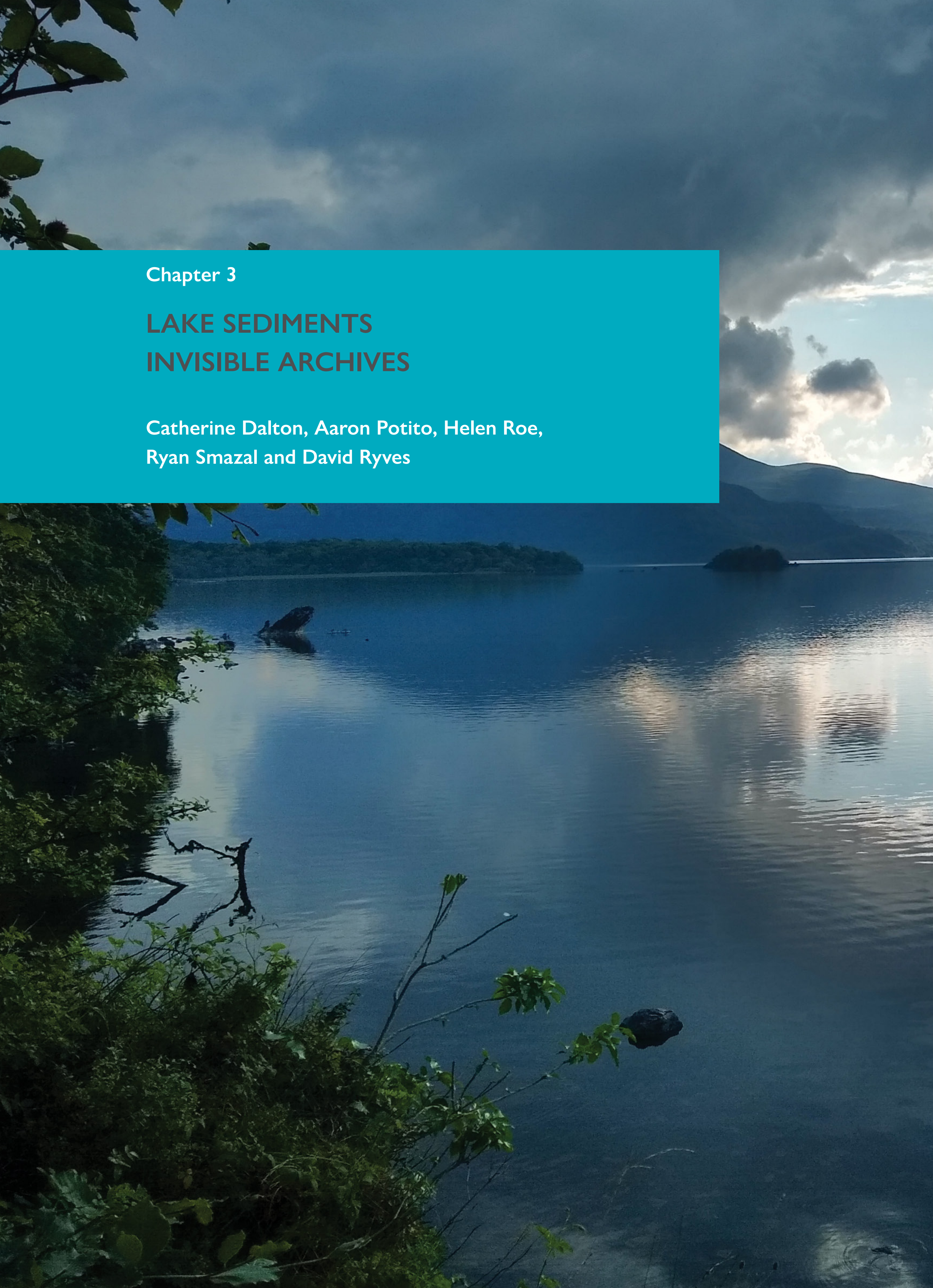


Chapter 3

LAKE SEDIMENTS
INVISIBLE ARCHIVES

Catherine Dalton, Aaron Potito, Helen Roe,
Ryan Smazal and David Ryves

SUMMARY

Sediments are deposited over the life of a lake. Materials that sink through the water column are washed in from the catchment, fall from the sky, or are produced within the lake itself. As lake sediments are laid down over time, materials preserved in these sediments can provide a record of changing environmental conditions. Lake sediment studies have proven to be very useful archives for the study of climate change, ecosystem development and anthropogenic influences across a range of timescales. This chapter collates the range of sediment studies that have been established for lacustrine systems on the island of Ireland. Sediment profiles mainly cover the Late Glacial (c. 16,000-11,700 years ago), Holocene (c. 11,700+ years), industrial period (c. AD1750+), and the Anthropocene (c. AD1950+). Detailed lake sediment or palaeolimnological investigations addressing a range of research questions have been conducted on almost 400 lake sediment cores or surface samples from over 283 Irish Ecoregion lakes. Most of these are low altitude (< 100 m) lakes with a small (< 0.1 km^2) surface area and are either oligotrophic (low) or mesotrophic (medium) in nutrient (trophic) state. The spatial and temporal summary illustrated in this review provides context for site selection in future investigations.

Keywords lake sediment, palaeolimnology, sediment chronology, proxy indicators, environmental change

LAKE SEDIMENTS

Lakes and ponds (the latter defined as < 5 ha (0.05 km^2)) are core constituents of river drainage networks and are generally found in glacially carved depressions in the landscape (see Chapter 2), making them important natural sediment repositories or sinks. Lakes integrate terrestrial and aquatic materials in their sediment infills which are fundamental to all aquatic ecosystems, providing essential substrate and habitats. Sediment is generated through natural erosion and human-induced activities and is deposited in wetlands and lakes throughout a catchment, with both constructive (habitat building) and destructive (habitat degradation) effects. The erosion, transport, and deposition of sediments is an essential natural service, providing habitat for aquatic organisms, regulation of water quality, and supporting nutrient recycling (Aylward et al., 2005).

These natural aquatic ecosystem services are being impaired globally through human activities, over-fertilisation with human and livestock waste, climate change and invasive species. These disturbances are having a range of intentional and unintentional impacts, including altered hydromorphology (the movement of water and sediment) in freshwater catchments and lake systems (Beletti et al., 2020). Excessive sedimentation can occur with accelerated land erosion, while sediment starvation can result from human modifications to the drainage network (Alyward et al., 2005). Lakes play a crucial role in reflecting and responding to environmental changes and have been viewed as valuable 'sentinels' (see Chapter 12) for assessing the impacts of pollution, climate warming and land use change (Williamson et al., 2008).

LAKE ONTOGENY AND SEDIMENT ACCUMULATION

Sediment types

Lake sediment is derived from allochthonous (or external) inputs from the catchment and autochthonous (internal) materials produced within the lake itself. Lake sediments comprise both inorganic and organic constituents, including eroded catchment minerogenic materials, plant matter (e.g., aquatic algae, aquatic and terrestrial plants, pollen, and spores), zooplanktonic remains, and microscopic dust and other airborne particulates. The dominant depositional components generally characterise sediments. Most lake sediments in Ireland can be characterised as lake *gyttja,* a Swedish word for highly organic black lake mud which typically forms in relatively productive lake environments. Lake marl – soft, light-coloured (white to light grey) sediments high in calcium carbonate – is common within lakes formed on limestone bedrock and in productive/eutrophic lakes with calcite precipitation in summer. As glacial processes originally formed most lakes in Ireland, the base of each sedimentary infill typically comprises inorganic grey clays that were deposited in the final stages of deglaciation under unproductive conditions, and washed into depressions by glacial meltwater (see Chapter 2). Sediment accumulation rates in lakes are determined largely by lake basin shape (morphology) and by water residence time, lake productivity and the degree of natural and anthropogenic catchment disturbance. For example, catchment afforestation and drainage operations generate erosion materials, which are subsequently transported to the lake. The term 'legacy sediment' (James, 2013) has been used to describe rates of sediment accumulation in downstream lakes far in excess of those expected in the absence of anthropogenic disturbance. Hydrological connectivity (e.g., inlets, outlets, drainage, groundwater influence), position of lakes in the landscape and hydraulic structures (e.g. weirs, dams) contribute to variance in lake water quantity and quality and in turn sediment accumulation. Runoff, soil permeability, stream density, connectivity and catchment slope are just some of the many influencing hydromorphological factors.

Basin infill: natural and anthropogenic

Sediments are sequentially deposited over the life of a lake system, and this is part of the natural lake development process or lake ontogeny (Downing, 2010). Lake basin infill or lake extinction can occur (and were called 'Blind Loughs' on historical maps in Ireland (see Chapter 17)). In erosive, nutrient-enriched environments small lakes and ponds may disappear in a few decades thus contributing to their status as temporary landscape features. Downing (2010) calculated that with sediment deposition of c. 1 mm yr^{-1}, a small lake (< 0.01 km^2) and 1 m in depth would have a lifetime of c. 1000 years, while in less productive landscapes with sediment deposition rates < 1 mm yr^{-1}, a lake could take up to 10,000 years to infill. Anderson and Battarbee (1994) estimated that an accumulation rate of > 5 mm yr^{-1} is indicative of a eutrophic lake system or a system with high external sediment inputs. Catchment and lake basin morphological characteristics are individually unique, therefore, and rates of sediment accumulation are highly variable over space and time (Appleby, 2001; Rose et al., 2011) and thus are difficult to predict.

LAKE SEDIMENT STUDIES

How aquatic ecosystems accumulate sediment is a fundamental question palaeoenvironmental science can address. Evidence of past- or palaeo-environments can be preserved in sediment, rock, or archaeological records. Palaeolimnology or the study of past aquatic environments is a sophisticated and multidisciplinary science involving not only palaeo-botany, -zoology and archaeology, but also geochronology, inorganic and organic geochemistry,

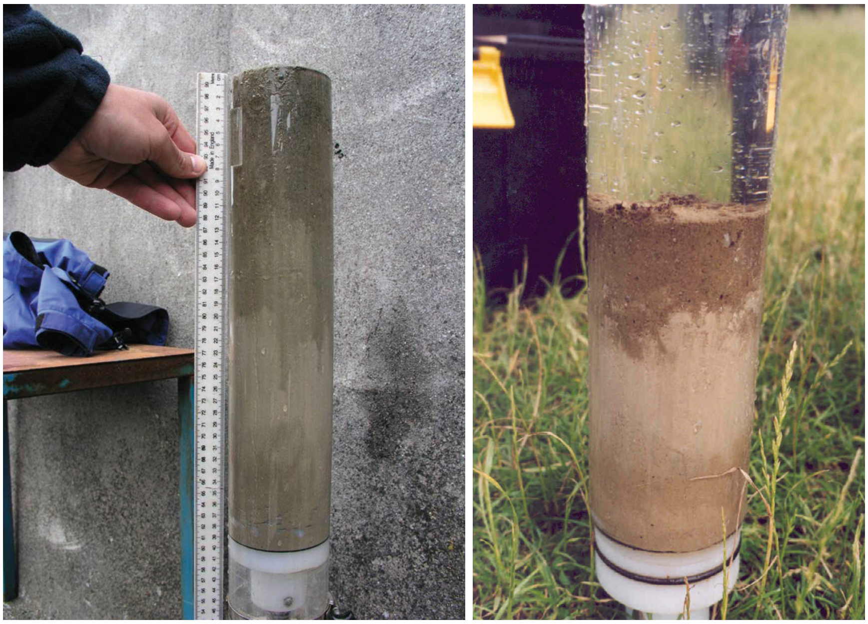


Figure 3.1 Short surface sediment gravity cores from different lake sediment basins demonstrating great variability in sediment characteristics with distinct colour changes. The core on the left is ~40 cm long, and on the right, ~20 cm, and 9 cm in diameter.

stable-isotope analysis, modelling, and statistics (Birks, 2008). Exploring the past through terrestrial (e.g., peatland) and aquatic sediment archives has been a very powerful approach as it has provided important information on baselines (pre-disturbance conditions) as well as analogues for future climate changes (Seddon et al., 2014).

Aquatic sediments are exploited as archives of our geomorphic, ecological, and anthropogenic heritage because they contain stratigraphic signatures (strata = layers) or accumulations of physical, chemical, and biological signals and thus the environmental memory of past events and activities in lakes and their catchments (Smol, 2009). Palaeolimnology involves the extraction of sediment samples (sediment coring), the application of dating techniques to determine absolute or relative ages, and the analysis of the stratigraphy and palaeoenvironments represented by the sediments (Dalton et al., 2009) (Figure 3.1). The array of studies in glacial northern hemisphere mainly incorporates four main periods: (i) Late Glacial (c. ~16,000-11,700 years); (ii) Holocene (since c. 11,700 years); (iii) industrial period (c. AD1750+), (iv) Anthropocene (c. AD1950+) (Zalasiewicz et al., 2015; Foreman et al., 2022).

A variety of themes have been investigated using palaeoecological and palaeolimnological techniques including climate change, catchment vegetation change, lake water acidification and eutrophication, and aquatic biodiversity, as well as providing important validation for lake characterisation and classification studies. Peat deposits were historically targeted for landscape (pollen) reconstructions while lake sediments were utilized in concert with developments in coring technology (Livingstone 1955; Mackereth 1958; Glew 1988) that allowed the extraction of undisturbed lacustrine (lake) sediment deposits of several metres (and potentially spanning the entire Holocene and into the Late Glacial).

Establishing sediment chronologies

In undisturbed conditions, lake sediments deposited over the life of the lake provide a continuous or near continuous record or chronicle of time. To utilise these important sedimentary archives and infer past environmental change, accurate dating is essential. Absolute dating techniques have been widely applied to date lake sediments. Radiocarbon dating, developed in the late 1940s (Reimer et al., 2013), is used to date sediment records up to c. 40,000 years of age (occasionally up to ~50,000 years), while more recent sediments (e.g. spanning the last 100-200 years) have been dated by other radioisotope techniques, including ^{210}Pb, ^{241}Am and ^{137}Cs dating (Appleby 2001; Björck and Wohlfarth, 2002). Methods that establish age equivalence (points or horizons of synchronous deposition) between sediment records can also be used to supplement absolute dates and interpret the relative age of lake sediments. These include tephra layers from volcanic eruptions (Pilcher et al., 1996; Plunkett et al., 2004), pollen markers linked to known episodes of vegetation or landscape change (Molloy and O'Connell, 2004), and fly-ash particles from combustion (Rose and Appleby, 2005). These markers, which may be well constrained chronologically, can be applied across wide geographical areas, providing age equivalency across multiple records. These methods can be more cost-effective than radiometric dating approaches. Fly ash or Spheroidal Carbonaceous Particles (SCPs), for example, a by-product of the combustion of fossil fuels, can be applied to date sediments from the last c. 50-150 years. This method is cheaper, although less precise, than the radiometric dating equivalent (Rose and Appleby, 2005). Surface sediments (the uppermost c. 1-2 cm of the sedimentary infill) have additionally been targeted as samples with the premise that they provide an integrated sample of recent limnological conditions (Smol, 2009).

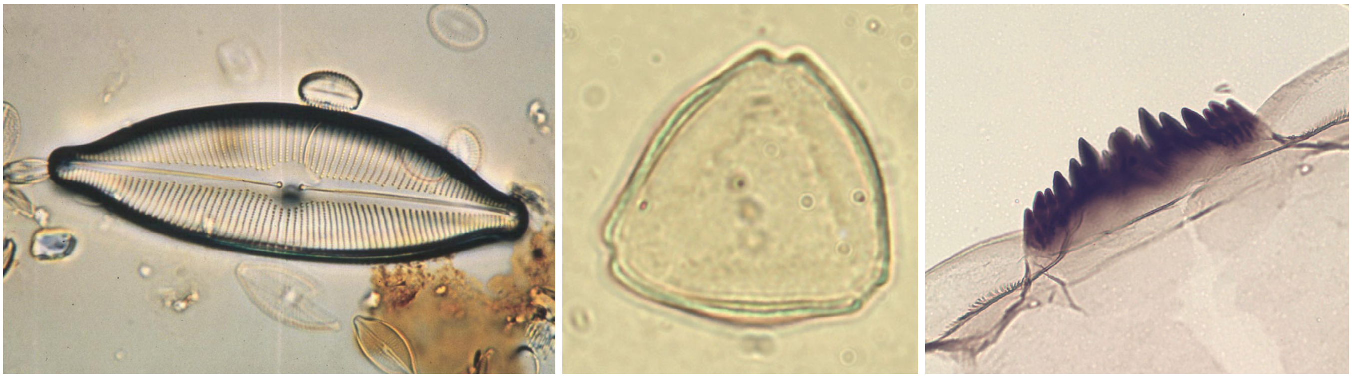


Figure 3.2 Biological proxies (a) diatom valve (*Cyclotella* spp.), (b) pollen grain (Hazel), and (c) partial midge remains (*Chironoimus Anthracinus-type*).

Physical, chemical and biological proxies

The concept of using sedimentary biological remains to infer past environmental conditions originates from biological monitoring. The rationale is that the biological response acts as a proxy or substitute for the environmental variable of interest. This approach is especially valuable when environmental variables cannot (or have not been) measured directly but a biological record exists, preserved in aquatic sediments. Proxy indicators can comprise physical, chemical, or biological remains that act as indicators of past environmental conditions (Figure 3.2). For example, diatoms (siliceous algae) are a commonly used biological proxy, as they preserve well in sediments and are sensitive to a wide range of water quality and other variables. They occur in both shallow and deep water lake habitats where there is enough light for photosynthesis and are influenced by physical, chemical and biological changes (diagenesis) when deposited in sediments. Amongst their many applications, fossil diatom assemblages have been used to infer past ecological responses to temperature change, acidification, salinity change, nutrient enrichment, and other pollutants. Pollen and spores are another important palaeolimnological proxy, providing insights into the changing composition of regional forests in response to climate change, land use change, and other catchment disturbances (e.g. fires), as well as local changes within lakes. The remains of aquatic vegetation (plant macrophytes) can further aid in the interpretation of past episodes of limnological change, including the impacts of eutrophication.

Sedimentary particle size analysis of lake sediments has similarly been applied to infer a broad array of environmental changes, for example, changes in catchment hydrology, erosive conditions associated with storms or flooding, and changing influxes of airborne particulates into lakes. Other proxy indicators of environmental change in lake sediments that reflect different limnological processes, environments, habitats, or trophic levels include chironomids, Cladocera, Ostracoda, testate amoebae (Arcellinida), fungal spores, algal pigments, (bio)geochemical elements, compounds and minerals and isotopes, and more recently, environmental, sedimentary, and ancient DNA (or preserved genetic material) (Smol, 2009). Species abundance data from sediment layers can allow for inferences about the historical quality of lake water.

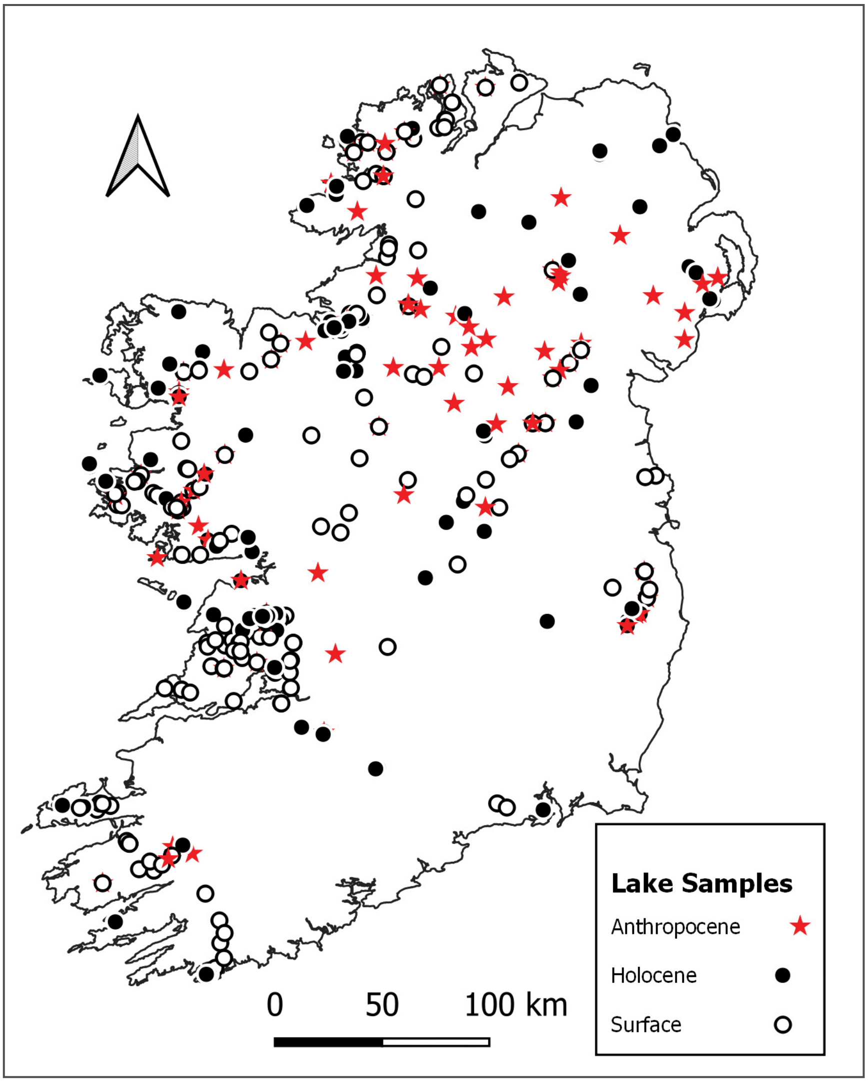
LAKE SEDIMENT STUDIES GEOGRAPHY

Lake sediment records were collated from published and grey literature sources from across the island of Ireland following Web of Science and Google Scholar searches and publicly accessible databases. These span the Late Glacial, Holocene, post-Industrial and 'Anthropocene' periods, and include lake surface sediment samples. Hereafter, the Industrial period (after AD 1750) and Anthropocene records (after AD 1950) will be referred to as Anthropocene sediment records. The following attributes were recorded: lake name, georeference, altitude (m), surface water area (km^2), length of core (cm), sediment surface age, basal core age, and source reference.

First, data were extracted from the Irish Pollen Site Database (IPOL) (Mitchell et al., 2013). This valuable source (which is no longer accessible) included details on 475 records with Holocene pollen profiles. IPOL also included 106 lake sediment studies and 18 other lake-type deposits. Other data were assembled from multi-lake palaeolimnological investigations (Rose et al., 1998; Leira et al., 2006; Taylor et al., 2006; Chen et al., 2008; McElarney et al., 2009; Woodward et al., 2012). The Neotoma palaeoecological database (www.neotomadb.org) includes 69 Republic of Ireland sites. Additionally, published single-site investigations and work contained in project reports or conducted as part of undergraduate (dissertation) or postgraduate studies (MSc and PhD dissertations; also known as grey literature) were assembled.

Some 392 lake sediment cores or surface sediment samples have been examined from 283 lacustrine systems in the Irish Ecoregion as of 2020 (see Figure 3.3). Some lakes were cored multiple times e.g. in different basins, times, and projects. The lake sediment sample sites reflect lake distribution on the island with a preponderance of sites on the western seaboard.

Figure 3.3
Location of lakes in the island of Ireland that have been sampled for Holocene, and Anthropocene, and surface sediment samples.



These palaeoenvironmental lake sediment investigations incorporate 106 long (Holocene) sediment profiles, 113 short sediment cores and 173 surface sediment examinations (Figure 3.4). Most investigations targeted lakes just once (72%), while 20 lakes (8%) have been examined for a combination of surface, Anthropocene and Holocene investigations.

Studies targeting Holocene sediment sequences usually extract long cores. The Holocene cores had an average estimated length of 455 cm (n = 82). The maximum core length extracted was 14.34 m from Molly's Lough in Clare (Lamb and Thompson, 2005). Anthropocene or surface cores are shorter in length, as expected, and have averaged 35 cm (n = 75).

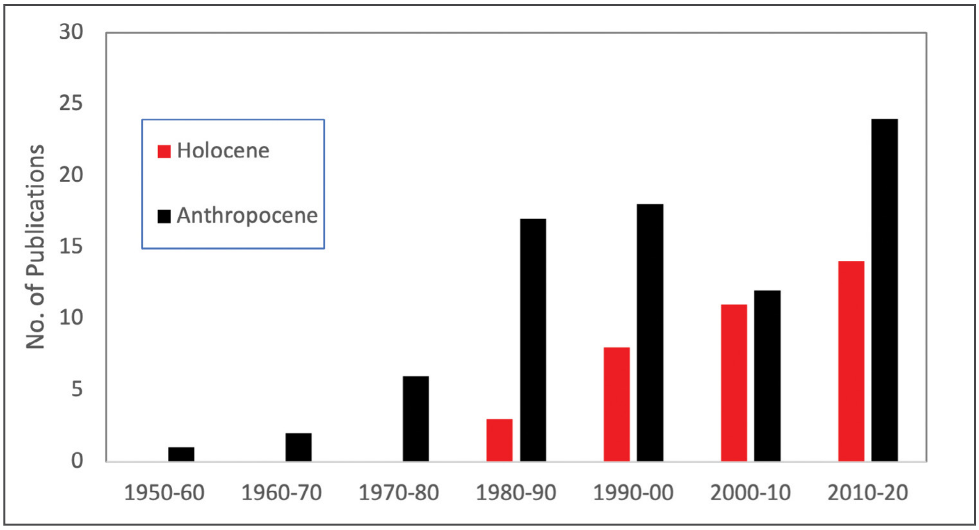


Figure 3.4 Number of palaeolimnological sediment core samples in the island of Ireland incorporating Holocene long cores, Anthropocene short cores and surface sediments (n = 392).

Of the 106 Holocene sediment profiles, radiometric chronologies have been established for approximately 81 lake sediment sequences, while relative dating (using pollen and tephra marker horizons) is estimated for a further 25 cores. The average number of radiocarbon dates per lake sediment core was six (range 1-33). Lakes with high-resolution chronologies include An Loch Mór (Inis Oírr) with 33 dated levels, Nadurcan (Donegal) and Beag (Cork) with 17 dates, and Templevanny Lough (Sligo) with 16 dates. Of the 113 Anthropocene profiles mentioned earlier were most determined using radioisotopes and SCPs to a lesser extent (24%). Down-core variations in SCP concentrations allowed estimation of the age of the sediment core bottom samples in 18 of 35 lake cores (Taylor et al., 2007).

The lakes targeted for these investigations ranged in surface area from 0.0015 to 383 km^2. Of the lakes cored, 75% (n = 247) were < 0.1 km^2 (Figure 3.5). The largest lakes sampled include loughs Neagh, Corrib, Derg, Erne Lower and Ree, which are all greater than 100 km^2. On average, Holocene sediment core sampling has targeted smaller lakes compared to the Anthropocene core samples. Lakes sampled for Holocene cores (need more and heavier coring equipment and generally rafts systems) average 12 km^2 surface area (n = 100). Extraction of surface sediments using gravity corers (which are easily deployed from a boat) in contrast enables larger lakes to be targeted in sampling programmes with an average lake size of 24 km^2 (n = 112).

Figure 3.5
Surface area (km2) of lakes in the island of Ireland targeted for sediment sampling (n = 242).

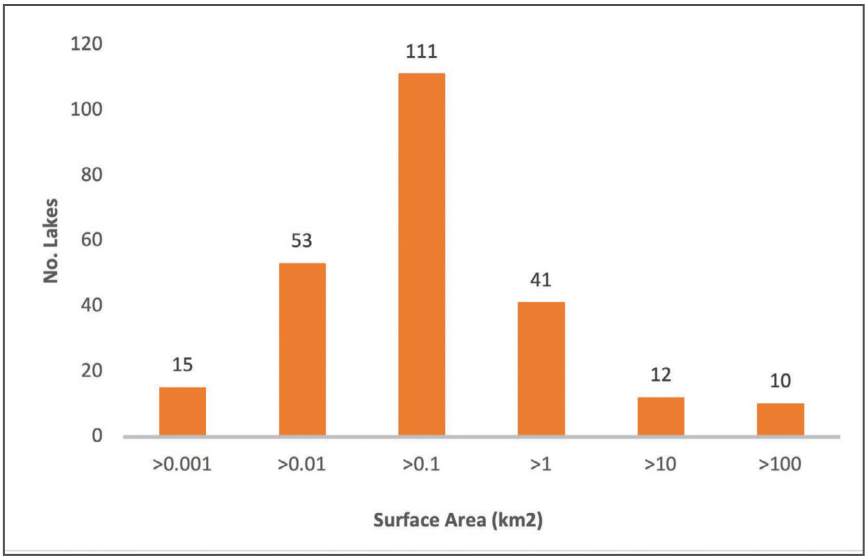
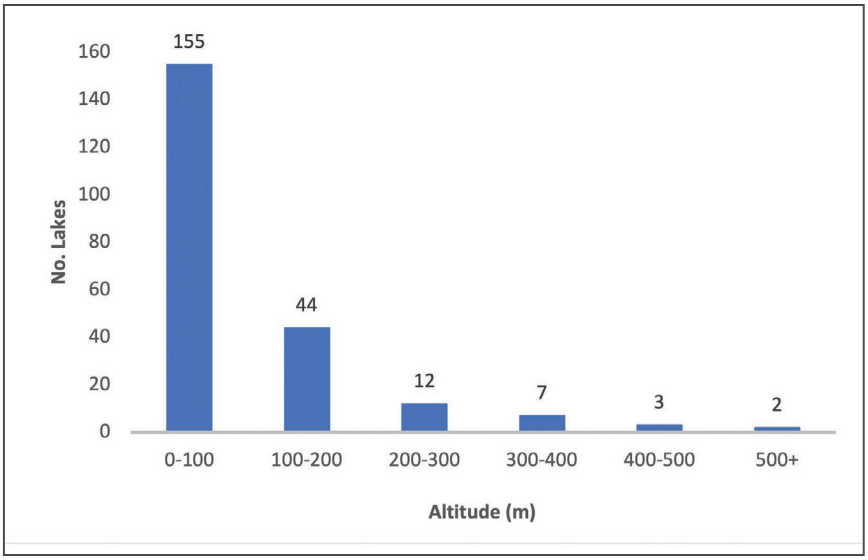


Figure 3.6
Altitude (m) of lakes in the island of Ireland targeted for sediment sampling (n = 221).



The lakes studied range in altitude from just above sea level to greater than 500 m (Figure 3.6). The two highest altitude lakes cored are Kelly's Lough, Co. Wicklow at 585 m and Diheen Lough, Co Tipperary at 554 m. 70% of the lakes cored for sediments were at altitudes below 100 m a.s.l.

Most lakes targeted for sediment sampling are today classed as having oligotrophic (48%) and mesotrophic (40%) status, while more nutrient-enriched lakes (eutrophic and hypertrophic) were in the minority (< 12%) (Figure 3.7) (see Chapter 11). The eutrophic lake category is underrepresented relative to the national population of Water Framework Directive (WFD) monitored lakes.

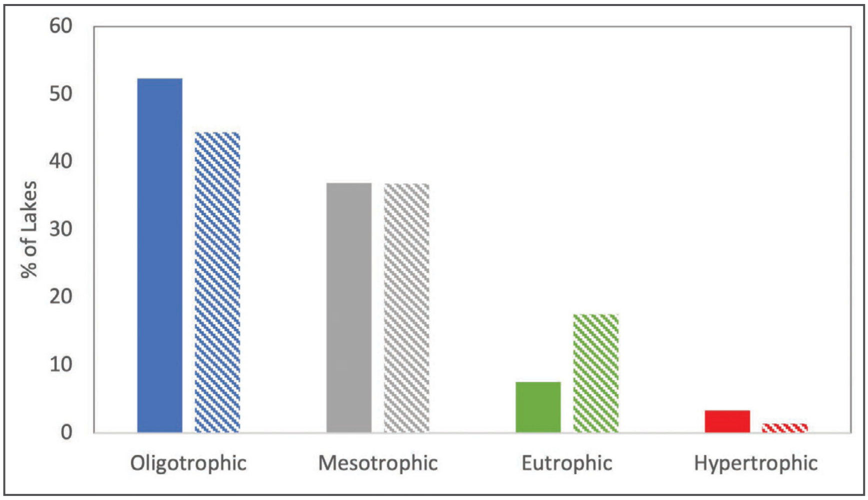


Figure 3.7
Trophic status of lakes targeted for sediment sampling (solid columns; n = 214) and national lake monitoring programme (patterned columns (n = 224).

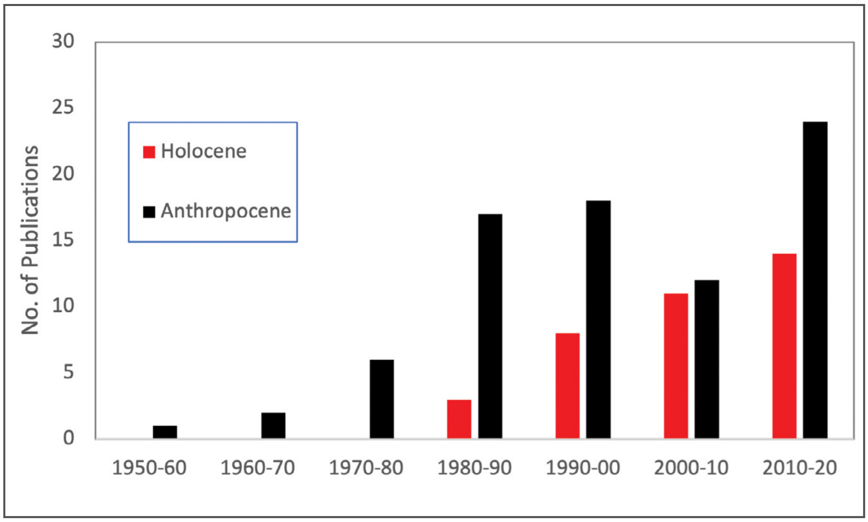


Figure 3.8
Number of publications for Holocene and Anthropocene lake sediments per decade (n = 116).

Data from these investigations have been published in c. 116 publications with more than 50% available in international publications and 18% in national publications (Figure 3.8; from the 1950s to 2020). The remaining 29% are found in undergraduate and postgraduate theses and project reports. Most of the Holocene investigations were published in the 1980s, 1990s and in the 2010s. Anthropocene investigations have expanded in the last three decades. Over three-quarters (78%) of the lakes studied were published as single-lake publications or reports while the remainder were published as part of multi-lake projects and publications.

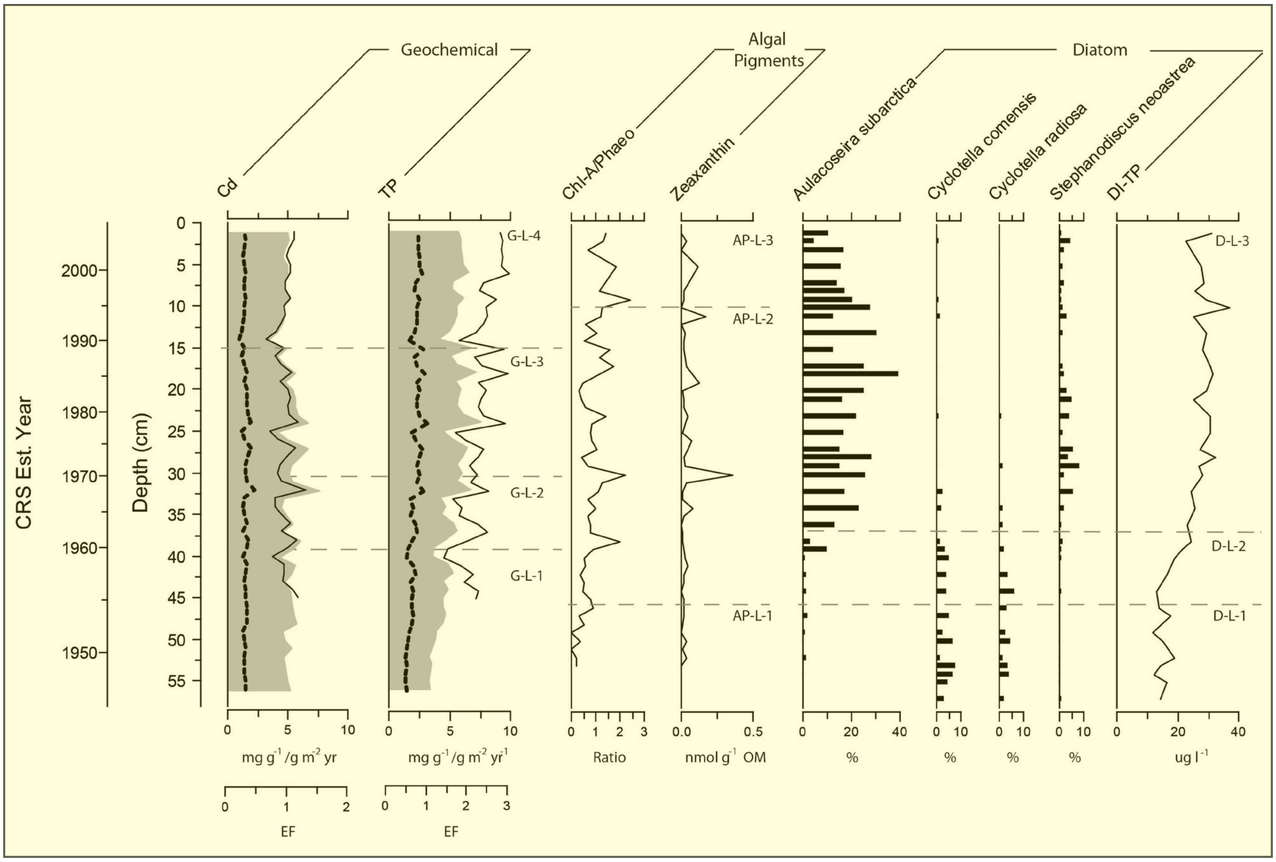


Figure 3.9 Multi-proxy palaeolimnological (geochemical, algal pigments, diatoms and diatom-inferred Total Phosphorus (DI-TP)) data collected from Lough Leane (Co. Kerry), illustrating environmental change over 6 decades. (Modified from Dalton et al., 2016).

Proxies used for environmental reconstructions

Initially, site-specific reconstructions were a major research focus for studies on the island of Ireland, while efforts to test specific ecological hypotheses emerged later with multiple-proxy (multiproxy) data used as indirect measures of several environmental variables. Studies focussing on aquatic proxies lagged terrestrial proxies (i.e. pollen). Frank Oldfield and Rick Battarbee pioneered the use of pollen and diatom records in dated lake sediment cores from Lough Neagh in the 1960s/70s. Palaeo-studies have enabled reconstructions of beetle biodiversity (e.g., Slugan Bog (Antrim)), (Whitehouse, 2006), rate-of-change analysis of contamination of lakes by atmospheric pollution (e.g., Glendalough (Wicklow) Maam, Muck (Donegal)) (Cox and Murray, 1991;

Flower et al., 1994), and hypothesis testing of lake response to a range of environmental drivers (e.g., Ballybeg (Clare), Muckno (Monaghan)) (Taylor et al., 2006, 2007; Chique et al., 2017). A sediment stratigraphic profile of multiproxy data from Lough Leane (see Figure 3.9) confirmed that eutrophication in the lake dates at least to the 1950s, and particularly from the 1970s (Dalton et al., 2016). Genetic examination using eDNA (e.g. free DNA, tissue, faeces) has emerged more recently enabling the reconstruction of individual species-specific (e.g., mammal, fish, invertebrates, plants) demographic and population responses. Correlating multiple proxies and disentangling the synergistic effects of multiple natural and Anthropogenic influencing factors (e.g. climate change, fire, land cover, land use change) remains an ongoing challenge and key to studying the sediment record. Lake ecosystems represent complex multi-dimensional systems, responding to drivers on a range of spatial and temporal scales, with different leads, lags, and thresholds across the different elements, which experience often dynamic fluctuations. Future pathways in lake sediment research need to focus on the threats posed by new and emerging pollutants, invasive species, and pest-pathogen outbreaks, plus evolving climate change effects on hydrology and land use.

RESEARCH PHASES

Quaternary research

The historical use of unconsolidated sediments to reconstruct past glaciated environments expanded in Ireland with the establishment of a Quaternary Research Committee within the Royal Irish Academy in 1933 (Dalton and O'Brien, 2019). The Committee, chaired by Robert Lloyd Praeger (1865-1953) invited Knud Jessen (1884-1971) to demonstrate Quaternary investigation techniques including sediment coring and pollen analysis. Frank Mitchell (1912-1997) was one of the students Jessen trained and he went on to become one of Ireland's most important Quaternary scientists. He was instrumental in the development of the radiocarbon dating laboratory at Trinity College Dublin that was active during the 1960s. Holocene pollen investigations of peat bog and lake sediments have been central to an active all-Ireland Quaternary research community with c. 475 pollen profiles generated as of 2011 (Mitchell et al., 2013). The first radiocarbon-dated profiles from lakes in Ireland were published in the 1970s, including in Belle Lake Co. Waterford (Craig, 1978). Holocene-scale studies have broadened to include multi-sensor sediment core loggers for lithology, x-ray florescence for geochemistry (metals), stable isotopes, and biological fossils (diatoms, chironomids, and cladocera), eDNA, and foraminifera and ostracods in coastal and marine sediments.

Pleistocene (the last ice age) and Late-glacial sediments have provided researchers with a valuable basal chronological marker confirming the potential presence of a full Holocene sediment record in the field, prior to radiocarbon analysis. Studies focusing on the Late Glacial generally focus on the timing of glacial retreat (Watson et al., 2010; Foreman et al., 2022) and the transition into the Holocene (Craig, 1978; Molloy and O'Connell, 2004). Glacial clays are often noted but not analysed in detail in many Holocene reconstructions as they generally lack organic (and biological) material. Recent work by Smazal (2024) uncovered 1.5 m of glacial clay underlying 6.3 m or 10,000 years of organic Holocene sediments in Lough Feeagh (Mayo) and conducted the first hydroacoustic investigation of lake sediment volume. A synthesis of work on the extent of Late Glacial sediments that lie at the bottom of lakes is warranted to ensure accurate representation of these deposits relative to organic deposits. This is especially important in the context of carbon sequestration estimates.

Anthropocene studies

Studies specifically using post-industrial, and more recent Anthropocene sediments commenced in the late 1960s, at the New University of Ulster at Coleraine, Northern Ireland, under the leadership of Frank Oldfield and aided by his student Rick Battarbee who pioneered quantitative diatom work. Pollen, diatom microfossil and geochemical examinations as well as palaeomagnetism investigations were undertaken and provided a critical contribution to the development of ^{210}Pb dating techniques. From the 1970s, Declan Murray at University College Dublin pioneered palaeolimnological studies in relation to the then-growing issues of eutrophication and acidification, mainly using chironomids, pigments, and geochemistry. A 1998 review of lake sediment investigations undertaken in Ireland highlighted lake responses to human activities in the surrounding catchment areas (Murray, 1998). Another wave of studies was enabled following the WFD in 2000, a directive which made specific reference to the use of lake sediments in the absence of long-term monitoring data (Annex II, 1.3), leading to enhanced funding for palaeolimnological research across Europe.

RESEARCH FOCUS

Detailed lake sediment or palaeolimnological investigations addressing a range of research hypotheses have been conducted to date in some 280+ lakes in the Irish Ecoregion. These studies contain a range of data pertaining to aquatic responses to climate, vegetation, and human impact over a variety of geographic conditions and time scales.

Climate

Cold (glacial and postglacial) and warm (interglacial and Holocene) climate periods have been the focus of lake sediment studies in an effort to infer past climate conditions. Periods of abrupt climate change, warmer intervals, environmental thresholds, and tipping points are all useful analogues for modern (and future) climate change scenarios (Seddon et al., 2014). For example, recent work has identified a more rapid and widespread deglaciation than previously thought for the Connemara ice centre at c. 17 ka, under full glacial conditions (Foreman et al., 2022).

The post-glacial Holocene period affords multiple opportunities to explore in detail climate drivers and aquatic system responses. For example, specific periods of interest include the postglacial-Holocene transition, the 8.2 K and 4.2 K cold events (Holmes et al., 2016), when there were sudden decreases in temperature because of glacial melting and disruption of ocean currents. Events such as the arrival of key tree species in lake catchments across Ireland, initiation and expansion of peat bogs, and sea-level intrusion have all been identified for Irish sites (Cassina et al., 2013; O'Connell and Molloy 2017). More recent events include the Little Ice Age, a cold period that occurred between the sixteenth and nineteenth centuries, when temperatures dropped in northern Europe and precipitated changes in catchment land use (Molloy and O'Connell, 2004; Chique et al., 2017).

Human impact

The arrival of people, the removal of tree species in the catchment, and the introduction and intensification of farming (establishment of arable crops and livestock that resulted in landscape-scale land-use change) emerged in the mid-Holocene (Taylor et al., 2018; Chique et al., 2017). Examination of sediments before, during and after these events enables assessment of changes in organic matter deposition, species presence, as well as changes in cultural eutrophication drivers: sedimentation, nutrient loading, and stratification. Land-water-sediment linkages have been examined within heavily modified landscapes in the mid to late Holocene (Taylor et al., 2017; Chique et al., 2017) and in the Anthropocene, especially in the context of nutrient (N, P) enrichment of lakes with largescale fertiliser use and animal slurries, as well as sewage effluents from settlements and industry (Dalton et al., 2016; Potito et al., 2014; Chique et al., 2017). However, the land-water-sediment association in relation to longer temporal scale climate changes is less understood in an Irish context (Taylor et al., 2018). An ongoing challenge for palaeoecologists is to understand when specific natural events (e.g., climate warming or cooling) and anthropogenic activities (including deforestation, agriculture, and the impact of settlements) began altering ecosystems and thus sediment burial, at regional and globally relevant scales. Additionally, further exploration of lake sediment carbon sinks is warranted in the context of climate warming and human pressures on freshwater systems. Landscape-scale changes in energy and matter fluxes, sediment, and nutrient transfer, affect lake processes and carbon dynamics (Anderson et al., 2020). Eutrophic temperate lakes can act as carbon sinks, while humic/dystrophic lakes can be carbon sources.

Acidification histories were examined using diatom analysis, trace metal analysis, sediment lithology and ^{210}Pb dating with higher altitude lakes Maam and Muck (Donegal) demonstrating acidification (Flower et al., 1994), while mining activities around 1850 and conifer afforestation in the 1960s were responsible for declines in lake water pH in Glendalough (Cox and Murry, 1991). The EU Flame project (Rose et al., 1998) examined fly ash particles and trace metals in lake sediments to characterise the spatial extent of industrial pollution.

In recent decades multiple Anthropocene short surface cores (< 50 cm) (Figure 3.10) were collected in three projects; INSIGHT (Leira et al., 2006; Taylor et al., 2006), an INTERREG Project (McElarney et al., 2009) and a Millennium Research Fund project at the University of Galway (Woodward et al., 2012). The INSIGHT project examined 75 lakes which were used to help validate lake typologies, conduct core top-core bottom examinations of environmental change, and enable the development of Irish ecoregion diatom and Cladocera calibration or training sets enabling inferences of past lake water quality from species data (Chen et al., 2008; 2010). This project provided pre-impact baseline conditions (generally c. AD1850) as a lake restoration target thus fulfilling EU WFD objectives, the fundamental framework for managing river basins and water quality across Europe in the first decades of this century. Twenty-three lakes in Northern Ireland had

Figure 3.10 Collecting a short (< 50 cm) sediment core Upper Lake, Killarney.

sediment investigations carried out to assess the limnological impacts of commercial forestry in the uplands (McElarney et al., 2009), while 50 lakes were examined for carbon and nitrogen stable isotopes to track changes in response to land cover and the intensification of agricultural practices (Woodward et al., 2012). Collectively these studies have succeeded in elucidating in considerable detail the recent Anthropocene histories of lakes in Ireland and have mirrored the development of palaeolimnology as a more quantitative, data-driven, and critical environmental science.

CONCLUSION

Lake sediment studies form a relatively modest subset of the Irish Ecoregion population of lakes and confirm that the island of Ireland is an excellent region to explore further the role and contribution of lake waterbodies and their sediment deposits. This chapter has synthesised research on lacustrine sediments in Ireland over the last ~75 years, as palaeolimnology has matured from a descriptive account of landscape history to a critical, data-rich, hypothesis-driven science. The range of lake sites examined to date is limited and exploration of the data confirms that much work remains inaccessible in grey literature; more catchment and sediment core data need to be collated into accessible databases. Low altitude and oligotrophic lakes have been the main targets for research (reflecting their dominance of lake type in Ireland), and natural and culturally eutrophic lake systems are under-researched relative to other trophic types. Further exploration of total lake sediment volumes, sediment accumulation rates, and lake basin characteristics will provide additional spatial and temporal context from which regional and national patterns in aquatic system response can be elucidated. The deeper understanding of the past that palaeolimnology provides offers fundamental insights into maintaining, improving, conserving, and managing these key aquatic resources into the future.

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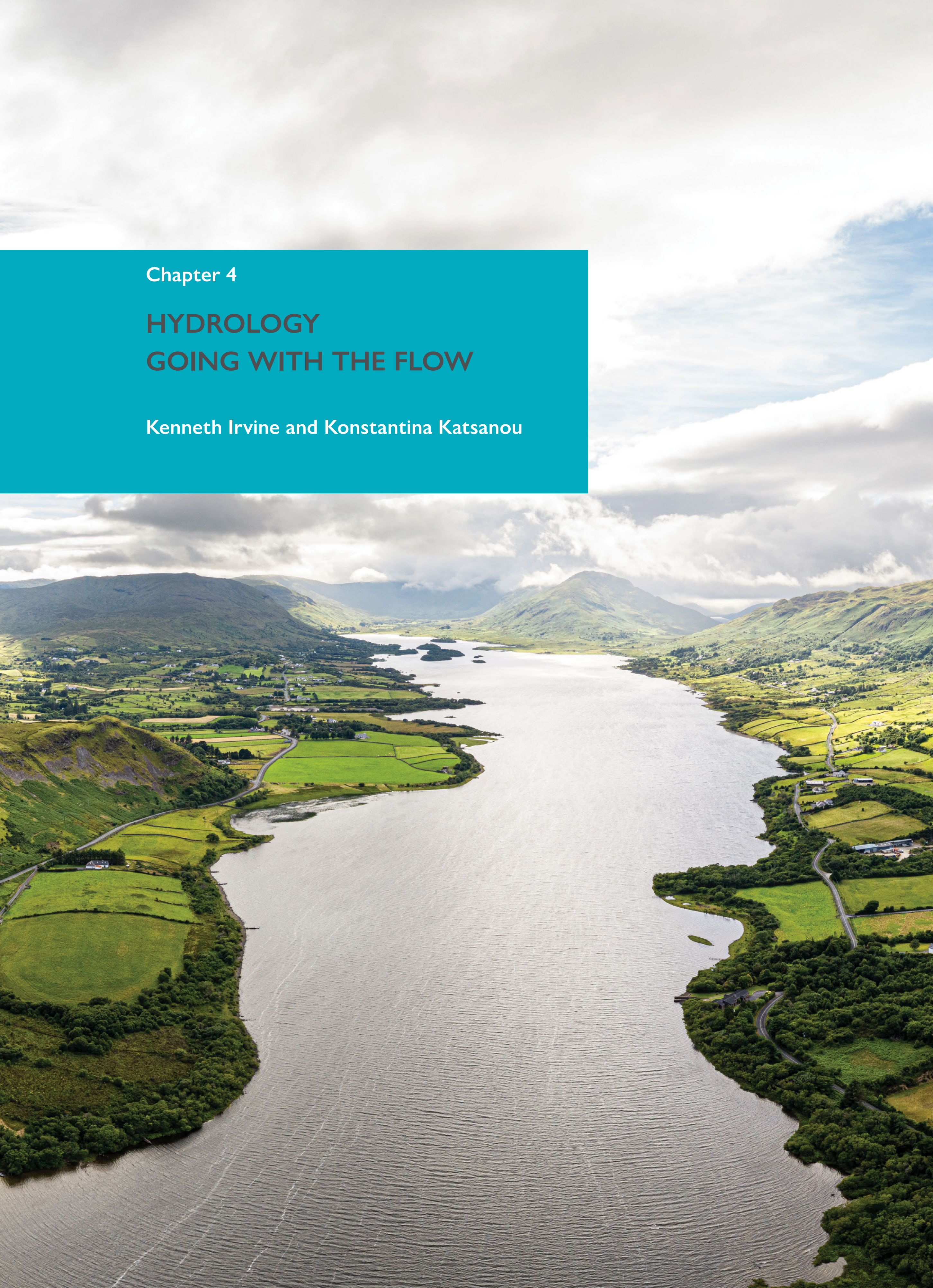
Chapter 4

HYDROLOGY
GOING WITH THE FLOW

Kenneth Irvine and Konstantina Katsanou



SUMMARY

Ireland's small land mass has an extraordinarily large number of lakes spanning an extensive range of shapes, sizes, hydrology, and geological settings. This supports diverse ecological structures, which face various pressures affecting lake ecology. Commonly known pressures are from nutrients, acidification, and other pollutants, but their impact is also moderated by lake size, shape, and water residence time. An often overlooked but increasingly recognised pressure is change in hydrological regime (quantity and dynamics of flow, connection to groundwater); continuity (ability of sediment and migratory species to pass freely up and down rivers and laterally within the flood plain); and morphology (i.e. physical habitat – compositions of substrate, width/depth variation, structure of bed, banks and riparian zone). Collectively, these are aspects of hydromorphology, the alteration of which is explicitly recognised in current water policy. This chapter provides an overview of the importance of hydromorphology for the status and management of lakes in Ireland and their ecology. It concludes with case studies that illustrate some key points.

Keywords Hydromorphology, lakes, Ireland, pressures, policy, management

INTRODUCTION

The high variation in geomorphological character of catchments across Ireland has resulted in many different types of lakes (see Chapter 1 and 2). Their physical dimensions vary from shallow to deep, circular to dendritic and with water residence times of days to years. Given the natural history and diversity of lakes in Ireland, it is no wonder that the country's lakes were historically well appreciated for their natural history, tourism, and fishing (see Chapters 6 and 18). However, Ireland has not escaped the consequences of economic growth, which have increased human pressures and impacted its lakes. While there is evidence of declines in water quality as a consequence of the high human population in the period leading up to the Great Irish Famine, followed by recovery (Donohue et al., 2010), the scale and intensity of pressures have accelerated over the last 50 years (see Chapter 11). These pressures can arise some distance from the lake but still affect its ecology. This illustrates that lakes are not isolated entities, but hydrologically connected sentinels of changes in activities on the land. This chapter provides an overview of the hydrology of lakes across Ireland. It does this through the concept of hydromorphology. The chapter considers how hydromorphology shapes the ecological integrity of a lake, the connection with the wider landscape and how the management of hydromorphological alterations fits within the policy framework of European legislation. The chapter concludes with two case studies to better illustrate how pressures on the hydromorphology can affect the ecological status.

HYDROLOGY, EUROPEAN WATER POLICY, AND NEW DEFINITIONS

Political agreement on the need to manage environmental protection in light of economic growth and social aspiration lies at the heart of sustainability. In Europe, a range of Environmental Directives instigated in the 1970s were a response to the decline in water quality and habitats. Recognition that policies to reduce impacts on waterbodies through piecemeal European Directives were, nevertheless, insufficient and led to the passing into law of the EU Water Framework Directive (WFD) (2000/60/EC). The requirements of the WFD are extensive but have an overall aim of:

> maintaining and improving the aquatic environment in the Community. This purpose is primarily concerned with the quality of the waters concerned. Control of quantity is an ancillary element in securing good water quality and therefore measures on quantity, serving the objective of ensuring good quality, should also be established (WFD, preamble (19)).

A new element in the WFD was that the assessment of waterbodies would be based primarily on ecological status, judged against a defined baseline or reference condition, and assessed along a five-class gradient of high, good, moderate, poor and bad. Also included in the Directive is the specific need to assess hydromorphology and hydromorphological alteration relative to reference state.

Under the WFD, hydromorphological elements comprise:

- hydrological regime (quantity and dynamics of flow, connection to groundwater);
- continuity (ability of sediment and migratory species to pass freely up and down rivers and laterally within the flood plain); and
- morphology (i.e. physical habitat – compositions of substrate, width/depth variation, structure of bed, banks and riparian zone).

Like the WFD approach to water chemistry, hydromorphology should be assessed so that prevailing conditions are compatible with a defined ecosystem status. This means that good hydromorphological conditions provide physical habitat for biota, such as fish, invertebrates, and aquatic plants, commensurate with good ecological status, as measured by biological quality elements. In Annex V of the WFD, hydromorphological conditions are, however, only described explicitly for high-status waterbodies that 'correspond totally or nearly totally to undisturbed conditions'. For other status classes, 'conditions [are to be] consistent with the achievement of the values specified [above] for the biological quality elements'. This led to an interpretation by the Irish Environmental Protection Agency (EPA) that 'Only sites that are at high status based on other ecological quality elements may be downgraded to good status based on the hydromorphological assessment failing to reach high status. As the rules of the Directive currently stand, this is the only scenario where hydromorphology can be used in classification' (EPA, 2021a). This assumes that assessment of the biological elements can be independent of the physical environment. Clarity on the point seems to be an ongoing issue. Advice to the European Commission ECOSTAT, the WFD advisory group, was that assessment methods should be able to reliably assess hydromorphological conditions along the full range of the five status classes (Kampa et al., 2019). WFD guidance is not specific in what physical attributes comprise a hydromorphological element; it is only that changes in the conditions of the elements can have an impact on the ecological state (European Commission, 2003). This reveals the need for further description of how identified and measured hydromorphological alterations affect the biological communities of waterbodies (Argillier et al., 2022). The assessment of hydromorphology is, therefore, crucial for the management of all water bodies to assist in identifying and mitigating the impacts of hydromorphological alterations.

A separate category of lake type is reservoirs or lakes that have undergone substantial physical modifications that could affect ecological health. These are defined as either Heavily Modified Waterbodies (HMWBs) or Artificial Waterbodies (AWBs). For these waterbodies, targets of acceptable condition are defined as having good ecological potential. It is not reasonable to automatically equate the ecological structure of hydromorphologically modified standing waterbodies with true lakes (Moss, 2008). These definitions and their implications for lake management are very relevant for the interpretation of the WFD in Ireland, including different approaches between the Republic of Ireland (RoI) and Northern (NI) Ireland. For example, Lough Derg in the Republic is considered a natural lake, while Lough Erne in NI is a HMWB, yet both have major controls of water levels.

HYDROMORPHOLOGY OF LAKES

A lake comprises a complex matrix of habitat patches, comprising both the hydrological structure of open waters and varied sediment composition with or without plant growth. Exposure, direction, duration, and strength of wind further influence sediment structure and seasonality of plant and animal communities. The physical structure of a lake inevitably means that there are different zones, each with ecological communities that are adapted to the ambient environment. Some organisms will be restricted to particular areas. Others will be able to utilise a variety of habitats. Traditional assessment of lakes was based mainly on open water measurements of water chemistry and phytoplankton densities (OECD, 1982). This view of lake assessment was seriously challenged with both increasing evidence of how phytoplankton communities could be strongly influenced by open-water plankton dynamics and the behaviour of fish and that the littoral (nearshore) zones of lakes can be extremely important for lake ecological functioning. The vulnerability of the littoral zone to anthropogenic pressures is often overlooked (Vadeboncoeur et al., 2002).

Littoral zones

Morphologically intact littoral zones support rich, diverse biological communities, act as biological dispersal pathways, sequester nutrients and other pollutants, and dissipate wave energy that reduces bankside erosion (Strayer and Findlay, 2010). The heterogeneity of littoral habitats is high within and among lakes. Common littoral habitats are stony substrata,

Figure 4.1 Examples of the littoral areas present in many lakes in Ireland. Photos: K. Irvine.

sand, macrophyte beds and tree roots (Figure 4.1), but the distinctiveness of invertebrate communities (and likely other groups) within lakes is often nested among a range of lake types (White and Irvine, 2003). However, the spatial heterogeneity of littoral invertebrates within similar types of lakes is reduced with increasing nutrient status and other habitat modifications (Donohue et al., 2009; McGoff et al., 2013; Evtimova and Donohue, 2016).

The WFD opened up discussions more generally on the application of littoral invertebrates for lake assessment, often against a prevailing view that while they had long been used in the monitoring of rivers, their use in lakes was limited. Several EU projects (see links at end of chapter) further investigated the pan-European application of littoral invertebrates for lake assessment, including Irish sites. A key finding has been that littoral invertebrates can be highly useful indicators of hydromorphological alterations (Poikane et al., 2020). Bankside modifications in lakes in Ireland tend to be predominantly from riparian land use changes, with an overall lower number of harbours, jetties, or hard embankments than in many other European countries.

In ecology, a positive relationship between taxa richness and structural complexity is common. For the hydromorphological assessment of lakes, the Lake Habitat Survey (LHS) was developed by Rowen et al., (2006), using sediment structure, aquatic plants, and a range of easily recognised physical components that can potentially affect ecological response to hydromorphological changes. It covers both small-scale spatial effects and larger ones over sections of the littoral parallel to the shore. It was tested successfully for its relationship with littoral macroinvertebrates in Lough Carra (McGoff and Irvine, 2009) and then across European Lakes (McGoff et al., 2013), where a good relationship was found between some metrics of the LHS and littoral invertebrate communities. Currently, Lake-MImAS (Rowan et al., 2012), a simplified and more rapidly applied version of LHS, is used as part of the WFD monitoring programme in the RoI and NI.

A major hydromorphological alteration within lakes is water level fluctuations, with frequent and high amplitude water level fluctuations (WLF) of reservoirs having a notable impact on littoral biotic communities (Hofman et al., 2008; Wantzen et al., 2008). Evtimova and Donohue (2016) working in four Irish sites with high (Anure, Eske, Muckno and Oughter) and four with low (Ennell, Moher, Owel and Sleagh) WLF showed that the former had significantly more coarse substrata in the shallow littoral, less macrophyte vegetation and greater proportions of motile diatoms and omnivorous invertebrates than those with low WLF.

Dynamics of flow and residence time

The starting point for a good understanding of any individual lake is a reasonable estimation of lake bathymetry, volume, and physical structure. Hypsographic curves (Rounds et al., 2003) provide a means to visualise bathymetry as the relationship between lake area and water depth and can be easily compared across lakes. A hypsographic curve also offers important information for modelling processes in lakes that can change with depth, such as nutrient transformations. While measuring lake bathymetry may seem like a simple data collection exercise, it is time-consuming and resource-intensive. For example, a simple empirical model to estimate phosphorus loading to several lakes across Ireland (Figure 4.1) was conducted as part of the lead-up to the implementation of the WFD in Ireland (Irvine et al., 2000). However, this required estimates of volume and hydrological inputs and outputs to estimate the mean hydrological residence time for each of 31 study lakes (Figure 4.2). Using the technology of the day, catchment areas were digitised from Ordnance Survey 1:25000 scale maps. Estimates of the lake volume were calculated using either existing bathymetric charts or field surveys. Mathematical interpolation techniques using raster modelling software were applied to the data to give a continuous estimate of the depth across the lake, enabling estimates of lake volume as well as mean and maximum depth. Meteorological data of Met Eireann were used to estimate hydrological inputs, which, divided by lake volumes, provided estimates of retention times. Estimates of the loss of rainfall to runoff from evapotranspiration to derive net effective rainfall rates were developed from measurements of evapotranspiration from 14 Synoptic Weather Stations. Temporal patterns of meteorological data allowed for estimates of summer and winter retention.

The field surveys conducted as part of Irvine et al., (2002) and the interpolation of the data provided a more accurate measure of volume than simply multiplying mean depth by area. While traditionally, lake bathymetry was collected in the interests of navigation or as single studies on a lake (Figure 4.3), it is essential for the analysis of hydrometric impact, and an openly accessible repository for such data would be a valuable resource. This does not seem to be part of standard dissemination, although it is extremely useful for lake research and management. However, work by Moe et al., (2016) assessing environmental risks of Unconventional Gas Exploration & Extraction involving hydraulic fracturing (fracking), collated bathymetries and lake volumes from 33 lakes, including some larger lakes (Upper and Lower Lough Erne, Lough Melvin, Lough Gill, Lough Arrow, Upper and Lower Lough Macnean, and Lough Allen) equipped with staff gauges for water level measurements.

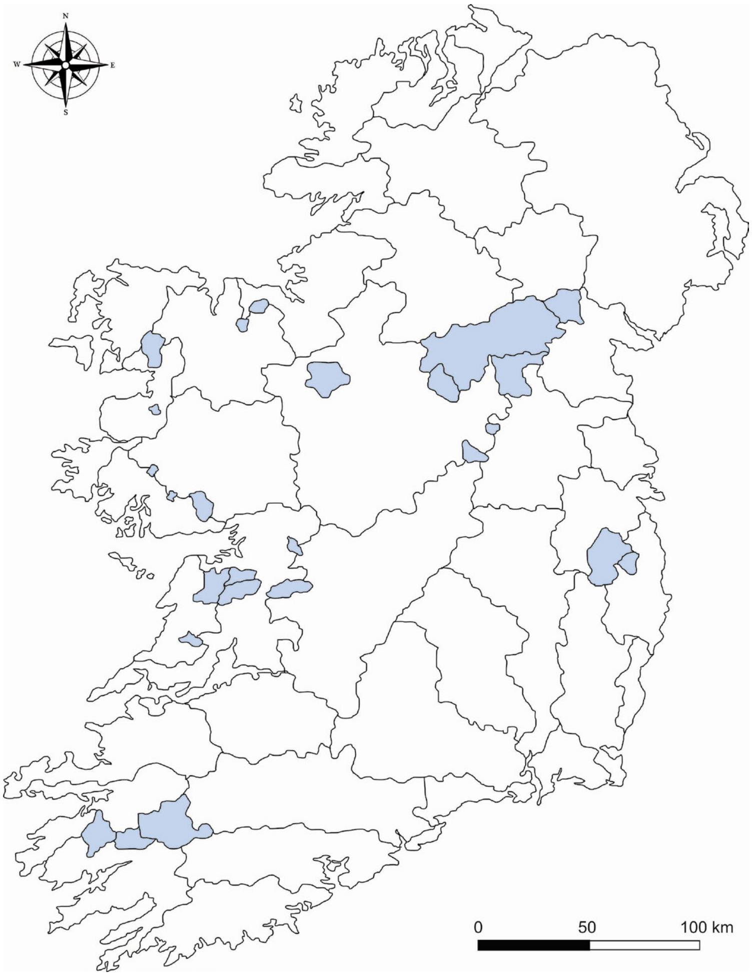


Figure 4.2
Map of the Irish hydrometric areas showing the catchment boundaries of lakes studied in Irvine et al., (2001).

Beyond the description of lake bathymetry, a variety of modelling techniques can support the management of lakes by estimating lake resident times and circulation patterns. With some notable exceptions for the exploration of particular management options (e.g. Bell et al., 2005; Irish Water 2016a), these have not been much used in Ireland.

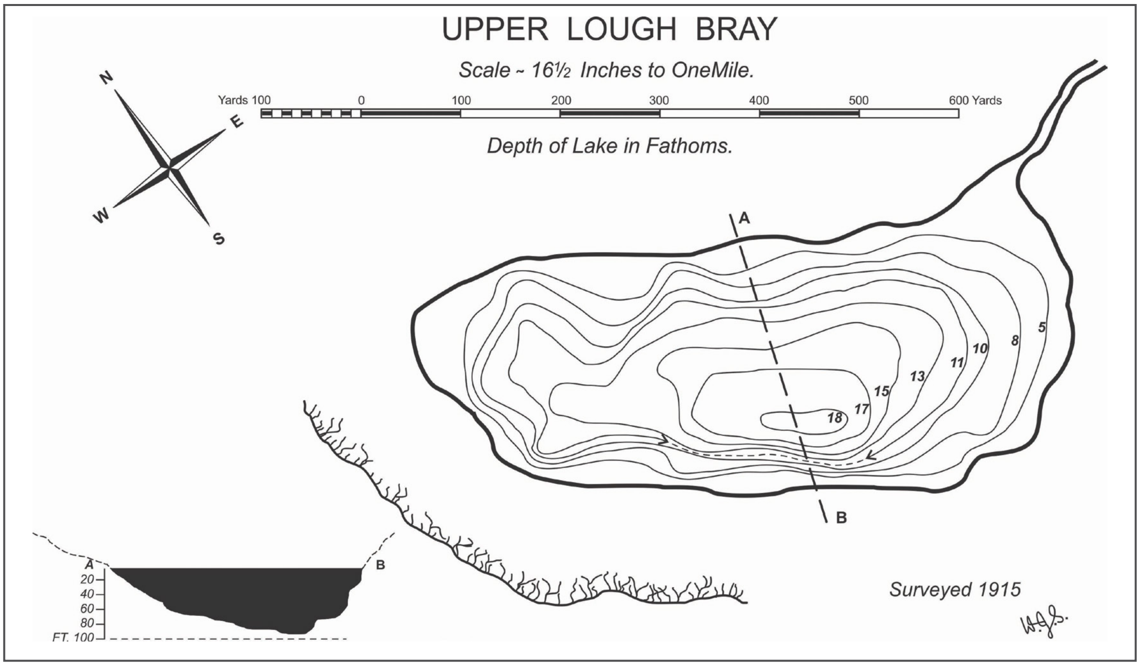


Figure 4.3
Bathymetric chart for Upper Lough Bray (1915), reproduced from Beirne (2020).

Groundwater

Connection between lakes and groundwater, while very important for the functioning of many lakes, remains largely qualitative across Europe (Argillier et al., 2022). Despite its acknowledged impact, understanding groundwater discharge and associated nutrient loading to lakes is limited in Ireland's water monitoring and management programmes (Wilson, 2016). The spatial and temporal heterogeneity of groundwater discharge makes locating and quantifying inputs difficult. Quantifying groundwater discharge as a substantial source of freshwater and nutrients to lakes is important for nutrient management of lakes and implementation under the WFD of so-called programmes of measures. This requires a three-dimensional understanding of catchments, considering surface and groundwater transport and contamination sources, along with geochemical processes influencing nutrient flux from groundwater to surface waters.

In karst aquifers, conduit flow is the primary type of flow. In many cases, there can be a strong groundwater connection with a lake, particularly where the drainage network is poorly developed. Temperature variations are commonly used to investigate the inflow of groundwater into lakes since the consistent temperature of groundwater can be easily tracked compared with the seasonal fluctuations in surface water temperature. In Ireland, during summer, groundwater discharge is identifiable in satellite imagery through

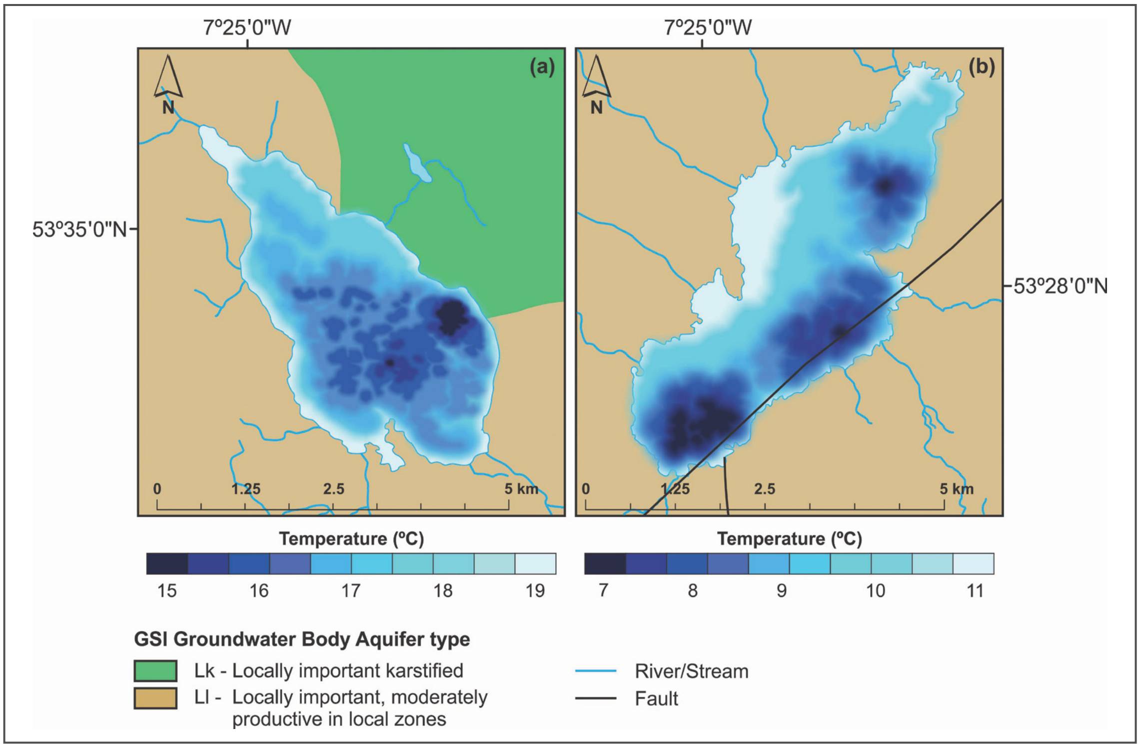


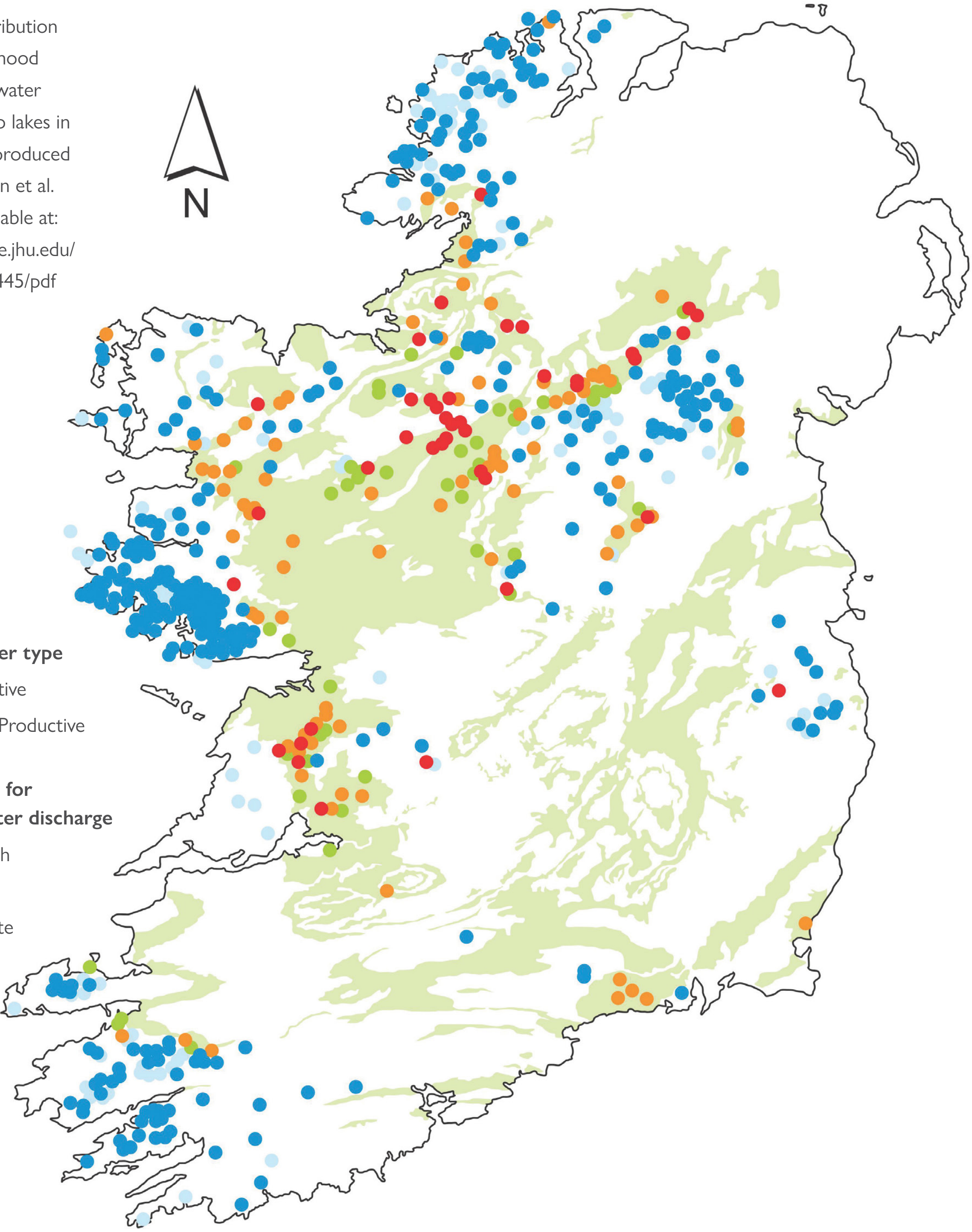
Figure 4.4 Surface water temperature maps generated from Landsat thermal imagery acquired for (a) Lough Owel on 20 July 2013 and (b) Lough Ennell on 18 April 2014. Reproduced from Wilson (2016) https://muse.jhu.edu/article/809445/pdf

cooler thermal signals. Wilson (2016), utilising Landsat thermal imagery to map surface water temperature patterns, identified cold anomalous plumes along the shoreline of Loughs Owel and Ennell, suggesting groundwater input (Figure 4.4).

As part of the categorisation of Irish waterbodies required for the WFD, Dublin Council Report (2009) identified that 18 of 127 lakes for which data was collated may be groundwater-dependent lakes. Nearly all of these are low-lying lakes (less than 200 masl) with hard water and high alkalinity, occurring particularly in the karst limestone area of central and western Ireland. Ten have karst conduits; four are surrounded by bedrock with karstic features, and three are surrounded by bog. For one (Bofinna Lough, Cork), it was difficult to attribute likely flow patterns.

Wilson et al. (2016) conducted a nationwide evaluation of the probability of connectivity between groundwater and surface water. They used GIS and satellite images to detect thermal signals that could suggest groundwater discharge into lakes by analysing remote sensing images and creating temperature anomaly maps. The conclusion of this process led to the national spatial distribution map of the likelihood for groundwater discharge to lakes (Figure 4.5).

Figure 4.5
Spatial distribution of the likelihood for groundwater discharge to lakes in Ireland. Reproduced from Wilson et al. (2016) available at: https://muse.jhu.edu/article/809445/pdf



PRESSURES AND CASE STUDIES ON LAKE HYDROMORPHOLOGY

Many of the pressures on lakes through hydromorphological alterations are referred to above. In this section, we focus on some particular pertinent pressures, using case studies to identify and elaborate on them.

Water Abstraction

An important source of water for public use is abstraction of water from lakes. This requires effective management to ensure the sustainability of supply and protection of ecosystems. Uncertainty of supply will increase with climate shifts (see Chapter 14). Water abstraction is a key issue in the WFD. On 26th January 2024, the European Commission announced that it would take Ireland to the European Court of Justice for 'failing to correctly transpose Water Framework Directive protecting waters from pollution'. Particular areas identified for improvement were 'water abstraction, impoundment and activities causing hydromorphological changes such as dams, weirs and other interferences in natural water flow' (https://ec.europa.eu/commission/presscorner/detail/en/ip_23_166). The indication is, therefore, that the Water Environment (Abstractions and Associated Impoundments) Act 2022 did not allay the Commission's concerns, which have been ongoing for many years.

The Act requires the registration of abstractions greater than 25 m^3 day^{-1} and the issuing of a licence for abstractions of 2000 m^3 day^{-1} and above. The 2000 m^3 threshold could provide enough water to supply the population of a medium-sized town such as Nenagh, Co. Tipperary. The threshold volume for registration of 25 m^3 day^{-1} is equivalent to the supply for approximately 42 households. In NI, England and Wales, abstractions over 20 m^3 day^{-1} require a licence. Registration in NI and Scotland is required for abstractions from 10 m^3 day^{-1}. However, in response to a complaint that the Northern Ireland Environment Agency had failed to enforce abstraction permits on the Crumlin River, where parts of the upstream channel dry out, in breach of Water Environment (WFD) (Northern Ireland) Regulations 2017, the Office of Environmental Protection (OEP) in NI decided 'not to prioritise further investigation or enforcement action, partly because there are a large number of unregulated abstractions in NI across more sectors' (ENDS Report, 2024). The implication is that successfully managing water abstraction for environmental protection is a widespread challenge.

Table 4.1 Monthly abstractions as percentage of lake volumes and estimated residence times. Reproduced from Dublin City Council (2009).

Lake Name	County	Lake Volume (m^3)	Monthly Abstraction (m^3)	Monthly Abstraction (as % of Volume)	Q50 Inflow m^3/s	Lake Residence Time (days)
Anaserd (Lough)	Galway	2,794,800	26,460	0.95%	0.085	381
Doo Lough	Clare	7,304,080	105,000	1.44%	0.589	144
Acorrymore (Lough)	Mayo	2,720,718	41,550	1.53%	0.093	339
Talt (Lough)	Sligo	8,664,150	233,670	2.70%	0.144	696
Loughaunwillan	Galway	2,189,257	67,980	3.11%	0.132	192
Nadreegeal Loughs	Cavan	3,892,810	130,080	3.34%	0.067	672
Cummernamuck (Lake)	Kerry	682,066	23,850	3.50%	0.042	188
Aille Lough	Mayo	164,922	5,850	3.55%	0.005	382
Lickeen Lough	Clare	3,285,360	126,000	3.84%	0.172	221
Skeagh Lough Upper	Cavan	1,348,380	64,500	4.78%	0.070	223
Moher Lough	Mayo	1,446,247	102,240	7.07%	0.182	92
Illauntrasna (Lough)	Galway	162,822	19,230	11.81%	0.018	105
Loughaunore	Galway	190,808	27,030	14.17%	0.027	82
Fawna (Lough)	Galway	22,778	4,080	17.91%	0.006	44
Nambrackkeagh (Lough)	Galway	91,277	19,080	20.90%	0.020	53
Carrowlustia Lough	Sligo	233,463	177,330	75.96%	0.158	17
Eirk Lough	Kerry	269,514	11,730	2.50%	0.025	125
Callee Lough	Kerry	1,772,452	45,420	8.10%	0.081	253
Mount Eagle Lough	Kerry	300,679	15,000	2.10%	0.021	166
Tooreen Lough	Kerry	69,917	6,000	8.58%	0.015	54
*Lene	Westmeath	35,214,750	135,000	0.38%	0.254	1605
*Labe (Lough)	Sligo	271,015	3,990	1.47%	0.015	209
*Bofinna Lough	Cork	318,923	45,000	2.40%	0.024	154
*Holan (Lough)	Mayo	217,385	3,450	1.59%	0.006	419
*Bane (Lough)	Meath	3,953,580	120,000	3.04%	0.060	763

*: The contribution of groundwater inflow to the lake is not considered in the calculation of residence time

In the RoI, the new Act provides an exemption for Environmental Impact Assessment or Appropriate Assessment under the Habitats Directive for Electricity Supply Board (ESB) hydroelectricity projects. An evaluation of the fitness for purpose of the new Water Environment (Abstractions and Associated Impoundments) Act 2022 should be undertaken, also in light of the differences in approach and experience in the RoI and NI.

From the initial characterisation stage of WFD (Article V) implementation in Ireland (see above), an analysis of abstraction pressures of the 127 lakes found that 78 had ratios of abstraction to net surface inflow >10%, which based on expert judgement were at risk of not meeting the environmental objectives of the WFD (Dublin City Council, 2009). Of these, 65% have catchments <2 km^2. Seven lakes (including Carrigavantry Reservoir in County Waterford) were estimated to have >100% abstraction:net inflow. This should indicate a major groundwater supply to the lake. Some of these lakes were also estimated to have low groundwater supply relative to abstraction. These included the calcareous Loughs Lene and Owel, suggesting the need for further investigation (e.g. Wilson et al., 2016).

Table 4.1 identifies the percentage of volume abstracted from 25 lakes with highest abstractions and their estimated residence times. Many of these would exceed an average of 2000 m^3 day^{-1}. Several others would probably exceed this threshold from time to time unless abstractions are held constant. Eight of the lakes exceed a monthly average of 5% of the estimated average water volume, whose potential impact on ecological status should be reviewed case-by-case.

Linking the catchment to the lake

Hydromorphological alterations upstream of a lake or in the catchment can change water volume and throughflow, and hence temporal residence time. The most dramatic hydrological impact on a lake is from the conversion of a river or lake to a reservoir by the construction of a dam or from upstream dams that affect water flow into a downstream lake. These can also reduce sediment movement and species migrations through the river network, even as a consequence of relatively small barriers up or downstream. Reduced continuity of river flow, relating to the pressures from dams and abstractions, now accentuated by climate change, is of major international concern (Grill et al., 2019).

Changes in the catchment that lead to alterations (usually increases) in sediment and nutrient loads can affect the accumulation and nature of the sediment in the littoral or deeper parts of a lake. Alternatively, sediment trapped behind a barrier can lead to the depletion of the sediment budget downstream. Both sediment depletion and excess of fine sediments can have a major impact on biological communities, and the lack of attention to sediment dynamics as a part of hydromorphological assessment may overestimate ecological quality status (Nones et al., 2017).

Across many parts of Ireland, the hydrological connectivity between land and waterbodies has been enhanced by the clearance of (semi)natural vegetation, development on floodplains and land drainage. The 1945 Arterial Drainage Act in the Republic of Ireland, so as to provide long-term improvement to agricultural incomes, with more areas for livestock grazing or production of higher crop yields (OPW, 2021), also altered hydrological regimes and habitat structure of surface waters. The Arterial Drainage (Amendment) Act 1995 further allows for localised Flood Relief Schemes to protect cities, towns, and villages. The Office of Public Works (OPW) is responsible for the maintenance of 11,500 km of channels, 800 km of embankments, some 19,000 bridges and further ancillary structures such as weirs, sluice barrages, sluices, pumping stations and tidal flap gates. Currently, the drainage schemes are reported to cover 260,000 ha of agricultural land (https://irishriverproject.com/2021). While the effects of land drainage most immediately affect rivers, there are also potential effects on lakes connected to the river network. Land drainage increases water flow and transport of nutrients, and sediments are invariably deposited in lakes. Alterations of sediment structure because of river maintenance can reduce habitat used for spawning of fish that also rely on lakes.

Hydromorphological alterations, especially when coupled with increased nutrient loads, can lead to a disturbance that promotes the expansion of alien species. These are serious problems in many lakes (see Chapter 13). For lakes and rivers and their riparian zones, several species that pose particular concern include Japanese knotweed (*Fallopia japonica*), Himalayan balsam (*Impatiens glandulifera*), zebra mussels (*Dreissena polymorpha*), and crayfish plague (*Aphanomyces astaci* infecting the white-clawed crayfish *Austropotamobius pallipes*). For sedentary species, the coverage of the lake bed means that they themselves become the hydromorphological alteration.

Climate change

In Loughs Neagh and Feeagh, featured in Chapter 12, the mean annual water temperature from the mid-1990s has been steadily increasing. In Lough Feeagh, the surface water temperature of the lake has warmed at an annual average rate of 0.18°C each decade between 1970 and 2020. It continues to increase into the current decade, with temperatures in 2023 being higher than any other year in the record. Seemingly modest changes can have large impacts on the physical structure of the open water of lakes, the response of nutrient to phytoplankton growth, the spread and proliferation of invasive species and many other facets of lake ecology. Yet, the effects of climate change are largely disregarded by the WFD, even though this will have a dramatic impact on how hydromorphology relates to ecological state. The need for an adaptive management strategy will apply to a range of pressures, including invasive species spread, more extreme climate events, and the need for greater hydropower production and associated impacts to meet climate targets (Vaughan et al., 2009). Because the WFD is based on the changes in an ecosystem relative to a reference state or estimated high ecological potential, this provides difficulty in assessing pressures and impacts in lakes if there is now a climatic 'magnifier' that also affects estimated reference state (Nones and Pescaroli, 2016).

IRISH CASE STUDIES

This section of the chapter illustrates some of the challenges for the management of lakes in Ireland using examples of hydromorphological alterations from along 1. the River Shannon and, 2. Poulaphuca and its connection to the Liffey catchment.

Case study: River Shannon: Ardnacrusha Dam and Parteen Basin

The Shannon River, the longest in Ireland, covers about 30% of the country and is classified as an international river basin as its upper catchment lies just inside NI. With 113 lakes, including 53 over 50 hectares, it has diverse morphological features and is a significant waterway. The Shannon is, furthermore, hydrologically connected with the River Erne system through the Shannon-Erne Canal. As would be expected for such a major river, hydromorphological alterations have affected the main stem and many tributaries. Most notable has been the Shannon hydroelectric scheme at Ardnacrusha, as well as the arterial drainage and management of the Shannon Callows that lie between Lough Ree and Lough Derg. Hydrological alterations that could have possible impacts or changes in ecological state are alteration of flow and sediment regime, water level management, impediment to fish migration and hydrological connectivity between the main channel and floodplain. A proposed pipeline from the Shannon to Dublin to address water stress in the Dublin Metropolitan area has stimulated much debate and controversy. While the potential impacts of riparian alterations related to ports, harbours, and jetties may be widespread, they are generally local and limited.

Ardnacrusha

Ardnacrusha Dam (Figure 4.6), downstream of the town of Killaloe, was constructed in the 1930s to provide the newly independent Ireland with a secure national electricity supply. Once supplying almost 90% of national demand, it now accounts for <3% of the country's electricity. At the time of its construction, the Shannon was one of the largest salmon (*Salar salar*) runs in Europe. While the potential loss of salmon because of the dam raised controversy during its planning and construction, economic considerations were prioritised over the fishery (Reale, 2011). Parteen Basin, just upstream of the dam, was created by the power plant.

Ardnacrusha Dam regulates water retention upstream in Lough Derg, where water fluctuations are maintained to a narrow operating band of 460 mm, except in flood periods (Irish Water, 2016b). The lough's hydrodynamics have the character of a lake, and it is designated as such, although subject to extensive hydromorphological modifications, along with major other pressures from nutrients and the infestation of the zebra mussel (*Dreissena polymorpha*) (EPA, 2021b).

The ESB, which manages the dam as well as holding a statutory duty to manage and preserve the Shannon (along with the Rivers Erne, Lee, and Liffey) and its fishery resources, diverts water at Parteen into a headrace canal to the power station. There is a requirement for a minimum statutory compensation flow of 10 $m^3 s^{-1}$, into the original channel equal to the low summer flow that was present before construction of the dam. This affects flow rates along 15 km of the Lower Shannon SAC (Special Area of Conservation). Cullen and McCarthy (2006) reported mean annual flow of the River Shannon at Killaloe as 186 $m^3 s^{-1}$, mean summer discharge as 99 $m^3 s^{-1}$ and mean winter discharge as 274 $m^3 s^{-1}$. However, flows may be as low as 10-15 $m^3 s^{-1}$ in dry summers or over 700 $m^3 s^{-1}$ during major floods. During high flows, water can also be discharged down the old river channel through spill gates at the Parteen Regulating Weir. Local observers indicate that water supply to the power plant is estimated to regularly comprise about 95% of the flow (W. O'Connor, Ecofact, pers comm). The maintenance and relevance of a

Figure 4.6 Ardnacrusha headrace, Parteen basin and Old Shannon River. Photo: Adobe Stock

minimum ‘statutory compensation flow’ into the Lower Shannon SAC is due for review. Despite the highly regulated water levels of Lough Derg, the lake is not designated as heavily modified.

The impact on salmon migration was recognised when Ardnacrusha was constructed, with added pressures reported by Reale (2011) that high water discharge led to a drop in salmon population on the Limerick fishery from ‘414,000 to 42,000 pounds’, or about 188,000 kg to 19,000 kg, respectively. A fish pass installed when Ardnacrusha was built probably only minimally mitigated the barrier to fish passage. A fish hatchery to support salmon survival was constructed in 1958, with salmon migrating upstream collected for broodstock. Although there is evidence of an increase in fish passing through Ardnacrusha following the construction of a new fish pass in 1962, concerns remained about its effectiveness, with a notable further decline of migrating salmon in the mid-1970s (ESB, 2020). There are also undoubtedly multiple pressures that would have contributed to this. Overall, the salmon population assessed in the Parteen Basin were reported to have reduced from 23,322 in 1963 to 1,904 fish in 2003 (OPW, 2019). In 2018, a multiagency review panel (including Inland Fisheries Ireland, the Marine Institute, Waterways Ireland, OPW, National Parks and Wildlife Service, ESB and Irish Water) was convened for ‘Improved fish passage on the Shannon’. The consultants involved in that study identified that ‘Neither fishway at Ardnacrusha and Parteen meets modern best practice and do not facilitate multi-fish species passage as required by the Water Framework Directive’ (https://www.cdmsmith.com/en-EU/Client-Solutions/Projects/Improving-Fish-Migration-in-the-Lower-River-Shannon-Catchment; accessed 3rd February 2024), but no report appears to have yet been published.

There are also indications of high mortality of the European eel (*Anguilla anguilla*) moving through the Ardnacrusha turbines on their seaward migration (Cullen and McCarthy, 2006). A previous commercial eel fishery is now replaced with a conservation management programme. The European eel has undergone serious declines in recent decades, with international restoration programmes now common and governed by European Council Regulation 1100/2007 ‘Establishing measures for the recovery of the stock of European eel’.

The construction of Ardnacrusha, aimed at fulfilling the nation’s energy needs, had a lasting impact on the Lower Shannon’s water levels and severed a major salmon run in Europe. Controversies during its construction, known as the ‘Battle of the Tailrace,’ are now local folklore. Despite generating less than 3% of national electricity, the rationale for retaining Ardnacrusha is its ability to generate electricity at short notice. Maybe its persistence is more a matter of national and engineering history, and cultural heritage rather than power generation.

Proposed Shannon to Dublin Pipeline scheme

Because of projected water scarcity in the Dublin Metropolitan area, it has been proposed to extract 330 million L day^{-1} of water from the lower Shannon to the Dublin area (Irish Water, 2016b). It is estimated that the extracted water will reduce an average of 2% of the volume of water flowing down the Shannon River. Concerns over water abstraction focus on possible extended periods of low flow. Calls to fix leakages in the Dublin pipeline and reduce the dependence on the water coming from Shannon will unlikely alleviate the need because of the anticipated growth of Dublin's population, associated water demands, and pressures exerted on available water resources from climate change. Given the governance challenges, including water charging and historical regional positions, one thing that can be assured is that any progress with a pipeline proposal will attract considerable further debate and controversy. The Shannon-Dublin pipeline proposal highlights the political nature of water supply and demand (Kelly-Quinn et al., 2014).

Shannon Callows

The hydrology of the River Shannon between Lough Ree and Lough Derg, as well as the low gradient of the area, leads to seasonal flooding of the Shannon Callows, an area exceptionally important for birds and plants (Maher, 2015). Under the EU Habitat Directive, 5700 ha of the floodplain are designated as the River Shannon Callows SAC and a Natural Heritage Area. Changing agricultural practices have had an impact on the wet meadows and seasonally flooded habitats, with national agri-environmental schemes not managing to sufficiently protect the natural landscape. The Callows have many of the features and controversies of seasonally flooded wetlands, seen the world over. Water management in the Callows has stimulated much debate with respect to the flooding of fields and homes. Conservation and economic interests can, at times, seem incompatible. Still, a results-based agri-environment pilot scheme trialled between 2005-2018 reported positive results from agricultural stakeholders for High Nature Value farmland (Moran et al., 2021). However, local concerns remain about the impact of summer flooding on hay and silage production and animal grazing. Increasing floods affect both people's livelihoods and wading birds that nest in the Callows.

The pressure for further drainage to the Callows is likely to continue, with a possible large impact on the conservation status of the Callows, while not assured that it will have the desired effect of alleviating flooding for farming or residences. For the Callows, a written response on 10th March 2021 in the Irish Parliament about flooding drew this response from Minister Patrick O'Donovan: 'In December, 2019, the Government noted that the Shannon Flood Risk State Agency Co-ordination Working Group agreed to provide €7 m from the OPW to Waterways Ireland to implement a co-ordinated strategic programme of maintenance activities for the River Shannon and for the removal of a number of constrictions in the Callows region. These proposed works can delay flooding and also benefit navigation and agricultural lands'. There was no acknowledgement of the conservation importance of the Callows, or it seems any discussion on whether such a scheme would be compliant with the WFD because of the potential effects of hydromorphological alterations.

With respect to the flooding of the River Shannon, accommodating the natural dynamics of the river and finding other mechanisms for addressing concerns about the flooding of the land would be a wise choice. In 1956, a report of a study by the Corps of Engineers, a body renowned for large-scale engineering and water management schemes, concluded: 'The problem of Shannon River flooding has been the subject of much study over the past 150 years. Because of the flat terrain through which the river flows, the almost imperceptible gradient of the stream with its series of lakes and connecting channels, and because of the large volume and long duration of flooding, no simple or obvious solution has heretofore been found - nor has the writer now found one' (Page S-2 of Summary Report: III. General Considerations) (Rydell, 1956).

Case study: Poulaphouca Reservoir, Liffey Catchment

In the catchment of the River Liffey, hydromorphological alterations are a significant concern, involving issues such as excess fine sediment, changes in river channel morphology, and habitat alterations caused by various factors such as river and field drainage schemes, forestry activities, animal access, and quarry discharges.

Poulaphouca Reservoir (Figure 4.7), also known as Blessington Lake, situated southeast of the town of Blessington in Co Wicklow, faces notable

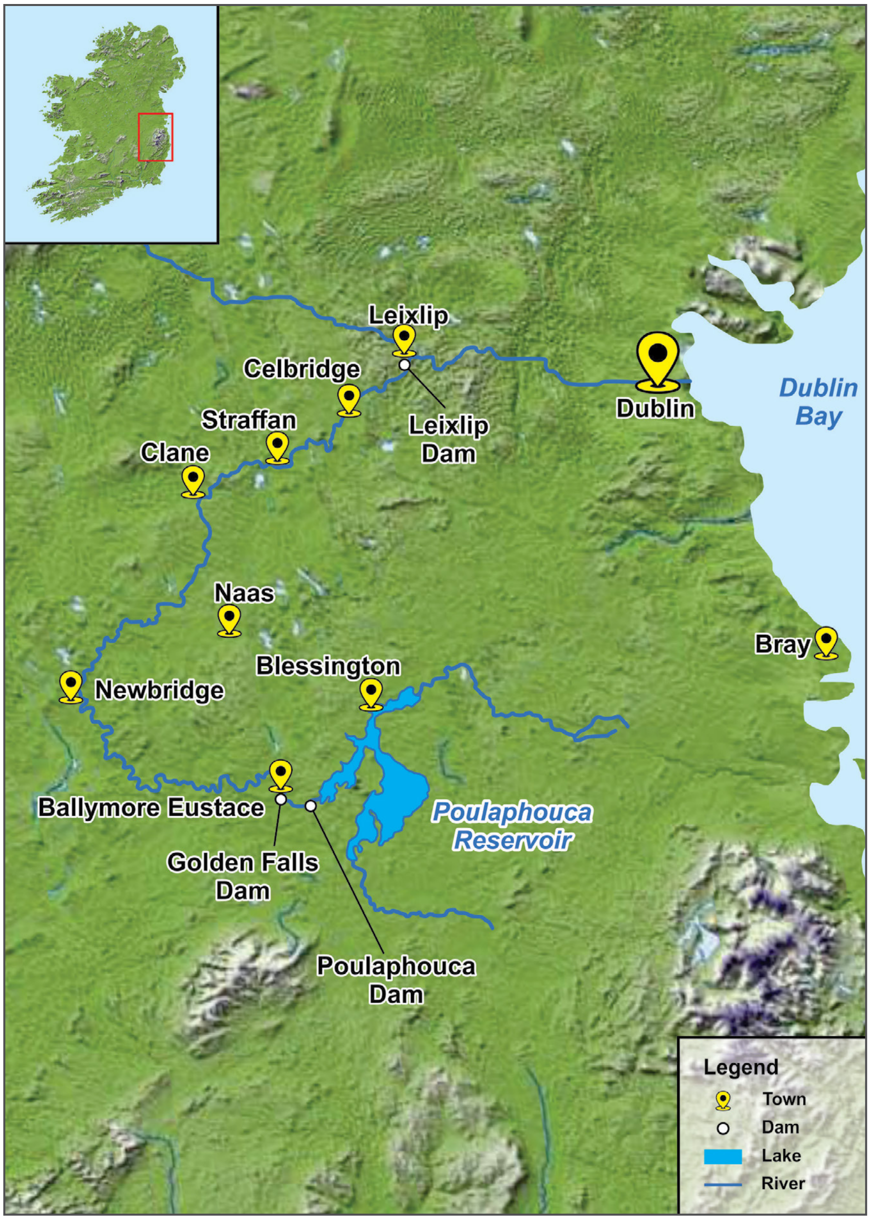


Figure 4.7
Liffey River and its reservoirs. This figure is based on work by ESB cited at: https://irishriverproject.com/category/hydro-power/. The DEM layer is from: https://www.bing.com/maps/.

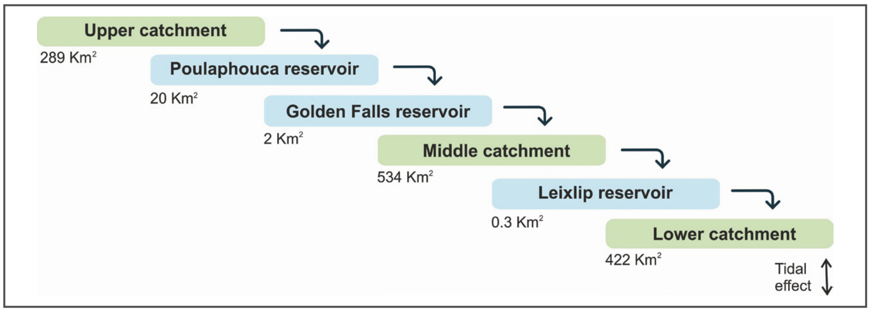


Figure 4.8
Schematic presentation of the Liffey reservoirs. Figure reproduced from OPW (2012).

hydromorphological pressures. Created in 1944, it covers around 20 km^2 and serves as a water source for the Dublin Metropolitan area and is connected to a reservoir chain. The reservoir receives water from the River Liffey and Kings River, but increasing demand may lead to water shortages and reduced water level fluctuations. The reservoir is part of an interconnected system of water bodies from the upper to the lower catchment (Figure 4.8).

In July 2021, dead fish were discovered in the reservoir, prompting an EPA investigation, although no industrial discharge or wastewater contamination was identified. Irish Water obtained planning permission to upgrade the Blessington Wastewater Treatment Plant (WWTP), which discharges into Golden Falls Reservoir downstream of Poulaphouca Power Station. The flow from Poulaphouca into Golden Falls Reservoir is intermittent and regulated by the ESB. The Ballymore Eustace Trout & Salmon Anglers' Association highlighted concerns about periods when no water flows into Golden Falls Reservoir, leading to potential issues with dilution of the Blessington WWTP discharge when Poulaphouca Station is not operating.

CONCLUSION

The concept of hydromorphology and its application to lake management has been greatly stimulated by the legal requirements of the WFD. The need to assess hydromorphological alterations exposed many conceptual and methodological gaps across the EU and has also led to infringement proceedings against the RoI. Infringement proceedings against Member States are not uncommon but take many years to proceed following earlier 'reasoned opinions'. They generally reflect either a lack of capacity of countries to effectively implement a Directive or political inertia or resistance.

The Irish EPA, with the support of other agencies, have a hydromorphology technical work programme to develop the necessary evidence for establishing the link between the physical integrity of water bodies and ecological status for the management of hydromorphological pressures on water bodies. These inform the River Basin Management Plans (RBMPs). Similar work has occurred in NI, including regular knowledge exchange and transboundary projects, often with earlier support in joint WFD work from the Scottish and Northern Ireland Forum for Environmental Research. It is through RBMPs that translation of research findings commissioned by the EPA and others are implemented in practice. Still, knowledge transfer to action for RBMP is at the behest of the Government Departments responsible for

WFD implementation. A number of factors and parties influence this. In the RoI, a national Water Act that effectively consolidates the fragmented nature of water and, by extension, water management is an old recommendation (Irvine et al., 2002). Multiple agencies, legal ambiguities and contradictory remits provide a recipe for non-compliance with the WFD's environmental objectives. For lakes, the *de facto* connection with the river network and catchment and, hence, land management accentuates the challenges. There are, therefore, scientific and policy issues that can be further developed.

Large-scale EU projects that investigated use of littoral invertebrates in the ecological assessment of lakes:

- REBECCA Relationships between ecological and chemical status of surface waters. https://cordis.europa.eu/project/id/502158/reporting
- WISER Water bodies in Europe WISER - http://www.wiser.eu/results/deliverables/

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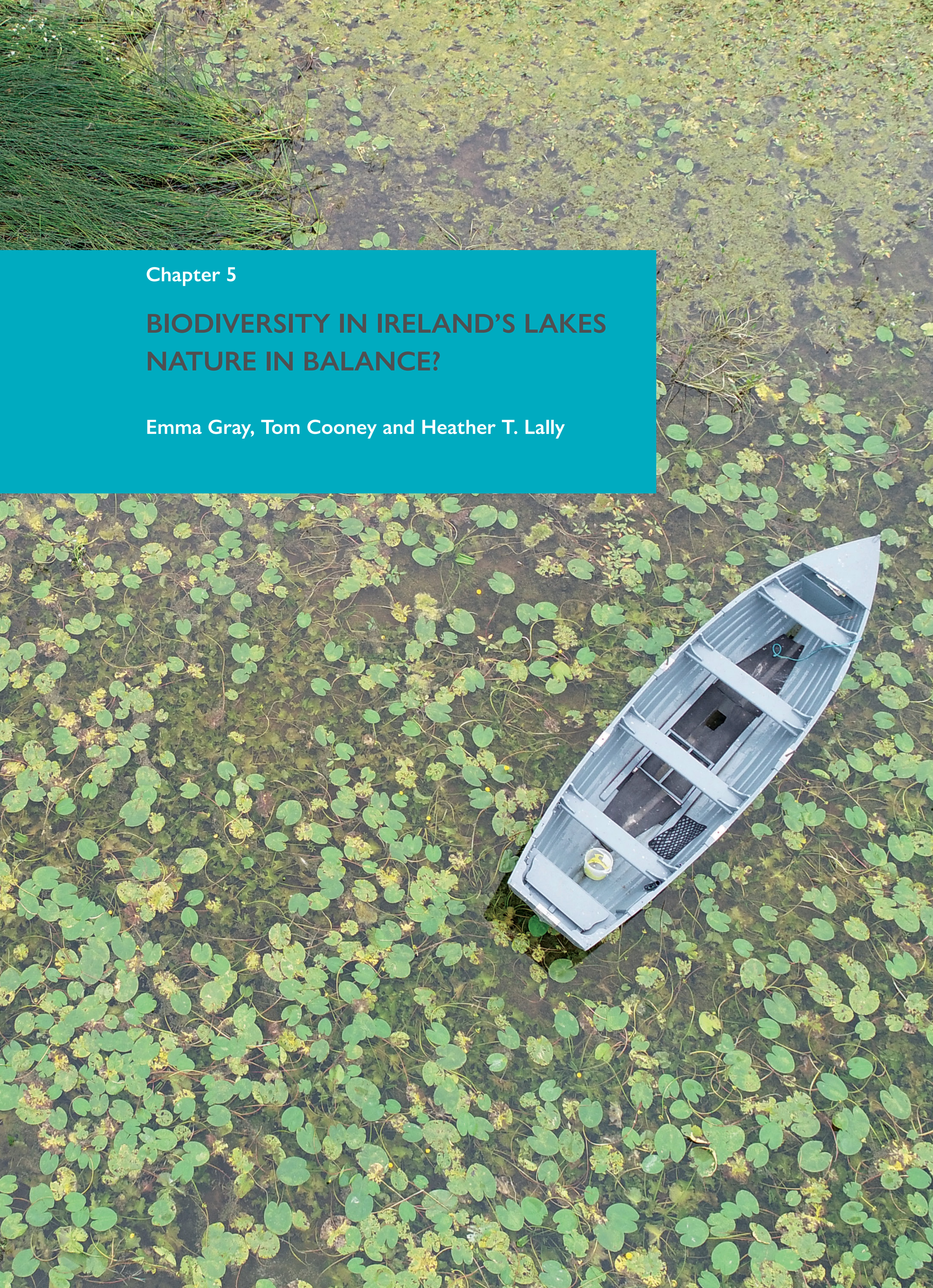

Chapter 5

BIODIVERSITY IN IRELAND'S LAKES NATURE IN BALANCE?

Emma Gray, Tom Cooney and Heather T. Lally

SUMMARY

This chapter provides an overview of the key biota that rely on lakes in Ireland from the micro to macro-scopic scale. It provides a typical food web of a lake, followed by a description of key primary producers (algae and macrophytes), secondary consumers (zooplankton and macroinvertebrates) and higher consumers (birds and mammals). There is then a special focus on the importance of small lakes for biodiversity, which are often overlooked in legislation, management, and conservation efforts. Small peatland lakes are used as a case study, highlighting the importance of *Sphagnum* for providing microhabitats for desmids along with the occurrence of rare and threatened macroinvertebrate species that occupy peatland lake habitats.

Keywords Phytoplankton, macrophytes, macroinvertebrates, fish, peatland lakes, small lakes

INTRODUCTION

There is currently a global crisis, with freshwater biodiversity declining at a more rapid rate compared to marine and terrestrial environments (McRae et al., 2017). This loss is driven by impacts, on a catchment level in Ireland, such as urbanisation, eutrophication, overgrazing peat cutting and afforestation, along with the added stressor of climatic changes. Ireland contains many lake habitats that support species that are considered rare or threatened on national, European, and global scales (e.g. King et al., 2011; Nelson et al., 2016). This chapter, therefore, focuses on the importance of Ireland's freshwater lakes for supporting biodiversity from the micro- to macro-scopic scale. It provides an overview of the different ecological components within lake ecosystems using examples from lakes in Ireland. The chapter also highlights the importance of small, peatland lakes for supporting biodiversity.

LAKE TROPHIC DYNAMICS AND FOOD WEBS

Lake aquatic food webs comprise a variety of organisms which range in size from those that are invisible to the naked eye such as viruses, bacteria, fungi, protozoans, phytoplankton, and zooplankton, right up to those that can be easily observed such as macrophytes, macroinvertebrates, fish, birds, and mammals (Brönmark and Hansson, 2017). Viruses, bacteria, fungi, and protozoans are essential components of the microbial loop within the food webs of all lakes, and which underpins the transfer of carbon and nutrients (ammonium, nitrate, and phosphate) to primary producers such as algae and macrophytes. Primary producers in turn provide food for higher trophic levels within the food web. There are two main groups of primary producers: macrophytes and phytoplankton with their presence and dominance dependent on water depth, turbidity, water colour, and nutrient availability. Shallow, clear, low-nutrient systems tend to be macrophyte-dominated, whereas deep, turbid, nutrient-rich systems tend to be phytoplankton-dominated. This is because increased water depth, turbidity, and nutrients (which fuel phytoplankton growth) result in light being absorbed, limiting the light reaching benthic areas where macrophytes develop. Phytoplankton and macrophyte dominance can differ interannually and the transition between the states is nuanced.

The trophic dynamics of dystrophic (humic) lakes differ from that of clear-water systems. Dystrophic lakes are brown in colour due to organic matter and have an acidic pH (3-6). The high level of organic matter in dystrophic lakes means that the food web is dominated by bacterial metabolism, often resulting in these lakes having a higher respiration rate than primary productivity rate. Dystrophic lakes are numerous in Ireland, particularly in the west, where they are located within areas of Atlantic and mountainous blanket bog or in catchments that drain a significant area of peatlands such as the Connemara Bog Complex, County Galway, Owenduff/Nephin Complex, County Mayo and Wicklow Mountains.

COMMON BIOTA OF LAKE FOOD WEBS

This section provides an overview of the key biota responsible for the ecological functioning of aquatic food webs using a simplified food web as the basis (Figure 5.1). This lake food web uses example species from Lough Corrib County Galway, note the presence of two invasive species (*Lagariosiphon* and *Dreissena polymorpha*). In reality lake food webs are much more complex and

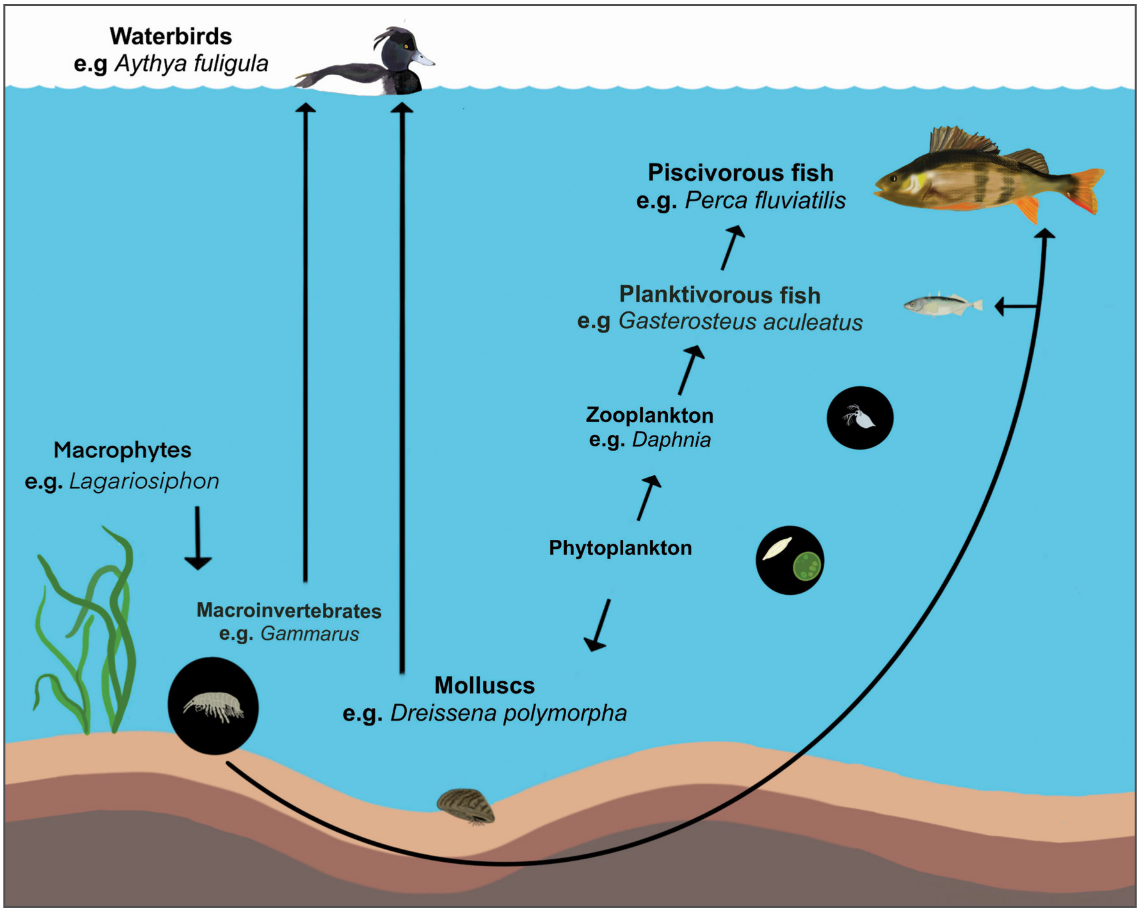

Figure 5.1
Simplified lake food web using example species recorded in Lough Corrib County Galway.

can be comprised of hundreds of different species from microscopic plankton up to fish and mammals.

Primary producers

Primary producers are aquatic plants, green in colour due to the presence of chlorophyll. The presence of chlorophyll results in these plants absorbing energy from sunlight allowing photosynthesis to occur (Brönmark and Hansson, 2017). Primary producers can be divided into two key groupings: algae and macrophytes.

Algae

Algae comprise a diverse range of aquatic plants with single-celled, colonial, and filamentous species living as either planktonic (free-floating) or periphytic (living attached to lake substrates and macrophytes) algae within lakes (Bellinger and Sigee, 2015). Some 2,879 algal species have been recorded in

Ireland, but the actual number may be much higher (Guiry, 2019). Important groups of freshwater algae found within lakes include cyanophyta (blue-green algae), chlorophyta (green algae), bacillariophyta (diatoms), and dinophyta (dinoflagellates) (EPA, 2021).

Cyanophyta are distinctive from other algae in that they lack a nucleus and chloroplasts and are, therefore, classified as prokaryotic (bacteria), but they also have the ability to fix nitrogen through specialist cells called heterocysts (Bellinger and Sigee, 2015; Brönmark and Hansson, 2017; Bowling, 2019). They form single-celled species (e.g., *Aphanocapsa*), loosely bound colonies (e.g., *Merismopedia*, *Microcystis*) and filamentous species such as *Dolichospermum*, *Nostoc*, *Oscillatoria* and *Aphanizomenon*. Cyanophyta are important indicators of water quality and, under eutrophic (high nutrient) environmental conditions, can form nuisance species with *Microcystis*, *Dolichospermum* and *Oscillatoria* capable of forming toxic blooms of public and animal health concerns (Bellinger and Sigee, 2015; Bowling, 2019). In recent years, Lough Leane in Killarney County Kerry, Lough Melvin on the Leitrim/Fermanagh border and Lough Neagh in Northern Ireland have been subject to large cyanophyta blooms. Such blooms are likely to become more common and widespread within lakes because of nutrient pollution and increasing water temperatures due to climate change.

Chlorophyta are the largest and morphologically most diverse group of algae with 90% of species occurring in freshwater environments and commonly comprising the majority of planktonic algal species in freshwater lakes (Bellinger and Sigee, 2015; Bowling, 2019). They form non-flagellated, single-celled species (e.g., *Chlorella*), flagellated, single-celled species (e.g., *Chlamydomonas*), colonies (e.g., *Scenedesmus*, *Pediastrum*), unbranched filamentous species (e.g., *Spirogyra*, *Zygnema*) and branched filamentous species (e.g., *Cladophora*). Desmids (Order Zygnemetales) are a distinctive group of chlorophyta comprising large, solitary unicells and colonies with mirror-image halves which can be deeply incised or lobed, and often perforated with pores and highly ornamented (Bowling, 2019). Desmids are a key characteristic feature of highly coloured dystrophic water, acidic, low alkalinity and nutrient-poor peatland lakes (Free et al., 2006; Gray et al., 2022), with *Staurastrum*, *Cosmarium*, *Staurodesmus* and *Xanthidium* common (Lally et al., 2012).

The Order Charales (stoneworts), including *Chara* and *Nitella* species, have a complex morphological structure, resembling that of macrophytes, with whorls of branches and can grow to over one metre (Bellinger and Sigee,

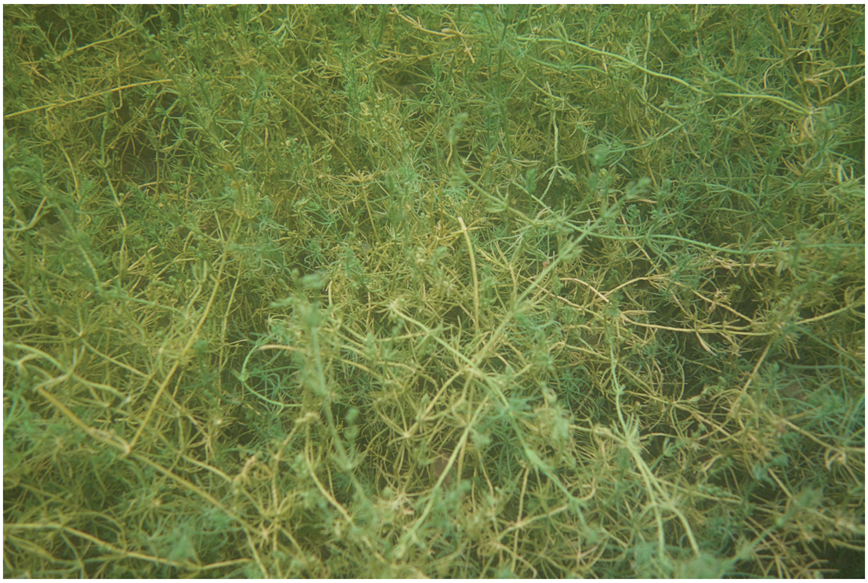

Figure 5.2
Chara beds along the shores of Lough Corrib County Galway
Photo: Cilian Roden

2015) (Figure 5.2). A unique feature is the accumulation of calcium carbonate ($CaCO_3$) in the form of calcite on their stems, making the algae appear whitish in colour and, over time this leads to the formation of marl lake sediments – comprising calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) deposits (Lee, 2018). *Chara* and *Nitella* are, therefore, indicative algal species of alkaline, calcium-rich waters and are a key characteristic feature of marl lakes (Roden et al., 2020) such as Lough Carra, County Mayo and Lough Bunny, County Clare. Chlorophyta are an important indicator of water quality and some filamentous species such as *Spirogyra* can form nuisance species in early summer reflecting increased nutrient availability, but none are toxic (Bellinger and Sigee, 2015; Bowling, 2019).

Bacillariophyta (diatoms) are mostly periphytic, living attached to lake substrates and macrophyte stems but can also be planktonic. A distinguishing characteristic of bacillariophyta is their cell wall (frustule) which is composed of silica and comprises two halves which are ornamented with pores forming lines or patterns (Brönmark and Hansson, 2017; Bowling, 2019). The diatoms are categorised as either centric or pennate. Centric diatoms include single-celled *Cyclotella* and *Coscinodiscus* or colonial *Aulacoseira* and *Melosira* which form filamentous centric strands. Pennate diatoms include single-celled *Navicula* and *Brachysira* or colonial *Asterionella* or *Fragilaria* which form star and raft-shaped colonies, respectively. Planktonic diatoms tend to peak in abundance in spring. For example in Lough Neagh, the spring phytoplankton bloom is dominated by *Aulacoseira subarctica* and *Stephanodiscus astraea*

(Gibson and Foy, 2000). Bloom die-off occurs subsequently due to silica depletion which the diatoms require to form their frustule.

Dinophyta are flagellated, single-celled species. Some species have a cell wall (e.g., *Peridinium*, *Ceratium*) while others without a cell wall are referred to as naked dinophytes (e.g., *Gymnodinium*) (Brönmark and Hansson, 2017). They have two distinct flagella. The transverse flagellum sits within a groove around the centre of the organism and has a wave-like (helical) shape which beats counterclockwise, allowing the dinophyta to move forward and rotate at the same time while the second longitudinal flagellum, projects out of the cell creating a trailing flagella typically 100 μm beyond the cell body (Bellinger and Sigee, 2015; Lee, 2018). This longitudinal flagellum provides a steering function to the dinophyta in addition to backward swimming and rotation (Bellinger and Sigee, 2015; Lee, 2018). Both flagella working together give the unique helical swimming motion observed in dinophyta. Some species of dinophyta can have bioluminescence which is most obvious at night when they emit a bluish-green flash of light of roughly 0.1 seconds when the cells are disturbed within the water column. This phenomenon can be observed in Lough Hyne in County Cork in July and August.

Macrophytes

Macrophytes show unique zonation along lake shores (littoral zone) in response to changes in water level with emergent macrophytes found along the shore followed by floating leaved and submerged macrophytes (Cronk and Fennessy, 2001; Preston and Croft, 2014; Brönmark and Hansson, 2017) (see Chapter 10). Emergent macrophytes, similar to those of the terrestrial environment, have their stems, leaves and reproductive organs always above the water while their roots grow beneath the surface of the water in the lake sediment. Common native emergent macrophytes of lake shores include *Phragmites australis* (common reed) (Figure 5.3), *Typha latifolia* (bulrush), and *Iris pseudacorus* (yellow flag iris). Submerged macrophytes have their stems, leaves and roots beneath the surface of the water with only their flowers floating on top of the lake surface. Stems are soft and leaves are typically ribbon-like or highly divided to allow for flexibility to withstand water movements. Common native submerged macrophytes of lake shores include *Callitriche stagnalis* (common water starwort), *Ceratophyllum demersum* (rigid hornwort) and *Myriophyllum spicatum* (spiked water milfoil) . Floating-leaved macrophytes float on the surface of the lake with both their leaves and flowers visible while their roots anchor them to the lake sediments. Leaves of floating

Figure 5.3 From top:: *Nuphar lutea* Lough Corrib, County Galway, and *Phragmites australis* found along the shores of Lough Corrib, County Galway Photos: Cilian Roden.

leaved macrophytes tend to be circular, oval or heart-shaped with smooth margins and a tough leathery texture to reduce tearing and withstand water movements. Common native floating leaved macrophytes are *Potamogeton* spp. (pondweeds), *Nymphaea alba* (white water lily) and *Nuphar lutea* (yellow water lily) (Figure 5.3).

Secondary consumers

Zooplankton

Zooplankton live in the water column of lakes and are an important central component of the pelagic (open water) lake food web, grazing on the phytoplankton and providing food primarily for planktivorous fish and other organisms (Brönmark and Hansson, 2017). The community composition of zooplankton, therefore, depends on the edibility of the phytoplankton groups and top-down feeding. The zooplankton range in morphology and fall under three major groups: Crustacea, Rotifers and Protozoans (Thackeray, 2021). Additional members of the zooplankton include the larvae of flies e.g. *Chaoborus*, also known as 'phantom midge' or 'glass worm' due to their transparent body (Thackeray, 2021).

Within the Crustacea is a superorder, Diplostraca (or Cladocera), commonly known as the water fleas. They are distinguished by having a large compound eye and a two-valved carapace (Thackeray, 2021). They are small (0.2-3mm) and use abdominal leg appendages to create currents for filter feeding of organic matter, phytoplankton, and bacteria (Thackeray, 2021). Cladocera families and examples of species found in lakes include Chydoridae (*Alona guttata* and *Chydorus ovalis*), Ceriodaphnia (*Ceriodaphnia setosa* and *Ceriodaphnia quadrangula*), Bosmina (*Bosmina longisrostris* and *Bosmina longispina*), Daphnia (*Daphnia hyalina* and *Daphnia cucullata*), and Diaphanosoma (*Diaphanosoma brachyurum*).

Copepods measure between 0.5 mm to 2.0 mm in length and have a segmented body, they feed on bacteria, phytoplankton, and sometimes smaller zooplankton (Thackeray, 2021). Copepods have a single, usually red, eye spot which is used to sense light. There are three main orders of copepods common to lakes: calanoids (e.g. *Eudiaptumus gracilis, Arctodiaptomus laticeps*), cyclopoids (*Eucyclops serrulatus*, *Tropocyclops prasinus** rare), and nauplii.

Rotifers (also called 'wheel animalcule') have a distinctive 'mouth' called a corona comprising a circular arrangement of cilia. The corona has a dual function allowing for movement and suspension feeding (Thackeray, 2021). The morphology of rotifers is varied, they range in size from 50-2000 μm, they are commonly cylindrical but can appear spherical, flattened, or worm-like. The body is divided into three parts; the head (corona), trunk (organs) and foot. They have a jaw (trophi) for capturing, piercing, and breaking down prey. *Keratella* are the most common rotifer recorded in lakes in Ireland.

Macroinvertebrates

Aquatic macroinvertebrates are insects in the nymph, larval, or adult stage, inhabiting the benthic and littoral areas of lakes. Ireland has 2,500 known species of macroinvertebrates, representing 60-80% of British species with 22 unique to Ireland (Feeley et al., 2020). They are an important component of lake food webs, decomposing organic matter, aiding nutrient cycling and providing food for higher consumers such as fish (e.g. salmonids) and birds (e.g., Little Grebe *Tachybaptus ruficollis*, Tufted Duck *Aythya fuligula*). Groups include the larvae or nymphs of Ephemeroptera (mayflies), Plecoptera (stoneflies), Trichoptera (caddisflies), Coleoptera (beetles) and Diptera (true flies) and adult Coleoptera, Hemiptera (true bugs), Arachnida (mites), Crustaceans (freshwater shrimp and crayfish), Molluscs (mussels, snails and clams), Annelida (leeches and worms), Platyhelminthes (flatworms) and Nematoda (roundworms) (Feeley et al., 2020).

Plecoptera (stoneflies) have two hair-like tails, six legs and long antennae, they have gills located on their legs and are poor swimmers and there are 19 species found in Ireland (Figure 5.4) (Feeley et al., 2020). They prefer highly oxygenated waters with low temperatures and a low pH (acidic). Ephemeroptera (mayflies) have a long, streamlined body, a large head, and legs with claws, they have three long tails, six legs and small antennae, they have seven pairs of gills along the body which can have a leaf-like oval or fringed shape (Figure 5.4). They are mobile and can swim, crawl, cling, or burrow. Similarly to Plecoptera, they prefer low temperatures and highly oxygenated waters but do not tolerate acidity. Trichoptera (caddisflies) have elongated soft bodies with finger-like gills on their abdomen, a terminal hook (anal appendage) and six legs. The three segments behind the head are hardened, with the remaining body being soft. They typically cannot swim and can either be cased or free-living. They construct portable or non-portable cases (shelter) by spinning silk threads to join debris (stones, sand and leaves) together.

Odonata consist of two orders Zygoptera (damselflies) and Anisoptera (dragonflies) (Figure 5.4) (Feeley et al., 2020). They have six legs, small wing buds and three leaf-like gills that extend from the rectum. They can swim aided

Figure 5.4 Examples of macroinvertebrates. Left *Heptagenia sulphurea* (mayfly), Middle: *Diura bicaudata* (stonefly), Right: Damselfly larvae, Glenveagh, Donegal. Photos: Hugh Feeley .

by the gills that can act as a tail, and there are 30 known species in Ireland. Coleoptera (beetles) have two forewings that are hardened and protect the flying wings below. They are often predatory, having well-developed mouth parts. Most freshwater beetles crawl but some can swim such as the whirligig beetle (Gyrinidae) which often aggregate on the water surface.

The Freshwater Pearl mussel (*Margaritifera margaritifera*) is a filter-feeding bivalve that can grow up to 140mm and can live for more than 100 years (Moorkens, 1999). They usually occur in fast-flowing, low-nutrient, and highly oxygenated waters and are indicative of near-pristine conditions (Moorkens, 1999). They are highly beneficial to the waters they inhabit, filtering water which can help maintain good water quality (Moorkens, 1999). They usually occur in river systems, but pearl mussel beds have been found in lakes such as Lough Cloon, County Kerry (Cowhig, 2021). In contrast, the Zebra mussel (*Dreissena polymorpha*), an invasive species, now has a widespread distribution in Ireland (see Chapter 13).

The White-clawed Crayfish (*Austropotamobius pallipes*) is the only freshwater crayfish in Ireland. It is considered a globally threatened species with Ireland having one of the largest populations. The White-clawed Crayfish inhabits lakes with a pH above 7 and requires significant calcium concentrations. They are, therefore, often found in limestone and marl lakes (Wilson, 2023). They graze on plants and are an important food source for otters, herons, trout, and pike. The White-clawed Crayfish have been impacted by 'crayfish plague' caused by *Aphanomyces astaci,* which has a 100 % mortality rate (Swords and Griffin, 2022). The first outbreak occurred in 2015 in the Bruskey River, and following the most recent assessment, *Aphanomyces astaci* has been detected at 29 sites in nine different catchments (Swords and Griffin, 2022).

Freshwater jellyfish

Ireland's only freshwater jellyfish (*Craspedacusta sowerbyi*) is a non-native invasive species from China first recorded in lakes such as Lough Derg, County Clare and Lough Erne, County Fermanagh in 2013 (Minchin et al., 2016). They have a two-part life cycle, a resting 'polyp' stage found in the benthic areas of the lake and a free swimming 'medusa' stage where they swim through the water column and feed on the phytoplankton. The first records of the medusae coincided with an unusually warm summer where water temperatures exceeded 21°C. It was, therefore, thought that the polyp stage may have been present in the benthic areas of the lakes for some time, more widespread blooms of the medusa are expected as lake waters warm due to climate change.

Higher consumers

Fish

Fish can be split into two groups according to their feeding strategy planktivorous (plankton-eating) and piscivorous (fish-eating) fish. They can spend a significant amount of time in freshwater (e.g. three and ten-spined stickleback), enter freshwater to spawn (e.g. Twaite shad and Smelt), or spend limited time in freshwater (e.g. Allis shad, Sturgeon and Flounder) (King et al., 2011).

Ireland has 29 species of freshwater fish, 15 are classed as 'native' (King et al., 2011) (see Chapter 6). Of the native species, the European eel (*Anguilla anguilla*) is critically endangered, pollan (*Coregonus autumnalis pollan*), Arctic char (*Salvelinus alpinus*), twaite shad (*Alosa fallax*), Killarney shad (*Alosa fallax killarnensis*) and Atlantic Salmon (*Salmo salar*) are vulnerable, whereas sea lamprey (Petromyzon marinus) is near threatened. Additional fish species include rainbow trout (*Oncorhynchus mykiss*), pike (*Esox lucius*), perch (*Perca fluviatilis*), common carp (*Cyprinus carpio*), gudgeon (*Gobio gobio*), tench (*Tinca tinca*), common bream (*Abramis brama*), minnow (*Phoxinus phoxinus*), rudd (*Scardinius erythrophthalmus*), brown trout (*Salmo trutta*), roach (*Rutilus rutilus*), dace (*Leuciscus leuciscus*), chub (*Leuciscus cephalus*) and stoneloach (*Barbatula barbatula*) amongst others.

Highlight Box

BIRDLIFE

Tom Cooney

Freshwater lakes and associated shoreline habitats support a diversity of bird species whether they are resident, summer visitors, winter visitors or passage migrants. The trophic status of lakes is a significant factor influencing species diversity and abundance of birds (Hoyer and Canfield 1994). Oligotrophic lakes, for example Lough Feeagh, are generally poor habitats for birds but eutrophic lakes like Lough Neagh and Lough Ree, support a wide range of species and large populations throughout the year. Little is known about nutrient input to lakes in Ireland by birds but studies elsewhere have shown that faeces from waterbirds, particularly when they are in high concentrations on small lakes, can contribute in excess of 70% of the total lake nutrient budget (Adhurya et al., 2022). A popular name for nutrient enrichment of freshwater lakes by bird droppings is Guanotrophication.

In summer, waterfowl use the emergent and shoreline vegetation for feeding and nesting. Common resident species include Great Crested Grebe *Podiceps cristatus*, Mallard *Anas platyrhynchos*, Tufted Duck *Aythya fuligula* and Eurasian Coot *Fulica atra*. In winter, Ireland's mild climate and ice-free waterbodies attract large numbers of waterfowl that nest in northern latitudes in summer. Lough Neagh and Lough Beg in Northern Ireland are particularly rich sites supporting an average of 39,919 birds in winter (2018/19 - 2022/23) including internationally important concentrations of Mute Swan *Cygnus olor* (1,291), Whooper Swan *Cygnus cygnus* (2,019) and Common Pochard *Aythya ferina* (4,593) (Woodward et al., 2024). Dabbling duck species such as Eurasian Wigeon *Mareca penelope* are also common in winter. In the Republic of Ireland, other noteworthy sites include Lough Ree and Lough Corrib. However, national trends in overwintering populations from 1994/95 - 2019/20 have indicated large declines for several species that occur in lakes. Largest decreases were recorded for Greater Scaup *Aythya marila* (-89.2%) and Common Pochard (-79.1%) (Kennedy et al., 2023). These declines are likely to be climate driven as wintering ranges shift north-eastwards in Europe (Lehikoinen et al., 2013) resulting in fewer birds returning to Ireland in winter.

Lakesides vegetation, particularly when dominated with stands of Common Reed *Phragmites australis* and patches of Willow *Salix spp*. provide a habitat for the Common Reed Bunting *Emberiza schoeniclus* throughout the year

Figure 5.5 Eurasian Wigeon (*Mareca penelope*). Photo: Sean A. O'Laoire

and nesting habitat in summer for sub-Saharan migrants like Sedge Warbler *Acrocephalus schoenobaenus* and Willow Warbler *Phylloscopus trochilus*. Additions to the avifauna of lakes in Ireland within the last few decades, mainly due to northward shifts in species breeding ranges in Europe, include Little Egret *Egretta garzetta* and Reed Warbler *Acrocephalus scirpaceus*.

Great Cormorant *Phalacorcorax carbo*, a species normally associated with salt water environments is common in most lakes and, on a small number of wooded islands, there are long-established tree nesting colonies. Grassy and rocky islands on some of the larger lakes like Lough Ree, support large breeding colonies of Common Tern *Sterna hirundo* and Black-headed Gull *Chroicocephalus ridibundus*.

Following a successful reintroduction programme, White-tailed Eagles *Haliaeetus albicilla* are now nesting in Ireland again and they are an increasingly familiar sight hunting for fish in lakes in the south and west of the island. In 2023, Osprey *Pandion haliaetus*, another fish-eating bird of prey, bred for the first time in two centuries at a lakeside site in County Fermanagh and the species is also the subject of a reintroduction programme which coincidently, started in 2023.

Mammals

The Eurasian otter (*Lutra lutra*) occurs in lakes where there is a rich abundance of fish and crayfish, and where the surrounding habitat provides cover. The American mink (*Mustela vison*) is classed as an invasive species, and they rely on lake habitats. They have a varied food source and can hunt underwater for crayfish, molluscs and crustations as well as eels, trout, and young salmon. They can also prey on aquatic birds such as ducks (see Highlight Box on Birdlife).

SIGNIFICANCE OF SMALL PONDS AND POOLS

Small lakes and pools are the most numerous lake environments and are critical for supporting biodiversity and providing ecosystem services. In Ireland, 66% of lakes are < 1 ha in size but 2% comprise 80% of the surface area (McGarrigle, 2014; Dalton, 2018)). Until recently, the importance of small lake habitats for biodiversity has largely been overlooked in favour of studying larger water bodies, due to the ecological theory of larger lakes being able to support more species (van Rees et al., 2021). This has meant that many small lakes are not protected by EU legislation and are often neglected in monitoring and conservation programmes. However, small lakes are very important habitats for some organisms such as Odonata. Many small lakes and pools in Ireland (particularly in the West) are located in areas of blanket bog or peatland catchments. These habitats are brown-tinted, shallow, and acidic, they are often low in nutrients with low macrophyte abundance and diversity (O'Connor, 2015). These unique physico-chemical conditions support rare or threatened aquatic species.

Aquatic Sphagnum – Home to a Microscopic Underworld

There are 24 species of *Sphagnum* in Ireland, and they occupy the benthic and littoral regions of peatland pools, as well as the wider bog. *Sphagnum* is important due to its ability to retain water which can help mitigate flooding and filter water, which improves water quality. *Sphagnum* also provides an important microhabitat for desmids as they grow attached to the surface of the plant and occupy the water that the *Sphagnum* stores. Amoeba and worms also inhabit *Sphagnum* providing a food source for dragonflies, damselflies, and beetles.

A focus on desmids

The unique conditions of peatland pools provide an ideal habitat for desmids. Desmids prefer oligotrophic (nutrient-poor) waters with an acidic pH (4-7) and are generally considered as indicators of good water quality. However, like the habitats they occupy, desmids are a threatened algal group. The peatland pools in western Ireland (particularly Connemara and South Mayo) provide a rich habitat for desmids with 476 species and 706 subspecies being recorded (John and Willamson, 2009). Records of the desmids in Ireland date back to 1890, with the first surveys being conducted by West. The assemblage of desmids can also be used to inform the conservation status of a water body. Coesel (2001) developed a Nature Conservation Value index using desmid species richness, species rarity, and species that indicate ecosystem maturity. The index is based on data from the Netherlands and has yet to be used in Ireland, but it could help identify sites with a high conservation value.

Oasis for Coleoptera, Odonata, Mayflies

Small peatland lakes in Ireland are important habitats for macroinvertebrates. Typical species found in these lakes include the Ephemeroptera *Leptophlebia vespertine,* Odonata *Aeshna juncea* and *Pyrrhosoma nymphula* (O'Connor, 2015), *Sympetrum danae* is also often present as it is adapted to cold acidic waters. They are also important habitats for Coeloptera, in particular the diving beetles (Dytiscidae family), which includes species such as *Acilius sulcatus*, *Dytiscus marginalis*, *Hydroporus obscurus*, *Hydroporus erythrocephalus*, *Ilybius aenescens* and *Nebrioporus assimilis* (Drinan, 2012; O'Connor, 2015). Rare species in this group that occupy these habitats include *Agabus arcticus* and *Dytiscus lapponicus* (Foster et al., 2009; O'Connor, 2015).

Baars et al. (2014) identified 202 taxa from 12 small upland blanket bog lakes dominated by Diptera, Trichoptera, Heteroptera and Coleoptera (see Chapter 9 also). Chronimidae were the most diverse group (100 species) followed by Trichoptera (27), Coeloptera (24), Heteroptera (13) and Diptera (11). Several rare and threatened species were also recorded by the study including *Diura bicaudata* and *D. lapponicus* which are arctic relics and five new records of Chironomid species in Ireland (*Cricotopus (Isocladius) brevipalpis, Synorthocladius semivirens, Micropsectra lindebergi, Micropsectra uliginosa* and *Tanytarsus aberrans*). Drinan et al (2011) also found the larvae of one of Ireland's rarest dragonflies, *Cordulia aenea* (Downy Emerald dragonfly), in eight blanket bog lakes in Connemara, County Galway.

A survey of 24 lakes and pools distributed within Connemara, County Galway and Owenduff/Nephin, County Mayo by Cappelli et al. (2024) also found four species included on the Irish Red List: *Agabus arcticus* (near threatened), *Boreonectes multilineatus* (near threatened), *Cordulia aenea* (endangered) and *Dytiscus lapponicus* (near threatened). The study found that 62% of the water bodies contained at least one threatened species, and one lake contained three near-threatened species.

CONCLUSIONS

This chapter has highlighted the importance of lakes in Ireland for biodiversity. It has also demonstrated how some species are under threat due to habitat loss and disease along with catchment modifications and climate change. The importance of small lakes was also demonstrated, showing that they provide habitats for rare and threatened species. It is, therefore, recommended that more small lake habitats be included in monitoring programmes to better understand the distribution of these rare species and to aid conservation efforts.

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Chapter 6

FISH, FISHERIES AND ANGLING THE STATUS QUO

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SUMMARY

This chapter aims to describe the fish species present in lakes in Ireland, their natural histories, origins and distribution. Lake fish populations are a mix of coldwater, coolwater and warmwater species. Their current distribution arises from natural colonisation events and through intentional and unintentional introductions and manipulations of freshwater ecosystems by humans since at least the twelfth century. Updated distribution maps for key species in lakes are presented. A description of how fisheries management practices have changed is also included. We detail the ecosystem services that fish provide and describe how fish can be used to assess the health of lakes. Lake fish stocks support culturally (and economically) important recreational angling fisheries that are highly valued by the communities that use them. Some lakes also support commercial fisheries. A summary of the main pressures affecting lake fish is also given. Fish populations in lakes are threatened by a range of pressures including eutrophication, water pollution, exploitation, hydromorphological pressures including physical habitat alteration, land management practices, exploitation, translocation of species, invasive alien species and climate change.

Keywords Fish, angling, distribution, management, research, pressures

INTRODUCTION

Fish in lakes in Ireland range from coldwater species that need low water temperatures and high oxygen levels to survive (e.g. Arctic char (*Salvelinus alpinus*), pollan (*Coregonus pollan*), Atlantic salmon (*Salmo salar*) and trout (*Salmo trutta*), through coolwater species (e.g. perch (P*erca fluviatilis*)) to warmwater species (e.g. roach (*Rutilus rutilus*), bream (*Abramis brama*) and tench (*Tinca tinca*)) that display a range of tolerances to low oxygen and prefer higher water temperatures (Table 6.1). They range in size from small species such as three-spined stickleback (*Gasterosteus aculeatus*) and minnow (*Phoxinus phoxinus*), to the largest predatory fish, the pike (*Esox lucius*). Migratory species, including diadromous (i.e. that migrate between fresh and saltwater environments) salmonids and eels (*Anguilla anguilla*), may form a significant component of lake fish species assemblages in systems directly connected to the sea. Warm water and more tolerant species typically dominate throughout the lowland lakes of the midlands, the Shannon, Neagh/Bann, and Erne catchments.

NATURAL HISTORY/ORIGIN/DISTRIBUTION

Ireland is relatively poor in terms of fish diversity compared to the rest of Europe. Twenty-five fish species including five varieties of trout are known to occur in lakes in Ireland at some stage in their life cycle (Table 6.1). Three cyprinid (e.g. carp family) hybrids are also present. The low fish species diversity can be explained by the glacial history of the island (see Chapter 2). Rising sea levels isolated Ireland from the rest of Europe soon after the ice caps retreated following the last period of glaciation forming an island about 14,000 BC. As a result, few fish were able to colonise before the island was cut off from Britain and mainland Europe. The initial fauna to colonise is considered to be composed of diadromous cold-water species such as Atlantic salmon, trout, European eel, Arctic char, pollan and lampreys. Recent research examining the taxonomy of Arctic char has revealed that the colonisation of Ireland by migratory fish species was likely to be complex and, in several cases, involved extinction, recolonisation, and/or secondary contact (Barthelemy, 2023). There is also still much uncertainty around which members of the fish fauna of Ireland are native and which are introduced, and some questions remain unresolved (e.g. Kelly et al., 2020). Many fish species considered introduced have been present for hundreds of years. While they are naturalised across much of Ireland, range expansions are still evident in some species (e.g. perch). More recent invaders (e.g. roach) are also continuing to spread. The current distribution of these introduced species varies throughout the island but in general, lakes in the northwest, west and southwest are the few areas remaining free of non-native introduced or translocated species. Coldwater species continue to dominate in areas where cyprinids have not been introduced or are restricted to few waters. Fish species are still spreading or being moved and there is often uncertainty as to what species occur where. Many small lakes have never been scientifically surveyed for fish.

Rare fish species

Killarney shad (*Alosa fallax killarnensis*), pollan and Arctic char are three of the rarest fish species present in lakes in Ireland. These species are often unique to specific or isolated lakes (i.e. the lakes act as islands) leaving them vulnerable to many pressures.

Killarney shad is the rarest fish species in lakes in Ireland, found only in Lough Leane, Co. Kerry in the southwest (Figure 6.1) and is endemic to Ireland. It is closely related to the diadromous Twaite shad (*Alosa fallax*) but lives exclusively in freshwater and is descended from an ancestral post-glacial population that became isolated in the lake (e.g. Coscia et al., 2010). Recent surveys have shown that the species has maintained a robust population despite pressure from urban waste-water treatment plants and other anthropogenic pressures (e.g. McLoone et al., 2022). Hydroacoustic and netting surveys in 2017 provided a population estimate of circa 17,500 comprising 59% juveniles and 41% adults (Connor et al., 2018).

Pollan shares its ancestry with the anadromous 'Arctic Cisco' (*Coregonus autumnalis*). Pollan is believed to have diverged from the ancestral line about 165,000 years ago (Bradley et al., 2005). Its distribution is restricted to five lakes in Ireland, i.e. Lough Neagh and Lower Lough Erne in Northern Ireland (NI) and Loughs Allen, Ree and Derg in the Republic of Ireland (RoI) (Harrison et al., 2010 and 2012 (Figure 6.1)).

They are present throughout Lough Neagh, but their summer distribution is restricted to the pelagic zones in the four remaining lakes. It is believed that pollan entered the Shannon system at the end of the last Ice Age, ca 14,000 years ago, and from there spread to Loughs Erne and Neagh, all of which were interconnected in the period of glacial retreat (Ferguson et al., 2004). Research indicates significant genetic differences between pollan populations from Lough Neagh and the Shannon lakes (Bradley, 2005; Ferguson et al., 2004).

The Lough Neagh pollan population represented on average 30% of the total fish biomass from 2012 to 2017 (DAERA et al., 2019), while the populations in the remaining four lakes have undergone significant declines since the 1970s. Recent annual larval, juvenile, and adult fish surveys have shown poor recruitment of Lough Neagh pollan from 2018 to 2022, corresponding with a rapid zebra mussel population expansion. Gillnetting and hydroacoustic surveys on the three Shannon lakes revealed that pollan abundance declines from north to south, from 120,411 in Lough Allen to 3,418 in Lough Derg (Morrissey, 2019).

Table 6.1 List of fish species in lakes in Ireland (scientific and common names)

Common Name	**Scientific Name**	**Specimen or largest recorded in a survey** (length/weight, location, year & method)	**Status**		
			Local or widespread	Rare, common, abundant	Irish Red List status (2022)
COLDWATER SPECIES					
Trout (Brown)	Salmo trutta	11.85kg, Lough Ennell, 1894, angling	W	A	LC
Trout (Sea trout)	Salmo trutta	7.43kg Lough Currane, angling	W	A	NT
Atlantic salmon	Salmo salar	25.85kg, River Suir, 1874	W	A	Vu
Arctic char	Salvelinus alpinus	31.4cm/385g Lough Mask, 2019, survey	L	R	VU
Pollan	Coregonus pollan	38 cm, 848g, Lower Erne,1994, survey	L	R	EN
Killarney shad	Alosa fallax killarnensis	22cm/151.5cm Lough Leane, survey	L	R	Vu
Sonaghen trout	Salmo nigripinnis	38.9/580g, Lough Melvin, survey	L	R	Vu
Ferox trout	Salmo ferox	96.5cm/10,75Kg Lough Corrib, 2012, Angling	L	R	Vu
Gillaroo trout	Salmo stomachicus	38.9cm/917g Lough Melvin, 2008, angling	L	R	Vu
Three-spined stickleback	Gasterosteus aculeatus	9.5cm, Lough Talt, 2020, survey	W	A	LC
Nine-spined stickleback	Pungitius pungitius	4.6cm, Lough Rea, 2010, survey			
Rainbow trout	Oncorhynchus mykiss	-	L	R	Maintained By Stocking
COOL WATER SPECIES					
Perch	Perca fluviatilis	2.49kg, Lough Erne, 1946, angling	W	A	LC
Pike	Esox lucius Linnaeus	19.39kg, White Lough, 2005, angling	W	A	LC
WARMWATER SPECIES					
European eel	Anguilla anguilla	3.15kg Lough Droumenisa, Co. Cork, 1979, angling	W	A	CE
Sea lamprey (lake resident)	Petromyzon marinus		L	R	NT
Common bream*	Abramis brama	6.07kg, Ballywillan Lough Fishery, Co. Down, 2012, angling	W	C	LC
Minnow	Phoxinus phoxinus	10cm, Columbkille Lough, Donegal, 2005, survey	W	A	LC

Common Name	Scientific Name	Specimen or largest recorded in a survey (length/weight, location, year & method)	Status		
			Local or widespread	Rare, common, abundant	Irish Red List status (2022)
Tench	*Tinca tinca*	4.05kg, Ballyeighter Lake, 1995, angling	L	C	LC
Gudgeon	*Gobio gobio*	14.5 cm, 51.2g, Portna canal, Lower Bann ISFC new record, 2022			
Stone loach	*Barbatula barbatula*	8.5cm, Lough Gill,2008, survey			
Roach*	*Rutilus rutilus*	1.425kg, Drumacritten Lake, 2002, angling	W	A	IAS
Common carp	*Cyprinus carpio*	14.24kg, Loughgall, Armagh, 2014, angling	L	R	IAS
Flounder**	*Platichthys flesus*	38cm/700g, New Lake, 2005, survey	W	C	LC

*There are also hybrids of these species present (rudd x bream, roach x bream and roach x rudd)

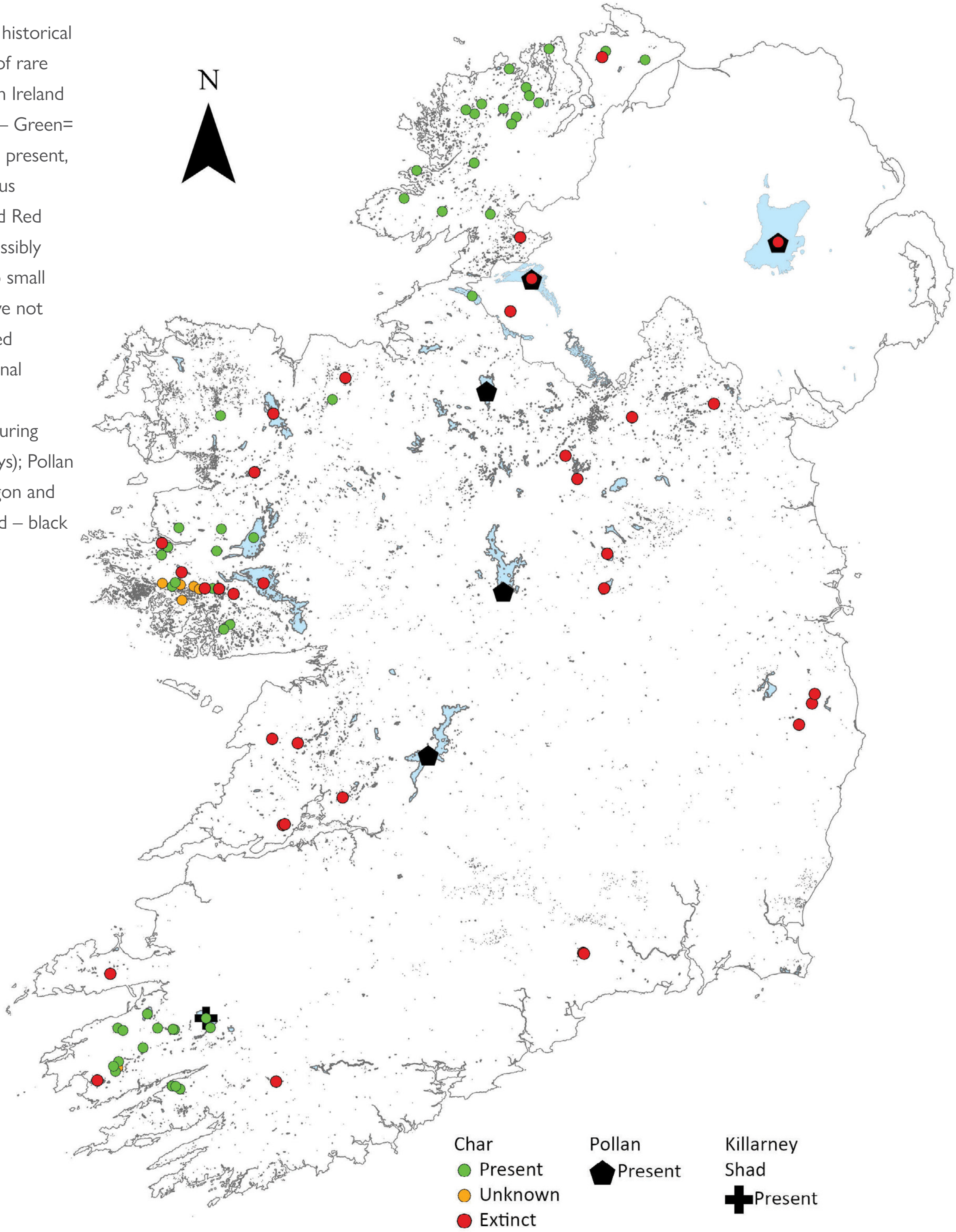
**Species which may enter lakes for variable periods but principally occur in marine or estuarine waters

L – Local; W – Widespread; R – Rare; C – Common; A – Abundant.

Irish Red List 2023: NT=Near threatened; LC=Least Concern; Vu=Vulnerable; EN=Endangered; CE= Critically Endangered; IAS=Invasive Alien Species.

All populations of Arctic char on the island of Ireland are lake resident but some fish may move between lakes via rivers. It is estimated that there are at least 86 lakes on the island where they were once present. Presence has been confirmed in at least 48 since 2004. The status of the population in six lakes is still unknown and 32 populations have been confirmed as 'extinct', possibly extinct, or so small that they have not been detected by conventional monitoring techniques during recent surveys (Figure 6.1). Historical records indicate that populations of Arctic char have been contracting since the 1830s (Ferguson et al., 2019a). It has been estimated that at least 11 extant populations of Arctic char are now at risk (Connor et al., 2018). Like shad and pollan, Arctic char occupy a mainly pelagic habitat and migrate to littoral areas to spawn in wintertime. Today Arctic char populations are mainly present in the north-west, west and south-west of Ireland but there are historical records from the midlands and east of the country; however, most of these latter populations are now extinct (Figure 6.1). (See Case Study Panel No. 1).

Figure 6.1
Current and historical distribution of rare fish species in Ireland (Arctic char – Green= known to be present, Orange=status unknown and Red = extinct, possibly extinct or so small that they have not been detected by conventional monitoring techniques during recent surveys); Pollan –Black hexagon and Killarney shad – black cross.



Salmon and trout

Trout and Atlantic salmon are widespread across the island and occur in all lakes to which they can gain access (Table 6.1). The trout is widespread, but several populations have been impacted by water quality, species introductions and other pressures, particularly in the midlands and in smaller, isolated lakes (see Chapter 11). Significant declines in Atlantic salmon have been observed since the 1970s and are currently considered vulnerable. There have also been declines in anadromous trout (more commonly called sea trout) populations since the late 1980s particularly in the lakes of the west of Ireland due to sea lice infestation causing marine mortality (e.g. Gargan et al., 2017).

Trout have diversified, adapted and developed different lifestyles (i.e. migratory and feeding strategies) since colonising the island. Genetic research has shown that most rivers inflowing to lakes hold their own variety or family of trout (e.g. Ferguson, 2019b). Researchers have described four life histories in lake trout populations, i.e. (1) lake resident (i.e. spend entire life cycle in a lake, including spawning) (2) lacustrine to adfluvial potamodromous (migrate to and from a lake inlet) or (3) allacustrine (migrate to and from lake outlet) potamodromous and (4) anadromous (migrate to and from the sea). The decision to migrate or remain resident is governed by genetic variation and environmental factors (Ferguson et al., 2019b). The lacustrine to adfluvial potamodromous migration strategy is the most common in lakes in Ireland (Ferguson, 2020). Information on lake spawning populations is lacking in Ireland but it is thought that it is common (Ferguson et al., 2019b). Trout populations can persist in high-altitude lakes without spawning streams. Several lake resident populations have also been identified, for example, trout have been observed spawning in Lough Mask (Gargan, pers. comm) and this has been supported by ICP-MS Laser ablation and genetic studies (e.g. Ryan et al., 2016). Other purely lake-resident trout populations have been noted in Loughs Bane (Co. Meath), Lee, Co Tyrone and Aghvog, Co. Donegal. The allacustrine (to and from lake outlet) potamodromous life history is probably the least common in lakes in Ireland. Two well-known examples are Lough Melvin, Co. Leitrim/Fermanagh and Lough Rea, Co. Galway.

Sympatric divergence (i.e. occurrence of two or more distinct groups of individuals that overlap geographically and generally segregate for breeding) has also developed in several lake trout populations in Ireland (Ferguson and Prodöhl, 2022). At least three different types of trout reside in Lough Melvin, and they display two migration and three feeding strategies (See Case Study

Panel No. 2). Two other unique migratory forms of trout include croneen and dollaghan. Croneen are a pelagic lake trout present in Lough Derg and migrate over 50 km upstream to the Camcor River in the Little Brosna catchment to spawn. The croneen commence their spawning migration in July or August, they behave like sea trout and feed only spasmodically. Comparable trout are reputed to be present in several other lakes, but this has not been proven. A similar trout in Lough Neagh is called the dollaghan. Genetic studies (Prodöhl and Keenan, 2015) showed that the stock in Lough Neagh is heavily dependent on reproduction at two sites, i.e. Sixmile Water entering Lough Neagh at Antrim and the Kellswater tributary of the river Maine, entering the lake near Randalstown, Co. Antrim.

Pike and coarse fish species

Coarse fish (the collective term encompassing all fish species which are not pike, trout, eels, or minnow as defined in byelaw 808, 2006 in the RoI) and pike, commonly occur in most high/moderate alkalinity river and lake catchments draining the central limestone plains. Cyprinid species include bream, rudd (*Scardinius erythrophthalmus*), roach and tench. Pike and perch are both predominantly predatory species, and their diet can influence the species composition of lakes where they are resident. Pike, perch, bream, rudd and tench are widespread if somewhat patchily distributed in the Shannon and Erne systems (some for several centuries) and all counties within NI (Counties Antrim, Down, Armagh, Tyrone, Fermanagh, and Derry/Londonderry) (Figure 6.2). While no definitive date of human introduction is known for many of these species, their patchy distribution and inability to inhabit salt waters has led to the assumption that most of these species occur in Ireland because of human intervention, although recent genetic studies suggest that some species (i.e. pike) may be present for several thousand years in certain lakes in Ireland (Pedreschi et al., 2014).

Rudd, tench and bream

Rudd, tench, and bream (Figure 6.2) have a limited distribution dependent upon when and where these species were introduced. A water temperature of approximately 15°C is sufficient to meet the spawning requirements of bream and rudd; however, a water temperature of 20°C is required for tench and in Ireland reproduction may be dependent on the occurrence of warm summer anticyclones (e.g. Kennedy and Fitzmaurice, 1970). In some years tench may fail to spawn.

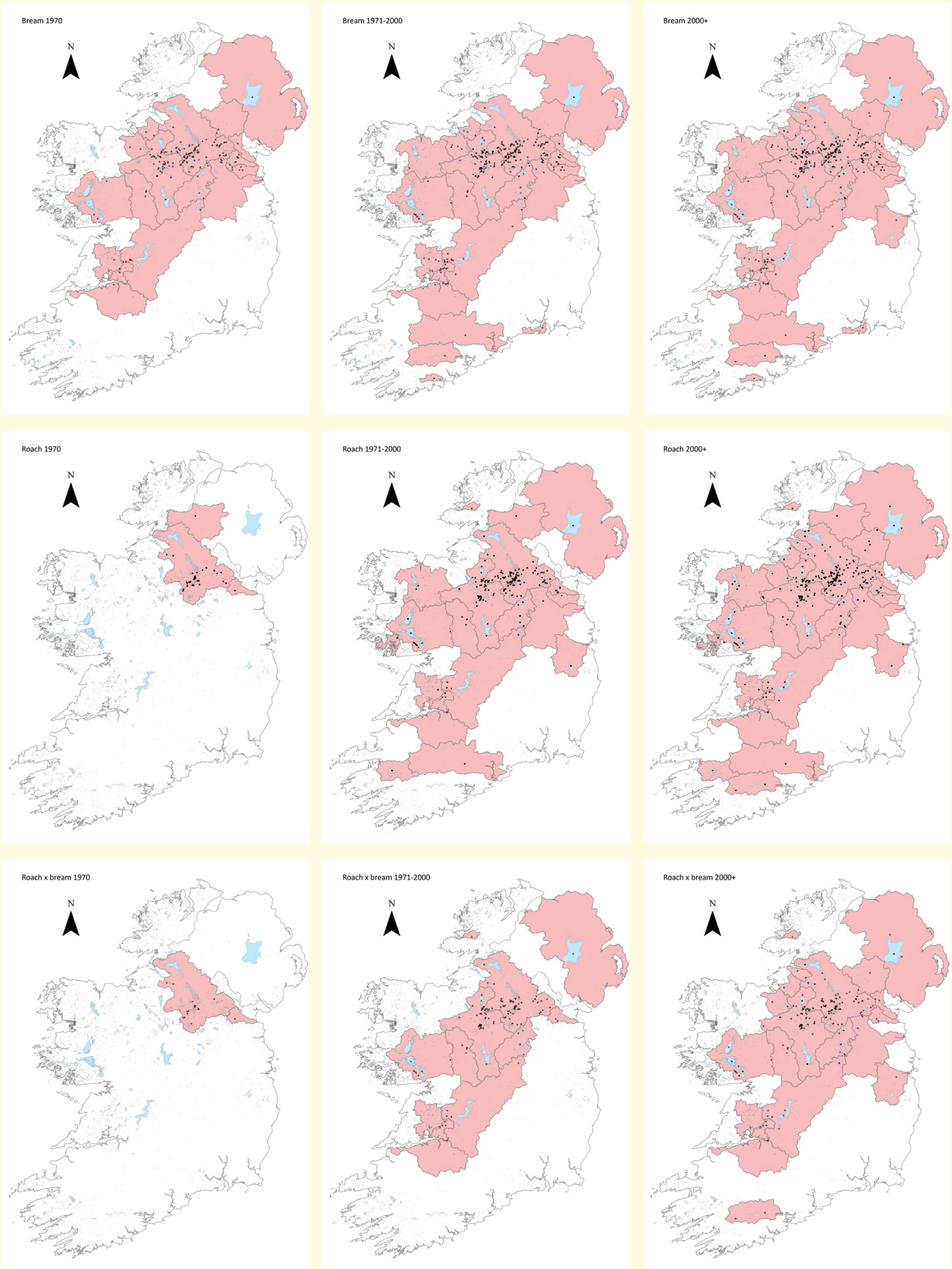


Figure 6.2 Distribution of bream, roach and roach x bream hybrids in Ireland 1970 to recent.

Figure 6.3
Eel boat on Lough Neagh

Tench were originally concentrated in the Shannon catchment and in several isolated lakes and ponds including larger lakes in the south-west such as Lough Leane in Co. Kerry. In the 1950s they were transferred by the Inland Fisheries Trust to other small lakes for angling purposes. Since 1990 they have become widespread in the Erne system. They are present in some small lakes in counties Armagh and Tyrone e.g. Loughgall lake and Lough Macronan (DAERA, 2023), and are occasionally caught by Lough Neagh commercial fishermen targeting eel and when fishing using gill nets (Figure 6.3). Their distribution has expanded since 1990 and local abundance of this species has increased in recent years where they are becoming more prominent in recreational angling and research survey catches. More recently they have been recorded in Loughs Corrib and Melvin.

Rudd were once widespread and introduced to many waters for angling purposes. However, they are particularly susceptible to hybridisation and competition from roach. Following the introduction and population explosion of roach in Lower Lough Erne, rudd disappeared (Cragg-Hine, 1973). Fish monitoring for the Water Framework Directive (WFD) since 2007 has revealed that their populations have become quite scarce. They are now largely confined to small, isolated lakes without roach (e.g. Lough Gur, Co. Limerick). While this has been observed in many large lakes containing rudd since that time, small numbers of rudd are once again being captured in routine surveys of many of the larger lakes (e.g. in both upper and lower Lough Corrib (McLoone et al., 2022). Despite the recent observed persistence in some larger lakes systems, their continued vulnerability to colonisation by roach is demonstrated by the discovery of the latter species in a survey of Lough Atedaun on the Fergus system where rudd was historically the most abundant cyprinid species. Rudd are still present in small lakes and ponds in Ards Peninsula, Co. Down, where there are few roach.

Before 1955 bream were mainly present in large inland low-lying lake catchments (i.e. the large Shannon Lakes such as Loughs Derg and Ree, the Erne, Corrib, and Neagh). Other catchments draining these central plains (e.g. lakes on the Boyne in the east and the Bonet (i.e. Lough Gill) in the west also historically held bream populations. However, with the growth in popularity of coarse angling bream were transferred to waters they did not previously occupy (Figure 6.2). In some of these, the subsequent arrival of roach and hybridisation has diminished bream numbers. In some cases (e.g. Upper and Lower Lough Erne), competition with roach reduced the growth rate and maximum size attained by bream. They are now also present in Lough Mask, while Lough Melvin is vulnerable to colonisation following stocking into Lattone Lough in the upper catchment. Lough Neagh, despite having roach, rarely produces significant numbers of hybrids.

Pike and perch – the predators

Pike and perch are widely distributed in all but the most westerly catchments. There is no evidence of the decline of either species, although both have been the subject of predator control to some degree since the 1950s in lakes managed for brown trout angling. Both species are present in a range of lake types, and both display a dietary switch from feeding mainly on macroinvertebrate to fish at a certain size depending on the lake type. Perch are the dominant species in many lakes, but their populations fluctuate (peak and then decline). Perch overtook roach as the numerically dominant fish species in Upper and Lower Lough Erne between 2004 and 2016 (DAERA, 2019) and other lakes (e.g. Lough Sheelin – see Chapter 12) following zebra mussel-induced lower plankton levels, higher water clarity and increased macrophyte growth (see Chapter 13). Growth rate and maximum size of perch also increased in the same period.

Invasive fish species - roach and common carp

Roach, common carp (*Cyprinus carpio*), dace (*Leuciscus leuciscus*) and chub (*Squalius cephalus*) are four fish species listed as non-native species subject to restrictions under Regulations 49 and 50 of the European Communities (Birds and Natural Habitats) Regulations 2011 [SI. 477]. Chub and dace are also listed in the Prohibition of Introduction of Fish (Northern Ireland) Order 1979. Dace and chub are mainly present in rivers in Ireland and, therefore, are not described further here (although dace were reported from the Ahaclare River, downstream of Doon Lake; however, an official survey did not confirm the species in Doon Lake. Chub were reported from the River Inny between Loughs Ree and Derravaragh in 2020 but not recorded in the lakes).

Roach

Roach (along with dace) were first introduced accidentally to Ireland when two tins of live bait spilled into the River Blackwater (Munster) around 1889 during a fishing trip (Fitzmaurice, 1981). From this incident, the species spread to the rest of the catchment. Subsequently, roach appeared in Co. Tyrone, NI, when Baronscourt Demesne was stocked as food for pike in 1905. It is believed that winter floods swept roach downstream to the Rivers Derg and Strule. In 1931 roach were stocked into Galbally Lake, Co. Fermanagh but a drain was opened by a dredger in the late 1960s allowing the species to escape downstream to the River Erne. Eyewitness reports at the time stated, 'those roach charged out in such a solid mass they couldn't all get through the eye of the bridge arch together. Some nearly spilled onto the road'. Roach were confirmed for the first time in the River Erne during a coarse fishing competition in 1963 and, by 1973, they had colonised the Erne catchment (Figure 6.2). In 1974 they were confirmed in the Shannon and Loughs Derravaragh and Kinale. In 1976 they were recorded in Lough Sheelin for the first time. During the 1980s and 1990s, the spread continued including through the Neagh-Bann system (Stokes et al., 2004). Despite the introduction of byelaws banning the use of live bait and efforts to contain them, there has been significant further spread and they are the dominant species along with perch in many lakes on the island today (Figure 6.2). Since the national fish in lakes monitoring programme began in 2007 at least six new populations have been officially identified (e.g. Lettercraffroe (Corrib catchment), Atedaun (Fergus Catchment), Lene (Co. Westmeath), Melvin, Castlewellan lake on the edge of the Mourne Mountains, Co Down, Lough Meenameen and other lakes on the Navar Plateau, Co Fermanagh).

Common Carp

Common carp (Carp - *Cyprinus carpio*) originate from the Caspian Sea and have spread to almost every continent via natural and human introductions since the glaciers retreated after the last ice age. Carp is considered an important aquaculture species and an increasingly popular recreational angling target worldwide, but also a potential nuisance where introductions become invasive (e.g. Australia (Stuart et al., 2021)). Introductions to waters in Ireland probably date back to the fourteenth or fifteenth century (e.g. Brazier et al., 2012). The species became popular with anglers in Ireland in the 1950s. The Inland Fisheries Trust 1951-1980 (the predecessor to Inland Fisheries Ireland) began to investigate carp in the mid-1950s as part of their promotion and development of coarse fish angling in Ireland and set up an artificial breeding programme. They carried out experimental stockings of carp into about 30 waters in the north midlands, east and south but many of those populations have not survived. The Central Fisheries Board (CFB) continued this work through the 1980s but had limited success at artificial rearing and it was difficult to create viable angling waters. A new carp-rearing facility was created at the CFB fish farm in Roscrea in 2000. In 2001 carp successfully spawned at the facility and carp fry were stocked into selected waterbodies. In subsequent years the demand for common carp reduced and the facility was closed in 2008.

Naturally reproducing populations are not currently common in Ireland and any range expansion is likely due to human intervention. Carp probably do not breed in the wild every year in Ireland as they require warm water temperatures (>20°C) during the breeding season (April to June). Breeding populations are probably restricted to sheltered shallow ponds where water temperatures are higher than larger more exposed waterbodies. Since 2015, all official common carp stockings are limited to waterbodies that have previously been stocked and that are artificial and isolated from main river and lake networks. One carp was recently (July 2023) found in Lough Corrib. Carp are present in a small number of stocked lakes that are privately and publicly managed for coarse angling in NI. They have also been recorded in Lough Neagh as accidental catches by eel fishermen.

The cyprinid hybrids

All permutations of possible hybridisation between roach, rudd and bream have been recorded in Ireland with roach x bream hybrids being by far the most common (Figure 6.2). From the 1990s to 2020, roach x bream hybrids have progressively outnumbered bream in surveys from the Erne System (DAERA, 2019). Identification of hybrids by appearance and external morphological features alone is not straightforward, and the Irish (rod caught) Specimen Fish Committee (www.specimenfish.ie) commissions genetic testing for definitive identification of specimens. In Ireland, most roach x bream hybrids are F1 (i.e. first generation) hybrids between both parent species. They can, however, breed with either parent species resulting in varied morphologies (Hayden et al., 2010). Rapid introgressive hybridisation is a mechanism by which roach could have supplanted rudd when introduced into the large lake systems and may also explain the decline of bream at many sites. Bream populations have also apparently stabilised and may be recovering in lakes where roach had colonised. For hybridisation to occur, spawning times must overlap. All three species spawn in late spring into summer. Maitland and Campbell (1992) give spawning temperature starting thresholds at 12 degrees for roach, and 15 degrees for the other two; hence raising the possibility of competition for food at the fry stage, with roach fry hatching first as another means by which roach could rapidly dominate a mixed cyprinid fish population. Hybridisation is more common in Ireland than in Britain (e.g. Hayden et al., 2010), perhaps a feature of the temperate climate.

Exotic species in lakes in Ireland

Ireland's lakes are vulnerable to the invasion of new fish species and ongoing vigilance is necessary to prevent the spread of any unwanted species. Occasional occurrences of 'exotic' non-native species have been noted (e.g. North American black bullhead catfish (*Ictalurus melas*) in 1984; a photo of the catfish *Ameiurus melas* (Black bullhead), was published in 2001 (Kersley, 2006) and there was a record of the white catfish (*Ictalurus catus)* from 1889 (Minchin, 2007)). However, there is no evidence that these species have become established in the wild in Ireland. More recently creditable reports of the angling capture of highly invasive round goby (*Neogobius melanostomus)* in Lough Ramor, Co. Cavan in 2018, led to efforts to confirm their presence in subsequent fish stock surveys, but none were found despite traps set during a survey in 2021. Occasional aquarists' exotics also turn up, e.g. two separate specimens of South American armoured catfish (*Hypostomus plecostomus*), probable aquarium releases and unlikely to be able to survive Irish winters were found in an urban lake in Belfast and a Lough Neagh draft net haul. In the RoI there are several 'commercial managed fisheries' on artificial ponds that advertise angling for non-native species which are not established in the wild. Examples featured in IFI's angling reports have included, e.g. grass carp - *Ctenopharyngodon idella)* and ornamental varieties of non-native cyprinids (e.g. koi carp and golden orfe (*Leuiscus idus*)).

Other species

The European eel is a long-lived catadromous fish species, spending most of its life in freshwater lakes and rivers and migrating to the Sargasso Sea to spawn. It is widespread across the island and occurs in all lakes to which it can gain access. Recruitment into Irish waters has declined in line with a European species-wide trend (International Council for the Exploration of the Seas (ICES), 2023) and is currently designated as critically endangered. A ban on commercial fishing and targeted recreational angling for eel was introduced throughout the RoI in 2009, as the stock did not meet threshold harvest criteria set by the EU (See Case Study Panel No. 3). At the same time, all fisheries in NI were closed except for Lough Neagh where spawning escapement targets continue to be met. Lough Neagh eel catches have declined from a peak of almost 1000 tonnes/yr in the 1980s to 200-300 tonnes/yr since 2000 and are partly supported by glass eel stocking.

Sea and river lamprey (*Petromyzon marinus* and *Lampetra fluviailis* respectively) are anadromous fish species that are parasitic in marine and lake waters and return to gravelled areas of rivers to spawn during late May to July. Reports of small sea lamprey attached to fish in lakes date to the 1950s. Juvenile lake-dwelling (feeding) sea lamprey has been recorded in several lakes in Ireland (e.g. Loughs Conn, Corrib, Derg, Gill, Leane (King and O'Gorman, 2018). Lough Neagh contains a rare landlocked population of the River Lamprey (Goodwin et al., 2006) which parasitises fish including pollan and salmonids (Kennedy et al., 2020). Brook lamprey (*Lampetra planeri*) can be found in muddy sediments in the shallow areas of lakes such as Lough Derravaragh in the Shannon catchment and the Erne system (McLoone et al., 2018b).

Flounder (*Platichtys flesus*) are mainly fish of brackish or saline waters but are often found in coastal and even inland lakes. There are records of flounder in lakes such as Lough Neagh (McCurdy, 1977) and Assaroe Lake, Co. Donegal, upstream of a 30 m high salmon ladder (Matthews et al., 2001). They are abundant in New Lake, Co. Donegal and have been recorded in Lough Gill and Glencar Lake in County Sligo, Lough Meela in Co. Donegal, Aughrusbeg Lough in Co. Galway and Lough Leane, Co. Kerry. To spawn successfully, flounder return to saline waters when they mature.

Rainbow trout are commonly reared and stocked for angling in lakes in Ireland. Self-sustaining populations developed in two known locations, Lough Shure, Arranmore Island, Co. Donegal (Department of Agriculture, 1937) and Lough na Leibe. Co. Sligo. A fish survey of Lough Shure in 2006 failed to produce a single fish and the rainbow trout population is thought to be extinct (Roche, pers. comm.). Lough na Leibe has not been surveyed for some years but the population there is also thought to have died out.

FISHERIES RESEARCH AND MANAGEMENT

Fisheries research

Effective fisheries management in lakes requires information on life histories comprising spawning, feeding, growth, age and size at maturity and inter-species relationships and a clear picture of natural typology and the associated characteristic flora and fauna. Fisheries management and development work by agencies on the island have been backed up by major programmes of applied biological research and surveys of the ecological conditions and stock status in selected lakes since the 1950s. See Case Study Panel No. 3 for an example of how information from scientific research studies was used to manage and inform future management of eel fisheries.

Fisheries scientists continue to monitor the status of waterbodies, mainly driven by EU nature Directives such as the EU WFD (EU, 2000) and the EU Habitats Directive (EU, 1992), and since leaving the European Union adhering to parallel legislation in NI (e.g. the Water (Amendment) (Northern Ireland) (EU exit) Regulations 2019). Most new research projects in respect of fisheries management are applied projects. Many include the use of new technologies such as acoustic telemetry (e.g. Kennedy et al., 2021), advanced modelling and mapping tools, sonar and hydroacoustic equipment (e.g. Morrissey, 2019), genetics (e.g. Delanty et al., 2021) and advanced high-frequency environmental monitoring equipment (e.g. Barry et al., 2023).

Fisheries management and development in lakes

Fisheries management and development work, including predator fish control (using methods such as gill netting, otter boards, traps, and long lines), stocking, fish farm development and instream development works, were undertaken to develop recreational fisheries in the 1950s to 1970s.

Some of this work continues but also includes the provision of angling access (e.g. constructing and maintaining accessible angling facilities) and invasive species management. Some of the work undertaken is attempting to address the legacy of human-mediated pressures on freshwater ecosystems (e.g. removing artificial barriers to fish passage). Funding is provided to various stakeholders to carry out conservation and development projects through various funding schemes (more information is available on the IFI website – www.fisheriesireland.ie).

Stocking in lakes

Since the mid-1950s, fish have been stocked into lakes by fisheries agencies on the island to encourage and sustain the recreational angling industry. In the 1950s, experimental stockings were carried out on a scientific basis to establish if it was worthwhile to stock certain species into Irish waters and if so, to identify what species would suit. Species included common carp, rainbow trout and tench. However, the capacity of added species to alter aquatic ecosystems (e.g. alteration of food webs and the potential for competitive exclusion of resident species) was not given the consideration it has acquired in recent years.

In NI, systematic surveys were carried out by the Department of Agriculture to find small lakes suitable for the stocking of rainbow trout and establish a range of state control waters available to the public for licenced and permitted recreational angling. In the late 1960s and the early 1970s, some sites were subsequently cleared of all coarse fish using rotenone (a broad-spectrum piscicide and insecticide) to make way for trout stocking. The Ministry of Agriculture for Northern Ireland Angling Guide (1973) documented efforts to remove coarse fish from Roughan Lake, Co. Tyrone, Glasdrumman Lake, Co. Armagh and Lough Brickland, Co. Down, Coolyermer Lake and Glencreawan Lough, Co. Fermanagh. This list is incomplete and there were more lakes where coarse fish removal programmes were at least attempted. Some of these sites (e.g. Glencreawan, Brickland) remain as part of the NI public angling estate now managed by DAERA and which includes "wild", coarse and game, non-stocked and stocked and non-cleared sites among *circa* 40 lakes available to anglers (DAERA, 2023). An equivalent programme was also implemented in several small lakes in the RoI during the 1960s and 70s.

It is very unlikely that fish removal programmes in favour of stocked brown trout and rainbow trout would be considered or permitted today due to stricter environmental regulations. Exceptions might include the discovery of a non-native, ecologically damaging and highly invasive fish species where there would be a high probability of its eradication and prevention of its spread to other sites in Ireland. Some of the coarse fish removal programmes carried out in the 1970s were unsuccessful and even lakes that were assumed to have been cleared have subsequently re-acquired coarse fish including pike, perch, and roach, probably through a mix of deliberate and accidental introductions.

Current advice recommends that fisheries in Ireland are managed to self-sustain populations of fish and the use of hatcheries and stocking particularly to supplement wild fish populations is not encouraged. Therefore, the present policy is to concentrate management efforts on habitat restoration rather than stocking. However, there are exceptions to this, e.g. in manmade water bodies and reservoirs and where stocking has existed for a considerable number of years (IFI, 2015). Currently, stocking in lakes for recreational purposes is mainly limited to reproductively sterile triploid fish (mainly brown trout and rainbow trout) in the RoI.

FISH AND ECOSYSTEM SERVICES

Fish provide many ecosystem services in lakes, both demand (e.g. angling, food source) and non-demand-driven (e.g. link in the food chain – see Chapter 5). They serve as food for other fish, birds such as herons, cormorants, and little and great crested grebes, and mammals such as otters, mink and even humans all while adding to the diversity of waterbodies. They are also an important indicator of water quality and ecosystem health and are considered sentinel species. The importance of fish since humans colonised the island has transitioned from a food source to one of recreation.

Role of fish in Irish history

Fish have played an important part in Irish history since humans colonised the island after the retreat of the glacial ice caps c. 14,000 BP (Kelly et al., 2020). The first settlers (Mesolithic period dating to c. 10,000-6,000 years ago) probably followed a hunter-gatherer nomadic life and lived by fishing, hunting, and foraging; lakes, rivers and coastal waters would have provided fish. Some early inhabitants may have been specialists in fishing following fish migrations from sea to river via lakes or settling around or on lakes and fished for food using various primitive methods. Some of the earliest archaeological evidence of fish consumption comes from a site excavated at Mountsandel, on the River Bann, County Derry/Londonderry in the 1970s. Carbon dating estimates the settlement to have been occupied *circa* 7000 BC, and identifiable fish remains included those of salmon, trout, and eel (Woodman, 1985). An artificial lake-edge platform and fish trap (dated to 5210-4970BP) at Clowanstown Co. Meath was found on the site of a raised bog that archaeologists believe would have been a small lake at the end of the last ice age (Fitzgerald, 2007). Other evidence of fishing in lakes by hunter-gatherers was found on Lough Leane in Killarney, Co. Kilkenny (c. 7000 to 7500 years BP) and Lough Ennell (at least 12 rock platforms were found in the northwestern section of the lake and were probably hunting or fishing platforms). Prehistoric tools (possibly Stone Age, Bronze Age/Mesolithic) were discovered on the shore of Glencar Lake, Co. Sligo in summer 2020 when lake water levels receded during a drought. The tools are believed to have been used for gutting and cleaning fish, woodwork, basket making and preparing food. Wrecks and dugout canoes have been discovered on many lakes (e.g. wrecks in Loughs Corrib, Derg, Lannagh (Castlebar), Owel, Ree and dugout canoes in Loughs Derravaragh, Neagh, Oughter and Gur). These discoveries provide evidence that prehistoric people availed of opportunities for fishing and boating around many lakes. (See Chapters 15 and 16 for more details).

Commercial fisheries

In the sixteenth century, pike and brown trout were exported from the south of Ireland (Youghal, Dungarvan and Kinsale) to southern English towns. Pike exports outnumbered brown trout and in 1507 AD, 3,850 pike were exported to England from Ireland (Pedreschi, 2013). In the nineteenth century, freshwater fisheries concentrated mainly on salmon and eel (Moriarty, 1997). Commercial fishing for other species was limited except for pollan in Lough Neagh. Pollan were sold locally in Belfast and exported to England. A large catch of c. 17,000 or *five one-horse carts* was reported in 1734 from Lough Neagh. Wilson (1993) cites reports of 400 tonnes of Lough Neagh pollan exported to England annually at the end of the nineteenth century. Arctic char and elvers were captured for pig feed where they were abundant (Moriarty, 1997). Lough Neagh still supports commercial fisheries. The fishery on Lough Neagh is one with a rich heritage, steeped in tradition and expertise handed down through successive generations. Close (2022) gives an account of the establishment of the Lough Neagh Fisherman's Co-operative Society, its governance, and its focus on protecting the future resource. Lough Neagh has also been the largest producer of wild-caught European eel in Europe. Species commercially targeted in Lough Neagh today include trout (dollaghan), pollan, perch, roach, bream, and pike. In the period 1996 to 2014, pollan catches as recorded in dealer registers ranged from 50 to 300 tonnes annually, eel catches were consistently in the range of 200-300 tonnes, lake trout (up to 11t/year), perch (up to 60 tonnes) and bream (2 tonnes) (DAERA, 2015 and 2019). It is estimated that the fishing industry on Lough Neagh has an annual turnover of approximately £3m (€3.45m) and is, therefore, of significant importance to the local rural economy.

A small commercial draft net fishery for brown trout still exists on Lough Ree (approximately 1.6 to 2.7 tonnes are taken annually). Commercial catches of eel in RoI ranged from 86 tonnes to 120 tonnes between 2001 and 2007 and a large proportion of these were taken from lakes (DCENR, 2008). However, recruitment into freshwater has declined dramatically since the 1980s and commercial exploitation is not sustainable; therefore, the eel fishery was closed in 2009.

Transition from food to recreation

The reasons for the importance of freshwater fish to humans have changed markedly from a simple food source to mainly a recreational resource, and more recently still recognition of fish as part of our wildlife and natural ecology. The selection of freshwater species for food in Ireland has traditionally focussed on salmonids (it was the opinion of many that salmon 'as a food surpasses all fish' (O'Sullivan Beare, 1625)) and to a lesser extent eel, with very limited use of cyprinid fish or pike, at least in surviving traditions of local consumption This is probably linked to the medieval (or later) arrival of some species, unpalatabilty (to Irish tastes) and boniness of most cyprinids and availability of palatable marine species. Local folk memory (Rogers, 1971) is that in times of hardship, Lough Erne bream were dried in smoke and preserved as a supplementary winter food source. Where there are or were commercial consumption fisheries for non-salmonid fishes, these tend heavily toward export markets. It is possible that the first common carp in Ireland were stocked into ponds for food in medieval monastic settlements (Brazier et al., 2012), but this did not result in any lasting tradition of eating this species, a popular food species elsewhere. Some new interest in eating cyprinid fishes, perch, and pike, caught by angling came to Ireland with immigration from EU Eastern European and

Baltic states, where these fish are more commonly eaten, from *circa* 1990. This resulted in the introduction of current harvest angling regulation by IFI, DAERA and Loughs Agency to prevent the depletion of popular fisheries and maintain populations of the larger specimens preferred by anglers, bringing coarse and pike angling into line with salmonid angling, where bag limits and harvest sizes were already in place for many sites. While regulations are in place for those who wish to harvest some of their catch, there is nevertheless a strong current trend among anglers to increase conservation and catch-and-release practice.

Recreation

In 2005, it was estimated that the net economic income from recreational angling in NI was approximately £22.5 million (€25.9m) and the authors projected this to increase to 31.5 million (€36.3m) by 2015 (DCAL, 2007). More recently, socio-economic studies for the RoI have estimated that recreational angling contributes approximately €836 million to the economy annually (NSAD, 2015) through direct and indirect services. Salmon and trout provide the largest income but revenue from coarse fish and pike angling has grown.

Anglers fish for a range of species on lakes in Ireland and employ various techniques when doing so. They will fish both for pleasure (simply for enjoyment) and/or competitively at numerous events organised by angling clubs or federations. While domestic anglers make up the greatest numbers fishing our lakes, Ireland has a significant influx of anglers from abroad, with visitors from Britain, France, Germany, Benelux and Italy all regularly fishing on lakes in Ireland. Traditionally, freshwater fishing has been divided into three distinct disciplines: Coarse, Game and Pike. While modern angling practices do not always fall neatly within these categories, they do offer an established framework enabling us to explore the role of lakes in Irish fishing.

Anglers fishing for pike and/or coarse fish generally return all the fish they catch to the water. There is also an increasingly strong catch-and-release ethos on many trout lakes, with many anglers choosing to return most of the fish that they catch. Anglers are now very aware of the importance of proper fish handling and the need to return fish to the water as quickly as possible to minimise impact, and they will often choose to use methods that facilitate a quick release, such as the use of barbless hooks.

Coarse Fishing

In coarse fishing, anglers primarily target species such as roach, rudd, tench and bream, along with perch. These species are widespread in Ireland, with concentrations in the Shannon and Erne systems. Key lake destinations for coarse fishing include Inniscarra Reservoir and Muckno (both renowned international competition venues), Ree and Derg, Upper Erne, along with a multitude of mid-sized lakes on the Erne/Oughter system (e.g., Garadice, Gowna, Guladoo), and the east Clare area (e.g., Bridget, Clondorney, Kilgory).

Coarse anglers are primarily bait anglers, using a wide range of natural baits such as worms, maggots, and sweetcorn. They often fish from the shore (as opposed to using a boat), and they use groundbait, which is a mixture of crumbed bread, seeds and flavourings to attract fish into the area they plan to fish. Coarse anglers usually adopt one of two approaches: 1) feeder fishing or 2) float fishing. In feeder fishing, a small cage-like apparatus known as a swimfeeder is attached to the line close to the baited hook. The swim feeder is then packed with ground bait and cast out where it sinks, thus presenting the baited hook either on, or close to the bottom. The groundbait then breaks down, attracting the fish close to the baited hook. In float fishing, the baited hook is suspended from a float which sits in the surface film. Groundbait is usually thrown in by hand, again attracting the fish close to the baited hook. Float fishing allows the angler to present the bait anywhere in the water column, from the bottom to just below the surface.

Game Fishing

Game fishing in Ireland involves fishing for salmon, sea trout and brown trout. Ireland has a strong tradition of fishing for all these species in lakes and fly fishing for these species from a drifting boat is regarded as a quintessentially Irish way of fishing.

Some of the primary lakes that are fished for salmon are Loughs Currane, Carrowmore, Leane, Corrib, and Beltra. Both Currane and Carrowmore are also two of Ireland's most popular sea trout fishing lakes. Ireland once had a strong tradition of sea trout fishing in the Connemara area, with lakes on the Costello and Fermoyle, Screebe, Ballynahinch Inagh and Kylemore fisheries all once noted for their fine sea trout fishing. Sadly, these fisheries suffered a severe collapse in sea trout numbers in the late 1980s and early 1990s, and unfortunately, they have yet to return to their former glory.

Trout fishing on lakes in Ireland is often associated with the 'Great Western Lakes,' originally encompassing Loughs Corrib, Mask, Carra, Conn and

Figure 6.4
Fishing boats
Lough Sheelin

Cullin, with the later addition of Arrow and Sheelin (Figure 6.4). These lakes are considered Ireland's most unique and valuable freshwater ecosystems and offer some of the best wild brown trout lake fishing in Europe. Other lakes that feature prominently for brown trout fishing are Loughs Ree, Derg, Ennell and Owel on the Shannon system, Lower Erne, and Melvin, which is noted for genetically distinct strains of trout in the lake, including the sonaghen, gillaroo, and ferox trout.

In general, game anglers adopt a range of different methods, often influenced by restrictions and/or regulations that may be placed on a fishery. However, the most common methods when fishing on lakes are fly fishing and spinning/lure, both of which are usually done from a boat. Of the two, fly fishing is by far the most widespread, and it usually involves casting a team of flies from a boat drifting with the wind. The flies normally imitate a food item for the fish and are either retrieved slowly or left static on the surface. Spinning involves using an artificial lure or spinner made of metal or plastic, which usually resembles a small fish when retrieved through the water. These are fished by two methods: 1) casting and retrieving by winding the reel back in or 2) trolling the lure at the end of a long line behind a moving boat.

Pike Fishing

Unlike the other two disciplines, pike fishing specifically targets one species, namely pike. Pike are mainly piscivorous and feeding strategies are largely determined by the availability of food in their ecosystems. Pike may migrate in response to seasonally or locally abundant increases in prey availability such as migrating salmonids and even lamprey. Lakes that feature prominently for the pike mirror those that are fished by the coarse angler, with the addition of some of the 'Great Western Lakes,' particularly Loughs Corrib and Mask.

Pike anglers use all the methods previously discussed. They use bait in the form of dead fish (deadbait), which is either fished on the bottom, suspended under a float, or cast and retrieved (known as wobbling). They will also fish with spinners/lures, using the cast and retrieve and trolling methods. Finally, in recent years, fly fishing for pike has become popular on lakes in Ireland. Pike anglers fish from both shore and boat and, when fishing from a boat, will often use fish finders to locate fish or fish-holding structures beneath the surface.

An important and growing element of the sport (particularly amongst competition anglers), which does not fit neatly into the above categories, is 'predator angling.' In predator angling, anglers target what they regard as predatory species, and in Ireland, this usually means pike, perch, and trout (often ferox trout). Predator angling takes place where there is a relative abundance of all three species, and both Loughs Ree and Derg are amongst the most popular venues.

Managed commercial fisheries

Managed commercial fisheries usually comprise lakes (which may be natural or manufactured) artificially stocked with fish, and where anglers pay a fee to fish. The most common species used in Ireland are trout (particularly rainbow trout). Coarse fish (particularly carp) are commonly used elsewhere in Europe but less so in Ireland. These fisheries play a key role, as they provide easily accessible fishing for the novice and/or the less able, with a relative abundance of fish, easy access to the bank and amenities such as toilets and shops which are generally not easily available on wild lake fisheries.

Regulation

There is no national rod licence in the RoI for brown trout, pike, or coarse fish, but many anglers pay a subscription to an angling club. There is, however, a licencing system in place for salmon and sea trout angling. In NI, a DAERA or Loughs Agency rod licence (specific to game or coarse fishing) is required for any freshwater angler over 12 years old alongside any permissions required by the fishery owner.

Fishing in Ireland is managed through various regulations which may limit or even ban fishing for certain species. Some regulations are national, such as size and bag limits for coarse fish and pike, yearly restrictions on salmon harvest and an all-island ban on targeted angling for eel. Other restrictions are more localised, such as bag and size limits for trout on individual lakes or bans on taking fish in wider geographical areas, such as killing any sea trout in large parts of the west of Ireland.

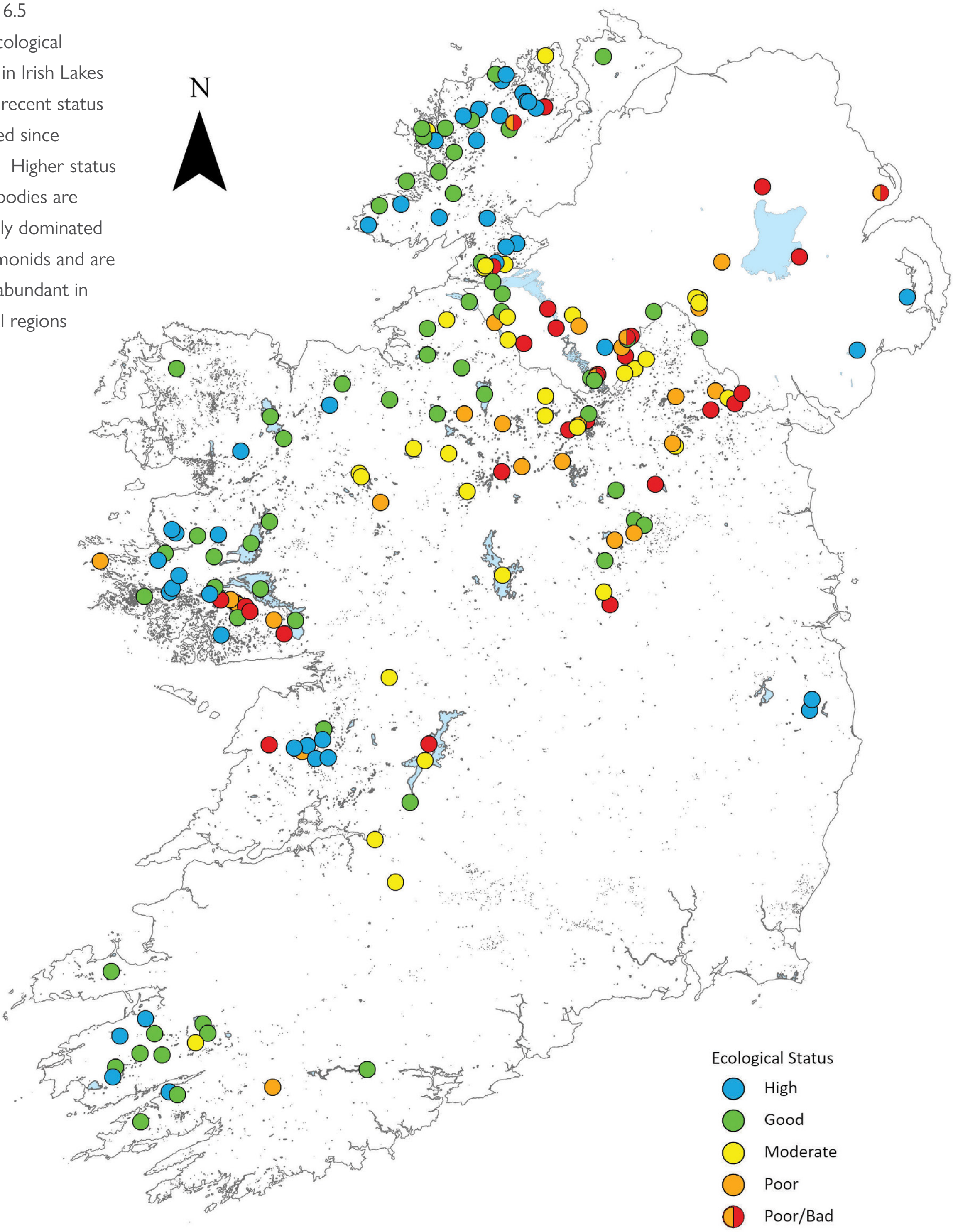
ASSESSING THE HEALTH OF LAKES USING FISH AND PRESSURES

Fish are an important indicator of water quality and ecosystem health and are considered sentinel species. Since the publication of the EU WFD in 2000 and subsequent initiation of national monitoring programmes fish have been used as one of the official indicators to assess the ecological health of waterbodies.

Fish stock assessment in lakes

Until the mid-late 1960s, fish stock assessments on lakes in Ireland were mainly confined to angler reports (e.g. IFT Creel Census Scheme 1964-1979) and visual sightings during annual pike and perch management operations between the 1950s and early 1970s. However, pollution from intensive agricultural activities in the late 1960s and early 1970s in managed trout lakes (e.g. Loughs Sheelin and Derravaragh) forced several agencies responsible for the environmental protection of freshwaters to monitor and act on the situation through a systematic programme of nutrient measurement and fish population abundance monitoring in addition to regulatory inspection and enforcement. In the late 1970s, a standardised survey method was developed to assess the abundance and health of wild brown trout populations in lakes. This targeted fish ranges in size from 19.8 to 48 cm. Using this method the fish population in large brown trout lakes were surveyed intermittently (e.g. O'Grady and Delanty, 2001). Investigative surveys of waters with angling potential for coarse fish were also conducted throughout the 1960s and 1970s and selected coarse fish waters (*circa* 250) were re-surveyed between 1994 and 1997. Reports of anglers catches, returns to the Irish Specimen Fish Committee, information compiled in occasional surveys of selected trout lake fisheries, intermittent localised surveys of riverine salmonid populations, fish kill incidents and surveys conducted by the Irish Char Conservation Group, provided the only updates regarding the current distribution of freshwater fish in Ireland up to

Figure 6.5
Fish ecological status in Irish Lakes (most recent status assigned since 2005). Higher status waterbodies are typically dominated by salmonids and are most abundant in coastal regions



mid-2000s as there was still no tradition of systematic monitoring of fish stocks in lakes in Ireland and no national monitoring programme existed.

In 2005, a new era of fish in lakes monitoring began when fisheries scientists on the island collaborated to develop a standard method for sampling fish in lakes for the WFD through an Interreg-funded project. Assessing the health of lakes using fish now involves a multimethod netting approach (Kelly et al., 2008) deployed at multiple sites in prescribed depth zones in selected lakes across Ireland and then assigning a score known as an Ecological Quality Ratio to each waterbody based on species composition, abundance and age structure of indicator species and other species present (Kelly et al., 2012). Since 1950 approximately 900 lakes in Ireland have had a general or systematic evaluation of their fish stock status (e.g. McLoone et al., 2018a).

Fish ecological status of monitored lakes

Since 2005, the fish ecological status of 189 lake waterbodies (149 in RoI, 34 in NI and 6 shared cross-border) has been assessed on the island (Figure 6.5). Several have been assessed every three years as part of the national WFD surveillance national monitoring programme. Other lakes are assessed less frequently. In general, lakes in the west, northwest and southwest have a higher fish ecological status than lakes in the north midlands where there is a high abundance of tolerant fish species such as roach and perch (Figure 5).

PRESSURES

The status of fish and other aquatic biodiversity is an essential measure of the health of lake environments. Freshwater fish in lakes in Ireland have been under increasing pressure from a variety of human activities for many years. Pressures on fish populations in lakes today include eutrophication (nutrient enrichment), water pollution, reductions in dissolved oxygen, land management practices, hydromorphological pressures including physical habitat alteration, exploitation, translocation of species, introduction of invasive alien species and climate change (including increasing water temperatures) (Table 6.2). Certain sentinel species such as Killarney shad, pollan, Arctic char, salmon and trout are particularly sensitive to anthropogenic impacts and require cool clean oxygenated water to survive. Trout, nearly ubiquitous in Ireland, comprises many discrete populations that may individually require protection. Species such as perch, roach, bream, and tench are generally more tolerant to these pressures.

Table 6.2 Pressures impacting fish populations in lakes

Pressure	Pressure type	Impacts
Pollution	Eutrophication Deoxygenating pollution Toxic and chemical pollution Acidification Sediment	Excessive nutrients and other pollutants lead to algal blooms causing oxygen reduction, reduction in fish habitat, increased fish kills and food availability to fish. The demise of Arctic char in several lakes has been attributed to eutrophication (e.g. Loughs Conn and Ennell). Algal blooms can also directly affect angling activity. Certain metals, industrial chemicals, and pesticides (herbicides, insecticides, and fungicides) can be extremely toxic to fish and other aquatic organisms. The demise of Arctic char in the Wicklow lakes (e.g. Dan, Tay, and Glendalough) is believed to be due to acidification. Silt has the effect of smothering spawning beds of certain salmonid and lamprey species and can cause a decrease in dissolved oxygen levels
Exploitation	Commercial Recreational Illegal (poaching)	Over-exploitation can lead to declines in fish stocks. Conservation measures (e.g. bag and size limits) are in place for anglers and few commercial fisheries in lakes remain. Catch and release practice is increasing as anglers become aware of pressures on fish species.
Introduction of species	Translocation Invasive aquatic species	Introduction of perch to lakes supporting Arctic char in Co. Galway has coincided with dramatic declines in the latter species. Introductions of pike to new waters (e.g. Owenriff catchment and south Donegal lakes) has coincided with losses of lake resident trout. Research has shown that relatively large, deep lakes with strong stream connectivity are likely to support coexistence of pike and trout. However, pike introductions to small lakes have potential for strong negative impacts on resident trout populations. IAS (e.g. Zebra mussels (Dreissena polymorpha), Asian clam (Corbicula fluminea), quagga mussel (Dreissena rostriformis), curly leaved water weed (Lagarosiophon major)) are continuing to spread affecting fish, their habitats and angling.
Hydromorphology and land management practices	Dams and impoundments Arterial drainage schemes Water abstraction and impoundments Water regulation Weirs and culverts Land management practices	Run of flow hydropower on lake outflows can prevent or restrict movement of diadromous fish into lakes. Lake regulation and water abstractions can affect lake resident fish, particularly gravel shore spawners. Arterial drainage works from the 1950s to the 70s caused fluctuations in lake levels for many years and disturbed feeding grounds of fish. Poor angling in the years following the works on several lakes (Conn, Ennell, Derravaragh, Sheelin) was attributed to the schemes. Drainage activities in the rivers have been associated with periods of increased sedimentation in lakes.
Climate change	Droughts High temperatures, Flooding and browning Increased sediment	Climate change is expected to modify water temperature, lake stratification patterns, and flow regimes, and cause loss of habitat. Biological functions of fish are dependent on the ambient water temperature and thermal tolerances are specific to each species. These changes may affect fish distribution, abundance, behaviour (e.g. timing of migration), species composition, community structure and dynamics and disease resistance. Warming lake water temperatures and resulting changes in stratification can restrict thermal habitat for cold water species dependent on cool refuges. Effects will be compounded by pre-existing pressures such as nutrient enrichment causing algal blooms and oxygen depletion; as water warms it loses oxygen saturation capacity essential for fish to survive.

CONCLUSIONS

The low species diversity of an island with a depauperate postglacial list of freshwater fishes is a feature of scientific interest. Conservation measures and legislation are required to prevent further losses and protect certain sentinel species, e.g. Arctic char, and various ecotypes of trout. Arctic char has as yet little protection in national law, which focusses on commercially or recreationally valuable fish species such as eel, salmon, and brown trout. Some sympatric populations of trout have a small population size making them particularly vulnerable (e.g. Lough Melvin trout ecotypes).

There is a clear requirement for more ongoing long-term studies to identify the actual and potential impacts of multiple pressures including climate change on fish in lake habitats in Ireland and the ecological consequences.

Temperature tolerance limits of key sentinel species and life stages are still to be described as even small further increases in winter temperature minima could further reduce the reproductive capacity of coldwater species including Arctic char and pollan. Any warming in spring and summer could trigger more regular breeding of cyprinids such as common carp and tench which are currently benign here, but highly invasive elsewhere.

The pressures caused by climate change must be evaluated in the context of non-climatic pressures such as angling (exploitation), non-native species introductions (e.g. the spread of warm water fish species), habitat modifications and changes in nutrient additions, flow obstructions and freshwater run-off patterns so that agencies and other stakeholders can protect and sustainably restore lake ecosystems currently under pressure from many areas and allow strategic prioritisation of conservation and protection measures.

Efforts also need to be maintained to look at what else could arrive on the island (horizon scanning) and prevent the introduction of temperate-zone lake fishes found in Europe (or anywhere else), but which have not colonised Ireland. Any new species could have unpredictable and potentially negative consequences.

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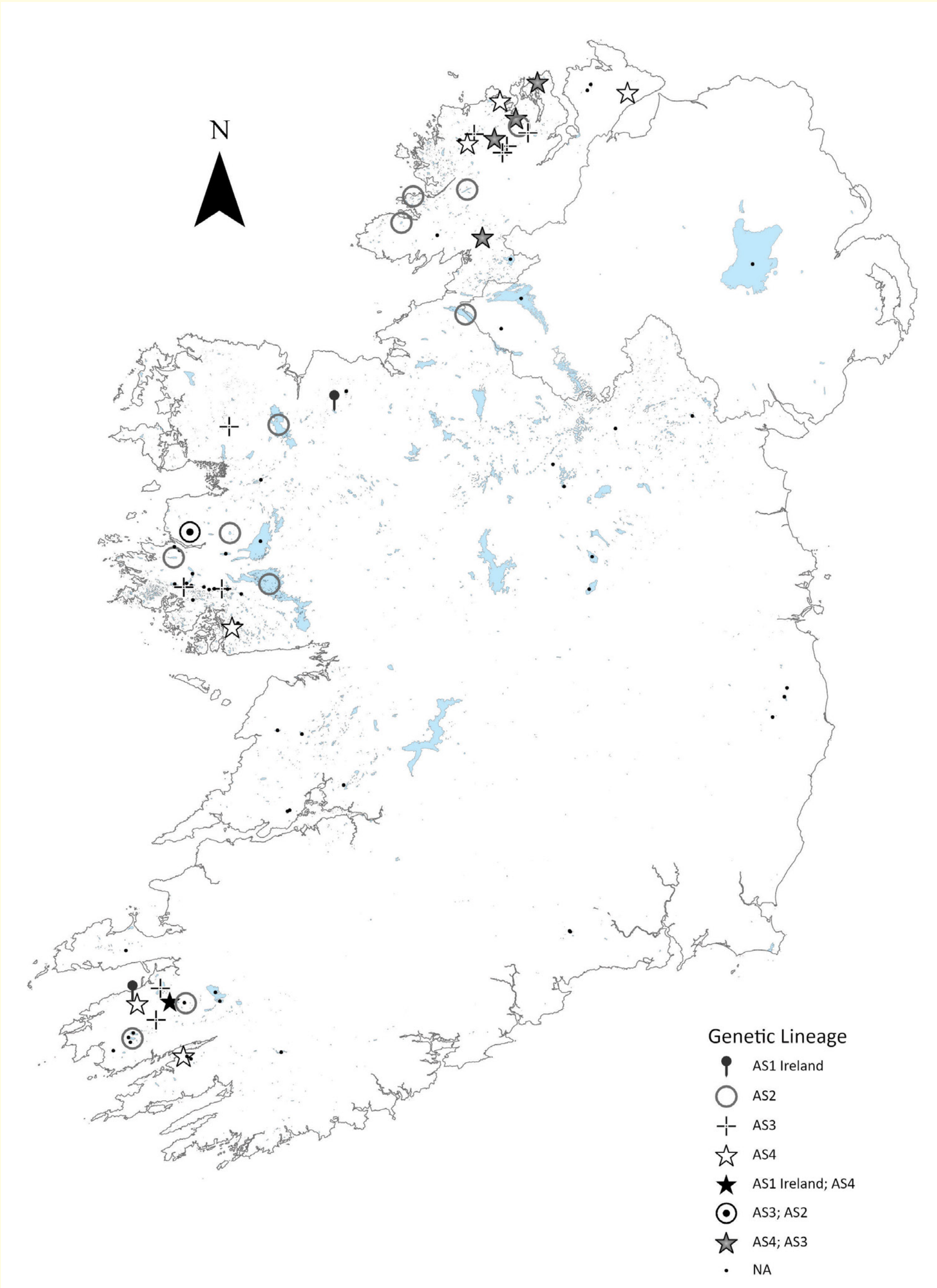
Case Study Panel No. 1:
TAXONOMY OF ARCTIC CHAR IN IRELAND

There has been a lot of debate over the taxonomy of Arctic char. Early taxonomists split the species into many species or subspecies based on a range of morphological, meristic, and other traits. In Ireland, the taxonomy of Arctic char has also been a source of confusion. In the 1800s, two species of char were recognised and later in the early 1900s, six species were identified based on meristic and morphometric measurements. Ferguson (1981) determined that Arctic char in Ireland were similar genetically and derived from a common ancestor. Most authorities now agree that all these stocks belong to a single polymorphic species complex *Salvelinus alpinus*.

A recent study investigating the taxonomy of Arctic char in Ireland has shown that there are four genetically distinct evolutionary lineages present in lakes in Ireland (Barthelemy et al., 2023). Two of these (Atlantic Subclade 1-Ireland (c. 87,000 years) and Atlantic Subclade 4 (c. 61,000 years)) appear to be restricted to Ireland. The other two lineages (Atlantic Subclade 2-Ireland (c. 44,000 years) and Atlantic Subclade 3 (c. 50,000 years), are well represented in Ireland but are also found in Britain (England and Scotland) and the North Atlantic (Iceland and Norway). Results revealed that these four lineages evolved separately before the last Ice Age and independently colonised Irelands lakes at different times following the retreat of the ice caps (between c. 23,000 and 13,000 years BP). The geographical distribution of these four lineages suggests that the colonisation of Ireland was complex and, in several cases, involved extinction, recolonisation, and/or secondary contact and admixture of Arctic char representing different lineages (Barthelemy et al., 2023). Arctic char in Loughs Acoose and Coomaglashlaw (Co. Kerry) and Lough Talt (Co. Sligo) seem to be the rarest lineage (Atlantic Subclade 1-Ireland) and were probably the first to colonise Ireland representing pioneer glacial relicts. This study also indicated that there may also be sympatric populations present in several lakes including Lough Acoose and Caragh, Co. Kerry and Loughs Glen and Kindrum, Co. Donegal (Barthelemy et al., 2023). This new research will contribute to future conservation measures of Arctic char in Ireland.



Left:
Distribution of Arctic char lineages.

Below, from left:
Examples of variation in head morphology of Arctic char from three lakes in County Donegal (a) Lough Dunlewy, (b) Sessiagh Lough and (c) Lough Gartan.

Below, right:
Arctic char from Sessiagh Lough, Donegal.

Case Study Panel No. 2:

SYMPATRIC TROUT IN LOUGH MELVIN

Three unique forms of Eurasian trout (ferox, gillaroo and sonaghen) are present in Lough Melvin. Ferguson and Prodöhl (2022) state that they are sufficiently genetically distinct to be regarded as three separate species of trout. Fisheries authorities on the island of Ireland recognise the three forms as separate species.

Gillaroo (*Salmo stomachicus*) (or gizzard) trout feed mainly on caddis flies, molluscs and Gammarus sp. and are known to spawn in the outflow of Lough Melvin on the River Drowes (Ferguson and Prodöhl, 2022). Their diet has resulted in this strain developing a distinctive heavy muscular stomach with which to crush shells. They have also been reported from several other lakes (e.g. Mask, Conn, Corrib, Derg, Neagh).

The ferox trout (*Salmo ferox*) is a piscivorous strain of brown trout present in lakes that is highly prized by trophy anglers. It represents a remnant of a once widespread type of trout which colonized areas of freshwater in immediate post-glacial times and evolved to occupy the fish-feeding niche in several lakes. These ferox trout appear to be present in low alkalinity lakes (e.g. Lough Caragh, Co. Kerry) in small numbers, but are more common in large (>1000ha) moderate to high alkalinity lakes in the west (e.g. Lough

Facing page: Gillaroo trout (top) and Sonaghen trout (bottom) from Lough Melvin.
Above: Ferox trout

Corrib and Lough Mask), northwest (Lough Melvin and Lower Lough Erne) and southwest (Lough Leane, Co. Kerry). Their life history is associated with fast growth following the switch to a piscivorous diet and extended longevity. Ferox trout are regularly captured on these lakes by anglers trolling baits, and because of their exceptional size and growth rate. In Lough Melvin, they spawn in the lower Glenaniff River (Ferguson and Prodöhl, 2022). Ferox trout are also present in Scottish lakes.

The sonaghen (*Salmo nigripinnis*) (or black finned trout) is a pelagic trout ecotype endemic to Lough Melvin, the most common of the trout strains (ecotypes) and leads a mainly planktivorous lifestyle feeding mainly on zooplankton) in the pelagic zone of Lough Melvin (Ferguson and Prodöhl, 2022). They are known to spawn in most of the inflowing rivers of Lough Melvin, including Ballagh, Glenaniff, Tullymore and Roogagh (on both RoI and NI sides). Sonaghen, are also thought to be present in Lough Mask and Corrib, but this has still to be established.

Case Study Panel No. 3:

THE IMPLEMENTATION OF THE 2007 EU EEL REGULATION IN LAKES IN IRELAND: How information from scientific research studies was used to manage and inform future management of fisheries.

Lakes in Ireland are feeding and growing sites for the European eel (*Anguilla anguilla*). The lakes of the Shannon, Bann, Erne, and Corrib systems are historically significant as eel fisheries and contributors to mature silver eel stocks leaving freshwater to the spawning grounds in the Sargasso Sea. Following decades of observed decline in the International Stock, and Advice from the International Council for the Exploration of the Sea (ICES), the European Commission enacted a regulation (European Commission, 2007) requiring Member States to put in place Eel Management Plans with the objective of all attaining escapement equivalent to 40% of pre-1980s production.

This resulted in concerted efforts to produce estimates of eel production for all systems in Ireland (e.g. DCAL, 2010), one Transboundary area of the Erne, Foyle and Donegal Catchments, and ongoing eel monitoring programmes.

Above: Silver eel, Lough Erne Facing page: Lough Neagh fishery.

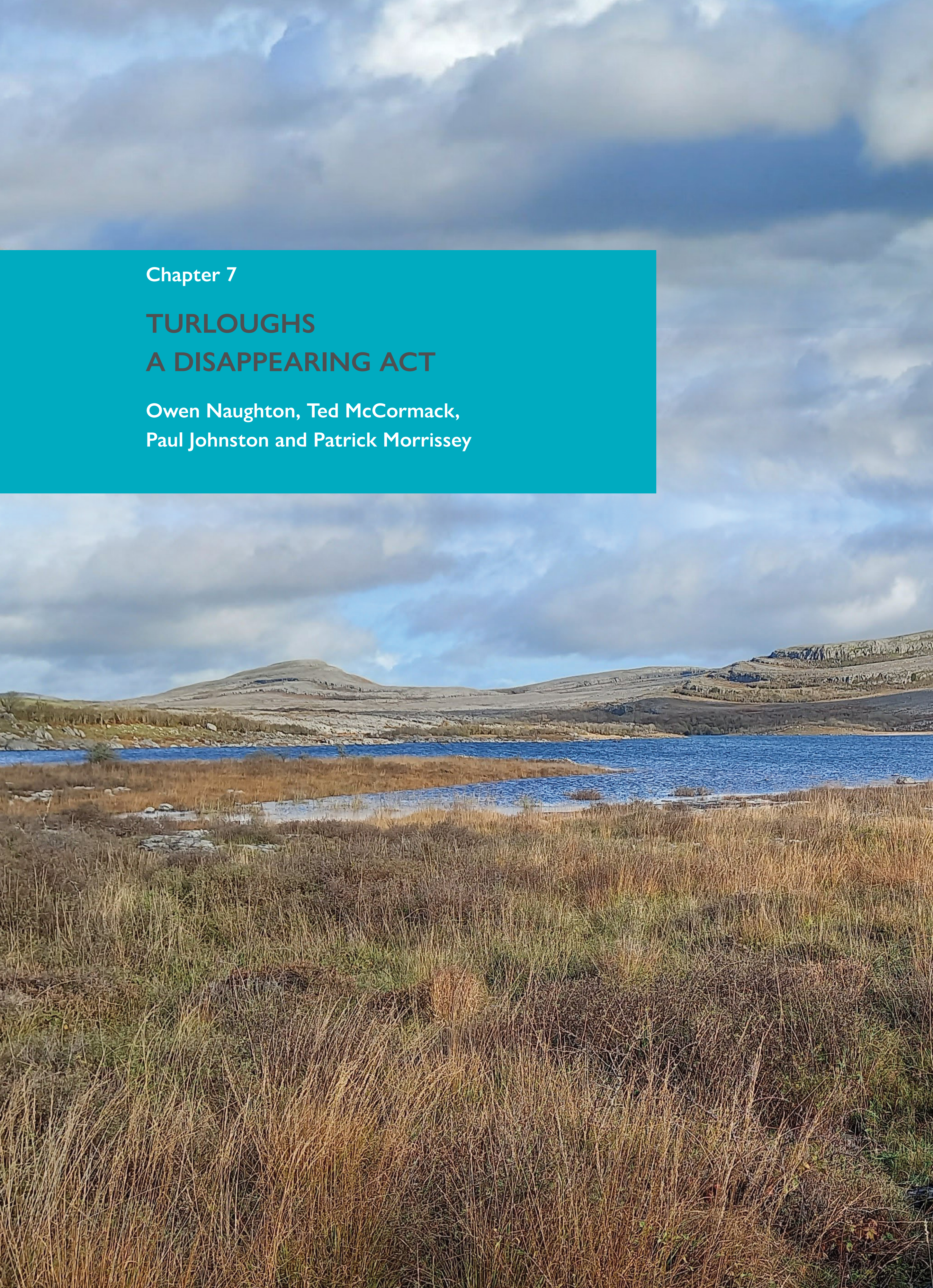
Models based on lake surveys, known recent glass eel recruitment history and the lags from recruitment as elver to emigrating mature silver eel indicated significant problems ahead. The Shannon and Erne lakes silver eels had to pass hydropower facilities en route to the sea. Lough Neagh seaward migrating eel are subject to a fishery.

The science informed a new and ongoing management framework for eels. RoI fisheries were closed, and replaced on Shannon and Erne system lake exits with new fisheries to transport emigrating silver eel past Hydroelectric stations. The Lough Neagh fishery continued, with 40% escapement target compliance checks via mark-recapture (Rosell et al., 2005) and a review of the targets set in the first management plan (Aprahamian et al., 2021).

Chapter 7

TURLOUGHS
A DISAPPEARING ACT

Owen Naughton, Ted McCormack,
Paul Johnston and Patrick Morrissey



SUMMARY

Turloughs are ephemeral lakes found in karst limestone depressions that periodically flood and dry in response to seasonal changes in rainfall. While turloughs have been reported in Slovenia, Germany, Estonia, and Croatia, they are principally associated with the karstified limestone lowlands of the west of Ireland. Turloughs act as seasonal storage, temporarily holding excess rainfall as surface flooding until it can drain back into the karst groundwater system beneath. The oscillation between flooded and dry phases disrupts the ecosystem by changing the environment and resources available, resulting in a species-rich mosaic of wetland habitats which has protected status under EU legislation. Turloughs are thus recognised as an internationally important 'standing freshwater' habitats under the European Union Habitats Directive.

As a habitat turloughs defy easy categorisation, representing as they do transitional zones between aquatic and terrestrial ecosystems. Turloughs vary along a range of hydrological, morphological, and ecological gradients which often overlap with and encompass other habitat types such as oligotrophic lakes and or alkaline fens. Turlough vegetation displays a regular zonation along the flooding gradient, ranging from dryland species at the outer edge of the turlough to wetland and aquatic species deeper in the basins. This chapter describes some of the key features of this unique habitat, including their hydrogeology, characteristic hydrology, and ecology, together with some of the current and future pressures facing these unique lake habitats.

Keywords Turlough, karst, groundwater-dependent wetlands, flooding

INTRODUCTION

Turloughs can be defined as topographic depressions in karst which are intermittently flooded on an annual basis, mainly from groundwater, and have a substrate and/or ecological communities characteristic of wetlands (Tynan et al., 2007). This definition, however, does little to convey how

Figure 7.1 Blackrock Turlough, Co. Galway during (left) summer and (right) winter 2006/2007.

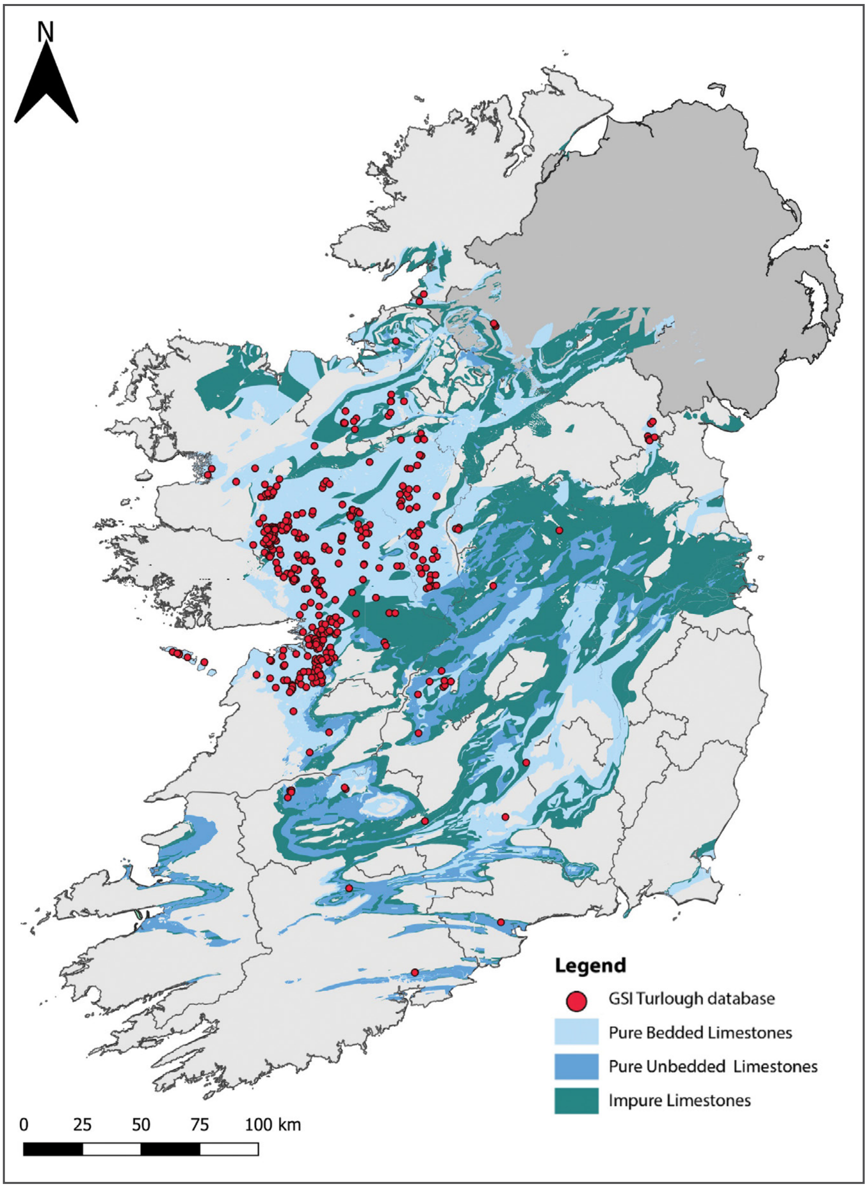
remarkable the intermittent flooding can be, and how unique it is amongst the lakes and wetlands of Ireland. Blackrock Turlough, for example, lying in the limestone lowlands centred around Gort, Co. Galway, can transition from an expansive commonage idly grazed by horses and cattle, to a lake over ten meters deep covering over a hundred hectares in a matter of days following heavy rainfall (Figure 7.1). While this is one of the more spectacular examples of the turlough habitat, similar cycles of filling and emptying are repeated in hundreds of larger and smaller topographic depressions across the limestone lowlands of Ireland every year. This chapter collates current knowledge of turlough habitats, under the headings of hydrogeology, hydrology, ecology, and pressures. The hydrogeological conditions which give rise to turlough habitats are explained, followed by a summary of turlough hydrology in terms of conceptual operation, depth, extent, and hydrological regime. Turloughs contain distinctive assemblages of plant, invertebrate and bird communities of high conservation value both nationally and internationally, and some of the key floral and faunal characteristics are outlined. The chapter concludes with a discussion on current and future pressures threatening the integrity of turlough habitats, namely eutrophication, drainage, and climate change, followed by highlighting some outstanding issues to be addressed for these quintessentially ephemeral lakes in Ireland.

HYDROGEOLOGY

The unique characteristic that sets turloughs apart from other lakes in Ireland is their seasonal pattern of flooding and drying. To understand how and why this occurs, it is important to first understand the karst groundwater systems that support turloughs and the role turloughs occupy within them. Turloughs are intrinsically linked to the Carboniferous limestone bedrock which underlies almost half the island of Ireland (Drew, 2018) (Figure 7.2). Limestone is a carbonate rock that is susceptible to dissolution. The movement of water through the fractures and pores within the rock enlarges groundwater flow paths in a process known as karstification. Much of Ireland's limestone bedrocks, particularly to the west of the River Shannon where it is relatively pure and well-bedded, have undergone significant karstification throughout their geological history (Drew, 2008). Natural surface drainage in these areas is frequently discontinuous or non-existent. Instead, subterranean networks of water-bearing fractures and conduits act as the main regional drainage routes, such as in the Gort Lowlands in south Galway (Naughton et al., 2018a).

While the fractures, conduits and caves within the bedrock can be large individually, they make up an extremely small proportion of the bedrock by volume. As the limestone bedrock itself is effectively impermeable, there is thus very little capacity underground to store excess recharge. Furthermore, most Irish limestones are relatively low-lying, with groundwater levels relatively close to the ground surface even during drier summer months. This combination of low storage and shallow depth to groundwater means that the exchange of water between groundwater and surface water systems becomes both common and complex on the karst lowlands (Drew, 2018). In summer months, when rainfall is relatively low and evapotranspiration high, Irish lowland karst systems normally have enough capacity to drain any recharge entering the catchment without any surface flooding. When rainfall levels start to increase, typically in the early autumn, the quantity of rainfall on the catchment overwhelms the capacity of the cracks, conduits, and caves to drain the water away. The system begins to back up, causing the recurrent flooding that is the defining feature of turlough habitats. Turloughs thus effectively act as temporary surface storage within karst groundwater systems, and overflow tanks for excess rainfall during the winter months. The distribution of turloughs across the island of Ireland is influenced by a combination of geological, hydrogeological, topographic, and climatic factors. They typically occur on the relatively pure, well-bedded lowland

Figure 7.2
Locations of limestone and turloughs in Ireland (limestone layers derived from Geological Survey Ireland Hydrostratigraphic Rock Unit Groups map).



limestones in the west of the country, where rainfall significantly exceeds evapotranspiration for lengthy periods over the winter months (Figure 7.2). Approximately 80% of turloughs on the island of Ireland occur in Galway, Clare, Mayo, and Roscommon, and 90% of turloughs occur under 80 meters above sea level (Figure 7.2). There are just three recorded turloughs in Northern Ireland, namely Fardrum Lough, Roosky Lough and Green Lough. Lying approximately 7 km north-west of Enniskillen in Co. Fermanagh, these sites represent the most northerly examples of the turlough habitat.

While the presence of turloughs has a strong link to karstification, the origins of turloughs are thought to be polygenetic in that both dissolution and glaciation played a part in their formation (Coxon and Coxon, 1994). Coxon (1986) proposed three scenarios to describe the formation of the bedrock hollows in which turloughs occur and the high permeability zones required for their cyclical filling and emptying: (1) a combination of glacial hollows with flow paths developed post-glacially, (2) glacial hollows developed along the line of existing pre-glacial flow paths and (3) pre-glacial karst features with flow paths that have been modified by glaciation. Drew (2018) further suggested that the blocking and diversion of surface and underground flow routes by glacial and fluvio-glacial deposits are at least partly responsible for the extensive groundwater-surface water interactions that give rise to turloughs (see Chapters 2 and 4).

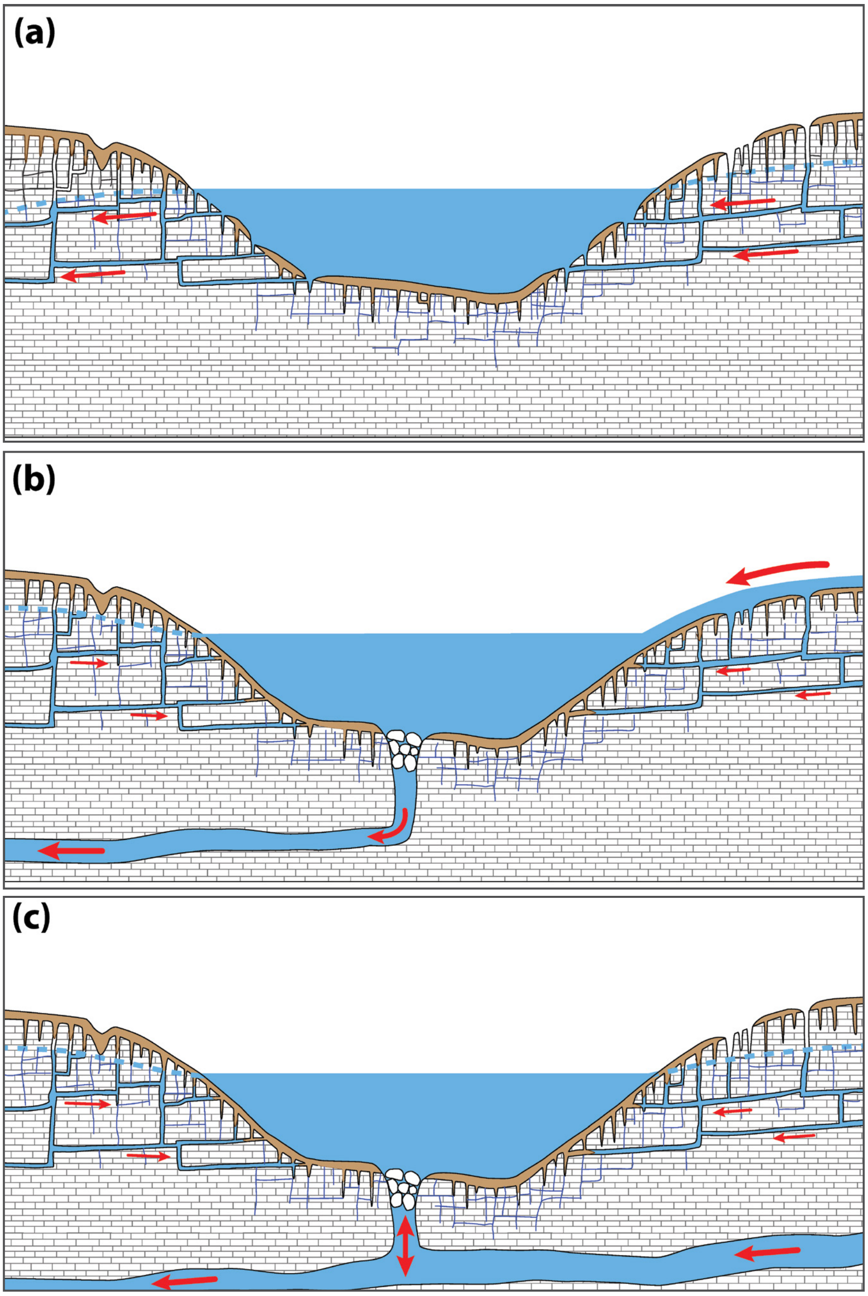
HYDROLOGY

Conceptual Operation

Turloughs are classified as groundwater dependent terrestrial ecosystems under the EU Water Framework Directive. However, the nature of this groundwater dependency varies significantly from site to site. Turloughs can fill in several different ways; by rising groundwater levels, estavelles (bidirectional sinkholes), springs, direct rainfall, overland flow from surrounding hillslopes and in some cases, river inputs. Turloughs naturally drain to the groundwater system through swallow holes, estevelles and fracture networks. In many cases, manmade drainage bypasses the natural groundwater system and removes floodwaters at upper levels via overland flow instead (Naughton et al., 2018b).

The way in which turloughs behave can be summarised using two conceptual models: the through-flow system and the surcharged tank system (Naughton et al., 2012; Naughton *et al.*, 2018b) (Figure 7.3). In through-flow systems, the flow paths through which the turlough fills and empties are isolated from each other, with no direct transfer of water between them without first passing through the main water body. For example, the turlough may lie in a bedrock hollow that intercepts shallow epikarst groundwater flow (Figure 7.3(a)) or may act as a swallow hole for point recharge and/or recharge from the surrounding shallow epikarst system (Figure 7.3(b)). Lough Aleenaun in the Burren, Co. Clare, is a good example of a through-flow system (Drew, 2018). In a surcharged tank system, the turlough effectively acts as overflow storage

Figure 7.3
Conceptual diagrams representing possible turlough hydrological operation:
(a) distributed through-flow,
(b) through-flow with distributed/point recharge and point discharge and
(c) surcharged-tank (from Naughton (2018b)).



for a conduit network that runs under the turlough basin (Figure 7.3(c)). When the conduit system is highly pressurised following sustained heavy rainfall, groundwater flows from the conduit system up into the turlough basin. When the pressure in the conduit system drops, the floodwaters in the turlough drain back into the conduit and floodwaters in the basin recede.

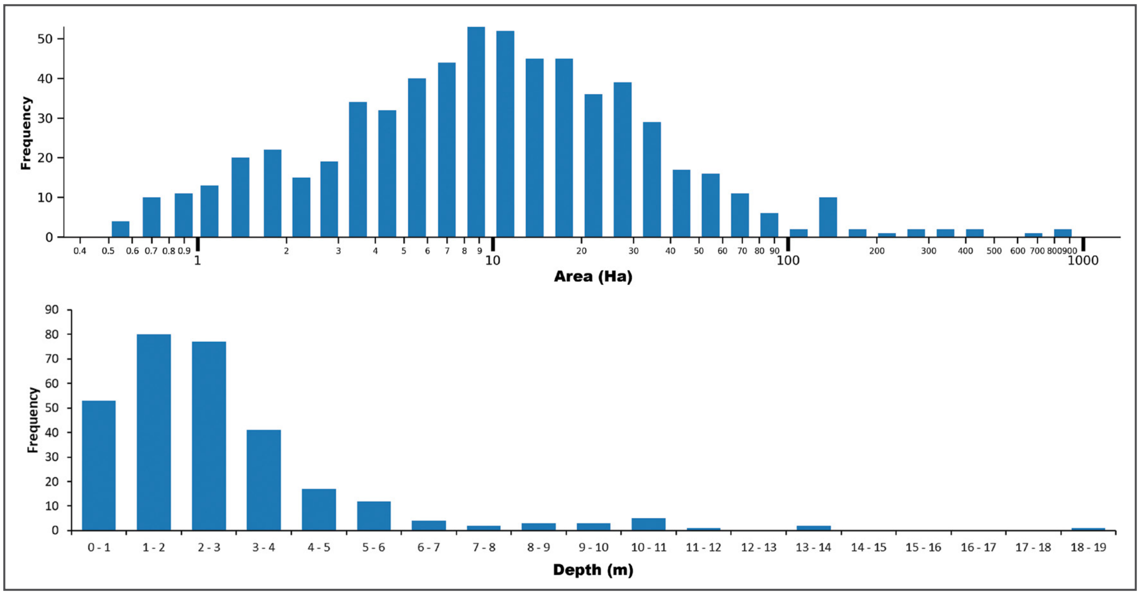
Turloughs in the Gort Lowlands such as Lough Coy and Garryland turloughs are archetypal examples of surcharged tank systems, sitting atop a massive conduit network that runs from the foot of the Slieve Aughty Mountains to the west of Gort, Co. Galway, through Coole Park and discharging at intertidal springs to sea in Kinvara Bay (Gill et al., 2013; Naughton et al., 2018a).

Flood Regime

Turloughs show a great variety of flood regimes in terms of the depth, area, and timing of flooding. Peak observed flood extents of turloughs vary widely, with the vast majority covering less than 100 ha at peak levels. However, some turloughs can flood much more than that, especially when they join with adjacent turloughs during extreme flood events. For instance, the Coole-Garryland complex of turloughs in South Galway had the highest observed turlough flood extent of over 900 ha in the winter of 2015/2016. The largest recorded flood from a single turlough is that of Lough Funshinagh, Co. Roscommon, which can flood to over 480 ha. The distribution of all peak observed flood extents is presented in Figure 7.4.

Due to the large number and scattered distribution of turloughs, information on their flood regimes has historically been quite scarce and discontinuous, with only turloughs causing severe or recurrent flooding being monitored and typically only as part of a short-term study. However, recent work by

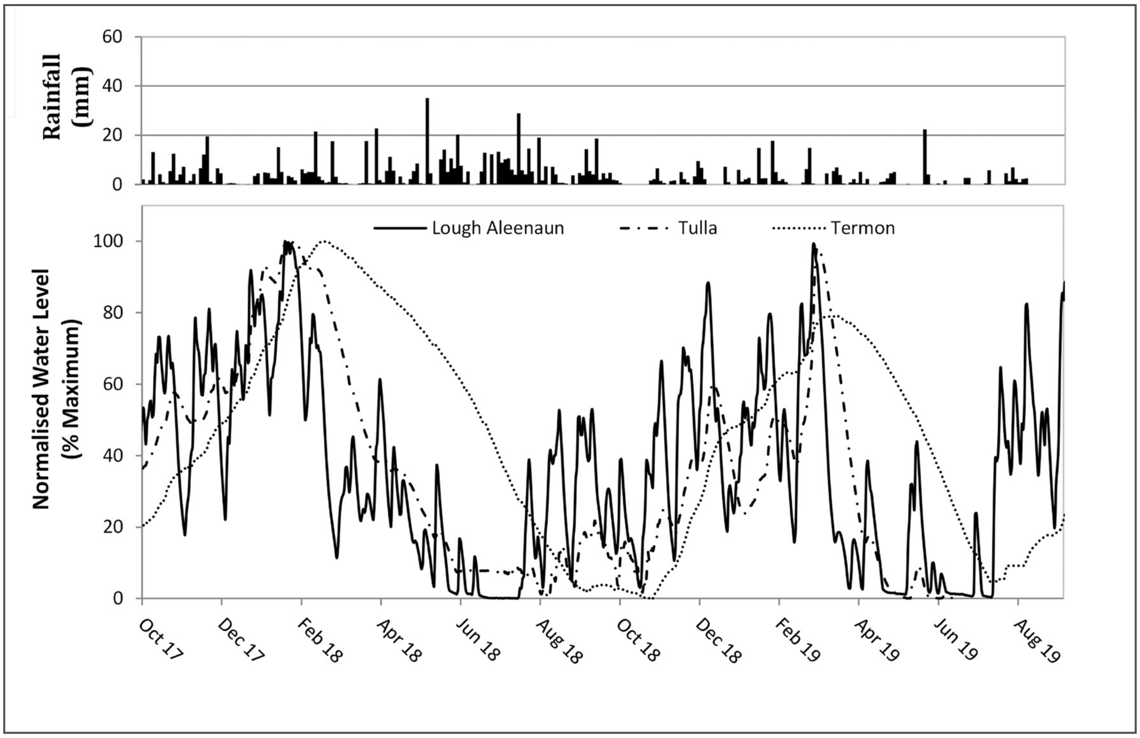
Figure 7.4 (Top) Distribution of maximum turlough depths (n=300) and (bottom) maximum flood areas (n=680).



Geological Survey Ireland (GSI) has focused on addressing this knowledge gap by initiating systematic monitoring of turloughs across the country. This has been carried out using both traditional field instrumentation as well as Earth observation techniques (McCormack et al., 2023). This work has enabled the assessment of flood dynamics at approximately 300 turloughs. In addition, 99 previously unrecorded locations were identified as potential turloughs based on their seasonal flood pattern, and 39 lakes were highlighted as having significant seasonal flood components (McCormack et al., 2020).

The peak depth of flooding in turloughs typically varies between less than 1 m and 3 m. Through the recent GSI work, it was found that only approximately 50% of turloughs have been observed to exceed 2 m depth, while only 6% of turloughs exceeded 6 m. The deepest flood level recorded in a turlough was 18.2 m at Blackrock turlough, Co. Galway in winter 2015/16. The rate at which water enters a turlough during filling periods varies widely but is typically less than 0.5 m^3s^{-1} on average. However, peak average daily flood rates of up to 27.7 m^3 s^{-1} have been observed at Coole Lough, Co. Galway, (part of the previously mentioned Coole-Garryland complex) which equates to approximately 1,000 Olympic-sized swimming pools per day.

Figure 7.5
Daily rainfall (top) and normalised water level hydrographs for Lough Aleenaun and Tulla Turlough, Co. Clare, and Termon South Turlough, Co. Galway, for the period 1 October 2017 to 30 September 2019.



Turloughs show a continuum of flooding behaviours, ranging from multimodal flooding regimes that rapidly fill and empty in response to relatively short rainfall events (days to weeks) through to strongly seasonal regimes that comprise a single long-duration flood event that reflects cumulative rainfall over the preceding months (Naughton et al., 2012). Despite receiving similar rainfall inputs to their catchments, the water level hydrographs in Figure 7.5 show distinct differences in terms of time to peak, flood frequency and duration. Lough Aleenaun in the Burren shows a rapid response to rainfall events, with water levels rising and falling in quick succession as shallow epikarst groundwater builds up in the bedrock hollow before dissipating back into the bedrock. At the other end of the spectrum lies Termon, Co. Galway, located approximately 15 km to the west of Lough Aleenaun. Termon shows a much more gradual rise in water levels reflecting the accumulation of weeks to months of excess antecedent rainfall and subsequent fall in the response to seasonal rather than shorter duration rainfall events. The fall or recession is also considerably slower, lasting many months The flooding regime of Tulla, 5 km to the northwest of Termon, lies somewhere in between these two, with damped filling and emptying superimposed on a semi-seasonal flood pattern.

ECOLOGY

Just as no two turloughs are exactly alike in terms of their hydrology, the same can be said about their ecology. The cyclical transition between dry and flooded conditions in turlough basins results in a species-rich mosaic of wetland and terrestrial habitats, with turloughs hosting a distinctive assemblage of plant, invertebrate and bird communities of high conservation value both nationally and internationally (Sheehy Skeffington et al., 2006; Visser et al., 2006). Turloughs are thus recognised as a priority habitat in Annex I of the EU Habitats Directive (see Chapter 10) and a total of 45 Special Areas of Conservation have been designated for turloughs in Ireland containing approximately 70 individual turloughs (O'Connor, 2017). Despite their designation as an Annex I habitat, turloughs do not fall easily into discrete categories. Instead, they are considered ecotones, transition zones between aquatic and terrestrial habitats where a continuum of aquatic and amphibious communities dominate in the lower zones, grading into terrestrial vegetation in the upper zones (Reynolds, 1996; Visser et al., 2006).

Flora

Environmental factors including soil type, substrate wetness, light or stress tolerance, grazing regime and nutrient loading all influence vegetation composition and distribution within a turlough basin. However, it is the depth, duration and frequency of flooding that most strongly influences the vegetation communities present (Casanova and Brock, 2000; Sheehy Skeffington et al., 2006; Waldren et al., 2015; Bhatnagar et al., 2021). The repeated cycle of flooding and drying poses a challenge to plant communities by periodically restricting the availability of light and oxygen. In response, turlough vegetation displays a characteristic zonation of vegetation communities, transitioning from grassland, scrub, and woodland communities at the upper less-frequently flooded zones to wetland communities further down into the basin where flood durations are longer (Praegar, 1932; Waldren et al., 2015).

Vegetation at the upper bounds of flooding reflects land cover in the vicinity, generally consisting of either dry ash or hazel woodland, limestone heath, grassland, or bogs (Goodwillie, 1992). Trees and shrubs are largely absent from main basins due to the controlling factors of duration of flooding and grazing. During the dry phase, turloughs are generally grass- or sedge-dominated (Sheehy Skeffington et al., 2006). Turloughs with low nutrient levels (oligotrophic and ultra-oligotrophic), such as Skealoghan Turlough in Co. Mayo, tend to be dominated by sedges (*Carex* spp.). In contrast, turloughs which have higher nutrients, such as Lough Coy, Co. Galway, are dominated by grass and forb species (Sharkey, 2012; Goodwillie, 1992; Waldren et al., 2015). In turloughs with longer flood duration, the grass- or sedge-dominated vegetation grades into wetland communities and fully aquatic species (Sheehy Skeffington et al., 2006).

Some species are present throughout the turlough basin, such as the buttercup *Ranunculus repens*, silverweed *Potentilla anserina* and the sedge *Carex panacea* (Goodwillie, 2003). The distinctive black moss *Cinclidotus fontinaloides* is also a common sight in turlough basins, clinging to rocks and sometimes trees and shrubs in areas that are fully submerged during the winter but dry out during the summer. Turloughs with semi- or permanent water bodies can support a range of fully aquatic species such as Amphibious Bistort (*Polygonum amphibium*), Water Mudwort (*Limosella aquatica*) and Rigid Hornwort (*Ceratophyllum demersum*) (Sheehy Skeffington et al., 2006). For a comprehensive description of turlough vegetation see Goodwillie (2003), Sharkey (2012) and Waldren et al., (2015).

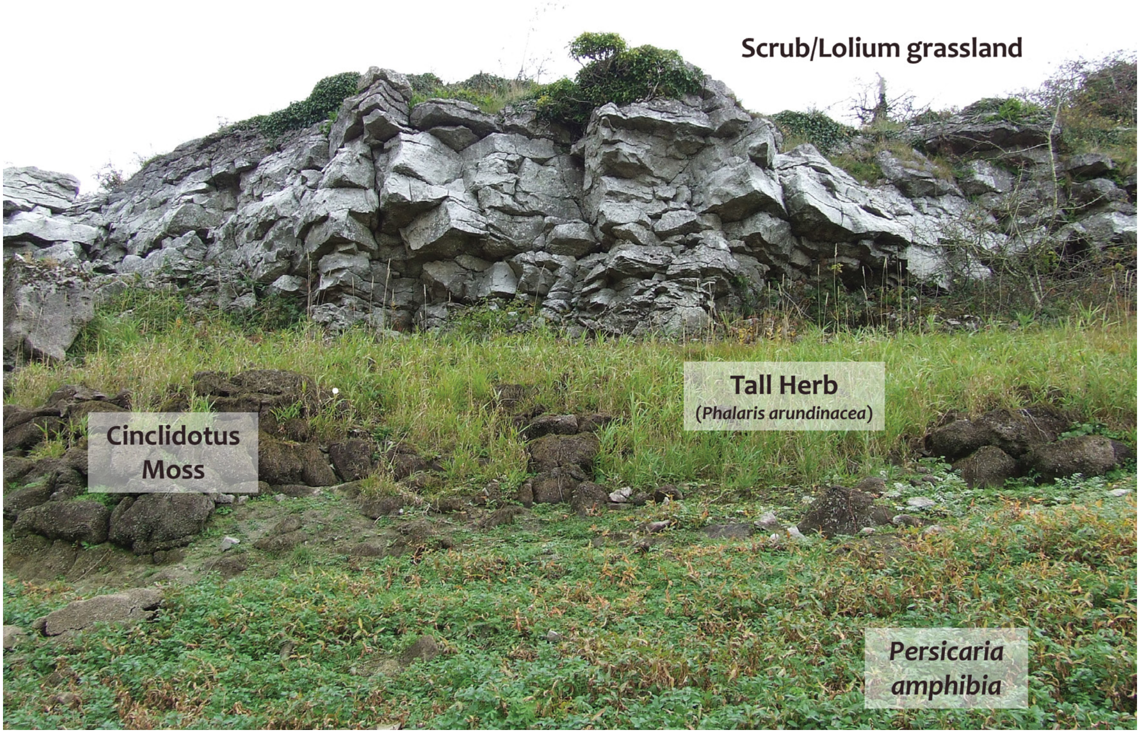


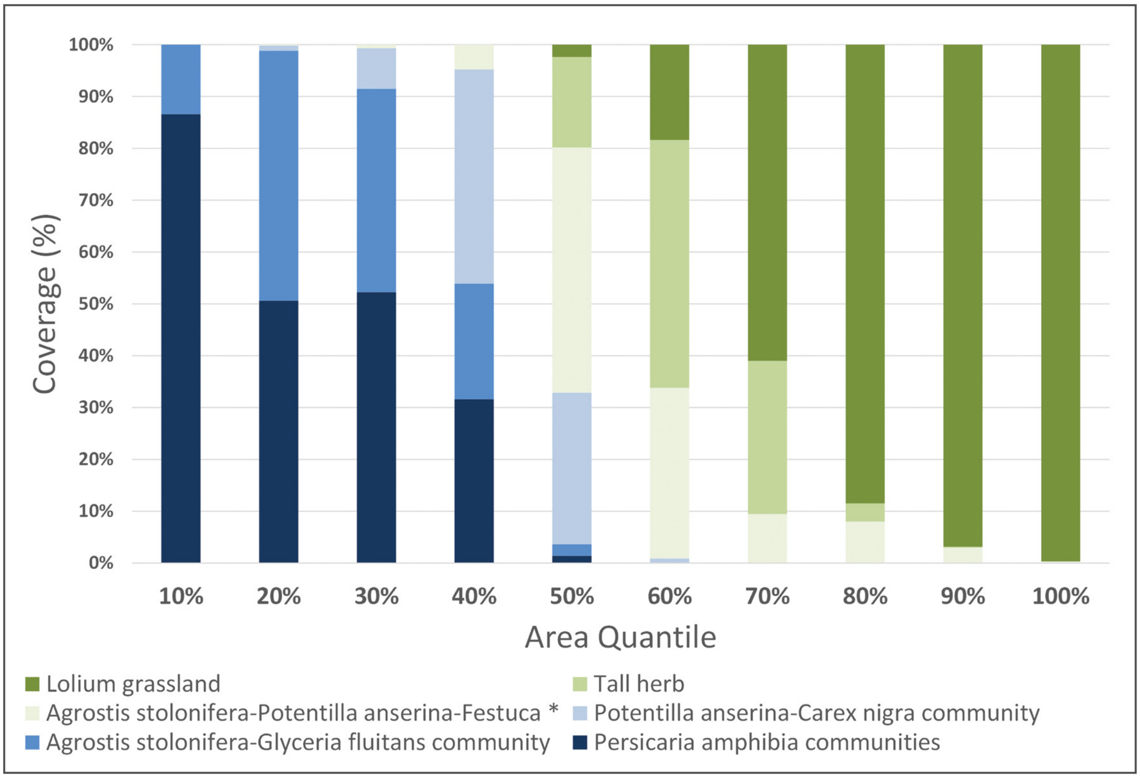
Figure 7.6
Zonation of vegetation in Ardkill Turlough, Co. Mayo.

A comparison by Sharkey (2012) of the flood duration distributions for 28 turlough vegetation communities shows a continuum from wet to dry, or from the amphibious and fully aquatic species of the *Persicaria amphibia* community to the relatively flood intolerant species of the *Lolium* grassland community. Communities which have a low flood tolerance appear and then dominate at the upper bounds of flooding within turlough basins and are indicative of seasonal flooding levels. The presence/absence of vegetation communities and changes in vegetation along the flooding gradient also gives a broad indication of the temporal flooding pattern within a turlough basin. A good example of vegetation zonation can be seen in Ardkill Turlough, Co. Mayo (Figure 7.6). Ardkill Turlough is located near Ballinrobe in south Co. Mayo and covers an area of approximately 25 ha, with floodwaters reaching a depth of up to 8 m. The transition from flood-tolerant to intolerant vegetation is clearly distinguishable in Figure 7.6, which was taken in the base of the turlough looking up a slope towards the low, limestone cliff located in the centre of the turlough.

The lower zone of the turlough around the swallow hole is dominated by semi-aquatic communities *Persicaria amphibia* and *Agrostis stolonifera* –

Glyceria fluitans, which have mean Ellenberg Moisture Index (EMI) values of 8.7 and 8.6 respectively, indicating wet conditions throughout much of the year. As you move up the slope the vegetation transitions from this to the Tall Herb (EMI: 7) and *Agrostis stolonifera-Potentilla anserina-Festuca* (EMI: 6.2) communities, before grading into shrub species and *Lolium* grassland (EMI of 5.7) at the upper margins of flooding. *Cinclidotus* moss is also visible on rock outcrops in the lower to mid-part of the basin, but not on the rock outcrop higher up the slope. This pattern of zonation is replicated across the turlough basin in Ardkill (Figure 7.7). Using a digital terrain model of the site the turlough and vegetation map produced by Sharkey (2012), the turlough was divided up into quantiles (deciles in this case so split up into 10 equal areas), with each quantile representing 10% of the total flooded surface area. The relative coverage of vegetation communities within each quantile was then calculated and plotted as percentage of the area (Figure 7.7). This shows the same pattern as described above, with a gradual transition from *Persicaria amphibia* communities at the base of the turlough to almost complete *Lolium* grassland at the flood margin. The boundaries between

Figure 7.7 Relative coverage of vegetation communities within Ardkill Turlough, Co. Mayo.



adjacent communities in this turlough also broadly followed topographic contours. As these boundaries are not directly linked with spatial variation in other environmental factors such land use or soil composition, it is probable they are due to the changes in flood duration and frequency that occur as they move up the flood gradient. The absence, presence, and relative positions of vegetation communities can thus give an indication of turlough hydrology. For example, in a turlough with a lower duration of flooding than Ardkill, *Lolium* grassland community could dominate lower in the basin and some of the aquatic or semi-aquatic species would be absent altogether. Alternatively, a site with a wetter regime than Ardkill would have more extensive areas of aquatic species.

Phytoplankton in turloughs tend to be dominated by cryptophytes and small diatoms, but with the dominant communities changing across the flooding season in response to changes in temperature and day length (Cunha Pereira et al., 2011; Waldren et al., 2015; Irvine et al., 2018). In a study by Cunha Pereira et al., (2011) a clear three-phase succession of communities was found in most of the 22 turloughs studied. Fast growing flagellates and filamentous varieties dominated at the onset of flooding in autumn, to be followed by the cryptophytes and diatoms characteristic of permanent lakes in the colder winter months (Cunha Pereira et al., 2011). In spring, as water temperatures and daylight hours increased, filamentous green species dominated particularly in nutrient-rich sites.

Fauna

Turloughs provide good sites for wintering waterbirds during their flooded phase, with the vegetation-covered basins offering abundant feeding grounds for a diversity of dabblers and grazers such as whooper swan, whimbrel, wigeon, and teal, as well as diving duck such as tufted duck and pochard (Sheehy Skeffington et al., 2006). The geomorphology and flooding characteristics of a turlough determine its suitability as a feeding site for birds; turloughs with wide, shallow basins and slow water level fluctuations provide ideal feeding grounds for bird species as the shallow waters result in plentiful marginal feeding areas (Madden and Heery, 1997). The wide shallow basin of Rahasane Turlough, Co. Galway, is designated as a Special Protection Area under the EU Birds Directive as it hosts nationally important populations of Greenland White-fronted Goose (*Anser albifrons flavirostris*), Whooper Swan (*Cygnus cygnus*), wigeon (*Mareca penelope*) and Golden Plover (*Pluvialis apricaria*), and is internationally important for Black-tailed Godwit

(*Limosa limosa*). Where turloughs retain some water throughout the year and are not heavily grazed, populations of nesting waders such as snipe (*Gallinago gallinago*), lapwing (*Vanellus vanellus*) and redshank (*Tringa totanus*) can be present. In contrast, sites which experience highly variable flooding or deep, steep-sided turloughs are less likely to support significant bird populations.

Turloughs and the surrounding areas also provide a habitat for many native Irish mammals including the Hare (*Lepus timidus hibernicus*) and Pine Marten (*Martes martes*), as well as foraging and roosting sites for bat species such as the Lesser Horseshoe Bat (*Rhinolophus hipposideros)* (Sheehy Skeffington et al., 2006). The presence of long-lived fish species is rare in turloughs due to their ephemeral nature, although Pike (*Esox lucius*) and eels (*Anguilla anguilla*) have been documented such as in Caherglassaun and Rahasane turloughs. Amphibians are relatively common in turloughs, helped in part by the widespread absence of predatory fish. During spring turloughs serve as spawning sites for common frog (*Rana temporaria*) populations, and the rarer smooth newt (*Triturus vulgaris*) may also be present in sites which retain water during the summer period such as Brierfield Turlough, Co. Roscommon (Waldren et al., 2015). The turlough habitat also provides a refuge for many rare and protected aquatic and terrestrial invertebrate species, such as the rare chydorid *Eurycercus glacialis*, the copepod *Diaptomus castor* and water beetle species such as the endangered *Berosus signaticollis* (O'Connor, 2017).

PRESSURES

Nutrients

On-going pressures related to drainage, ecologically unsuitable grazing, and eutrophication continue to pose a risk to the integrity of turlough habitats. Turloughs are predominantly fed by groundwater, however, some turloughs, such as Blackrock and Rahasane turloughs in Co. Galway, also receive inflows from rivers and streams. Turloughs also receive surface water runoff from adjacent lands since they are usually situated within low points or topographical depressions in the landscape. These unique ephemeral lakes are, therefore, very susceptible to contamination from various pollutants either directly from overland runoff and inflow from rivers and streams, or indirectly from polluted groundwater filling the turlough during the flooding season (see also Chapter 11).

The land area which supplies water to the turlough, either from overland flow or from groundwater (referred to as the turlough's catchment) is key to determining both the water quality within the turlough and the pollutants which are of most concern. The most common land uses within turlough catchments are agriculture and forestry mainly due to their being situated in rural areas. For this reason, agriculture is reported as the predominant significant pressure type in surface and groundwater bodies which feed this form of lake (DHLGH, 2022). There are two key issues related to farming in turlough catchments. The first is diffuse phosphorus loss to surface waters due to poorly draining soils which then drain into the turlough and contribute to eutrophication. The second is related to the fact that turloughs are situated in areas in which the soil cover above the karst bedrock is thin or completely absent (this is referred to as an extreme groundwater vulnerability area). This results in excess nutrients (phosphorus and nitrogen) entering the groundwater system which eventually causes enrichment of the turlough.

The issue of nutrient enrichment is further exacerbated due to the fact the many of the areas on which turloughs are located are mostly dry during the summer months with the land used for livestock grazing as shown in Figure 7.8. This raises the levels of soil phosphorus and nitrogen which can then become mobilised once the area floods. Since the flooding can often

Figure 7.8 Cattle grazing near the swallow hole at the base of Foleys Turlough near Foynes, Co. Limerick during the summer dry period

occur quite quickly during spring or autumn, other contaminants such as bacteria or viruses can become mobilised and drain through the turlough base polluting groundwater downstream. This can happen by water coming into direct contact with faecal matter. Excess nutrients or eutrophication can cause excessive plant growth which smother out other nutrient sensitive flora which occur in turlough wetlands. Another issue is the transport of excess fine sediment to the turlough which then becomes deposited at the base through settlement. This sediment can, over time, clog the normal drainage of the turlough altering its cyclical flooding pattern which impacts the delicate wetland habitats and can cause flooding of adjacent lands. Sediment can also bring nutrients to the turlough bound to the fine particles. In a similar manner, forestry situated on lands which drain into turloughs can provide a source of nutrients and sediment to the turlough. This is often the case when forestry is situated in upland areas which drain overland towards turlough lakes at lower elevations.

Another common pressure on water quality within turloughs is domestic wastewater treatment systems (e.g. septic tanks and percolation areas) draining to the epikarst and in turn to the adjacent turlough bringing pollutants with it. Malfunctioning domestic wastewater treatment systems can also contribute contaminated water to adjacent turloughs overland where the associated percolation system is not capable of accepting the treated effluent (Waldren et al., 2015).

Drainage

Drainage activities associated with various land uses (forestry, agriculture, urbanisation etc.) can also pose a threat to the normal functioning of turlough wetlands. Widespread historic drainage works carried out in the nineteenth and early twentieth century substantially reduced turlough flood extent across much of the lowlands to provide more arable land for agriculture. It is estimated that approximately a third of larger turloughs (over 10 ha) were drained, permanently reducing their flood extent by 50% or more below their historic extents (Coxon and Drew, 1986; Drew and Coxon, 1988). In some cases, drainage led to the effective destruction of the turlough as a wetland, such as in Turloughmore, Co. Galway. Covering some 400 ha in area, Turloughmore was once the largest recorded turlough in the country before dredging and realignment of the Clare River dramatically reduced its flood extent, leaving the turlough acting more like a fluvial flood plain than a turlough in the present day (Sheehy Skeffington et al., 2006).

While further widespread large-scale drainage works are unlikely due to their prohibitive cost, limited benefit, and ecological damage, smaller-scale activities such as excavation of overflow channels, land drainage and swallow-hole alteration still pose a threat. A limited number of turloughs are located within close proximity to either villages, towns, or clusters of dwellings (such as in the Gort Lowlands) and excessive flooding which can occur less frequently (i.e. once every 10 or 20 years) can threaten properties or cause disruption by flooding access roads. This has led to the proposal of several significant drainage schemes to reduce water levels in the associated turloughs thus reducing flood risk, such as in the Gort Lowlands, Co. Galway (Southern Water Global, 1998) and more recently around Lough Funshinagh, Co. Roscommon. This changes the hydrology of the turlough and can threaten sensitive habitats.

Climate Change

A future pressure which presents a potential risk to the status of these unique wetland ecosystems is that of changing climate. A study by Nolan and Flanagan (2020) examined the potential changes likely to occur in Ireland's climate by the end of the century under various future scenarios. Two key findings from this study which will affect turlough hydrology were the increase in the frequency of summer heatwave events and the development of more variable precipitation. This variability in precipitation is projected to produce substantial increases in the occurrence of both dry periods and heavy precipitation or extreme rainfall events.

A case study which examined the impacts of such climatological changes on a series of turloughs in South Galway predicted more significant groundwater flooding events becoming far more common by mid-century (Morrissey et al., 2021). In addition, the depth and duration of flooding, which is of extreme importance for sensitive turlough habitats, is projected to be altered and quite significantly for more pessimistic future scenarios (i.e. emissions to the atmosphere do not decrease and observed climate change continues or accelerates). The seasonality of annual flooding is also predicted to shift later in the flooding season, this currently tends to occur between October and March, which could have consequences in terms of turlough ecology and land use in the associated catchments. Another indirect climate change impact which could impact turlough habitat is from projected sea level rise off the Irish coast. The Office of Public Works are working towards anticipated sea level rise of approximately 0.5 to 1 m across various future design scenarios.

Turloughs systems which discharge to the sea via intertidal and submarine springs such as Caherglassaun and the turloughs of the main Gort Lowlands system) may be impacted by such sea level rises, although the Morrissey et al. (2021) study did not observe a significant impact in turlough hydrology mainly due to the system still draining sufficiently during low tides.

The implications for turlough hydrology and the associated ecology and turlough habitats are the subject of current scientific study and are not yet well understood. In terms of hydrology, a broad response is not expected as each turlough will have a different impact based on their unique hydrogeological conditions. However, in general, turloughs which exhibit a slow response to precipitation events (i.e. slowly draining) will experience a more profound impact due to a projected longer inundation duration. This will occur due to their limited outflow capacity coupled with greater inflow quantities from more extreme precipitation events.

In terms of turlough ecology, with increased wetting, there may be an overall expansion spatially in the wetland habitats characteristic of turloughs. However, with increased drought frequency some sensitive species potentially could be lost. Furthermore, changes to the duration, frequency and timing of flood events could cause a realignment of communities within and between basins. Habitats which prefer wetter conditions would shift inward during drought periods, however, this would be potentially offset by new habitat formation in areas which were typically wet during the summer months and now are dryer for longer. This loss could occur in locations which would empty during summer months in the future, but which typically stayed wet all year round under current conditions.

CONCLUSIONS

Turlough habitats are dynamic lakes that defy easy categorisation, representing transitional zones between aquatic and terrestrial ecosystems. Their unique hydrodynamics result in a species-rich mosaic of wetland habitats hosting plant, invertebrate and bird communities of considerable conservation importance both national and internationally. The behaviour of a turlough as a habitat is fundamentally driven by hydrology; the periodic flooding and drying that characterises the turlough landform exerts a dominant influence on the distribution of species and the development and succession of ecological communities. This chapter has described some of the key features of this unique habitat, including their hydrogeology, characteristic hydrology and ecology. However, as with most lakes and wetlands in Ireland, the future is uncertain in the face of widespread pressures such as eutrophication and climate change which pose a risk to the integrity of turlough habitats. Further work is needed to quantify and generalise the relationships between turlough hydrology and vegetation communities. While key hydrological metrics have been identified and some links derived on a limited scale, a better quantitative understanding is needed if we are to effectively conserve and protect these valuable transitional ecosystems against pressures such as eutrpohication and a changing climate.

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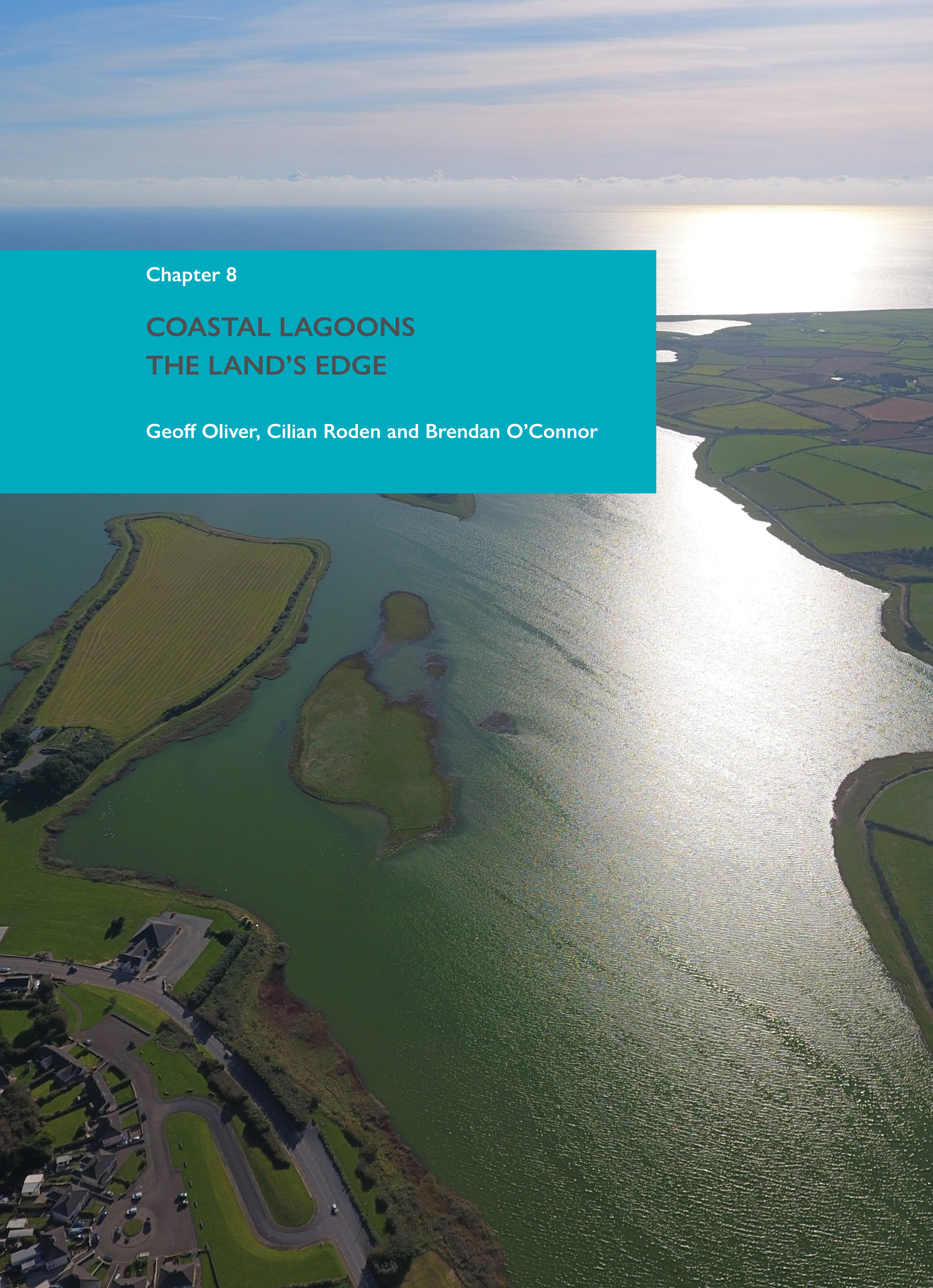
Chapter 8

COASTAL LAGOONS
THE LAND'S EDGE

Geoff Oliver, Cilian Roden and Brendan O'Connor



SUMMARY

Coastal lagoon habitat, being neither totally freshwater nor fully marine has been somewhat neglected in the past but was listed in the EU Habitats Directive as a priority habitat. Following the surveys funded initially by the National Parks and Wildlife Service (NPWS) and subsequently also by the Environment Protection Agency (EPA), 89 coastal lagoons are now listed in the National Inventory of Ireland covering an area of 2,424 hectares and another 30 are listed for Northern Ireland, compared with almost 14,000 freshwater lakes on the island of Ireland. As well as the traditional barrier lagoons such as Lady's Island Lake and Tacumshin in Wexford, some of those listed for Ireland such as the karst lagoons and the rock/peat lagoons of the west coast are unusual and rare lagoon types in Europe and contain several species of animal and plant, that are not only rare in Ireland but in Europe as a whole. Although most of the lagoons in Ireland are protected within Special Protection Areas (SPAs) and/or Special Areas of Conservation (SACs) the necessary legislation is not always enforced, and many suffer from extreme eutrophication resulting mostly from farming and forestry activities. This chapter aims to outline the different types of coastal lagoons and the animals and plants that they contain, their conservation status, and the main threats to this fascinating habitat.

Keywords Lagoons, lagoon types, salinity, lagoonal specialists

INTRODUCTION

To many people, the word lagoon conjures up images of tropical beaches. Many of the world's lagoons fit this image, especially along extensive barrier coastlines and on volcanic islands. Lagoons in Europe are smaller and less exotic, but they are nevertheless of great scenic and conservation value. In 1992, the European Habitats Directive (Council Directive 92/43/EEC) listed coastal lagoons (Code 1150) as a priority habitat (see Chapter 10) in special need of protection owing to the fact that so much of the habitat in Europe had, for a variety of reasons, disappeared or been degraded.

At this time, only four lagoons were well known in Ireland: Lady's Island and Tacumshin in Wexford, Lough Murree in Clare, and Lough Furnace in Mayo. When describing the distribution of coastal lagoons in Europe, Barnes (1994) showed the entire habitat in Ireland concentrated in Wexford due to the lack of available information for Ireland, and a restrictive definition of coastal lagoon. Apart from the work by Parker & West (1979) in Lough Furnace and Pybus & Pybus (1980) in Lough Murree, the late Dr Brenda Healy (lecturer in the Zoology Department at University College Dublin) was the only biologist to take a particular interest in lagoons in Ireland at that time. She investigated Lady's Island Lake in Wexford (Healy et al., 1982, Healy & O'Neill, 1984), helped considerably by Jim Hurley (Hurley 1997, 1998) and under her supervision, one of her students, Paul Galvin, surveyed lagoons along the Wexford and Cork coastlines in 1992 as part of an undergraduate thesis.

The Habitats Directive required member states to compile an inventory of coastal lagoons and protect the best examples of the habitat within SACs. Some of these lagoons were unknown to the NPWS before the surveys, and some came as a complete surprise, especially many of those found in Connemara where lagoons were unexpectedly found in the middle of peat bogs. There are good examples in Ireland of the traditional type of sedimentary lagoons with sand and shingle barriers. Still, other lagoons, described under various names, such as the karst lagoons in limestone areas and those on the west coast with impressive cobble barriers or formed in peat

Table 8.1 Lagoon types according to different authors

Healy and Oliver (1998)	Good and Butler (1998)	NPWS (2007)	Other
Sedimentary lagoons Rock lagoons Natural saline lakes Artificial saline lakes	Sand barrier lagoons/saline lakes Shingle barrier lagoons Peat shore lagoons/saline lakes Karst lagoons/saline lakes Drumlin lagoons/saline lakes	Natural Sedimentary Artificial Rock/peat Karst Estuarine Saltmarsh	Obs (Scotland) Flads (Baltic states) Gloes (Baltic states)

bogs are unusual lagoon types in Europe (Table 8.1). Many of these contain a biological community of typically brackish-water species of animals and plants, many of which are rare, not only in Ireland but also in Europe. Coastal lagoons in Ireland are not exploited to the same extent as in many other parts of Europe for tourism and aquaculture but unfortunately, like many other waterbodies in Ireland are suffering from eutrophication due to excessive inputs of nutrients from mostly agricultural sources.

WHAT IS A COASTAL LAGOON?

The Habitats Directive defines coastal lagoons as 'expanses of shallow coastal salt water, of varying salinity or water volume, wholly or partially separated from the sea by sand banks or shingle, or, less frequently, by rocks. Salinity may vary from brackish water to hypersalinity depending on rainfall, evaporation and through the addition of fresh seawater from storms, temporary flooding by the sea in winter or tidal exchange, with or without vegetation from *Ruppietea maritimae, Potametea, Zosteretea* or *Charetea*. Amended versions included artificial lagoons described as 'salt basins and salt ponds…providing that they had their origin on a transformed old natural lagoon or a salt marsh and are characterised by a minor impact from exploitation'. Unusual types, such as the Baltic flads and gloes were also included as the European Union was enlarged (Table 8.1).

Member States may interpret the definition as they think best in the interests of nature conservation, and for this reason, the brackish rocky water bodies in Western Scotland, known as obs, have been accepted as coastal lagoons. However, it is difficult to define lagoons precisely as there are no clear distinctions between lagoons, estuaries, and bays. The classic sedimentary coastal lagoons, such as Lady's Island Lake and Tacumshin in Wexford are worthy of protection as interesting and valuable coastal landforms in themselves, but the Habitats Directive is intended to give protection to the biological community which the habitat contains. Many lagoons do not conform with the official definition and, therefore, are unprotected and for this reason, certain lagoonal habitats recognised by characteristic fauna and flora, though not strictly covered by the official definition, have been regarded as coastal lagoons in Ireland.

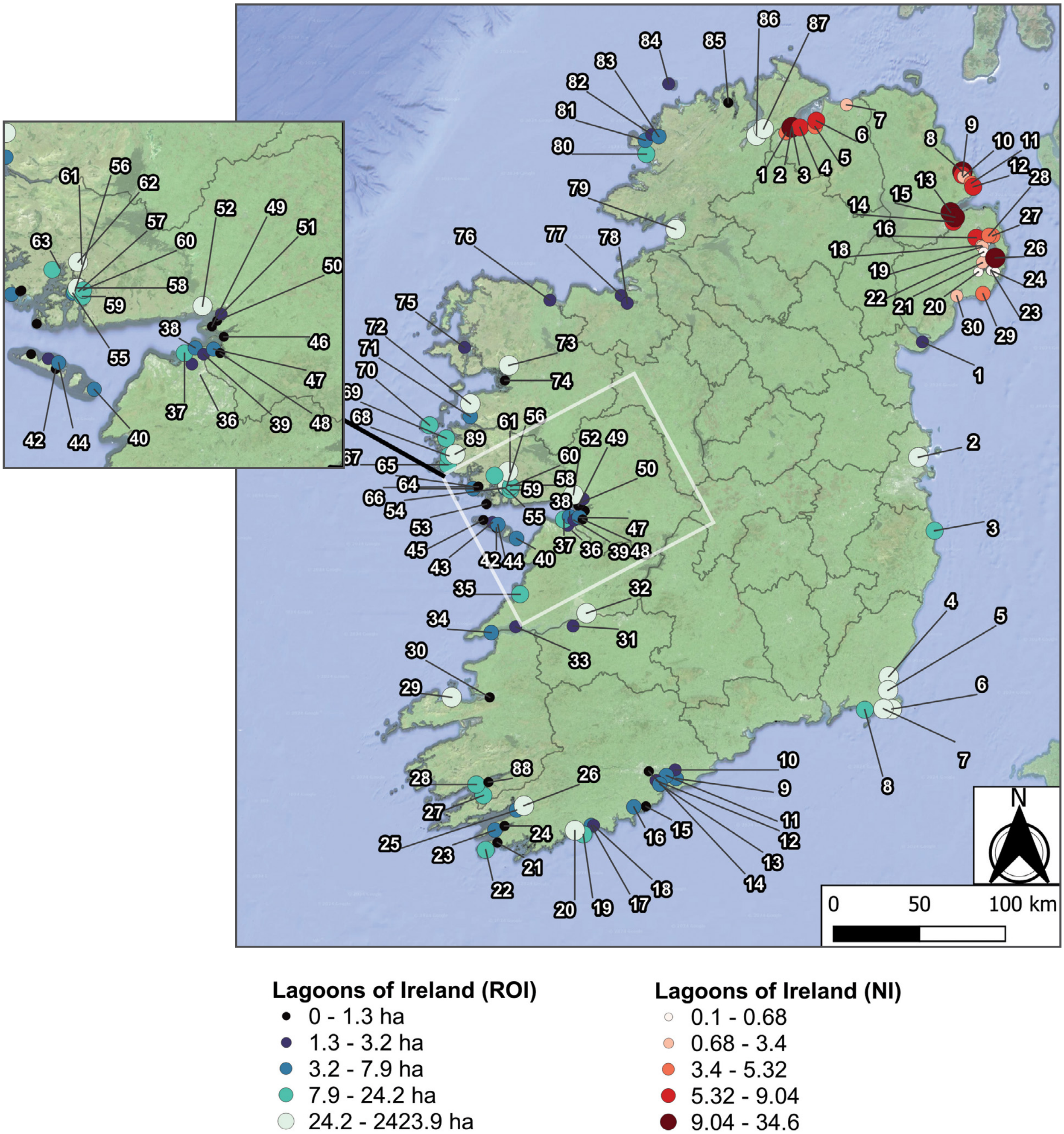


Figure 8.1 Location map of designated coastal lagoons for RoI (89) (AQUAFACT 2017) and Northern Ireland (30) (DOENI, 2015). Numbers refer to sites listed in Tables 2 and 3; dots indicate size of lagoon.

IRISH LAGOON SURVEYS

Under the obligations of the Directive, the NPWS commissioned a series of surveys of coastal lagoons in Ireland. Surveys were carried out in 1996 and 1998 (Hatch and Healy, 1998; Healy and Oliver, 1998; Oliver and Healy, 1998; Good and Butler, 1998, 2000). The surveys culminated in 89 lagoons being listed in an inventory of coastal lagoons in Ireland (NPWS, 2007; AQUAFACT et al., 2017; Table 8.2), and a further 30 are designated in Northern Ireland by the Department of Environment of Northern Ireland (Oliver, 2005; DOENI, 2015: Table 8.3). Many of the lagoons comprise clusters and are very small with more than 25% less than 1 ha. Cumulatively the lagoons cover an all-island area of 2,601 ha and their locations are illustrated in Figure 8.1.

Table 8.2 Code, name, County, Natura designation, lagoon type and size (ha) of sites identified as coastal lagoons in the RoI, (modified from AQUAFACT et al., 2017)

Code	Site (No of lagoons in brackets)	County	Natura Designation	Lagoon type	Area (ha)
01	Greenore Golf Course (4)	Louth	None	Artificial	2.4
02	Broadmeadow	Dublin	SAC, SPA	Artificial	321.4
03	Kilcoole (3)	Wicklow	SAC, SPA	Artificial	12
04	North Slob channel	Wexford	SPA	Artificial	51
05	South Slob channel	Wexford	SPA	Artificial	47.4
06	Lady's Island Lake	Wexford	SAC, SPA	Natural, sedimentary	299.6
07	Tacumshin	Wexford	SAC, SPA	Natural, sedimentary	393
08	Ballyteige channels	Wexford	SAC, SPA	Man made	12.6
09	Rostellan Lake	Cork	SPA	Artificial	7.5
10	Ballyvodock lagoon	Cork	NONE	Artificial	1.7
11	Cuskinny Lake	Cork	NONE	Artificial	4.2
12	Raffeen Lake, Shanbally	Cork	SPA	Artificial	2.8
13	Lough Beg. Curraghbinny	Cork	SPA	Artificial	3.6
14	Bessborough Pond, Cork	Cork	NONE	Artificial	0.2
15	Oysterhaven Lake, Clashroe	Cork	NONE	Artificial	1.3
16	Commoge Marsh, Kinsale	Cork	NONE	Artificial	6.4
17	Clogheen/White's Marsh (2)	Cork	SAC, SPA	Artificial	3.6
18	Inchydoney	Cork	SAC, SPA	Artificial	3.2
19	Kilkeran Lake	Cork	SAC	Natural, sedimentary	21.4
20	Rosscarbery Lake	Cork	NONE	Artificial	24.6

Code	Site (No of lagoons in brackets)	County	Natura Designation	Lagoon type	Area (ha)
21	Toormore lagoon	Cork	NONE	Artificial	1
22	Lissagriffin Lake	Cork	SAC	Artificial (partly)	17.2
23	Farranamanagh Lake	Cork	SAC	Natural, sedimentary	4
24	Reen Point Pools	Cork	SAC	Natural, sedimentary	0.4
25	Kilmore Lake	Cork	NONE	Natural, sedimentary	5.3
26	Reenydonegan Lake	Cork	NONE	Natural, sedimentary	24.7
27	Lauragh	Kerry	SAC	'Saltmarsh' lagoon	17.3
28	Drongawn Lake	Kerry	SAC	Natural 'rock' lagoon	11.7
29	Lough Gill	Kerry	SAC, SPA	Natural, sedimentary	129
30	Blennerville lakes (2)	Kerry	SAC	Artificial	1.2
31	Quayfield/Poulaweala (2)	Limerick	SAC	Karst	2.5
32	Shannon Airport Lagoon	Clare	SAC, SPA	Artificial	24.2
33	Scattery lagoon	Clare	SAC, SPA	Natural, sedimentary	2.8
34	Clonconeen Pool	Clare	SAC	Natural, sedimentary	3.9
35	Lough Donnell	Clare	SAC, SPA	Natural, sedimentary	12.5
36	Muckinish Lake	Clare	SAC	Karst	2.5
37	Lough Murree	Clare	SAC, SPA	Karst/sedimentary	14.1
38	Aughinish	Clare	SAC, SPA	Karst/sedimentary	7
39	Rossalia	Clare	SAC, SPA	Artificial	3.1
40	Loch Mór, Inish Oírr	Galway	SAC	Karst	6.3
41	Port na Cora, Inis Meain	Galway	SAC	Karst	0.3
42	Loch an tSaile, Arainn	Galway	SAC	Karst	0.4
43	L. Phort Chorruch, Arainn	Galway	SAC	Karst/sedimentary	3.2
44	Loch an Chara, Arainn	Galway	SAC	Karst	3.4
45	Loch Dearg, Arainn	Galway	SAC	Karst	1
46	Rincarna pools (2)	Galway	SAC, SPA	Karst	0.8
47	Bridge Lough, Knockakilleen	Galway	SAC, SPA	Karst	5.3
48	Doorus Lakes (3)	Galway	SAC	Karst	1.5
49	Mweeloon pools (2)	Galway	SAC, SPA	Saltmarsh	0.7
50	Ardfry Oyster pond	Galway	SAC, SPA	Estuarine	0.6
51	Turreen Lough (Rinvile)	Galway	SAC, SPA	Saltmarsh	2.7
52	L. Atalia and Renmore pool	Galway	SAC	Estuarine	41.1
53	Lettermullen	Galway	SAC	Rock/Peat	0.6
54	Loch Fhada upper pools (2)	Galway	SAC	Saltmarsh	1
55	L. an Ghadaí	Galway	SAC	Rock/Peat	5.2

Code	Site (No of lagoons in brackets)	County	Natura Designation	Lagoon type	Area (ha)
56	L. Fhada	Galway	SAC	Rock/Peat	8.1
57	L. Tanaí	Galway	SAC	Rock/Peat	9.4
58	L. an Aibhnín	Galway	SAC	Rock/Peat	54.2
59	Loch Cara Fionnla	Galway	SAC	Rock/Peat	13.9
60	L. Cara na gCaorach	Galway	SAC	Rock/Peat	22.7
61	L. Doire Bhanbh	Galway	SAC	Saltmarsh	1.3
62	Loch an tSaile (L. Ahalia)	Galway	SAC	Rock/Peat	89.7
63	L. Conaorcha (Aconeera)	Galway	SAC	Rock/Peat	24.1
64	L. an Mhuilinn (Mill L.)	Galway	SAC	Rock/Peat	5.4
65	L. Ateesky	Galway	SAC	Saltmarsh	1.4
66	L. an Chaoráin	Galway	NONE	Rock/Peat	1.5
67	L. Ballyconneely	Galway	SAC	Natural, sedimentary	10.3
68	L. Athola	Galway	SAC	Rock/Peat	12
69	Lough Anillaun	Galway	NONE	Natural, sedimentary	11.2
70	L. Bofin	Galway	SAC	Natural, sedimentary	8
71	Corragaun Lough	Mayo	SAC	Natural, sedimentary	7.9
72	Roonah Lough	Mayo	SAC	Natural, sedimentary	40.2
73	Furnace Lough	Mayo	SAC	Rock/Peat	162.5
74	Claggan lagoon	Mayo	SAC	Saltmarsh	1.2
75	Dooniver Lough, Achill Is.	Mayo	NONE	Natural, sedimentary	2.5
76	Cartoon L., Killala Bay	Mayo	NONE	Saltmarsh	2.8
77	Portavaud, Ballysadare (2)	Sligo	NONE	Saltmarsh	3.2
78	Tanrego	Sligo	SAC, SPA	Artificial	1.8
79	Durnesh Lake	Donegal	SAC, SPA	Natural, sedimentary	73.8
80	Maghery Lough	Donegal	SAC	Rock/Peat	15.3
81	Sally's L.	Donegal	SAC	Rock/Peat	4.9
82	Kincas L.	Donegal	SAC	Rock/Peat	3.2
83	Moorlagh	Donegal	SAC	Rock/Peat	6.9
84	L. O Dheas, Tory Is.	Donegal	SAC, SPA	Natural, sedimentary	3.2
85	Carrick Beg Lough	Donegal	NONE	Artificial	1.5
86	Blanket Nook Lough	Donegal	SAC, SPA	Artificial	29.6
87	Inch Lough	Donegal	SAC, SPA	Artificial	176.1
88	Coornagillah	Kerry	NONE	Natural, sedimentary	0.5
89	Ardbear Salt Lake	Galway	SAC	Rock/Peat	35.5
				TOTAL (ha)	2424

Table 8.3 Inventory of coastal lagoons in Northern Ireland, with size, naturalness, and conservation status (DOENI, 2015). Area of Special Scientific Interest = ASSI; Special Protection Area = SPA; Special Area of Conservation = SAC.

Code No.	Lagoon	Size (km2)	Natural/ Man-made	Conservation Area	Qualifying Feature
1	Gransha	0.041	Man-made		
2	Black Brae	0.095	Man-made	ASSI/SPA	
3	Donnybrewer	0.092	Man-made	ASSI/SPA	Lough Foyle ASSI
4	Longfield	0.088	Man-made	ASSI/SPA	Lough Foyle ASSI
5	Ballykelly	0.038	Man-made	ASSI/SPA	
6	Myroe/Ballymacran	0.090	Man-made	ASSI/SPA	Lough Foyle ASSI
7	Ballyaghran	0.012	Man-made	ASSI/SPA	
8	Larne	0.100	Man-made		
9	Glynn A	0.064	Man-made	ASSI/SPA	Larne Lough ASSI
10	Glynn B	0.028	Man-made		
11	Oldmill	0.052	Man-made	ASSI/SPA	
12	Ballycarry	0.084	Man-made	ASSI/SPA	
13	Whitehouse	0.120	Man-made	ASSI/SPA	
14	Victoria Park	0.058	Man-made	ASSI/SPA	
15	Belfast Harbour Lagoon	0.210	Man-made	ASSI/SPA	
16	Castle Espie	0.055	Man-made		
17	Mahee Point	0.006	Man-made	ASSI/SPA/SAC	
18	Cadew Point	0.015	Man-made	ASSI/SPA/SAC	
19	Quarterland	0.009	Man-made	ASSI/SPA/SAC	
20	East Down Yacht Club A	0.001	Man-made		
21	East Down Yacht Club B	0.007	Man-made	ASSI/SPA/SAC	
22	Rathgorman	0.002	Natural	ASSI/SPA/SAC	
23	Castleward	0.003	Man-made	ASSI/SPA/SAC	
24	Blackcauseway	0.003	Man-made	ASSI/SPA/SAC	
25	Granagh	0.001	Natural	ASSI/SPA/SAC	
26	Dorn	0.346	Natural	ASSI/SPA/SAC	Strangford Lough Part 3 ASSI/SAC
27	Rosemount	0.040	Man-made	ASSI/SPA/SAC	
28	Ann's Point	0.038	Man-made	ASSI/SPA/SAC	
29	Strand Lough	0.051	Man-made	ASSI	Killough Bay and Strand Lough ASSI
30	Dundrum South	0.021	Man-made	ASSI/SAC	
	TOTAL (177 ha)	1.77 km2			

Lagoon surveys have continued up to the present to fulfil obligations under the Habitats Directive and Water Framework Directive (WFD), respectively. The most recent assessment of the conservation status of the habitat was published in 2017 (AQUAFACT et al., 2017). It is important to note that lagoon research is ongoing, and more lagoons may be listed as they are discovered. The habitat is dynamic, so some lagoons may, with sea-level changes or changes in coastal morphology, gradually become freshwater lakes, or on the other hand become tidal estuaries or marine bays.

LAGOON EXAMPLES

Just over a quarter of the lagoons in RoI are classed as sedimentary lagoons (25.8%) followed by saline lakes (23.6%) and karst lagoons (13.5%) (Table 8.2). Artificial lagoons dominate types in Northern Ireland (90%) and in the RoI (32.6%).

Sedimentary lagoons

Lady's Island Lake is arguably the biggest and best example of a coastal lagoon in Ireland (Figure 8.2) and is an excellent example of a classic sedimentary lagoon with an impressive barrier of sand and shingle.

Figure 8.2
Aerial photograph of Lady's Island Lake, showing the sedimentary barrier in the distance, and the highly fertilised fields along the shoreline. Photo: Richard Conway

Figure 8.3
Lough Donnell showing management work being carried out on the barrier in 2023. Photo: Geoff Oliver

Several sedimentary lagoons along the Irish west and northwest coasts are particularly unusual in that the barrier is composed of large cobbles (for example Kilmore Lake in Cork, Lough Donnell and Lough Murree in Clare, Lough Anillaun and Lough Bofin in Galway and Lough O Dheas on Tory Island in Donegal). According to Barnes (1989), lagoons with shingle barriers are relatively unusual in Europe and mostly confined to macro-tidal, glacial coastlines on West European coasts. These cobble barriers in Ireland are presumably particularly characteristic of the high energy, macrotidal, glacial coastlines, though a barrier like this is also found in Galicia, Northwest Spain and on the volcanic island of Santo Jorge in the Azores.

Lough Donnell in County Clare is impounded by a massive cobble barrier, 7 to 8 m high and 40 m wide at its base (Figure 8.3), which presents some difficult management problems for land use behind the barrier. Under natural conditions, the barrier restricts the exit of flood water from the River Annageeragh and water inundates the flood plain. Storms or the pressure of dammed-up water, (or a combination), can cause the barrier to collapse and allow water levels to drop and enable salmon and seatrout to enter the river to spawn. As a form of management, a permanent concrete structure was installed to reinforce the natural barrier and to protect lands from flooding. The artificial barrier was destroyed by storms and after a lot of public complaints and negotiations, it is now being rebuilt at great expense.

Karst lagoons

Also noticeable in Ireland is the high number of karst lagoons (13.5%) with subterranean connections to the sea (see Chapter 7). These are particularly important in European terms as they appear to be unique to Ireland along the Atlantic coast. Lough Murree in County Clare is a fine example of a karst lagoon, which has a cobble barrier which is over-topped during gales, but seawater also enters by percolation through the barrier and underground fissures in the bedrock. The underlying bedrock is limestone, which is rare along the Atlantic coast apart from a stretch of the Asturian coastline, which has no coastal lagoons, though it does have a marine sinkhole 100 m from the sea into which tides enter.

Saline lake lagoons

These can also be referred to as rock/peat lagoons and are common along the west coast of Ireland and particularly in Connemara, with a barrier composed mostly of granite, and very often with a granite sill (ledge), or with a barrier of small peat islands (e.g. Athola). They appear to be very similar to lagoons in Scotland known as obs. Though appearing to be very natural, they may well owe their origin to a certain extent to former peat cuttings. The channel through which seawater enters may have been cut,

Figure 8.4, left
Loch an Aibhnín, and the river that acts as both an inlet and outlet.
Photo: Geoff Oliver

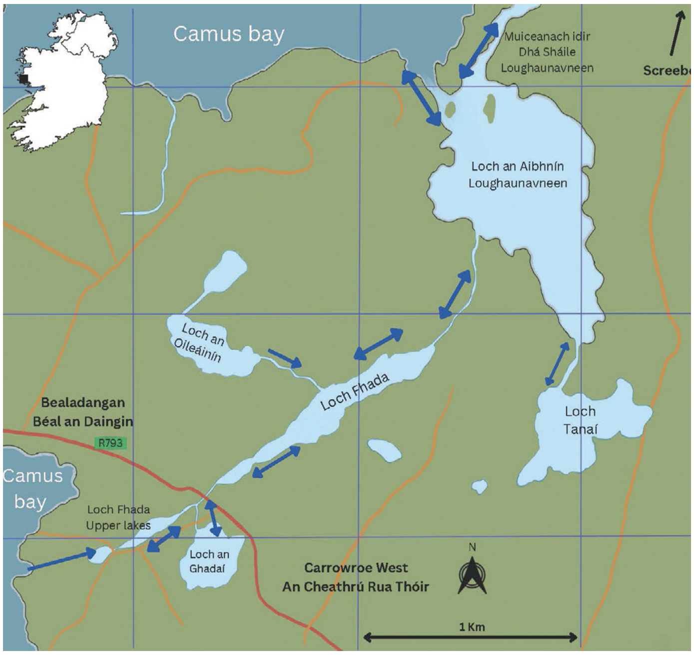


Figure 8.5, right
Interconnected lagoons in Connemara

partly to drain the bog, but also possibly for transporting the cut turf in small boats to the coast. Within Europe, this type of lagoon appears only to be found in Scotland and Ireland.

Loch an Aibhnín (Figure 8.4) is a particularly interesting lagoon in terms of hydrology and biodiversity. It is a large shallow (2 m) lagoon with extensive beds of eel grass (*Zostera marina*) festooned with sea anemones (*Anemonia viridis*) and tunicates (marine invertebrate) such as *Ciona intestinalis*. Not only does seawater enter Loch an Aibhnín through the narrow channel but it flows south and enters Loch Tanaí (Figure 8.5) in the middle of a peat bog which contains carpets of the rare charophyte the Fox-tail Stonewort *Lamprothamnion papulosum*. It also flows southwest into Loch Fhada and on spring tides, enters the upper pools and Loch an Ghadaí. It appears that in very high tides and storms, the tide also enters the upper pools from the west and flows in the opposite direction. Although Loch Fhada appears to be freshwater, there is seawater at depth and the freshwater that sits on top flows into it from Loch an Oileáinín to the northwest. When Loch Fhada was sampled by snorkel, it was found that below the surface layer of freshwater, lay the halocline with denser seawater below it and in one area a cold-water spring of freshwater was found below the salt water.

Artificial lagoons

Many of the artificial or modified lagoons were created as a result of the construction of causeways to carry a railway or road. For example, Broadmeadow lagoon causeway in Dublin carries the Dublin-Belfast railway line. Along the south coast, many lagoons were formed, where estuaries were dammed up by causeways to carry roads such as at Commoge Marsh, Cuskinny and Rosscarbery. In some cases, these causeways may have been built on top of natural barriers, but little of the original barrier now remains. Others were formed by building causeways to islands such as at Inch in Donegal and White's Marsh in Cork.

PLANTS AND ALGAE OF LAGOONS

Lagoons have a wide variety of salinities from 2 psu (practical salinity units) to full salinity (35 psu); the vegetation of lagoons reflects this range. One of three angiosperm genera often constitutes the dominant vegetation: *Stukenia* (*pectinata*) in near fresh water, *Ruppia* sp. (*maritima* or *spiralis*) in most brackish water and *Zostera* sp. (*marina* and *cf. angustifolia*) in near full salinity. These plants are often accompanied or replaced by a variety of charophytes and marine algae. *Chara aspera* is found up to 5 psu, while *Chara cannescens* and (rarely) *Chara baltica* can occur to 10 psu. Foxtail stonewort is restricted to brackish water and forms an unusual plant community with *Zostera marina* and *Ruppia spiralis* in some Connemara lagoons such as Loch an Aibhnín.

The green algal family Cladophoraceae is an important species group in Irish lagoon sites. *Chaetomorpha linum* often forms very dense but unattached mats which blanket all other vegetation. This profusion may be a result of eutrophication, but this is not established. Floating masses of *Cladophora* sp. are, however, very likely a result of excess nutrient input. However, the exact species involved is difficult to establish. Other rarer species are also found, including *Cladophora battersii* and *C. coelothrix* in sites such as Loch an Aibhnín. Red and Brown algae often occur in more saline lagoons with *Fucus* species common in shallow but non-tidal water. A variety of red algae are recorded from more saline lagoons, but most also occur in bays and estuaries. These different plant groups combine to form the vegetation of lagoons. Roden (1998) distinguished four types of lagoon vegetation reflecting differing lagoon salinities. A low salinity type (oligohaline) was characterised by *Stukenia pectinata* (a largely freshwater pond weed) and some *Ruppia sp*., as well as a freshwater phytoplankton and abundant *Potentilla anserina* in the marginal vegetation. A second type (mesohaline) was dominated by *Ruppia* species, marine phytoplankton, marine fucoid algae, *Chaetomorpha linum*, the charophyte *Lamprothamnion papulosum* and salt marsh species such as *Juncus gerardii* and *J. maritimus*. A higher salinity type (meso to polyhaline) resembled type 2 but also contained marine red algae and *Zostera marina* as well as the absence of all freshwater taxa, a fourth group was essentially marine (euhaline) lacking lagoonal specialists such as *Ruppia sp*. and *L. papulosum* but with the uncommon species *Cladophora battersii*.

While salinity is the most important factor determining lagoon species composition and vegetation, nutrients (especially nitrogen) must also be considered. Excess nutrients cause large mats of green algae (*Cladophora* and *Ulva sp*.) to form and float on the water surface. These algae can blanket and supress other vegetation and have often altered the original species composition of many lagoons. Healy (2003) gives a good summary of lagoon vegetation but some points, such as the extent of *Chara baltica*, have been revised subsequently.

Table 8.4 Proposed list of lagoonal specialists for Ireland (based on Oliver & Healy 1998; Roden, 1998; Oliver 2005).

FLORA	
Non-charophyte algae	**Charophyte algae**
Chaetomorpha linum	*Chara baltica?*
Cladophora battersii	*Chara canescens*
Spermatophyta	*Chara connivens?*
Ruppia cirrhosa	*Lamprothamnion papulosum*
Ruppia maritima	*Tolypella nidifica*
FAUNA	
Cnidaria	**Insecta**
Cordyllophora caspia	Coleoptera
Gonothyraea loveni	*Agabus conspersus*
Crustacea	*Enochrus bicolor*
Idotea chelipes	*Enochrus halophilus*
Jaera nordmanni?	*Enochrus melanocephalus*
Lekanesphaera hookeri	*Ochthebius marinus*
Allomelita pellucida?	*Ochthebius punctatus*
Corophium insidiosum	*Haliplus apicalis*
Gammarus chevreuxi	
Gammarus insensibilis	Hemiptera
Leptocheirus pilosus	*Sigara selecta*
Palaemon adspersus	*Sigara stagnalis*
Palaemon varians	
Mollusca	Diptera (Chironomidae)
Ecrobia ventrosa	*Glyptodentipes barbipes*
Littorina "tenebrosa"	
Onoba aculeus	**Bryozoa**
Rissoa membranacea var. *Cerastoderma glaucum*	*Conopeum seurati*

Lagoonal Specialists

Animal and plant species that are very characteristic of lagoons are referred to as lagoonal specialists and are broadly equivalent to the category of species inhabiting blocked brackish waters in the Netherlands and elsewhere (Verhoeven 1980) and the species characterising brackish lentic communities in Denmark (Muus 1967). Perhaps specialist is the wrong word to use as most of these species can be found in neighbouring habitats, but far less commonly so, and characteristic species may be a more appropriate description.

Lists of lagoonal specialists exist for the United Kingdom (e.g. Bamber, 1997) and were proposed for Ireland by Oliver and Healy (1998), Roden (1998) and Healy (2003), and updated (Table 8.4) following additional surveys, and with the more recent discovery of species not previously recorded in Ireland. On the other hand, some species previously regarded as lagoonal specialists have since been recorded at inland sites and are now omitted from the list. Research in lagoons in Ireland is ongoing and some of the taxa in this list remain uncertain as their ecological requirements are poorly known in Ireland. Some of the taxa listed are known from other habitats but occur in a particularly lagoonal form. The gastropod *Littorina tenebrosa* for example is regarded by many biologists simply as a junior synonym of *L. saxatilis*. The alga, *Chaetomorpha linum,* is found on the open coast where it is attached to hard surfaces. In lagoons it grows unattached and often forms dense floating masses, favoured by the isopod crustacean *Idotea chelipes* and as a place for attachment of the spat of the bivalve *Cerastoderma glaucum.* Some of these species are rare in Ireland, and indeed in Europe. Since lagoon habitat itself is rare the biota is also likely to be rare. Also, the habitat was described by Barnes (1980) as 'neglected' and, therefore, many species were probably under-recorded.

Rare species of lagoonal specialist

Many of these lagoonal specialists are rare species in Ireland and some are rare in Europe as a whole. The water-boatman *Sigara selecta* is common in SE England but was previously recorded in Ireland only from Ventry on the Dingle peninsula in 1978 when only six specimens were found (McCarthy and Walton, 1980). The Ventry record was difficult to explain at the time since it was not found at other brackish water sites nearby, despite extensive searching. In 1998, a very large population was found at Loch an Chara in the Aran Islands and since then a few individuals have been found on a neighbouring island (Inis Meain) and the mainland at Bridge Lough, Galway.

Unusually, this species is common in SE England and on one of the Aran islands but nowhere else in Ireland.

The water beetles on the list are all relatively uncommon and largely confined to the coast and brackish water but *Agabus conspersus* is described as endangered on the NPWS red list of beetles and *Enochrus melanocephalus* is regarded as near threatened (Foster et al., 2009).

The habitat of the bryozoan *Conopeum seurati* is described in the IUCN Red Data Book as limited to brackish lagoons and riverine areas, frequently on plant stems (e.g., *Ruppia*). It is found in many lagoons but is not listed in a review of Irish marine Bryozoa (Wyse Jackson 1991). Either the species is under-recorded or is truly a lagoonal specialist.

The amphipod crustaceans *Corophium insidiosum, Gammarus chevreuxi* and *Gammarus insensibilis* are all rare in Ireland. The prawn, *Palaemon adspersus* is referred to in Hayward & Ryland (1995) as found along the west and northwest coast of Ireland though there are no published records of the species in Ireland. This is a large, conspicuous prawn and unlikely to have been overlooked in previous surveys.

As for the plants, both *Ruppia* species are largely confined to non-tidal brackish water with their largest populations in lagoons and can be regarded as lagoonal specialists. *R. spiralis* is found in the larger deeper lagoons such as Loch an Aibhnín or Loch an tSáile, while *R. maritima* is found at most sites. Several charophyte species appear to be confined to brackish water. *Lamprothamnion papulosum* is a rare lagoonal species and was known only from three sites in the country before the lagoon surveys. It is now known from an additional 11 sites, clustered in Connemara and south Wexford, but also in Donegal. *Chara canescens* occurs in somewhat less saline water than *L. papulosum* and occurs in south Wexford, around Galway Bay, Donegal, and Derry. *Chara baltica* was thought to occur in Connemara but recent genetic analysis shows this is not the case, but probable populations occur in north Clare. *Tolypella nidifica* is confined to the Wexford Slobs.

HYDROLOGY AND ANOXIA

Water depths in lagoons vary from as shallow as 1 to 30 meters. The latter is found in Ardbear Lake, Clifden, Co. Galway (Leahy, 1991). Due to the physical characteristics of having narrow, silled entrances, tides are asymmetrical, with flowing tide duration a lot shorter (ca. 3 hours) than ebbing tides (*ca.* 9 hours). Measurements made at Tawin Lagoon, Inner

Galway Bay clearly show this (Kavanagh, 2021). One of the consequences of this is that the extent of exposure of the intertidal habitat is greatly reduced compared to non-silled, symmetrically tidal systems. This is one of the physical characteristics of lagoons that has notable biological effects.

Hydrological velocities are highest at the entrances to lagoons and these, along with associated increased turbulence, give rise to the scouring out of benthic sediments at such locations. Ferrarin et al. (2018), working in the Venice Lagoon in Italy refer to these features as scour holes. Observations in Atalia and Tawin Island (Galway) record the presence of scour holes at the lagoon mouths. However, these features are not present at all lagoons.

Redox Potential and periodic anoxia

Further inside lagoons, flow velocities decrease such that sediments in suspension settle out to the bottom of the lagoon. However, as ebb tide velocities are too low to re-mobilise the sediments, lagoons act as sediment sinks and are, therefore, subject to sedimentary build-up. These fine particulates are typically organically enriched, and this, therefore, gives rise to reduced oxygen in the sediment. Low oxygen conditions in the benthos mean that faunal assemblages can be described as early colonisers or shallow dwellers (Rhoads and Germano 1982).

The deeper waters of some Irish lagoons experience periods of anoxia (Leahy, 1991; Henry et al., 2008; Kelly et al., 2018). The reasons for this phenomenon relate to the fact that interchange between the open sea and the lagoons is restricted due to ridges or sills. Additionally, the asymmetrical tidal character means that replenishment by fully oxic sea water of these deeper waters is restricted to spring tides and also by the length and depth of the connecting channel to the open sea. For example, the channel for Ardbear, is 50 m, while Furnace and Atalia, are approximately 500 m. The biological consequences of such events are that the sessile flora and fauna in these lagoons can die because of the anoxic conditions.

Sea-water is delivered under spring tides into Lough Furnace and in the 1990s sea trout brood stock were being kept in cages in the lake. An event in 1995 caused the lake layers to mix (or overturn) (see Chapter 1) and bring the anoxic waters from the bottom to the surface killing all the brood stock (Anon. 1995). Kelly et al. (2018) also recorded dead eels (*Anguilla anguilla)* from fyke nets set in Furnace and suggest the cause of death was asphyxiation. They also note that deoxygenated water may affect benthic fauna and that sessile or slow-moving benthos may be most vulnerable to anoxic water.

The same sort of event happened in Atalia (which, like Furnace, experiences pulses of sea water during spring tides) where salmon smolts were being held in cages and were killed when the lake overturned.

Leahy (1991), when studying the reproductive cycle of the tube worm, *Serpula vermicularis* in Ardbear recorded such a deoxygenation event in this silled lagoon. Recorded oxygen levels fell to 0 ml/l below water depths of 5 m killing all sessile flora and fauna. Dead serpulid reefs, draped in thick, cobweb-like mats of the sulphur-reducing bacterium, *Beggiatoa* spp. which is another indication of anoxic conditions were noted. These anoxic conditions persisted into autumn but by spring only the deep basin remained anoxic and by which time, re-colonisation of the benthos in shallower depths was evident.

Given the physical characteristics of deepwater salt lakes, it is considered likely that such physical events have naturally occurred in the past and will continue to occur into the future. They give rise to short-duration (months) extinctions with re-colonisation of the benthos occurring once oxic conditions return.

THE MANAGEMENT OF THREATS TO IRISH LAGOONS

Lying on the northwest perimeter of Europe many lagoons in Ireland, especially along the more remote west coast are still very natural compared with other parts of Europe where they have been managed and exploited for centuries, initially for aquaculture but then for salt production and agricultural reclamation and more recently for tourism and harbour development. But even those classed as natural lagoons in Ireland have often been modified to some extent. Many are fitted with non-return valves, usually by local authorities, to allow freshwater to exit but prevent saltwater from entering. The maintenance of the brackish nature of many lagoons is only possible because the non-return valves become jammed with stones or branches. If these valves were repaired and worked efficiently, the lagoon would probably become a freshwater lake.

Sally's Lough in Donegal (Figure 8.6) has an impressive channel cut through bedrock with a barrier that can be closed in bad weather, though this seems to have fallen into disrepair. It is assumed that this channel was cut historically possibly to drain land but also to bring small boats into safety during bad weather.

Other lagoons with sedimentary barriers gradually fill with freshwater in the winter and water levels rise causing surrounding land to flood, which is particularly troublesome for farmers, but also floods coastal roads. In Lady's Island Lake, the NPWS breaches the barrier to lower water level to free up nesting habitat for breeding terns. Wexford County Council also conducts breaches to prevent the electrical system operating their sewage treatment plant from being inundated when water level threatens to rise exceptionally high. Both statutory authorities consult with the members of the Lady's Island Lake Drainage Committee to maintain local good relations. The barrier was breached 61 times in 48 years; three times during 2023 which must have had a significant impact on the lagoon's biodiversity (Jim Hurley pers. comm.). There is now a local authority plan to install a permanent pipe outlet, but calculations suggest that pipe diameter may be too small to allow the lagoon to remain saline, thus preserving the brackish nature of the lagoon.

A comparable problem occurs at Roonah Lough in Mayo. Winter rainfall results in extensive flooding of surrounding land, used not only for farming but for nesting by waders. In recent years increased rainfall has resulted in increased flooding. The only solution is to alter or deepen the outlet channel,

Figure 8.6
Sluice in the channel from Sally's Lough, County Donegal.
Photo: Emer Magee

to allow more freshwater escape to the sea. The impact of such alterations on the lagoon's ecology is not well understood but is currently being investigated in connection with the ongoing EU LIFE on Machair project. Both Roonah and Lady's Island illustrate the dilemma of much conservation management, an increase in human pressure (increased winter rainfall, due to climate change, in this case) disrupts a historical balance and forces a choice on us to preserve one aspect of biodiversity at the expense of another.

While increased winter rainfall is probably due to human activity, there can be no doubt whatsoever, about human responsibility for the other serious threat to Irish Lagoons, excess additions of plant nutrients. The 2009-2017 surveys show that many Irish lagoons are not in good or high condition in terms of the WFD, especially those on the east and south coasts. At present most of these sites are in moderate or poor conservation condition, with high nutrients and chlorophyll and lacking well-developed benthic plant communities. As much of the biological diversity of lagoons is found in the benthos, the absence of this community reduces conservation value. Thus, a reasonable inference is that good conservation conditions can be equated with benthic macrophyte dominance.

Unfortunately, one of the most interesting and well-researched Irish lagoons, Lady's Island Lake, has a reduced benthos, anoxic sediments and water column chlorophyll exceeding 100 µg/l on occasion. The collapse of wigeon grass *(Ruppia* spp.) and charophyte communities have been noted since 2000. The lagoon was the subject of the recent CLEAR project (Coastal Lagoon Ecology and Restoration) (O'Connor et al., 2024). This research attempted to measure nutrient inputs into the lake and calculate the reduction necessary to restore the now vanished but once extensive benthic macrophyte communities.

In situ growth experiments indicated that nitrogen (N) rather than phosphorus (P) appears to limit growth in Lady's Island and other saline lagoons, therefore, a reduction of N should result in a decline in plankton and the re-establishment of a wigeon grass community. The project concluded that for sufficient light to reach the lakebed to allow macrophyte growth, water column chlorophyll must be reduced from 30 µg/l to 5 µg/l, a sixfold reduction; to achieve this reduction, nitrogen addition to the lagoon must be reduced elevenfold. A further problem lies in the large sediment reserve of nitrogen about 7 times greater than a nearby control site in good conservation condition. The input of nitrogen into Lady's Island Lake can be expressed as a loading of kilograms of N per hectare, per year. We calculated this figure as 200 kg/ha/yr. Published accounts (Schallenberg et al., 2012) indicate that N loadings greater than 30 kg/ha/yr. may lead to the collapse of lagoonal macrophyte communities. It appears that nitrogen loadings for Lady's Island Lake are over six times greater than this figure. While the CLEAR project was the first attempt to quantify nutrient inputs into an Irish lagoon, EPA survey results show that similar extremely high chlorophyll and nutrient concentrations are common in the country. To restore many of our lagoons,

Figure 8.7 Gravel pits at Ballyteige, County Wexford.
Photo: Mahon Fox Architects with kind permission of Inish Pebble Co. Ltd

very ambitious nutrient reduction programmes will be necessary in the surrounding catchments. Lagoons are a priority habitat under the Habitats Directive and must be conserved, but the scale of nutrient input reduction is daunting, a sixfold reduction equates to an 80% reduction, a figure so great as to be perhaps, politically impossible. The future management of our lagoons will be problematic, balanced between the need to protect a priority habitat and gain community acceptance of necessary changes.

While changes to the management of lagoons and their catchments will not be easily implemented, two other approaches to lagoon habitat conservation management are still possible-strict enforcement of existing conservation law and new habitat creation. Some very important lagoons occur along the west coast and are both SACs and at present, in good conservation condition; sites such as Lough Atholla, Lough Aconeera and the Aibhnín-Fhada group. Catchment management plans should be strictly implemented which prevent any further impacts such as increased fertiliser use, badly managed septic tanks, turf cutting or land drainage. These sites must be protected from degradation in a manner that did not happen in the case of the once impressive lagoons of southeast Ireland, supposedly protected by the Habitats Directive.

The second possibility of creating or restoring former lagoonal habitats might appear overly ambitious, but inadvertantly such habitat creation has recently occurred at Ballyteige Co. Wexford through the excavation of gravel pits close to the coast (Figure 8.7). The excavation pond was found to contain PLEA communities including a *Ruppia maritima* and *R. spiralis* sward with the charophyte *L. papulosum* and the brittlestar (*Amphipholis squamata*), water transparency was high while chlorophyll and nutrient levels were low. The site was in such good conservation condition it served as a control to compare with the badly damaged Lady's Island Lake in the CLEAR project. In 2023 another rare charophyte, the bearded stonewort (*Chara canescens*) appeared in another exploratory pool nearby. As Figure 8.7 shows a much larger working pit exists which in time will be worked out and with suitable management could also develop lagoonal communities. It is known that a much larger lagoon existed in the Ballyteige area before 1850. Creating new habitat might be interpreted as habitat restoration. The ability to control excess nutrient input in such an agriculturally intensive district, however, will be central to the success of such a project. Given the bad conservation condition of the nearby Tacumshin and Lady's Island sites, habitat creation offers some hope of maintaining lagoonal communities along the south Wexford coast, where otherwise the loss of such ecosystems is a very real possibility.

CONCLUSIONS

Many of the lagoons in Ireland are unique in Europe and contain rare animals and plants. Unfortunately, many have suffered from the effects of excessive nutrient inputs, mostly from agriculture. Coastal lagoons are still a somewhat neglected habitat, and a greater effort is needed to publicise their value and importance as a priority habitat in Europe. Coastal lagoon research in Ireland did not start in earnest until the surveys in 1996. Some lagoons have changed considerably in the 25 years since then and will change again with climate warming. Thus, the definition of a coastal lagoon may have to be broadened and the national inventory updated.

Recent work on the CLEAR project has helped us understand the nutrient dynamics of Irish lagoons, including the importance of nitrogen and the role of excess nutrients in the decay of sites such as Lady's Island. The possibility of lagoon restoration is rendered more difficult due to the very large nutrient reductions calculated to be necessary. The use of a recently excavated pond as a control site suggests that future opportunities to create new or artificial sites are well worth exploring.

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This chapter is dedicated to the late Dr Brenda Healy.
Photo by kind permission of Kevin and Siobhan Healy
Described by a mutual friend of the authors as 'not only an excellent scientist but also as an excellent human being' and the pioneer of studies on Irish coastal lagoons. It is largely thanks to her and to Jim Hurley's tireless work that we became aware of the importance of Lady's Island Lake and to coastal lagoons in general.

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Chapter 9

UPLANDS
LAKES IN THE CLOUDS

Mary Kelly-Quinn

SUMMARY

The term upland is broadly defined as areas located at higher elevations than the surrounding landscape and generally refers not only to mountains and hills, but also plateaus. Thus, the definition is often context-dependent and in Ireland mostly refers to areas above 200 m. Lakes in Ireland have been typed for monitoring under the European Union (EU) Water Framework Directive based largely on their mean depth and alkalinity. This has resulted in twelve main types and a further Type 13 consisting of lakes in the uplands above 200 m. These lakes have not been systematically or extensively studied on the island of Ireland. This chapter, therefore, brings together disparate available information from published papers and unpublished reports to provide insight into the distribution, origin, and chemical and ecological characteristics of these relatively understudied upland lakes. Reference is made to those sites occurring above 200 m, but most of the chapter will bring together what information is available for some of the island's higher-altitude lakes. Their potential as outdoor laboratories to capture changes and provide insight into current and future threats to their integrity is highlighted. It is also important to note that these small lakes are very much the jewels in the Irish upland landscape contributing to its aesthetic qualities which are important from a visitor and general recreational perspective. Carn Lough (Figure 9.1) Co. Donegal is one of the many lakes that add beauty and mystery to the upland landscape.

Keywords Upland lakes, altitude, macroinvertebrates, acid sensitive, dystrophic, oligotrophic

WHERE ARE THE UPLAND LAKES?

There are an estimated 1,300 lakes above 200 m on the island of Ireland, cumulatively accounting for c.11% of the lakes in the country and as expected, most of these lie in mountainous areas, with the highest concentration in Donegal and Kerry (Figure 9.2). On the east coast, they are mainly located in

Figure 9.1
Carn Lough,
Co. Donegal.
Photo:
Jan-Robert Baars.

the Wicklow Mountains. Just over 70 of the lakes lie above 600 m, while only four are above 700 m. Among those above 600 m are the Devil's Punchbowl and Lough Cummeenapeasta (*Loch Coimín Piast*) in Co. Kerry, and Cleevaun Lough and Lough Firrib in Co. Wicklow. In terms of area, 73% of these upland lakes are less than 1 hectare. The largest is Lough Dan (102.8 ha) in Co. Wicklow followed by Glenawough Lough (*Loch Ghleann an Bhua* (73 ha) in the Erriff River catchment in Mayo, both lie between just under 200 m above sea level. The lakes above 300 m are generally much smaller, the largest being Lough Belshade (27.4 ha) in Donegal. Lough Cummeenoughter in the MacGillycuddy Reeks at over 700 m is reputed to be Ireland's highest lake. Although many of these lakes have a small surface, they are extremely deep, reaching up to almost 50 m in depth. For example, Lower Lough Bray, a corrie lake, reaches a depth of 46.7 m (Figure 9.3).

ORIGIN AND PHYSICAL CHARACTERISTICS

Most of the upland lakes lie in landscapes sculpted by glaciation during the last ice age (see Chapter 2). As the ice caps flowed off the mountains, they produced over-deepened U-shaped valleys. Ribbon lakes were left where water filled deep hollows or where the flow was blocked by a wall of moraine. Loughs Dan and Tay (Figure 9.4) in the Wicklow Mountains are typical examples of ribbon lakes.

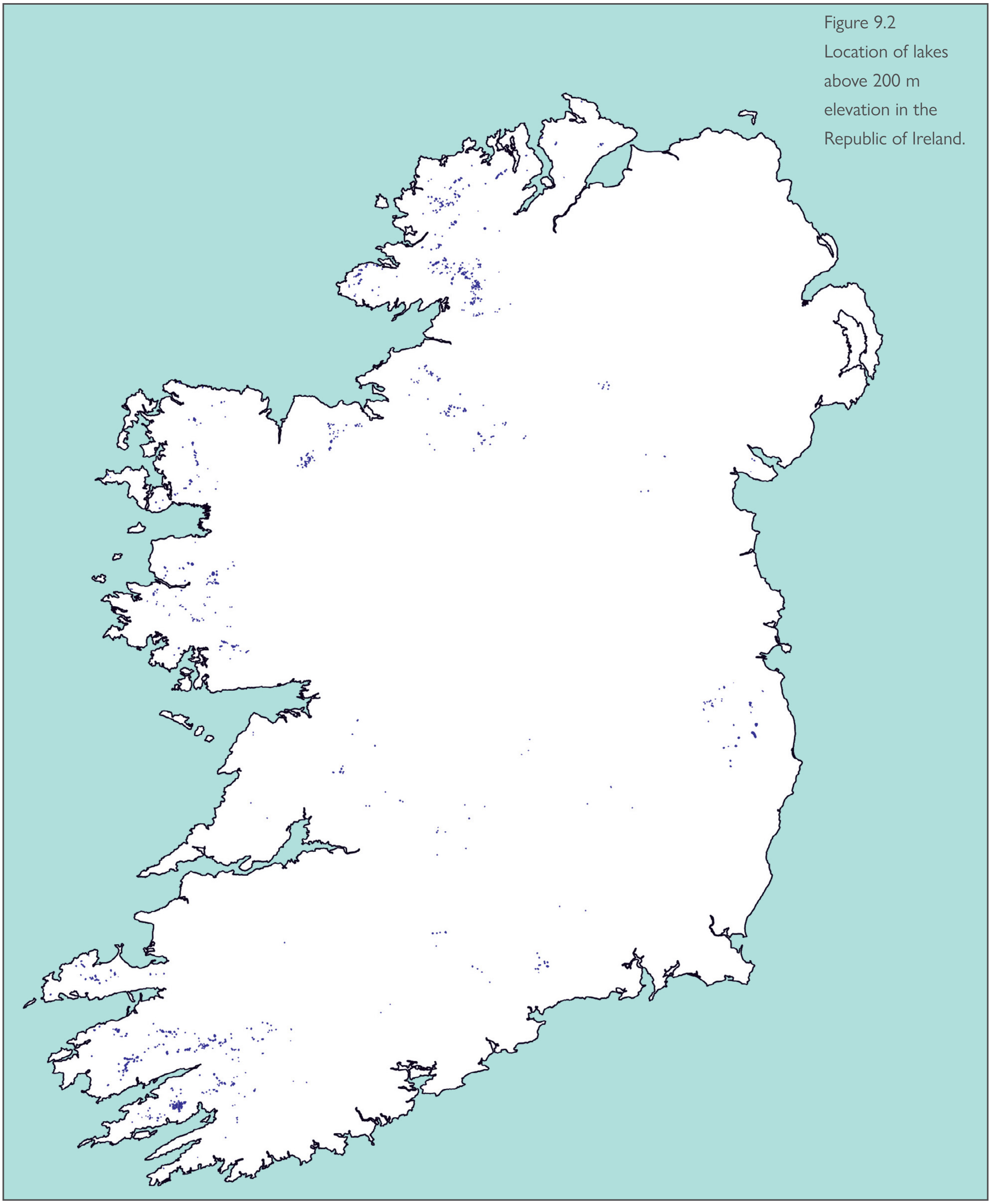


Figure 9.2
Location of lakes above 200 m elevation in the Republic of Ireland.

Figure 9.3
Lough Bray, a deep corrie lake in the Wicklow Mountains.
Photo: Hugh Feeley.

Figure 9.4
Lough Tay in the upper Avonmore catchment in Co. Wicklow.
Photo: Noel Quinn.

Many of the smaller lakes are known as corrie lakes or tarns. Corries are arm-chair-shaped depressions that have been scooped out by glaciers. Snow accumulated in hollows and over the years it was compressed into ice and became a corrie or cirque glacier. Pressure and abrasion at the base of the glacier deepened the hollow. As gravity caused some movement of the glacier, it plucked rock from the back of the hollow which together with freeze-thaw,

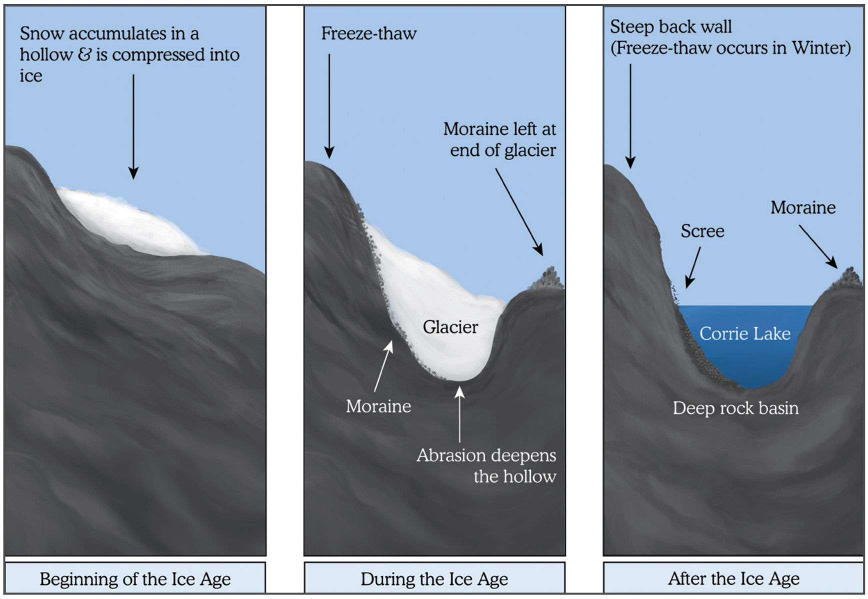


Figure 9.5 Stages in the formation of a corrie lake. Redrawn and modified by Aoife Quinn from https://mammothmemory.net/geography/geography-vocabulary/glacial-landscapes/corrie.html

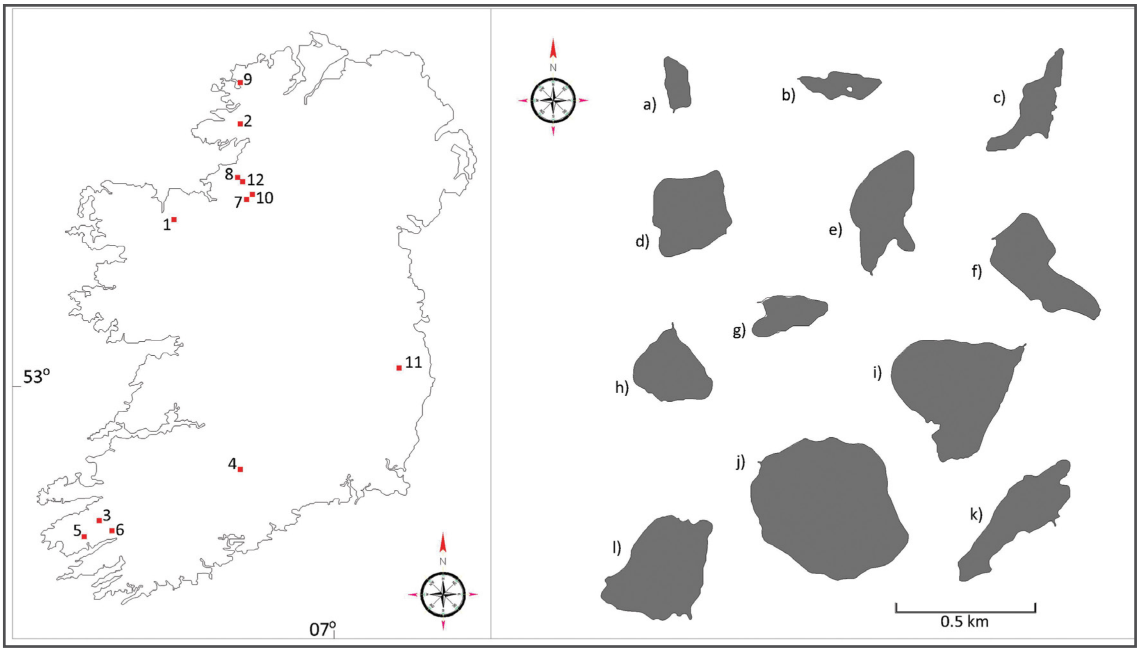
created a steep back to the corrie (see Figure 9.5). Melting of the ice at the end of the ice age left behind small deep lakes.

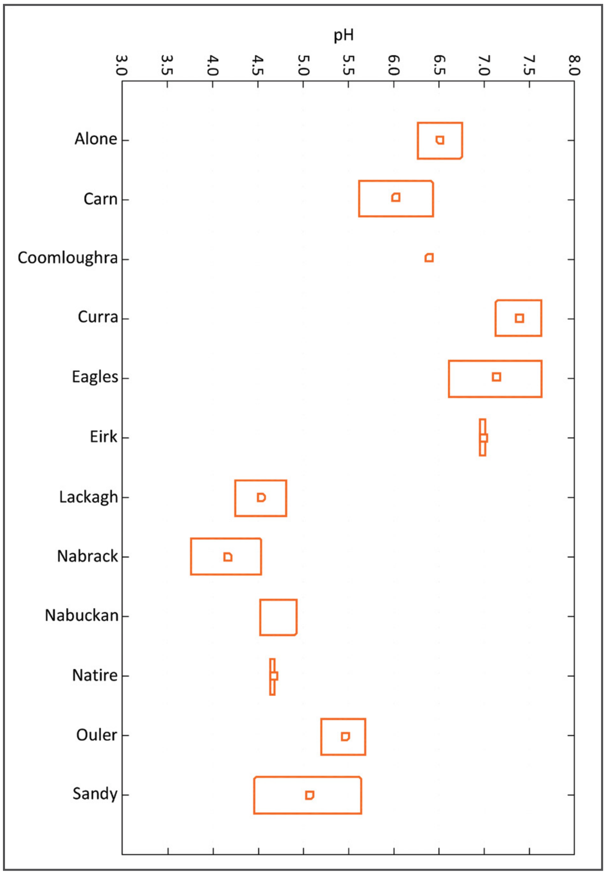
Many of the small lakes on blanket bog on the east and west coast of the Island of Ireland would fall into two categories protected under the EU Habitats Directive; 'Oligotrophic waters containing very few minerals of sandy plains (with vegetation belonging to the *Littorelletalia uniflorae* order)' (3110 lake habitats) and 'Natural dystrophic lakes and ponds' (3160 lake habitats) (see Chapter 10). The dystrophic lakes for example lie within the following Special Areas of Conservation; Bellacorick Bog Complex, Boleybrack Mountain, Caha Mountain, Connemara Bog Complex, Cuilcagh-Anierin Upands, Glenamoy Bog Complex, Mweelrea/Sheeffry/Erriff Comples, Owenduff / Nephin Complex, Ox Mountain Bogs and the Wicklow Mountains.

A CHALLENGING WATER CHEMISTRY ENVIRONMENT

The geological and topographical setting of these upland lakes results in a challenging physical and chemical environment. These lakes act as outdoor laboratories revealing natural and man-made pollutants that can be transported in the atmosphere for long distances and deposited in freshwaters. A snapshot of the composition of the water can be gleaned from the work by Aherne et al. (2002) on lakes sampled between February and April 1997. The study also illustrates the value of these lakes in detecting atmospheric inputs without the complication of other human-produced pollutants from the catchment. The sampling programme was concentrated in areas of the country considered to be acid-sensitive. i.e. areas where acid deposition is not buffered or neutralised as in catchments with geology such as granite, gneiss and quartz-rich rocks and thus pH of surface waters can become quite acidic. This formed part of a study on the estimation of critical loads of atmospheric pollutants (sulphur and nitrogen compounds) for freshwaters in Ireland. Ninety-three of the 190 lakes lay above 200 m. Critical loads are an estimate of the amounts of atmospheric pollutants below which significant harmful impacts on the ecosystem do not occur. Rocks such as granite are not easily weathered and together with peaty soils contribute to the acid sensitivity and low pH of many of the lakes, with 59% having pH values below 6.0 (3.93-5.89). Low ionic content was also typical with few values above 100 µS/cm. This was dominated by chloride (average 17.69 mg/L Cl), followed by sodium (average 10.24 mg/L Na) with little calcium (most values less than 2 mg/l Ca) in these acidic waters. Similarly low pH and conductivity waters with a dominance of chloride ions were reported from four upland lakes in Northern Ireland by Maberly et al. (2002), 12 upland lakes in the Republic of Ireland, all above 300 m, by Baars et al. (2005) (Figures 9.6 & 9.7) and for six lakes by Drinan et al., (2013a). Apart from Lough Ouler in Co. Wicklow and Lough Curra in County Tipperary, the lakes surveyed by Baars were located on the west coast in Counties Kerry (Lough Coomloughra, Eagles Lough and Eirk Lough), Mayo (Lough Alone) Leitrim (Lough Nabrack, Lough Natire and Lackagh Lough), Donegal (Carn Lough and Lough Nabuckan).

Changes over time in atmospheric emissions and transboundary pollution have also been captured by upland lakes. A small number of the lakes sampled by Aherne et al. (2002) had excess deposition of acidifying pollutants, mainly sulphate. Sixty of these lakes were resampled in spring of 2007 (Burton and Aherne, 2022) and showed a decrease in the concentration of non-marine or atmospheric-derived sulphate, most likely due to reductions in overall atmospheric emissions of sulphur dioxide in response to the Gothenburg Protocol under the UNECE Convention on Long-Range Transboundary Air Pollution. Later in 2017 and 2018, Nelson and Aherne (2020) revisited 29 (all above 300 m) of the lakes sampled in earlier studies to analyse the lake water for 18 trace metal pollution indicators. Relatively low concentrations of the metals were detected, mainly dominated by iron, aluminium, zinc, manganese, boron, barium and strontium. One lake in Northern Ireland, Blue Lough, is part of the UK Upland Waters Monitoring Network. Here





Above

Figure 9.6 Location of the upland lakes in Ireland sampled in 2005 (left image). Relative size of the lakes is shown on the right; a) Nabuckan, b) Carn, c) Nabrack, d) Sandy, e) Natire, f) Lackagh, g) Alone, h) Curra, i) Ouler, j) Coomloughra, k) Eirk, and l) Eagles. Scale bar 0.5 km. From: Baars et al., (2005).

Left

Figure 9.7 The range of pH values recorded at the 12 upland lakes (> 300 m) sampled during the spring and summer sampling periods in 2005. From Baars et al., (2005) again, the water chemistry had shown a response to reductions in atmospheric deposition. While pH has risen slightly, dissolved organic carbon (DOC) has risen by almost 50%, possibly due to the increased decomposition of peat, while inorganic aluminium concentrations (i.e. aluminium that can easily bind to animal tissues), continue to create potentially toxic conditions for aquatic organisms (Monteith et al. 2022). Interestingly at that site, the effect of moorland fires in 2011 resulted in a drop in pH, a four-fold increase in nitrate concentrations and a doubling of inorganic aluminium concentrations. According to the authors it took almost five years for the water chemistry to return to the improving water quality trajectory noted before the fire.

Many other pollutants have been deposited in freshwaters. For example, Aherne et al. (2023) sampled water from four upland lakes (Lough Cleevaun in Wicklow, Sgilloge Lough in Waterford, Lough Cummeenoughter in Kerry, and Mullincrick Lough in Donegal). Interestingly, chemicals of wastewater origin such as caffeine, codeine, paracetamol, and even artificial sweeteners were detected in these remote locations. These may have been released into the atmosphere from the aeration ponds at the wastewater treatment plants.

The sediments at the bottom of the lakes also tell a story of the land-use activities that have occurred in the catchment and are explored in detail in Chapter 3. For example, the sediment cores taken from Lough Tay by Cox (1984) highlighted periods of afforestation and the associated drainage in the iron and manganese ratios.

THE BIOTA OF THESE UNIQUE ENVIRONMENTS

Macroinvertebrates

The acid, low nutrient, and cool waters of most of the upland lakes curtail the diversity and abundance of the macroinvertebrate species that inhabit their waters. Here we focus on a few of the small number of disparate studies on upland lake macroinvertebrates. As noted above, Baars et al. (2005, 2014) sampled 12 upland lakes (Figure 9.6). The study sampled macroinvertebrates at several points around the shore and from foam samples (for Chironomidae or non-biting midge larvae) in April and August 2005. The study is among the few that have species-level data. Across all lakes, 202 species were recorded, however, only 33 to 77 species occurred in any one lake. The Chironomidae were most diverse (100 species) followed by Trichoptera (caddisflies - 27 species), Coleoptera (beetles - 24 species), Heteroptera (water bugs - 13

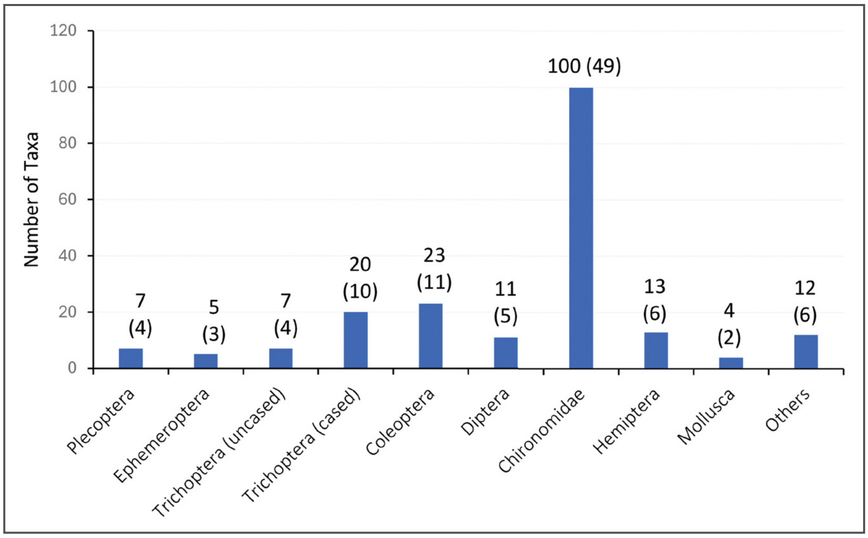


Figure 9.8 Number of taxa in each major taxonomic group collected in 12 upland oligotrophic lakes over two sampling periods in 2005. The number of taxa in each group is given above the bars and the percentage of the total taxa is given in parentheses. Hydracarina (mites) and Oligochaetae (bristle worms) are identified to order only and are included in the other 'group' which includes Crustacea (e.g. shrimps), Cladocera (water fleas), Odonata (dragonflies and damselflies) and Oligochaetae Chironomidae (non-biting midges) were identified to species using pupal exuviae. From Baars et al., (2005)

species) and Diptera (true flies - 11 - excluding Chironomidae) (Figure 9.8). This represents a fraction of the 2,500 known species of macroinvertebrates in Ireland (see Chapter 5).

Contrary to the 25-plus species that one would encounter in river sites, only five species of Ephemeroptera (mayflies) and Plecoptera (stoneflies) were recorded. The acid tolerant *Leptophlebia vespertina* (Figure 9.9) was the only mayfly occurring at 10 of the 12 sites and one species (*Ecdyonurus venosus*) was picked up near a river inflow. *Nemoura cinerea* also occurred at 10 sites while three caddisfly larvae, *Plectrocnemia conspersa* and *Polycentropus kingi,* and *Halesus radiatus* also occurred at most sites. The arctic relic species *Diura bicaudata* occurred in two lakes.

Lough Bray, Lower (374 m) and Upper (430 m), in the Wicklow Mountains were sampled by O'Neill (1997) in October 1996 and January 1997, respectively. Here the lake pH never exceeds 4.7 and probably accounts for the relatively low species diversity, with only 12 and 19 species, respectively in Lough Bray Lower and Upper. It should be noted that the Chironomidae were not identified to genus or species level. The only mayfly

Figure 9.9 *Leptophlebia vespertina* adult with nymph shown in the insert. Photo: Jan Robert Baars.

was the aforementioned acid tolerant *Leptophlebia vespertina*. The Plecoptera were represented by just *Leuctra* sp. and *Diura bicaudata.* The Trichoptera recorded were most abundant in Lough Bray Lower, dominated by *Tinodes waeneri and Polycentropus kingi.* No invertebrates were recovered from a grab sample taken from the bottom of the lake at 20 m depth.

Lough Dan, the slightly less acid (pH 4.89-5.3) and larger waterbody at just under 200 m has been studied since the 1970s (O'Connor, 1975; O'Connor and Bracken, 1978). Further studies were carried out in 1996 and 1997 on water quality, macroinvertebrate communities and fish, particularly checking for the presence of char (Kelly-Quinn et al., 2000). The number of macroinvertebrate species recorded was not too dissimilar to what was reported previously from the lake, 17 taxa in October and 38 taxa in May. The sheltered shore with reeds (*Carex* sp.) supported the highest diversity. Overall and in contrast to many of the lakes surveyed by Baars et al. (2005), Trichoptera larvae formed the bulk (32.25%) of the individuals present and also in terms of species richness. A total of 13 trichopteran species were recorded, a figure that is not too dissimilar to the 1970 studies. The 1971 study spanned 4 seasons, and this accounts for the higher checklist of 50 species.

From the available studies on upland lakes in Ireland, it appears that pH (influenced by solid geology and the presence of peat) and altitude (and its covariable temperature) are the key factors shaping the macroinvertebrate communities of upland lakes.

Figure 9.10
Lobelia dortmanna
(Campanulaceae).
Photo: Ruth Little.

Macrophytes

Data on the macrophytes (plants) of upland lakes are also rather patchy for lakes in Ireland but generally indicate communities with low species diversity. Baars et al. (2005) provided some detail about the macrophytes of 19 upland lakes across the country that yielded just 19 aquatic species with some sites having just two species. They noted that few submerged plants characterised lakes with brown humic waters. The rare species, *Lobelia dortmanna* (Figure 9.10) known only to exist in the extreme west, was found at sites in Counties Kerry and Donegal. *Myriophyllum alterniflorum* was also recorded, a species more common to the north and western areas of Ireland. Several plants with floating leaves were present at most sites. These included *Sparganium angustifolium* and a broad-leaved *Potamogeton* spp. And often occurred in relatively large clumps

Drinan et al. (2013a) focussed on six upland lakes in the west of Ireland varying in altitude between 183 and 429 m, all acidic, low conductivity waters. They recorded 12 species, among the dominant and abundant taxa were *Carex rostrata, Equisetum fluviatile*, *Juncus bulbosus*, *Nuphar lutea*, *Phragmites australis* and *Potamogeton natans*. Interestingly, they noted the presence of the newt *Lissotriton vulgaris* in two of these upland lakes.

Fish

The fish communities of most of the upland lakes are mainly composed of brown trout (*Salmo trutta*) but some lakes have stickleback (*Gasterosteus aculeatus*), eels (*Anguilla anguilla*) and arctic char (*Salvelinus alpinus*). Among the arctic char lakes outlined in Chapter 6 are five above 200 m that have char. These include Loughs Callee, Cloonee, Coomaglaslaw, Glenawough and Gouragh. The highest is Lough Gouragh at 350 m. Upland lakes that have lost their char populations include Loughs Dan and Tay in Co. Wicklow where substantial numbers were present in the 1800s (Went 1953) and considered to have persisted until the 1980s. As noted by Igoe and Kelly-Quinn (2002), no subsequent records were authenticated, and gill net surveys failed to locate char. The authors acknowledged that it is difficult to identify causative factors but suggested that periods of low pH, in combination with toxic levels of inorganic aluminium, may have contributed to the loss of char.

Many of the upland lakes that hold populations of brown trout are isolated from other water bodies or have outflowing streams that would present barriers to any upstream movement of fish. Ferguson (2004) explains that certain brown trout populations, such as those living in historically isolated mountain lakes, or waterways which are particularly acidic or alkaline, are 'likely to possess unique adaptations'. One example is Lough Ouler (596 m) which has no permanent input stream, and its outflow is via a high-gradient small stream which joins the Glenmacnass River. On 29 and 30 July 2009, the Eastern Regional Fisheries Board (now Inland Fisheries Ireland) conducted a fish survey in Lough Ouler (Connolly, 2010). The maximum length of the fish caught was 15.2 cm and only three fish were larger than 14 cm (Figure 9.11). These fish have low growth reaching a length of just 4.53 cm and 8.59 cm at the end of their first and second years, respectively. In year three, they only grow a further 2 cm. Their growth stands in marked contrast to upland lakes such as Dan (200 m) and Tay (250 m) and unsurprisingly from the lowland Lough Sheelin (Figure 9.12). The estimated ultimate length that most fish attain in Lough Ouler is 14 cm. The stomach contents of 66 trout were examined and all but 11 had food items. The one-year fish were mainly feeding on planktonic Cladocera which made up the bulk of the contents followed by dipteran (fly) larvae and terrestrial flies. Other items occurred in less than 10% of the stomachs. The dominant food items were relatively similar in the two-year and three-year old fish but the dipteran larvae, terrestrial flies and Coleoptera (adult and larval beetles) occurred more frequently.

Many of the isolated upland lake trout populations likely have similar low growth rates. Spawning habitats are also most likely limited. For example, trout eggs are deposited between boulders and cobbles in a short section of the small outflowing stream from Lower Lough Bray (Kelly-Quinn, personal observations). In summary, fish in remote upland lakes most likely present unique genetic and morphological characteristics of conservation interest and warrant further research.

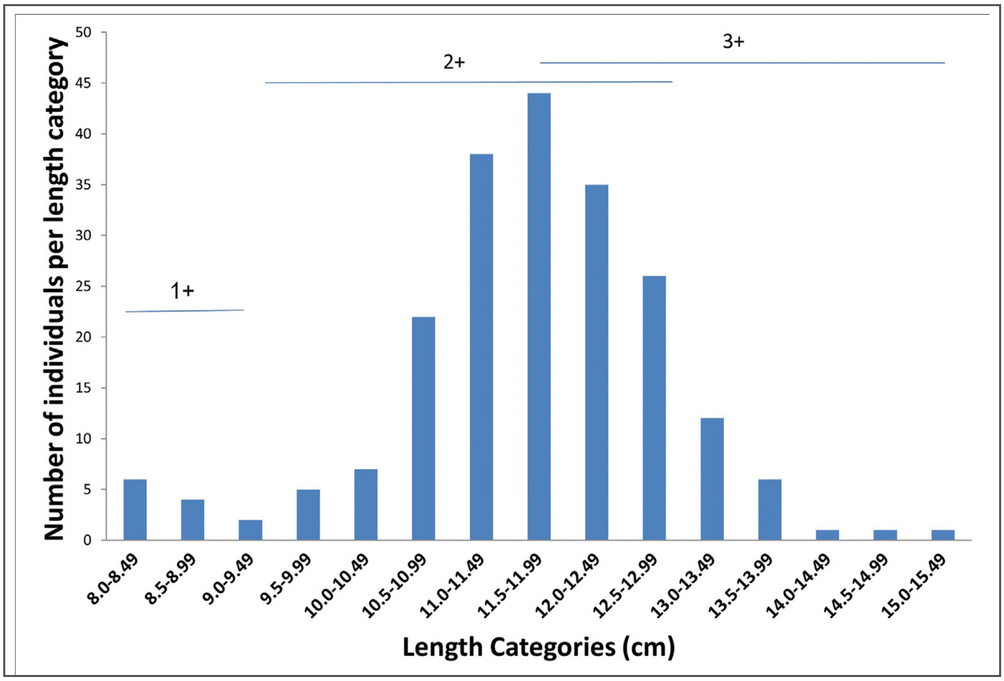


Figure 9.11
Length frequency distribution of brown trout captured in Lough Ouler in August 2009. Length range per age group is indicated.
From: Connolly (2010)

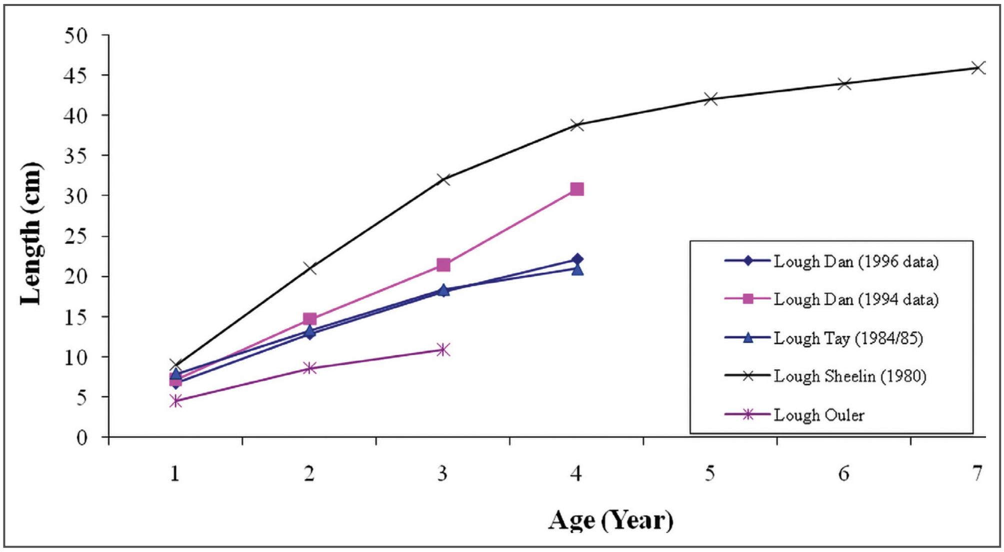


Figure 9.12
Back-calculated lengths of brown trout in several lakes for comparison with Lough Ouler, Co. Wicklow. From: Connolly (2010)

THREATS PAST, PRESENT AND FUTURE

Excluding the Vartry reservoir, there are only five upland lakes on the EPA monitoring programme (see Chapter 11). These include Loughs Salt, Tay and Dan, Lower Lough Bray and Cam. All are reported to be at Good Status with the exception of Lough Tay, which is failing in terms of macrophyte and other aquatic plant status. There is growing evidence that even the most remote of upland lakes are not free from the influence or impact of human activities. The key threats to these delicate ecosystems are acid deposition, nutrient enrichment from forestry operations, increasing levels of DOC and fine sediment inputs from peat erosion and forest felling. Ideally, long-term studies are needed to identify changes and potential impacts. The few paleolimnological studies on Ireland's uplands lakes provide some insights into changes over time (see Chapter 3). For example, sediment coring and examination of diatom remains in Kellys Lough, a small corrie lake located at 585 m in the Wicklow Mountains, by Leira et al. (2007), provided some evidence that acid deposition probably exacerbated the natural acidity. The diatom community changes were also hypothesised as potentially resulting from increasing erosion and in wash of organic matter from the catchment which reduced water transparency and lowered pH. Linnane and Murray (2000) attributed the increased organic content of the sediment in cores from Lough Bray to likely changes in erosional patterns in its catchment

Although one of the upland humic lakes sampled by Stevenson et al. (2016) was just under 200 m, the results may provide insight into the potential impact of forestry on these delicate ecosystems. The authors noted that mineral and nutrient enrichment from forest fertilisation can increase abundance of cyanobacteria and cryptophytes, thus altering the abundance and composition of algal species. In an earlier study on small blanket bog lakes, which included eleven above 200 m, Drinan et al. (2013b) highlighted that some lakes with afforested catchments had elevated levels of phosphorus, nitrogen, total dissolved carbon, aluminium, and iron. The nutrient inputs were generally associated with felling operations or forest fertilization. Two of the lakes above 200 m had total phosphorus values of 0.051 and 0.059 mg/L P (Kelly-Quinn et al., (2016). This resulted in changes in Chydoridae (cladoceran) communities. The forestry-impacted lakes had a community dominated by *Chydorus sphaericus*, along with *Alonella nana, Alonella excisa* and *Alonella exigua* as opposed to *Alonopsis elongata* in the lakes with no forestry in their catchments (Drinan et al., 2013c). Nutrient enrichment also resulted in enhanced growth and size of trout in some of the lakes.

As noted previously many other atmospheric pollutants of anthropogenic origin have been detected in upland lakes, albeit at low concentrations. At present the potential impact of those pollutants is unknown.

CONSERVATION IMPORTANCE AND RESEARCH NEEDS

As indicated, the upland lake groups protected under the EU Habitats Directive include some 'Oligotrophic waters and 'Natural dystrophic lakes and ponds'. Apart from supporting several rare and notable species, these and other upland lakes present variable environment conditions and thus habitat heterogeneity which often yields widely differing assemblages of aquatic organisms. Although any one lake is not necessarily species-rich, the lakes collectively make a significant contribution to regional biodiversity.

Compared to other freshwaters, upland lakes although representing 11% of the lakes in the country, remain understudied. Their upland and often remote settings create challenges in terms of getting adequate spatial and temporal data on their biodiversity. The priority is now to gain a better understanding of their unique biodiversity contributions at local, regional and national levels and what is required to minimize anthropogenic activities, including climate change on these fragile, fascinating upland laboratories. As noted by Sayer (2014), conservation efforts need to focus not on individual sites or water bodies but on all the 'watery patches' in the landscape and the linkages between them.

ACKNOWLEDGEMENTS

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Chapter 10

LAKES OF DISTINCTION HABITATS DIRECTIVE ANNEX I LAKE HABITATS

Cilian Roden and Áine O Connor

SUMMARY

This chapter focuses on the biodiversity – or nature – value of lakes in Ireland. This is recognised under the EU Habitats Directive, and Ireland is charged with protecting and reporting on the conservation condition of five separate lake types listed in Annex I, denoted by the EU codes 3110, 3130, 3140, 3150 and 3160. In an international context, our large, stony marl lakes filled with vegetation of primitive organisms (stoneworts and cyanobacteria) are probably the rarest. Ireland also has significant European responsibility for low-productivity, soft-water lakes in peatland and rocky catchments. In an Irish context, perhaps our rarest type is the intermediate-alkalinity lake, home to species such as the protected Slender Naiad, for which Ireland is the centre of its European distribution. Unfortunately, all our lake types are degrading fast; few lakes can now be described as in good conservation condition. Unless we rapidly and radically reduce our impact on nature throughout their catchments, we must expect to lose our most important lake ecosystems in the twenty-first century.

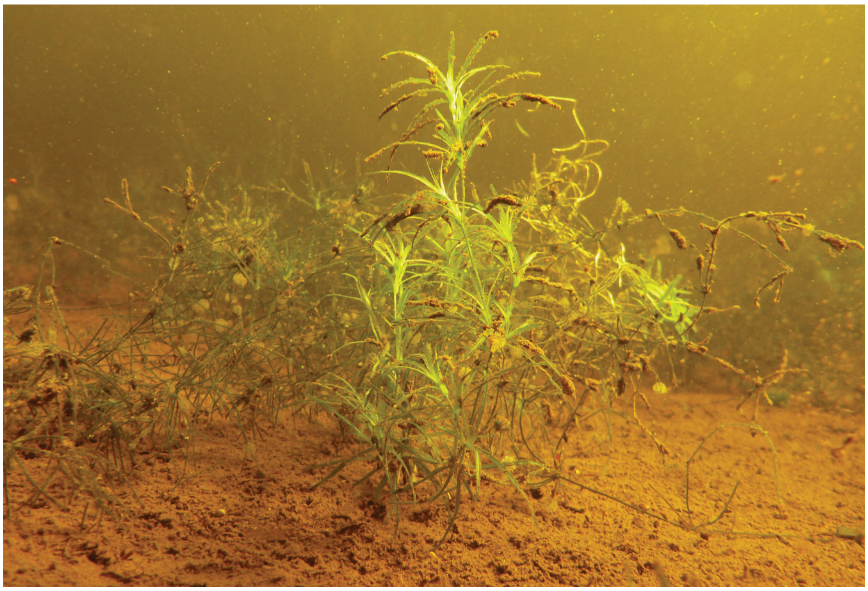
Keywords Vegetation, Habitats Directive, marl, Slender Naiad

INTRODUCTION

Lakes and their fauna and flora are, to an extent, an acquired taste. Unlike oak woods or Burren grasslands, their character and condition are difficult to judge merely by an inspection from the shore. Normally we estimate a lake's natural history value by examining and comparing lists of species; lists which are compiled only with some effort and skill. This somewhat intangible information is often supplemented by equally intangible tables of chemical or physical parameters. Unfortunately, none of these convey a strong visual impression of what a lake in excellent conservation condition looks like. The only observer who will develop a visual appreciation of such lakes is the diver or snorkeller (and possibly soon the underwater drone operator). That appreciation will be based not so much on seeing a variety of species but, overwhelmingly on water clarity.

Shallow lake theory emphasises a connection between water transparency and a developed and well-oxygenated lake benthic community (Scheffer, 2004). For the diver, this ecological link translates into sites with wonderful visibility and species-rich plant communities extending to a depth of more than 10 m, as well as large populations of native or even endemic fish. Such lakes make a wonderful contrast to the all too common, rather miserable, dark, plankton-rich sites with little else in them except algal blooms, introduced fish species, Canadian Waterweed *Elodea canadensis* Michx., Yellow Water-lily *Nuphar lutea* (L.) Sm., Bulrush *Typha latifolia* L. and Zebra Mussel *Dreissena polymorpha* (Pallas, 1771), and no plants growing much below 1-2 m. Regrettably, such lakes are steadily increasing in Ireland and almost unique sites with Slender Naiad *Najas flexilis* (Willd.) Rostk. & W.L.E. Schmidt (Figure 10.1), rare stoneworts (charophytes) or endemic fish such as Pollan *Coregonus autumnalis* (Pallas, 1776) are steadily being destroyed. As these changes take place out of sight below the water surface, they rarely give rise to comment even amongst naturalists; only when clots of *Cladophora* Kütz. drift on the surface or dog-killing scums of cyanobacteria accumulate along the shore is the alarm raised.

Figure 10.1 Slender Naiad (*Najas flexilis*) growing at 2 m in Lough Leane, Kerry in 2013. This population has now disappeared, probably because of eutrophication. *Nitella flexilis* agg. on left side of photo. Photo: Cilian Roden



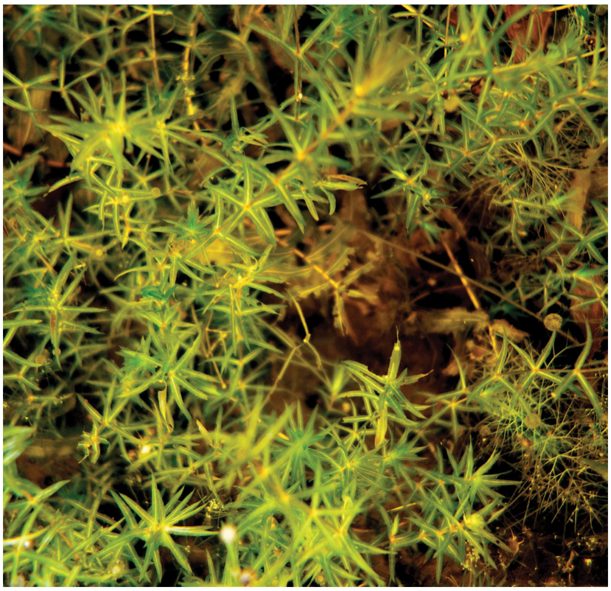
BEST IN CLASS

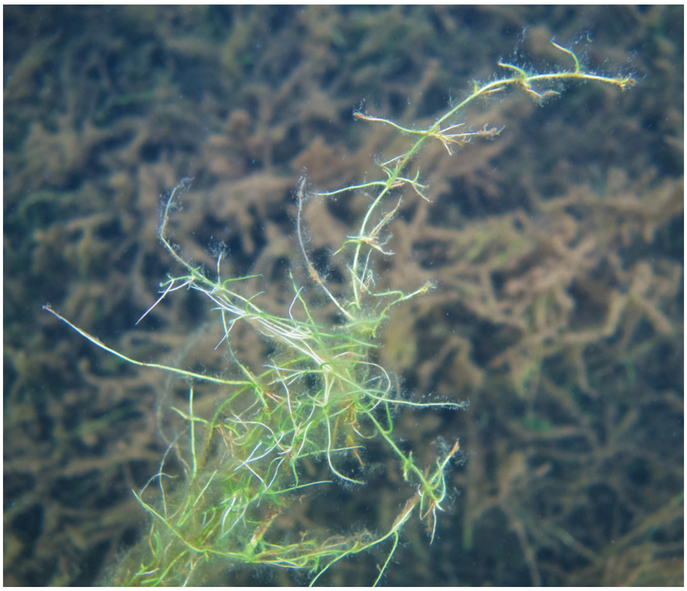
Three wonderful lakes

Selecting examples of the best lakes in Ireland must, in part, be subjective, but in terms of species diversity and rarity, water clarity, visual impact and size, some sites stand out. The two-kilometre-long Ballynakill Lough in northwest Galway (Connemara) is one such site. Its distinctive character was first realised in 2004 when the very rare *Hydrilla verticillata* (L.f.) Royle (Figure 10.2) was found to grow there in abundance (the plant was previously only known in Ireland and indeed Western Europe in the nearby Rusheenduff Lough). Further work has shown that no less than three species listed in the Flora (Protection) Order, 2022 (S.I. No. 235 of 2022) occur there, the others being Slender Naiad and Pillwort *Pilularia globulifera* L. (Figure 10.3), as well as a further five rare or local species (Roden et al., 2021a). Its zoology has yet to be studied. Its total flora of 36 aquatic species is very large and the extensive deep-water communities are

Figure 10.2, left: *Hydrilla verticillata* in Ballynakill Lough, Connemara, Galway: a plant known only from a few lakes in western Europe. Photo: Cilian Roden

Figure 10.3, right: *Pilularia globulifera*, a rare aquatic fern grows in great abundance in the western arm of Lough Mask, around an underwater spring. The plant forms long streamers only loosely attached to the lake bed; an unusual growth-form for the species. Photo: Cilian Roden





almost unique due to the abundance of *Hydrilla* and reflect its great water transparency. Species which are rare or absent in many parts of Europe such as Pipewort, *Eriocaulon aquaticum* (Hill) Druce, *Isoetes echinospora* Durieu, Slender Naiad and Water Lobelia *Lobelia dortmanna* L. form a considerable proportion of the vegetation, and the rarely seen *Nitella confervacea* (Bréb.) A. Braun ex Leonh. is abundant. It is doubtful if a comparable lake survives in Western Europe although Esthwaite Water in the English Lake District may once have been. A visitor who simply views the lake from the shore will be unaware of its biodiversity, but a snorkeller is at once impressed by the abundance of rare species and benthic vegetation in all but the very deepest parts, all easily seen in clear water.

An equally interesting, though less well-documented soft-water lake is Lough Adoolig at *c*. 250 m ASL in Kerry. It contains many of the species found in low-alkalinity soft-water lakes but is most unusual in having an iron-rich underwater spring at depth supporting abundant growth of two poorly understood stoneworts, *Nitella gracilis* (Sm.) C. Agardh and *Nitella cf. spanioclema* J. Groves & Bull.-Webst. ex Bull.-Webst. The former is only known from two other lakes in Ireland while the latter's status is still not understood (Bryant and Stewart, 2011). It was first described in 1920 based on material found in Donegal (Bullock-Webster, 1919) but was not reported from elsewhere until recently when similar forms were seen from some other lakes. The Adoolig material closely matches the description of the Donegal specimens and is abundantly fertile. DNA analysis is necessary to establish the correct status of the taxon, but its abundance along with *Nitella gracilis* demonstrates the lake's unusual ecology and shows how little we know about the vegetation of many upland lakes in Ireland.

While soft-water lakes are not common in Europe, they are known from Scandinavia, Britain, and Ireland as well as more locally on the European mainland. Our marl lakes, however, are even more unusual. The great extent of Carboniferous limestone in the Irish lowlands combined with glacial history and a wet climate has resulted in several very large (for example, Lough Corrib in Galway is greater than 165 km^2) and many smaller high-conductivity (>100 mg/l alkalinity) or marl loughs, with apparently few similar sites known in lowland Western Europe. The typical western limestone lake scenery of wide flat horizons, outcropping grey limestone shores and green tree-clad islands (Figure 10.4) is perhaps more uniquely Irish than often realised. Certainly, the marl lakes found in this landscape are of European interest and support vegetation rarely reported elsewhere.

Figure 10.4
'The typical western limestone lake scenery of wide flat horizons, outcropping grey limestone shores and green tree-clad islands is perhaps more uniquely Irish than often realised'. Lough Carra, Mayo. Photo: Cilian Roden

An extreme example of an Irish marl lake is Lough Cooloorta in Clare (Figure 10.5), nestled in the limestone pavement of the Burren (Roden et al., 2020a). On aerial images, the lake displays a turquoise-blue colour usually seen above coral reefs, surrounded by white marl flats. These features reflect the great transparency of the water, with plant growth occurring to 10 m, and the precipitated calcium carbonate that forms much of the lake sediment. For the average botanist, the lake seems of little interest as no recognisable flowering plant can be seen in its waters. Instead, in the shallows, both outcropping rock and soft marl are covered by an orange-brown limey crust (Figure 10.6) which is, in fact, a cyanobacterial community (Doddy et al., 2019). There is also evidence that the crust can etch into and shape or even dissolve the underlying limestone (Roden et al., 2021b). Other than the crust, the most obvious photosynthetic organisms are stoneworts which occur in small numbers in shallow waters but constitute the lake's vegetation at depth. Up to 12 different stoneworts can occur in marl lakes, eight of which are known from Cooloorta. The species, like seaweeds on a rocky shore, occur in zones. Scattered about the crust is *Chara virgata* var. *annulata* (Walman) N.F. Stewart & J.A. Bryant, followed by a dense band of *Chara curta* Nolte ex Kütz. at 1-2 m, followed in turn by *Chara subspinosa* Rupr. (Figure 10.7) between 2-5 m, and from 5-10 m *Chara virgata* Kütz. In places another species *Chara contraria* A. Braun ex Kütz. replaces *Chara virgata* at depth (a sign of great water clarity). *Chara contraria* itself is followed by an extremely uncommon species *Chara dissoluta* A. Braun ex Leonh. in about ten lakes in

Clockwise from top: Figure 10.5 The wonderful whites, greys, and blues of an unspoilt marl lake: Cooloorta, marl lake in the Burren, Clare.
Figure 10.6 The cyanobactrial crust of marl lakes. It is formed largely by cyanobacteria of the *Schizothrix* genus. It forms a layered, calcium carbonate-rich deposit over limestone rock and in places can grow to more than 10 cm thick.
Figure 10.7 A dense bed of *Chara subspinosa* at 4 m depth in Lough Carra. Lake vegetation is often composed of single-species swards or 'meadows'.
Photos: Cilian Roden

Ireland and a handful of other European sites. Flowering plants are scarce in Cooloorta: three species of pondweed including the scarce *Potamogeton praelongus* Wulfen and, most surprisingly, the normally soft-water Bulbous Rush *Juncus bulbosus* L. possibly occurring here owing to the extremely low nutrient levels. Indeed, the combination of high alkalinity, extremely low nutrients and largely karstic drainage result in this unusual and little-reported marl lake type, the most striking characteristics of which are the dominance of cyanobacteria and stoneworts and the marginal role of flowering plants.

This unusual vegetation is mirrored in the presence of an even more unusual aquatic beetle. *Ochthebius nilsonii* Hebauer was recently discovered in several marl lakes in the Burren as well as in Lough Carra in Mayo (O'Callaghan et al., 2009; Nelson et al., 2019); elsewhere it is recorded in single Swedish and Italian localities. Its habitat appears to be the cyanobacterial crust which itself is rarely reported in Europe outside Ireland.

Habitats Directive lake classification

Five of the natural lake habitat types of community interest listed in Annex I of the EU Habitats Directive (Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora) occur in Ireland (Table 10.1), and each is described by lake vegetation (CEC, 2013). Some types are easily recognised, such as marl lakes (3140) dominated by stoneworts (Cooloorta is an excellent example). Lake alkalinity helps to separate the types. Thus, marl lakes have alkalinity >100 mg/l $CaCO_3$. Soft-water lakes are more problematic and show more variation than is often appreciated. In our experience lakes containing Slender Naiad such as Ballynakill, have intermediate alkalinity between 20-80 mg/l, even though most contain Quillwort *Isoetes lacustris* L., often regarded as an indicator of a general soft-water lake type. The distinguishing feature is that most lakes with Slender Naiad also contain broad-leaved pondweed species, especially *Potamogeton perfoliatus* L. This possibly counter-intuitive species combination, along with high macrophyte species richness and a rare deep-water flora (which can, but does not have to, include Slender Naiad) is a characteristic of lakes which we include in the EU category 3130. The majority of soft-water lakes (3110 and 3160), however, have alkalinity <20mg/l and (with the exception of some lakes in Munster) contain neither broad-leaved pondweed species nor stoneworts other than *Chara virgata* and some *Nitella* spp. Most do contain *Isoetes* species often combined with Water Lobelia and, in western Ireland, Pipewort. There has been less research on the vegetation of these lakes

Figure 10.8
Dystrophic pools in blanket bog, Ox Mountains, Sligo. Photo: Áine OConnor

but those largely in rocky catchments have very clear water and consequently deep-water vegetation. Lough Adoolig is an example, as is Glenbeg Lough in Cork. Many soft-water lakes in peatland also have surprisingly clear water. Where the vascular plant flora is reduced in diversity and abundance, the lakes appear to belong to the 3160 dystrophic type. Recent work suggests that the conservation value of dystrophic lakes and pools in peatland (Figure 10.8) lies mainly in the algae, particularly the highly diverse desmids, and macroinvertebrates such as water beetles (Coleoptera) and dragonflies (Odonata) (Gray et al., 2022; Cappelli, 2023).

Recognising natural eutrophic lakes (type 3150) in Ireland is difficult as so many sites are eutrophic owing to human interference. Neither have targeted surveys for this lake type been undertaken to date. It can clearly be distinguished from the 3130 type owing to the absence of the oligotrophic isoetid zones, as well as many of the rarities of the deep-water zones, and from marl lakes by the lower abundance of stoneworts. A possible approach to furthering our knowledge of 3150 is to seek out lakes with rich pondweed floras or Frogbit *Hydrocharis morsus-ranae* L., which is not found in other lake types.

While not covered in this chapter, it is important to note that standing waters are a significant component of other Annex I habitats such as turloughs (3180) (see Chapter 7), machairs (21A0), dune slacks (2190), calcareous fens (7210 and 7230) and coastal lagoons (1150) (see Chapter 8), and these are vulnerable to the same pressures as lakes. Similarly, many of these habitats, as well as others such as blanket bog (7130), wet heath (4010), limestone pavement (8240), calcareous grassland (6210), juniper formations (5130) and alluvial woodland (91E0), surround Ireland's most important Annex I lakes.

DISTRIBUTION

The distribution of lake types in Ireland

The five broad categories are widely distributed in Ireland, an island with an exceptional number and variety of lakes. This variety reflects the geological history, especially the contrast between the Carboniferous central plain and the diverse coastal uplands of sandstone in the south, schists, marbles and quartzites in the north and west, and granite in the east. Drainage across each rock type produces different water chemistries and our wet climate promotes bog growth. In general, our marl lakes (3140) are found in areas of limestone, especially where glacial drift is thin, stretching from the Shannon estuary north to Mayo, but also across the midlands to Westmeath. Recently an excellent marl lake, Lough Nahinch, was noted in Tipperary.

Machair loughs are coastal lakes on sandy plains, separated from the sea by a sand barrier. Most are found along the coast between Dingle in Kerry and Donegal, and along the west coast of Scotland, especially in the Hebrides, but not elsewhere in Europe. They contain a wide variety of species and even EU habitat types, with elements of both marl (3140) and intermediate-alkalinity (3130) communities and even brackish water taxa. Roden (1999) described sites between Donegal and Galway recording over 50 species.

Perhaps the rarest lake type in Ireland is now the intermediate-alkalinity *Najas*-type lake (3130). There are many lakes with intermediate alkalinity, but the majority appear to be nutrient-enriched. Nineteenth-century plant lists from the largest lake in Ireland, Lough Neagh, include typical *Najas*-type lake species, and seeds of *Najas flexilis* itself were recorded from sediments just downstream of the lake. These species no longer occur, and the lake is now seriously polluted. A similar story probably applies to many smaller lowland lakes on shales, sandstone and some sites with a small proportion of limestone in the underlying basin, and the older perception that *Najas*-type lakes were confined to western areas of Donegal, Galway (Connemara) and Kerry may not be correct. We recently documented an excellent example of this intermediate-alkalinity lake type in south Clare (Knocka Lough) on Carboniferous shale and another example is known from lower Carboniferous sandstone south of Castlebar, Mayo (Lough Nageltia). *Najas*-type lakes are often found close to the coast on a variety of rock types, probably due to the addition of both sea spray and wind-blown shell sand. While not all intermediate-alkalinity lakes are found in Kerry, Galway (Connemara) and west Donegal, the converse also holds; only a small proportion of lakes in these areas are intermediate-alkalinity *Najas*-type lakes. Rock type appears to be important. Ballynakill Lough, Port Lough in Donegal, and other examples all lie in basins of Dalradian metamorphic limestone. Others such as Lough Caragh in Kerry are in mixed basins of sandstone with some limestone.

While the total area of lakes on limestone is large, the number of (small) lakes on more acidic rock is greater than the number found on limestone. Most will have alkalinity below 20 mg/l and conform to the 3110 or 3160 types (see Chapter 9). These soft-water lakes are concentrated along the west coast, especially in Galway (Connemara), Mayo, Kerry, and Donegal, with a smaller number in other upland areas such as Waterford and Wicklow. Several little-known peat lakes also occur amongst the raised bogs of the Central Plain.

Some small lakes on clay in the Shannon and Erne catchments may qualify as naturally eutrophic (3150), but in the absence of techniques to separate natural from artificially eutrophicated sites, it is difficult to be precise about the distribution of this habitat.

CONSERVATION STATUS

Every six years, Ireland assesses and reports on the conservation status of habitats and species protected under the Habitats Directive. Table 10.1 gives the conservation statuses of the five lake habitat types and the Slender Naiad in the two most recent reporting periods. Conservation status is assessed across the state, covering the habitats and species both inside protected areas (Special Areas of Conservation (SAC)) and in the wider countryside. The Habitats Directive provides explanatory text on when the conservation status of a habitat and species is favourable, which includes having a stable or increasing natural

Table 10.1 The Conservation Status of lake habitats and the lake species Slender Naiad in Ireland, 2007-2018. The five lake habitats are listed in Annex I of the Habitats Directive, and Slender Naiad is listed in Annexes II and IV. The Slender Naiad is also protected under the Irish Wildlife Acts, 1976-2023 (Flora (Protection) Order, 2022 (S.I. No. 235 of 2022). Under the Habitats Directive, Special Areas of Conservation (SAC) have been designated to protect lakes with these habitats and species (Article 3), conservation status is monitored (Article 11) and is reported to the EU (Article 17).

EU Code	EU name	Name used in text	Conservation Status 2007-2012	Conservation Status 2013-2018
3110	Oligotrophic waters containing very few minerals of sandy plains (*Littorelletalia uniflorae*)	Low-alkalinity lakes /soft-water/ peat lakes	Unfavourable Bad, deteriorating	Unfavourable Bad, stable
3130	Oligotrophic to mesotrophic standing waters with vegetation of the *Littorelletea uniflorae* and/or of the *Isoëto-Nanojuncetea*	Intermediate-alkalinity/ *Najas*[-type] lake	Unfavourable Inadequate (Poor), stable	Unfavourable Inadequate (Poor), deteriorating
3140	Hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp.	Marl lake	Unfavourable Bad, deteriorating	Unfavourable Bad, deteriorating
3150	Natural eutrophic lakes with *Magnopotamion* or *Hydrocharition*—type vegetation	Natural eutrophic lakes	Unfavourable Inadequate (Poor), stable	Unfavourable Inadequate (Poor), stable
3160	Natural dystrophic lakes and ponds	Dystrophic lakes/ low-alkalinity lakes/ peat lakes	Unfavourable Inadequate (Poor), deteriorating	Unfavourable Inadequate (Poor), stable
1833	Slender Naiad *Najas flexilis*		Unfavourable Inadequate (Poor), stable	Unfavourable Inadequate (Poor), deteriorating

range and area/population, and having self-sustaining, resilient ecosystem structure and functions. European guidelines (e.g. DG Environment 2023) set reporting standards based on four parameters (for habitats: Range, Area, Structure and Functions, Future Prospects; for species: Range, Population, Habitat for the species, Future Prospects), data for which are summarised into an overall conservation status (as presented in Table 10.1). Reports are published at national level (e.g. NPWS, 2013 and 2019a, b, c), biogeographic and EU levels (European Environment Agency, 2015, 2020; https://nature-art17.eionet.europa.eu/article17/). Irish reports are substantially based on data from dedicated survey of a sample of lakes, such as for *Najas*-type lakes (Roden et al., 2021a) and marl lakes (Roden et al., 2020a), however, as the assessment covers the full national resource, information must also be drawn from other sources (e.g. Water Framework Directive (WFD) monitoring, academic research). In mapping the distribution of each habitat, it is assumed that all lakes can have one or more of the Annex I habitats (see O Connor, 2015). As lakes are seldom destroyed and because it is highly challenging to accurately measure the area of lake vegetation, range and area have not proved useful indicators of change, so information on structure and functions is key to determining the national conservation status of lake habitats. As a result, work has focussed on developing indicators of the components of a habitat (structure) and the ecological processes that drive it (functions).

CONSERVATION CONDITION

How to measure ecological structure and function

As in most ecosystems, the ocean excepted, the greater part of the biomass of many lakes is in the plants or primary producers, consequently, community classification and conservation condition assessment are most easily done using these organisms. In deep-water lakes with small littoral zones, lake phytoplankton is often used for these purposes but in Ireland the majority of lakes are shallow. In shallow lakes, macrophytes often dominate large areas and play important roles in carbon sequestration, sediment formation, primary production, and habitat creation. In consequence, macrophytes have been the focus of study for clear-water lake types in Ireland. It should be remembered, however, that many other organisms are essential parts of the lake ecosystem and are deserving of further study.

In Ireland, underwater survey of lake plants by diving was pioneered by Hester Heuff and Jim Ryan, who used plant abundance and species composition to propose a number of different lake types (Heuff, 1984). More recently, a series of studies that used snorkelling and scuba methods to survey vegetation was funded for marl lakes (Roden and Murphy, 2013; Roden et al., 2020a, b) and intermediate-alkalinity lakes (Roden and Murphy, 2014; Roden et al., 2021a), while the PeAT lakes project trialled an underwater drone, in addition to snorkel-survey (https://peatlakes.wordpress.com/). For each lake type, there are high-quality examples as well as many others suffering differing degrees of human impact. For each type, a difficult problem is to gauge the acceptable degree of human disturbance and thus assess its conservation condition.

The basic assumption underlying nature conservation is that ecosystems subject to human pressure suffer the decline or extinction of specialised and often scarce species and their replacement by more generalised widely distributed or 'weedy' species. As previously noted, an underwater observer will immediately identify light penetration as a measure of good conservation condition. Light penetration can be quantified by the most simple of limnological tools, the Secchi disk. An alternative measure is the depth of plant colonisation or euphotic depth measured by a diver's depth gauge. Both methods yield an objective quantitative measure. The difference is that Secchi depth reflects conditions on the day of measurement, while the depth of colonisation integrates light availability over a season.

It may seem rather sweeping to claim that a single factor, water clarity, characterises our most valuable lakes but our field experience over the last 25 years supports this statement. The greater the euphotic depth, the larger the area available for plant colonisation, and the greater the number of depth-determined vegetation zones. In certain marl lakes, e.g. Cooloorta, Lough Rea (Galway), parts of Lough Carra and Lough Bane (Meath and Westmeath), euphotic depth greater than 9 m has been recorded, with a series of zones as already described for Cooloorta. Similarly, in some *Najas*-type lakes (Ballynakill, Port, Kiltooris (Donegal)), three zones can be recognised: an initial *Lobelia—Eriocaulon* zone to 1.5 m depth, an *Isoetes* zone from 1-3 m and an *Najas flexilis—Nitella confervacea* zone from 3-5 m, and in some lakes another layer of *Nitella translucens* (Pers.) C.Agardh occurs at depth.

In marl lakes a decline in euphotic depth not only reduces the number of vegetation zones but is accompanied by changes in species composition. Thus, at a euphotic zone of 10 m, only stonewort zones (normally *Chara virgata*, *Chara contraria* or *Chara dissoluta*) are recorded, but when the euphotic zone is only 5 m deep, the deepest vegetation usually consists of species of pondweed or the invasive *Elodea canadensis*. At even shallower euphotic depths, Ivy-leaved Duckweed *Lemna trisulca* L. is found. In intermediate-alkalinity lakes at euphotic depths of 4-5 m, a deep-water vegetation occurs, often characterised by abundant Slender Naiad and other rare species. When euphotic depth is shallower, this deep-water vegetation is either missing or fragmentary, with an *Isoetes* zone forming the deepest vegetation usually at less than 3 m. A shallowing euphotic depth consequently leads to the elimination of lake vegetation zones and a reduction in lake biodiversity, especially of species such as Slender Naiad, *Nitella confervacea* and *Chara dissoluta*, all scarce species of conservation concern.

For low-alkalinity, deep-water lakes, limited field experience indicates that again vertical vegetation zonation occurs, with a Shoreweed *Littorella uniflora* (L.) Asch.—Water Lobelia zone followed by an *Isoetes* zone and a deep-water zone with forms of *Potamogeton berchtoldii* Fieber. Certain rare species such as *Nitella gracilis* or Floating Water-plantain *Luronium natans* (L.) Raf. may be restricted to this lake type. Some commoner species are also characteristic such as the deep-water form of Bog Pondweed *Potamogeton polygonifolius* Pourr. and *Callitriche brutia* Petagna. In general, low-alkalinity lakes (3110 and 3160) appear species-poor compared to intermediate-alkalinity lakes (3130).

The conservation condition of lakes in blanket bogs was the subject of the recently completed PeAT Lakes project, where a more comprehensive approach was taken to defining typical biota through studies of algae and macroinvertebrates, as well as vegetation. It showed that dystrophic pools (3160) have Menyanthes trifoliata L. and Utricularia minor L. but lack isoetid species (Water Lobelia, Shoreweed, Pipewort) (Cappelli, 2023). A systematic collection of field data from additional sites would help to further define the characteristic biota of 3110 and 3160 lakes and establish typical euphotic depths, vegetation zones and commoner species.

For dystrophic habitats, difficult questions arise: is peat staining a consequence of disturbed catchments or a natural phenomenon; and what are the characteristics of dystrophic lakes in good conservation condition? Cappelli et al. (2023) showed that, in largely undisturbed bogs, dystrophic pools have water colour (median 28.8 mg/l Pt-Co) comparable to some of the best intermediate-alkalinity lakes (see Figure 10.9). Colour was higher in peat lakes in good conservation condition (median 43.2 mg/l Pt-Co), possibly as a result of larger catchments (Cappelli et al., 2023), but considerably less than values for damaged 3130 lakes (>100 mg/l Pt-Co) (Roden et al., 2021a).

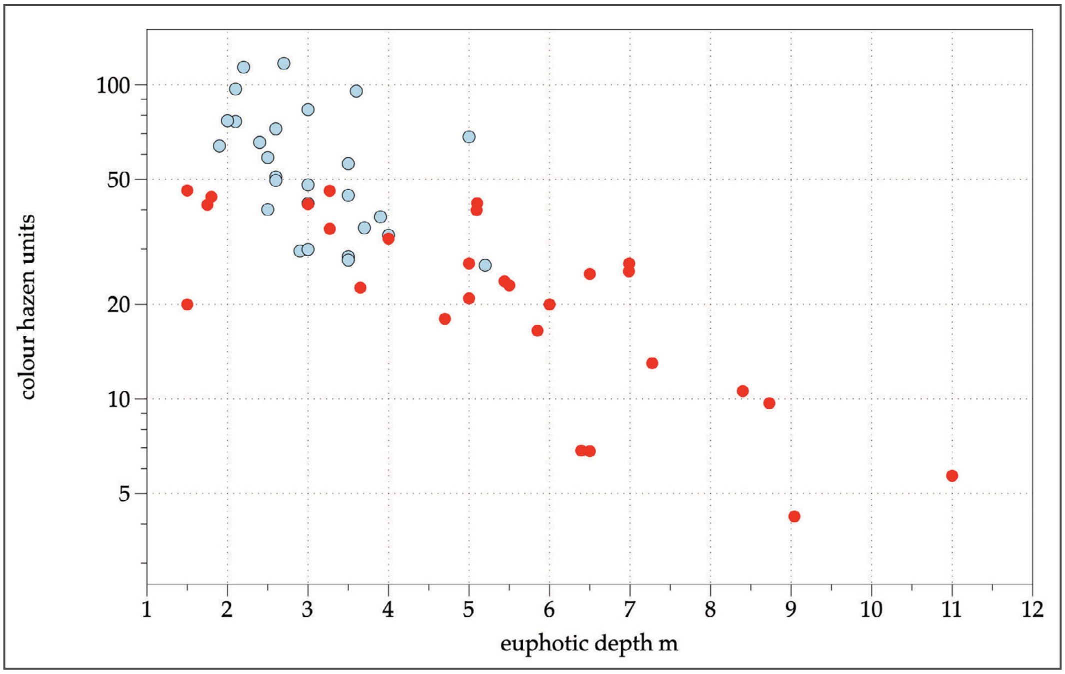


Figure 10.9 Both in marl (3140) and intermediate-alkalinity (3130) lakes euphotic depth declines with increasing water colour. Blue dots represent intermediate-alkalinity lakes and red dots marl lakes. Note the great transparency of marl lakes. Cappelli et al. (2023) report values for peat lakes (median 43) and dystrophic pools (median 28) that fall within the same range as types 3130 and 3140.

Gray et al. (2022) discuss the difficulty in arriving at a European-wide definition of dystrophy. Dystrophy may be more a function of catchment condition than a characteristic of the lake type or the individual water body. Both clear water and strongly coloured examples of 3110 lakes are known in Ireland, but insufficient work has been done to separate their biota and ecology. While many lakes are autotrophic, dystrophic lakes may, like some streams, be heterotrophic. The single-celled organisms that dominate dystrophic lakes and pools are typically mixotrophs feeding on the carbon in the brown water as well as photosynthesising, suggesting that these habitats are net consumers rather than producers of carbon. It may be of some interest that the most conspicuous plant species in these lakes are carnivorous Bladderworts (*Utricularia* spp.), indicating the importance of consumption over photosynthesis in this unusual habitat. The extent to which heavily peat-stained water is a natural occurrence remains to be resolved.

A suite of now-widespread, high nutrient-tolerant species (Yellow Water-lily, duckweeds) are possibly members of a natural eutrophic lake flora that has spread from a more restricted suite of naturally mineral-rich lakes and rivers as eutrophication increased, much as nettles and brambles have spread across the Irish countryside with increasing use of artificial fertilisers. A list of species possibly indicative of naturally eutrophic sites might include some pondweed species, Rigid Hornwort *Ceratophyllum demersum* L., Frogbit and Arrowhead *Sagittaria sagittifolia* L. As in dystrophic lakes, water clarity may not be a useful measure of conservation condition.

If euphotic depth is a measure of 'naturalness' in lakes in Ireland, the question arises did all impacted lakes of a certain type once have greater water clarity? Given that water clarity is determined in turn by inflowing nutrient concentrations and water colour, this is a question about catchment quality rather than lake quality. To what extent pre-human catchments exported either nutrients or organic matter is unknown but historical investigations do point towards a nutrient-scarce environment that would yield clear water and deep plant growth.

WHAT IS GOING WRONG?

Successive EPA reports, past surveys and the authors' own experience all confirm that Ireland is steadily losing many of its most distinctive and conservation-worthy lakes. As recently as 2013, Lough Leane in Kerry held a large population of Slender Naiad, and at one time was home to many other unusual species. By 2019, however, Slender Naiad had all but vanished: just five plants were noted in a single location; none has been seen since. A similar fate has overtaken plants such as Awlwort *Subularia aquatica* L., *Nitella confervacea*, *Chara aspera* Dethard. ex Willd., Pillwort, *Potamogeton praelongus* and Needle Spike-rush *Eleocharis acicularis* (L.) Roem. & Schult., all found in intermediate-alkalinity lakes in good conservation condition, such as Ballynakill. At the same time, the euphotic depth in Lough Leane has decreased to about 2 m and the introduced Fringed Water-lily *Nymphoides peltata* Kuntze and other invasive macrophytes are spreading rapidly. From being one of the best examples of an intermediate-alkalinity lake in Europe, Lough Leane is quickly approaching the state of Lough Neagh, dismissed by Moss (2015) as 'yet another heavily eutrophicated, shallow lake'.

Our great marl lakes such as Corrib and Mask also show signs of severe damage to marl crust and stonewort communities, loss of species such as

Arctic Char *Salvelinus alpinus* (Linnaeus, 1758) and the spread of introduced exotics ranging from Zebra Mussel to Curly Waterweed *Lagarosiphon major* (Ridl.) Moss ex V.A. Wager. The most spectacular marl lake in Ireland, if not western Europe, Lough Carra shows signs of significant degradation of deep-water communities and a dramatic reduction of euphotic depth in some of its basins, as well as a 75% reduction in brown trout populations since 2000. Even in areas with excellent macrophyte communities, mayfly populations have collapsed in recent years (Chris Huxley pers. comm.). Several marl lakes such as Lough Arrow (Sligo and Roscommon) with rich stonewort floras as recently as the 1980s now have few characteristic marl lake species, little or no cyanobacterial crust, and are now of little conservation interest. 'Fossilised' marl crust and remnant populations of characteristic species such as *Chara dissoluta* and *Chara tomentosa* L., strongly suggest that Lough Derg also supported marl lake communities in the past.

The fate of smaller lakes is seldom better. Of about 60 populations of Slender Naiad recorded since 1977, at least eight appear to be now extinct. For example, *Loch na gCaisleach* (Natawnymore) (Galway, Connemara) supported a large Slender Naiad population in 2005 but by 2020 the *Najas* community had been replaced by broad-leaved pondweed species, probably due to increased nutrient concentrations. Clearly, lake habitats in Ireland are quickly degrading and just as we lost our great forests in the seventeenth century and our equally wonderful raised bogs in the twentieth, we must expect to lose our extensive lake ecosystems in the twenty-first century, unless we rapidly reduce our impact on nature.

As we have explained above, we consider the most conservation-worthy lakes to be those with greater euphotic depths. Factors that reduce euphotic depth degrade such lakes. Plant communities at the greatest depth are most vulnerable to shading (and least well-known to the investigator); if water transparency is reduced, these communities are the first to disappear. The strong empirical evidence of reductions in euphotic depth or water clarity leading to lower biodiversity and ecosystem complexity supports shallow lake theory, which explains how increasing nutrient concentration and falling water clarity lead to the collapse of the lake benthos and the dominance of planktonic algae (Scheffer, 2004). It is clear, however, that nutrients are not the sole cause of declines in euphotic depth in Ireland.

We suggest that two factors are reducing transparency in lakes in Ireland; excess plant nutrients and strongly coloured inflowing water. The first factor is well known to promote planktonic algal growth, with the consequent blooms

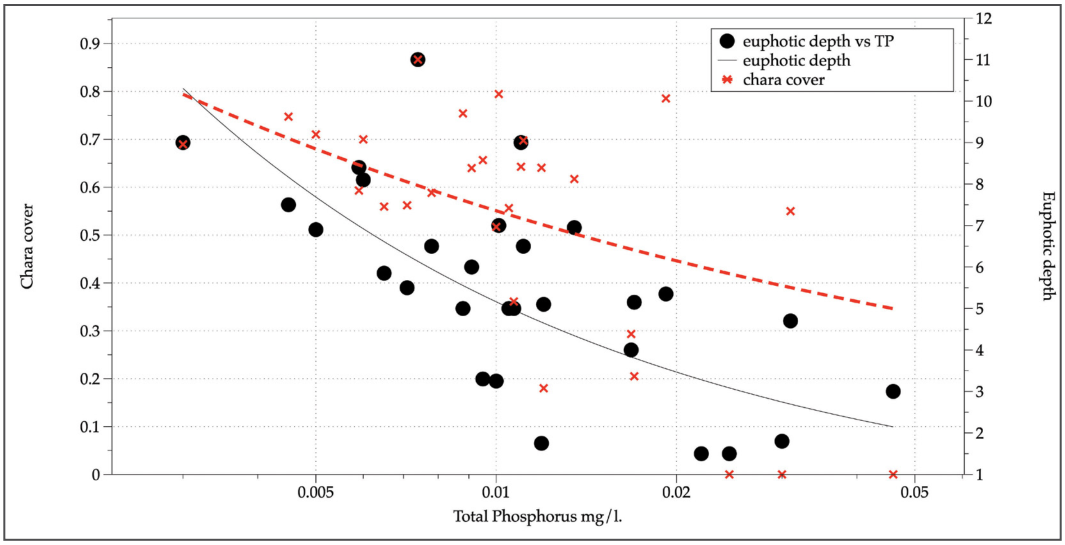


Figure 10.10 In marl lakes, as average total phosphorus increases, euphotic depth and charophyte cover declines. The data show euphotic depth (in black) and the proportion of total vegetation cover contributed by charophyte species (in red) as lake total phosphorus increases. See Roden et al. (2020a) for further details.

reducing light penetration and euphotic depth. An extreme example of this process is seen in the coastal lagoon (1150), Lady's Island Lake in Wexford where, since 2000, a formerly extensive vegetation of stoneworts and flowering plants (tasselweed *Ruppia* and pondweeds) has been replaced by bare anoxic mud and planktonic blooms of 100 µg/l chlorophyll or more. More generally, data from marl lakes (Figure 10.10) show that euphotic depth and charophyte cover rapidly decline with increasing total phosphorus concentration (Roden et al., 2020a). Work by Doddy et al. (2019a) showed that the cyanobacterial crust of marl lakes was only present in lakes with <0.02 mg/l Total Phosphorus (TP), and broke down when TP exceeded 0.010-0.015 mg/l.

Not only do additional nutrients favour plankton growth and thus reduce light penetration, but they also promote the growth of large angiosperms such as the broad-leaved pondweed species or *Elodea canadensis* at the expense of smaller often rarer species like stoneworts. Angiosperms are better able to exploit lower light levels owing to adaptations such as rapid spring growth and large, buoyant propagules (Blindow, 1992). Furthermore, stoneworts have an active role in maintaining water clarity in lakes (e.g. van Donk and van de Bund, 2002). Excess nutrients will also promote the growth of reed and bulrush which shade the benthic communities of shallow water and increase the rate of terrestrialisation of shallow lakes. Phosphorus concentration in marl sediment is also increased, possibly promoting microscopic algal growth. A notable feature in Lough Carra has been the gradual greening of formerly white marl sediment, which may affect benthic invertebrates.

Independently of plant nutrients, water colour, representing an influx of carbon from catchment sources and made up largely of dissolved humic material but probably also suspended matter, can reduce lake euphotic depth. For intermediate-alkalinity and marl lakes, there is an inverse relationship between water colour and euphotic depth (Figure 10.9). Highly coloured *Najas*-type lakes (Loughs Nahaltora, Mayo, or Bofin, Galway (Connemara)) have poorly developed or absent deep-water vegetation. In contrast, clearer water lakes such as Port Lough (and formerly Sessiagh, Donegal) have deep euphotic zones and a diverse flora. Similarly, with marl lakes the best examples have low colour. The most likely source of coloured water is damaged bog land. While there is a long history of exploitation of Ireland's bogs, large-scale damage to western and upland peatlands commenced in the 1940s with the coniferous afforestation programme. There followed, from the 1980s, over-grazing caused by the increasing sheep herd and mechanisation of turf cutting, and clear-felling and reforestation with conifers from the 1990s. More recently, intensification of agricultural use on western and upland bogs has included large-scale soil movements and fertilisation with chemicals and slurry. These land uses typically involve drainage and destruction of the characteristic bog vegetation, and result in the decomposition of peat. Lakes such as Loughs Cutra and Graney in the heavily afforested Slieve Aughty Hills of South Galway and East Clare have surprisingly dark water and extremely impoverished vegetation. Several marl lakes (e.g. Loughs Urlaur and Errit, Roscommon), with a substantial proportion of damaged peatland in their catchments, despite low phosphorus values, have shallow euphotic zones and highly coloured water. In contrast to marl lakes, in intermediate-alkalinity lakes water colour, appears more important than lake total phosphorus in determining conservation condition (Roden et al., 2021a).

Taken together, phosphorus and colour pose a major threat to our best lakes, but other factors are also of note: excess abstraction, channelisation and land drainage can lower lake levels and have a major impact on lake ecology. While much arterial drainage occurred in the past, as recently as 2017, the lake level was lowered, and water transparency and euphotic depth were reduced, at the valuable Kiltooris Lough. In 2005 the level of Lough Bane was lowered through excess water abstraction, the shoreline and shallow sublittoral communities were destroyed but have regrown since.

The spread of introduced species is also an increasing problem in lakes already subject to disturbances such as nutrient enrichment. *Lagarosiphon major* has spread both in Lough Corrib and Lough Inchiquin (Kerry). Two likely-introduced stoneworts *Nitellopsis obtusa* (Desv.) J. Groves and a variety of *Nitella mucronata* Miq. are established in Lough Derg and Lough Ree, while *Nitellopsis obtusa* has recently also been found in the Corrib system. Even *Elodea canadensis*, although long established in Ireland, recently spread to Sessiagh Lough in north Donegal and, as a consequence, a large population of Slender Naiad, present in the Lough until about 2012, has disappeared.

Targets for nature

The methods developed to assess the conservation condition of a marl lake (Roden et al., 2020b) and an intermediate-alkalinity lake (Roden et al, 2021a) defined specific boundaries to separate favourable from unfavourable condition. Other than a target for the area to be stable or increasing, all attributes are indicators of habitat structure and functions. Depth of colonisation and vegetation zonation are the most important measures of structure. Marl lakes, having the deepest euphotic zone, have targets for favourable of at least 7 m with a minimum of three stonewort zones, plus a shallow-water cyanobacterial crust zone (Roden et al., 2020a, b). Intermediate-alkalinity lakes have targets of at least 3 m euphotic depth and full development of the characteristic deep-water vegetation zone (Roden et al., 2021a). Euphotic depth is also a key measure of how the ecosystem is functioning as it indicates the light environment over time. Other functional indicators used in assessing conservation condition include species richness, typical species composition, water colour, total phosphorus, and chlorophyll concentration of crust (Roden et al., 2020b, 2021a).

These indicators are also used in the site-specific conservation objectives for lake habitats and Slender Naiad. A conservation objective defines favourable conservation conditions for a habitat or species at SAC level. SACs can be extensive with one or more lake habitats distributed across many lakes (see, for example, NPWS, 2015, 2021; O Connor, 2015). Where a habitat or species is in favourable condition in an SAC, the conservation objective is to 'maintain' that condition. Where the condition is unfavourable, the objective is to 'restore' and, where possible, the specific structural and functional attributes that need to be restored are identified. In addition to the indicators used to assess conservation condition, a wider list of targets is set in conservation objectives for attributes that are not routinely monitored or not well understood, such as lake substratum quality, water level fluctuations and dissolved organic carbon. This is to ensure ecological assessments and conservation planning consider all potential influences and impacts on the habitat or species. Notes are provided to help with interpreting the objectives; for example, land drainage or channelisation upstream of a lake can increase sediment load and cause changes to water clarity or lake substratum and may also change water level fluctuations. Key to assessing potential impacts from land use or other developments is an acceptance that freshwater habitats and species are invariably subject to multiple interacting stressors, and that it is essential to understand the complex ecological interactions and mechanisms by which lake structure and functions can be changed.

For most targets, a standard approach is used across all sites, for example, the total phosphorus target for marl and *Najas*-type lakes is ≤0.01mg/l TP. However, the objectives also acknowledge the natural variation in habitat types across their range, and that the targets may be too stringent (for example, total phosphorus may naturally be higher in coastal variants of marl lakes that receive rain and wind-blown maritime nutrients and minerals) or not stringent enough (for example, for highly oligotrophic marl lakes in the Burren).

WFD monitoring delivers important data, such as total phosphorus and water colour, used in assessing the conservation condition of lake habitats. However, it must be understood that WFD chemical standards (known as 'Environmental Quality Standards' or EQS) differ from conservation targets. For example, the conservation targets for total phosphorus, for all lake habitats, are more stringent than the EQS (<0.025 mg/l) for good status and, for low-alkalinity, intermediate-alkalinity and marl lakes, match the high status target of <0.01 mg/l. WFD targets have yet to be established for water colour, while conservation targets for marl lakes and intermediate-alkalinity lakes are <15 and <40 Hazen units (= mg/l Pt-Co), respectively, and for the most sensitive examples may need to be below 5 Hazen units. Furthermore, the ecological status of a lake, as assessed under WFD, cannot be used to indicate the lake habitat's conservation condition. To illustrate, WFD ecological status assessments (2013-18) were available for 16 of the 32 *Najas*-type lakes assessed between 2016 and 2018 by Roden et al. (2021a). Nine lakes in unfavourable conservation condition were in good or high ecological status, six of which had good macrophyte status and three high macrophyte status. It is concerning that for over half of the lakes sampled, where conservation monitoring showed a significant decline in the habitat's structure and functions owing to water quality or quantity pressures, WFD status was satisfactory and did not flag the need for measures under the River Basin Management Plan. The discrepancy is even more surprising given that the WFD uses a one-out, all-out approach, in contrast to the conservation condition assessment methods where habitats and species cannot fail on chemical parameters alone but must also demonstrate biological decline.

HOW DO WE PROTECT AND RESTORE THE NATURE OF LAKES IN IRELAND?

If our best lakes are not to follow our woodlands and raised bogs into obscurity, then radical changes are required to our catchment land uses. These lakes cannot be saved through tinkering, or voluntary, short-term incentive schemes. There must be true integration of environmental policy, involving an acceptance that we cannot do everything everywhere and that some places are more precious than others. It will also be necessary to acknowledge when and where current land use is not compatible with environmental objectives. All environmental objectives must be given due consideration: nature, air and water quality, and climate adaptation and mitigation. Prioritising the lakes to protect and restore for nature must take account of all their biodiversity values, from vegetation communities to rare and threatened invertebrates, to water birds and fish, and ecosystem functions in the lake and its catchment (Mainstone and Rehklau, 2022).

Research will be necessary to better understand how these lakes work, how their ecosystems function. Recent study of cyanobacterial crusts in marl lakes beautifully illustrates how much more we have yet to learn. Doddy et al. (2019) showed that what, to most observers, is slime on rocks is in fact an entire, largely self-sufficient ecosystem of tiny plants, animals and other organisms nestled within the wider marl lake ecosystem. A continuous study programme is needed to build on current knowledge and advise on how to protect and restore our best lakes. Allowing that this chapter is very plant-centred, we espouse the need for the study of the microbes that break-down organic matter and the invertebrate assemblages in lakes; as well as how these and primary producers contribute to food webs up to and including fish, birds, and mammals. We also need to continue searching for conservation-worthy lakes, in particular eutrophic and rocky oligotrophic lakes (Figure 10.11).

People may be uneasy about the degree of change necessary to save our most distinctive and conservation-worthy lakes, but already possible solutions

Figure 10.11
Upper Lough Bray, an upland, rocky oligotrophic lake in Wicklow.

are being explored. For example, the community-based group Lough Carra Catchment Association, along with Mayo County Council, NPWS and the Geological Survey of Ireland secured an EU LIFE grant of five million euro to reverse the gradual eutrophication of Lough Carra. The results of this project will become apparent in the next five years. The findings will likely show that large changes in land management are required to save the lake. If, however, we hesitate to make such radical changes, the future is bleak. As Pentecost (2009) has already predicted for the marl lakes of Britain and Ireland, we will lose our best lakes and their associated characteristic species and communities even before some are documented, unless we act.

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Chapter 11

STATE OF LAKES
LAKE HEALTH

Deirdre Tierney

SUMMARY

The Water Framework Directive (WFD) was transposed into Irish legislation in 2003. The basic objective was for all waters to attain good status by 2015 and by 2027 at the latest. The WFD necessitated the implementation of a routine national lake monitoring programme which has driven advancements in the development of biological assessment classification tools. However, WFD assessment provides little indication that Ireland's lakes will achieve good ecological status by the latest deadline. The number of monitored lakes in good or better status, currently at 47.8% (2016-2021), is not increasing. Ireland has a long history of water related legislation from at least 1876. However, the last 50 years of lake monitoring and assessment show little significant change in national lake health. A small number of lakes had management plans implemented in the 1970s, 1980s and 1990s but few of these achieve good ecological status today. Input of nutrients from multiple sources causing enrichment of waters particularly from agriculture, remains the greatest challenge facing lakes in Ireland. This will be exacerbated by climate change and is already moderated by continued invasions of alien species. A renewed focus on lakes for the River Basin Management Plan 3rd Cycle (2022-2027) and the emergence of new lake-focused projects, potentially heralds a new phase of improved lake health on the horizon.

Keywords monitoring, assessment, legislation, ecological status, WFD

INTRODUCTION

The EU WFD was transposed into Irish legislation in 2003. It frames water resource management in Ireland. All lakes over 50 hectares (0.5 km^2) and smaller lakes on the protected areas register must be characterised, assigned status, and reported on every six years in a River Basin Management Plan (RBMP). It requires a programme of measures (PoMs) with each RBMP including ‘basic measures’ drawn from 11 existing directives, to maintain or restore water quality and ecological status. This chapter outlines the impact of the WFD on lake monitoring and assessment, the role of legislation, and the quality of lakes set against a pre-WFD historic backdrop.

LAKE MONITORING - A HISTORY

Monitoring is crucial and underpins every aspect of the WFD. It is one of the important cornerstones of the WFD. Monitoring provides the evidence for status assessment, risk assessment, trends in key parameters, measuring progress in the PoMs, and setting objectives.

Where it all began – early lake monitoring 1970s-1980s

In 1971, the Inland Fisheries Trust (IFT) started the first monitoring programme of the important lake fisheries; Lough Ennell and Lough Sheelin (WPAC, 1983). IFT expanded their surveys through the 1970s and 1980s and as the Central Fisheries Board from 1980 to 2005 when the Inland Fisheries Ireland (IFI) was formed (see Chapter 6).

In 1973/1974, the first nationwide survey of lakes in Ireland was undertaken by An Foras Forbatha (AFF) (Flanagan and Toner, 1975), prompted by the concern for important trout fisheries under threat from enrichment (WPAC, 1983). The survey campaign covered 53 lakes plus Ross Bay as part of Lough Leane, Lough Corrib Upper and Lower constituting Lough Corrib and Lough Oughter surveyed as North and South. Between 1976 and 1982, AFF surveyed the larger lakes of Ramor, Gowna, Derg, Muckno, Conn, Cullin, Ennell and Ree, including lakes from the earlier survey where trophic status was uncertain, and important lakes not being surveyed by IFT; Loughs Key, Lickeen and Owel. The purpose was to establish baseline surveys of lake quality and determine phosphorus loads.

Acid Lake Monitoring

In 1984/1985, lakes in acid sensitive areas; Loughs Maumwee, Nahasleam, Bray Lower and Upper Glendalough, were surveyed in detail (Toner et al., 1986). The initial purpose was to establish a baseline of acidification arising from acid deposition. Between 1987 and 1989, Loughs Veagh, Maumwee, Doo and Naminna were monitored to determine the effects, if any, of the Moneypoint coal burning power station that opened in 1985 (Clabby et al., 1992). The programme was then expanded to cover the effects of forestry in poorly buffered acid sensitive waters. Occasionally additional lakes were surveyed e.g., in 2000, 98 additional lakes were monitored (McGarrigle et al., 2002).

Barriers to National Lake Monitoring Programme

A national lake monitoring programme is logistically challenging to implement, and resources are always limited. 'Manpower restrictions made it impossible to sample these [lakes] on more than two occasions' (Flanagan and Toner, 1975). It was subsequently noted that 'In view of the difficulties involved in sampling, a large scale programme of water quality monitoring in lakes does not seem feasible and would be hard to justify where resources are limited' (WPAC, 1983). Irvine et al. (2002) identified historical limitations of resources and varied application of legislation as hindering the development of a monitoring system.

Remote Sensing

To overcome these obstacles, remote sensing of lakes was explored. Remote sensing was first carried out in 1979 as a collaborative initiative between AFF and University College Dublin using satellite imagery (Landsat). Its purpose was to quantify chlorophyll concentrations in lakes from light reflection. Further work demonstrated the feasibility of using satellite imagery from 1981 for 144 lakes (Toner et al., 1986, McGarrigle and Reardon, 1986). In 1989 and 1990, an alternative method was deployed, an aircraft borne spectrometer. A survey of 360 lakes was undertaken using the airborne spectral scanner and video footage and visual data were collected (Clabby et al., 1992). The last survey using the airborne spectral scanner took place in 2000 (McGarrigle et al., 2002). Remote sensing still has potential as a survey and assessment method, but a nationally applicable method has yet to be developed for lakes in Ireland (see Highlight Box on Remote Sensing at end of this chapter).

Preparing for the WFD

In 2001, to comply with the 1992 EPA Act, a discussion document proposed a national lake monitoring programme of 862 lakes drawn from large lakes (> 0.5 km^2) with the WFD in mind, including branded fisheries, trout fisheries, acid-sensitive lakes, enriched lakes, and lakes with drinking water abstractions (Bowman and Toner, 2001).

WFD Monitoring – what it is today

The WFD requires the implementation of a national lake monitoring programme. It has been in operation since 2007 (EPA, 2006). The programme represents a significant increase in terms of coverage, frequency of sampling, biological elements sampled, and chemical parameters analysed compared to previous programmes (Bowman, 2009). There are 224 lakes on the current programme (2022-2027) with surveillance monitoring (SM) and operational monitoring (OM). There are also subnets representing types of significant pressures, drinking water abstraction lakes categorised by the number of people served, and lakes sensitive to acidification. The quality elements assessed and the monitoring frequencies for lakes are set out in the WFD according to network and subnet membership. Lakes on the SM network are monitored where possible for all the biological elements; macrophytes (plants), phytobenthos (diatoms), phytoplankton (algae), invertebrates (insects) and fish. Lakes on the OM network are monitored for macrophytes where feasible and phytoplankton (chlorophyll). Physical and chemical parameters used to determine nutrient, oxygenation, thermal and acidification conditions are also monitored. Additional physical and chemical parameters are measured for lakes on the acid lake subnet. Specific pollutants and hazardous substances are measured for surveillance lakes. The EPA collect and assesses the biological samples, with the exception of fish which IFI sample and assess. Local Authorities collect water samples that are analysed and assessed by the EPA.

Other Lake Monitoring

Other agencies and organisations undertake monitoring of lakes for different purposes:

- IFI has several lake monitoring programmes, see Chapter 6.
- National Parks and Wildlife contract surveying of lakes to assess conservation status and for Article 17 reporting of the Habitats Directive, see Chapter 10.
- Local Authorities monitor Bathing Waters and undertake projects to improve lake quality.
- Marine Institute monitor Lough Feeagh.
- Local Authority Waters Programme (LAWPRO) undertake some lake sampling in Priority Areas for Action (PAAs) and Areas for Action (AFAs).
- Research projects also play a role in providing lake water quality data.

LAKE ASSESSMENT TOOLS

Trophic Status

The first national survey of lakes (Flanagan and Toner, 1975) assessed impairment of water quality due to enrichment in terms of trophic status as either productive (eutrophic) or unproductive (oligotrophic). These assessments were based on values of chlorophyll, phosphorus, secchi depth, phytoplankton composition and observations, they were in effect qualitative assessments.

Modified OECD Scheme

By 1982, the first quantitative assessment method for lake quality, the OECD scheme, was published (OECD, 1982). The OECD assessment is based on annual average concentrations of chlorophyll, phosphorus and ecchi depth. To overcome the lack of data due to the absence of a national monitoring programme, Ireland modified the OECD scheme (Table 1). Maximum values for chlorophyll were used and the eutrophic category band widths were changed.

Table 11.1 Modified Irish version of the OECD scheme based on values of annual maximum chlorophyll concentration. Indicators related to water quality and the probability of pollution are also shown.

Irish Classification Scheme				**Category Description**		
Lake Trophic Category		Annual Max. Chlorophyll mg/m^3	Algal Growth	Deoxygenation in Hypolimnion	Level of Pollution	Impairment of Use of Lake
Oligotrophic		<8	Low	Low	Very low	Probably none
Mesotrophic		8<25	Moderate	Moderate	Low	Very little
Eutrophic	Moderately	25<35	Substantial	May be high	Significant	May be appreciable
	Strongly	35<55	High	High	Strong	Appreciable
	Highly	55<75	High	Probably total	High	High
Hypertrophic		≥75	Very High	Probably total	Very high	Very high

Assessment Tools for Acidification

Acid rain was an issue in the 1970s and 1980s. In the 1986 Water Quality in Ireland (Toner et al., 1986), acidification impacts were assessed by describing biological communities and physical chemical characterisation. An Acidification Score Index was proposed by the Norwegian Institute for Water Research (NIVA) and was applied until the 2007-2009 Water Quality in Ireland report. A WFD-compliant acidification tool was developed and adopted to assess acid sensitive lakes in 2021 (Little et al., 2020).

Water Framework Directive Compliant National Assessment Classification Tools

The WFD required member states to develop national tools for the most prevalent pressures for each of the biological quality elements (BQEs). For each of the tools, five classes and reference conditions had to be established and at a minimum, the high/good and good/moderate boundaries were established in line with the definitions of class as set out in Annex V of the WFD. The deviation from reference must be measured as ecological quality ratios on a scale of 0 (worst/bad status) to 1 (reference/high status).

To ensure reference conditions and boundaries were comparable for each pressure related BQE classification tool, member states participated in an intercalibration exercise organised into geographical intercalibration groups. There have been three phases of intercalibration, 2003-2008, 2009 -2012, and 2013-2017, with outcomes published in three decisions (E.C., 2008, 2013, 2018). Another intercalibration decision was due in 2023. To date, intercalibration has covered biological classification tools responding to eutrophication for all biological elements and invertebrates responding to acidification.

The WFD drove advancements in quantitative lake ecological assessments in Ireland which, previously had no or limited data for most biological elements. The sampling methods, tools, and expertise were developed over a series of research projects (McCarthy, 2001: Irvine et al., 2001 Free et al., 2007) and subsequently modified and adapted through the intercalibration process.

Macrophytes

The WFD imposed a methodical and standardised approach to the sampling and assessment of macrophytes which was lacking (Irvine et al., 2002). Irvine et al. (2001) found macrophyte communities did distinguish between lakes but found no strong relationships with water quality variables. This was likely due to the limited sampling in lakes and the small number of lakes sampled, therefore, more data was needed. Free et al. (2007) sampled over 200 lakes and a lake typology based on macrophytes was developed along with a multimetric index responding to enrichment. This index: the Free Macrophyte Index, was successfully intercalibrated in the first phase of Intercalibration (EC, 2008; Hellsten et al., 2014) and incorporated into statutory regulations as Statutory Instrument (SI) 272 of 2009 and its amendment (DHPLG, 2019).

Phytobenthos

Phytobenthos were not covered in any of the WFD-related research projects except as epilithic algae measured as chlorophyll in Free et al. (2007). This was a considerable gap that was replicated across EU member states. Consequently, no phytobenthos tool was in place for the first phase of intercalibration (EC, 2008). By phase 2 of intercalibration, sufficient samples had been collected and identified through the Irish WFD monitoring programme that it was possible to adapt and successfully intercalibrate the index developed for UK lakes for the Irish situation; the Lake Trophic Diatom Index (IE) (EC, 2013; Kelly et al., 2014; Kennedy and Buckley, 2021).

Phytoplankton

Irvine et al. (2002) noted the capacity for the identification of phytoplankton was limited in Ireland and the development of expertise was necessary. The fallback suggested was to use indicator groups. A phytoplankton index, incorporating a metric for nine taxa that increase with nutrient enrichment, was developed along with a metric for chlorophyll (Free et al., 2007). Chlorophyll was successfully intercalibrated in the first phase of intercalibration (EC, 2008) and the full Index, the IE Lake Phytoplankton Index (IPI) was intercalibrated in the second phase (EC, 2013). The IPI is used to assess and classify lakes on the SM network. Chlorophyll is used as a separate metric to assess and classify lakes on the OM network according to the 2008 Intercalibration Decision (EC, 2008) with standards set out in SI No. 77 of 2019 (DHLGH, 2019).

Invertebrates

Irvine et al. (2002) noted there was a long history of using profundal invertebrates in ecological assessments of lakes but few studies used littoral invertebrates. Irvine et al. (2001) found relationships between profundal invertebrates and lake trophic status but densities across lakes with the same trophic status were too variable to develop a classification scheme applicable at national level. The potential for a profundal invertebrate tool was again explored by Free et al. (2007) using variations of several existing profundal tools and components thereof. The results supported the development of a lake typology based on biological elements but did not yield a nationally applicable tool or typology-based tool. Development was hampered by a lack of a eutrophication gradient in low alkalinity lakes, depth and phosphorus interactions, stratification, and profundal components providing conflicting results.

Irvine et al. (2001) considered that a new littoral invertebrate methodology was required for lakes and not the application of existing river tools. Lakes and their invertebrate communities are different from rivers which had many well-developed tools available. Irvine et al. (2002) was one of the first studies ever to attempt to develop a lake classification tool based on invertebrates and while relationships were found, more work was considered necessary. Several river-based invertebrate tools were tested by Free et al. (2007), which proved promising, but again were hampered by the lack of a gradient in low alkalinity lakes and the lack of reference lakes for moderate alkalinity lakes. In 2020, the Lake Acidification Macroinvertebrate Metric (LAMM) developed for UK lakes, was adapted for lakes in Ireland and successfully intercalibrated (Little et al*.,* 2020).

Fish

IFI, the national competent authority for the management and conservation of fish, was tasked with the delivery of a fish-based WFD-compliant classification tool. There was a monumental gap to address because, although extensive surveying of fish had been done, quantitative and reference-based information of the type needed for WFD assessment did not exist (Champ et al., 2009). Intense research and development was undertaken resulting in the Fish in Lakes tool, but it required further work to be WFD compliant resulting in the Fish in Lakes 2 (FIL2) (Kelly et al., 2012). The FILS2 multimetric tool was successfully intercalibrated (EC 2013: Olin et al., 2014).

Hydromorphology

Hydromorphological condition is assessed using the Morphological Impact Assessment System developed under a research project (Rowan, 2008). There is no requirement for intercalibration of national hydromorphological condition tools, and it is the most challenging of all the elements to address.

However, like other member states, there is no biological tool developed for Ireland that responds to hydromorphological-related pressures, for example, water level fluctuations due to abstraction.

General Physical Chemical Parameters and Other Chemicals

General physical and chemical parameters are assessed in all lakes, and specific pollutants and hazardous substances are analysed for surveillance lakes using environmental quality standards (EQS) set at community level for example under Directive 76/464/EEC or at national level legislation under SI 77 of 2019. There is no requirement to intercalibrate the EQS for physical-chemical parameters set by individual member states.

Other Assessments of Lake Health

Other assessments of lake health are undertaken for a variety of directives. There are designated bathing water areas in six lakes under the Bathing Water Directive: Ballyallia Lough, Lough Rea, Keeldra Lough, Loughs Ennell (Lilliput), Owel (Portshanagh) and Lene (The Cut). The assessment focuses on levels of bacteria but operationally, the potential for short-term pollution events and algal blooms must also be considered. All lakes with designated bathing waters have been assessed as excellent for the years 2019-2022 except Lough Ennell which has improved to good having previously been assessed as poor. Bathing waters can be frequently closed where the probability of contaminants is high after heavy rainfall, or when an algal bloom (of cyanobacteria) is evident that may be potentially toxic, both posing a threat to human health.

There are 11 lakes designated under the Urban Waste Water Directive as nutrient sensitive: Loughs Naglack, Monalty, Muckno, Oughter, Leane, Ree, Ennell, Derg, Ross Bay, Cullin Lake, and Leixlip Reservoir. All these lakes receive an urban waste water discharge. All were assessed as sensitive for the most recent 2020 assessment. Under the Habitats Directive, lakes with protected habitats or water-dependent protected species, are assessed for their conservation status and trend.

LEGISLATION

Legislation plays a significant role in lake water quality and health. It requires monitoring, the setting of standards, and setting out actions for water protection and/or remediation.

Irish environmental legislation pre-EU

Environmental legislation existed predating membership of the EU. Toner and O'Sullivan (1977) noted that there were at least 18 Acts in place dealing with various aspects of water pollution control and prevention. Key Acts included:

- River Pollution Prevention Acts of 1876 and 1893.
- Inland Fisheries (Consolidation) Act 1959 highlighting Sections 171 and 172.
- Local Government (Water Pollution) Acts 1977 and 1990
- The Fisheries 1959 Act is still enacted up to and including the Inland Fisheries (Amendment) Act 2017 (16/2017).

Membership of the EU

Membership of the European Economic Community in 1973 (subsequently the European Union) brought in an era of environmentally related legislation over the past 50 years including several directives that require lake monitoring and protection to meet the standards necessary for their specified uses or for protection. Directives such as the WFD are transposed into Irish legislation as SI's giving effect to the directive as a regulation. EU Directives are not static but are amended, repealed, or recast i.e., new versions are drawn up. No Directive, Regulation or Act works in isolation but is integrated into other relevant pieces of legislation and policy. This is particularly true of the WFD. However, Ireland has been found wanting and there are several infringement cases brought by the Commission, including failing to correctly transpose the WFD.

Irish Environmental legislation pre WFD

There were key pieces of Irish legislation before the WFD. The Local Government (Water Pollution) Acts 1977 and 1990 set out a system of effluent licensing. The success of this Act hinged on the production of catchment-based water quality management plans (WPAC, 1983). Fifteen plans were adopted between 1984 and 1997 with a focus primarily on the control of point source pollution from domestic and industrial discharges, five plans had commenced, and a further five plans were in draft by 1999 (Fanning et al., 1999).

The Act had many shortcomings, local authority managed wastewater treatment plants were exempt, it did not prescribe for the content and structure of the management plans and agricultural waste was not included under the licensing regime (WPAC, 1983).

The 1992 EPA Act established the Environmental Protection Agency and required the preparation and publication of national monitoring programmes (Bowman and Toner, 2001) and research programmes. The EPA was assigned responsibility for the regulation of larger facilities including animal husbandry, urban waste water treatment plants (WWTP), industrial units, and any activity with a large pollution potential.

The 1998 Phosphorus Regulations (P regs) (DELG, 1998) required that water quality be maintained or improved based on the 1995-1997 assessment of trophic status for lakes or the first assessment if it occurred later (Cleneghan et al., 2005). If water quality was unsatisfactory, i.e., eutrophic, or hypertrophic for lakes, it must be improved within 10 years of the baseline assessment. The P regs were unique in Europe and echoed the forthcoming WFD, with the emphasis on ecological assessment to set objectives (Cleneghan et al., 2005). The responsibility for implementing the P Regs was with the Local Authorities who were tasked with identifying and implementing measures to improve or maintain water quality and develop plans.

Irish Environmental legislation post-WFD

Ten European directives are listed for inclusion in the PoMs in the WFD as basic measures because they are applied nationally. Two are potentially key to bringing about improvements in lake water quality:

- The Urban Waste-water Treatment Directive (91/271/EEC).
- The Nitrates Directive (91/676/EEC).

The Urban Waste Water Treatment Directive was transposed into Irish legislation in 2001 (SI No. 254/2001 - Urban Waste Water Treatment Regulations). The purpose of the directive is to prevent pollution of water from urban and industrial waste water discharges by setting standards for infrastructure, treatment of effluent, and the discharged water, undertaking monitoring, and managing waste sludge. The regulations require the identification of nutrient-sensitive waters which include Lough Derg and Lough Ree on the River Shannon, Lough Leane, Kerry and Lough Oughter, Cavan.

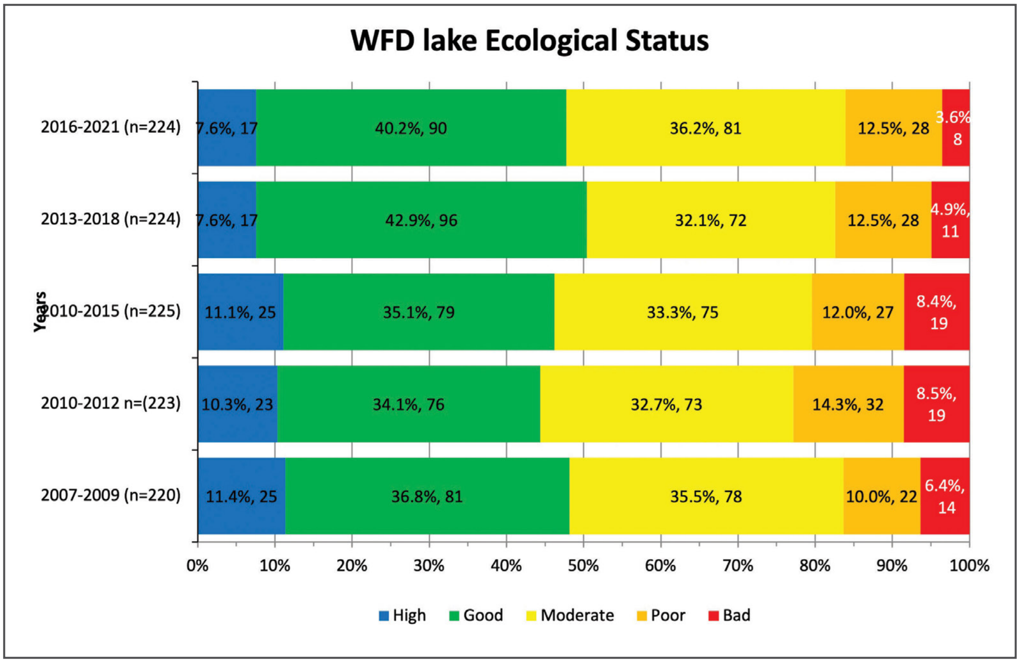
The Nitrates Directive was transposed into Irish legislation in 2005 (SI No. 788/2005 - European Communities (Good Agricultural Practice for Protection of Waters). The primary aim of the directive is to prevent water pollution from agricultural sources primarily from nitrates but also phosphates. The prevention mechanism is the promotion of good agricultural practices through the implementation of a nitrates action programme which sets out the obligations on farmers. The nitrates action programme sets out animal stocking rates, timing and application rates of nitrates, phosphates, organic and chemical fertilisers, storage for animal manures, and many more actions (DHLGH, 2022). The nitrates action programme is a legal obligation on all member states.

LAKE QUALITY

Current WFD National Picture

There has been little change in lake quality at a national level since monitoring and assessment started for the WFD in 2007 (Figure 11.1). The percentage of lakes in high or good status has hovered around the 50% mark. The percentage change in lakes in high or good condition has ranged from a loss of 5% (Tierney et al., 2015) to a gain of 4.3% (O'Boyle et al., 2019) over the five three-year Water Quality in Ireland Reports published since 2007 (EPA, 2022; O'Boyle et al., 2019; EPA, 2017; Tierney et al., 2015; Tierney et al., 2010). At a national level, the number of monitored lakes in satisfactory condition (good or better status) is not increasing with each RBMP. There seems to be a decline in the number of lakes of high status. There also seems to be a decline in the number of lakes in bad status. The number of lakes concerned is low in both instances.

Figure 11.1
Change in WFD Lake Ecological Status of monitored lakes in each assessment period since 2007.



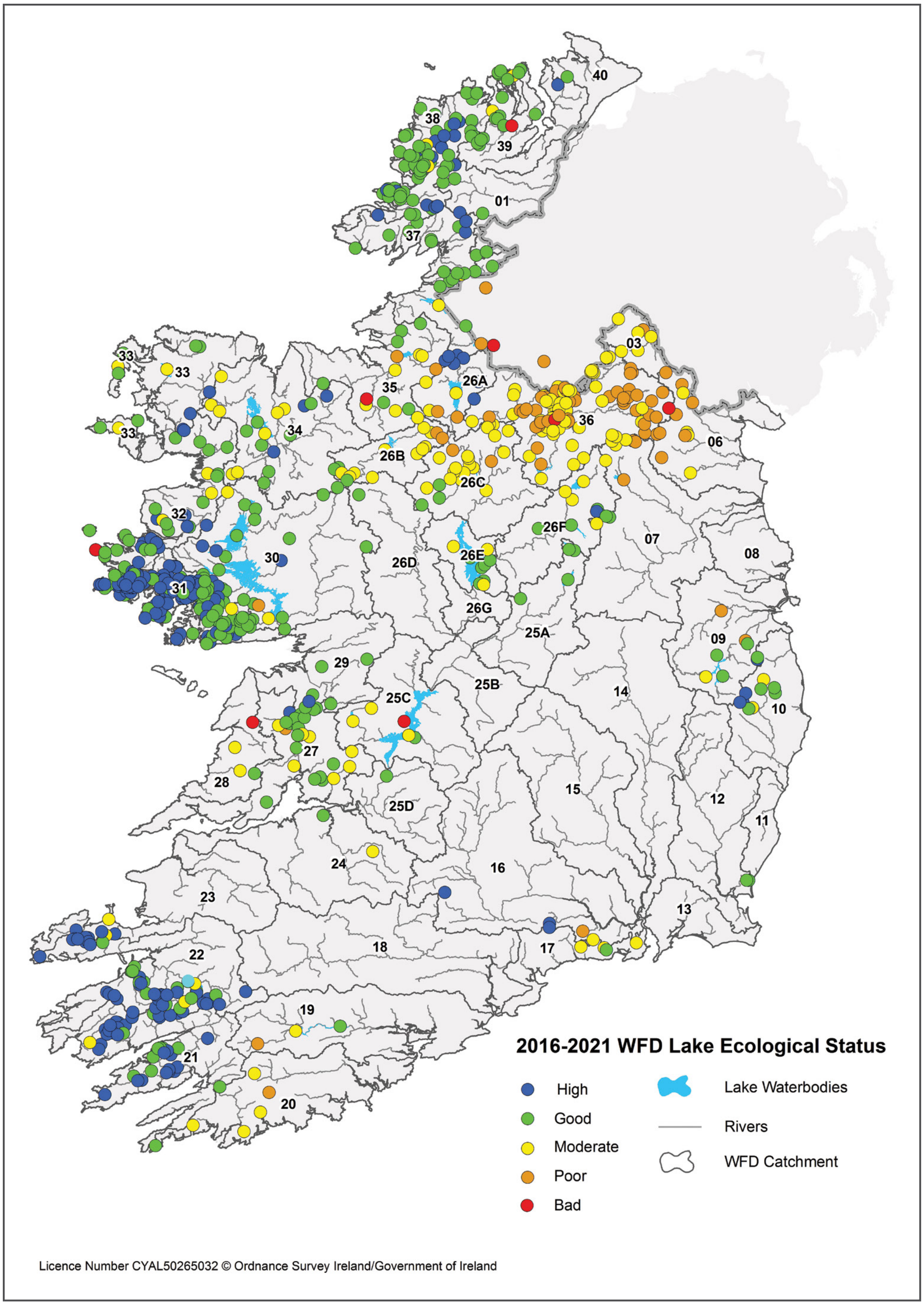


Figure 11.2
The ecological status of all (monitored and unmonitored) WFD lake waterbodies for 2016-2021 (after EPA, 2022).

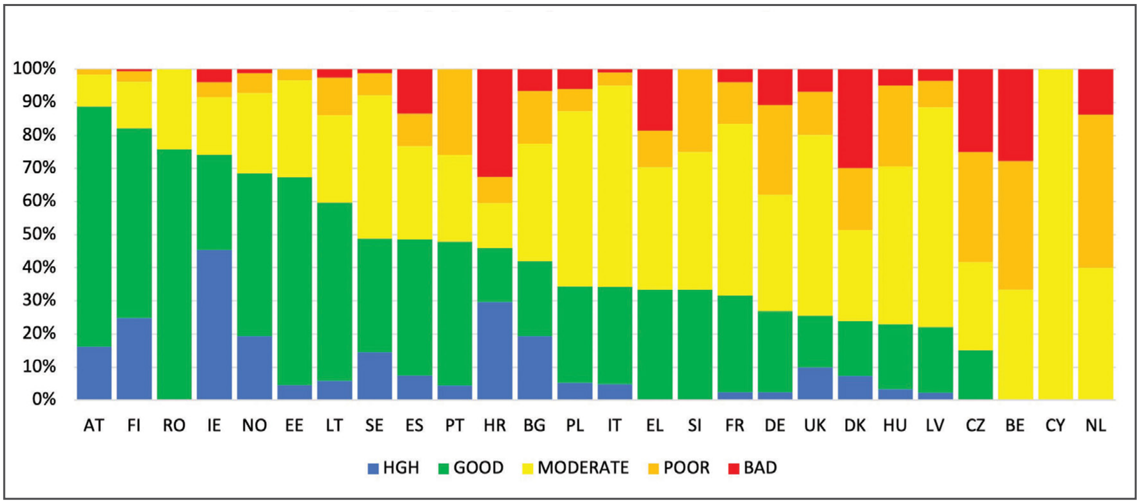


Figure 11.3
Lake ecological status as reported by member status for the second RBMP (https://www.eea.europa.eu/data-and-maps/dashboards/wise-wfd, accessed 28/08/2023, with unassigned lakes omitted). For Ireland, the status is for the period 2010-2015.

Current WFD Regional Picture

Unmonitored WFD lakes are also assigned ecological status either modelled or using expert judgement for 2016-2021.. The map in the Water Quality in Ireland 2016-2021 report (Figure 11.2) clearly shows that WFD lakes with a good or better ecological status are located along the north-western, western, and southwestern seaboard in the counties of Donegal, Mayo, Galway, and Kerry but also in mountain areas in other counties. Lakes with a moderate or worse ecological status are in the drumlin counties of Monaghan, Cavan, into Roscommon and Leitrim. This distribution of lakes and their status reflects the difference in population distribution, land use intensity, hydrogeology, and soil types.

European Context

In a European context, Ireland's lake quality is in a better position than most member states (Figure 11.3). This is because most WFD lakes (449 of 812, 55%) are located along the western, and northwestern seaboard in counties Galway, Mayo, Sligo and Donegal, areas well known for their low pressures, low population densities, little industry, and low intensity agriculture.

Zebra Mussel

Colonisation and spread of zebra mussel complicates the interpretation of changes in water quality. The potential influencing role of zebra mussel on water quality outcomes was first noted in the 1998-2000 Water Quality in Ireland report (McGarrigle et al., 2002). By the time the 2007-2009 Water Quality in Ireland report was published, zebra mussel was widespread throughout the Shannon system and expanding in distribution (McGarrigle et al., 2010). Only moderate and high alkalinity lakes can support populations of zebra mussel because of their high calcium levels. Low alkalinity lakes are not known to have populations of zebra mussel. Therefore, the biological and chemical information provided along with knowledge of the distribution of zebra mussel is beneficial. Any lake that is moderate or worse in status for total phosphorus or for the biological elements has a water quality issue regardless of whether zebra mussel are present or not. A moderate/high alkalinity lake that has a population of zebra mussel and is assessed as high or good ecological status may have a masked water quality issue.

The Best and Worst WFD Lakes

Thirteen monitored lakes have been at high status for general supporting conditions and BQEs for the five WFD assessments. The lakes are located on the western seaboard in counties Donegal (1 lake; Greenan), Mayo (2 lakes; Doo and Glencullin), Galway (7 lakes; Mask Upper, Bofin, Derryclare, Pollacappul, Nahasleam, Enask, and Fadda) and Kerry (3 lakes; Guitane, Cloonaghlin, and Muckross). All are deemed to be 'Not at Risk' for the 3rd RBMP cycle (2022-2027) except Greenan and nine lakes are in AFAs. All except one lake, Greenan; are in Special Areas of Conservation (SAC) namely, Killarney National Park, Macgillycuddy's Reeks and Caragh River Catchment SAC (3 lakes), Connemara Bog Complex SAC (4 lakes), Lough Carra/Mask Complex SAC (1 lake), The Twelve Bens/Garraun Complex SAC (2 lakes) and Mweelrea/Sheeffry/Erriff Complex SAC (2 lakes).

Eleven lakes have been moderate for nutrients and at best assessed as poor or bad status for biological quality for the five WFD assessments. These lakes are in counties Cavan (7 lakes; Skeagh Upper, Drumkeery, Ramor, Lower Macnean, Sillan, Glasshouse, and Erne Upper), Monaghan (3 lakes; Naglack, Inner, and Egish), and Sligo (1 lake; Templehouse). Zebra mussel are recorded as being present in eight of the lakes. As expected, all are 'At Risk' of not meeting their environmental objectives and eight lakes are in AFA for the 3rd RBMP cycle. Upper Erne is in Lough Oughter and Associated Loughs SAC and Templehouse is in Cloonacleigha Loughs SAC.

The Water Quality in Ireland report 2016-2021 (EPA, 2022) indicated strong increasing trends for 2016-2021 in total phosphorus for Inner Lough and Lough Naglack. Loughs Inner, Sillan, Naglack and Egish always figure in the top ten lakes with the highest concentrations of chlorophyll and total phosphorus for the five WFD assessments.

KEY ISSUES FOR LAKES

There is a long history of lake pollution in Ireland. In the 1950s it was considered water quality in Ireland was satisfactory, mainly because the population of Ireland was small with urban areas concentrated along the coast, there was little industrial development and agriculture was poorly developed (Keys, 1954; Downey, 1977). The 1960s through to the 1980s, saw the population increase, urbanisation increase, changes in agricultural practice and intensification, and industrial development. The impact of those changes on our waters was realised in the late-1960s and early-1970s with pollution induced enrichment resulting in eutrophication of lakes, notably in Loughs Sheelin, Leane, and Ennell.

The sources of enrichment were initially identified as arising from discharges from the food industry, agricultural wastes, and detergents (WPAC, 1983). Agricultural practices were identified as a contributing factor to the eutrophication of Sheelin, Ennell, Gowna, Ramor, Derravaragh and Garadice in the 1970s (Morgan, 1977). Point sources from urban waste water treatment were also identified as key issues for Ennell, Leane, and Muckno.

Throughout the 1980s and 1990s, the EPA's Water Quality in Ireland Reports, repeatedly cited three key sources of lake pollution, i.e., input of nutrients causing enrichment leading to eutrophication as point source discharges and non-point or diffuse pollution from agriculture, industry, and domestic sources. While point source discharges from urban wastewater treatment plants could be remedied, it was recognised that the control of non-point sources would be a challenge for the future (WPAC, 1983).

The key issue for lakes in Ireland remains enrichment causing eutrophication due to activities in their catchments that release nutrients and adversely impact water quality. Historic enrichment has an additional role in some lakes. Agriculture is identified as the main significant pressure followed by invasive species, and anthropogenic pressures in the 3rd RBMP cycle. Some lakes have multiple significant pressures.

LAKE MEASURES

Pre-WFD

There are limited lake examples documented where deliberate actions have been taken and resulted in improved water quality. Most examples relate to the catchment management plans produced in the 1970s, 1980s and 1990s to meet the 1977 Water Pollution Act or the P regulations.

Lough Sheelin has been monitored since 1971 (Champ, 1977), because of a eutrophication issue due to pig effluent, caused by an increase in pig numbers from 9,000 to 19,000, between 1968-1971 (Toner and O'Sullivan, 1977) (see Chapter 12). A pig slurry management plan was implemented, and improvements were seen in 1990, but deteriorations were evident until zebra mussel were recorded around 2005. Lough Sheelin is in moderate ecological status. Agriculture is identified as the significant issue, and although slurry management is ongoing, Lough Sheelin has not attained good status.

Loughs Derravaragh and Kinale benefited from the management practices in Lough Sheelin's catchment. The former has been monitored since 1971 with issues of agriculture and domestic sources of enrichment. Lough Kinale is in moderate ecological status and agriculture is identified as a significant issue. Lough Derravaragh is in good ecological status (2016-2021) and consequently, no assessment of pressures has been made. Both lakes have populations of zebra mussel.

Lough Ennell has also been monitored since 1971 when there was a switch from charophytes to planktonic algae, an algal bloom indicative of enrichment. The issue was the sewage effluent from the Mullingar WWTP that had been discharging to the lake since the 1920s (Toner, 1977). A new treatment plant was installed in 1975, and fully functional by 1976 with an almost continuous improvement in water quality (Toner et al., 1986; Bowman et al., 1996; Toner et al., 2005). Lough Ennell continued to improve reaching oligotrophic status in 2010-2012 to the most recent assessment. Lough Ennell is currently in good ecological status (2016-2021), but agriculture is identified as a significant issue along with Industry (Section 4 discharge licences).

Lough Leane was surveyed in the early 1970s and the issues identified were domestic (houses, hotels) and municipal (town) sewerage (Bracken et al., 1977) (see Chapter 12). Phosphorus removal was implemented at the treatment plant and improvements were seen in both Lough Leane and Ross Bay which was receiving the discharge via the Follies stream. However, 1997 saw a dramatic decline in water quality in Lough Leane due to a series of events that resulted in phosphorus flushing from the catchment and a catchment plan was developed. Both Ross Bay and Lough Leane were assessed as mesotrophic since 1998-2000 and 2004-2006 assessments, respectively. While Lough Leane is currently assessed as having good ecological status, there is no room for complacency given what happened in 1997. Ross Bay, directly connected to Lough Leane, is in moderate status and will only achieve good status if further improvements in the urban wastewater treatment plant happen.

Lough Muckno had excessive enrichment due to sewage discharge from the urban WWTP from Castleblaney (Toner et al., 1986). An improvement was noted following phosphorus removal (Bowman et al., 1996) only to deteriorate (Toner et al., 2005). Lough Muckno has recently reached moderate status (2016-2021), but given its high maximum chlorophyll values, it remains enriched and is in the strongly eutrophic category, even though zebra mussel are present. The treatment plant was overloaded, with breaches, and there have been pumping station incidences. The treatment plant was upgraded in early 2020, it may take some time before improvements are evident in the lake itself.

Lough Derg was noted as receiving effluent from towns on inflowing streams (Toner and O'Sullivan, 1977). Toner et al. (1986) attributed increased eutrophication to the expansion of towns in the catchment and changes in agricultural practice over the previous 60 years. Lough Derg was still in trouble in the early-1990s (Clabby et al.,1992), and a catchment investigation commenced. Improvements were noted in 1997 (Lucey et al., 1999) when phosphorus removal was installed at the Nenagh WWTP, but the improvement also coincided with the first records of zebra mussel in the catchment. Zebra mussel was probably introduced in 1994 (McGarrigle et al., 2002). McGarrigle et al. (2002) referenced remedial measures including phosphorus removal at 17 urban WWTPs in the River Shannon Catchment which includes Lough Derg and Lough Ree. The ecological status of Lough Derg is moderate due to fish with all other biological elements and chemical parameters high or good. The significant pressures identified are hydromorphology (dams, barriers, locks, weirs), invasive species (of which there are many), and agriculture (historically the case). Urban waste water treatment plants are identified as a pressure but do not discharge directly to the lake. The ecological status of Lough Ree is good for the most recent two ecological assessments, 2013-2018, and 2016-2021.

Clabby et al. (1992) attributed the eutrophic conditions of Inniscarra Reservoir to non-point source agriculture. Water quality improved following nutrient management in the catchment (McGarrigle et al., 2002; Toner et al., 2005) reaching mesotrophic status for the period 2016-2019. Inniscarra Reservoir has just achieved good status in the most recent WFD ecological assessment (2016-2021).

WFD Measures

The WFD requires all member states to set out a PoMs for each RBMP. It was recognised during implementation of the first RBMP (2009-2015), that a new approach was needed. In 2014, the integrated catchment management (ICM) system was developed for the PoMs, the European Union (Water Policy) Regulations were passed giving effect to a new three-tier governance framework and placing new obligations on local authorities in coordinating the catchment management and public participation elements of the WFD. Irish Water now Uisce Éireann was formed as a single utility for delivery of water services under both the Drinking Water and Urban Waste Water Treatment Directive with a significant programme for investment.

In 2016, LAWPRO was established to support the delivery of Local Authority commitments (see Chapter 20). Other supports were introduced to improve or maintain water quality including the Agricultural Sustainability Support and Advisory Programme.

The ICM approach involves the publishing of 46 catchment assessments, identifying AFA, and producing the PoMs. The catchment assessment reports provide an overview of water-related issues at a catchment level. The reports set out the status and risk for all WFD waterbodies, provide details on the protected area and an overview of the significant issues and pressures. For the 3rd RBMP cycle (2022-2027), the catchment assessment reports also provide a measure of progress, an overview of the 2nd cycle PAAs, the proposed 3rd cycle AFAs and recommend priority AFAs led by LAWPRO. A structured approach is adopted for recording, tracking, and achieving the objectives in AFAs. The approach involves carrying out a desktop study, public engagement, identifying further actions, and referring actions to relevant organisations to address pressures.

There are 34 national measures from the 2nd RBMP cycle (2018-2021) continuing into the next cycle (2022-2027), including the Nitrates Action Programme and national inspection programmes for licensing, agriculture, and septic tanks. Some have targeted benefits for lakes either directly or through measures that improve rivers connected to lakes.

The Irish Water Capital Investment Plan continues into the 3rd RBMP cycle 2022-2027, including Uisce Éireann's 20 million euro European-funded RBMP Enhanced Ambition Programme involving the upgrade of 12 (WWTPs) and completing feasibility studies for 20 plants that discharge to priority waterbodies. The feasibility studies were completed and published in December 2023 (Uisce Éireann, 2023) with two lakes set to benefit from the identified improvements when implemented. Lough Allua is downstream of the Ballingeary WWTP which discharges into the river Lee causing a water quality issue in the lake. The plant is to be replaced with an activated sludge process among other recommendations. The Blacklion WWTP was identified as a pressure on Lough McNean impacting water quality and will be upgraded with improved treatment.

There are 15 catchment projects listed for the 3rd RBMP cycle 2022-2027, some of which include a lakes element such as the IFI National Climate Change Mitigation Research, where buoys have been deployed on lakes to measure temperature, oxygen, and light. Other projects have lakes within their study area. The National Salmonid Index Catchment - Erriff; has Loughs Tawnyard and Glenawough in its study area. The Pearl Mussel Project includes catchments with lakes such as Cloonaghlin, Kylemore, Pollacappul, Namona, Acoose, Fadda and Brin that will benefit from measures taken in rivers to protect pearl mussel.

Three EU LIFE Integrated Projects; Waters of LIFE, Wild Atlantic Nature LIFE Integrated Project and Lough Carra LIFE are underway in 2024. The Waters of Life project aims to restore rivers to their high status objective. It has six demonstration catchments, and three have lakes in the catchment: Graney Demonstration Catchment (Graney, Atorick); Avonmore Demonstration Catchment (Tay, Dan); Island Demonstration Catchment (Coolcam, Potleagh), which are not designated under the WFD. The Wild Atlantic Nature objective is to improve the conservation status of blanket bogs. It has a focus on blanket bog Natura 2000 sites across Galway, Donegal, Mayo, Sligo, and Leitrim. Within these protected areas are lakes such as Loughs Ballynahinch, Ardderry, Bofin and Lettercraffroe in the Connemara Bog Complex SAC. Lough Carra LIFE aims to reduce nutrients entering Lough Carra, restore the marl lake habitat and improve the conservation status of other protected habitats and species.

Two lake catchment projects have commenced in areas for restoration: Lough Muckno Road to Recovery Project and Lough Ennell Catchment Management Project. Lake health directly benefits from catchment projects with a lake water quality focus. Lake health may also benefit from measures or recommendations coming from catchment projects with a different focus that indirectly includes lakes.

There are over 500 AFAs in the 3rd cycle of RBMPs, categorised into AFAs for restoration and AFAs for protection. Each AFA can have multiple actions including catchment projects and application of the national measures across a variety of waterbodies. AFAs are progressing through the multi-step process, but few have reached the stage where all actions are complete i.e., measures are in place.

There is a greater focus on lake waterbodies in the 3rd cycle (2022-2027). This is reflected by the increased number of lakes captured in the AFAs for the 3rd cycle and the commencement of specific lake catchment projects. Past experience has demonstrated that where there are few and simply remedied issues such as improving an urban WWTP, a response will be evident in the chemistry and biology. However, most enriched lakes have historic issues and are in catchments with multiple or complex pressures. It will be some time before improvements in these lakes are evident.

CONCLUSION

The basic objective to attain WFD good status by 2015 has passed and 2027 is fast approaching. There have been no significant improvements in lake water quality at national level in 50 years. It would seem our long history of legislation aimed at protecting water and the PoMs including basic measures drawn from 11 pre-WFD directives is not enough to bring all lakes to good status. Input of nutrients causing enrichment for over 50 years remains the greatest challenge facing lakes in Ireland. This will be exacerbated by climate change. May et al. (2022) demonstrated the effects of climate change are already being expressed in Scottish lakes with increasing air temperatures leading to increased water temperatures affecting lake biology and function. The findings likely equally apply to Ireland. Continued invasions of alien species are expected and already change lake quality e.g., zebra mussel. There are excellent examples of lake-focused catchment management plans that yielded good results, but these were few in number and in the past. There has been a renewed focus on lakes for the 3rd RBMP cycle, the emergence of new lake-focused projects, and potentially a new phase of improved lake health is on the horizon.

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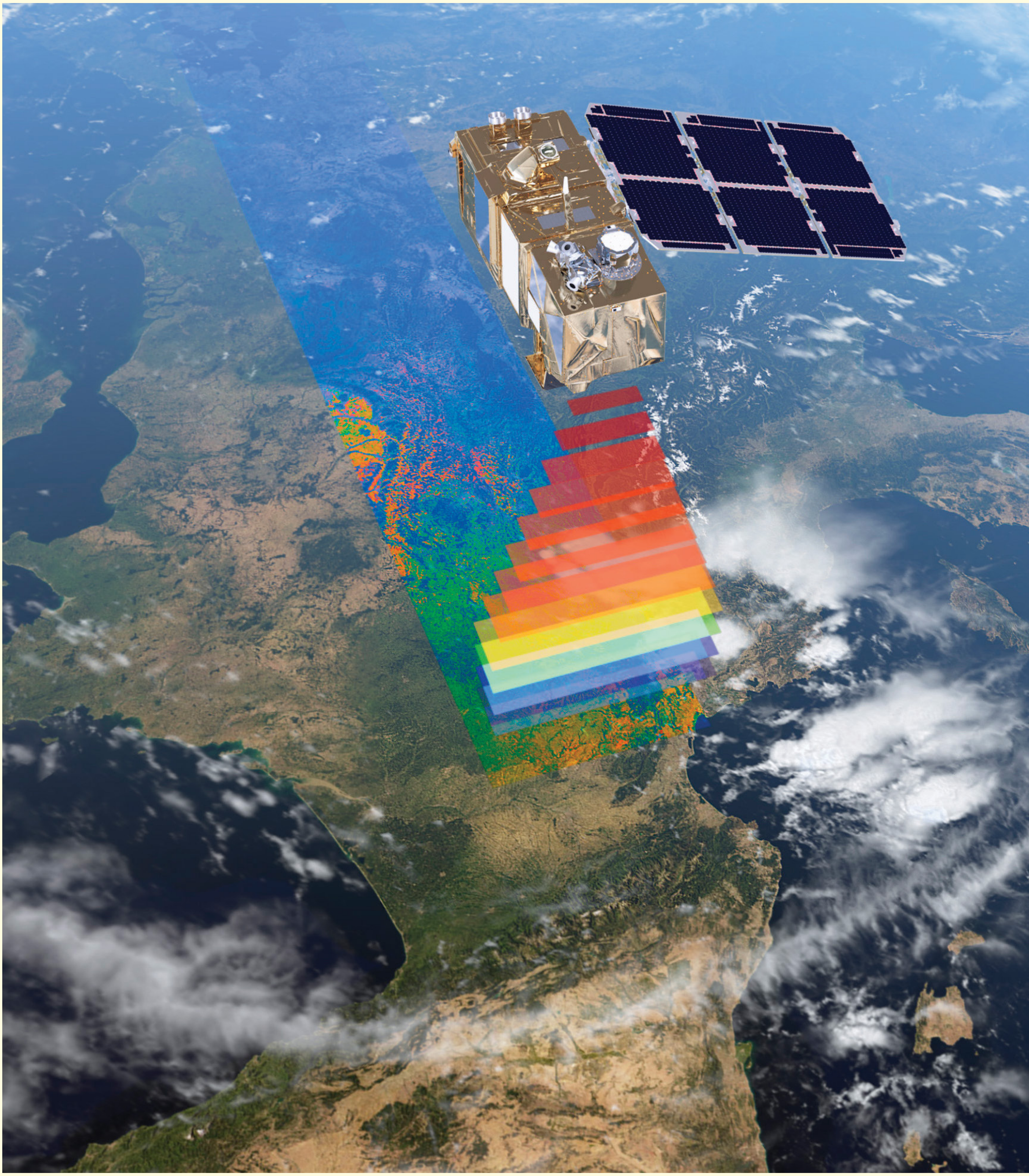

Highlight Box

REMOTE SENSING OF LAKES

Gary Free

With NASA's Landsat programme, remote sensing using satellites in space for environmental purposes was initiated in the 1970s. Over time, the technology and availability of remotely sensed data have progressed rapidly. Currently, the EU's Copernicus programme, which includes a series of dedicated satellites (termed Sentinels) with an open access data policy, is allowing the widespread use and development of novel applications, including for lakes.

One example is the recent European Space Agency Climate Change Initiative (Lakes_CCI: https://climate.esa.int/en/projects/lakes/) that has gathered and harmonised historical data from the satellite record for over 2000 lakes globally, including six lakes on the island (Melvin, Corrib, Derg, Sheelin, Erne and Neagh). Parameters include lake water level, lake water extent, lake ice, temperature and reflectance leaving the lake surface (Carrea et al., 2023). Lake water levels are important in understanding a catchment's hydrological balance and can be determined using radar altimeters, for example aboard Sentinel 3. Similarly, the SAR (Synthetic Aperture Radar) aboard Sentinel 1 can be used to determine lake extent. This is also useful for mapping the extent of flooding as carried out by the Copernicus Emergency Management Service following a national request in 2017 around Lough Funshinagh (Co. Roscommon). SAR has the benefit of not being affected by cloud cover which occurs more than 50% of the time in Ireland (Rohan, 1986; Mercury et al., 2012) and reduces the usefulness of satellite optical sensors such as those aboard Sentinel 2 and 3.

Most people are probably familiar with satellite imagery presented as an aerial photograph and these are created often using only the red, green, and blue visible light bands from optical sensors which are in fact multispectral - collecting data on many wavelengths (13 for Sentinel 2, 21 for Sentinel 3, see Figure 1 below). The reflectance values of the different wavelengths can be used to reveal a lot of information about lakes, for example serving as input into algorithms that are calibrated to provide estimations of lake chlorophyll-a or turbidity. However, even simply looking at the images can

Figure 1, facing page: Sentinel-2 mission collecting layers of information. Image courtesy of ESA/ATG medialab.

Figure 2 Sentinel-2 image from June 2017 showing an algal bloom on Lough Inner (County Monaghan).

provide information on the intensity and distribution of algal blooms. The second picture (Figure 2) shows three lakes in Co. Monaghan in June 2017, the intense algal bloom on Inner Lough has turned the lake so green it is difficult to distinguish it from the surrounding forestry and fields. Collecting and processing information from satellite imagery attempts to quantify such blooms or chlorophyll-a concentrations spatially and over time. The maximum pixel size of Sentinel 2 is 60 m with a revisit time of every 2/3 days allowing even small lakes to be examined frequently.

One of the main benefits of using satellites to study lakes is their synoptic nature, allowing the entire island to be examined frequently and as Ireland has 10,215 lakes and ponds over 1000 m^2 in area (Dalton, 2018), remote sensing provides an attractive solution to monitor this natural resource. Work on using remote sensing to monitor lakes was trialled in Ireland as early as 1976 (McGarrigle and Murray, 1981). Recently the EPA-funded project INFER examined methods for atmospheric correction of images and application of algorithms to estimate chlorophyll-a and turbidity (Karki, 2022). Other recent work includes defining empirical relationships with the ecological assessment of lake macrophytes including the estimation of their depth of colonisation within the lake, an important indicator of lake health (Free et al., 2020). However, more work and investment are still needed in Ireland to build an operational system for lake assessment using remote sensing. Recent advances in machine learning and big data move closer to the unlocking of this important resource on lakes in Ireland and globally.

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Chapter 12

SENTINEL LAKES
CHRONICLES OF CHANGE

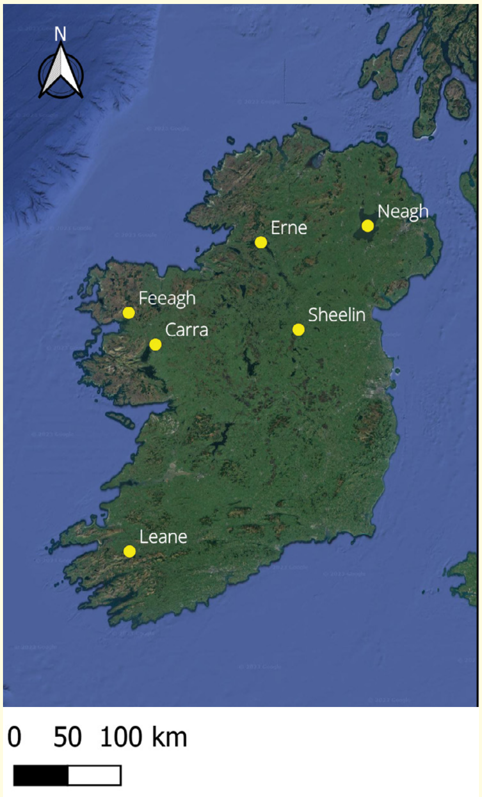
Elvira de Eyto, Helen Twomey, Fiona Kelly,
Yvonne McElarney, Valerie McCarthy, Ken Irvine,
Bill Quirke and Pascal Sweeney

SUMMARY

Long-term ecological monitoring of lakes over decades, using consistent methods, provides data that can be used to detect and understand environmental change. Although there are nearly 14,000 lakes and ponds on the island of Ireland, a minimal number have been the focus of sustained, sub-annual (i.e. daily, weekly or monthly) monitoring. In this chapter, we bring together datasets from six lakes in Ireland, which, for a variety of reasons, have been the focus of sustained monitoring efforts over decades (Table 12.1, Figure 12.1). For each lake, we describe its characteristics, the history of the monitoring programmes, and some important signals observed in the data. Lakes are impacted by multiple, interconnected pressures. We do not attempt to document all of these for each of our case study lakes but instead, demonstrate how long-term data can be used to track one or two impacts in each lake and provide references for further reading. Eutrophication is a common theme in several of the lakes (Sheelin, Leane, Neagh). Increasing water temperature resulting from global climate change is ubiquitous but is specifically discussed for Neagh and Feeagh. We use Carra as a case study of how incremental changes threaten a valuable habitat type, and we highlight the impact of invasive species in Erne and Sheelin. We finish with some discussion about Feeagh, which is displaying subtle signals of change related to land use in the catchment and global warming.

INTRODUCTION

Lakes can be thought of as sentinels in the landscape that bear witness to the ebb and flow of activities over millennia whilst storing signals of change in their water, flora, fauna and sediment. As indicators of environmental change, they integrate signals from diverse impacts, including land use modification, climate warming and pollution (Williamson et al., 2008). The types and abundance of species in and around a lake can reveal the overall health and stability of the catchment, as well as the lake itself. Changes in



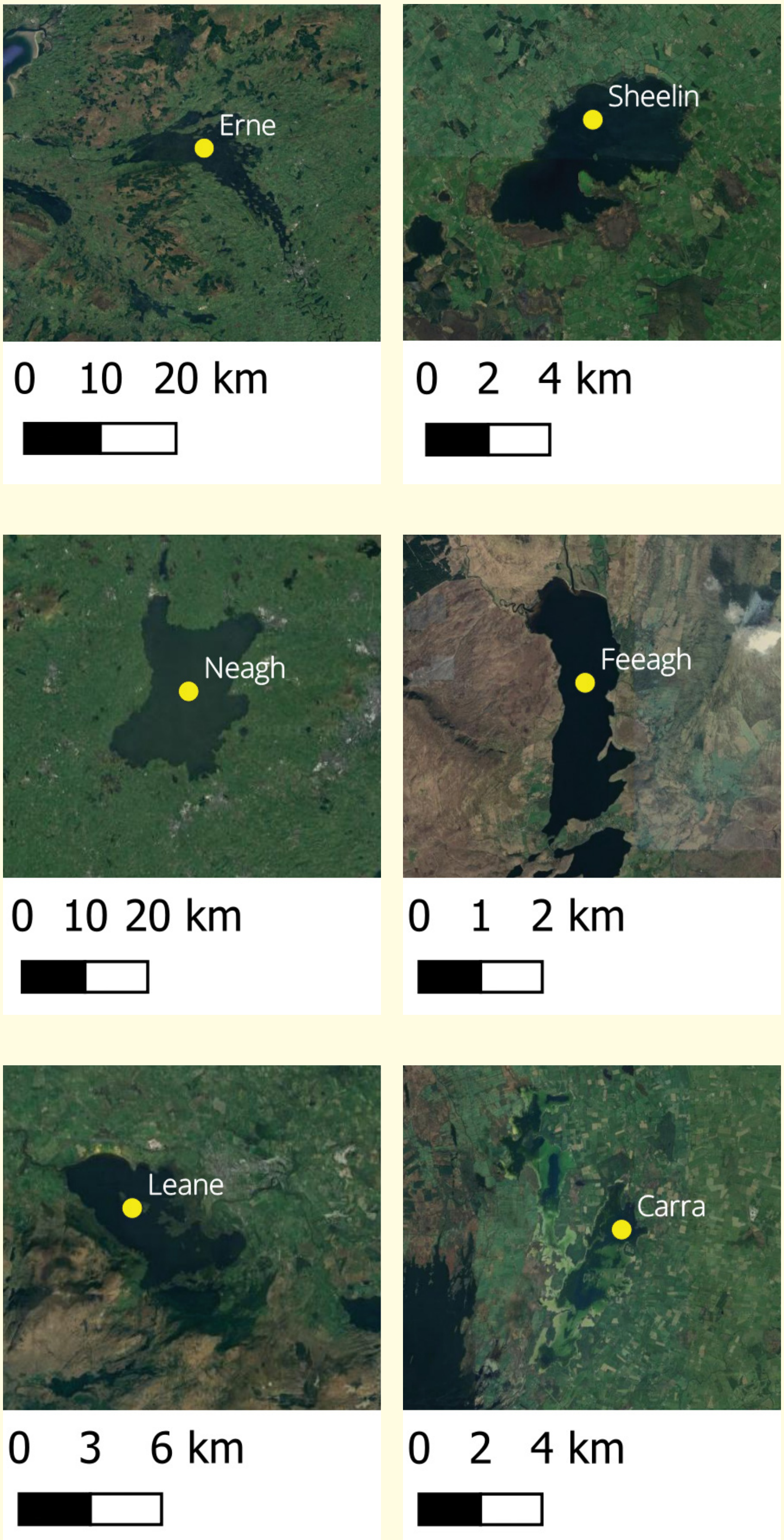


Figure 12.1 Map of Ireland showing the location of lakes mentioned in this chapter, and satellite images of each lake. Note the varying scale bars.

Table 12.1. Characteristics of study lakes. Ecological status according to the EPA's 2016-2021 WFD or DAERA's 2021 assessments. HMWB indicates a heavily modified waterbody

Lake	Area km^2	Mean depth m	Max depth m	Dominant Geology	Ecological status
Sheelin	19	4.4	15	Limestone, Shale	Moderate
Leane	19	13	66	Sandstone, Limestone, Shale	Good
Neagh	383	9	34	Basalt	Bad (HMWB)
Erne (lower)	110	12	69	Limestone	Moderate (HMWB)
Feeagh	4	13	46	Quartzite and schist	Good
Carra	16	2	19	Limestone, Shale	Good

the clarity, colour, or chemical composition of the water can signal pollution in the water draining into the lake. Changes in temperature, water level and the seasonal patterns of biological activity can provide insights into broader climate trends. Here, we delve into those lakes where long-term monitoring has been carried out by a wide range of agencies and individuals, leading to a unique view of changes in the Irish landscape since the 1950s.

LOUGH SHEELIN

Lake type

Lough Sheelin is a high-alkalinity lake located in the Drumlin belt of the central-northern part of Ireland (counties Cavan, Meath and Westmeath). It is situated on the upper reaches of the Inny river, a tributary of the River Shannon (Figure 12.1). Sheelin has a maximum depth of 15m, an average depth of 4.4m and a surface area of 19 km^2 and has high alkalinity (>100 mg/l $CaCO_3$). The geology of the catchment is predominantly Carboniferous limestone, but Silurian/Ordovician formations underlie the western and northern drainage basin. Low permeability gley soils, vulnerable to waterlogging and nutrient loss, predominate in the north and western parts of the catchment. Deep, well-drained soils are predominant in the eastern subcatchments, while the soils closer to the lake shore around the Inny outlet comprise blanket and basin peats. Agricultural activity is extensive, including pig rearing, beef and dairy cattle, poultry farming and mushroom production/composters. Almost 57% of farms are located on wet drumlin soils. There are nine active Integrated Pollution Prevention and Control (IPPC) licenced facilities in the inflowing catchments to the lake, including one meat processing plant, one woodcraft facility and seven pig farms (EPA, 2023). Two small towns, Ballyjamesduff and Oldcastle, are in the eastern side of the catchment (Mountnugent and Upper Inny (Ross) subcatchments, respectively). Human settlement in the remainder of the catchment is characterised by scattered dwellings, each linked to domestic septic tank systems for wastewater treatment. As an important site for wintering waterfowl, the lake is a Special Protection Area (SPA – site code 004065) under the EU Birds Directive.

Monitoring history

In the 1950s and 1960s, Lough Sheelin was one of Ireland's top trout (*Salmo trutta*) angling lakes, managed and developed by the Inland Fisheries Trust (IFT, now Inland Fisheries Ireland). It was one of the first lakes where nutrient pollution was observed, and in response, the IFT set up a systematic nutrient monitoring programme in 1971. Intensive water quality sampling was initiated on ten tributary streams in 1982 (Kerins et al., 2007). These programmes aimed to identify problem areas and to take corrective action with the objective of restoring the lake to a premium brown trout fishery. The EPA took over the routine monitoring in 2007 (see Chapter 11), so preserving the time series, albeit at reduced resolution.

The fish population in Sheelin was monitored annually in spring between 1978 and 2022 (Shephard et al., 2019; Delanty, Feeney and Fitzgerald, 2023) as well as being part of the fish monitoring programme for the WFD (see Chapter 6). In 2020, Inland Fisheries Ireland (IFI) selected Sheelin and its surrounding watersheds as a sentinel catchment for further detailed studies to investigate the impact of ongoing environmental and climate change and interactions between stressors on Ireland's inland fish populations, and instrumented the lake and its tributaries with high temporal resolution sensors and acoustic telemetry receivers (Barry et al., 2023; Kelly et al., 2023).

Impacts and signal of change

The first blue-green algal bloom on Sheelin was reported in March 1971 (IFT, 1972). The lake continued to deteriorate in the following year, and at one point, the whole lake turned green (Champ, 1991). Subsequent comprehensive investigations by IFT followed, identifying at least 40 different sources of pollution in the catchment. The major ones were associated with 16 piggeries (totalling approximately 50,000 pigs), nine sizeable silage pits, three large poultry farms, four industrial units, two urban, and ten domestic sources of deleterious effluent in the catchment (IFT, 1972), with the principal source of nutrients being pig slurry (Dodd, 1973). The water in the lake continued to deteriorate. In 1979, IFT reported that 'Lough Sheelin would cease as a viable trout fishery within a few years unless positive measures are introduced to halt the ingress of excessive nutrients in the lake' (IFT, 1979). In response to the obvious deterioration in water quality, a state-sponsored subsidy scheme to transport the excess slurry out of the catchment was initiated between 1980 and 1984 on recommendations arising from various state agencies at the time. An estimated 238,000m^3 of slurry was removed from the catchment by 1984 (Kerins et al., 2007). After that, water quality started to improve and by 1984, aquatic vegetation began recolonising. However, the recovery was short-lived as the scheme was terminated at the end of 1984, and new arrangements were not successful (Champ, 1991). Despite several additional phases of nutrient mitigations in the catchment (e.g. upgrade of the Ballyjamesduff WWTP from primary to tertiary treatment, issue of an IPPC licence to limit the loading of P from a meat processing plant in 1999, an interim P removal regime for the overloaded Oldcastle WWTP in 2003, agricultural bye-laws to regulate the storage and management of livestock wastes in 2003, licensing of trade discharges to water, septic tank compliance, pollutant investigations and farm surveys in 2003, catchment-wide septic tank bye-laws in 2004, and implementation of the Good Agricultural Practice (GAP) regulations and WFD), there has been no apparent improvement in the long-term trophic status of the lake. Interpretation of any recovery of the water quality in Lough Sheelin has been further complicated by the invasion of zebra mussels (*Dreissena polymorpha*) around the year 2000 (see Chapter 13 for more details).

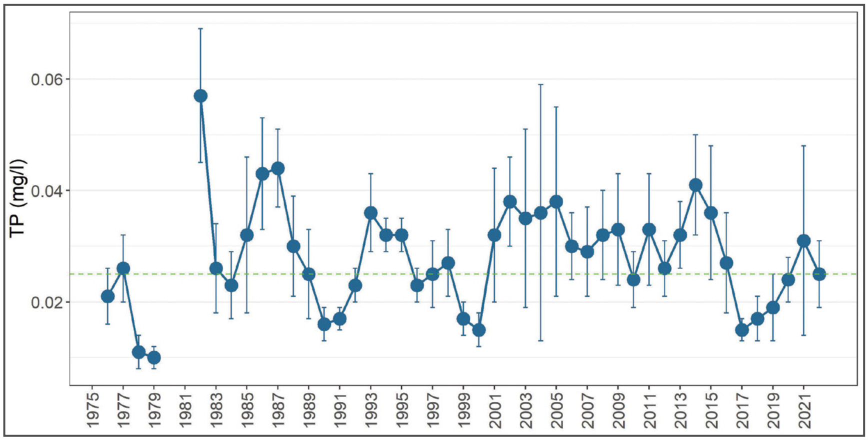
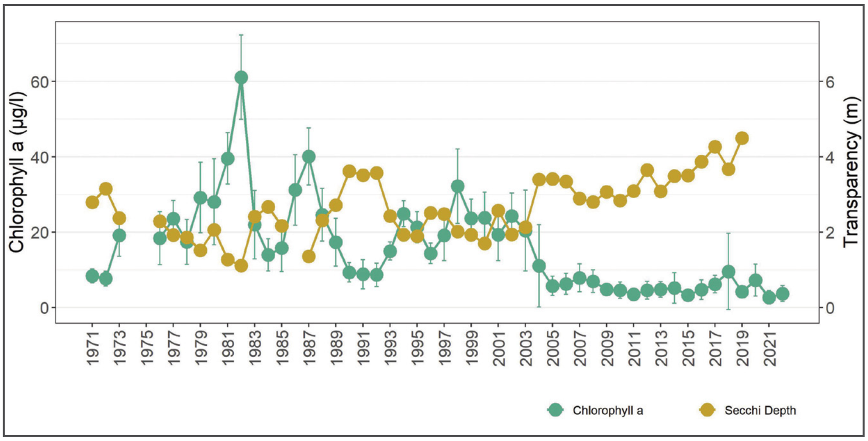


Figure 12.2 Mean total phosphorus (and 95% confidence interval) on Lough Sheelin (mid-lake) 1976 to 2022 (total n=589 samples) (Note: less than five water samples were taken in 1979, 2000, 2017 and 2018; green dashed line indicates EQS of Good status (0.025 mg/l P).

Figure 12.3
Mean Chlorophyll *a* (µg/l) (total n=720) and transparency (Secchi depth in m) (total n=606) on Lough Sheelin (mid-lake) 1971 to 2022. (Note: less than five water samples were taken in 1979, 2000, 2017 and 2018. Zebra mussels were first noted in the lake in 2001).



The lake's trophic status has been well documented (see Kerins et al., 2007 and references therein). The annual mean total phosphate (TP) value for Sheelin over a 45-year period (1976 to 2022) was 0.029 mg/l, ranging from a low of 0.010 mg/l P in 1979 to a high of 0.057 mg/l P in 1982 (Figure 12.2). There were signs in the 1980s and late 1990s that the water quality in the lake was improving. However, since 2000, TP has generally been ≥0.024 mg/l. Overall, since 1976, 60% of monitoring years equalled or exceeded the Ecological Quality Standard (EQS) for good status under the WFD, based on TP (0.025 mg/l P). Annual mean chlorophyll *a* values

Figure 12.4
Algal bloom on Lough Sheelin, September 2023.
Photo: Brenda Montgomery

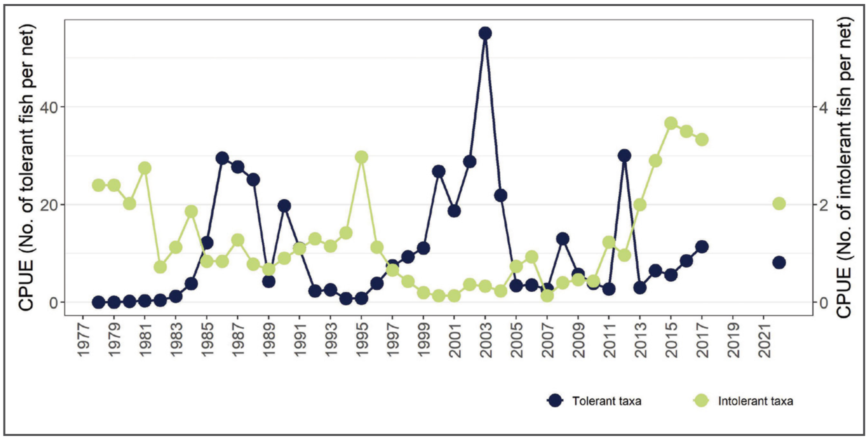


Figure 12.5 Survey catch per unit effort (CPUE, no. fish per net) on Lough Sheelin from standardised spring gill netting surveys for intolerant (trout) and tolerant (roach, rudd, bream, tench and hybrids) fish species. (Three missing years (1991, 1997 & 1998) when no surveys occurred were estimated as the average of the two most proximate values). Data were not collected between 2018 and 2021.

for Sheelin over a 51-year period (1971 to 2022, excluding 1974 and 1975) ranged from 2.6 to 61.1 µg/l, averaging 15.8 µg/l (Figure 12.3). It reached an all-time high in 1982, with increases observed again in 1986, 1994 and 1998 (Figure 12.3), following a very similar trend to that of TP. There was an obvious decoupling of this relationship after 2004, consistent with dreissenid mussel grazing rather than improvement in trophic or ecological status, as TP remained elevated (Figure 12.2). Decreasing chlorophyll *a* has coincided with increased transparency in the lakes, probably also a reflection of increased mussel filtration (Figure 12.3). Blue-green algal blooms were observed on the lake for the first time in several years in September 2012, 2013, and May 2014 and are continuing (Figure 12.4).

Results collated from the IFT Creel Census Scheme initiated in 1964 indicated that trout (*Salmo trutta*) catches in Sheelin had declined in the late 1960s and were attributed to the Inny arterial drainage scheme (1960-1968) but were beginning to recover by 1972 (IFT, 1979). However, by the mid-1970s, changes in the fish stocks in the lake were again observed (John et al., 1982). Standardised monitoring began in 1978 and indicated that trout CPUE (catch per unit effort) declined after 1980 for several years, with evidence of a temporary recovery in the early to mid-1990s (Shephard et al., 2019). A consistent decline was again observed after 1995, with recovery again from 2007 (Figure 12.5). A small number of cyprinids (e.g. bream (*Abramis brama)* and rudd (*Scardinius erythrophthalmus)*) were present in the lake during the early surveys. Roach *Rutilis rutilis*, a non-native invasive species, was first reported in the lake in 1974 and was recorded in standardised fish stock surveys for the first time in 1980. Their population has fluctuated dramatically since then. Survey CPUE for tolerant fish species (including roach and other cyprinids) initially increased exponentially from 1980 and then fluctuated strongly throughout the time series in years when trout abundance was low (Figure 12.5). Recent WFD fish surveys have assigned good ecological status to the lake, an increase from moderate in 2014. Despite the overall moderate status of the lake and algal blooms becoming more prevalent in recent years, Sheelin has remained a viable trout fishery. Sustained efforts (e.g. preventing phosphate from entering the lake) are required to restore Sheelin to at least Good status, and this should be supported by continuous monitoring and scientific studies to disentangle the underlying water quality pressures from climate change.

LOUGH LEANE

Lake type

Lough Leane is the largest of the Killarney lakes. The catchment contains numerous rivers, streams, and lakes that drain the mountainous subcatchments of the MacGillicuddy reeks to the southwest and the mainly agricultural grasslands to the east. It has a maximum depth of 66 m, an average depth of 13 m, a surface area of 19 km^2 and is of moderate alkalinity (20-100 mg/l $CaCO_3$). The River Laune flows from Leane to the sea just northwest of Killorglin after a distance of approximately 22 km. Leane is part of Killarney National Park and is protected as a UNESCO Biosphere Reserve, a Special Protection Area, and a Special Area of Conservation (Killarney National Park, Macgillycuddy's Reeks and Caragh River Catchment SAC Site Code: 000365). The lake and its catchment contain many designated habitats and species, including the only lake-resident shad population in Northwestern Europe, the Killarney shad, *Alosa fallax killarnensis* (Coscia et al., 2013) the twaite shad (*Alosa fallax*).

Monitoring history

Concern regarding the water quality of Leane was expressed as early as 1967 in an An Foras Forbartha report on the Killarney Valley (Fehily and Shipman, 1967). At the time, untreated sewage from Killarney town was discharged directly into the lake. Following recommendations for further investigations, a study of various aspects of the Killarney Lakes was carried out from 1971 to 1975 by the Limnological Research Unit, University College Dublin. Subsequent to this, biological and chemical investigations and monitoring were carried out on a full-time contract basis from 1976 to 1992 for the

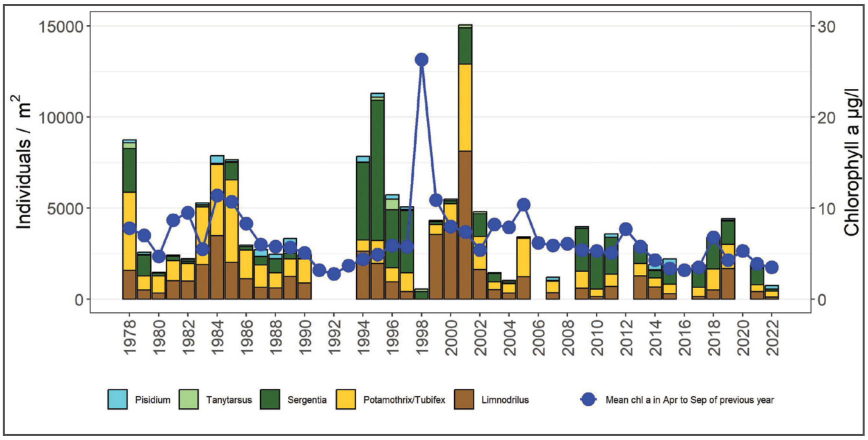
National Board for Science and Technology, Office of Public Works and Kerry County Council. From 1993 to the present, Kerry County Council and EPA have carried out routine water sampling for the Killarney lakes, and biological monitoring has been carried out on contracts for Kerry County Council. Following a severe algal bloom in 1997, a Working Group was established to coordinate efforts to monitor and manage water quality within the Leane catchment. The Leane Catchment Monitoring & Management System Final Report was published in November 2003 (Kirk McClure Morton, 2003). This report identified significant inputs of phosphorus to the Lough from agriculture (primary source), urban agglomeration and industry, septic tanks and forestry, in addition to natural background loading. Specifically, the Final Report stated that 'the high phosphorus levels in the algal bloom year of 1997 were not due to the Killarney WWTP but were due to a rising trend in phosphorus inputs from the rural catchment, and in particular from the River Flesk.'

Impacts and signal of change

The impact of eutrophication can be traced in many of the variables that are routinely monitored in lakes, such as nutrient concentrations, oxygen levels, biomass of algae and the occurrence and density of various groups of animals. As part of the monitoring work on Leane, annual quantitative monitoring of macroinvertebrates was included in the monitoring programme. This included monitoring of the profundal (deep water) invertebrates of Leane throughout the period from 1978 to the present, largely under contracts for OPW and Kerry County Council. The presence and abundance of profundal macroinvertebrates (those that live in the sediment at the bottom of lakes) are known to be particularly indicative of eutrophication pressures (Poikane et al., 2016) and the consistent monitoring of this group provides a clear indication of the impacts of eutrophication on the ecosystem of the lake. Profundal invertebrate data for Leane are available for 38 of the 44 years since 1978. Between 1978 and 1996, the density of tubificid worms (Family Naididae, Sub Family Tubificinae) in the profundal zone of Leane (at a depth of 60m) was correlated with the biomass of planktonic algae (as indicated by chlorophyll *a*) recorded over the growing season between April and September in the previous year (Figure 12.6). This indicates a generally strong relationship between these tubificid worm species and the trophic state of the lake.

From 1978-1996, the tubificid worm component of the profundal fauna of Lough Leane consisted almost entirely of *Limnodrilus* sp., individuals of

Figure 12.6
The annual density of major profundal taxa and previous year mean April-September planktonic chlorophyll a 1978-2022. Profundal invertebrates were not monitored in 1993, 2006, 2008, 2012, 2016 and 2020, and data from 1991 and 1992 are not shown (see text for details).



the *Potamothrix hammoniensis/Tubifex tubifex* group, and *Ilyodrilus templetoni* (LPTI group), all of which are tolerant of enriched conditions. Due to a chance influx into the profundal zone of littoral (shallow shoreline) material in the form of mats of filamentous algae and associated littoral invertebrates, the profundal tubificid data for 1991 and 1992 can be discounted as an index of lake productivity and have been excluded from Figure 12.6. The correlation between the LPTI Group and chlorophyll *a* broke down after a major algal bloom that occurred in 1997. In that year the density of algae decomposing in the profundal zone caused complete deoxygenation of the deep-water sediments of Leane and the demise of macroinvertebrate fauna in the deepest part of the lake. Following this major perturbation, the profundal invertebrate community entered an unstable phase. LPTI group tubificid worms initially increased to unprecedented densities, followed by a population crash in the period 2001 – 2004.

Since 2004, the relationship between algal chlorophyll *a* and profundal invertebrates has stabilised, and the normal correlation of LPTI tubificid group density with planktonic algae (chlorophyll *a*) with a one-year time lag appears to have re-established itself. Density of the LPTI tubificid group increased in 2018, reflecting the increase in planktonic chlorophyll *a* in 2017. The LPTI group density increased further in 2019 despite the reduction in mean April-September planktonic chlorophyll *a* recorded in the previous year. However, in 2021, the LPTI group density reduced to a low level, similar to 2015, with further declines in 2022. Densities of the chironomid midge larvae *Sergentia* sp., which were low in 2005 and 2007, increased in 2009, and *Sergentia* was moderately abundant (c.1000-2000 /m^2) from 2009 to 2021 (except in 2014 when numbers were lower, c.400 /m^2). This taxon is characteristic of moderately

Figure 12.7 Lough Leane, Co. Kerry. Photo: Helena Twomey

productive lakes and, in Leane, has generally reached higher densities after several years of low chlorophyll *a* levels; however, in 2022, *Sergentia* density was relatively low (117/m^2). The pea mussel *Pisidium* sp., which had been recorded on every sampling occasion prior to 1998, was not recorded in the profundal samples from 1998 (following the 1997 algal bloom) to 2003. The mussel was again recorded in small numbers in 2004 and 2005, recovered to a density that was within its normal range of variation in 2007, and remained within that range since 2009.

After the period of perturbation caused by the major algal bloom in 1997, since 2005, the planktonic chlorophyll (algae) in the open lake section of Leane has been compliant with the Water Framework Directive threshold for Good status (or better) without any major fluctuations. This relatively stable period is reflected in the invertebrates of the profundal zone of the lake: the density of the invertebrates has been relatively low, and the density of species that indicate eutrophic conditions is less than that of the more sensitive species. These findings, while encouraging, leave no room for complacency. The report on The Monitoring of the Killarney Lakes 1967 to 1997 (Towmey et al., 1998) concluded that algal blooms in Leane are likely to occur when (1) mean total phosphorous concentrations (April-Sept) is more than 0.015 mg/l combined with (2) unusually calm and unusually warm water conditions in the spring and summer period (Figure 12.7). The 1997 bloom was not the culmination of a series of years with increasing algae; in 1997, the mean chlorophyll (May – Sept) was four times the level in the previous year. Heavy rain causing spates with high phosphorus concentrations in the River Flesk, followed by calm, warm weather, could still potentially generate substantial algal blooms. Managing the catchment to minimise phosphorus runoff in spate conditions remains vital.

LOUGH NEAGH

Lake type

Lough Neagh is the largest lake on the island of Ireland, with an area of 383 km^2. The total catchment area draining into Lough Neagh is 4,450 km^2, a small portion of which is in the Republic of Ireland (390 km^2). It is a shallow lake relative to its large size, with an average depth of only 9 m. The maximum depth is 25 m, and the water is of moderate alkalinity (~100 mg/l $CaCO_3$). The lake and its catchment have a complex geology, underlain predominantly by igneous lava of the Antrim group ((Burke et al., 2022). Lough Neagh is a designated area, being an Area of Special Scientific Interest (ASSI 30), and SPA and a RAMSAR site, notable for its wintering and breeding birds; its wetland vegetation, which includes a large number of rare plant species; and the presence of a number of rare invertebrate and fish species. Nevertheless, Lough Neagh was designated as a Heavily Modified Waterbody (HMWB) for legislative purposes under the WFD, as it is considered to be affected by flood prevention measures and impoundments.

The water of the lake is generally mixed and well-oxygenated, supporting a significant commercial fishery, which includes the European eel (*Anguilla anguilla*), pollan (*Coregonus autumnalis*) and other scale fish. The entire Lough Neagh fishing Industry has an estimated turnover of approximately £3 m per year. The lake is also a source of drinking water for over one million people in Northern Ireland. Its main inflows are the Upper River Bann and Blackwater, and its main outflow is the Lower Bann.

Monitoring history

Routine assessment of water quality dates from 1967, after a large algal bloom caused great public concern. A Freshwater Biological Investigation Unit (FBIU) was established in the early 1970s, and so began one of the longest time series of freshwater data on the island of Ireland. Neagh has been a focus of many diverse scientific studies (e.g. Wood and Smith, 1993;

Rippey et al., 2022). The Agri-Food and Biosciences Institute (AFBI), funded by the Department of Agriculture, Environment and Rural Affairs Northern Ireland, currently maintains the monitoring programme, and the data collected continues to help Northern Ireland meet its water quality legislation requirements. Lough Neagh is part of the Environmental Change Network, the UK's long-term ecosystem research network (https://ecn.ac.uk).

The information from this monitoring programme has provided managers and policymakers with valuable information to support the management of the Lough. For example, nutrient source apportionment models (e.g. McElarney et al., 2015) help determine the catchment sources of nutrients and whether they are from point or diffuse sources. While the monitoring programme was initially set up to investigate the inflowing nutrients that resulted in the algal blooms, the focus of the work has changed over the years. As well as external sources of nutrients, Lough Neagh also has a large mass of nutrients stored in its sediment that has accumulated over many years (Rippey et al., 2021). During the summer, these nutrients can be released and can have negative impacts on the water quality. The long-term data has been used to characterise and quantify the mass of phosphorus released from the Lough sediment, concluding that the amount of P released from the sediment will impact lake recovery for many decades (Rippey et al., 2022).

Impacts and signal of change

In addition to helping set water quality objectives, the long-term research has also demonstrated just how rapidly the lake water temperature is increasing (Figure 12.8), especially since the mid-1990s. From the late 1960s to the mid-1990s, water temperature at 10 m depth was variable and showed no trend;

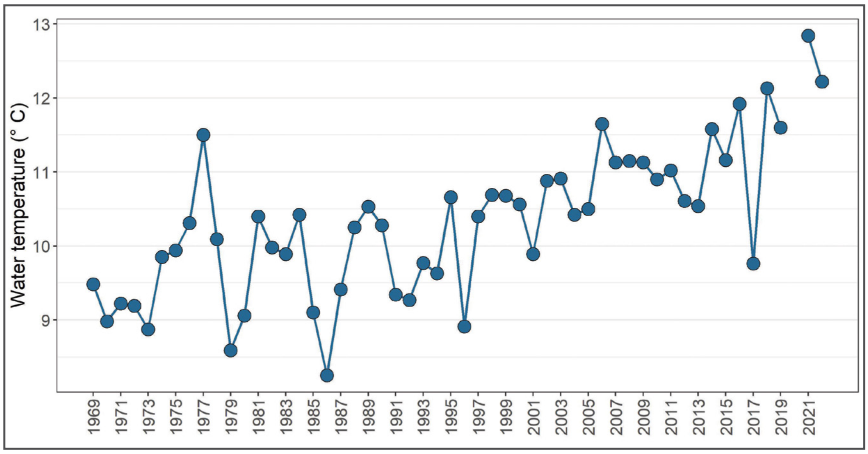


Figure 12.8
Average annual water temperature in Lough Neagh at 10m depth.

Figure 12.9
Chlorophyll *a* in Lough Neagh composite sample, 1995 – 2022, composite sample.

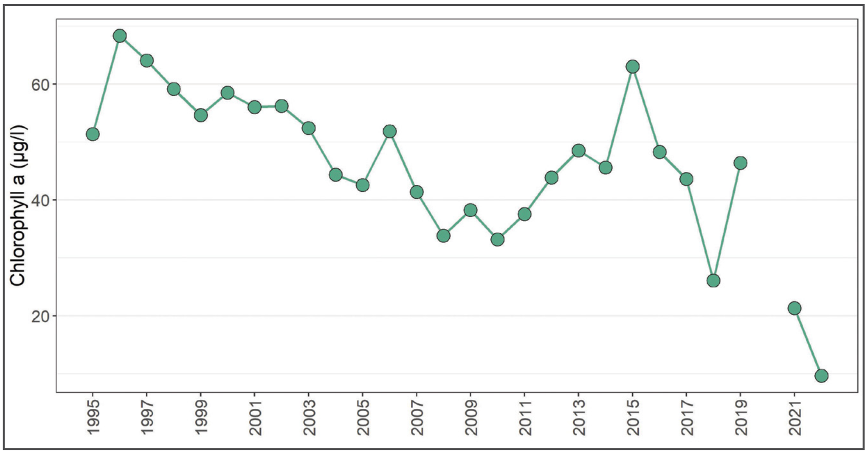


Figure 12.10
True-colour satellite image from 4 September 2023 showing algal bloom conditions on Lough Neagh in Northern Ireland. Source: European Union, Copernicus Sentinel-2 L2A imagery.

the average of this period was approximately 10°C. From the mid-1990s, the mean annual water temperature has been rapidly increasing, and the average value from the mid-1990s to 2022 was almost 11°C. Although the increase in water temperature may appear modest, it still has the potential to have wide-ranging impacts on all elements of lake chemistry and biology. Diverse lake processes, from nutrient cycling to fish breeding, are influenced by water temperature. It's important to note that the increase has occurred throughout most of the water column, not just the surface water. Recent summer heat waves, in part, drive this increase in annual lake water temperature, and these heatwaves appear to be more frequent.

Changed conditions in the lake, such as the observed increase in water transparency, altered nutrient ratios and increased water temperature (e.g. McElarney et al., 2021), allow different algal taxa to proliferate (Elliott et al., 2016). These blooms can release toxins, and their eventual decay uses up oxygen, leading to stress on fish and other lake dwellers. Although the lake has experienced an overall annual decrease in phytoplankton biomass (Figure 12.9), likely due to the expansion of zebra mussels and some years of summer nutrient limitation, the algal bloom in 2023 was greater than usual and was dominated by different algal taxa (*Dolichospermum* and *Microcystis*) than usually occurs (*Planktothrix*). The 2023 bloom received global media attention and expressions of concern. It was visible from space by September, and the image captured by the Sentinel-2 L2A satellite shows large accumulations of blue-green algae on the eastern shore (Figure 12.10). Government scientists are working closely with fisheries and other stakeholders to try to mitigate the impacts of these changes.

LOUGH ERNE

Lake type

The Lough Erne lake system is in a designated cross-border UNESCO site, the Cuilcagh Lakelands Global Geopark. The system comprises two large, linked, nutrient-enriched lakes, Upper and Lower Lough Erne. The Upper Lough is 34 km^2 in size and has an average depth of 2 m. The much larger Lower Lough (110 km^2) has a mean depth of 12m, is 69 m at its deepest point, and is of moderate alkalinity (79 mg/l $CaCO_3$). This deep area of the Lower Lough occasionally stratifies in summer. The entire lake is designated as a Heavily Modified Waterbody (HMWB) for legislative purposes under the WFD due to its two hydropower stations (Cliff and Cathleen's Falls) and flow regulation on its outflowing river. The Lower lough is underlain mostly by carboniferous limestone. A local saying describes the Lough as having an island for every day of the year, and these numerous islands are an important attraction for tourists and recreational activities such as boat cruising, kayaking, swimming and angling that contribute to the local economy.

Monitoring history

In 1973, the Freshwater Biological Investigation Unit (FBIU) began water quality monitoring of the Erne system, which was then taken over by AFBI. Water quality monitoring and research on Erne is supported by the Department of Agriculture, Environment and Rural Affairs, Northern Ireland. The Lough Erne system is part of the Environmental Change Network, the UK's long-term ecosystem research network (https://ecn.ac.uk). The catchment of the Lough has had relatively little intensification, and the lake has retained moderate water quality in relation to nutrients. The research carried out by AFBI assists with the management of the lake, and the monitoring data show significant changes resulting from the impact of invading species (McElarney et al., 2015).

Impacts and signal of change

European eel is an important component of the fish stocks of Erne but has been impacted by the presence of hydroelectric stations, blocking the migration of glass eel and elvers into the lake and silver eel out of the lake. A conservation eel fishery programme transports a proportion of these migrating eels safely past the hydroelectric stations (~50% of the total production), as there is significant mortality during periods of electricity generation (Technical Expert Group on Eel, 2022). The only commercial fishery on the lake is for pike (*Esox lucius*). Although there is some debate around how and when pike arrived in Erne (Pedreschi et al., 2014; Ensing, 2015), there is no doubt now that, in addition to perch (*Perca fluviatilis*), rudd and bream are well established. After roach first appeared in the Lough in the 1960s, it rapidly became the most abundant fish in the Lower Lough (Rosell et al., 1998). Zebra mussels have also spread in the lake since their introduction in 1996. The mussel can now be found on almost all hard surfaces in the lake, and their presence has had a devastating effect on the phytoplankton biomass (Figure 12.11) and the native freshwater *Anodonta* mussel (Maguire et al., 2003). The invaders keep arriving with the latest introduction being the crustacean,

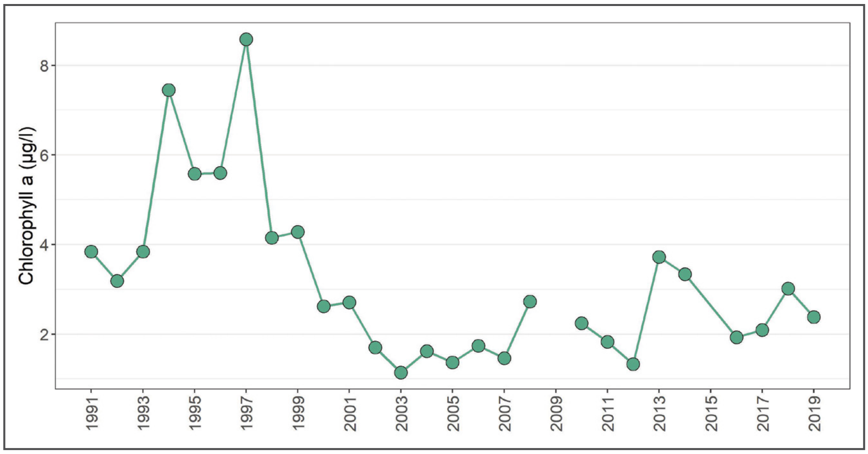


Figure 12.11
Chlorophyll *a* of Lower Lough Erne 1991 to 2019. Annual averages are calculated from composite samples

Figure 12.12
Lough Erne. Photo Yvonne McElarney

the Bloody Red Shrimp (*Hemimysis anomala*), in the Upper Lough in 2015 (Gallagher et al., 2015). This crustacean is a voracious predator and is known to prey on the eggs and larvae of the already endangered pollan (*Coregonus pollan*), a glacial relict fish (Gallagher et al., 2010). The consequences of these frequent invasions, in combination with changing climatic conditions, leads to the conclusion that the ecosystem of Lough Erne is in a state of flux, and continued monitoring will be essential in determining realistic conservation measures (Figure 12.12).

LOUGH FEEAGH

Lake type

Lough Feeagh is an oligotrophic, humic freshwater lake located in Co. Mayo. Humic means the lake water is brown, as it is fed by rivers and streams draining the upstream peat bogs. It is the smallest lake included in this chapter, with a surface area of 3.95 km^2, but is the largest lake in the Burrishoole catchment, lying in the Nephin Beg mountains and draining into the northeast corner of Clew Bay. The lake is 48 m deep, with an average depth of 13 m. Similar to many of the lakes along the western seaboard, Feeagh has a predominate base geology of quartzite and schist, leading to low alkalinity water (-2.7 to 7.5 mg/l $CaCO_3$). It is situated in a wet, stormy part of Ireland with an average rainfall of 1.7m and prevailing winds coming from the southwest, straight off the Atlantic Ocean. Average monthly wind speeds are high at 5.0 $ms^{-1,}$ and the lake is subject to multiple storms in any year, including during summer (Andersen et al., 2020). Commercial coniferous forest covers a quarter of the freshwater catchment with afforestation starting in the 1950s (Dalton et al., 2014). The other major land use is hillside grazing by sheep. Feeagh lies within the Owenduff/Nephin Complex SAC (Site Code: 000534), which is one of the best and largest examples of intact blanket bog in the country.

Monitoring history

The Burrishoole catchment is unique in terms of the long-term monitoring effort that centres around its diadromous fish populations of Atlantic salmon (*Salmo salar* L.), Sea Trout and European Eel, all of which pass through Lough Feeagh on their way to and from the Atlantic Ocean. Diadromous fish are species that move between freshwater and marine habitats for parts of their life cycle. Monitoring commenced following the establishment of a research station on the eastern shore of Lough Feeagh in the mid-1950s, operated by the Salmon Research Trust, funded by the Guinness family. Throughout the 1980s, Guinness gradually phased out its involvement and in 1990, they gifted the SRT to the Irish state. It was then run as the Salmon Research Agency of Ireland until 1999, when it was amalgamated into the Marine Institute. While the main work of the research station focused on fish, the role of climate and catchment processes in determining fish production was not ignored. Increasing concern in the 1980s about how land use changes such as afforestation and overgrazing were affecting the catchment kick-started a concerted effort to monitor the lakes and rivers upstream of permanent fish traps. These traps fully enclose the freshwater part of the Burrishoole catchment at the base of Feeagh and capture all migrating salmon and trout, and adult eel. Since the early 2000s, there has been an increased focus on limnological studies of Feeagh, including high-frequency (sub-hourly) measurements of physicochemical variables and monthly spot samples of water chemistry and plankton. Much of this data has been published as part of collaborative projects with academic partners, and with colleagues as part of the Global Lake Ecological Observatory Network (www.gleon.org).

Impacts and signal of change

Lough Feeagh has not been impacted by the type of significant nutrient enrichment described for other lakes in this chapter, as intensive agriculture and wastewater discharges are not present in the catchment. Nevertheless, reconstructions of the ecological history of Lough Feeagh using palaeolimnology revealed significant changes in the ecosystem in the second half of the 20th century. These manifested as an aquatic biotic response (phyto- and zooplankton) to peat-soil erosion and nutrient enrichment associated with the onset of commercial conifer afforestation. These effects were subsequently enhanced as a result of increased overgrazing in the catchment (Dalton et al., 2014) These pressures have had less impact in the last twenty years, and monitoring data indicates that the ecosystem of Feeagh has been relatively stable recently. The surface water temperature of the lake has warmed at an annual average rate of 0.18°C per decade between 1970 and 2020 (de Eyto et al., 2022), and warming continues into the current decade (Figure 12.13), with temperatures in 2023 being higher (11.85°C) than any other year in the record. This was precipitated by warmer-than-average temperatures all year, but particularly in early summer.

Figure 12.13.
Annual average surface water temperature of Lough Feeagh, 1961-2023 measured at the Mill Race outflow at midnight of each day. Years with incomplete data are removed (1960,1990, 2005). The red line indicates the linear regression between year and water temperature, with the equation temperature = 0.026 (year) – 40.46

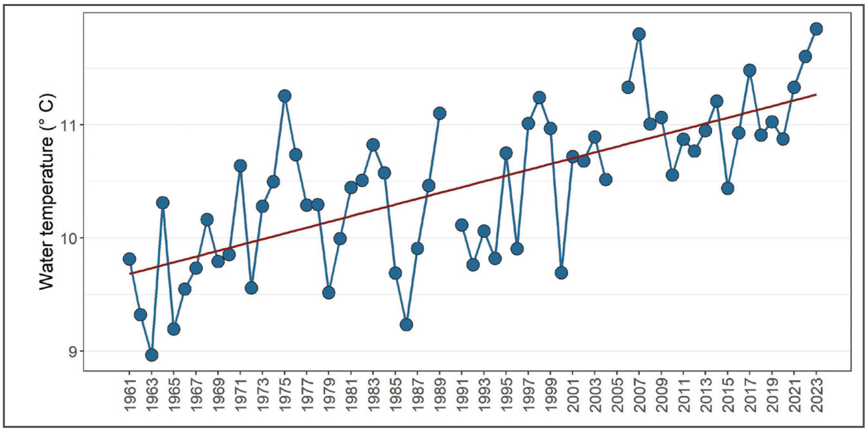
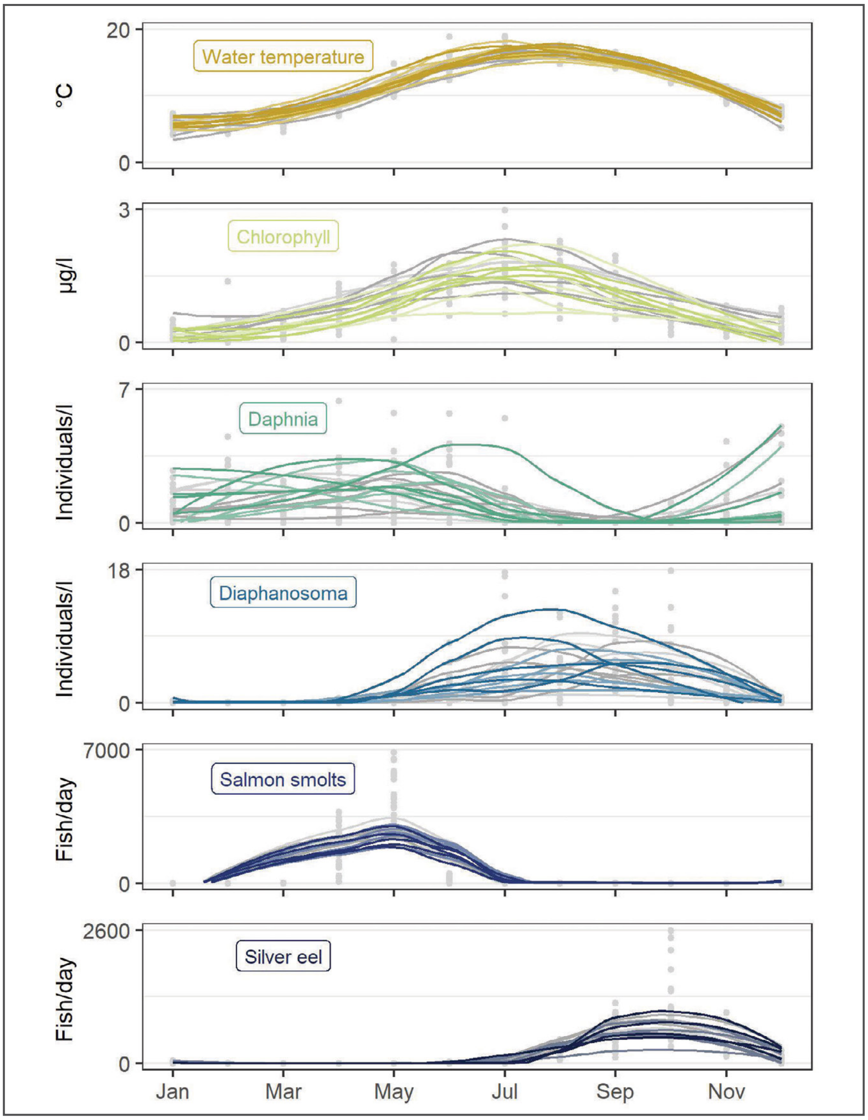


Figure 12.14
Timing of significant biological events in Lough Feeagh, 2024-2023 (timeframes vary according to data availability). Lines are coloured: light grey: 2004-08, dark grey: 2009-13, light colour: 2014-18, dark colour: 2019-23. Data are represented as light grey points and lines are loess smoothers. Outliers have been removed.



With these warming water temperatures, changes in the phenology (or timing) of biological events are expected, as they are intrinsically linked to temperature. This can be observed in the marked seasonality of these events across two decades (Figure 12.14). For example, the growth of phytoplankton (as indicated by the concentration of chlorophyll *a*) increases as the water warms over the year, with maximum biomass observed in mid-summer. While populations of herbivorous zooplankton such as *Daphnia longispina* complex and *Diaphanosoma brachyurum* respond to changes in their food sources, they also respond differently to water temperature and predation, and these bottom-up and top-down forces result in competitive advantages for each species at different times of the years. *Daphnia* does well in colder temperatures, while *Diaphanosoma* increase in late summer. The migration of salmon and eel out of fresh water to the sea is enabled by physiological changes ("smoltification" and "silvering", respectively), which allows a transition to salt water. Temperature is a known driver or cue for the transformation of these changes (Durif et al., 2005). Phenological change within the ecosystem of Feeagh has started to become apparent. Silver eel are now migrating out of the lake and upstream catchment one month earlier than they did in the 1970s. The start of the salmon smolt migration has advanced by 1.8 days per decade (de Eyto et al., 2022). There is some indication that the pelagic community is changing, with the diversity of the size and species of zooplankton decreasing (Calderó-Pascual, 2023). More work and continued monitoring are needed to attribute these changes to climate rather than other variables, such as seasonal availability of nutrients, water discharge from the upper catchment, and top-down control by fish.

LOUGH CARRA

Lake type

Lough Carra is the largest marl lake in Ireland, situated in Co. Mayo and joined to Lough Mask by the Keel River. It is a shallow, predominantly spring-fed lake with a striking turquoise colour and clear waters. Marl lakes are characterised by their calcareous nature, occurring mainly in low-lying limestone terrain. Calcium is precipitated in these lakes and forms fascinating characteristic calcareous encrustations on the lake floor and shores called *krustenstein*, which are a complex combination of inorganic and organic components. The organic component may be dominated by cyanobacteria, with the specific taxonomic composition varying among lake types (Roden, 2001; Doddy et al., 2019a). Owing to their clear water and calcium content, marl lakes also contain distinct macrophyte communities dominated by Characeae and Potamogetonaceae (Pentecost, 2009). Ireland is recognised as having some of the best representations of charophyte vegetation types in Europe, and the combination of invertebrate life and extensive plant beds provides excellent trout habitat. Marl lakes are a priority habitat in Annex I of the EU Habitats Directive (92/43/EEC), where they are identified as habitat category 3140 - hard oligo-mesotrophic waters with benthic vegetation of *Chara* spp. The lake forms part of the Lough Carra/Mask Complex SAC (Site code IE0001774) and the Lough Carra SPA (site code IE0004051), with qualifying interests including its lake habitats, as well as the fens, limestone pavements and alluvial forests that surround it.

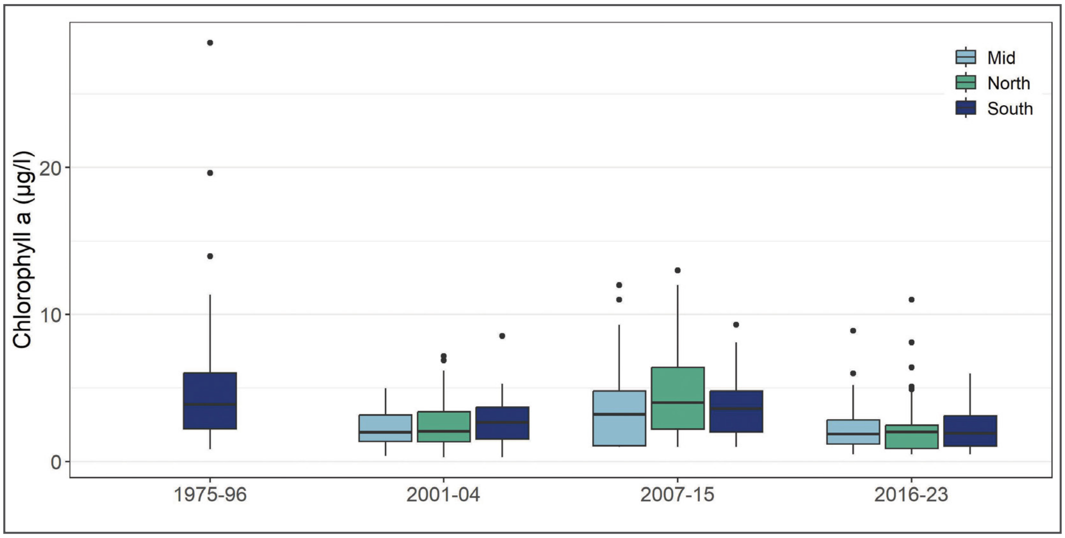
Monitoring history

Lough Carra has been the subject of significant research interest over the years. The EPA also monitors it as part of their operational and surveillance monitoring programs for the national WFD monitoring programme. National Parks and Wildlife Service (NPWS) also commission or conducts work on the lake, owing to its importance from a habitat conservation point of view (e.g. Roden et al., 2020a). Fishery rehabilitation and enhancement works were undertaken in Carra's spawning streams by IFI during the 1990s, and this led to increased recruitment of juvenile brown trout to the lake (O'Grady and Wogerbauer, 2009). IFI surveys the lake for the WFD fish surveillance monitoring programme, and data indicates that the lake supported a healthy stock of brown trout in pre-2009 surveys. However, Perch are the most numerous fish in more recent surveys, with brown trout numbers declining slightly (Corcoron et al., 2020). Pike are considered an invasive species in Carra and are managed as such using appropriate fishing bylaws. Both the NPWS and the EPA consider Carra to be environmentally and ecologically sensitive to nutrient enrichment, eutrophication, clearance of lakeshore vegetation, arterial/artificial drainage and channelisation (of associated catchment streams). Accordingly, Carra was included as a Priority Area for Action in the RBMP for the 2018–2021 period. The local community around Lough Carra are heavily involved in conservation efforts on the lake (see Chapter 20).

Impacts and signal of change

On the face of it, Carra appears to be healthy, having been classified as having 'Good' ecological status for the WFD monitoring period 2016 – 2021, based on monitored physicochemical and biological elements including fish. However, indications of a deterioration in water quality have accumulated in recent decades, with concern regarding the degradation of marl crusts, particularly in the southern basin of the lake (Doddy et al., 2019b), and deterioration in macrophyte assemblages recorded between 2011 and 2018 (Roden and Murphy, 2018). The lake has been the subject of many intensive monitoring and research projects, largely driven by the unique nature of its ecosystem and concern about its ecological integrity. For example, an intensive monitoring programme was carried out between 2001 and 2004 during the EU-funded BUFFER project led by a team at Trinity College Dublin (Irvine et al., 2004). These data, in combination with surveillance monitoring data from the EPA, indicate that there has generally been little detectable change in the formal status of Carra based on average open water nutrient and chlorophyll *a* concentrations, with values generally suggestive of a lake with good ecological quality status. Earlier data, taken from King and Champ (2000), gives a range of 1-28 µg/l of chlorophyll *a*, with a mean value of 5.4 µg/l (Figure 12.15). A more recent EPA dataset shows a higher

Figure 12.15 Chlorophyll *a* measurements from Lough Carra. Data from 1975-96 are taken from King and Champ (2000), 2001-04 from the Buffer project (Irvine et al., 2004) and McCarthy and Irvine (2010), and 2007-2023 from the EPA's data portal www.catchments.ie. Sampling points were matched to the relevant basin where appropriate.



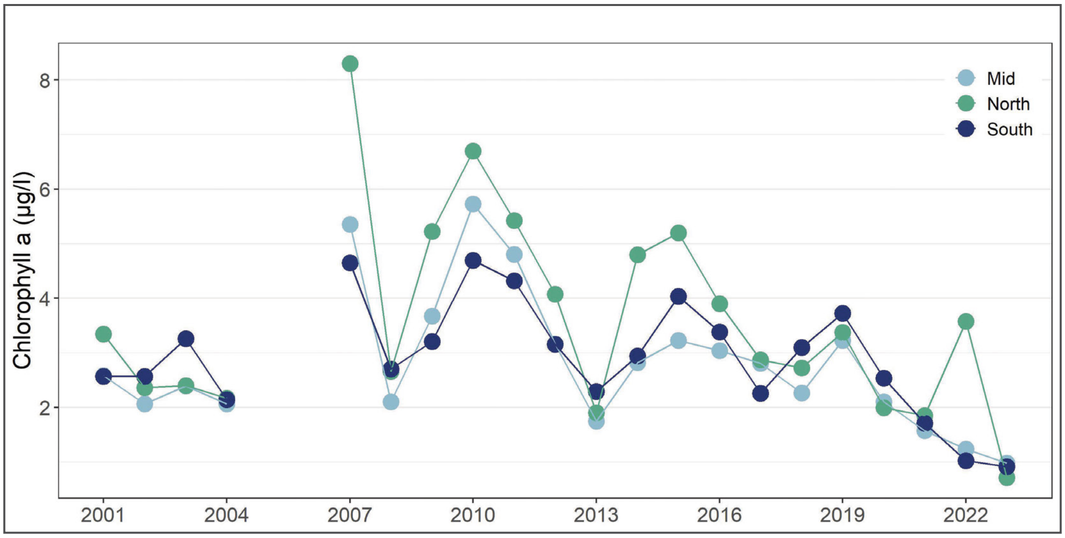


Figure 12.16 Chlorophyll *a* measurements from Lough Carra. Data from 2001-04 are taken from the Buffer project (Irvine et al., 2004) and McCarthy and Irvine (2010), and 2007-2023 from the EPA's data portal www.catchments.ie. Sampling points were matched to the relevant basin where appropriate.

spread of chlorophyll *a* concentrations with higher maximum values recorded across the lake compared with the earlier BUFFER dataset. When viewed over many decades, it appears that average measurements of chlorophyll *a* are trending downwards, which is particularly evident in the last number of years (2020 – 2023; Figure 12.16).

Despite the apparent good status suggested by water quality monitoring mainly measured in the pelagic (open water zone) of the lake, there are ongoing concerns about the ecological health of Carra. An analysis of historical sediment chemistry using paleolimnological techniques in 2002 indicated a consistent increase in sedimentary organic matter, sedimentary phosphorus, and phosphorus accumulation rates from the 1960s to 2000 (Hobbs et al., 2005; Donohue et al., 2010), likely a result of diffuse nutrient pollution. The NPWS considers Lough Carra, overall, to be in poor conservation condition under the Habitats Directive (Roden et al., 2020a). A decline in the condition of vegetation in Carra is evident in the charophyte beds and marl crusts (krustenstein), both of which are vital in ensuring proper ecosystem functioning as a marl lake. In addition, phosphorus can be incorporated into marl crystals, reducing the concentration of phosphorus that is available for biological growth in the water column and consequently reducing phytoplankton production (Wiik et al., 2014) Thus, high densities of charophytes can reduce detectable nutrients in the water column, which instead become sequestered in the benthos and do not manifest as increasing open-water phytoplankton biomass. Consequently, any increase in indicators of phytoplankton production, such as chlorophyll *a* concentrations may only be evident after substantial degradation in the ecosystem has already occurred (Wiik et al., 2015b).

In the sublittoral vegetation surveys of Carra carried out in 2018, *Sparganium emersum*, *Oenanthe fluviatilis*, *Lemna trisulca*, *Ceratophyllum demersum*, *Elodea canadensis* were recorded along with very dense stands of *Schoenoplectus lacustris*. Although these assemblages are considered typical of lowland lakes and ponds, they are not representative of the normal charophyte-dominated vegetation with species-poor cyanobacterial crusts expected from marl lakes in good condition (Roden et al., 2020b). In addition, large stands of *Myriophyllum verticillatum* were found to occur in the South Basin, growing at depths of 4 to 5 m yet forming visible mats on the surface. It was noted that this represented a change in the benthic vegetation in Carra, with records from the early 1900s indicating an almost complete absence of macrophytes apart from those occurring at depth (Roden and Murphy, 2013). The first records of *Chara tomentosa* appeared in the mid-1990s (King and Champ, 2000), and since then, its formation of monospecific stands have displaced previous *Chara curta* vegetation in the North Basin of the lake in the 2011 survey.

Unimpacted marl lakes should be considered to be lakes with low macrophyte biomass, extremely clear water, white sediments and open littoral habitats (Figure 12.17), and degradation in the benthic vegetation of marl lakes may occur long before impact is detectable in the pelagic system (Wiik et al., 2015a). Provisionally, Roden and Murphy (2018) noted that indications of ecological impact for marl lakes on carboniferous limestone can be identified as a decay of marl crust, disappearance of *Chara globularis* or shallower charophyte zones, and/or a Secchi transparency less than 3m. Consequently, for a lake such as Carra, continued emphasis on gaining insight into the mechanisms determining littoral zone ecosystem health is vital, given that these impacts have already been observed in Carra but are barely reflected in water quality indicators in the pelagic zone. Early indications of reduced phytoplankton biomass in the pelagic zone of Lough Carra may signal improvement, but until it is clear whether the impact of eutrophication has been reduced in the benthic and littoral zones, continued focus must

Figure 12.17 Lough Carra, Co Mayo. Photo: Bryan Kennedy

be placed on mitigation measures aimed at reducing inputs of nutrient-rich organic matter and sediments to the system. Further investigation of the role that reported increases in the perch population may have on the lake's trophic interactions and ecosystem health is highly recommended.

CONCLUSION

Hughes et al. (2017) have shown that policy decisions are disproportionally influenced by the availability of long-term data, as the results of such monitoring programmes are often compelling. As long as they are maintained, the analyses of long-term datasets will continue to provide the necessary evidence to guide the answers to complex environmental problems, many of which have not yet become apparent. Jeppesen et al. (2014) have highlighted that due to resource constraints, funding authorities around the world are ceasing their long-term monitoring of freshwaters just at the time when they are needed the most. As we move into an era of climate chaos and biodiversity loss, jointly bringing about a planetary crisis, the need for long-term ecological monitoring has never been more crucial. The occurrence of such long-term data in Ireland for freshwater ecosystems is relatively unstructured at an all-island level. It would benefit from interaction with international networks such as the eLTER (https://elter-ri.eu/) or similar. At the very least, a coordinated effort to collate, preserve and maintain the datasets described in this chapter must be seen as an important investment for future generations.

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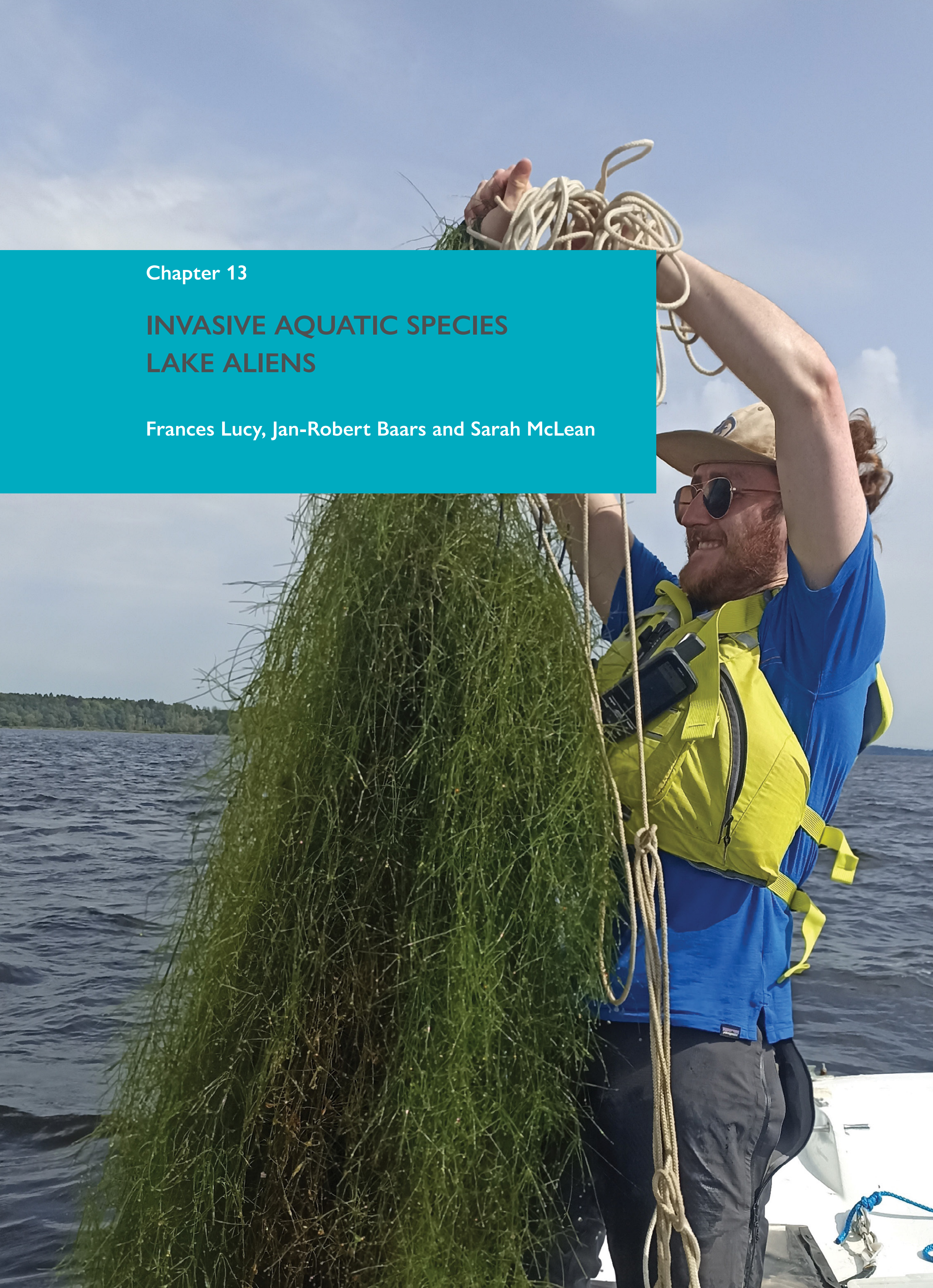

Chapter 13

INVASIVE AQUATIC SPECIES
LAKE ALIENS

Frances Lucy, Jan-Robert Baars and Sarah McLean

SUMMARY

Invasive aquatic species pose significant threats to ecosystems worldwide, including those of lakes in Ireland. Among these invaders, curly weed, golden clam, quagga and zebra mussels have emerged as particularly troublesome occupants. Their introduction often occurs via various pathways, including accidental transport through ballast water or attachment to recreational boats. Once established, these invaders rapidly colonize lake ecosystems, outcompeting native species and altering habitats. The spread of zebra mussels throughout the island of Ireland highlights the challenges of managing such invasions. The influence of environmental stressors like excess nutrients, elevated fine sediments and those related to climate change are singly and in combination likely to influence each alien species with new invaders continually threatening ecosystems. Efforts to control their population and mitigate their impact require a multifaceted approach, involving both preventative measures and active management strategies. Effective management of invasive aquatic species demands a comprehensive understanding of the ecological dynamics (establishment, persistence, success and spread) at play and the implementation of adaptive strategies to safeguard the integrity of lake ecosystems in Ireland and beyond.

Keywords Biological invasions, natural ecosystems, exotic species, naturalized population, invasion risk.

INTRODUCTION

Ireland is an island on Europe's western seaboard, and due to its long-term geographical isolation, there are fewer native species of flora and fauna than in mainland Europe. However, the island of Ireland is highly connected to other landmasses through human transport systems and, therefore, its biotic isolation has been significantly reduced. Given the small number of native species and their restricted range, the potential impacts of invasive species introductions in Ireland are greater than would be expected in mainland Europe (Lucy et al., 2020).

Freshwater systems are acknowledged to be at particularly high risk from biological invasions and the increased numbers of vectors and pathways of introduction and spread have reduced Ireland's biotic isolation, increasing the risk of new introductions and their associated impacts on native biodiversity. It is likely that these risks are greater here than they are in continental European member states, where the native biodiversity is richer (Simberloff, 1995; Stokes et al., 2006; Cabot, 2009). An 'invasive alien species' means an alien species whose introduction or spread has been found to threaten or adversely impact biodiversity, related ecosystem services and the economy.

The biogeography of lakes in Ireland has been outlined in chapters 4, 5 and 6, with descriptions of diverse sizes, level of connectedness within river basins and the location of isolated lakes. Underlying geology in catchments has also been described and the natural water quality of waters in terms of alkalinity, calcium, and pH. These elements are important in terms of the establishment of invasive species in Irish waters. Although a species may become invasive in some lakes, it may not become established in others due to geology or other factors. The case studies later in this chapter will provide some examples.

In 2007, the first attempt was made to compile a list of all aquatic (freshwater, brackish and marine) invasive species in Ireland. In 2007, 112 aquatic alien species were recorded in Ireland of which 68 were thought to be established. Some early introductions (nineteenth century) have become naturalised, most notably the Canadian pondweed (*Elodea canadensis*) and the mud snail (*Potamopyrgus antipodarum*). Various coarse fish species have long become naturalised in lakes and ponds in Ireland, some here as long as the seventeenth century and probably earlier, namely Carp (*Carpio* spp.) and tench (*Tinca tinca*) (see Chapter 6). Other introduced species, the roach (*Rutilus rutilus*), rudd (*Scardinius erthyrophthalmus*) and bream (*Abramis brama*) hybrids continue to be spread to more lakes and may be invasive. Currently, the pike (*Esox lucius*) is considered a native species (Pedreschi et al., 2014), and although this is a matter of debate, what is certain is that this species is a high-impact invader in isolated lakes where it has been introduced. Since the list was compiled, many new taxa, including some high-impact species have arrived in Ireland. In 2017, a horizon scanning exercise indicated that 18 out of the top 40 high-impact invaders expected to arrive in Ireland were freshwater species (Lucy et al., 2020). Freshwater IAS dominated the top ten in this list (seven out of ten) and by 2022, two high-impact freshwater invaders were identified, the Chinese mitten crab (*Eriocheir sinensis*) and the Quagga mussel (*Dreissena rostriformis bugensis*), the latter now well established in parts of the Shannon system, and without effective management is likely to spread as widely as the zebra mussel by 2030.

The international consciousness on aquatic invasive species was awoken with the arrival, in the 1980s, of the zebra mussel in the Great Lakes of North America. Similarly, it was the arrival of this well-known high-impact freshwater shellfish species, native to the waters of the Caspian and Black seas, that sounded alarm bells in Ireland for lake ecosystems. Further invasions of invasive alien species are presented in this chapter. Although not an exhaustive account, those chosen demonstrate their introduction, spread, and impacts in the face of climate change and multiple stressors. The challenges of managing invasive species are then discussed with some recommendations for future actions.

PATHWAYS OF INTRODUCTION, ESTABLISHMENT OF SPECIES

In the last fifty years, anthropogenic activity has led to a sharp increase in global connectivity (Ruiz and Carlton, 2003; Hulme, 2021). Increases in rates of introduction of invasive alien species have been observed in all habitats. In addition to the increased rate of movement of people and trade, climate change will influence species distributions by affecting potential species ranges.

There are multiple pathways by which a species can move to habitats beyond its native range. A pathway is a route through which a potentially invasive species can be introduced into a new environment outside its native range with further pathways of spread once introductions are made. The dispersal capabilities of aquatic organisms coupled with anthropogenic use of freshwater systems and the interconnectivity of watercourses (Ricciardi, 2001), means that freshwater systems such as lakes are more at risk from invasive species than terrestrial systems. In the case of freshwater systems, the main pathways for invasive species are linked to human activities both recreational and commercial. Broadly speaking, there are four of these:

Ships and boats. Invasive species can be dispersed as a result of ballast waters, water trapped in other crevices in the craft, or as fouling organisms attached to hulls or caught in the mechanisms of the vessel (Gherardi et al., 2009). Aquatic plants entrained on trailers, boats or fishing gear can carry other small invasive shellfish or crustacean species on them and result in subsequent simultaneous introductions.

Deliberate stocking. Many invasive species have been deliberately introduced into non-native freshwater systems to create recreational angling opportunities, promote commercial wild fisheries and fulfil the cultural desires of human populations (Gherardi et al., 2009). An example of this was the introduction of the chub to the Inny River in the 1990s (Caffrey et al., 2008) and the amphipod *Gammarus pulex* as food for fish (Strange and Glass, 1979).

Ornamental/pet trade/aquarium. Subsequent instances of release, escape and reproduction of the ornamental species that result in species introductions (Copp et al., 2010; Strecker et al., 2011). Typical for aquatic plant introductions including the curly weed *Lagarosiphon major* in Lough Corrib, and *Stratiotes aloides* in Lough Derg (Minchin and Higgins, 2021).

Interconnectivity of waterways. The Shannon-Erne waterway, where two major systems are connected by canal (Shannon-Erne waterway) was the pathway of spread of the zebra mussel in the 1990s and Asian clam after 2010, detailed later in this chapter.

Whether the species becomes established or not will depend partly on some site specificity conditions and the composition and timing of individual invasions. However, if the habitat and water chemistry are favourable the probability is increased when there are multiple introductions and when the number of introduced individuals is large enough to reproduce and form a successful new life cycle. There is no magic number, however, and in some hermaphroditic species e.g., the Asian clam, only one individual can create a whole new population. Species with high rates of reproduction, e.g., zebra mussel or those which can reproduce from plant fragments, e.g. curly weed also have a high probability of establishment and further spread to other waters. There are cases where introduced species may become invasive only after a long undefined period known as a lag phase. Species may persist at low densities in aquatic systems during this phase challenging their detection and management.

IAS from a wide variety of taxonomic groups have the potential to transform freshwater ecosystems (Strayer, 2010; Simberloff et al., 2013). Of particular concern is the phenomenon whereby the introduction of invasive species may also bring the introduction of associated pathogens. The introduction of pathogens associated with the introduction of their native host species has the potential to upset ecological interactions in the invaded system (Havel et al., 2015) and may not be as obvious as the host species invasion. In aquatic systems, the internal organs of fish and crustaceans provide a pathway for the introduction and dispersal of pathogens (De Schryver and Vadstein, 2014).

An example of an aquatic pathogen which is having a significant impact on Irish lake species is the swimbladder nematode *Anguillicoloides crassus*, an eel-specific parasite endemic to Eastern Asia where its native host is the Japanese eel *Anguilla japonica* (Moravec and Taraschewski, 1988; Nagasawa et al., 1994). Worldwide, the spread of *A. crassus* is facilitated by both natural and anthropogenic inter- and intra-catchment movement of eels (Belpaire et al., 1989). *A. crassus* was first identified in Ireland in 1998 (Evans and Matthews, 1999). European eels *Anguilla anguilla* suffer more severe pathological effects than *A. japonica* as a result of *A. crassus* due to a lack of host-parasite co-evolution between the species (Kirk, 2003). In *A. anguilla*, fibrosis caused by *A. crassus* burrowing through the swimbladder wall causes a thickening of the wall (Van Banning and Haenen, 1990). The pneumatic duct can also become blocked (Kirk et al., 2000). Alteration of swimbladder function may significantly reduce swimming performance leaving eels more susceptible to predation and capture (Sprengel and Lüchtenberg, 1991; Barse and Secor, 1999). The effects of *A. crassus* on the swimbladder are long-lasting and do not diminish during the silver eel's migration in salt water. This damage can interfere with buoyancy control and cruise speed, thus reducing the likelihood that the eel will complete its migration and contribute to recruitment (EELREP, 2005). *A. anguilla* with heavy *A. crassus* burdens also show reduced ability to withstand stress and are thus more susceptible to secondary infections (Kirk, 2003).

Once an invasive species has been introduced further regional spread can occur through natural and human pathways in the recipient ecosystem. The ultimate success of the invasion and the significance of its impacts is dependent upon the efficiency of this secondary spread (Lodge et al., 1998) and the efficacy and application of biosecurity decontamination methods by relevant stakeholders (e.g., check, clean dry campaign).

IAS SPREAD ON THE ISLAND OF IRELAND

Zebra Mussels

The zebra mussel arrived on the island of Ireland, in Lough Derg, on the Shannon system sometime between 1993 and 1994 (Minchin and Moriarty 1998; Minchin et al., 2002b), although it was not discovered until 1997 (McCarthy et al., 1997). The means of introduction was via the importation of second-hand boats with attached zebra mussels (Pollux et al., 2003); a window of opportunity for invasion occurred in 1993 when there was an increased number of second-hand boat imports to Ireland from Britain (Maguire, 2002) related to changes in European law. By the late-1990s, zebra mussels had spread to the Upper Shannon system (Minchin et al., 2002a) and to the Erne (Rosell et al., 1999). In Republic of Ireland (RoI), spread occurred subsequently to the Great Western Lakes (Conn, Corrib, and Mask), and the midland lakes (Sheelin, Ennell and Owel). The zebra mussel was first reported in Northern Ireland in 1998 in Lower Lough Erne (Rosell et al., 1999) and in the greatest lake, Lough Neagh in 2010 (McLean et al., 2010). Before 2005, at least 58 water bodies throughout the island of Ireland were known to be infected (Minchin and Lucy, 2003). These water bodies included all of the Shannon, Boyle, and Erne systems. By June 2007, there were 308 regions/lakes known to be infected. Of these, 47 regions/lakes are isolated from the three main systems infected, thus highlighting the importance of overland transport of boats and associated equipment as vectors for introduction.

In the summer season, once water temperatures reach 15^0C, adult zebra mussels can produce tens of thousands of larvae per female per year and, therefore, populations can increase exponentially in just a few years (Lucy, 2006). Larvae are produced in summer, settling within 2-3 weeks as juveniles on the hard lake substrates, on native shells and aquatic plants. Once established, zebra mussels can spread naturally downstream to connected lake systems, or when lake bodies become temporarily connected due to flood events (Lucy et al., 2008). They also settle on boat hulls, which in addition to attached plants and fouled equipment, provide an effective pathway of spread when no biosecurity measures are taken.

Zebra mussels can expand populations very rapidly in a lake system, e.g. Lough Key, a 9km^2 lake in the Upper Shannon, where in 2002 within six years (estimated) of introduction, their biomass and density were at their maximum exponential phase at 4.2 kg x 10^6 and 5,900/m^2 in 2002 (Lucy et al., 2005), remaining at 2.1kg x 10^6 and 640/m^2 in 2015. A similar time frame for maximum population size was observed in Lough Erne (Maguire, 2002)

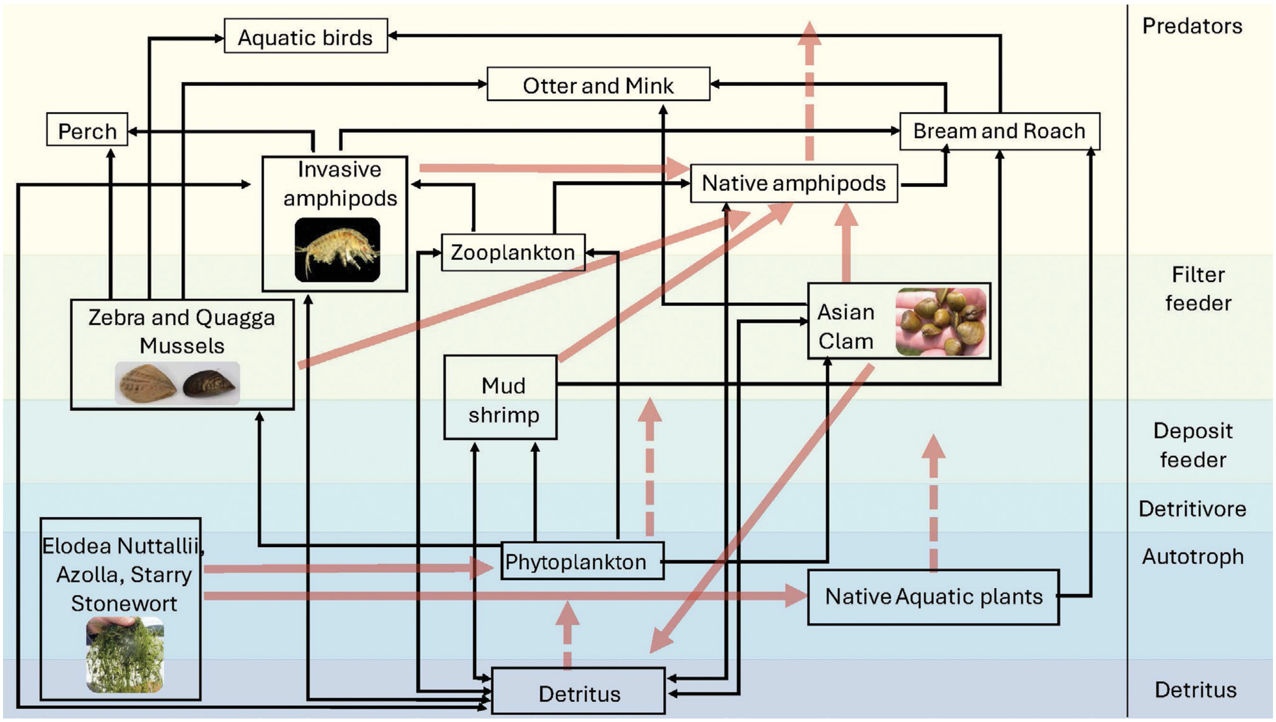

Figure 13.1
Trophic food web.

and Lough Sheelin (Millane et al., 2008). Alternatively, a long lag phase may result in populations remaining low for many years after establishment before exponential growth occurs. For example, in Lough Neagh where the first mussels observed were on the hull of a boat from Kinnego Marina (McLean et al., 2010) it was likely that the introduction was of a few adult mussels. The Lough Neagh zebra mussel population exhibited a lag between introduction and population expansion (McLean, 2012) and was slow to expand in terms of both population density and range. While introductions to Loughs Erne and Key on the Shannon navigation are likely to have been repeated via many individual boaters, the introduction to Lough Neagh, an isolated lake, may have been at one location and a single event involving the movement of adult mussels in low densities. Introduction to Lough Sheelin has been attributed as a deliberate introduction(s) to 'improve' water quality for anglers.

Zebra mussels will not spread to acid lakes with a low pH (<7.4) and will not thrive unless alkaline conditions are present as they require calcium for shell growth (Karatayev et al., 2015). Therefore, their distribution has been limited to areas where limestone occurs in lake catchments and they have not spread to acid lakes in Connemara, or to those in the north-west, south-west or east, even where salmonid angling is popular.

Figure 13.2 The quagga mussel *Dreisenna rostriformis bugensis* attached to boat (top left); the golden clam *Corbicula fluminea* from Lough Ree (bottom left); the stary stonewort *Nitellopsis obtusa* forming dense beds in Lough Derg (centre); the amphipod *Gammarus pulex* collected in Lough Ramor (above); three invaders golden clam, quagga and zebra mussel -mutual facilitation (below); the aquatic macrophyte *Lagarosiphon major* collected by weed cutting boat (bottom right). (Photos: Jan-Robert Baars).

A three-year study of Lough Key (2001-2003) determined that six years after the appearance of small numbers of zebra mussels were noted in the lake, the population had reached 34 billion and was capable of filtering the entire lake volume in a ten-day period (Lucy et al., 2005) and in 20 days in 2015. The impact of this filtering on the lake ecosystem was a significant decrease in phytoplankton, and increased transparency resulting in a greater abundance of native aquatic plants close to shorelines, some of which were highly colonised by zebra mussels during the early years of colonisation. Increased benthic aquatic plants and algae are a direct response to resultant increased transparency and continued bioavailability of nutrients for growth. The greatest direct ecological impact was on the native duck mussel *Anodonta anatina*. These were heavily colonised by the zebra mussels resulting in in an extinction in the lake by 2001 (Lucy et al., 2005). The knock-on impacts of this ecosystem engineer are illustrated in the trophic food web (Figure 13.1).

Zebra mussels also result in social and economic costs. Zebra mussel shells have accumulated on some lake shores and can cause cuts to bathers and other recreational users, leading to risks of secondary infections, e.g., weils disease. The economic costs of zebra mussels are significant and ongoing for water abstraction as screens, pipework and plant machinery become blocked or infiltrated by zebra mussels.

Since its discovery in the Barrow River in 2010 the golden clam spread to Lough Derg, the River Shannon and upper Lough Ree (Minchin, 2014), the Erne River in 2017 and River Foyle in Northern Ireland. It is now widespread in the Shannon catchment and major tributaries and is present in all the lakes, some in high densities. The mechanism of spread within a watercourse is predominantly downstream (Minchin & Boelens 2018) but between water bodies is unclear but, likely linked to human activities, some possibly even deliberate. A substantial proportion of lakes in Ireland are suitable for colonisation by the Golden Clam (Lucy et al., 2012).

Plants that propagate asexually through fragmentation pose a significant risk of secondary spread. Fragments untreated and entangled on equipment or that lie undetected in damp conditions on crafts are easily transferred to new water bodies. The slender stems of the starry stonewort, (*Nitellopsis obtusa*) an invasive macroalgae in Ireland easily go undetected on boats and equipment (Flynn et al., 2024).

NEW INVADERS

Despite the routine/periodic evaluation of the alien species likely to arrive through known pathways, new taxa are being detected as established more frequently than ever, some while horizon scanning is in process. The list of recent invaders includes some of the most significant species with a global reputation of impact. The quagga mussel, a species similar to zebra mussel, was detected in 2021 (Baars et al., 2022) but appears to have been established in Ireland since 2016/17 (Flynn et al., 2024). Now in its exponential growth phase, it is expected to outcompete zebra mussel on hard substrates and establish on soft sediments increasing overall densities in lakes. Presently confined to the lakes in the Shannon catchment, like the zebra mussel, the quagga mussel is likely to spread to the rest of the water bodies in Ireland in the coming decade. As an ecosystem engineer, the quagga mussel threatens to fundamentally change the water properties (e.g. water clarity and nutrients) and biota (e.g. macroinvertebrates and fish) of invaded lake ecosystems.

Little is known about the impact and even distribution of many of the more recent introductions, like *Crangonyx floridanus* (Baars et al., 2022), *Chelicorophium curvispinum* (Lucy et al., 2004), and *Hemimysis anomala* (Minchin and Boelens, 2010). The challenge remains to determine how these species impact the relatively unique complex of native fauna and flora and environmental context of lakes on the island of Ireland (see Figure 13.1). Those species that do not have a preceding reputation based on past introductions elsewhere may still pose a significant threat to the lake ecosystems in Ireland especially if the combined impact is considered. Even species native to mainland Europe but not Ireland have had a significant impact and pose a serious future threat. For example, *Gammarus pulex* was introduced to supplement the food for hatchery fish and escaped and now dominate and outcompete native amphipods. Similarly, the macroalga *Nitellopsis obtusa* has recently been established in lakes in the Shannon catchment where it forms monospecific beds totalling over 100s of ha in Lough Ree alone (Flynn et al., 2024). Even vertebrates like the Alpine newt (*Ichthyosaura alpestris*) have been established widely in the midlands and pose a threat to the native invertebrates and vertebrates in small bog lakes and woodlands.

MANAGEMENT

Biosecurity includes all measures to prevent the introduction and spread of invasive species and the resulting disruption of IAS pathways is a fundamental aspect of any management plan. Currently, there is no overall guiding policy on IAS management for the island of Ireland and given the transboundary nature of biological invasions, the island of Ireland is susceptible to the introduction of IAS from either jurisdiction (Lucy et al., 2022). Unfortunately, there are no dedicated resources at ports and airports on the island of Ireland to check for the presence of invasive species on boats, trailers, or fishing gear. Legislation in the RoI – principally Article 49 of EC (Birds and Natural Habitats) Regulations 2011 – and in Northern Ireland (NI) – Wildlife and Natural Environment Act (NI) 2011 – prohibit the introduction and dispersal of introduced species in their own jurisdictions. Brexit has complicated matters also as the EU Regulation on Invasive Alien Species (1143/2014), which obliges all member states to prevent and manage the introduction and spread of 88 IAS, is only legally binding in the RoI. As a positive step, both Angling and Recreational Boating and Watercraft Pathway Action Plans have been produced in RoI for the management of the freshwater pathways in compliance with the regulation. While the 'Check, Clean, Dry' code of practice to prevent spread is promoted and utilised at fishing competitions, there is no legislation yet in place to ensure that boats are certified as clean when moving between waters. The spread of zebra mussel throughout Ireland has shown that although many angler/boater stakeholders may be conscientious about boat and gear cleaning, the combined impact of code and legal enforcement is needed to manage spread. One shortfall of the Check-Clean-Dry campaign (now acknowledged in the UK) is the lack of consideration for the need to disinfect, particularly to prevent the spread of parasites and pathogens (e.g. *Gyrodactylus*, Crayfish plague). The Conservation Actions for the Natura Network Interreg project implemented a biosecurity route, biosecurity facilities and signage at Lough Arrow to prevent the spread of the invasive Nuttall's pondweed from the lake (Garland et al., 2022). The response to disinfection methods may be species or life-stage specific which makes the recommendation of a single product to ensure biosecurity more complicated. Any use of disinfection must be shown to be effective (extremely high kill rate), especially under real-life conditions (e.g. trailered boats).

Once it becomes established in a lake, the decision to control a species on an annual basis may relate to the regional importance of the waterbody.

An example would be the annual management programme for curly weed (*Lagarosiphon major*) carried out by Inland Fisheries Ireland in Lough Corrib and supported by several organisations since 2013 (Morrissey et al., 2021). Curly waterweed was first confirmed in Lough Corrib in 2005. It spread rapidly and widely in this large lake in subsequent years, primarily as a consequence of boating and angling activities. This plant is a known high-impact invader and has been on the European IAS since 2016. In littoral habitats to 5m deep, the plant can form extremely dense surface vegetation canopies at the water surface. These impede navigation, angling, and water movement, as well as blocking light from penetrating the water column to enable photosynthesis among submerged native plants. Research conducted by IFI developed a suite of control procedures that included hand pulling in shallow water, mechanical cutting using V-blades and harvesting and covering the weed with light-occluding jute matting (Caffrey et al., 2010). These methods have been employed by a dedicated weed control team working on Lough Corrib under IFI direction from 2013 to date. Weed management operations to date have achieved significant control of this invasive weed as few surface vegetation canopies are currently evident on the lake and water-based activities can continue, unobstructed by the weed. In addition, the risks posed for native macrophytes, macroinvertebrates and salmonid fishes are minimised. This management programme in Lough Corrib has cost in the region of €4 million and the annual cost of managing the weed in the lake is more than €300,000. In the absence of this control, Lough Corrib would also have been lost as a world-class, wild salmonid fishery and many of the protected species and habitats for which the lake is renowned would have been compromised. The net loss to the environment, and the local and Irish economy, would have been appreciable (Lucy et al., 2022).

COMPLEXITIES OF IAS LAKE INVASIONS

The establishment, persistence, success and spread of invasive species in lakes is dependent on the environmental conditions. The success of an invasion is facilitated by similarities between the recipient and native ranges and compatibility with the invasive species tolerances and introduction effort or 'propagule pressure'. The prevailing conditions in lakes that affect the success of an invasive species are largely predetermined by the surrounding catchment. The human activities that influence the inputs into the lake can have a considerable influence on the potential impact of IAS on the lake ecosystem. Excess phosphorus utilised by plants and phytoplankton had a major influence on the invasion of zebra and now quagga mussel (Karatayev and Burlakova, 2022). The combined influence of environmental stressors like excess nutrients, elevated fine sediments and those related to climate change like average temperature, the amount and timing of precipitation and extreme events and CO_2 levels are singly and in combination likely to influence each IAS (Stephens et al., 2019). Many of the lakes in Ireland now have a complex of aquatic species that occupy all the different trophic levels, e.g. autotrophs, detritivores, filter feeders and predators (see Chapter 5). How these interact with each other and with native species that form the communities will be determined by each species' response to multiple stressors including climate change. Where native species rely on climate refugia to avoid impact from invasive species, thermal increases may lead to significant changes (Hesselschwerdt and Wantzen, 2018). The outcome of climate-induced change may not be of benefit to the IAS (Stephens et al., 2019). However, many of the high-impact aquatic invasive species are expected to have wider ecological tolerances and are, therefore, more likely to cope with climate-induced changes. Some taxonomic groups of IAS seem more likely to lead to a rapid change in the ecosystem, especially in shallow lakes (Reynolds and Aldridge, 2021).

CONCLUSION

In this chapter, several case studies are presented which clearly demonstrate pathways of introduction, establishment, impacts and management of IAS in lakes in Ireland. However, cognisance must be given to the fact that there are many other IAS which occur in lake systems that are not covered in this chapter, but which have significant impacts on native flora and fauna. IAS from a wide variety of taxonomic groups have the potential to transform freshwater ecosystems (Strayer, 2010; Simberloff et al., 2013). In addition, the reader should consider that there are many door-knocker species which may invade at any time given the overall lack of biosecurity to prevent introductions of invasive alien species to Irish waters.

RECOMMENDATIONS

Education and outreach from primary school upwards on the threat of invasive species to the biodiversity in Irish lakes, should be included in core texts with materials and training provided by competent authorities and via researchers.

An all-Ireland approach is truly needed particularly as many lakes, including Lough MacNean and Lough Melvin, are cross border including contingency plans.

Checks at ports and airports and the implementation of legislation for certification of boats and equipment moving between waterbodies would reduce the risk of the spread of invasive species between lakes.

Routine monitoring is required targeting the hotspots, led by experts, to ensure the early detection of species which will facilitate a rapid response if appropriate and required.

A long-term funding mechanism is required to support research on the status of invasive species in lakes and how single or multiple species can be effectively managed in future. Basic ecological research is required to support evidence-led management.

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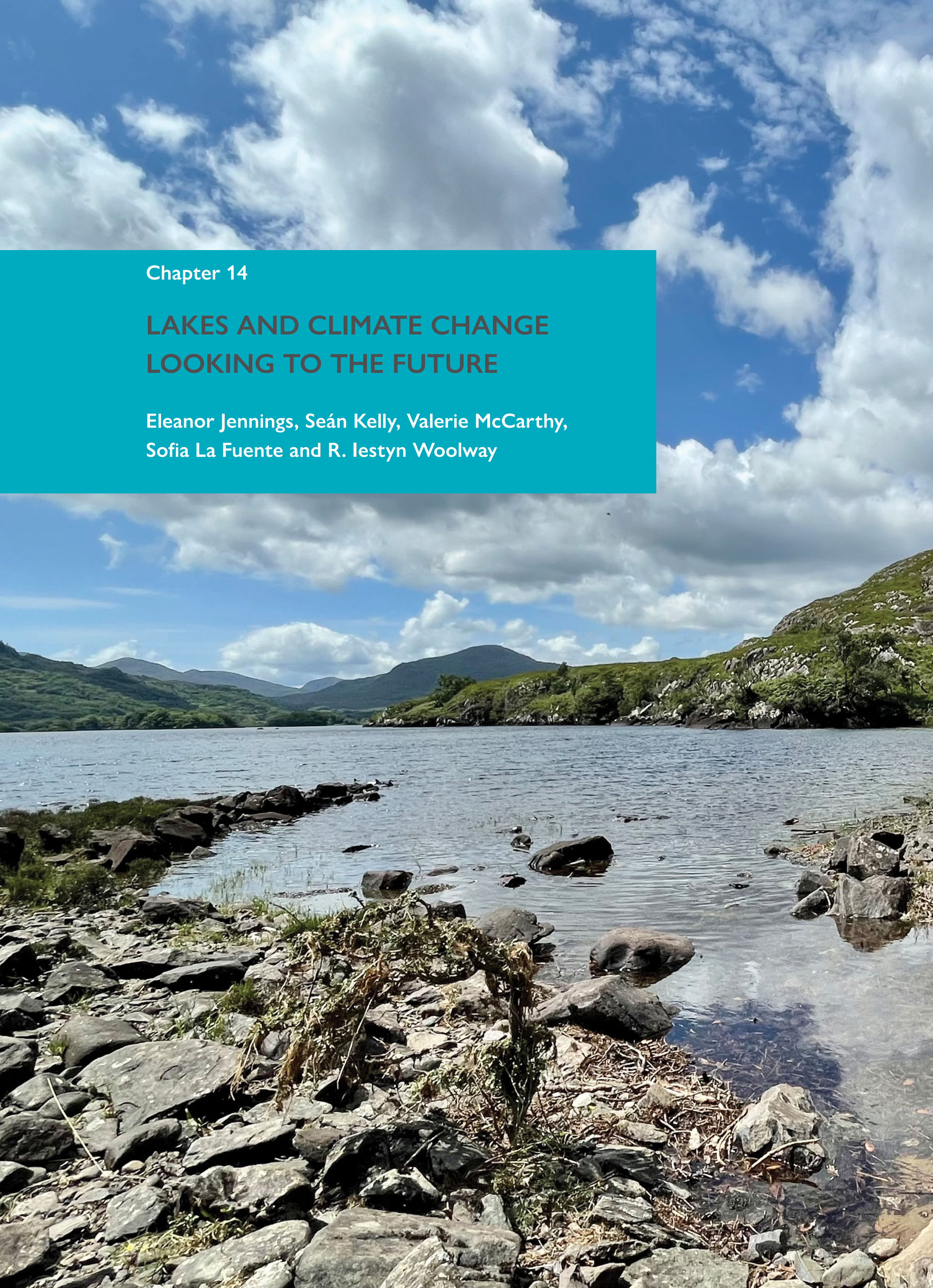
Chapter 14

LAKES AND CLIMATE CHANGE LOOKING TO THE FUTURE

Eleanor Jennings, Seán Kelly, Valerie McCarthy, Sofia La Fuente and R. Iestyn Woolway



SUMMARY

The island of Ireland sits on the Atlantic fringe of Europe and has a temperate oceanic climate, with few temperature extremes but with high rainfall and frequent storms. These conditions influence how our island ecosystems function. Lakes are especially sensitive to changes in local weather due to a high degree of connectivity to their surroundings. They are linked to the atmosphere through the air-water interface and to the catchment through their river network. High rainfall and river flows dictate that lakes in Ireland have relatively short water retention times, generally less than a year. Stratification of the lake water column is also often weaker than at sites that are in more continental locations but at similar latitudes. Our climatic conditions have, however, been changing due to global warming, and are projected to change further over the coming decades. These changes have the capacity to fundamentally alter how lakes in Ireland function. While there are multiple studies describing the effects of climate in general on our lakes, there are fewer that have quantified these future impacts. Projected changes at the catchment scale include increases in winter inflow rates and associated nutrient export, with decreases during summer. Within the lake itself, surface water warming is predicted to enhance stratification which will become more prolonged and more intense. These more stable, calm conditions will further increase the risk of nuisance algal blooms occurring. Freshwater fish that are cold-water adapted will be particularly sensitive, especially our native salmonids. Warming during winter, when developing fish eggs are vulnerable, is, therefore, a major threat. Mitigation and management of all these changes will be the key challenge facing those overseeing Ireland's lacustrine systems in the coming decades.

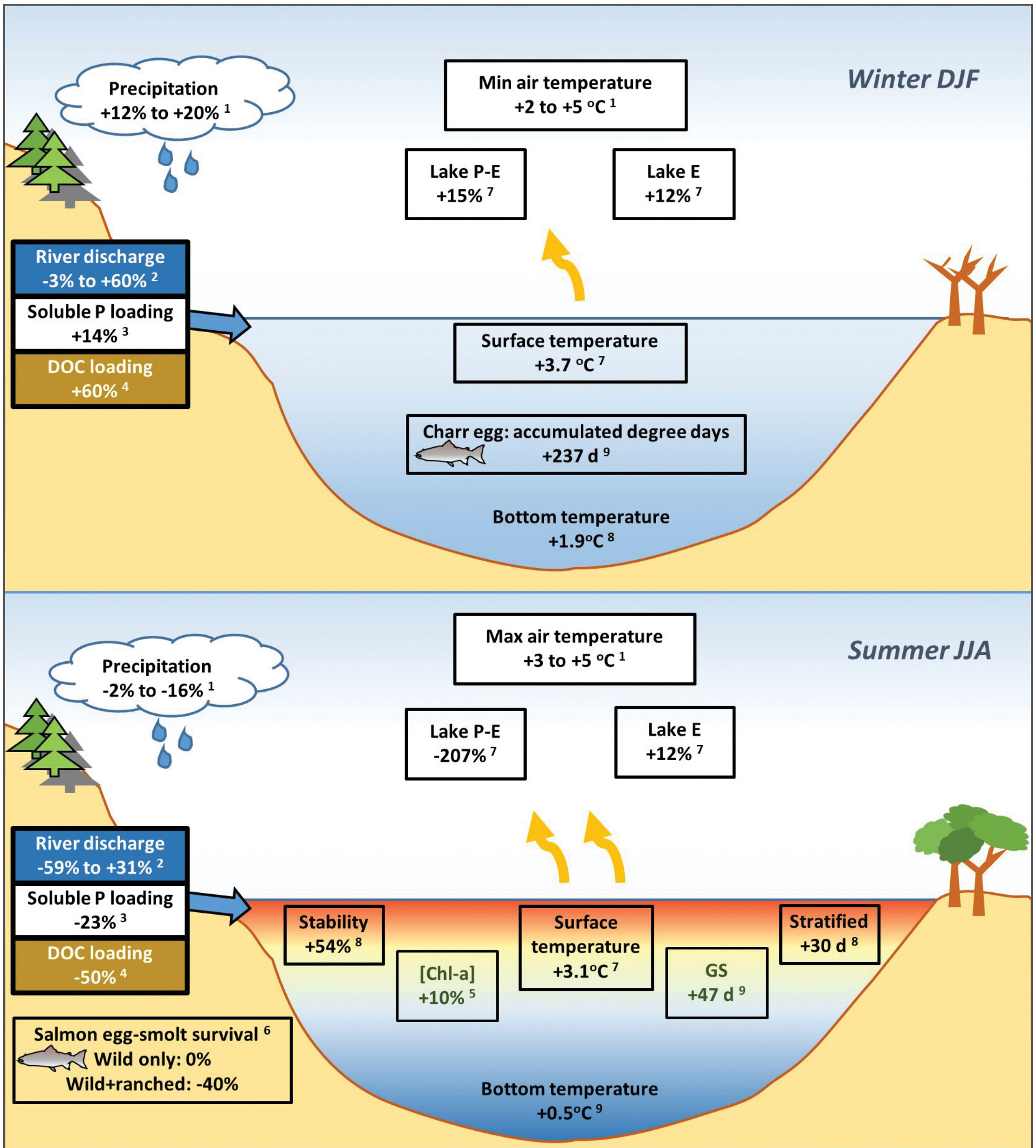
Keywords Global warming, modelling, lake physics, lake biota, freshwater fish, multiple stressors

INTRODUCTION

Lakes occupy a unique position in the Earth's ecosystem. Not only are their waters in direct contact with the underlying geology and sediment but they are also linked to both the surrounding catchment and downstream aquatic systems through the river network. In addition, the surface waters share a direct interface with the atmosphere, an air-water boundary that controls the exchange of energy and gases. It is through these multiple connections that lakes experience changes in the state of the atmosphere, changes that we commonly refer to as weather. This unique position in the landscape also means that lakes can integrate longer-term climatic signals, including those that occur at seasonal, annual, and decadal timescales. Multiple studies, most recently summarised by the International Panel for Climate Change (IPCC, 2022), have long concluded that the Earth is now experiencing the impacts of human-related global warming and that it will continue to be affected over the coming decades. Indeed, historical assessments have shown that globally, the Earth's population has remained on a trajectory that has followed the more pessimistic scenarios for the emission of greenhouse gases (GHGs) (Pedersen et al., 2021). Even if stringent measures were implemented immediately to reduce emissions, it is predicted that warming will continue until at least the mid-twenty-first century (IPPC, 2022). Because of both their central position within the landscape and their strong connectivity, lake ecosystems will be strongly impacted by these changes (Jennings et al., 2022a).

Due to its location as a small island on the fringe of the Atlantic, Ireland experiences a temperate oceanic climate. This results in mild winters and summer temperatures that are cooler than locations at similar latitudes. Lakes in Britain and Ireland are particularly sensitive to weather systems moving across the Atlantic (George et al., 2010). To date, in-lake responses to historical changes in weather have received far more scientific attention in Ireland than studies that assess future change. The sparsity of site-specific studies has been due, in part, to the data and computational requirements for such investigations (see Highlight Box). Projecting future change requires, as a first step, the calibration and validation of dynamic models of lake

Facing page: Figure 14.1 Overview of climate change impacts based on Irish studies for winter (top) and summer (bottom) for a higher GHG emissions scenario (either A2 or RCP8.5). Details for the GHG emissions scenario, the future time period and site/s are included in the table at the base. GS = phytoplankton growing season. P-E = precipitation-evaporation, Soluble P = Soluble phosphorus; DOC = dissolved organic carbon, d = days



1. O'Brien and Nolan (2023): RCP8.5; ICHEC ensemble (2071-2100); range for all island.
2. Murphy et al. (2023): RCP8.5; ICHEC ensemble (2070-2099); range for 26 Irish catchments.
3. Jennings et al. (2009): A2; 3 GCMs (2071-2100); Flesk catchment, Kerry.
4. Naden et al. (2010): A2; 3 GCMs (2071-2100); Glenamong River, Mayo.
5. Dalton et al. (2016): A2; 3 GCMs (2071-2100); L. Leane, Kerry.
6. McGinnity et al. (2009): A2; 2 GCMs (2071-2100); L. Feeagh, Mayo.
7. La Fuente et al. (2024) : RCP8.5; 4 GCMs (ISIMIP 2b ensemble) (2070-2099); 18 Irish representative lakes.
8. Ayala et al. (2023b): RCP8.5; 4 GCMs (ISIMIP 2b ensemble) (2070-2099); L. Feeagh, Mayo.
9. Kelly et al. (2020b): RCP8.5; 4 GCMs (ISIMIP 2b ensemble) (2070-2099); L. Bunaveela, Mayo.

ecosystem processes. This step needs suitable observed data from the target sites. The models are then run using future weather data that has been output for Ireland from large-scale General Circulation Models (GCMs). In addition to site-specific studies, however, information on potential effects on our lakes is now becoming available as part of larger regional or global scale assessments (e.g. Woolway et al., 2021; La Fuente et al., 2024).

Research on historical and current responses to climate also has its own data requirements. Investigations of longer-term trends, for example, need to span multiple decades so that patterns related to regional-scale climatic signals, such as the North Atlantic Oscillation, are accounted for (George et al., 2010). In contrast, short-lived climate extremes, such as storms and heatwaves are best captured using high frequency monitoring (i.e. sub-daily), usually collected using in-situ sensors that measure a suite of variables in the lake water column (Jennings et al., 2022b). Multi-decadal datasets are still relatively scarce for Irish Ecoregion lakes, but those that are available have proved invaluable in assessing change in response to a range of pressures (see Chapter 12 for case studies from Loughs Neagh, Leane, Erne and Feeagh). To date, high-frequency monitoring of lakes has also been deployed at a few sites on the island. Examples include the lakes in the Burrishoole catchment, Co. Mayo (e.g. Kelly et al., 2020a; de Eyto et al., 2016), and Lough Namachree, Co. Monaghan (Crockfort et al., 2015). All these data sources contribute to a growing body of work describing how lakes function in our variable climate, including, for example, the way in which climatic signals are modulated and integrated through the catchment-lake continuum (Kelly et al., 2020a).

Future projections for Ireland from the most recent high-resolution climate models indicate that, in the coming decades, mean summer temperatures and the frequency of anomalous heatwave events will increase. At the same time, wind speeds will decrease, particularly under the more severe warming scenarios (Nolan and Flanagan 2020). Conversely, increases in the frequency and magnitude of storms are also expected. This chapter aims to review the effects of such changes on lakes on the island of Ireland. We include indirect effects, through the links to the catchments, and direct effects related to warming and climate extremes on lake physics, biogeochemistry, and biota. We summarise impacts that have been quantified for Ireland for the highest emissions scenarios as an example of what the future may hold should the Earth continue our current high GHG emission trajectory (Figure 14.1). We also discuss these changes in the context of other stressors that together with global warming represent major challenges for lake research and management in the coming decades.

CLIMATE CHANGE IMPACTS ON CATCHMENT PROCESSES

All the water that flows through lakes will have previously interacted with the catchment soils and river networks. Historically, annual rainfall in Ireland has been relatively high, ranging from 800 mm year^{-1} in the east to over 2000 mm year^{-1} in the west, and over 3000 mm year^{-1} in western upland areas. This drives elevated levels of river discharge and, therefore, affects lake flushing rates. Most lakes in Ireland have short retention times, often less than one year, making them especially responsive to changes in their catchments. Generally, research on the impacts of global warming for Irish catchments has been dominated by changes in flow rates and there have only been a handful of studies on water quality or nutrient export. More generally in the global literature, the number of studies quantifying climate change impacts on nutrient export remains low, a fact that has been highlighted by Bol et al. (2018). Assessments from Irish sites have included changes in the export of phosphorus, nitrogen, dissolved organic carbon (DOC: a proxy for dissolved organic matter), and microbial loads.

Global warming modelling for the period 2020-2100 indicate wetter winters and drier summers, with air temperatures increasing in all seasons (Nolan and Flanagan, 2020; O'Brien and Nolan, 2023) (Figure 14.1). An assessment of 26 Irish catchments estimated that the resultant change in river discharge would vary from site to site, but with a general pattern of higher flows in winter, lower flows in summer and a less certain direction of change in spring and autumn (Murphy et al., 2023). For the highest emissions scenarios, changes ranged from -3% to +60% in winter and from -59% to +31% in summer (Figure 14.1). These shifts in the seasonal pattern will affect downstream lakes, with increased inflow in winter and potentially lower lake levels in summer. At the same time, increases in extreme flood events are also expected throughout the year. Groundwater-fed systems such as turloughs may be especially vulnerable. Morrissey et al. (2021) found that the pattern of flooding at turloughs in the west of Ireland is likely to change significantly under climate change scenarios, with higher mean flood levels over longer durations. Flooding of turloughs may, therefore, become more regular. This seasonality in flow is also reflected in projections for future nutrient and microbial loads. A suite of modelling studies for European catchments was undertaken between 2003-2005. It included two Irish sites: the River Flesk, an inflow to Lough Leane (Co. Kerry), and the Glenamong River, an inflow to Lough Feeagh (Co. Mayo). The estimated phosphorus loads from the Flesk for the end of the century (2071-2100) were 14% higher in winter but were -23% lower in summer for the highest GHG emissions scenario, A2 (Jennings et al., 2009) (Figure 14.1). However, the export of nutrients will also be affected by other human-related factors. By further including some of these projected changes, Jennings et al. (2009) also estimated that policy-driven increases in national cattle stocking rates had the potential to result in even higher exports, especially in spring and early summer, a time when the risk of algal blooms is greatest. They also estimated, however, that shifts in the timing of slurry spreading to avoid risk periods could mitigate this effect. A more recent assessment for an intensively monitored agricultural Irish catchment found that climate change alone may increase the average annual total phosphorus concentration from the 0.120 mg P/L observed between 2010-2019 to 0.184 mg P/L by 2070-2100, an increase of over +50% (Mellander et al., 2023).

For DOC export from the Glenamong River, a peatland catchment, a similar seasonal pattern of change was projected. Future changes in DOC loads exported included an increase of 60% in winter and a decline of -50% in summer (Naden et al., 2010) (Figure 14.1). However, autumn peaks in concentration and export were also amplified due to higher rates of summer peat decomposition and higher autumn flows. O'Driscoll et al. (2018) separately assessed changes in DOC loads but for the River Boyne (Co. Meath), a primarily agricultural catchment that is also a source of drinking water. In contrast to the peatland site, they found that the future DOC load would be similar to that currently observed. This lack of any effect was due to an offset in two processes: increases in concentration and decreases in summer flows. For potable water supplies, however, the DOC concentration is of most concern, as this is linked to the formation of toxic by-products during water treatment that have human health implications. Only one other study has examined any chemical or biological aspects of water quality for Irish catchments. Effects on microbial loads were assessed for the River Black in Co. Galway and the River Fergus in Co. Clare for the period 2041–2060 (Coffey et al., 2016). Here again, the changes in the load tracked seasonal fluctuations in streamflow, with greater relative increases in the winter and reductions in the summer. In this case, however, land use change was a greater contributor to future increases in microbial loading than climate change.

CLIMATE CHANGE IMPACTS ON LAKE PHYSICS

As might be expected, the physical environment in lakes in Ireland is directly modulated by our oceanic climate. Consequently, global warming will have the capacity to substantially alter lake physical structure. Currently, extremes between winter and summer limnology are less apparent in our lakes than at other locations at similar latitudes. Regular ice cover is absent, with ice formation typically being a phenomenon related to rare cold snaps. Irish summers are also highly variable. Spells of hot, sunny weather, conducive to the formation of vertical thermal stratification of the water column, are typically broken up by cooler, windier conditions (see Chapter 1). Storms are also relatively common, even in summer (Andersen et al., 2020) (Figure 14.2). It is, therefore, unsurprising that several limnological studies have highlighted that some lakes in Ireland, particularly those that are more shallow, can exhibit transient summer stratification, a physical regime termed polymictic. These include, for example, small lakes in Co. Clare (Allott, 1996), Lough Melvin (Girvan and Foy, 2006), and even the larger Lough Neagh (Wood et al., 2000). Lakes with substantial areas of deeper water may sustain a seasonal unbroken period of stratification under warm calm conditions (a monomictic regime) (Figure 14.2). Even at these sites, however, stratification is often weak and easily perturbed by high winds.

During summer, heat input via the lake surface will be larger than any loss through surface water cooling. This net warming intensifies stratification once the wind force remains either unchanged or decreases. Since climate projections for Ireland indicate higher summer temperatures, together with more frequent and intense heatwaves and lower wind speeds, many lakes that are currently polymictic may have prolonged periods of unbroken stratification in the future. These more extreme heating events have been defined as 'lake heatwaves' and are projected to change stratification patterns across many regions (Woolway et al., 2021). Lakes on the island of Ireland that currently show monomictic regimes may, therefore, experience both an increase in the duration of stratification, and a more stable structure less easily destroyed by storms. However, it should be stated that the mixing regime has only been characterised fully for a small number of Ireland's ~14,000+ lakes (Dalton 2018) and that those are mostly confined to western regions. The perceived convention of weak, ephemeral stratification may apply to some lakes along the Atlantic coastline. Lakes located further inland already show patterns of prolonged unbroken summer stratification. This is true even in small, shallow lakes (mean depth 5-6 m), such as Lough Namachree, Co. Monaghan

Figure 14.2 Stormy and calm conditions on Lough Feeagh, Co. Mayo. Top: High winds will contribute to mixing the lake water column. Below: calm, warm conditions result in stratification of the water column. Photo: Mikkel René Andersen

(Crockford et al., 2015) and Lough Augher, Co. Tyrone (Rippey, 1983). Such midland lakes may be more vulnerable to intensified stratification in the future. These conditions may result in hypoxia in the bottom waters when they become depleted in dissolved oxygen, and associated water quality deterioration when sediment-bound nutrients are released (Crockford et al., 2015).

In general, however, a detailed overview and understanding of lake physics in the Irish context is lacking. Studies often include a basic assessment of the physical structure of the water column to provide a backdrop for a biogeochemical or ecological study. Without a process-based understanding of the drivers of lake physical dynamics, accurately predicting how climate change will affect individual lakes will remain challenging, given the diversity of lake sizes and shapes on the island, our oceanic climate, and factors such as variable water transparency and inflow levels. The main sites where detailed investigations have been undertaken include the large lakes of the Galway-Mayo region. These illustrate the complex pathways through which the physical structure in lakes can respond to climate. Lough Mask (Co. Mayo), for example, responds in a complicated manner to wind stress across its surface, owing to its complex topography that includes a shallow littoral zone connected to a large deep basin (Bowyer, 2001). This topographically driven flow drives mixing in the deep interior, which modifies the thermal structure in summer and contributes to an overall weak stratification, despite the 60 m deep water column. In nearby Lough Corrib (Co. Galway/Co Mayo) another large, topographically complex lake, faster rates of cooling in shallow embayments generate offshore currents of colder water which invigorate overturning and mixing in the deep interior waters (Cannaby et al., 2007). Such topographically induced mixing may inhibit complete isolation of the deeper interior waters and prevent deep-water deoxygenation from affecting the oxy-thermal habitat of any cold-water fish that inhabit the profundal zone. A more detailed knowledge of such physical dynamics will help to inform on how these lakes will respond to future climate conditions. A similar mechanistic understanding of the response of small- and medium-sized lakes to climate forcing is needed, however, given the preponderance of these lake types across Ireland.

Only a small number of modelling studies have assessed the implications of future climate change on lake physical and thermal dynamics. Simulations for Lough Leane (Co. Kerry) comparing surface water temperatures between a historical climate period (1961-1990) and a future projection period (2071-2100) found that the largest changes would occur during summer,

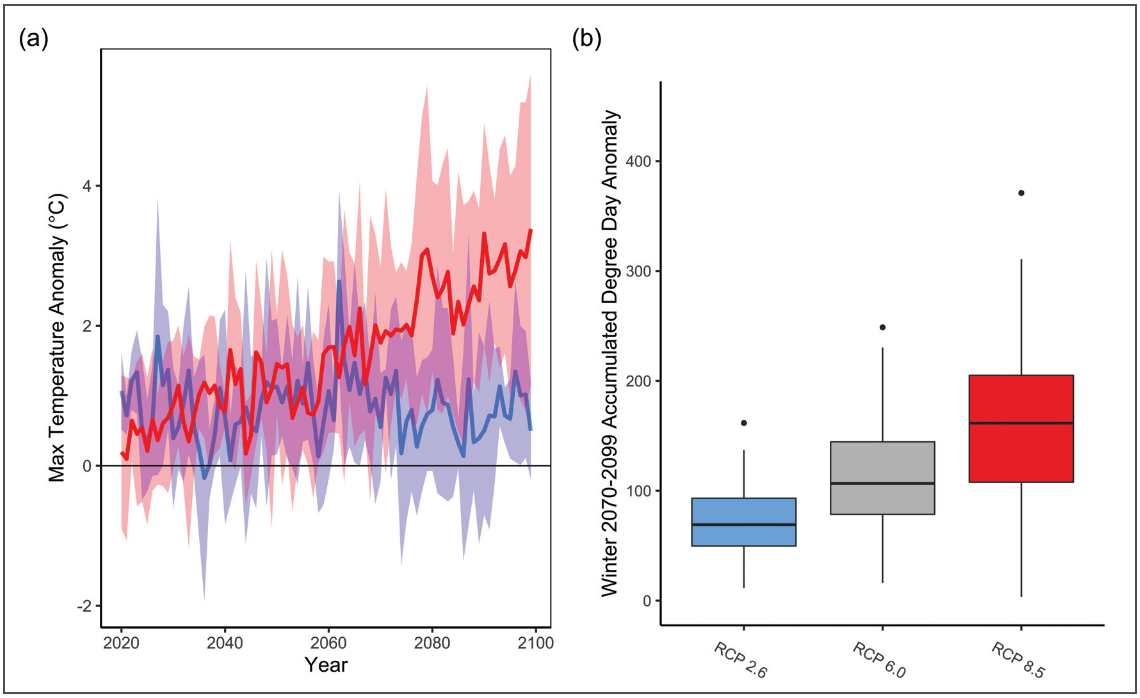


Figure 14.3 projected climate change impacts on Arctic charr at Bunaveela (Co. Mayo); a. time series of winter water temperature anomalies for RCP 2.6 (blue) and 8.5 (red); b. accumulated degree days in winter (November – December) for RCPs 2.6 (blue), 6.0 (grey), and 8.5 (red). Anomalies are between a reference period of 1975–2005 and a future period of 2070–2099 (after Kelly et al., 2020b).

with increases of ~4 °C in peak temperatures under the high emissions (A2, see Highlight Box) scenario (Dalton et al., 2016). The winter limnology of a small mountain lake, Lough Bunaveela (Co. Mayo), was modelled under future climate scenarios motivated by concerns over the fate of the relict Arctic charr population still inhabiting the lake (Kelly et al., 2020b). Results indicated that under the most severe emissions scenario (RCP 8.5, see Highlight Box), mean winter water temperatures could be 3-4 °C warmer in 2070-2099 compared to the period 1976-2005 (Figure 14.3a). Of note was that the lake showed less warming under future climate scenarios than other lakes in the same study from England (Windermere) and Central Europe (Lake Geneva and Lake Bourget). Whether this was related to its smaller size or less severe climate projections for Ireland was unclear.

Aside from such impacts on winter limnology, warming winter temperatures could have physical effects that propagate into spring and summer, for example by setting the upper temperature of deep water at the onset of stratification. An analysis of long-term observed historical surface water temperatures from a range of sites globally has shown that, for the larger Lough Feeagh (the lake immediately downstream of Bunaveela), winter temperatures have warmed more rapidly over the past decades when compared to summer temperatures (Woolway et al., 2019).

The most detailed assessment for any lake in Ireland of projected changes in stratification and heat transfers between the atmosphere and the surface waters is contained in two papers published recently for Lough Feeagh, Co. Mayo (Ayala et al., 2023a, 2023b). This work has highlighted some of the complexity of future climate change impacts. End of century mean lake surface temperatures in winter were predicted to increase by 2.0 °C, with a 2.6 °C increase in summer (Ayala et al., 2023a). The study reported an increase of similar magnitude for winter bottom temperatures of 1.9 °C, but a lower increase for bottom temperatures in summer (0.5 °C) (Figure 14.1). Overall, this warming was predicted to increase water column stability in summer by an average of 54%, extend the period of stratification by 30 days and extend the phytoplankton growing season by 47 days. Substantial modifications of lake surface heat fluxes were also simulated for the same lake, with lower spring heating but less cooling in autumn, the period when most heat loss to the atmosphere occurs (Ayala et al., 2023b). The net effect across the year was still an increase in whole-lake average temperature.

Global-scale investigations of climate change impacts are now becoming more common and can be used to give an insight into future changes for lakes on the island of Ireland. These are usually based on outputs from a set of GCMs together with simulations from ecosystem models (see Highlight Box). The models are run for a single, generic lake in every grid cell on the globe that contains lakes (Golub et al., 2022). These single sites are referred to as 'representative lakes'. Their depth and surface area are based on the average information for that cell from the Global Lakes and Wetland Database. There are 18 such 'representative lakes' used in these studies for the island of Ireland. To give an example of future changes for the island, data were extracted for the Irish representative lakes from one recently published dataset (La Fuente et al., 2024) for three key physical properties: 1. surface water temperature, 2. lake surface evaporation and 3. the net change in the balance of the precipitation minus lake surface evaporation. On average, the assessment showed that the annual surface temperature for representative Irish lakes was projected to increase by 2.8 °C (31%) by the end of the current century for the highest emissions scenario (RCP 8.5), with lower increases for the two other emissions scenarios: +0.9 °C and +1.9 °C for RCP 2.6 and 6.0 respectively (Figure 14.4 and Table 1).

Average lake evaporation increased by between 8% and 12% depending on the RCP, with a lower percentage change for the balance between precipitation minus evaporation (range: -6% to 1%).

Table 14.1 Lake surface temperature, lake evaporation and the balance of precipitation minus evaporation under historical (reference) and future scenarios of climate change for Irish representative lakes. Historical is the average for the period 1970-1999. Representative Concentration Pathways (RCP) 2.6, 6.0 and 8.5 values are the average for the period 2070-2099. Changes are quoted relative to the 1970-1999 reference period average.

Variable	Scenario	Value	Change	
			Absolute	Percentage
To [°C]	Historical	9.1	-	-
	RCP 2.6	10.1	0.9	10
	RCP 6.0	11.0	1.9	21
	RCP 8.5	12.0	2.8	31
Evaporation [mm day^{-1}]	Historical	1.7	-	-
	RCP 2.6	1.8	0.1	8
	RCP 6.0	1.8	0.2	10
	RCP 8.5	1.9	0.2	12
P-E [mm day^{-1}]	Historical	1.9	-	-
	RCP 2.6	1.8	-0.1	-3
	RCP 6.0	1.8	-0.1	-6
	RCP 8.5	1.9	0.0	1

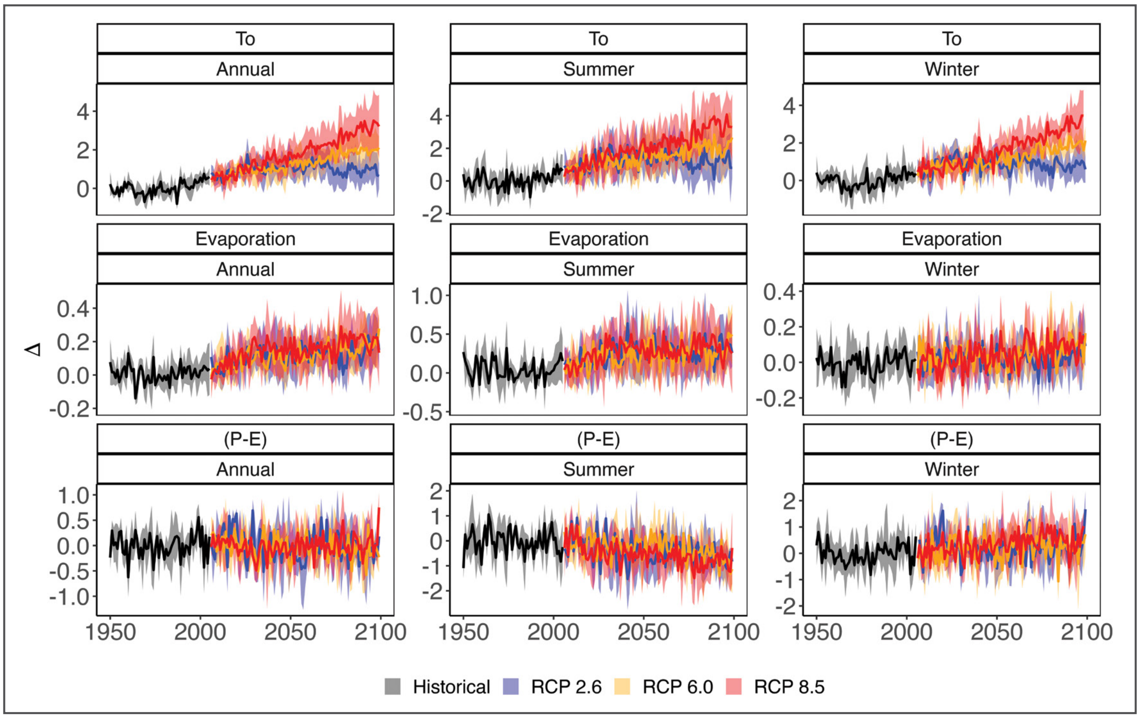


Figure 14.4 Projected changes in annual and seasonal water temperature (To) [°C], evaporation, and precipitation minus evaporation (P-E) [both mm day^{-1}], under historical and future scenarios of climate change. Anomalies (Δ) are relative to the 1970-1999 base period. Black lines represent the historical period, and the coloured lines represent the future period, with the blue, orange, and red representing RCPs (Representative Concentration Pathways) 2.6, 6.0, and 8.5, respectively.

But these annual values also masked large seasonal differences. For example, the average future increase in lake surface temperature in summer and winter for the highest emissions scenario (RCP 8.5) were 3.1 °C and 3.7 °C respectively (Figure 14.1). The winter change represented a relative increase of +113% when compared to a reference period, while that for summer was +20%. For lake evaporation, the average increase was similar in both seasons at 12%. However, in the case of the balance of precipitation minus lake evaporation, the seasons again differed substantially. Across the 18 representative lakes on the island of Ireland, there was a small relative increase in this balance in winter (+15%), but a large relative decrease in summer (-207%). The latter was due to both lower rainfall and higher evaporation. These changes in summer would affect both lake water levels and water availability. Given that, without mitigation, the Earth will continue at least on the trajectory of the RCP 8.5 scenario, these changes will challenge future lake management on the island of Ireland.

Apart from these studies on Feeagh, site-specific studies of the potential impacts of climate change on future lake stratification and mixing regimes are notably absent for the island. Overall, there is a large knowledge gap in relation to how different lake types (e.g. morphometry, trophic state, geology, and catchment characteristics) from different regions (e.g. midlands, southwest, northwest) will respond to changes in atmospheric conditions. It is only when these physical assessments have been performed, that we will have any accurate insight into how whole-lake biogeochemical and ecological regimes will respond to future climate change.

CLIMATE CHANGE IMPACTS ON LAKE BIOGEOCHEMISTRY AND PLANKTON SPECIES

Climate change is likely to cause both direct and indirect alterations to both biogeochemical processes and the biota of lakes, impacting food web dynamics, biodiversity, species distribution, phenology, and production. Biological communities in lakes in Ireland, as elsewhere, can be grouped into four main categories (see Chapter 5). The littoral community is found in the near-shore zone, where sunlight penetrates to the bottom sediments. The deeper open water or pelagic zone can be divided into 1. communities in the surface layers (the euphotic zone) where light attenuation is highest; 2. those adapted to lower light in the limnetic zone; and 3. communities in the benthic zone or bottom surface sediment layer. The community structure in each zone is based around interconnecting pathways or food webs. These begin with primary producers at the base, such as phytoplankton (predominantly algae) in the open water or larger rooted macrophytes in shallower water, both of which fix carbon from the atmosphere through photosynthesis. These are fed on by primary consumers, such as filter-feeding zooplankton or larger macroinvertebrates. The latter dominate the littoral and are composed of crustaceans, molluscs, worms, or larval insects. Some of these primary consumers also graze on zooplankton but are themselves food for fish. Other piscivores (fish-eating fish) sit at the top of the food web. Lakes also have mixotrophic plankton species, which can both produce carbon photosynthetically or make use of in-lake or catchment-derived carbon (Hansson et al., 2019). Linking all of these are the microbial communities, which also use carbon produced within the lake or washed in from the catchment.

Although functionally separate, the microbial and grazing loops are interconnected and control lake ecosystem production. Carbon, oxygen, and other nutrients are processed along the food web pathways but also exist as compounds or elements in the open water and sediments. Lake food webs rely on supplies of these substances, and changes in their quantity and quality can have complex and diverse effects on in-lake production. In addition, lake communities are highly sensitive to changes in weather, including levels of sunlight, temperature, precipitation, and wind. These can alter individual growth rates and photosynthetic efficiencies but can also act through indirect impacts via changes in nutrient availability and water column stability. The availability of dissolved oxygen will also dictate the distribution of all species, including microbes. Prolonged periods of thermal stratification can lead to the isolation and deoxygenation of sub-thermocline waters, reducing the availability of oxygen to the lake biota. Warming can then further increase the risk of oxygen depletion, as warmer water holds less dissolved oxygen per unit volume.

The consequences of global warming for lake food web structure remain poorly understood (Tanentzap et al., 2020). Fluctuations in water temperature can affect all levels of the food web and drive changes in metabolic rates and efficiencies. As most lake biota are ectotherms, they will be particularly sensitive to temperature-related change. Some recent studies have concluded that an increase in the average temperature of lakes could simplify food web structure, shortening pathways of energy flux between consumers and resources, with negative consequences for the stability of lake ecosystems (O'Gorman et al., 2019). Nevertheless, conclusions from the few observational studies that exist on the longer-term effects of warming have shown conflicting results. There is still, therefore, a general need for additional multi-year observational datasets which span trophic levels, both from Ireland and elsewhere, to better establish the effects of warming across lake types.

For the island of Ireland, as noted above, it is projected that warming will alter lake water column stability, increase the frequency of storms, and increase and alter the timing of organic matter and nutrient export into lakes. Higher wind speeds and rainfall during storms have been shown to result in thermocline weakening and mixing of the water column, with phytoplankton suddenly being transported from light-rich surface waters to darker waters at depth (Calderó-Pascual et al., 2020; Thayne et al., 2023). Surface waters may also become enriched with nutrients following storm-related mixing (Crockfort et al., 2015). The combined effects of increased temperatures and a greater frequency of storms may also have a dual impact on lake communities, although the exact effects may be site or event specific. In Ireland in the summer of 2018, Storm Hector was preceded and followed by periods of extreme heat (Calderó-Pascual et al., 2020). An unusual stratification pattern developed in Lough Feeagh, Co. Mayo, during this heatwave, resulting in an extended period of calm stable conditions. This encouraged the rapid growth of phytoplankton in the upper layers of the lake. This calm period was then disrupted by Storm Hector, which deepened the mixed layer, leading to a two-fold reduction in phytoplankton but a three-fold increase in zooplankton. In addition, the ratio of nutrients in the inflows was decoupled from that of the lake after the storm, altering nutrient use by primary consumers and leading to a cascade of effects on higher trophic levels (Calderó-Pascual et al., 2020). The responses to this storm differed, however, from a 2009 study in the same lake following extreme rainfall in July (de Eyto et al., 2016). After the event, there was a loss of thermocline stability for the rest of the year. That, in turn, reduced lake primary production, briefly increased bacterial biomass, and altered the zooplankton assemblage. Nevertheless, despite the extreme nature of the event, the overall long-term impact on the biological community was considered relatively small, with the communities showing a high level of resilience, and resetting after the following winter. Based on data from a set of lakes that included Feeagh, Thayne et al. (2023) concluded that eutrophic lakes will be less resilient to the impacts of storms when compared to these oligotrophic systems.

Water level fluctuations, which may be more common in future due to changes in inflow and lake evaporation, can also significantly affect lake ecosystems. Lake levels will be affected by both changes in precipitation and by changes in lake evaporation described earlier. The littoral zone is particularly vulnerable (Carmignani and Roy, 2017). For instance, even small reductions in lake water level can lead to a significant portion of standing water becoming air-exposed, enhancing nutrient cycling (Leira and Cantonati, 2008), while high flows and flooding can release nutrients from riparian areas along the edge of lakes (Baldwin and Mitchell, 2000), impacting the survival of littoral organisms by reducing their diversity and abundance. The littoral zone in lakes in Ireland with greater water level fluctuations has been found to have a coarser substrate, less macrophyte coverage, and a higher proportion of motile diatoms species and omnivorous benthic invertebrates, with a more homogenous algal and benthic invertebrate assemblage (Evtimova and Donohue, 2016). Overall, there is still a poor understanding of the full impact of water level regimes on ecological functioning in lakes in general, assessing future effects more challenging.

To date, there have been only two studies that have modelled the impacts of global warming on any aspect of the biogeochemistry or biota of Irish Ecoregion lakes, both of which were focused on phytoplankton (Dalton et al., 2016; Elliott et al., 2016). Dalton et al. (2016) modelled changes in lake phosphorus and chlorophyll a (a proxy for phytoplankton) concentrations in Lough Leane, Co. Kerry. The simulations included changes in the human population and agricultural management (Jennings et al., 2009) as well as climate changes based on the earlier A2 and B2 emissions scenarios (see Highlight Box). Future phosphorus concentrations in surface waters were higher in winter and spring and lower in summer. There was little projected difference in the average biomass of phytoplankton, but there was a shift to an earlier peak during summer, which also increased by 10%, in simulations using the higher emissions A2 scenario (Figure 14.1). The peak was dominated by cyanobacteria, a group which thrives under calm, warm nutrient-rich conditions. For Lough Neagh, Northern Ireland, Elliot et al. (2016) ran a biogeochemical model using an incremental change approach that increased air temperatures by 4°C. They found a switch in dominance for phytoplankton to the bloom-forming cyanobacterial species *Dolichospermum*. The model indicated a temperature-related increase in algal growth that drove nitrogen consumption to the point where it became limiting, thus allowing nitrogen-fixing species to gain an advantage. These two studies for lakes in Ireland also reflect results from other similar locations in Western

Europe (e.g. Elliott, 2021). Overall, these highlight the potential for warmer and more stable conditions to facilitate increased occurrence of nuisance algal species over the coming decades.

There is a more limited number of studies globally that have assessed climate change impacts for zooplankton, and none for an Irish site. Running process-based models for higher trophic levels is complex, due to species interactions, effects of food source and quality, as well as climate responses. One study from a shallow lake in Estonia used a statistical model based on a long-term dataset coupled with future climate projections from GCMs (Cremona et al., 2020). It found that temperature was by far the most important variable for explaining past zooplankton biomass and abundance, followed by pH, phytoplankton biomass and nitrate concentration. Interestingly, some predictive variables had opposing effects, often mitigating the effect of higher temperatures. Only in a scenario where future temperature changes stabilised did the biomass and abundance of larger zooplankton (for example cladocerans) not increase. In all other scenarios, the group's biomass and abundance exceeded historical ranges, while, in contrast, smaller ciliates did not increase. The study noted that such differences in responses between groups will have important consequences for lake trophic structure and ecosystem functioning. The implications under future climatic conditions for our island lake zooplankton communities, however, remain unclear.

CLIMATE CHANGE IMPACTS ON FRESHWATER FISH

Freshwater fish are considered important indicators of global warming, owing to the multiple pathways through which climate affects fish habitat and ultimately fish ecology (Kelly et al., 2022) (Chapter 6). This is especially true for Irish species that are deemed cold water adapted, the foremost of which includes the ecologically and culturally important salmonids (salmon, trout and charr species). Following an expert-based assessment of Ireland's 32 freshwater fish species, the Arctic charr (*Salvelinus alpinus*) was considered the most climatically vulnerable (Barry et al., 2023). Species classified as moderately to highly vulnerable included Atlantic salmon (*Salmo salar*), pollan (*Coregonus pollan*) and brown/sea trout (*Salmo trutta*), along with three additional Irish subspecies of brown trout: Gillaroo trout (*Salmo stomachicus*), Sonaghen trout (*Salmo nigripinnis*) and Ferox trout (*Salmo ferox*). The Killarney shad (*Alosa fallax killarnensis*) was considered moderately to highly vulnerable.

A uniting feature of the salmonids is their affinity for colder temperatures and the occurrence of metabolic stress at temperatures over 18-20 °C (Elliott and Elliott 2010). Thus, the warming of freshwaters will have considerable ecological consequences. Furthermore, except for Atlantic salmon, the Irish species considered most vulnerable to climate change exhibit a lacustrine life mode (Barry et al., 2023). This is particularly relevant for Arctic charr, pollan, Killarney shad and the brown trout subspecies, which are confined to an increasingly smaller number of Irish sites. Lacustrine species are especially vulnerable to both direct climate impacts and habitat deterioration, as opportunities for dispersal to more suitable environments are often not possible.

Warming can have both direct and indirect consequences for the ecology of these species. Firstly, excessively warm temperatures will invoke thermal stress, with fish unable to regulate their internal body temperature to any significant degree. As cold-water fish begin to experience metabolic stress, they typically exhibit behavioural and physiological adaptations to thermoregulate, such as seeking cold-water refugia. However, this results in a divestment from feeding and growth and it ultimately can decrease fecundity and spawning capability. Another major concern for lake fish is deoxygenation. Fish attempting to thermoregulate by seeking cooler deep-water refugia may be faced with hypoxic or even anoxic conditions at depth. Additional concerns associated with climate change impacts for lake fish include phenological change, for example, changes in the timing of thermal cues that trigger feeding, migratory or spawning events (e.g. de Eyto et al., 2022) and modification of inter-species competition where warm-adapted species gain a competitive advantage. The gravest concern, however, is the potential for climate effects to interact with pre-existing stressors, chiefly water quality deterioration and introduced species with higher thermal tolerances. This may create a compounded situation for native species not previously challenged with such multi-stressor scenarios (Kelly et al., 2022).

Two Irish studies have highlighted the survival challenges for cold water-adapted fish in a warming climate. Climate and lake water temperature projections were used to quantify the effects of an end-of-century increase in winter temperatures of 3°C to 4 °C on Arctic charr in Bunnaveela (Co. Mayo) (Figure 14.3b) (Kelly et al., 2020b). This species completes spawning in gravels along wind-swept lake shore. The higher temperatures resulted in an increase in accumulated degree days (ADD) over winter for all three emissions scenarios, a measure that was greatest for the highest emissions scenario at

+237 ADD (Figure 14.1). It concluded that this could impair egg quality and spawning capacity for this sensitive species. McGinnity et al. (2009) also used projections of changes in water temperature coupled with a regression model based on a 37-year dataset of wild and sea-ranched Atlantic salmon (*Salmo salar*) (Figure 14.1). It predicted that escapes of captive-bred fish into the catchment could substantially depress wild stock recruitment and, more specifically, disrupt the capacity of natural populations to adapt to higher winter temperatures. This effect was estimated to be even more pronounced in the future, increasing the risk of extinction for the studied population within 20 generations. Minimising additional non-climatic pressures that reduce stock recruitment (e.g. over-exploitation, water quality deterioration, and invasive species introductions) will be critical if these sensitive species are to have sufficient population diversity to adapt to climate change, including warmer temperatures and changes in physical and biogeochemical regimes.

CLIMATE CHANGE IMPACTS AND OTHER STRESSORS

On-going and future climate change is even more concerning as it is affecting lakes at the same times as multiple other stressors, most of which are also linked to changes in human behaviour (McElarney et al., 2021; Reid and Emerson, 2023). These include eutrophication, abstraction, increases in invasive species, as well as pressures from other more recently recognised pollutants such as microplastics and so-called 'forever' chemicals (the per- and poly-fluoroalkylated substances). Multiple pressures acting together may potentially increase negative effects. Projected increases in lake evaporation as noted earlier will occur at the same time as changes in precipitation patterns, but also at a time when abstraction for human consumption will likely be increasing, pushing more communities into water stress (Greve et al., 2018). Lower lake levels not only have implications for the availability of drinking water but also for lake ecosystem function, especially in lake margins or littoral zones.

The combined effects from multiple stressors are complex to predict and can also differ depending on lake characteristics and biota (Richardson et al., 2018; Jeppesen et al., 2020). Data from the world's longest-running shallow lake experimental mesocosm facility in Denmark has shown that heatwaves, for example, affect multiple aspects of lakes, including oxygen levels and both bacterial and algal communities (Jeppesen et al., 2020). Toxic algal blooms are expected to be even more common in the future (Paerl and

Barnard, 2020). These are increasingly being reported from lakes in Ireland, with huge negative implications for ecosystems, for example in Lough Neagh (Northern Ireland) (Reid and Emerson, 2023). An assessment of variation in cyanobacteria and chlorophyll a levels in response to changes in temperature, nutrients, and retention time for 494 European lakes, including Irish sites, found that sensitivity also varied across eight lake types (Richardson et al., 2018). Overall, chlorophyll a was more sensitive than cyanobacterial levels, with the highest sensitivity for both humic and polymictic lakes that had medium alkalinity levels. The authors stressed that it is critical to take site-specific differences into account when forecasting responses to both climate and local management changes. Implementing mitigation strategies to control nuisance algal blooms may be further complicated by the fact that reductions in catchment nutrients do not always result in a similar downward trend in downstream lakes (McElarney et al., 2021). Enriched lake sediments can release nutrients when deeper waters become anoxic, conditions will be more likely to occur in future as more lake heatwaves develop, with summer stratification becoming more prolonged and pronounced (Woolway et al., 2021).

KNOWLEDGE GAPS AND RESEARCH NEEDS

Following this review, we identify the following key gaps in our knowledge of the impacts of climate change on lakes in Ireland:

1. More studies are needed that explore changes in lake thermal structure in response to the range of atmospheric conditions found on the island, especially studies using high frequency sensors. As well as describing current dynamics, these would provide calibration data for models to simulate impacts of global warming on lake mixing regimes in a wider range of lake types.
2. Lakes and their catchments are tightly coupled. Modelling of in-lake chemical or biological responses is best approached by running a chain of models that includes both catchment and lake models. Such studies are scarce, both at the global scale and for Irish sites. New work being undertaken by the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) Lake Sector (see Highlight Box) is paving the way for simulations at the global scale and could provide a vehicle for researchers to undertake this work for Irish sites.
3. More studies on climate change impacts in clear-water lakes are required for Ireland, but these also need appropriate calibration and validation data, including data on thermal structure, catchment biogeochemistry and lake biota.

Such comprehensive datasets are still scarce and need a long-term commitment of personnel and budget.

4. The value of long-term datasets that use a consistent methodology cannot be overstated for assessing long-term change. Existing data collection programmes should continue to be supported and it is never too late to start new initiatives.
5. Substantial water level changes are likely given the projected changes in precipitation and evaporation that we describe above. These will particularly affect the littoral zone, however, data collection for lakes in Ireland is more often focused on the pelagic. Without baseline data, we cannot assess future impacts.
6. There may also be interactions between climate and novel stressors, whose behaviour we do not yet fully understand and, therefore, cannot yet simulate. The potential for new synergistic interactions should always be considered.

CONCLUSION

Global warming is the major challenge facing our freshwater resources and our society over the coming decades. The modelling studies that we have collated in this chapter quantify and highlight the potential for very fundamental change in how lakes in Ireland will function, affecting, for example, heat fluxes, stratification patterns and evaporation. These changes will also affect lake biota and, therefore, the ecosystem, although we do not yet have a full understanding of how. The potential effects on fish are especially concerning. In tandem with these impacts will be alterations in patterns of riverine flow and nutrient export, together with concurrent increases in human-related pressures such as water abstraction and pollution. Some of these effects can already be discerned for lakes on our island, such as significant increases in lake water temperatures and the duration of stratification. Reports of nuisance algal blooms are also now becoming more common. The research that has been undertaken to date can inform future management and mitigation. However, there remain major gaps in our knowledge, with a scarcity of climate impact modelling studies that take account of our unique island conditions. Addressing these will be essential for the future of our lacustrine systems.

Highlight Box

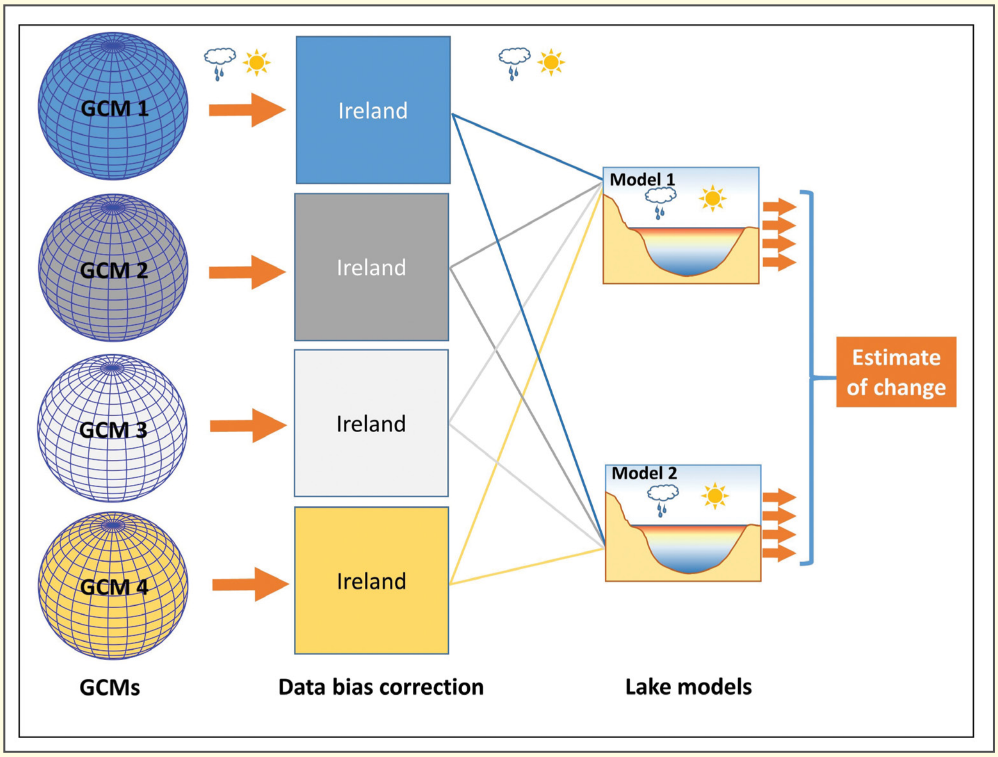
MODELLING THE EFFECT OF FUTURE CLIMATE CHANGE

The impacts of increased concentrations of carbon dioxide and other GHGs in the atmosphere can only be estimated using complex computer models of the Earth. GCMs are models that simulate the Earth's climate using equations describing the atmospheric, terrestrial, and oceanic processes that control our weather. In a GCM, the Earth and its atmosphere are divided into a 3-D grid of cubes, with each square on the surface representing several degrees of latitude by several degrees of longitude (Box Figure 14.1). There are then between 10 and 40 stacked vertical cubes that go upwards into the atmosphere and downwards into the oceans. Such models are computationally intensive and run on powerful high-speed computers. The output usually consists of daily values for common weather variables for each grid square. They are run for a future period, typically up until the year 2100 and are also run for a historic period to provide a baseline against which to assess future change.

When simulating future climates, GCMs are run with differing concentrations of GHGs. These are chosen to reflect the Earth's anticipated future use of fossil fuels. These emissions scenarios include storylines where the population adopts strategies to reduce fossil fuel use and those where with little or no reduction or mitigation. The latter usually results in the largest increases in air temperatures. The first set of these scenarios was developed in the 1990s. The scenario with the most extreme GHG level (A2) was based on a heterogeneous world with both a continuously increasing population and increasing economic growth. These original scenarios were then replaced with Representative Concentration Pathways (RCPs), four pathways reflecting different increases in atmospheric concentrations, referred to as RCP 2.6., 4.5, 6.0 and 8.5. The RCPs were not, however, related to any specific socioeconomic storyline. The latest storylines combine these RCPs with five Shared Socioeconomic Pathways based on narratives for changes in the Earth's population, economic growth, education, urbanisation, and technological development.

The grid size of a GCM is large in area. For example, it may be 200 km on each side, an area of 40,000 km^2. In contrast, the majority of lakes in Ireland have an area of less than 1 km^2 (Dalton, 2018). To represent weather that reflects these more local scales, the GCM data are usually downscaled, or bias-corrected, to a smaller grid (Box Figure 14.1). This step may use statistical methods or another intermediate model. There have been many GCMs developed in the past decades, each with its own mathematical characteristics. Because of this, it is now more usual to use data from multiple GCMs when modelling future climate impacts, referred to as an 'ensemble of models', as input for ecosystem models, such as a model of lake physics or lake biology. The ISIMIP (www.isimip.org) is a network of modellers that is currently contributing to a comprehensive and consistent picture of the Earth under different climate change scenarios using a wide range of ecosystem models, including for lakes (Golub et al., 2022). ISIMIP has produced downscaled data that are now used in many projects, including those presented in Table 14.1 and Figure 14.3. Usually, more than one ecosystem model is also used, with each ecosystem model driven by the output from each GCMs (Box Figure 14.1). All the outputs from the selected GCMs and lake models are then combined to provide the final estimate of future change.

Box Figure 14.1 An example of a multi-model ensemble. In this, four GCMs are used to produce future weather data. The data from each GCM are then bias-corrected to reflect past observed weather for a given location. The bias corrected data from each GCM are then used to run each of two different lake models. The eight outputs are all used to produce an estimate of future change.



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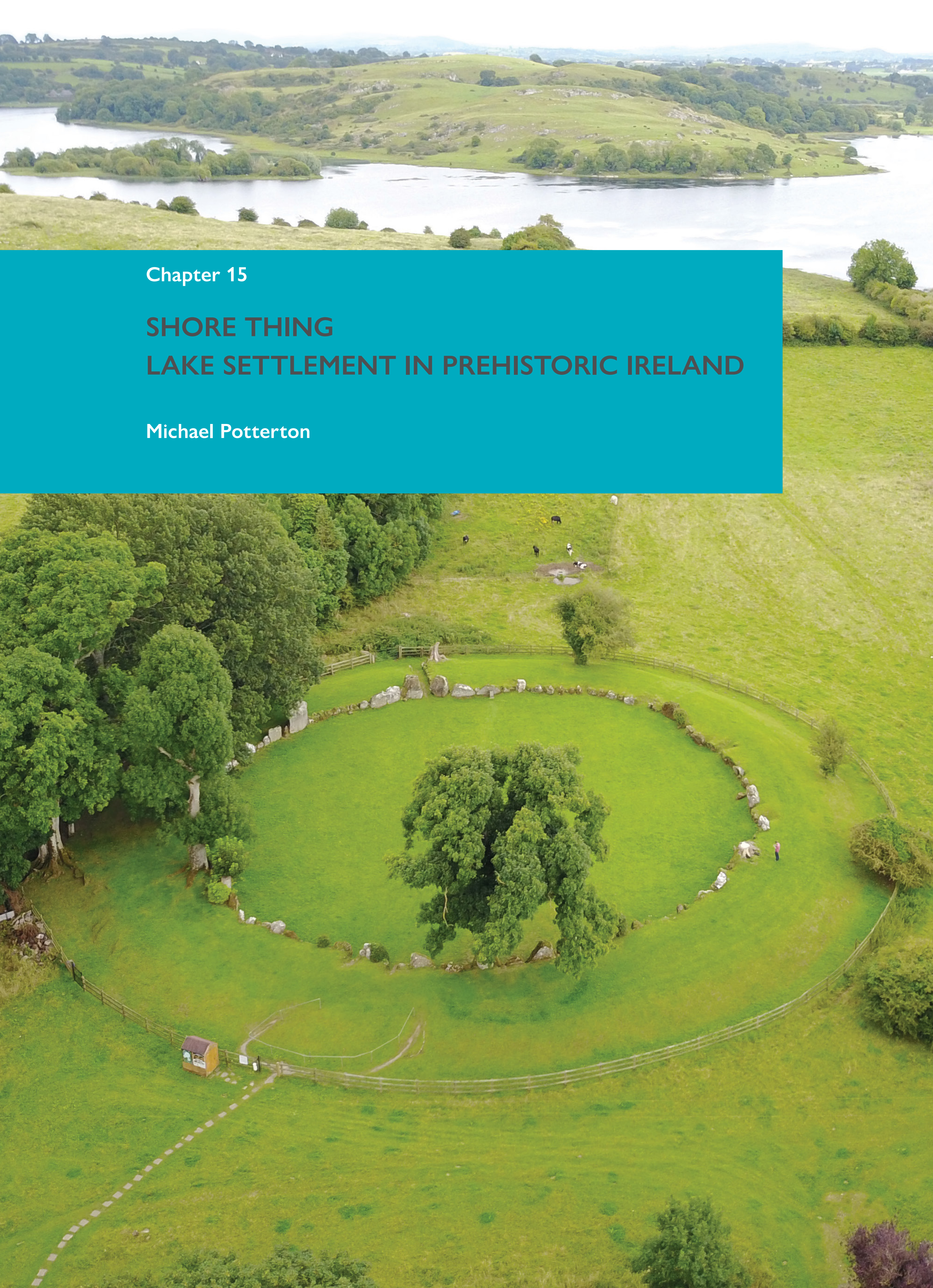
Chapter 15

SHORE THING
LAKE SETTLEMENT IN PREHISTORIC IRELAND

Michael Potterton



SUMMARY

Almost every lake in Ireland – from the smallest seasonal turlough to the great expanses of Lough Neagh, Lough Corrib, and Lough Derg – contains a rich archaeological tapestry stretching back as much as ten millennia. Some of the archaeology is still visible in the form of field monuments, while much more is sealed in deep lake muds accumulated gradually over time. Ireland's museums and heritage centres boast great treasures and ancient artefacts dredged from these lakebeds, caught in fishing nets, picked up by shoreline mud-larkers or excavated by professional archaeologists. A sizeable part of the National Museum of Ireland's archaeology display, for instance, originated in lakes, from the tiniest microliths found at Lough Boora in Co. Offaly (see Figure 15.2) to the enormous Lurgan logboat from Co. Galway (see Figure 15.8). Some of the most extraordinary and significant archaeological discoveries have been found in or beside lakes. In his preface to Aidan O'Sullivan's ground-breaking 1998 monograph on *The archaeology of lake settlement in Ireland*, George Eogan remarked that the subject was 'rich, complex and intriguing'. Research in the quarter of a century since that publication has demonstrated the field to be even richer, more complex and more intriguing than Eogan could have imagined. This chapter charts the archaeological evidence for human interactions with lakes in Ireland from the earliest times to the end of prehistory (*c.*8000BC–AD400). It is divided into sections on purely chronological grounds (Table 15.1) and is intended as a companion to the chapter that follows it (Chapter 16).

Keywords: Archaeology, logboats, material culture, museums, prehistory, wetlands

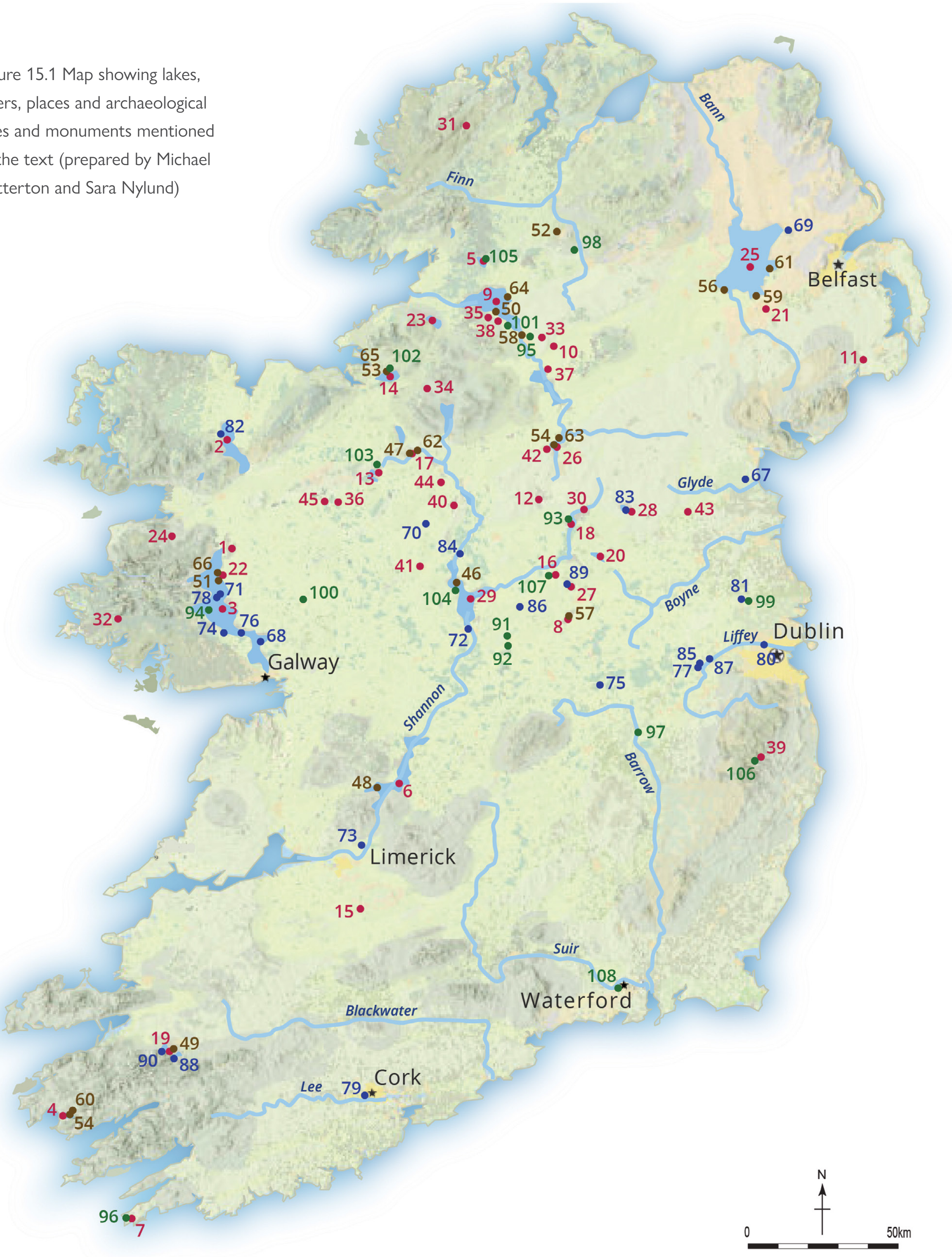


Figure 15.1 Map showing lakes, rivers, places and archaeological sites and monuments mentioned in the text (prepared by Michael Potterton and Sara Nylund)

Fig. 15.1
KEY

Lakes
1. Lough Carra
2. Lough Conn
3. Lough Corrib
4. Lough Currane
5. Lough Derg (Ulster)
6. Lough Derg (Munster)
7. Dun Lough
8. Lough Ennell
9. Lough Erne
10. Lough Eyes
11. Lough Faughan
12. Lough Gabhna
13. Lough Gara
14. Lough Gill
15. Lough Gur
16. Lough Iron
17. Lough Key
18. Lough Kinale
19. Lough Leane
20. Lough Lene
21. Lough Lurcan
22. Lough Mask
23. Lough Melvin
24. Lough Moriarty
25. Lough Neagh
26. Lough Oughter
27. Lough Owel
28. Lough Ramor
29. Lough Ree
30. Lough Sheelin
31. Lough Veagh
32. Ballinahinch Lake
33. Ballydoolagh Lough
34. Belhavel Lough
35. Carrick Lough
36. Cloonacolly Lough
37. Corban Lough
38. Drumcorban Lough
39. Glendalough
40. Kilglass Lough
41. Loughnaneane
42. Mill Lough
43. Moynagh Lough
44. Tully Lough
45. Urlaur Lough

Islands
46. Inchcleraun, Lough Ree
47. Inchmacnerin, Lough Key
48. Iniscealtra, Lough Derg
49. Inisfallen, Lough Leane
50. Inishmacsaint, Lough Erne
51. Inishmaine, Lough Mask
52. Island MacHugh, Co. Tyrone
53. Church Island, Lough Gill
54. Church Island or Inis Uasal, Lough Currane
55. Clogh Oughter, Lough Oughter
56. Coney Island, Lough Neagh
57. Cro-Inis, Lough Ennell
58. Devenish, Lough Erne
59. Oxford Island, Lough Neagh
60. Rabbit Island, Lough Currane
61. Ram's Island, Lough Neagh
62. Trinity Island, Lough Key
63. Trinity Island, Lough Oughter
64. White Island, Lough Erne
65. Church Island, Lough Gill
66. Castle Hag, Lough Mask

Places
67. Annagassan, River Glyde
68. Annaghdown, Lough Corrib
69. Antrim, Lough Neagh
70. Ardakillen, Co. Roscommon
71. Ashford, Lough Corrib
72. Athlone, Lough Ree
73. Athlunkard, River Shannon
74. Aughnanure, Lough Corrib
75. Ballintemple, Co. Offaly
76. Carrowmoreknock, Lough Corrib
77. Clane, Co. Kildare
78. Cong, Lough Corrib
79. Cork, River Lee
80. Dublin, River Liffey
81. Dunshaughlin, Co. Meath
82. Errew, Lough Conn
83. Knockatemple, Lough Ramor
84. Lanesborough, Lough Ree
85. Loughbollard, Co. Kildare
86. Loughsewdy, Co. Westmeath
87. Moortown, Co. Kildare
88. Muckross, Lough Leane
89. Portloman, Lough Owel
90. Ross, Lough Leane

Sites and Monuments
91. Ballinderry Crannog 1, Co. Westmeath
92. Ballinderry Crannog 2, Co. Offaly
93. Ballywillin Crannog, Lough Kinale
94. Caisleain na Circe, Lough Corrib
95. Drumclay, Co. Fermanagh
96. Dunlough Castle, Co. Cork
97. Dunrally, River Barrow
98. Kilsampson Crannog, Co. Tyrone
99. Lagore Crannog, Co. Meath
100. Loughpark 'crannog', Co. Galway
101. Monea Castle, Co. Fermanagh
102. Parke's Castle, Lough Gill
103. Rathtinaun, Co. Sligo
104. Rindoon, Lough Ree
105. St Patrick's Purgatory, Lough Derg
106. Temple na Skellig, Glendalough
107. Tristernagh, Lough Iron
108. Woodstown, River Suir

Table 15.1
General chronology of key archaeological periods in Ireland

Period	Sub-period	Years
Palaeolithic		Before 8000BC
Mesolithic	*Early*	8000/7800–6500BC
	Late	6500–4000/3800BC
Neolithic	*Early*	4000/3800–3500BC
	Middle	3500–3000BC
	Late	3000–2500/2450BC
Chalcolithic		2500/2450–2200BC
Bronze Age	*Early*	2200–1600BC
	Middle	1600–1200BC
	Late	1200–800BC
Iron Age	*Early*	800–400BC
	Middle	400BC–AD1
	Late	AD1–400
Medieval	*Early*	AD400–1100
	Late	AD1100–1600
Early Modern		AD1600–1700
Late Historic		AD1700–1900
Modern		1900 to present

INTRODUCTION

The richness of Ireland's lacustrine archaeology can be explained in part by the lakes' natural attributes that attracted settlers from earliest times, and in part by the extraordinary preservative qualities of waterlogged soils and anaerobic muds. At a basic level, it is also very easy to lose things in a lake and often very difficult to find and retrieve them. Certain belief systems and reverence for watery places also encouraged ritual or votive deposition, while (much to the delight of archaeologists) waste was often dumped into lakes too. Difficulty of access was a positive feature for security-conscious island-dwellers, and the same challenge has also helped to preserve some lake archaeology from unwanted attention in subsequent centuries. The flip side is that secluded late prehistoric and medieval lake settlement sites have in more recent decades provided rich pickings for illicit and indiscriminate metal-detectorists and treasure-seekers (see, for example, Manning, 2012; O'Sullivan, 1998, 29–30).

PALAEOLITHIC

From time to time over the past century, new discoveries have brought into focus the possibility of Palaeolithic activity in Ireland. On each occasion, however, the evidence has been dismissed for one reason or another (e.g., 1927 stone tools found in Sligo (Burchell and Reid Moir, 1928); 1968 flint flake from Mell, Co. Louth (Mitchell and Sieveking, 1972); 1974 hand-axe from Inishmore (Murphy, 1977); 2008 flint from near Newtownards, Co. Down (Stirland, 2008)). In 2015, however, a reassessment by Marion Dowd and Ruth Carden of animal bones (bear, deer, lemming) excavated in 1903 at Alice and Gwendoline Cave, Co. Clare, revealed compelling evidence for human activity in Ireland *c.*12,700 years ago (Dowd and Carden, 2016).

Not much is known about Ireland's first human settlers, but there can be little doubt that they lived near lakes – or even on them – and they almost certainly exploited them for food, water, raw materials, transport, and defence. Apart from the more obvious resources such as fish and water, lakes could supply fuel (washed up on the shoreline), waterfowl, molluscs, waterlilies, reeds (for roofing), sedges, timber, clay (for pottery making), stone, ice, and carr woodland resources for a wide variety of activities. To date, though, no evidence has been found of human activity in lakes in Ireland before the Mesolithic. Sea-level changes and the growth of bog had major impacts on the landscape of Ireland during the Palaeolithic; for example, Peter Woodman (2015, 24) estimated that the Bog of Allen engulfed a lake of almost one thousand square kilometres – three times the size of Lough Neagh (see Chapter 2). Larger lakes also contracted – indeed, Frank Mitchell and Michael Ryan went so far as to suggest that there may once (seasonally at least) have been a great central 'Lough Ree-Derg' (1997, 104). Other lakes that are now separate may also have formed much larger expanses, such as Sheelin-Kinale-Derravaragh, Erne Lower and Upper, Forbes-Bofin-Boderg-Scannal and others (Woodman, 2015, 25, fig. 2.8).

MESOLITHIC

As we begin to emerge from the very sketchy vista of the Irish Palaeolithic, we can be more confident that the island's Mesolithic inhabitants were fully engaged with lakeshore life and the opportunities and challenges it presented. The archaeological record is rich with evidence of nomadic hunter-gatherer-fisher-fowlers living in temporary encampments close to lakes and rivers (Warren, 2022, 70–1; Woodman, 2015, 79; Little, 2005; McHugh and

Scott, 2014). Mesolithic people first arrived in Ireland about ten thousand years ago, probably from Britain (Woodman, 2015, 119, 185). The nature and distribution of known early Mesolithic artefacts indicate that these people used the coast and river systems to navigate around and across the densely forested countryside and, in this way, they quickly encountered many of the island's freshwater lakes. Indeed, more Mesolithic finds in Ireland have come from lake contexts (225) than from all other known contexts combined (rivers 59, bogs 43, beaches 73, estuaries 4) (Woodman, 2015, 80, fig. 4.5).

Some of the lakes of Mesolithic Ireland have disappeared beneath the raised bogs that grew and absorbed them and, because most bogs have not been cut right down to the 'natural' mineral soil beneath the peat, the interface upon which most Mesolithic material is likely to be present has generally not yet been encountered. Lough Boora is an exception – this early Mesolithic site was discovered in 1977 when a small lake in the bog was drained (see Figure 15.2). Excavations directed by Michael Ryan revealed the remnants of a minor summer shoreline encampment with fire sites, stone tools and burnt animal bones. There were chert microliths, blades and polished axes as well as hazelnuts and the remains of pig, pigeon, jay, teal, grouse, mallard, trout, and eel. The site appears to have been in use between *c.*7000 and *c.* 6000BC when it was sealed by advancing peat.

The identification of many late Mesolithic lake-edge platforms as well as the discovery of a variety of harpoons, traps and fishing spears underlines the importance of fishing in that period. Platforms constructed on the shore or in the shallows facilitated the trapping or spearing of fish. Salmon, trout, eel and possibly lamprey were exploited, with summer and autumn runs of salmon and eel on inland lakes and rivers being especially important. At Clowanstown, near Tara in Co. Meath, four conical fish-traps were found next to the remains of a late Mesolithic timber platform in a former lake (now bogland) in 2004 (FitzGerald, 2007) (see Figure 15.3). Alder, birch, and rosewood were used in the making of the traps, which have been radiocarbon-dated to *c.*5000BC. Isotopic analysis of late Mesolithic human remains from Stoneyisland, Co. Galway, on the shore of Lough Derg suggests that the diet of the individual included a significant amount of freshwater fish (Kador et al., 2014).

Flint and chert were commonly used for making tools in the Mesolithic, and both these stone types can be found naturally exposed on lakeshores. 'Festoon' (or festooned) chert is a distinctive variety first recognised in modern times at Lough Derravaragh, Co. Westmeath, where a Mesolithic flake industry was

Figure 15.2
Archaeological excavations underway at the Mesolithic site Lough Boora, Co. Offaly in 1977 (©National Museum of Ireland)

Figure 15.3
One of four Mesolithic fish-traps discovered in a former lake at Clowanstown, Co. Meath, in 2004 (©National Museum of Ireland)

established on the shore to take advantage of this resource (Jackson, 1994, 35; O'Sullivan et al., 2007). A prolonged period of dry weather in the summer of 2020 resulted in the lowering of water levels at Glencar Lake in Co. Sligo (McDonagh, 2020). This exposed a Mesolithic 'knapping floor' represented by almost one thousand pieces of chert. Archaeologists recovered waste pieces from the manufacture of stone tools as well as some finished implements.

Some 20km south of Limerick city lies Lough Gur, which was accessed by early settlers along the Camoge and Morningstar rivers (Cleary, 2018). With almost one thousand recorded archaeological sites within 5km of the lake, Lough Gur is a shining example of the significant role played by even very small lakes in Ireland's long settlement history. At least four sites on

Figure 15.4
Only a part of Moynagh Lough remains – at the centre of this image – after nineteenth-century drainage
Photo: Kevin Weldon

Knockadoon Hill overlooking the lake have produced evidence for 'transient hunter-gatherer communities' (Cleary, 2018, 44–7) and the production of quartz tools (46–7). Mesolithic stone tools have also been found on the shore of Derryhowlaght Lough in Co. Fermanagh (Welsh and Welsh, 2021, 214), while an assemblage of diagnostic late Mesolithic stone implements was recovered at the site of a former lake at Corralanna, Co. Westmeath, in 2000 (Stanley, 2000). Mesolithic lake occupation is also attested at Clonava Island on Derravaragh (Mitchell, 1972), Derragh Island on Kinale, Co. Longford (Fredengren, 2004; Fredengren et al., 2010), Moynagh, Co. Meath (Bradley, 1991; Potterton, 2022), as well as sites on Allen (O'Sullivan, 1998, 55), Catherine (Welsh and Welsh, 2021, 284), Eskragh (Welsh and Welsh, 2021, 299), Gara (Fredengren, 2002) and Iron (O'Sullivan, 1998, 52), among others.

Moynagh Lough lies just over 400m south-west of Nobber in north Co. Meath, surrounded by a drumlin landscape of rich pasturelands (Bradley, 1991; Potterton, 2022). The surviving pool (200m by 60m) is all that remains of a once much larger lake that was drained in the early nineteenth century (see Figure 15.4). Excavation revealed that initial human occupation of the site commenced in the centuries immediately before 4000BC when a community of Mesolithic hunter-gatherers constructed a series of platforms in the lake. Some two thousand stone artefacts were recovered as well as a handful of bone and wooden objects. In time, the climate became wetter and rising lake water covered the Mesolithic surface with mud.

Logboats

While there can be no doubt that Mesolithic people travelled extensively by boat, very little direct evidence has been found for this mode of transport. Woodman (1978, 337–9; see also Fry, 2000, 63) noted the discovery in Lough Neagh of a 6.2m-long oak 'canoe' containing a Bann Flake, a flint core and two possible trident fishing spears. While Bann Flakes are typically Mesolithic in origin, and several Mesolithic sites have been identified on the nearby shore, the boat has not been dated definitively (and the Bann Flake and flint core could have washed into the boat from an adjacent site). Elsewhere in Lough Neagh, part of a possible logboat of Mesolithic date was discovered at Brookend, Co. Tyrone, in 1995 (Fry, 2000,116; Breen and Forsythe, 2004, 31). Among the finds from Clowanstown, mentioned above, is a possible toy or model logboat dating to *c.*5000BC (FitzGerald, 2007). Given the dearth of boat finds from this period, the Clowanstown object is particularly significant.

NEOLITHIC

The dawn of the Neolithic heralded the firm beginnings of agriculture in Ireland (there had already been tentative moves in this direction in the late Mesolithic). Early farmers were responsible for woodland clearance to make way for new crops, and this can be traced in cores taken from peatbogs and lake sediments in some parts of the country (see Chapter 3). For instance, analysis of pollen from Scragh Bog, Co. Westmeath (which was a lake until the early Middle Ages), demonstrates that the landscape there was overwhelmingly wooded before the Neolithic and then, as farming took hold, tree-pollen counts plummet while pollen from cereals and weeds of cultivation increase

Figure 15.5
The Great Stone Circle at Grange, Lough Gur, Co. Limerick, is part of one of the richest archaeological landscapes in Ireland. Photo: Rose Cleary

markedly (O'Connell, 1994, 44–5). Similarly, the early Neolithic population at Lough Sheeauns in Connemara, Co. Galway, 'had a major impact on the local environment' (O'Connell, 1994, 45–6). Woodland (notably oak, elm and hazel) was almost entirely cleared for agriculture but unlike at Scragh Bog, here it was for pasture rather than arable. The absence of soot and charcoal in the core indicates that woodland clearance was achieved by axe and not by burning. This and the density of megalithic tombs around the lake suggest a sizeable population. In Co. Fermanagh, a remote-sensing investigation of the bed of Lough Erne revealed evidence of vegetation changes during the transition from the Mesolithic to the Neolithic (Lafferty et al., 2003). On the other hand, the results of pollen analysis of sediments taken from Lough Fark in Co. Mayo did not indicate any major Neolithic land clearance in the area (Fuller, 2002; see also Whitehouse et al., 2010). As an aside here, it can be seen clearly how the lakes of Ireland have captured important snapshots of the archaeological record through time, not just of the lakes themselves, but of the evolving landscapes that surround them (see, for instance, Spencer, 2022; McNeary and Bourke, 2009).

It has been noted that a characteristic feature of Neolithic settlements in Ireland is that they typically overlook lakes or rivers (Grogan, 1994, 59). The observation is underlined in a recent catalogue of prehistoric finds from Northern Ireland that lists Neolithic artefacts from Camlough Lake, Clea Lakes, Enagh, Eskragh and Ushet on Rathlin Island (Welsh and Welsh, 2021, 145, 178, 274, 299, 54). Lough Erne, too, has yielded a variety of Neolithic finds (see, for example, Day, 1895). The Rossfad logboat from Lower Lough Erne is a Neolithic vessel dating to roughly 3500–3350BC (Fry, 2000, 50, no. 6). In Co. Limerick, drainage at Lough Gur in the 1840s revealed many artefacts and sites along the newly exposed shoreline. Subsequent surveys and excavations led to the discovery for the first time in Ireland of Neolithic stone house foundations, still visible on Knockadoon Hill. The earliest houses were rectangular, but the later ones were circular in plan. Among the artefacts recovered were pottery, axe heads and tools of bone and stone.

In 2006–7, Neolithic houses were excavated by a team of archaeologists from University College Cork at a multi-period site at Tullahedy, Co. Tipperary, on an esker in an otherwise flat, boggy landscape (Cleary and Kelleher, 2011). The houses are adjacent to a former lake and were enclosed by a timber palisade. There were more than one hundred polished stone axes and one thousand chert flakes as well as flint flakes, worked quartz crystal, clay cooking vessels, a stone bead and a pendant.

CHALCOLITHIC/BRONZE AGE

As its name suggests, the Bronze Age was characterised by the use of metal – notably copper, tin, silver, and gold. Metallurgy emerged on the Continent and gradually reached Ireland. The first metal tools here were probably imported, but soon they were manufactured locally. Initially, metal tools were cast in pure copper, and so the period is sometimes referred to as the *Chalcolithic* or 'Copper Age'. Although simple, these flat metal axes were twice as effective as stone ones for tree-felling. Copper is quite soft, and it was found that alloying it with tin (imported from south-western England) made it much harder and more durable. Design improvements to axe handles further accelerated woodland clearance, which, in due course, precipitated soil erosion, waterlogging and the growth of bogs. The toolmarks on prehistoric timbers recovered from wetland contexts can be as clear as the day they were made, aiding tool-analysis even in the absence of the tools themselves.

In addition to metal, a wide variety of other raw materials were used by Bronze Age communities, including wood, bone, antler, horn, leather, clay, and stone. Quern-stones (notably 'saddle' querns, named for their distinctive shape) were used for extracting flour from grain. Spindle whorls and loom weights, which were used in preparing textiles, could be made from stone, clay, bone, or antler. A particular type of decorated hand-made pottery vessel – probably for drinking – is closely associated with early metalworking (especially copper) in western and central Europe. Generally termed 'Beaker Pottery', fragments of these elegant pots have been recovered on a variety of sites in Ireland. Lignite was used for making bracelets and other items. Extensive deposits of lignite occur naturally around Lough Neagh, and these were widely exploited (Jackson, 1994, 34). Some lignite was probably imported, in addition to amber, faience, tin and other metals.

Dating to *c.*2400BC, one of the oldest known copper mines in north-western Europe was found at Ross Island on Lough Leane in Killarney, Co. Kerry (O'Brien, 2004) (see Figure 15.6). Among the artefacts recovered were cattle-scapula shovels, stone hammers and more than four hundred sherds of Beaker pottery. The mould for an early Bronze Age axe was found at Lough

Figure 15.6
Ross Island on Lough Leane in Co. Kerry is home to a remarkable Bronze Age copper mine excavated by archaeologists. Photo Billy O'Brien

Guile in Co. Antrim (Welsh and Welsh, 2021, 57), and another is known from Lough Scur in Co. Leitrim (Wood-Martin, 1886, 72; Fredengren, 2002, 114). An early Bronze Age bowstave (*c.*2200BC) of yew was found by the Irish Archaeological Wetland Unit (IAWU) in 2001 at the edge of a former lake, now subsumed by Ballybeg Bog in Co. Offaly (McDermott et al., 2003). Among the more unusual discoveries in the palaeo-environmental remains from Ross Island were pollen grains from the strawberry tree (*Arbutus unedo*), which in Ireland is known almost exclusively in lakeshore settings in Cork and Kerry as well as an 'outlying population on Lough Gill in Co. Sligo' (Sheehy Skeffington and Scott, 2022). It has been suggested that the strawberry tree was introduced to Ireland from Iberia by beaker-using copper-miners about four thousand years ago (ibid.).

Close to Ballyarnet Lough in Co. Derry, excavations directed by John Ó Néill revealed a lake settlement defined by a wooden platform enclosed by a palisade 6m in diameter (Ó Néill et al., 2007; Welsh and Welsh, 2021, 238). Initial construction of the platform and palisade was followed by the erection of a series of posts around a clay hearth, while two substantially deeper posts in the interior suggest the former presence of a roofed structure. Palisade timbers returned a date of 1740–1520BC. Among the Bronze Age finds were metalworking debris, sherds of cordoned urn and undecorated coarse-wares, fragments of saddle querns, hammer stones, a polished stone-axe fragment, a possible anvil stone, two tanged projectile points, scrapers, debitage, modified flakes, a perforated stone net-sinker or loom weight and a fragment of faience bead. The projectile points may have been used in hunting and the scrapers could have been used to clean the skins. In Co. Armagh, a middle Bronze Age enclosed lakeshore building excavated in 1956 at Cullyhanna Lough was interpreted by the excavator as a hunting lodge (Hodges, 1958).

A relatively common feature of the Bronze Age archaeological record is the *fulacht fiadh*, a cooking pit or trough (possibly also used for bathing, textile processing and other activities). These sites are frequently represented in the field by 'burnt mounds' or overgrown oval or horseshoe-shaped piles of stones and charcoal adjacent to a hearth for heating stones to be thrown into the water-filled stone-/wood-lined trough to heat the water. They tend to have a quite narrow middle Bronze Age date range (*c.*1900–1200BC) and are usually found near natural water supplies. Lakeshore locations were commonly chosen, and examples are known from close to lake settlement sites at Knocknalappa, Co. Clare (O'Sullivan, 1997) and Moynagh Lough in Co. Meath (Corlett, 1997) (see Figure 15.4).

Climatic improvement around 1900BC enabled early Bronze Age settlers to return to Moynagh Lough (see above) to deposit timber and stones on the now-dry surface (Bradley, 2004; Potterton, 2022). This formed the foundations for a habitation layer containing the remains of two circular houses associated with pottery, scrapers, arrowheads, bone, and querns. The site was again abandoned, however, probably due to inundation. By about 890BC it dried out and became suitable for settlement again. There were several open-air hearths associated with quern-stones, coarse pottery, a spindle whorl, and a bronze ring. This level was covered by stones, debris and charcoal dated to *c*.890–790BC. It contained animal bones and bronze weapons, tools, and jewellery, as well as amber, antler, ceramic, glass, lignite, and stone. These finds indicate inhabitants of high status. The site was abandoned again around 790BC when open-water mud began to build up once more.

During the dry summer of 1953, a series of late Bronze Age settlement sites were revealed along the eastern shore of Lough Eskragh, Co. Tyrone, three using timber piles driven into natural rises in the lakebed, and a fourth platform on the shore (Welsh and Welsh, 2021, 299, 301). Almost six hundred birch and ash piles were recorded, one of which yielded a radiocarbon date of 767–414BC. There was a metalworking area in which pottery and other artefacts were recovered. Several saddle querns were also retrieved, as well as a socketed bronze axe. In the early 1990s, a late Bronze Age palisaded settlement – possibly a farmstead – was discovered in a former lake at Clonfinlough, Co. Offaly (Moloney et al., 1993). The site, which was still waterlogged, included well-preserved platforms, hearths, wattle walls, flagstone floors, huts, worked timbers and trackways. It was dated to *c*.900BC. Among the artefacts were sherds of pottery, a whetstone, an axe-head, a grinding stone, a quern-stone, amber beads and two wooden paddles.

Among the prehistoric monuments at Lough Gur, the Great Stone Circle at Grange (see Figure 15.5) was begun as an embanked enclosure *c*.3000BC and then was refitted as a stone circle by Beaker-pottery-using people *c*.2500BC (Cleary, 2018). Other Bronze Age monuments on the lakeshore comprise several enclosures on Knockadoon Hill and a wedge tomb (the 'Giant's Grave') on Killalough Hill. The tomb contained the remains of at least nine adults and four children buried *c*.2200BC, possibly by the Beaker people. It was reused in the middle Bronze Age *c*.1600BC. Among the large assemblage of Bronze Age artefacts known from Lough Gur are a decorated 70cm sheet-bronze shield (*c*.1000BC) and a rare type of gold-mounted spearhead (*c*.1400BC). A spectacular twisted gold torc of middle Bronze Age date was found recently at Corrard near the shore of Lough Erne (Ramsay, 2013).

Bronze Age pottery – indicative of settlement – has also been found at lacustrine sites in Ulster at Lough Enagh, Loughermore/Loughanmore, Raffrey, Tonystick and Tremoge (Welsh and Welsh, 2021, 198, 232, 274, 318). The Tremoge site, between Black Lough and White Lough, was the burial of a cremated adult female accompanied by a clay loom weight and a bronze awl. Charcoal from the burial was dated to *c.*1600BC (Welsh and Welsh, 2021, 318).

At Rathtinaun on Lough Gara, Co. Sligo, a multi-period structure exposed in 1952 also produced rich evidence for late Bronze Age metalworking (O'Sullivan, 1998, 89–90). Bronze Age weapons including axes, palstaves and spearheads have been found at Lough Guile, Loughconnelly, Lisleitrim (Kiltybane), Raffrey ('Dumb Lough') and Kilsmullan (Welsh and Welsh, 2021, 57, 100, 146, 198, 224). A sword and possible horse-harness equipment were recovered during excavations at the late Bronze Age lakeshore settlement at Knocknalappa in Co. Clare (Raftery, 1942).

In addition to single 'stray' finds such as these, a feature of the late Bronze Age is the deposition of hoards – perhaps ritualistic and often in wetland locations such as bogs and lakes. Two centuries ago, labourers working at Dowris near Lough Coura in Co. Offaly discovered a cache of more than two hundred metal objects including spearheads, musical instruments ('crotals', horns, trumpets), axes, swords, three buckets, a cauldron, and various tools (chisels, knives) (Eogan, 1983) (see Figure 15.7). During the Bronze Age, this area was covered by a shallow lake, which later silted up. The 'Dowris Hoard', as it has become known, may be the result of a series of ritual deposits into the lake. In the 1850s, one of the most important Bronze Age hoards ever found in north-western Europe came to light beside Mooghaun Lake in Co. Clare (Eogan, 1983). Containing more than 150 gold objects, the 'Mooghaun Hoard' is also likely to have been a votive offering.

Our understanding of Bronze Age travel and transport has been greatly improved by the chance discovery of a series of wooden boats and associated equipment of the period. Of the 600 or so logboats recovered in Ireland, some 60 per cent have been retrieved from lacustrine settings (Gregory, 1997; Karl Brady, pers. comm.). The above-mentioned Lurgan logboat found in Co. Galway is over 15.2m long and was hollowed from a single tree *c.*2500BC (Breen and Forsythe, 2004, 36–7) (see Figure 15.8). Two roughly contemporary alder boats from Derrybrusk in Lough Neely have

Figure 15.7 Discovered near Lough Coura in Co. Offaly, the Dowris Hoard contains Bronze Age tools, weapons and musical instruments (©National Museum of Ireland)

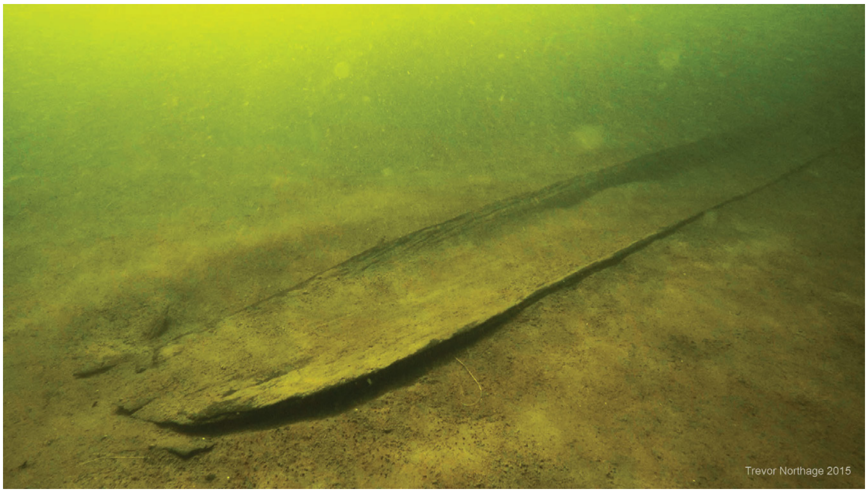
been dated to 1210–940BC and 1260–1000BC respectively. These are rare examples of logboats not made from oak, the species of choice for nearly all logboats constructed throughout history (Lanting and Brindley, 1996; Fry, 2000, 110–11, nos 104, 105). In 1989 a Bronze Age logboat was found during drainage operations in a former lake at Ballyvoghan in Co. Limerick (Lanting and Brindley, 1996, 87), while a four-thousand-year-old vessel was raised from Island Lake near Ballyhaunis in Co. Mayo in 1995 (Lanting and Brindley, 1996, 88). Also in Mayo, a logboat (*c*.1300BC) was recovered from a 'dried-up lakebed' at Cloongalloon in 1974 (Lanting and Brindley, 1996, 88). Of particular interest, two large and unusual ash paddles were excavated

Figure 15.8 The Bronze Age Lurgan logboat, retrieved from a former lake in Co. Galway in 1901 (©National Museum of Ireland)

at Clonfinlough, Co. Offaly (Moloney et al., 1993; Breen and Forsythe, 2004, 37, 41). An unusual Bronze Age hollowed-out oak log discovered in 1999 at Tomies East on the shore of Lough Leane in Co. Kerry is unlikely to be a boat; instead, it has been (tentatively) interpreted as a prehistoric bath, trough, or coffin (Dunne and Doolin, 2001). Karl Brady (pers. comm.) agrees that this enigmatic object is definitely not a boat and suggests it was a ceremonial bath or trough imbued with ritualistic significance, or a coffin associated with burial in a lacustrine environment.

One of the most exciting archaeological finds of recent years is a series of at least 30 logboats from the early Bronze Age to medieval date in Lough

Figure 15.9
Dating to the early Bronze Age, the 'Annaghkeen boat' is a well-preserved 12m-long logboat from Lough Corrib, Co. Galway.
Photo: Karl Brady and Trevor Northage



Corrib, Co. Galway (Brady, 2014). Ongoing surveys by Karl Brady and the Underwater Archaeology Unit of the National Monuments Service have identified weapons, tools, oars, and other items as well as the boats themselves. The 4,500-year-old 'Annaghkeen boat' is a 12m-long canoe-style logboat so well preserved that the central spine and cross ridges dividing it into compartments can still be seen (see Figure 15.9). This Chalcolithic or early Bronze Age vessel would have required a large crew of perhaps ten or twelve to paddle it effectively. From the late Bronze Age, the 9.6m-long 'Killbeg boat' contained a socketed bronze spearhead with fragments of wood that were radiocarbon dated to the ninth century BC. Beside the boat was a complete spear carved from yew, which may have fallen out as the boat sank. The location of this boat and several others dating to the middle and late Bronze Age, in the narrowest section of Lough Corrib, suggests that this spot was important as a crossing point at that time. In addition, the weaponry in the Kilbeg boat implies that the vessels were not used solely for ordinary tasks, potentially serving a multitude of purposes including raiding, hunting, warfare, and security (Brady, 2014). The increase in weaponry over time appears to indicate a rise in warfare and the need for protection. This could reflect the growth of a more militaristic society and might help to explain the selection of more defensive lakeshore and island sites.

An enigmatic site discovered by divers in Lough Carra, Co. Mayo, in the 1990s consists of two causeways formed of rows of oak posts extending towards each other from either side of a narrow stretch of the lake (Lavelle, 1994). As the causeways do not join, the timbers are not considered to have been a bridge. Dating to the middle to late Bronze Age, they could have been used for ceremonial or ritual activity (Karl Brady, pers. comm.). More generally, the majority of votive deposits (literally, 'offered in fulfilment of a vow') from prehistoric Ireland have been found in wet environments such as bogs and lakes. Individuals and communities seem to have performed these rituals as offerings to thank or appease a god or as part of religious ceremonies; watery locations held special importance as sacred places.

IRON AGE

It appears that climate deterioration contributed to the demise of the Bronze Age *c.*600BC (Raftery, 1994; Waddell, 1998). Population decrease from this time is suggested by evidence for woodland regeneration in some parts of the country, including Co. Mayo (Fuller, 2002). While many Bronze Age crafts and trades continued, the gradual introduction of ironworking revolutionised the range and capabilities of weapons, tools, and other items. Ireland was influenced by two major continental styles – named after lake settlements in Austria (Hallstatt) and Switzerland (La Tène) respectively. The archaeological record of the Irish Iron Age is also characterised by increased numbers of wetland trackways (such as those at Doogarrymore (Co. Roscommon), Corlea (Co. Longford), Annaholty (Co. Tipperary) and Lullymore (Co. Kildare)), linear earthworks (e.g., the Black Pig's Dyke and the Doon of Drumsna (Co. Leitrim)) – some of which are associated with lakes (O'Sullivan, 1998, 100) – and bog bodies. Lakeshore promontories provided naturally defensive locations for settlers to establish bases. It is likely that the promontories at Treanbeg on Lough Feeagh, Errew and Ringall on Lough Conn and Doon Point/Castlecarra on Lough Carra were fortified during the Iron Age.

Close to Emain Macha (Navan Fort), the Iron Age royal centre of the Ulster kings in Co. Armagh, is Loughnashade ('Lake of the Treasure'), a manmade pond associated with ritual activity in the Iron Age. Among the artefacts retrieved from Loughnashade are four large, decorated bronze horns or trumpets dating from the first century BC. Three of the trumpets are now lost, but examination of the 187cm-long fourth reveals that it is fashioned from two riveted tubes, the join between which is cleverly concealed by a ring. The decoration, which includes symmetrical tendrils and buds, has been created using the repoussé technique. Recent palaeo-environmental investigations at Lough Lugh, Uisneach, Co. Westmeath, suggest that it too could be a manmade lake with prehistoric origins (McGinley et al., 2015). A lake made by humans in much more recent times is Poulaphuca Reservoir

Figure 15.10
The largest collection of Iron Age metalwork known from Ireland came to light at a drained lake at Lisnacrogher, Co. Antrim (©National Museum of Ireland)

or Blessington Lakes in Co. Wicklow, created in 1940 as part of the Liffey Reservoir Scheme. When the water level drops, archaeological artefacts and monuments can be seen on the artificial shoreline, having been exposed as the lake-water has washed away the topsoil during the last eighty years (Corlett, 2010). Recently recorded features date to the Mesolithic, Neolithic, Bronze Age, Iron Age, and medieval periods.

In 1882 a remarkable hoard of high-status Iron Age weapons, tools and ornaments was discovered in a drained lake at Lisnacrogher in Co. Antrim (O'Sullivan, 1998, 98–9; Fredengren, 2007) (see Figure 15.10). It is difficult to ascertain how the metalwork came to be deposited, but it may have been a votive offering. Regarding the deposition and recovery of Iron Age artefacts beside lakes more generally, Eamonn Kelly noted that the shores of large lakes constitute major boundaries and that perhaps 'the boundary, rather than the water, is the crucial element' (Kelly, 2006). He cited a bridle bit from the shore of Lough Corrib at Cong South, which is effectively the boundary between the baronies of Kilmaine and Moycullen, and a hoard from the shore of Lough Allen at Cormongan, Co. Leitrim, on the barony border between Leitrim and Boyle. On the one hand, these discoveries shed light on the Irish Iron Age but, on the other, they also lend support to its characterisation as the most 'enigmatic' period of Ireland's past (Raftery, 1994).

Lakes facilitated trade, communication, and social interaction. Many larger lakes were transport routes in their own right – Loughs Derg, Ree, Forbes and Bofin, for example, all form important and lengthy stretches of the Shannon system, Ireland's most important waterway. While many served as communication routes, some lakes also acted as barriers and boundaries, even helping to define modern provincial, county, and other territorial borders (for example, five baronies join at the centre of Lough Corrib). Some of these boundaries originate in prehistoric tribal borders and the deposition of artefacts may reflect the symbolic marking of liminal spaces or territorial bounds or gifts offered in exchange for otherworldly protection.

In 1968 a boat and two willow oars were found at a depth of 5m in Lough Lene, Co. Westmeath, and in 1987 the boat was re-excavated (Brindley and Lanting, 1990; O'Sullivan, 1998, 99–100; Breen and Forsythe, 2004, 41–3). Of carvel construction with mortise-and-tenon joints, this extraordinary vessel is unique in an Irish context, representing a Mediterranean method of boatbuilding. It probably dates to the first century BC/AD and demonstrates contact with the Roman world at that time. Paddy Healy (1992) described the boat as 'a fusion of indigenous and Mediterranean techniques at a time when Britain was under Roman occupation'. Its importance extends beyond its links to the Roman world, however, as it is among the earliest plank-built boats discovered in Ireland.

More typical logboats of Iron Age date have been recovered at various sites around the country, including Gortgill, Co. Antrim (350BC–AD70) (Lanting and Brindley, 1996), Lough Eskragh, Co. Tyrone (370–110BC) (Lanting and Brindley, 1996; Welsh and Welsh, 2021, 299; Breen and Forsythe, 2004, 29, fig. 12) and Comeenatrush Lake, Co. Cork (AD393–537) (Cleary, 2003). A 10.5m-long oak logboat found in Crevenish Bay near Kesh, Lough Erne, Co. Fermanagh, was dated AD10–340 (Fry, 2000, 77–8, no. 49). A second boat from the same location measures 16.2m in length, making it one of the longest prehistoric logboats in Europe (Fry, 2000, 78, no. 50). Fragmentary remains of a third boat were also identified at Crevenish (ibid., 79, no. 51).

Among the above-mentioned underwater discoveries in Lough Corrib, the 'Lee's Island 5' logboat is a 7.3m-long parallel-sided vessel radiocarbon-dated to 50–410BC (Brady, 2014). Among the surviving features were two round-wood seats and – astonishingly – a 2m-long steering paddle. An iron spearhead was found under the front seat, while a carved recess beneath the stern seat accommodated a socketed and looped iron axe with a two-piece wooden handle. A notch in the handle as well as some other design features demonstrate that the axe was attached permanently in this location. Brady (2014) has postulated that the boat, along with its contents of prized objects, was deliberately sunk as part of a ritual deposition or votive offering. The intentional deposition of precious metals, weapons, and other metal objects (including hoards) took place in various lakes across Ireland throughout the Bronze Age and Iron Age. There is a widespread tradition of ritual deposition of boats as votive offerings throughout Europe during prehistory, and the Lee's Island 5 logboat appears to be a rare and fascinating example of this practice in an Irish context.

CONCLUSION

People have lived in proximity to lakes in Ireland since the first human settlement of the island over ten thousand years ago. Lakes provided resources, aided defence, and facilitated travel. Little is known of Ireland's Palaeolithic inhabitants, but people in the Mesolithic certainly lived on lakeshores and lake islands. These were hunter-gatherer-fisher communities who constructed temporary dwellings and opportunistically exploited the lakes' resources. The advent of agriculture at the start of the Neolithic changed the nature of human interaction with lakes, but lacustrine settlement continued and developed across the country. In the Bronze Age, farming families and others involved in various crafts built enclosed lakeshore settlements and occasionally lived on islands. There is less evidence for Iron Age activity on Ireland's inland waters and it seems that the nature of human engagement with lakes changed considerably during that period.

The knowledge accumulated by chance finds and amateur digs in the nineteenth century has been greatly added to by systematic surveys and scientific excavations in the twentieth and twenty-first. Notable contributions to our knowledge and appreciation have been made in the past half-century by the IAWU, the Underwater Unit of the National Monuments Service, the Crannog Archaeology Project, the Discovery Programme's Lake Settlement Project as well as various archaeological consultancies, universities, and individuals across the country. Drone, remote sensing and lidar surveys, coupled with geophysical investigation and GIS-based landscape analysis have revolutionised our understanding of prehistoric lake settlement in Ireland. Focused pollen studies from lake and bog cores continue to reveal the microscopic legacy of a wetland landscape through time. The subject is no less 'rich, complex and intriguing' now than it was a quarter of a century ago.

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Chapter 16

WAVES OF TIME
LAKE SETTLEMENT IN MEDIEVAL IRELAND

Michael Potterton

SUMMARY

This chapter is intended as a companion to the one that precedes it (Chapter 15), in which the important role of lakes in prehistoric Ireland was outlined. In the present chapter, it will become clear that the multifaceted functions of lakes continued to multiply and expand through the medieval period (*c.*AD400–*c.*1600). Our understanding of lake settlement in the Middle Ages is both fuller and more nuanced for several reasons, most notably because of the existence of historical sources that complement the archaeological record. Crannogs and ringforts were first built in late prehistory, but they flourished in the early medieval period. These local and native developments were part of a complex landscape in which we can recognise the growing impact of outside influences – Christianity, the Vikings, Romanesque architecture, the Anglo-Normans and continental religious orders – all of which left their imprint on the medieval lakescape of Ireland.

Keywords Church, crannog, dwellings, interdisciplinary, medieval, settlement

EARLY MIDDLE AGES

The arrival of Christianity and literacy to Ireland in the late fourth century from Britain or Gaul probably had limited immediate impact. Still, it sowed the seeds for long-term and fundamental change at most levels of society. The remains of *c.*5,500 medieval churches survive in Ireland (O'Keeffe, 2015, 22), and many of these are to be found in lakeland settings. In terms of secular settlement, this was generally dispersed (rather than nucleated), with agriculture being a cornerstone of daily life. The *rath* or ringfort – a semi-defended circular farmstead – was the most widespread type of home. They remain the most numerous archaeological monument in Ireland (*c.*45,000 can be identified: Stout, 1997, 53). In a painstaking study of the early medieval archaeology of Lough Ree, historical geographer Matthew Stout

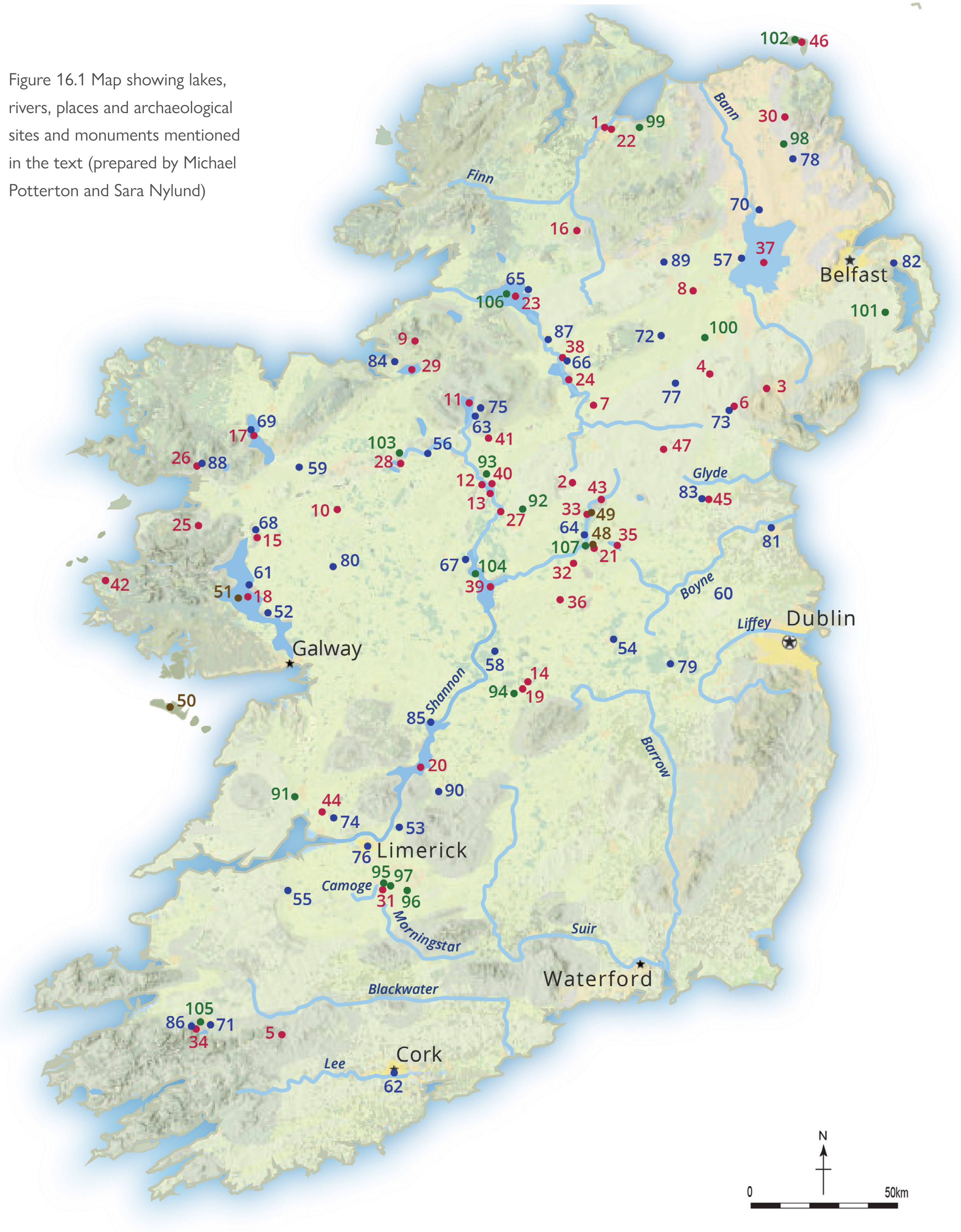


Figure 16.1 Map showing lakes, rivers, places and archaeological sites and monuments mentioned in the text (prepared by Michael Potterton and Sara Nylund)

Fig. 16.1

KEY

Lakes

1. Ballyarnet Lough
2. Black Lough
3. Camlough
4. Clea Lakes
5. Comeenatrush Lake
6. Cullyhanna Lough
7. Derryhowlaght Lough
8. Eskragh Lough
9. Glencar Lake
10. Island Lake
11. Lough Allen
12. Lough Boderg
13. Lough Bofin
14. Lough Boora
15. Lough Carra
16. Lough Catherine
17. Lough Conn
18. Lough Corrib
19. Lough Coura
20. Lough Derg
21. Lough Derravaragh
22. Lough Enagh
23. Lough Erne Lower
24. Lough Erne Upper
25. Lough Fark
26. Lough Feeagh
27. Lough Forbes
28. Lough Gara
29. Lough Gill
30. Lough Guile
31. Lough Gur
32. Lough Iron
33. Lough Kinale
34. Lough Leane
35. Lough Lene
36. Lough Lugh
37. Lough Neagh
38. Lough Neely
39. Lough Ree
40. Lough Scannal
41. Lough Scur
42. Lough Sheeauns
43. Lough Sheelin
44. Mooghaun Lake
45. Moynagh Lough
46. Ushet Lough
47. White Lough

Islands

48. Clonava Island, Lough Derravaragh
49. Derragh Island, Lough Kinale
50. Inishmore, Aran Islands
51. Lee's Island, Lough Corrib

Places

52. Annaghkeen, Co. Galway
53. Annaholty, Co. Tipperary
54. Ballybeg Bog, Co. Offaly
55. Ballyvoghan, Co. Limerick
56. Boyle, Co. Roscommon
57. Brookend, Co. Tyrone
58. Clonfinlough, Co. Offaly
59. Cloongalloon, Co. Mayo
60. Clowanstown, Co. Meath
61. Cong, Lough Corrib
62. Cork, River Lee
63. Cormongan, Co. Leitrim
64. Corralanna, Co. Westmeath
65. Crevenish Bay, Lough Erne
66. Derrybrusk, Lough Neely
67. Doogarrymore, Co. Roscommon
68. Doon Point/Castlecarra, Lough Carra
69. Errew, Lough Conn
70. Gortgill, Co. Antrim
71. Killarney, Co. Kerry
72. Kilsmullan, Co. Fermanagh
73. Kiltybane, Co. Down
74. Knocknalappa, Co. Clare
75. Leitrim, River Shannon
76. Limerick, River Shannon
77. Lisleitrim, Co. Monaghan
78. Lisnacrogher, Co. Antrim
79. Lullymore, Co. Kildare
80. Lurgan, Co. Galway
81. Mell, Co. Louth
82. Newtownards, Co. Down
83. Nobber, Co. Meath
84. Sligo, River Garvoge
85. Stoneyisland, Co. Galway
86. Tomies East, Lough Leane
87. Tonystick, Co, Fermanagh
88. Treanbeg, Lough Feeagh
89. Tremoge, Co. Tyrone
90. Tullahedy, Co. Tipperary

Sites and Monuments

91. Alice and Gwendoline Cave, Co. Clare
92. Corlea, Co. Longford
93. Doon of Drumsna, Co. Leitrim
94. Dowris, Co. Offaly
95. Giant's Grave, Killalough Hill
96. Great Stone Circle, Grange
97. Knockadoon Hill, Lough Gur
98. Loughconnelly, Co. Antrim
99. Loughermore, Co. Derry
100. Loughnashade, Co. Armagh
101. Raffrey, 'Dumb Lough'
102. Rathlin Island, Ushet Lough
103. Rathtinaun, Lough Gara
104. Rindoon, Lough Ree
105. Ross, Lough Leane
106. Rossfad, Lough Erne Lower
107. Scragh Bog, Co. Westmeath

identified a remarkable 270 monuments of early medieval date within 3km of the lake, including some twenty-four church sites on its islands (Stout, 2015). Winter flooding discouraged farmers from settling close to the lake, so their characteristic farmsteads – ringforts – are typically found further from the shore on higher ground. But ecclesiastics certainly were attracted to lakes – their islands and their shores – and many of the sites identified by Stout are associated with the church. An early medieval palisaded house (sixth/seventh century) was excavated in 2003 at Ballintemple, Co. Offaly (Stanley and Moore, 2004). While it was not a lake-side dwelling per se, the excavators noted the former existence nearby of a lake called 'Duck Lough', which could 'have offered a favourable hunting spot exploited by those who constructed the Ballintemple house'.

Crannogs

In broad terms, a crannog (meaning 'young tree') is an artificially constructed island, usually in a lake (O'Sullivan, 1998; Fredengren, 2002; Farrell, 1991). While the concept has prehistoric origins, and some Iron Age crannogs are known in Ireland (Fredengren, 2000), most were built and occupied in the early medieval period. Some were royal sites, but the majority were farmsteads of wealthy farmers and craftworkers. The occupation platform was usually created by dumping layers of stone, soil, timber, peat, brushwood and even domestic rubbish into a shallow part of the lake. The island was sometimes reached by a serpentine causeway invisible beneath the water's surface, and most crannogs were defended by an enclosing timber palisade. Almost two thousand crannogs are known from lakes in Ireland – mostly smaller lakes and especially in the drumlin counties of Cavan, Fermanagh, Leitrim, Mayo, Monaghan, Roscommon and Sligo. Several very significant crannog excavations have taken place, including at Ballinderry 1 and 2 (Hencken, 1936; 1942; Johnson, 1999), Lagore (Hencken, 1950), Rathtinaun (O'Sullivan, 1998, 118–21), Drumclay (Bermingham, 2014) and Moynagh Lough (Bradley, 2011; Potterton, 2022).

The site at Moynagh Lough in Co. Meath was inhabited periodically from *c.*4000BC. It was abandoned in the Bronze Age *c.*790BC when open-water mud partly covered the knolls. The shallows attracted crannog-builders in the seventh century (Bradley, 2011; Potterton, 2022). Set in a landscape peppered with ringforts, the crannog was occupied for approximately two hundred years. The ground surrounding the knolls was reclaimed using stones, gravel, timbers, brushwood and much redeposited peat retained by a timber palisade. Excavation directed by John Bradley revealed the vestiges of round huts and houses, pathways, metalworking areas, cesspits, furnaces, hearths and palisades. There was a remarkable array of iron and bronze weapons, jewellery and tools, antler, horn and bone, glass, leather, crucibles, moulds, enamel, flint, lignite and gold. Imports included amber, Merovingian glass and E-ware, a domestic pottery probably produced on the west coast of Gaul. Two structural timbers were dated to AD625 and 748. At 11.2m across, the main house at Moynagh is the largest known from early medieval Ireland and may have been home to a king or senior aristocrat.

Drumclay in Co. Fermanagh was a large and stunning crannog, the post-excavation analysis of which is still underway a decade after the excavation ended in 2013 (Bermingham et al., 2013; Bermingham, 2014; Hurl, 2015). There was a central platform of overlapping logs, surrounded by at least eight other platforms. There were hearths, plank paths and at least thirty houses over several generations. The thousands of objects were made of metal, glass, wood, pottery, stone and leather.

A Viking sword with an inlaid silver hilt was discovered at Ballinderry crannog 1 in Co. Westmeath in 1928 (Wallace and Ó Floinn, 2002, 228, 243, fig. 6.16) and the site was excavated in 1933 by the Harvard Archaeological Expedition (Hencken, 1936). Much of the evidence was from the tenth and eleventh centuries and included a Viking-type bow, a socketed knife, glass linen-smoothers, a fire-steel (or fire-starter) and a Norwegian whetstone. Several bone gaming pieces were also found, as well as an ornately decorated yew gaming board possibly designed for playing the Viking game *Hnefatfl* (Wallace and Ó Floinn, 2002, 231, 248, fig. 6.22). It is not clear if the occupants of Ballinderry had acquired these objects (either legitimately or illicitly) from a Hiberno-Norse centre such as Dublin or if they were themselves Hiberno-Norse.

Vikings

The Vikings arrived in Irish waters in the late eighth century, initially carrying out hit-and-run raids on coastal sites. Gradually they began to encroach further inland, mostly via the river network, attacking church sites in particular, many of which were on lakeshores or islands. Viking activity – mostly raiding – is attested on more than a dozen lakes in the ninth and tenth centuries (see Table 1). In the 830s Glendalough in Co. Wicklow was attacked (see Figure 16.2). This lakeside church is some 20km inland, as the crow flies, and it is not on a navigable river. Getting there would have

Table 16.1 Viking attacks recorded in lakes in Ireland, ninth and tenth centuries

Lake	Year/s	Source/s
Lough Leane	812	*CGG* IV; *CS*, *AU*, *AFM* 807
Glendalough	834	*CS*, *AU*, *AClon*. 830, *AFM* 833, *CGG* VII
	836	*AClon*. 833, *AFM* 835
	842?	*CGG* XVII
	889	*AFM* 886
	983	*CS*, *AT*, *AClon*. 977, *AFM* 982
Lough Erne	837	*CS*, *AU*, *AClon*. 834, *AFM* 836
	842?	*CGG* XVII
	924	*AU*, *AFM* 922
	933	*CS*, *AClon*. 928, *AFM* 931
	936	*CS*, *AClon*. 930, *AFM* 934
Lough Derg	837	*AU*, *CS*, *AClon*. 834, *AFM* 836, *CGG* XI
	845	*CGG* XI
Lough Neagh	837?	*CGG* XVI
	839	*CS*, *AClon*. 836, *AFM* 838, *CGG* IX
	900	*AFM* 895
	928	*AU*
	930	*CS*, *AU*, *AClon*. 925, *AFM* 928 et al.
	945	*CS*, *AU*, *AFM* 943
Lough Ree	844	*CS*, *AU*, *AClon*. 841, *AFM* 842
	845	*CS*, *AU*, *AClon*. 842, *AFM* 843, *CGG* XI
	922	*CS*, *AU*, *AI*, *AClon*. 918, *AFM* 920, *CGG* XXXIV
	924	*CS*, *AClon*. 920, *AFM* 922
	931	*CS*, *AU*, *AClon*. 926, *AFM* 929
Lough Owel	845	*CS*, *AU*, *AFM* 843, *CGG* XIV
Lough Ramor	847	*CS*, *AU*, *AFM* 845
Lagore	849	*CS*, *AFM* 847
	850	*CS*, *AU*, *AFM* 848
	935	*AU*, *AFM* 933
Lough Gur	926	*AI*
Lough Corrib	929	*CS*, *AU*, *AFM* 927
	930	*CS*, *AClon*. 925, *AFM* 928
Lough Gabhna	933	*CS*, *AClon*. 928, *AFM* 931
Lough Ennell	990	*AFM* 989

Figure 16.2
The twin lakes of Glendalough, Co. Wicklow, attracted settlers and raiders throughout the Middle Ages (©National Monuments Service Photographic Unit)

taken some determination as well as local knowledge – and probably some horses – in addition to an expectation that the prize at the end was worth the considerable effort.

By *c*.840, hit-and-run raids had begun to give way to overwintering. One year, the Vikings raided several islands in Lough Neagh, returning the following year for more. The annals then report a new twist, however, when it was noted that the Viking fleet that had been on the lake in the autumn was still there the following spring. The raiders had been penetrating further and further into the Irish midlands in the 830s, and the 840s witnessed an increased intensity of raiding. We now see larger fleets controlled by named leaders. Overwintering probably began in the mid-830s. Raiding bases soon became more permanent settlements. Ship camps (*longphuirt*) were built on rivers such as the Barrow (Dunrally), Glyde (Annagassan), Lee (Cork), Liffey (Dublin), Shannon (Athlunkard) and Suir (Woodstown); another was built on Lough Ree. Overwintering enabled the Vikings to take advantage of the prevailing winds to sail to Ireland from Scandinavia, and then back the following year.

Even when the Vikings were not active in lakes in Ireland – which happened briefly between 902 and 917 when they had been expelled from Dublin – traces of their influence can be found. The Lough Ennell silver hoards from Co. Westmeath are, at 51kg, among the largest Viking Age hoards known. They include Kufic and west Asian coins and can be dated to *c*.905–7. They appear to have come into Ireland when Dublin was no longer under Viking control. They arrived directly into the heartland of the powerful Irish royal dynasty Clann Cholmáin, at that time led by Flann Sinna, referred to in some sources as 'king of Ireland'.

Boats

Among the logboats recently discovered on the floor of Lough Corrib is a finely crafted eleventh-century vessel (Brady, 2014). The well-preserved 'Carrowmoreknock boat', as it is known, is 6m long and retains four plank-seats and four pairs of oar-holes. Recovered from within the boat were three battle-axes, an iron work-axe and two iron spearheads. Unusually, the cherrywood axe handles have also survived, one to a length of 80cm (see Figure 16.3). While the axes are Viking-style weapons, they were likely used here by Gaelic-Irish warriors. Early medieval logboat timbers have also been recovered at Ballinderry (Co. Westmeath) (Hencken, 1936), Lagore (Co. Meath) (Hencken, 1950), Oxford Island (Co. Armagh) (Breen and Forsythe, 2004, 69–70), Rathtinaun (Co. Sligo) (Hencken, 1950, 10, 151–2; O'Sullivan, 1998, 118–21), Lough Neagh (Lanting and Brindley, 1996, 86), Lough Moriarty (Co. Galway) (Lanting and Brindley, 1996, 87) and elsewhere (Fry, 2000). The annals refer to the wrecking of vessels on Lough Ree in the 750s and again in 935 (Breen and Forsythe, 2004, 51–2, 58), while fleets are mentioned on Loughs Erne, Ree and Derg (Table 1). When the water level dropped on Cloonacolly Lough, Co. Roscommon, due to dry

Figure 16.3 These axes – including handles – were found inside an eleventh-century logboat on the bed of Lough Corrib (©National Museum of Ireland)

weather in the summer of 2020, a 5.4 m logboat came to light close to the edge of the lake and just 100 m from a crannog (McCaughley, 2020; Karl Brady, pers. comm.). While scientific dates are awaited, it is possible that this was another medieval boat.

Church

From the earliest days of Christianity in Ireland, churchmen and women chose isolated sites for new religious buildings, and lakeshores and islands were among the most sought-after (Ó Carragáin, 2013). This is reflected now in surviving placenames, the presence of church ruins and the discovery of important ecclesiastical metalwork in lakes. Among the hundreds of known lake-island churches are Iniscealtra on Lough Derg, Church Island on Lough Gill, Inisfallen on Lough Leane (where one of the most valuable collections of early medieval annals was compiled) and Inishmacsaint, White Island and Devenish on Lough Erne, the latter of which was home to the eighth-century reliquary known as the *Soisceal Molaise* (Wallace and Ó Floinn, 2002, 233, 251, fig. 6.27; Ralegh-Radford, 1970) (see Figure 16.4). Side-scan sonar data acquired recently around Devenish indicates the presence of twenty anomalies of archaeological possible – including a possible dugout canoe – and the location of a potential causeway linking Devenish with the lakeshore (Lafferty et al., 2003; McNeary et al., 2013).

In addition, early grants of lands to churches appear to have favoured liminal spaces and the borderlands of tribal territories, as well as lacustrine routeways. Consequently, some four hundred churches were established on territorial boundaries (Ó Riain, 1972, 18, 28). Indeed, Lough Erne itself was the de facto border between Ulster and Connacht from as early as the sixth century until at least 818 (Simms 1977, 126).

On Lough Currane in Co. Kerry, Church Island or *Inis Uasal* was the premier church of early medieval Corcu Duibne (Ó Carragáin, 2021, 88–9, 186–8, figs 72, 73, 79, 189, 190). A visit to the island will reveal the remains of a Romanesque church, a burial ground, and an earlier large drystone building (Fínán's Cell) as well as several enclosures and other structures. On the same lake, Rabbit Island has a large enclosure containing a drystone building (Ó Carragáin, 2021, 92, figs 78, 189). Some lake islands have multiple churches; Inchcleraun on Lough Ree in Co. Longford has at least half a dozen.

In Co. Wicklow, Glendalough, 'the glen of two lakes', was home to a monastery founded by St Kevin (d. 618) in the sixth century (see Figure 16.2). It was to become one of the most famous religious centres in early medieval Ireland. Its significance is reflected in records of at least five Viking attacks in the ninth and tenth centuries (Table 1). Although few of the above-ground remains at Glendalough date to before the eleventh century, at least five of the churches were probably built within a generation or so either side of the year 1100. The largest and oldest of these is the 'cathedral', a simple nave-and-chancel structure with a sacristy. Standing 6m above the south shore of the Upper Lake are the slight remains, mainly a reconstruction on old foundations, of a small rectangular church – *Temple na Skellig*. The round tower at Glendalough – an internationally recognised symbol of medieval Ireland – is also likely to have been built around 1100; it is one of several to be found in lake settings in Ireland (including Devenish, Iniscealtra and Ram's Island (Lough Neagh)).

Much of the highly decorated metalwork from the medieval period was generated by the church – notably communion vessels, shrines and reliquaries. Many of these objects were entrusted to hereditary keepers, but many more were destroyed in the sixteenth-century Reformation. Almost all were melted down, but some objects were saved from this fate due to being lost or hidden in lakes. Among the notable examples of early ecclesiastical metalwork from

Ireland's lake contexts are the Lough Erne Tomb Shrine (Murphy 1892; Wallace and Ó Floinn, 2002, 181, 191, fig. 5.8; Harbison, 1999, 134), the ninth-century decorated Lough Lene Bell (Harbison, 1999, 216, 247, 161; Wallace and Ó Floinn, 2002, 183, 197, fig. 5.15), the Rinnagan (Rindoon) Crucifixion Plaque (*c*.AD850) from Lough Ree, the Cross of Cong (Wallace and Ó Floinn, 2002, 232, 249, fig. 6.24), the Tully Lough Cross (see Figure 16.5) and the Lough Kinale Book Shrine (Harbison, 1999, 72–4, 262, pl. 45). Dredged up in 1986, the latter is incomplete and dismantled (and missing its book), but it is the earliest-known example of its kind.

Important early medieval metalwork finds from lakes are not confined to ecclesiastical items; among the secular objects that have come to light are the Tully Lough sword (Wallace and Ó Floinn, 2002, 266, fig. 7.5), the seventh-century Lough Neagh bronze brooch (Harbison, 1999, 53), the eighth-century Lough Gara belt buckle (Harbison, 1999, 40) and the unique Ardakillen brooch (Wallace and Ó Floinn, 2002, 176, 180, fig. 5.1). Hints of former metalwork masterpieces can be seen in beautifully carved antler and bone 'trial-pieces' or 'motif-pieces' from lake settings such as Lagore Crannog in Co. Meath (Harbison, 1999, 216, 261, *154*; Wallace and Ó Floinn, 2002, 183, 196, fig. 5.14). Accidental loss and deliberate deposition in and around lakes have resulted in the preservation and discovery of a wide range of otherwise unknown material culture of early medieval date.

From left:
Figure 16.4
This is the *Soisceal Molaise*, an early medieval reliquary associated with the island monastery on Devenish in Lough Erne (©National Museum of Ireland)

Figure 16.5
The early medieval Tully Lough Cross was found by divers near a crannog in Co. Roscommon in 1986 (©National Museum of Ireland)

LATER MIDDLE AGES

In medieval and Renaissance Europe, Ireland was probably best known for St Patrick's Purgatory in Lough Derg (Haren and de Pontfarcy, 1988). The story had been well known across Europe since the twelfth century, and there was a long list of continental pilgrims and visitors to the site. As the Middle Ages progressed, Irish kings went on pilgrimage to Rome, missionaries set out across the Continent and ecclesiastics founded churches and monasteries in far-flung lands. The discovery of pottery from Normandy in late eleventh-century levels in Dublin reflects deepening contact between Ireland and the Norman world at that time. Once the Normans became established in England after 1066, trade between Ireland and Britain grew. Some major cultural developments in Ireland in the first half of the twelfth century had a Norman or Anglo-Norman background – notably church reform, the arrival of continental religious orders and the introduction of Romanesque architecture. The advent of the Anglo-Normans to Irish shores in 1169–70 would have a profound impact, the reverberations of which continue to be felt in the twenty-first century. They built and expanded castles, towns (boroughs) and trade networks across the country, patronised religious houses, cathedrals and parish churches, and instigated profound social, economic and political changes. There were, however, significant elements of continuity and overlap with existing settlement patterns.

Late use of crannogs

While there can be little doubt that most crannogs were built and occupied during the early medieval period, the portfolio of evidence for the late use of these island dwellings continues to expand (O'Conor, 1998, 77–82; 2018; O'Sullivan, 2001; O'Hara, 2004, 14–17; Brady and O'Conor, 2005; Foley and Williams, 2006). Among the contemporary documentary sources for this phenomenon are the annals, bardic poetry, state papers and the writings of Giraldus Cambrensis. Indeed, the word 'crannog' appears in the sources only after *c*.1200 (they are generally referred to as 'inis' (island) in earlier sources). Later medieval annals refer to crannogs on Oughter, Co. Cavan (ALC 1220, 1223), Loughnaneane, Co. Roscommon (*AU*, 1225), Belhavel, Co. Leitrim (AC; ALC; *AFM*, 1247), Kilglass, Co. Roscommon (AC; ALC, 1246, 1456), Veagh, Co. Donegal (*AFM* 1258, 1559; AC 1524), Ardakillen, Co. Roscommon (*AU*, 1388; AC, 1467), Melvin, Cos Leitrim and Fermanagh (*AFM*, 1419, 1455) and Island MacHugh, Co. Tyrone (*MCM*, 151 (1260); Wood-Martin, 1886, 155–6, 179 (1325); AC, 1436).

In 2003–4, a multi-proxy analysis of Ballywillin Crannog on Lough Kinale was carried out using plant macrofossils, pollen and spores, diatoms, chironomids and coleoptera from a core to reconstruct local and regional vegetation change and lake history (see Chapter 3). The results indicate that the 'crannog was constructed around AD620, with its most intensive period of occupation after AD1150' (O'Brien et al., 2005; Selby et al., 2005). Similarly, although it was constructed at an earlier date, the crannog of Island MacHugh produced evidence of habitation in the thirteenth and fourteenth centuries (Davies, 1950, 45–56, 92; Ivens, Simpson and Brown, 1986). In 1477 a great storm is said to have demolished many stone and wooden buildings and crannogs and ricks all over Ireland (AC). Various maps produced by English military cartographers in the sixteenth and seventeenth centuries depict crannogs in use at that time.

Finds of later medieval date – including coins, weapons, tools, pottery and dress accessories – have been found at many crannog sites on lakes including Gara, Island McHugh, Co. Tyrone, Faughan, Co. Down (Collins, 1955), Eyes, Co. Fermanagh, Ballydoolagh Lough, Co. Fermanagh (Donnelly et al., 2007), Ardakillen, Co. Roscommon (Wood-Martin, 1886, 236–9). Structural oak timbers from several Fermanagh crannogs have been dated by dendrochronology to the later Middle Ages: Carrick (1536); Corban (1476); Eyes (1510±9); Mill (1530±9) (O'Sullivan, 2004, i, 282, 289–91; Kelly, 1994, 122). In some instances, multiple strands of evidence come together, such as in the case of Kilsampson Crannog, Co. Tyrone, which is prominently marked with a small castle or tower house on the Josias Bodley map of 1609. The site was associated with Henry Óg McHenry O'Neill at this time, and it is recorded that 'many swords and other military weapons were discovered [there] during drainage' (Welsh and Welsh, 2021, 305). Hugh O'Neill used crannogs as supply depots and as strongholds in the war against the English; for example, he used a crannog on Lough Lurcan in Co. Armagh as a headquarters in 1600 (Kelly, 1994, 122). Some crannogs likely functioned as late medieval Gaelic strongholds, as is suggested, for example, by their proximity to Plantation castles, such as the crannog in Drumcorban Lough adjacent to Monea Castle, Co. Fermanagh (Rory McNeary, pers. comm.).

A reassessment by James Lyttleton of the excavation in 1913 of Loughpark 'crannog' in Co. Galway concluded that the site was, in fact, a late ringfort and that it was used (and perhaps constructed) in the thirteenth century (Lyttleton, 1998). The discovery at Loughpark of arrowheads, a crossbow bolthead and spurs was interpreted by Lyttleton as possible evidence for the use (or re-use) of this wetland ringfort as a military stronghold.

Island fortresses

In addition to crannogs and ringforts, some small natural islands were used as defended dwellings in the later medieval period. Several of the *inis* sites mentioned in contemporary documents appear to be defensive earthworks on completely natural islands. Examples include islands in Lough Gill, Co. Sligo (*AFM*, 1245), Oughter, Co. Cavan (*AFM*, 1231) and Key, Co. Roscommon (O'Conor, 1998, 76, 82). Lough Key was among the most important lakes of medieval Ireland (Finan, 2010). A campaign of historical and archaeological research has shed a great deal of light on the nature of activity in and on the lake in the Middle Ages (see, for example, Read et al., 2005; Finan, 2010; 2020) (see Figure 16.6).

Figure 16.6 The shoreline and islands of Lough Key are rich in archaeological evidence for medieval settlement (map prepared by Michael Potterton and Sara Nylund)

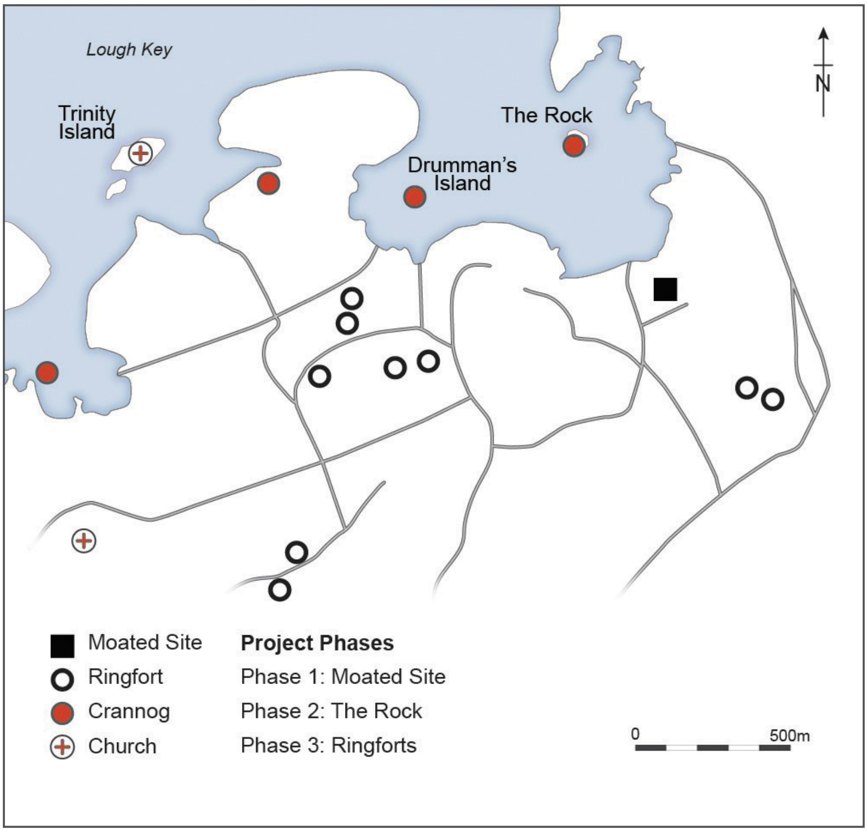
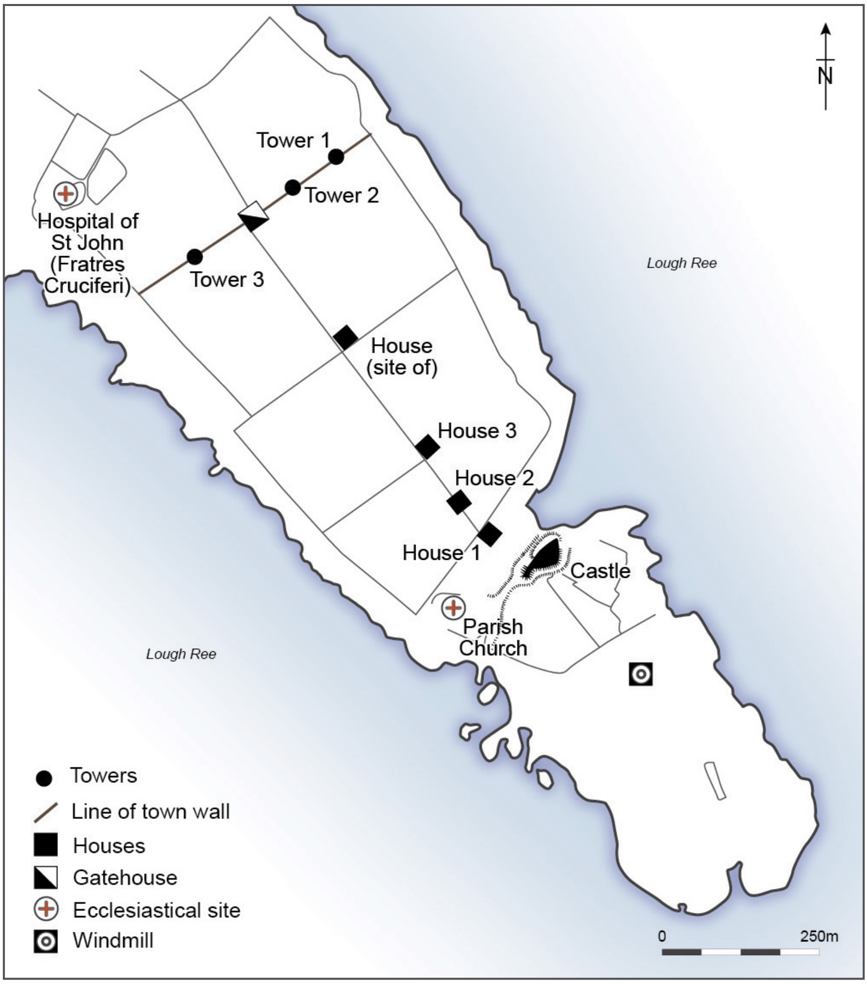


Figure 16.7
This fine dish-shaped reliquary or paten, known as the *Mias Tighearnáin*, is from Errew Abbey on Lough Conn (©National Museum of Ireland)

Churches and monasteries

While some went out of use, many early medieval church sites in lake settings continued to function into – and indeed through – the later Middle Ages. Some houses of the continental religious orders that arrived in Ireland in the twelfth and thirteenth centuries were established on lakeshores and islands – including the Premonstratensians on Trinity Island in Lough Key (see Figure 16.6) and its daughter house on the island of the same name in Oughter, the *Fratres Cruciferi* ('Crutched Friars') at Rindoon on Ree, the Franciscans at Muckross on Leane, the Dominicans at Urlaur in Co. Mayo, and the Augustinians at Devenish on Erne, Tristernagh on Iron in Co. Westmeath, Inchcleraun on Ree, Inchmacnerin on Key, Inishmaine on Mask, Annaghdown and Cong on Corrib and Errew on Conn. The *Mias Tighearnáin* is a fine late medieval paten from Errew Abbey (Wallace and Ó Floinn, 2002, 270, 290, fig. 7.23; Ó Floinn, 2004) (see Figure 16.7). Tracy Collins has identified ten late medieval nunneries situated on lakeshores (Collins, 2021, 117–20).

Figure 16.8
Rindoon on Lough Ree is a deserted medieval town with a castle, church and hospital. It was served by a ferry across the lake (map prepared by Michael Potterton and Sara Nylund)



Lakes were also used for watering livestock. St Thomas' Abbey in Dublin held extensive lands in Co. Meath including the grange of Dunshaughlin (*CDI, 1285–92*, no. 839, p. 381; *RST*, 26–7). The canons of St Thomas agreed that the men of Dunshaughlin should have access with their animals through their grange to the lake called Lagore.

Boroughs and towns

Sporadic and seasonal flooding around lakes was probably a disincentive to town founders choosing locations at which to establish urban centres in the Middle Ages, but a handful of boroughs were founded beside lakes nonetheless – Rindoon on Ree (see Figure 16.8), Cong on Corrib and Antrim on Neagh being cases in point. A bridgehead evolved at Athlone on the southern shore of Lough Ree at a place where prehistoric settlement had almost certainly preceded it. At the northern end of Lough Ree, the town of Lanesborough developed at an ancient fording – and then bridging – point on the River Shannon. There are occasional references to lake ferries operating in the later Middle Ages, including the one at Rindoon in the early fourteenth century (Breen and Forsythe, 2004, 76; Shanahan and O'Conor, 2020). The Anglo-Normans on Lough Ree were constantly under threat from fleets of Gaelic Irish boats, and the government ordered the construction of a thirty-two-oar galley to protect them (Breen and Forsythe, 2004, 76, 84). Recently, a case has been made for a site on Lough Key as 'Gaelic Ireland's first town' (Finan, 2020) (see Figure 16.6).

Later fortifications

The naturally defensible qualities of lake islands – whether natural or artificial – attracted late medieval individuals, families and communities. In addition to the re-use of crannogs and promontory forts, castles were built in a range of lacustrine locations – sometimes on top of former settlements. Cro-Inis on Lough Ennell in Co. Westmeath was a royal crannog where Mael Seachnaill II died in 1022 (Doherty, 2009). Among the remains at Cro-Inis now are a twelfth-century plank palisade and a later tower house, apparently the residence of the chief of the Ó Cobhthaigh, formerly poets to the kings of Meath (Brady and O'Conor, 2005, 130–1). It is likely that it was here that poet Domhnall Ó Cobhthaigh and two sons were murdered in 1446 (*AFM*). Similarly, at Island MacHugh a tower house was built on a crannog in the later Middle Ages (Davies, 1950, 56–85; Ivens, Simpson and Brown, 1986, 99).

At Clogh Oughter, a tiny island in Lough Oughter, Co. Cavan, a cylindrical masonry castle was built by the Anglo-Normans in the thirteenth century (Manning, 2013) (see Figure 16.9). Strategically sited, the castle may have been overlooking (but not on top of) the crannog of the O'Reillys, Gaelic Irish lords of east Bréifne. The castle was quickly captured by the O'Reillys and was later used as a prison, before being refortified during the seventeenth-century Ulster Plantation. It was archaeologically excavated and conserved as a National Monument.

The north-eastern shore of Lough Gill (Co. Leitrim) is dominated by the seventeenth-century Parke's Castle, but this was built on the site of a fourteenth-century tower house, home of the O'Rourke lords of Bréifne (Foley and Donnelly, 2012). A second tower house stood nearby. Further stone castles were built on lake sites at Ashford, Aughnanure and Caisleain na Circe (Corrib), Rindoon (Ree) (see Figure 16.8), Ross (Leane) and Castle Hag (Mask) as well

Figure 16.9 Later medieval Lough Oughter was home to crannogs, *inis* sites, churches and a cylindrical masonry castle at Clogh Oughter (©National Monuments Service Photographic Unit)

as others on Sheelin (Co. Cavan), Carra (Co. Mayo) and Ballinahinch Lake (Co. Galway). The remains of earthwork castles (notably mottes) are also known at Coney Island (Neagh), Knockatemple (Ramor), Portloman (Owel), Loughsewdy (Co. Westmeath) and elsewhere. At the tip of the Mizen Peninsula in Co. Cork, Dunlough Castle forms part of the defences between the shore of Dun Lough and the sea-cliffs to the south-west (see Figure 16.10).

By the sixteenth century, the extent and strength of English control in Ireland had waned considerably. Most of the country beyond the 'four obedient shires' of Dublin, Kildare, Louth and Meath had been reclaimed by the Gaelic Irish. When it came to constructing a physical boundary to the area known as the Pale (which appears never to have been completed), natural features and existing defences were incorporated where possible. Place-

Figure 16.10 Spectacular Dunlough Castle in Co. Cork comprises three strategically sited late medieval fortified towers (©National Monuments Service Photographic Unit)

name and cartographic evidence for the area around Clane, Co. Kildare, for example, indicate the former presence of lakes and moors that have since dried up. Seamus Cullen (1993) has demonstrated that gaps between long stretches of the Pale ditch in this area were once occupied by lakes – such as Loughbollard – and moors – such as Moortown.

The Dissolution of the Monasteries under Henry VIII had a major impact

on many parts of Ireland, in terms not just of churches and religion, but also land ownership, agriculture, economy and society more generally. As the sun set on the Irish Middle Ages, the political, religious and cultural landscape was experiencing significant change. The roles and significance of lakes, however, remained relatively constant.

CONCLUSION

As our knowledge of medieval settlement expands, so too does our recognition of the ways in which people engaged with lakes. This understanding is enriched by the survival of written sources, which greatly complement the archaeological evidence. Widespread lacustrine activity in this period includes crannogs, island residences and monastic islands. The richness of many of these settlements attracted Viking raiders and traders in the ninth and tenth centuries, and they too left their marks on the lakes. In the later medieval period, some crannogs, island ringforts, promontory forts and other earlier settlements continued to be inhabited, and a new relationship evolved between the people and the lakes. The arrival of the Anglo-Normans in the late twelfth century saw the construction of castles of timber and of stone on lakeshores and islands, while the Gaelic Irish frequently took refuge on secluded lake boltholes.

As the Middle Ages progressed, Ireland became increasingly engaged in international communication, and this is reflected in the wide range of overseas artefacts discovered in and around our lakes – from Kufic coins to Merovingian glass, Gaulish pottery and Baltic amber. Some lakes appear only periodically (turloughs), and others have disappeared forever – largely as a result of agricultural improvement and drainage since the eighteenth century (see Chapters 4 and 17). The history of several former lakes has been illuminated by discoveries in bogland and dryland, but much remains to be revealed.

Settlers have been drawn to lakes since earliest times. For more than two hundred years, antiquarians and archaeologists too have continually returned to lakes to discover, analyse and interpret the artefactual, monumental and microscopic traces of ancestors in the hope of more clearly understanding their activities, circumstances and motivations. While our archaeological heritage is constantly under threat from industrial development, land improvement, arterial drainage, climate change, treasure-hunters and other factors, nonetheless an unprecedented array of scientific methods, technology and equipment are being deployed to record and analyse the archaeological evidence – in this chapter alone we have benefitted from the evidence of dendrochronology, drone photography, geophysical prospection, isotopic analysis, lidar, palynology, radiocarbon dating and side-scan sonar.

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ABBREVIATIONS

AC: *Annála Connacht: the annals of Connacht (AD1224–1544)*, ed. A.M. Freeman (Dublin, 1944).

AClon.: *The annals of Clonmacnoise*, ed. D. Murphy (Dublin, 1896).

AFM: *Annála ríoghachta Éireann: annals of the kingdom of Ireland by the Four Masters from the earliest period to the year 1616*, ed. and trans. J. O'Donovan (7 vols, Dublin, 1851; repr. New York, 1966).

AI: *The Annals of Inisfallen (MS Rawlinson B503)*, ed. and trans. S. Mac Airt (Dublin, 1951).

ALC: *The Annals of Loch Cé*, ed. W.M. Hennessy (2 vols, London, 1871).

AT: 'The annals of Tigernach', ed. W. Stokes in *Revue Celtique*, 16–18 (1895–7) (repr. 2 vols, Felinfach, Wales, 1993).

AU: *The annals of Ulster (to AD1131), pt i: text and translation*, ed. S. Mac Airt and G. Mac Niocaill (Dublin, 1983).

CDI: *1171–1251* [etc.]: *Calendar of documents relating to Ireland, 1171–1251* [etc.] (5 vols, London, 1875–86).

CGG: *Cogadh Gaedhel re Gallaibh: War of the Gaedhil with the Gaill*, ed. J.H. Todd (London, 1867).

CS: *Chronicum Scotorum: a chronicle of Irish affairs … to 1135, and supplement … 1141–1150*, ed. W.M. Hennessy (London, 1866).

MCM: *The poems of Giolla Brighde Mac Con Midhe*, ed. N. Williams (London, 1980).

RST: *Register of the abbey of St Thomas the Martyr, Dublin*, ed. J.T. Gilbert (London, 1889).

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Chapter 17

LAKE CULTURAL HISTORIES SNAPSHOTS

Catherine Dalton and Paul O'Brien

SUMMARY

Lakes have always acted as natural focal points for human settlement, providing essential water and food resources, offering inspiration and also fear, and provoking the battle to control water. This chapter explores some of these tangible and intangible natural and cultural histories of water bodies in the landscape to reveal how human actions and lake environmental change are intertwined. Examples of where lakes were core influences on human affairs are explored, as well as instances where lakes played an active role in historical processes that affected cultural values and beliefs about nature. This snapshot of the interactions of people in/on/at and with lakes, including their influence on our culture, is focused on the period AD1600 up to AD1950.

Keywords Placenames, hydrolarty, leisure, artificial lakes, drainage, demesnes

INTRODUCTION

Freshwater is the lifeblood of the landscape of Ireland, actively flowing through its rivers, resting for a while in lakes, ponds, wetlands, and their organisms, evaporating to the atmosphere or eventually reaching the sea. The mild, wet temperate climate supports a tremendous number of waterbodies, as well as blanket and raised bogs, which are, of course, vegetation-filled wetlands and lakes. The wetness of Atlantic seaboard weather ensures that Ireland's waterbodies are often filled to capacity, many spilling over shallow floodplains and spreading far and wide in wet seasons. Lakes could be described as 'islands' in a sea of terrestrial land. However, the connection between rivers and lakes can be hard to distinguish in some systems. Lough Key has been described as 'merely an expansion of the Boyle river, which carries down the surplus waters of Lough Gara, to Ireland's great central canal, the Shannon' (Healy, 1878). The river Erne, meanwhile, with its lake-like expansions, prompted Praeger to describe it as 'a singularly sluggish course – a mere succession of

Table 17.1 A selection of evocative terms for lakes and wetlands

Geography	Descriptions
Hydronmys (names given to water bodies)	Churning waters
Limnonyms (lakes and ponds)	Ripple waters edge
Blind lakes (diminished lakes)	Smooth water
Water mearing (a water boundary dividing two pieces of land)	Molten mirror
Serpentine (serpent-like winding lake)	Piscatorial supply
Phenomenology of water (reflection, refraction)	Lake of memory
Berba (dumb and sluggish water)	Pellucid lake
Flooded voids (quarry lakes)	Vitrified lake
Unwater, Evacuate lakes (drain)	Sweet-water (freshwater)
Linn (Gaelic for pool, pond)	
Mythology	Wetlands
Liminal spaces (dividing worlds or states)	Sloughs (wetlands)
Un-place (neither in this world, nor in the next)	Callows, Corcasses & Bottoms
Lake bursts, outbursts, outbreaks	Wastelands
	Injuriously affected lands

island-filled lakes – till at Belleek it plunges over a lip of limestone and rushes down to meet the sea' (Praeger, 1934).

Rivers and lakes have attracted settlers from early times (see Chapter 15 and 16) and have been impacted by increasing agricultural modification and expanding settlement size with technological and economic developments. The Irish landscape has been transformed over millennia from wetland and wild woodland to domesticated field systems but has avoided some of the excesses of industrial and urban activities of its more populated neighbours. Thus, Ireland has retained a naturalness, wildness and ruggedness in upland and some lowland western regions. These wetlands and waterscapes have provided a natural stage for folklorists, pilgrims, artists, scholars, and engineers, each giving a different account of lakes in the landscape. These waterscapes have given rise to many evocative terms (see Table 17.1), but for many, wetlands have also been perceived as challenging, inhospitable, and unproductive terrain.

In the study of placenames (toponomy), hydronyms are the names of all water objects, limnonyms are lakes, and microhydronyms are ponds or wells (Table 17.1). Lake is 'Loch' in Gaelic, while 'Lough' is an English translation. The *gh* is thought to have been the English attempt to write the guttural *ch*.

Most Irish placenames have a medieval origin, while names of natural features such as lakes and mountains can predate this. Few placenames, however, were documented before the seventeenth century, and field names are largely of nineteenth-century origin (Mullen and Ludlow, 2015). First-hand observations of this wet landscape are documented in maps and many scholarly works throughout medieval and historical periods. The placenames database of Ireland (Loganim: https://www.logainm.ie) lists just 1,665 placenames for lochs/loughs/lakes, 41 *Lochán* (ponds) and 2 *Linn* (pools). At the same time, Environmental Protection Agency (EPA) digital datasets include lake names for one-third of lakes (n=4,407) of the total of 12,205 lakes and ponds in the Republic of Ireland (RoI) with an area greater 100 m^2 (Dalton, 2018). This suggests that there is a body of work outstanding to understand the toponymic significance of lakes in Ireland.

MYTHOLOGY AND FOLKLORE

Rivers and lakes appear in mythology as motifs of both physical and spiritual boundaries (Hopkins, 1992) that celebrate the ability of a body of water to serve as another world. Lakes are considered liminal spaces or transitions between *terra firma* and the aquatic realm, making them common locations for ceremonial and votive offerings (Brown, 2003). There are multiple references in the annals or ancient texts to lake bursts, outbursts, outbreaks, or eruptions (Hopkins, 1992). This aquatic phenomenon has been used to mark invasions and a rebirth of land in mythology. Interestingly, in ice age studies, a glacial lake outburst flood is a type of flood caused by the failure of a glacial debris-dammed lake (see Chapter 2). It is an apt description when ascribed to floods, overflows, and inundations, but in the annals, it is also used to describe the first appearance of a lake. A lake-burst (Old Irish: *tomaidm/tomhaidhm*) is when a previously non-existent lake appears. Hopkins (1992) depicts the sole survivor of a battle over two women, who builds a house over a spring: 'At the spot … in the glen beside Druim Sam, a spring rises there ... it boils over wall and plain.' One day, the spring arose, drowning one thousand men and creating a lake (Loch Riach or Lough Rea (Galway)). The origin of Lough Rea was recalled in 1838 when 'some light-hearted lass, it is told, thinking more on a bright pattern for a Sunday's gown, or on the last soft words of her sweetheart, forgot, one fine day, to cover the well, and the flood rose, which soon spread out into the wide breast of waters we now call Loughrea' (*Galway Patriot*, 13 June 1838). Sigerson (1875) noted that all lake outbreaks were associated with limestone and attributed their emergence to increased seismic energy and earthquakes. A fictional work from 1756 described 'Locherne [Lough Erne], in the county of Fermanagh ... was once a place where large and populous towns … the people and their fair habitations were destroyed in an earthquake, and mighty waters from the earth covered the place, and formed this lake' (Amory 1756). Turloughs, or temporary lakes caused by blocked channels, may additionally have been the inspiration for the abundance of these events in Irish myths. Lake bursts are also often associated with grave-digging, with a death balanced in nature by the birth of a body of water. Thus, lakes are motifs of both physical and spiritual boundaries.

Banshees, kelpies, shape shifters and muckies are spirits associated with water bodies. 'Curious beliefs prevail concerning fairies, banshees and phantom horses issuing from the bosom of the lake' are attributed to Lough Corrib' (*Weekly Irish Times* 15 June 1901). A 'Broicsighe or large hairy badger resembling a horse' was driven into the Lake of Corofin in Clare and chained in place, where it has remained ever since (*Irish Times*, 31 January 1931). Westropp (1911) refers to a 'Poulnapeasta' or water dragon's lair and comments that 'Probably no lake of any importance in Clare was untenanted by a serpent, a wonderful animal.' Lough Gur (Limerick) was 'conjectured to be the place of … unearthly transmutation from the human to the Fairy state' (Dickens, 1870).

HYDROLARTY AND PILGRIMS

Hydrolatry, or the worship of water, is panhuman and sacred lakes, wells and springs can be found across cultures. Lakes are referred to as homes of the gods and, thus, guardians of life and have been a focus for hydrolatry and pre-Christian and Christian votive offerings. Human remains, stone artefacts, and Iron Age metalwork have been found preserved in lake sediments (see Chapter 16). Healy (1878) states, 'their very names are the creation of romantic legend, their shores and islands are strewn with venerable ruins suggestive of historic and literary associations, and many of them hallowed by holiest memories.'

Monastic sites, including hermitages, churches, priories and nunneries, are common adjacent to and on lake islands. At the same time, ponds and springs/wells have long been a focus for religious expression and celebration (Rees, 1997) and have provided locations for patterns (devotional rituals) and

Figure 17.1
Pilgrims being rowed to Station Island, Lough Derg, County Donegal, 1876. Source: Etching by W.F. Wakeman, as in D. Canon O'Connor: St. Patrick's Purgatory, Lough Derg, (Dublin 1903), plate facing p.208). Reproduced courtesy of the National Library of Ireland

pilgrimages for millennia. The most famous pilgrim lake sites in Ireland are Glendalough Wicklow (mentioned from AD 951) and Lough Derg County Donegal (AD 1147) (Griffin and Raj 2015). Lough Derg is described by Healy (1878) as a 'dreary and desolate expanse of water' surrounded by 'heathy and barren hills'. He comments that 'nature here clothes herself in sackcloth and ashes; the very aspect of the place induces solemn thought and makes it meetest shrine for penance'. Sir John Leslie, the landlord, received £50 per year for permitting ferry access to the lake (Figure 17.1) and would 'not make a road to the lakes margin', causing an additional penance to the 'benighted papists… of walking a mile through mud' (Healy, 1878). The peak in pilgrims to Derg (St Patrick's Purgatory) saw some 35,000 pilgrims annually in the early 1950s.

Lake islands conjure evocative and fanciful images by their remoteness. Boate (1726) described lake islands 'doe float not keeping long in any certain place, but removing to and fro, as the force of the wind doth drive them.' A more unusual use of lakes, or more specifically islands in lakes, was as forts and island prisons ('fastness' natural secure places or 'redoubt' in military parlance). Fort Island on Ennell (Westmeath) had a garrison and was used for munitions storage 'by the Irish' in the war of 1641. Prisoners were held in these naturally secure places on Scaur and Glencar lakes in Leitrim and on Derg in Donegal while a the massive stone fortification on Doon Lough near Portnoo may date from the late Iron Age to Early Medieval times (Figure

Figure 17.2
Fort on Doon Lough
Portnoo, Donegal.
Photo: Emer Magee

17.2). Another use of lake islands with entrepreneurial intent was whiskey distillation. A raid by excise officers in 1809 on Lescrevain (Fermanagh) saw the destruction of two stills and the spillage of 800 gallons of pot-ale (*Freeman's Journal*, 30 June 1809).

The calming stillness of ponds and lakes is relaxing and, for many, therapeutic. The healing quality of lake waters is illustrated by one Mr Cunningham, who was afflicted with running sores and 'bathed in Lough Neagh for eight days after which his sores dried up, grew healthy, got married, begat children and lived several years after' (Barton, 1751). Subsequent attempts to scientifically verify 'yield[ed] upon evaporation a small quantity of bituminous or at least sulphureous matter, from which they seem to derive their healing quality' but differed in no way from other fresh and seawaters examined. The curing power of 'mearing' water (dividing farms and townlands) is on record in the Schools' Folklore Collection (Volume 0037, Page 0079), 'A person having boils gets rid of them by going to a three mearing water (that divides three divisions of a country, three villages, three parishes or three counties) putting water from the stream nine times on the boil with the hand.'

Lakes, like many other natural water features, have been the scene of many tragedies over time. On 12 July 1795, a boat carrying Catholic pilgrims and Protestants set out on Lough Derg in Donegal carrying 93 passengers to Friars' Island and Station Island. A leak in the hull due to the boat's age and bad repair, and an intoxicated crew celebrating the twelfth led to the boat sinking and the loss of between 70 and 90 lives (Smith, 2019). An overloaded old boat with 31 persons, 10 sheep and a quantity of lumber going to Galway Fair was holed and sank, and 19 people drowned in Lough Corrib (*Freeman's Journal* 1828). Ireland experienced Arctic weather conditions in the mid-1700s (Dickson, 1997) and ice-covered lakes feature many reports of drownings. The *Derby Mercury* of 7 February 1739 reported that 'a great number of people carrying a corpse over a lough, on the borders of Co. Mayo and Co. Galway, near a place called Con, the ice broke, and they were all lost.' Some lake ice crossings were more successful. In 1740, Lough Neagh was frozen over in the Great Frost of 1740-41 (Dickson, 1997). Several people walked from Mountjoy Castle in Tyrone to the Market of Antrim, some 25 miles, and back the next morning (*London Gazette* 1740), while one Richard Levigne was undaunted by the dangers of ice and 'ventured to drive a four-wheel chair and four ponies almost around the lake [Owel, Westmeath] and home through the middle of the lake (*Dublin Evening Post*, 10 February 1784).

ART AND LEISURE

Artists, writers, and poets have long depicted the natural beauty and tranquillity of lakes. The Romantic movement (late eighteenth, early nineteenth century) celebrated nature's sublime beauty and often idealised it as a source of inspiration, solace, and connection with the spiritual. Victorian illustrators who specialised in wild and romantic scenery often exaggerated its grandeur (Figure 17.3). Killarney became a popular subject with its rugged mountains, serene lakes, and picturesque landscapes. More latterly, artists Paul Henry (1876-1958) and Jack B. Yeats (1871-1957) showcased the untamed beauty of the Irish countryside and the play of light on water and the wild. The poet W.B. Yeats (1865-1928) expressed nostalgia, longing, and the mystical qualities of the natural world in his poem 'The Lake Isle of Inishfree', while thwarted efforts to restrict lake access through fencing are celebrated in a poem on Knockalough lake in Co. Clare 'So all passers-by to the Kilmihil fair can water their cattle and horses exhale' (Schools' Folklore Collection Volume 0602, Page 027). Literary descriptions of lakes can be both romantic, 'the lake is spread upon the canvas, the *marmoreum aequor*; pure, limpid, smooth as the polished mirror' (Swift, 1743), tragic 'The lake is heaving at our feet, by a silver-bosomed lake, how many a tale of human grief, sweet lake, thy waters know' (Hayes, 1856), and menacing 'the Lake is black, beyond all imaginable blackness of water, black in its vast depth and beneath the gloom of gathering clouds' (White, 2003).

The leisure traveller with interests in wild scenery is a relatively recent phenomenon, emerging only in the early 1700s, while the use of lakes for recreation emerged later. Jonathan Swift described 'the lake in Killarney range with supreme delight among the sweet vales of Switzerland' (Swift, 1743), while Twiss, on his tour of Ireland in 1775 visited Lough Erne and enjoyed 'ducks, teal and other waterfowl, sport in thousands and the water contain a myriad of fish' and 'the diversions of angling and shooting' commenting that 'there is not a spot in Europe which exceeds this lake.' Later, the *Connaught Telegraph* suggests that 'Diversified as the scenes of nature are, there is yet wanting a further provision for that insatiable demand of new amusement which characterises the mind of man' (*Connaught Telegraph*, 14 August 1844).

The importance of lakes to the nascent tourism industry of Ireland came to the fore after the visit of Queen Victoria to Killarney in August 1861. The visit was chronicled in countless newspapers, and writers detailed the minutiae of her trip 'the procession of boats through the middle of Torc Lake, passed the Eagle's Nest and the Upper Lake … on the return the boats

Figure 17.3
Luggelaw (and Lough Tay) by W.H. Bartlett 1844. The scenery and antiquities of Ireland (Vol. 1). George Virtue, London. Reproduced courtesy of the National Library of Ireland

passed through the Muckross Lake to Ross Island, where they landed and returned to Killarney House' (*Belfast Morning News*, 28 August 1861). Prior to the visits of high-profile individuals, lakes as destinations for day trippers or visitors from further afield often followed detailed descriptions in local newspapers. Take, for instance, a lengthy account in the *Galway Patriot* on 13 June 1838 entitled 'Legends of Loughrea' that described 'this fair sheet of water on a summer's morning, the solemn air of the surrounding landscape, the undulating mountains as you approach it from the town.' The writer continued 'there is a little green isle on which sometimes, parties on the lake partake of refreshment … the clearness of the liquid element here is astonishing … when the surface is calm, you can clearly observe the fine sand which covers the floor of the lake.' Such evocative and sublime descriptions of Lough Rea were surely designed to draw visitors to the area. In contrast, the *Connaught Telegraph* laments that 'The long-neglected beauties of our isle are at length being unfolded to the world—everywhere but in Mayo'. The county has been excluded from guidebooks because 'Pontoon, loveliest of lacustrine landscapes, been wiped out of existence because she has no poet or no tourist entrepreneur to sing her praises' (*Connaught Telegraph*, August 27, 1892).

The popular Temperance Movement organised excursions to lakes, including Killarney and Lough Derg, in which bands and musicians waxed lyrical about the lakes in song and dance: 'those who know the lakes longest and best … the splendid scenery never was seen to more advantage … I have witnessed many a stirring festival scene, but a happier serenity of picturesque enjoyment could not be imagined' (*Cork Examiner*, 27 May 1849). The Queen's visit in 1861 catapulted the Lakes of Killarney and, by association, other lakes to the attention of domestic and international tourists. Henceforth, lakes of all sizes throughout the country found a new audience of enthusiastic visitors, day trippers, scholars, writers, and explorers who all offered their interpretation of the history and nature of Irish lakes.

The use of lakes for recreation was a natural extension of voyeurism, and regattas and festivals featured in the 1800s on large (Derg, Erne, Gill, Ree, Ramor) and small (Lanach (Mayo), Muck (Tyrone)) lakes. Boat races, banquets, and balls provided 'innocent recreation ... necessary for the happiness of society ... promotive of social intercourse, benevolence and peace' (*Connaught Telegraph*, 14 August 1844). For the most part, these activities were the preserve of the landed gentry. However, some regattas permitted teams of estate employees to participate. From the 1860s, Lough Allen in Leitrim hosted a well-known annual regatta in July. The stewards were drawn from the local grandees. Races consisted of vessels from yachts to smaller pleasure boats. Separate races were organised for men and women, and the Royal Western Yacht Club of Ireland oversaw all races. The event in 1867 featured contestants ranging from the turf boats of the Upper Shannon to the gigs of the Carrick-on-Shannon Rowing Clubs. A local band 'played lively airs during the day.' Exclusively patronised by the landed gentry, organised stag hunts and accompanying balls were popular at the Lakes of Killarney from as early as 1838.

LAND AND DRAINAGE

Ireland's wet and boggy landscape has evoked strong feelings past and present. Peat bogs retain a considerable amount of water and thus were perceived as wastelands. In a presentation in 1685 to the Royal Society, William King, Church of Ireland Archbishop of Dublin and Lord Justice stated that 'every barbarous ill-inhabited country has them [bogs], and 'no wonder if a country, famous for laziness, as Ireland is, abound with them.' Boate (1786) was of a similar mindset and commented that the Irish 'let daily, more and more of their good land go boggy with their carelessness.' King elaborates that 'they [bogs] corrupt our water, giving colour and stink to a great many rivers' and advocates that work on source waters could prevent problems, 'I remember one high mountain, in the north of Ireland, has 4 loughs on the side of it near the tops; and no care being taken to clear the springs' (King, 1685).

Bogs were regarded as unstable and a cause of blockages to surface drainage requiring modification or removal. The precarious nature of water-laden bogs is demonstrated by a bogslide that occurred after torrential rainfall at Addergoole in Galway in 1745, damming Cregg River and 'forming a considerable Lough in half a days time' (Ousley, 1788). Land, river, and lake drainage were considered core to the creation of useable and productive lands and were deeply embedded in the mindset of landlords, engineers, and the Board of Works (later the Office of Public Works). 'Evacuation' of water from the land (drainage) enabled access to resources, including reeds for building, turf for fuel, usable land and marl (calcareous lake deposits) and was promoted to improve lands, develop waterpower, and provide employment for the labouring classes. King (1685) 'tis a work of charity, and imploys hands, and conduces to both the ornament & general profit for the Kingdom.'

Boate and Molyneux (1755) advise that 'the natural improvement of Loughs or lakes is to first drain them as low as we can; and then turn the residue of water into silt-ponds, by planting a few trees about them, and ordering them thus they can be made both useful and ornamental'. Draining lakes opened new land to grazing and arable planting and reduced the threat of standing water and bog formation. Often, this newly reclaimed land was prized for the 'luxurious' quality of grass it produced. Indeed, it was also noted that 'land well inhabited with English, and where great extents of bog have been drained and reduced to dry land, it had been found by observation of some years ... that they have dryer air and are much less troubled with rain, than former times' (Boate and Molyneux 1755).

Contrary to references to lazy Irish people, great capacity was demonstrated when a large drain was made from a temporary lake caused by a landslide which carried the water to the bed of the river, and 'in seven or eight days it diminished [from three hundred] to fifty or sixty acres' (Ousley, 1788). Furthermore, in 1795, a Galway landowner, James Fallon, assembled 850 men equipped with spades and shovels and set about draining a lake on his lands of Ballinglass. They cut through a sandy hill and a piece of bog about a mile in length and, in one day, drained the entire lake (*Saunders's News-Letter*, 15 September 1795).

The notion that lakes could be drained or 'unwatered' persisted into the late nineteenth century and found expression in legislation such as the Drainage (Ireland) Act of 1842 and subsequently in the twentieth century with the Arterial Drainage Act 1945. The 'benefit is extended to adjoining lands and tenantry, and its vicinity is relieved of the great evils arising at all seasons from the stagnant pool of water' (*Dublin Morning Register,* 2 December 1841). Engineer and geologist George Kinahan's seminal 1882 publication on 'Reclamation of Waste Lands' recommends that private individuals could unwater Lough Rea in Galway, reducing it by 50%, but suggests that reductions in Loughs Neagh, Erne and Corrib would have to be national undertakings. Kinahan additionally recommends 'warping' or 'the raising of the surface and the fertilising of land by carrying on to it by water, mineral, and vegetable or animal matter' and that sewage from towns and villages 'might easily be turned on to rivers and lake flats greatly to the improvement of both land and streams' (Kinahan, 1882).

Many turloughs and lake–turlough systems have been lost or diminished through drainage schemes from the nineteenth century onwards. Temporary lakes were also targeted for modification or 'inundation'. Turloughs deemed unsuitable for unwatering, 'instead conversion to permanent pools is recommended' (Kinahan, 1882). King (1685) pronounced the pleasantness and usefulness of turlough lands in their dry phase and highlighted the benefits of marl, which 'hinders the water from turning into a bog'. Lake marl or aqueous calcareous clay deposits were accessed after dredging or drainage works and excavated. 'The province of Connaught ... is much more plentiful in Marle than Leinster ... some being white as chalk, other grey and some black ... its depth is so great that yet anyone ever digged to the bottom of it' (Boate, 1726). Marl was used to 'manure' drained bogs to make land more productive.

A Bord of Works drainage scheme targeted 'injuriously affected' low-lying lands in southeast Clare along the river Owengarney (Hill, 1880). Five lakes along its course (Kilgorey, Doon, Gar, Ballymulcashel, and Castle) were greatly modified in the attempt to improve 2,595 acres of land. Drainage works included deepening or sinking streams and opening back drains, and lakes were targeted as reservoirs for regulating the flow of water in the main channel. Drainage reduced Lough Gur (Limerick) to about 80% of its original size in 1848, while Owel (Westmeath) was enlarged through damming and embankment construction to provide a source of water for the Royal Canal. Works were sometimes contentious – a Mr Comes wrote to the *Cork Examiner* in 1843 deriding the Swiss landowner at Gur 'I hate them all – let them eat dirt… This foreigner intends to deprive the country of its only picturesque attraction by draining the lake.' A cofferdam (an enclosure built within a body of water to allow the enclosed area to be pumped out) was constructed when draining Derrevaragh (Westmeath) was twice vandalised, flooding the

works in 1870 and 1871 (*The Drogheda Conservative*, 2 September 1871).

An unexpected consequence of land drainage saw the retrieval of ancient specimens of animals and bog oak together with the recovery of treasures such as shields and swords from lakes across the country (for example, from Gur, Limerick and, Drumgoon, Cavan). Landscape drainage, dewatering of lakes and subsequent excavations unearthed bones or red deer and antlers of the now-extinct Giant Irish deer. These beds of former lakes preserved bones (e.g., Ballynoe (Meath) and Ballinderry (Offaly)) in their anoxic sediments. Deer 'may have been stampeded into the lake by human or other agency or may have been mired when going to water' (Hencken and Stelfox, 1941).

An interesting feature in the landscape depicted on Ordinance Survey (OS) maps are 'Blind Loughs' which are found in many counties. Some Blind Loughs or former lakes have come to an end physically through declines in water or infill with sediment and other materials, also known as lake extinction. Others are extant and still retain water, and more again have diminished surface areas and now exist only as marshes in the centre of bogs. A now-extinct Blind Lough is seen on the 1st edition (1829-1834) OS map in Donegal at Rinboy (Figure 17.4a) and another at Glenameade in Limerick (Figure 17.4b). Loganim lists the Rinboy lough as *Loch Caoch* (translation: Blind Lough), along with nine other blind lakes in Sligo, Mayo, and Galway.

Figure 17.4
From left:
(a) Loch Caoch/Blind Lough, An Rinn Bhuí/Rinboy, Fanad Co. Donegal,
(b) Blind Lough, Glenameade Co. Limerick (6-inch First edition, 1829-1834)

Blind lake Lough-a-dian and diminished former lakes are described in the Ballyroney-Ballyward lakes (Down) and Ballydugan (Armagh) (Hume, 1853). The term 'blind lake' is also used in the context of karst geology, while dried lakes, for example, Turloughaheltia (Dried Lake of the Doe) and Turloughakip (Dried Lake of the Stock), and old lakes (Rahasane Turlough) feature in Ordnance Survey Letters for Galway (Redington, 1915).

Field names, historical maps and Ordnance Survey letters are important records of past wetland, bogland and former lake areas. Additionally, townland boundaries often follow streams and rivers; for example, Ballyarnet Lake in Derry occupies three townlands. Alterations through drainage schemes and natural changes meant some natural aquatic boundaries were cut off by human agency, requiring adjustment in the nineteenth century. These legacies warrant further exploration to understand such remnant features. This is especially important in the context of rewetting landscapes and the imperative to enhance carbon sinks.

FISHERIES AND DEMESNES

Lakes provided focal points and opportunities to build monasteries, abbeys, castles and great houses on their shores. The great abbeys of Cong and Inishmaine, near two noble wide-spreading lakes (Corrib and Mask), were described as 'scenic charms the old monks could enjoy in an evening's stroll ... lit up by every ray of sunlight in summer… and grander still, perhaps, in winter, when lashed … abundance of purest water … abundance of fish for fasting days' (Healy, 1904). In medieval Ireland, many fisheries were controlled by the monasteries, principally for salmon and eels and, to a much lesser extent, trout and coarse fish (Went, 1955). Roach, bream, pike and perch fed rich and poor alike until the nineteenth century, while angling on the lakes and rivers yielded salmon, trout, and perch. A parochial survey of Ireland was compiled by William Shaw Mason in 1814 and pronounced Lough Derg and Erne as 'well supplied with trout, pike, and eels; the second of which species of fish is sometimes taken of the large size of from 10 to 20 pounds weight.' Reports from Lewis's Topographical Dictionary (1837) termed two lakes 'called Cummeloughs, and the others Stilloughs (Waterford), the largest of which covers only five or six acres: they contain several inferior kinds of trout, and in the Cummeloughs are found also char.' Lakes, like the sea, however, were underutilised during the famine years largely due to lack of resources or means to engage in fishing. Bloomfield (1883) depicted 'a farm in Galway or

Donegal striving to eke out a miserable existence on the watery tuber, while close to the doors ... lies the lake, which might hold with half the labour of his potato plot, 15 times the nutriment'. Fish were a high-status food, angling an amusing sport, and fisheries were largely controlled by monasteries and the great houses that installed weirs and nets in suitable locations to maximise the catch. 'The silvery Loughs Derryclare, Glendaloogh, and Inagh, teem with salmon, trout, pike, and perch, and offer inexhaustible sport' (*Nationalist and Leinster Times*, February 16, 1895). Sometimes, the salmon fishery acquired a commercial significance (e.g., Eske, Ballyfin Donegal). Lough Neagh is the only significant commercial lake fishery remaining today, principally for eels and pollan (the latter until the twentieth century). 'Eelworks', Seamus Heaney's poem, encapsulates the fishery at Lough Neagh: 'On the line, not the utter, Flipstream frolic fish, But a foot-long.'

Demesnes were a dominant feature in the Irish landscape in post-medieval Ireland (Reeves-Smith, 1997). The English and Scots 'made several fair plantations and would have done more if it had not been hindered by the horrible rebellion of the bloody Irish' (Boate, 1888). An estimated 55 demesnes feature in Galway, most comprising hundreds of acres and some over one thousand acres (Mac Aodha, 1988). Demesnes were established in scenic spots by shore, lake or river or where natural beauty was limited, artificial substitutes were created by damning streams or excavating ponds. The bulk of the lands were designed for pleasures, including hunting, shooting, boating and fishing. While fashionable landscape architects such as Capability Brown could not be enticed to work in Ireland, their influence in creating idealised landscapes resplendent with enormous curving lakes in Irish demesnes is undeniable (Costello, 2015). Examples are found at Castle Coole (Fermanagh), where 'Banjo Lake' incorporated a half-moon basin at the house and a circular basin at the far north-east end (HERoNI 2020), Curraghchase which dams a stream that feeds into the Clonshire/Grenagh river (Limerick), and Kilcooley Fish Pond on the Ardreagh River (Tipperary). Two of the largest artificial lakes feature in the estates of Clandeboyne, Down (65 acres) and Brownlow, Armagh (58 acres), while Montalto Park in Down features a highly ornamental lake in the shape of a fish (2.5 acres), in the catchment of the Ballynahinch river (HERoNI, 2020) (Figure 17.5a). Montalto was built around 1760, and a house is evident on a 1790 map of the demesne. The house was extended in the 1800s, and the ornamental lake is visible on the 1834 edition of the OS map (Figure 17.5b). The lake epitomises idealised and 'naturalised' parkland features, which had become

Figure 17.5
From left:
(a) Lake at Montalto Demesne, County Down in the shape of a fish visible on the 1834 edition of the OS map.; (b) Montalto ornamental lake (Google Earth Image date: 4/24/2021).

the established style for demesne design, replacing more formal geometric landscapes.

Demesne lakes and ponds (both natural and artificial) featured prominently in sale notices for estates from the early years of the nineteenth century. In Limerick in 1844, a notice advised prospective buyers of the Grove estate that there were 'two large fishponds, which were filled up by the tenant but could be easily opened and stocked with trout from the river, which abounds with them' (*Dublin Evening Packet and Correspondent*, 9 May 1846). Far from just being picturesque features in manmade landscapes, the landed gentry recognised and exploited demesne lakes and ponds for their economic value. Ponds were generally used to supply fish for the manor, most frequently with non-native introductions of carp, pike, and tench. The ponds were managed for breeding and fattening (vivariums) and holding (servatoriums) prior to consumption (Reeves-Smyth, 1997). Decoy ponds were also created to attract migratory duck (mallard, wigeon and teal), which were then shot or trapped in nets. The Australian black swan, as well as pink-footed, Egyptian and Canada geese, were all ornamental lake introductions. Of course, this meant that poaching was also an issue on demesne lands and 'a hare mercilessly suspended in a gin, a pheasant robbed upon a roost, or a salmon speared by torch-light upon the Scaur or och Murther! For a trout or two', saw neighbouring gentry forming management committees to appoint water bailiffs (*Irish Times and Daily Advertiser,* 26 July 1859).

Blind Loughs are also referred to in demesne literature. In Fermanagh, a Regency-era demesne was altered in 1848 when Lough-na-Capple was infilled. At the annual meeting of the Royal Agricultural Society in 1847, the Earl of Erne described such a lake on his property.

> I had in my demesne a blind lake, in a wood, and I looked upon it as a regular treasure, I thought it would supply my whole demesne with manure forever. I measured the bottom and it was deeper than 30 feet, and it had an accumulation of vegetable matter there. I drained it. However, on further investigation, it was found that the contents were no better than average peat, and thus, I abandoned the endeavour.

Historically, neither appear to have formed part of a managed demesne. Blind loughs also feature in folklore 'It was said long ago that there was the full of an ass's skin of gold hidden in a little lough' (Schools' Folklore Collection Volume 1097, Page 5). This lough [near Tievecloghe Donegal] is all covered with moss and rushes, and the people call it the Blind Lough.

INDUSTRIAL USE

Lakes, both natural and artificial, were often harnessed for industrial use. An examination of historical map sources such as ordnance survey and estate maps reveal countless examples of corn, tuck, and paper mills, flax ponds, mill races, bleaching greens, textile bleaching and mining activity (Figure 17.6a). Lakes, therefore, were an important source of employment and economic output. Historically, these artificial ponds were used for cattle, water supply on droveways, cultivation of watercress, holding fish and fowl, dyeing, blacksmithing, alcohol stills, retting flax, ice provision in winter, moats, and milling (Reeves-Smyth, 1997). Ponds were used for textile bleaching (e.g., Clay Lake, Armagh, Lough Ross, Monaghan) until the late eighteenth century. Cloth needed repeated immersion followed by prolonged exposure to the sun to whiten to better allow it to absorb a dye. Other industrial facilities included situation malt kilns on the shores of lakes; an example of such an enterprise is recorded on the six-inch 1840 map of Lough Allen in Leitrim. Corn mills were often found along the shores of larger lakes such as Lough Sheelin and Lough Derg.

Other artificial ponds are flooded voids, legacies of industry, quarrying and mining operations. Examples include the chalk quarries of Antrim, Bunlicky

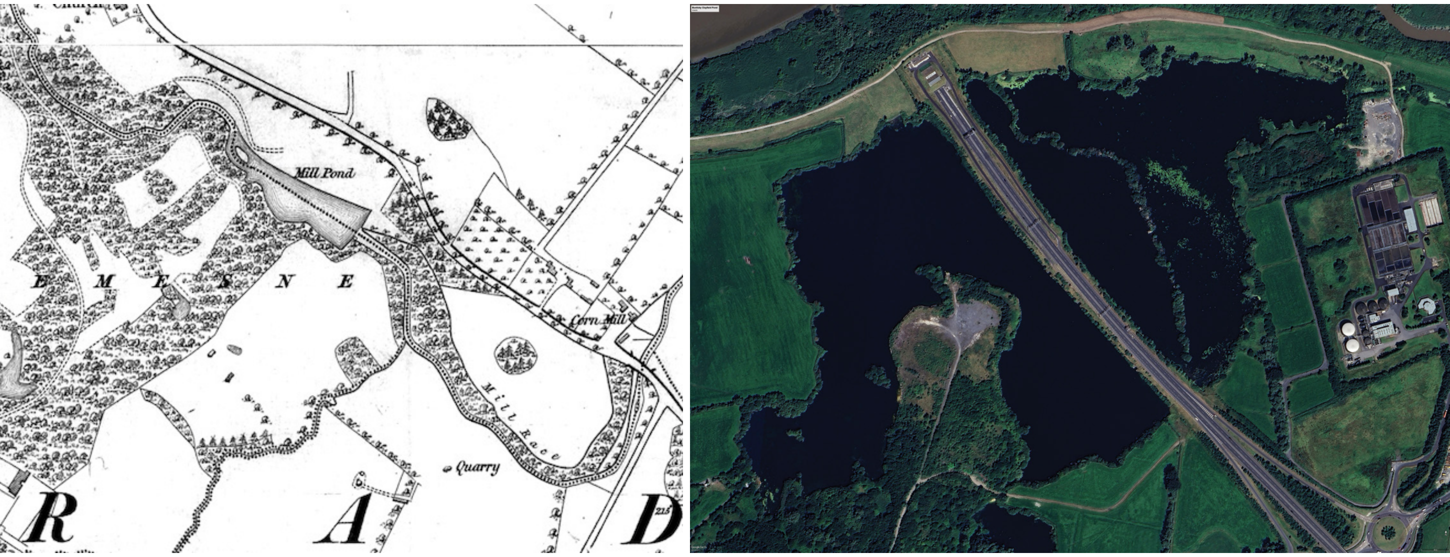


Figure 17.6
From left:
(a) Mill ponds Ballynahich Co. Down (1834 OS map), and
(b) Bunlicky clay pond Co. Limerick (Google Earth Image date: 06/08/2022)

clay ponds (Limerick) (Figure 17.6b) and the lead and zinc mines of Wicklow (Avoca) and Silvermines (Tipperary). Also, in Limerick, Bleach Lough at Dromore is a 55-acre body of water today and is stocked with rainbow and brown trout. Its previous incarnation was as a bleaching lough on the Earl of Limerick's estate. Many of these now-flooded industrial ponds constitute wildlife refuges but can also be sources of polluted water and silt deposits.

Poulaphuca Reservoir (or Blessington Lakes) in Wicklow, is an unusual artificial lake created in 1940 as part of the Liffey Reservoir Scheme. When the water level drops, archaeological artefacts and monuments can be seen on the artificial shoreline, having been exposed as the lake-water has washed away the topsoil during the last eighty years (Corlett, 2010). Recently recorded features date to the Mesolithic, Neolithic, Bronze Age, Iron Age and medieval periods.

Diatomite is an aquatic deposit of fossilised silica-based algal (diatoms) compressed over millions of years to form soft rock (akin to peat deposits on land). This naturally occurring, friable sedimentary rock was mined (cut like turf and dried) in small-scale workings across England and adjacent to Lough Neagh at Toome. Drainage operations in the river uncovered these 'infusorial earth' deposits (Movius et al., 1935). *Infusoria* is a word used to describe various freshwater microorganisms which the Rev. Smith described as 'deposits of diatomaceous earth, found on the shores of Lough Mourne as a mass of unbroken fragmental siliceous shells' (Smith, 1850). These deposits are used in brick manufacture and later as filter material and in thermal insulation.

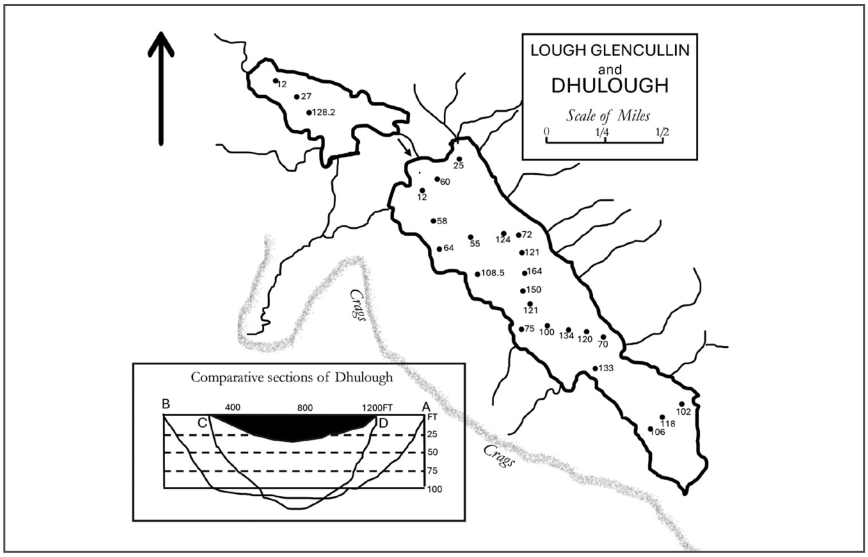


Figure 17.7 Water depths for Glencullin and Doolough (Mayo). Redrawn from Howarth (1905).

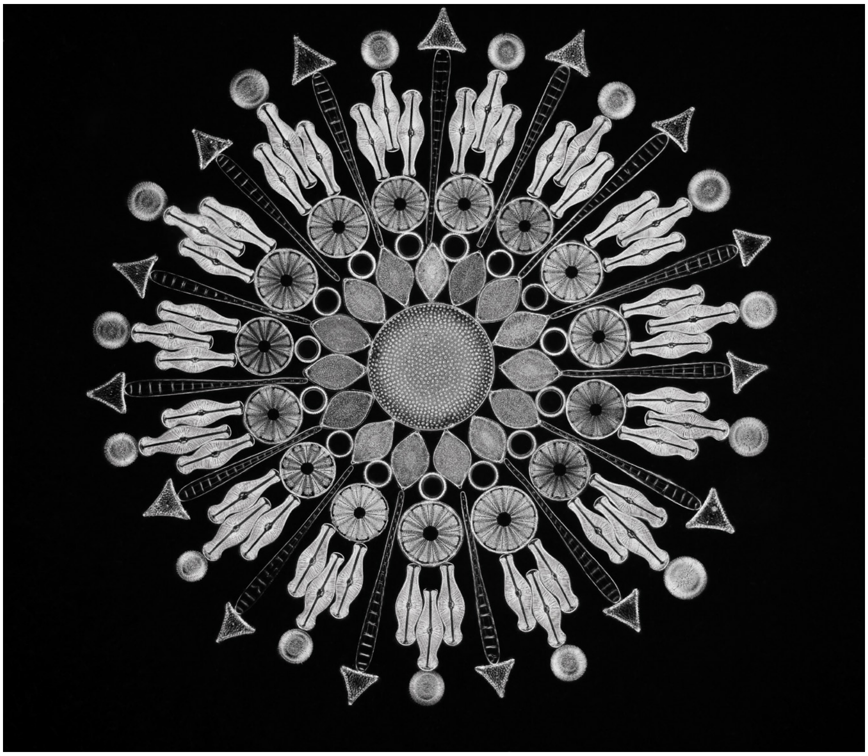
KNOWLEDGE OF LAKES

Systematic examination of large lakes began in the seventeenth century and was mainly an occupation of men of curious nature who were scholarly, wealthy and often clerical. The societal constraints specific to women (who were barred from universities, societies, and libraries) meant that there were few female naturalists and their roles as intellectual wives supporting their husband's work was undervalued. Lake study initially focussed on descriptions of hydrology, morphology, and geology, only later focussing on links with lake plant and animal life (Moss, 2015). Some of the most important discoveries were surveys of lake depths, water mixing and the lower diversity of species in freshwater. It is also interesting to note that fish and freshwater fish environments were treated as separate entities for centuries and not integrated until the twentieth century.

The larger Irish lakes (Neagh, Erne, Ree, Corrib, Mask, Derg) were surveyed by the Admiralty when nautical charts were constructed for British and Irish coastlines and published between 1835 and 1846 (Charlesworth, 1963). Depth soundings were taken with handheld lead weights (and later with lead sounding machines), and their position was fixed relative to the land detail by compass (Robinson, 1952). These depth soundings were the basis of the first bathymetric or lake basin contour maps in Ireland.

Efforts to survey the smaller lakes became a focus in the twentieth century. Howarth (1905) surveyed Glencullin, Doolough (Mayo) and Nafooey (Galway) (Figure 17.7) using a lead weight of 4.5 pounds and found a

Figure 17.8
Rosette slide
by Klaus Kemp.
Image courtesy of
JMC Scientific
Consulting Ltd
(https://jmcscientific-consulting.com/).



maximum depth of 164 feet in Doolough. Seymore (1938) attempted to survey all the mountain corrie lakes in Wicklow. Early georeferencing consisted of rowing a boat in a straight line and counting oar strokes between points. The war effort hampered this work, and maps were created for only three lakes (Upper and Lower Lough Bray and Glendalough Upper) (see Chapter 4) with some 400 soundings for each lake. The effort required 'a motor, motor-caravan, folding boat (with outriggers to prevent upset) and a crew of four, skilled in the use of the apparatus necessary and who are also swimmers' (Seymore, 1938).

A core effort to understand water centred on the examination of miniscule plant and animal life with the development of microscopy, which advanced in the 1800s. The siliceous algal group (diatoms) are very small in size (<100 μm) and have distinct surface ornamentation, which made them a preferred test objects for microscope lenses. Diatom arrangement was a pastime of Victorian microscopists who created intricate glass slides of diatoms arranged in geometric designs (Figure 17.8), which were sold along with microscopic photographs, to wealthy amateur naturalists who would then show them at social gatherings as an amusement.

A range of studies in the 1900s advanced the understanding of lakes and the diversity, ecology, and distribution of algae (including diatoms). West (1892) was one of the earliest comprehensive investigations of algae found in Irish lakes with 'washings and squeezings from submerged plants ... were found to yield many of the smaller species' providing a foundational understanding of algal diversity. Pearsall and Lind (1942) also examined algal distribution and its relation to water quality, providing insights into the ecological health of aquatic ecosystems. Their efforts to expand the dataset were thwarted 'in particular, to collect analytical information about the waters, but the war has made that project at present impractical.'

A Limnological Laboratory at Hayes Channel, near Portumna, Galway, on the River Shannon, was opened in 1921 and was the first state-funded institution devoted to the study of freshwater fisheries in Ireland and Great Britain (McDermott, 2019). Incredibly, this effort predated the establishment of the renowned Freshwater Biology Association laboratory in England's Lake District by ten years. The facilities included a shore laboratory on Hayes Island and three boats. The main purpose of the operation was to scientifically investigate fisheries to maximise yield by applying science to develop freshwater aquatic resources. The main goal was to produce fish on a large scale and achieve food security during the First World War. The Laboratory operated for just 17 months from November 1921 until the cessation of research in March 1923 and is described as a 'daring endeavour as Ireland transitioned violently from Empire to the emerging Irish Free State' (McDermott, 2019).

CONCLUSION

It might be said, in conclusion, that lakes have acted as natural focal points, providing inspiration and sometimes provoking fear. This chapter has explored some of these intangible natural and cultural histories of lakes via archival records, government folklore commissions and news media and provided snapshots of the nature of human interactions and cultural influences of lakes. Each topic warrants a chapter in itself to do justice and should/could be the focus of future literary endeavours. Further exploration of blind lakes and wetland map features as legacies of historical natural and human landscape change is warranted in the context of landscape rewetting initiatives. Additionally, there is a body of work outstanding to transcribe, collate and collect lake and pond names across the island to explore the toponymic significance and their environmental and cultural heritage.

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Chapter 18

RECREATION AND AMENITY LAKES HOTSPOTS FOR WILDLIFE AND PEOPLE

Catherine Dalton, Emer Magee, Elisha McGrane,
Donna Weiner and Marios Zachariou

SUMMARY

Lakes are one of nature's environmental endowments – their freshwaters belong to no one and can be considered common (public) goods, with inherent natural value. Our lakes are subject to multiple uses including water harvesting, waste disposal, and diverse recreational activities. The use of lakes for recreation and amenity plays an important role in our relationship with, and experience of nature. Opposing stakeholder values can exist within and between those who, on the one hand, highlight the anthropocentric value associated with ownership of and access to fish stock, development of recreational access or infrastructure, as most desirable destinations, management for water extraction or water level control. On the other hand, some stakeholders and advocates emphasise the high nature value of biodiversity, ecological status, water, and habitat quality. Our leisure pursuits have important sociological, economic, health, tourism, and sporting benefits, and many believe that lakes (habitat, fish, wildlife) should be managed as a resource for angling, water sports, boating, and tourist accommodation. This chapter reviews recreation provision and services, and considers the consequences for lake habitats, wildlife, and water quality. A balance between humans and nature is necessary in the face of increasing recreational use. After all, human and non-human users benefit from good water quality and high nature value.

Keywords Lake water bodies, water-based recreation, outdoor amenities, conservation.

USE OF LAKES FOR RECREATION

Outdoor Recreation

A survey conducted in 2022 found that 98% of people in Ireland like being outdoors, and aquatic environments feature prominently as destinations. Lakes, rivers, and canals were popular with 47% of respondents, 62% selected coasts, while 59% chose urban green space (CSO, 2022). Tourism demand for outdoor recreation is very strong (some 2.7 million overseas visitors to Ireland participated in outdoor activities (including water sports)) (Fáilte Ireland, 2019), while the most visited attractions feature inland water elements such as rivers, lakes, ponds, and canals near urban areas (NISRA, 2021). There are no public registers of water-based recreational users, so numbers are generally extrapolated from smaller surveys (Williams and Ryan 2004; Doherty et al., 2014; Waterways Ireland, 2016). The most comprehensive survey of water-based leisure activities was conducted in 2003 but was largely estuarine and coastal-focused, with almost 50% of the adult population participating in some form of water-based leisure activity per annum (Williams and Ryan 2004). More recent estimates of people participating in different types of recreational pursuits confirmed that the most popular water body visited is the sea (55.9%), followed by rivers (43.9%), and then lakes (27.8%) (Murphy et al., 2014). Increased leisure time means participation in water sports (canoeing, rowing, and sailing) has doubled during the period between 2011 and 2017 (Sport Northern Ireland, 2019).

The most common recreational reason cited for visiting water bodies was walking or jogging, with relatively few individuals participating in primary contact recreational activities such as boating, fishing, surfing or, swimming (Doherty et al., 2014; Sport Northern Ireland, 2019). Lake recreation can include individual or organised club activities, many requiring equipment, and all requiring access to water (DRCD, 2022). The number of all-island clubs listed on the web in 2023 includes 82 triathlon, 98 rowing, 55 coarse angling, 37 fly angling, and 123 canoe/kayak. Categories of primary recreational lake users include water-based anglers, sail boating, rowing, kayaking, canoeing, swimming, and secondary land-based lakeside activities such as picnicking, walking, cycling and bird and wildlife viewing (Table 18.1). A range of commercial providers rent and provide kayaks and paddleboard lessons (Figure 18.1). The largest categories of lake recreational users are boaters, anglers, and swimmers (Waterways Ireland, 2016), with the latter greatly expanding in recent years. In 2013, there were an estimated 14.5k registered boat owners and cruiser hires principally on the Shannon and Erne waterways. Lakes are important for recreational fishing and angling tourism. Inland Fisheries Ireland (IFI) are responsible for the conservation and protection of 128,000 hectares of lakes in Ireland (see Chapter 6). Coarse fishing for pike, carp, roach, tench and bream dominates lake angling, while game angling for trout and salmon is river based. 'Wild' swimming

Table 18.1 Categories of lake-based activities (after Schafft et al., 2021)

Zone	Activity	Interaction with water
Open water	Boating (motor boating), canoeing, kayaking, jet skiing, water skiing, sailing, rowing, kite surfing, windsurfing, stand-up paddling, diving, and boat angling	Direct/Primary
Near shore	Swimming, snorkelling, and paddling	Direct/Primary
Shoreline	Recreational angling	Direct/Primary
Shore	Walking, dog walking, horse riding, cycling, picnicking, camping, hunting, wildlife viewing	Indirect/Secondary

has grown rapidly in popularity in recent years and is considered uniquely beneficial for health and well-being. Most wild swimming has focused on sea swimming, however, the COVID pandemic saw an increase in lake swimming (McDougall et al., 2022).

Key hotspots for lake recreation activities are found on the larger lakes such as Loughs Neagh, Erne, Derg, Corrib, Ree, Key, Allen, and the Killarney lakes. In contrast, smaller lakes (less than 3 km2) with public access can be intensively used, for example, Ballyallia (Clare), Lannagh (Mayo), Camlough (Armagh), and Hyne (Cork).

Figure 18.1 Lake kayaking, Ballyallia Lake Clare

Figure 18.2
Public access boat slipway, Ballyallia Lake (Clare)

Infrastructure such as marinas, jetties, boat ramps, moorings, and fishing piers play a vital role in facilitating recreational activities by providing safe access to the water and helping to manage the flow of users. Facilities for users can include toilet, shower and washing facilities, parking, waste bins, activity providers, as well as fuel points and slipways for launching boats (Figure 18.2). Navigation aids such as buoys and their ground tackle or anchor, which secures them to the lakebed, are semi-permanent features in many lakes. Many lakes are provided with water safety signage and life-saving equipment such as life rings/buoys, some of which are fitted with sensors to deter theft.

Key agencies tasked with recreation development include Waterways Ireland, Sport Ireland, Comhairle na Tuaithe (the national advisory body on outdoor recreation), as well as Sport Northern Ireland and Outdoor Recreation Northern Ireland. The only all-island body is Waterways Ireland which has a North/South statutory remit to manage and promote over 1000km of inland navigable waterways for recreation. IFI protects, manages, and conserves inland fisheries and cooperates with the NI Agri-Food and Biosciences Institute and the Loughs Agency.

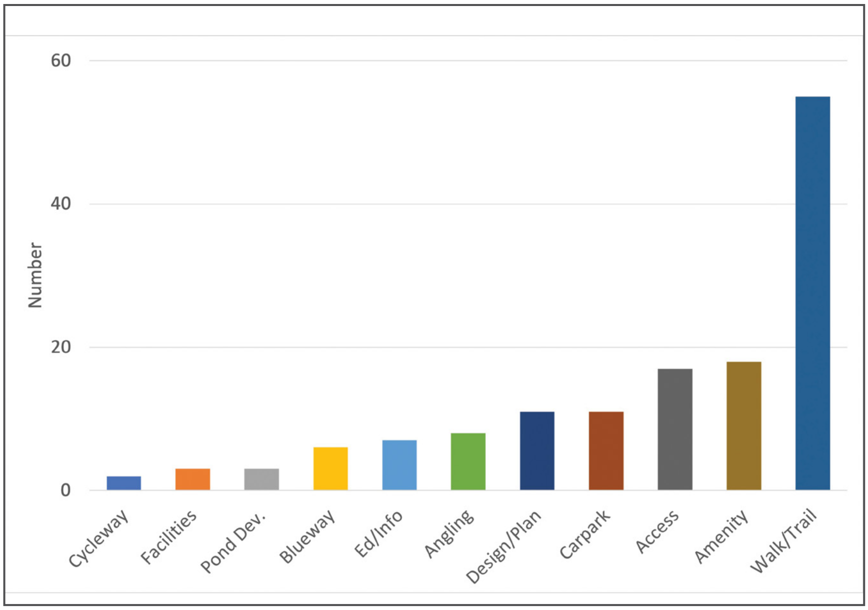

Figure 18.3 Outdoor recreation lake-focussed projects funded 2016-2022 (n= 143) by activity type (www.gov.ie/en/collection/90a66b-approved-funding-for-outdoor-recreation-projects/)

Government strategy aims to foster an appreciation of natural heritage, promote its recreational resource potential, and manage high-value recreational amenities (DHLGH 2021-25 Statement of Strategy). Increasing demand for the facilitation or provision of recreational access and infrastructure was the impetus for the development of outdoor recreation strategies (Sport NI, 2019; DRCD, 2022). The Department of Rural and Community Development (DRCD) has provided funding for the development and promotion of outdoor recreational infrastructure since 2016 via applications made by local authorities and local development companies. There have been 143 lake-focussed projects, the majority of which have included walks and trails, and to a lesser extent amenity enhancement, access, parking, and planning (Figure 18.3). Clare County Council has developed amenity enhancement plans for Ballaghafadda (Ballybeg, Killone) and Ballyallia lakes while, Galway County Council are planning on enhancing the public spaces and facilities at Long Point Lough Rea.

Water trails or 'Blueways' have recently become a tourism and outdoor recreation initiative of branded multi-activity recreational sites and trails linked with rivers and lakes. As of 2023, nine established blueway paddling trails traverse Loughs Derg (Clare/Tipperary), Eidin (Leitrim) Corry/Bofin (Leitrim/Longford), Forbes (Longford), Kiltybarden/St Johns/Marrave /Scar/Drumaleague/Derrycassan/Ballymagauran/Garadice (Cavan), Upper Erne (Cavan), while there are canoe trails on the Erne system and Lough Neagh.

Regulation

For lakes designated as a Special Area of Conservation (SAC) or as a Special Protection Area (SPA) for birds, the overarching legislation for recreational use of waterbodies is contained under Statutory Instrument (S.I.) No. 293/2010 European Communities (Birds and Natural Habitats) (Control of Recreational Activities), which regulates watercraft and water-based activities. The rules are channelled via local authority bye-laws which regulate, authorise, or licence operations or the conduct of people in the interests of the common good. Waterways Ireland oversees boat licencing, access permits, and navigation bye-laws as well as protocols on boat mooring, registration, permits, speed, and life jackets. Speed limits of 5 knots are recommended near marinas and harbours, and there is a no wake zone policy in the vicinity of moorings, jetties, and swimming areas. Boating and scuba-diving permits are required for a select number of lakes on state-owned lands (npws.ie/licencesandconsents), while licences to hunt wildfowl (16 species of duck, geese, and waders) are also required on state-owned lands and 43 lakes. Where lakes are used for public water supply, no boat engines are permitted, however, petrol engines are allowed on Poulaphuca Reservoir (Wicklow). NI Water provides recreation and access guidance (e.g., fishing permitted via affiliated clubs, no motorised boats, no swimming) for 36 reservoirs and requires usage agreement applications. Water Safety Ireland promotes water safety nationally, and all sport and recreation organisations also have their own safety standards, rules, and regulations. Responsible recreational use of the countryside is promoted through 'Leave No Trace' and 'Right Side of Outside' campaigns.

Water Access

The value of lakes as recreation and amenity assets is dependent on public accessibility. Access to lakes is limited on the island of Ireland as all lands are in private or state ownership (Zachariou and Burgess 2023). Moreover, many upland areas are owned as commonage, i.e., land that is jointly owned by several people. Thus, there is no legal right of access to, the Irish countryside. This restricts public access to lakes. This contrasts with the United Kingdom and other European countries, where public access or 'rights of way' apply.

The water in lakes and rivers are common resources and thus are not owned, however, the bed of a lake belongs to the owner(s) of the land surrounding it (landregistryservices.com). Landowners (e.g., farmers, fisheries) who own the riparian (bankside) rights have a legal right to prevent water access (OPW, 2020). Where there are multiple landowners, then ownership of the lake will extend to the mid-point of the lake for that part of the bankside owner. For example, Clare County Council owns c. 30% of the shoreline of Ballyallia Lake, and thus has the riparian right of navigation, along with other private landowners, over the entire surface water area of the lake.

Government and conservation organisations acquire ownership (nature reserves, national parks) to promote strict conservation goals and control access and usage. Apart from angling, which can benefit from exclusive permission rights, the diverse nature of most other pursuits of lake recreation renders them less effective in lobbying or negotiating for water access.

Large lakes (Neagh, Derg, Ree) are popular for recreation and are generally endowed with multiple public access points and a range of adjacent natural amenity sites, while many smaller lakes have private, informal, or no public access for recreation. A preliminary examination of publicly accessible boat slipways lists 18 public access slipways in Roscommon (gov.ie) but no data for other counties. No all-island public register currently exists.

LAKES AND WILDLIFE

Lakes provide important habitats for wildlife across a range of zones from shore, shoreline, and nearshore to deep water, each highly dependent on the other, and all influenced by the catchment drainage area. Most of our lakes are small (< 0.01 km2) with many less than 2 ha (Gibson and Crawford, 2002; Dalton, 2018).

Lake habitats

Lakes provide a variety of different habitats within a relatively small area (less than 2% of the land surface) (see Chapter 1). Their open waters are the most photosynthetically active with floating phytoplankton (algal) and zooplankton communities (copepods, cladocera, rotifers), as well as insects (macroinvertebrates, dragonflies, damselflies), and fish (trout, salmon, char, carp, roach, tench, bream) (see Chapter 5). They are home to resident and migrant waterfowl and other birds (Figure 18.4). The lake edge or littoral environment is a critical habitat for many invertebrates, amphibians, fish, and birds (Oertli et al., 2002). Lake shorelines act as an ecotone between land and water providing habitat, and a range of ecosystem functions, such as water purification, buffer zone, and erosion protection (Schmieder, 2004). In summer, shorelines of lakes provide important nesting and feeding

Figure 18.4
Mallard duck
Dromore Lough,
Clare. Photo: Emer
Magee

areas for waterbirds such as herons, egrets, and waterhens, while nearshore shallow waters are important habitats for amphibians, invertebrates, and fish. Additionally, lakes have areas of riparian vegetation such as willow, alder and ash, and shallow water plants including reeds, bulrushes, and water lilies. As well as floating surface plants, emergent and submerged plants grow only on the lake bed. This ecotone between land and open water provides vital nesting and feeding areas for a wide variety of birds and mammals.

Conservation

Statutory instruments and conservation measures aim to protect water quality and freshwater ecosystems in lakes. The overarching policy instrument is the Water Framework Directive (WFD) along with Habitats, Birds, Bathing Water, Floods, Urban Wastewater and Nitrates Directives, which are integral to ensuring good water quality (Daly et al., 2017). These attempt to integrate natural water function, human uses, and values, and thus achieve the dual goals of sustainable natural resource use and social good. Water policy in recent decades has evolved from an initial emphasis on public health, followed by environmental protection and, more recently, focussing on the 'sustainable use' of water and integration with an ecosystem-based approach to water management (Murphy et al., 2014).

Key habitats and species are protected through the designation of conservation areas (Natura 2000 sites: SACs and SPAs) as required under European and national legislation (Natural Heritage Areas (NHAs)). As of

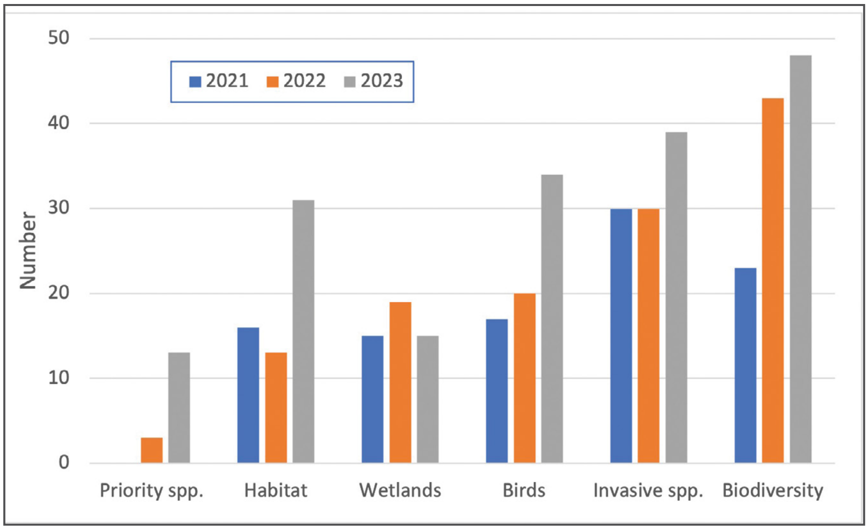

Figure 18.5 Local Biodiversity Action Funds awarded by project type 2021-2023 (n=417) (www.gov.ie)

2023, there are a total of 678 all-island Natura sites (498 SAC and 106 SPAs in the Republic of Ireland (RoI); 58 SAC and 16 SPAs in Northern Ireland (NI)). Half of the SACs in RoI contain nearly 5,000 lakes or 38% of the total lake population (Dalton, 2018). Each Natura site has an S.I. which details the reasons for the designation, and these are called the qualifying interests. For example, Durnesh Lough (Donegal) is designated as an SAC (S.I. No. 415/2018) because it is a priority sedimentary lagoon habitat as well as an SPA (S.I. No. 294/2011) because it has a significant number of wintering waterfowl. Included in both statutory instruments is a list of site-specific activities that require an application for consent from an appropriate statutory authority. These range from changes in farming practice to alterations to drainage, to development of recreational facilities, i.e. anything that has the potential to be a threat or pressure on the qualifying interests for the designations. Applications for consent are assessed by the National Parks and Wildlife Service (NPWS) to decide if there is an alternative to the project, if there are sufficient mitigation measures incorporated in the project to ameliorate causing harm during the activity, and if there are sufficient contingency measures in place to prevent harm from occurring. All statutory authorities are obliged to pursue this procedure for Natura sites. Activities are not granted consent if they are deemed to have the potential to adversely affect the qualifying interests for a Natura site.

National objectives for nature conservation are partly delivered via annual biodiversity action funds through local authorities. Funds of €1.1, €1.5, and

€2.6m were awarded to local authorities for 417 projects between 2021 and 2023 (Figure 18.5). Most of the project awards focus on biodiversity (plans, awareness, training), and alien invasive species. Almost 25% of the projects funded have wetland, lake, or river foci, principally focussed on the invasive Quagga or Zebra mussels as well as baseline surveys.

Valuing Nature

Inland waters with their networks of rivers, and intermittent lakes pepper the landscape, act as physical boundaries, and cross international, national, local authority, rural and urban areas. Engagement and attitudes towards lakes, rivers, and wetlands have changed over time from places of settlement (see Chapters 15 and 16) to areas requiring drainage (see Chapters 4 and 18). Today with the climate crisis causing extremes of drought and flooding, the challenge of mitigation and management of lakes is of increasing concern (see Chapter 14).

Lake waterbodies are valued for both their cultural use (consumptive and non-consumptive) and their non-use (ecosystem) (Murphy et al., 2014). Consumptive use-value is associated with ownership of, and access to fish stock and licences to extract freshwater or dispose of wastewater. Murphy et al. (2014) describe recreation as non-consumptive direct-use value. Other non-consumptive values can include historical significance, as well as artistic, literary, or poetic purpose, and can resonate with individuals who have never visited these lakes. On the other hand, there are non-use values of biodiversity, ecological status, water, and habitat quality. These values have been collectively described as lake ecosystem services (Table 18.2), or the positive benefits that nature provides to people. Wood et al. (2022) identify three types of benefits from cultural ecosystem services: spiritual interaction with nature, mental and physical well-being, and social bonding. In general, the public prefers landscapes with water features as a dominant attribute (Howley, 2011).

Recreation and amenity use both play an important role in our relationship with, and experience of lakes, with each user group placing a different value on their own activities and the perceptions of their impact (Buckley et al., 2016). Value placement is evident in the preferential choice of sites with good water quality, more accessibility, and longer outing duration among anglers, boaters, and water sports participants (Curtis et al., 2017). People can have individualised, commodified, and instrumental approaches to nature, in which nature is largely used as a resource for well-being (Winter et al., 2019). Most recreational studies focus on angling as an activity. Anglers

Table 18.2 Lake ecosystem services

Regulating Services	Supporting Services	Provisioning	Cultural Services
Water purification Flood regulation Carbon sequestration Climate regulation	Biological diversity Habitat Primary production Nutrient cycling Water filtration	Water supply Fisheries Aquaculture Hydropower Recreation use Water transport	Aesthetic & spiritual value Existence Tourism Research Education Literature, art

were found to value access, size of fish, and variety of fish species, and prefer more isolated sites away from areas with good local services (Deely et al., 2020). In an assessment of water attributes of importance, quality trumped visual aesthetics and the health of an ecosystem, while access for recreation was lowest, reflecting the fact that most amenity users have no water contact (Doherty et al., 2014). These figures attest to the value of nature and lakes among anglers and general amenity users.

An additional consideration is the urban and rural dichotomy concerning the type of values attached to lake ecosystem services. Rural residents were found to place higher value on water landscapes likely due to their greater familiarity with, and reliance on the associated provisioning services, such as water supply and fisheries (Howley, 2011). In contrast, urban residents show a larger appreciation for landscapes providing cultural (viewscapes, tourism) and regulating (flood control) services.

COVID-19 and the associated lockdowns (2020-2022), changed the relationship people had with nature (Soga et al., 2021). The two primary drivers for the growing trend of people spending time outdoors are personal health considerations and a desire to re-establish a connection with nature. This is especially apparent with the number of people participating in wild swimming. Lake swimming provides a particularly unique, direct, intimate, and enhanced experience of nature providing a combined experience of blue and green space (McDougall et al., 2022). Freshwater swimming differs substantially from sea swimming in its physical and hydrological properties, satisfying different preferences and values. The calmer nature of lakes can be associated with less hazardous situations, and small upland lakes can be seen as remote wild and pristine swimming opportunities.

A SHARED RESOURCE

Shared Use

Our lakes are shared resources, subject to multiple uses with varying socio-economic demands, requiring infrastructure and access (Winter et al., 2020). Because of their multifaceted benefits, lakes can experience significant pressures associated with the extraction of freshwater, disposal of wastewater, access to fish stock, and recreational use, creating challenges for environmental quality, biodiversity, and sustainability. Increasing human use of aquatic resources generates enormous health and societal benefits but can also leave a collective mark on these natural habitats (DEHLG, 2013). Impacts can include deterioration in water quality, wildlife disturbances and impaired biodiversity, increased litter and trampling of vegetation. Thus, not all lakes are equal in terms of their value as wildlife habitats.

All lakes – naturally productive lowland lakes (e.g., Muckno (Monaghan)), sensitive upland lakes (e.g., Upper and Lower Bray (Wicklow)), and marl lakes (e.g., Conn (Galway)) and turloughs (e.g., Bunny (Clare)) – can experience threats and pressures from recreation. Recreational infrastructure and recreational areas are recognised as a high-level category of pressure or threat on species and habitats (NPWS, 2019). The most frequent sub-category of pressure (F07) is associated with sports, tourism, and leisure activities.

Amenity enhancement areas are subject to more intense human pressures and recreation developments often require the removal of shoreline (riparian) scrub to open views to the lake, paved surfaces, bins for waste, and lighting for safety with consequences for aquatic ecosystem and sediment loads. Lake shores are more developed when near urban or suburban areas. Across Europe, settlement, industry, agriculture, and recreation have resulted in lake shore deterioration causing severe consequences for ecological integrity (Smeider, 2004). Lake shorelines are the primary zone of human interaction and are often modified for diverse human uses (Porst et al., 2019; Schafft et al., 2021). While the RoI has comparatively few heavily modified lakes (Porst et al., 2019), with just 20 (mainly dammed) lakes, there are no public registers of the many (formal and informal) alterations to shorelines, generally associated with buildings, roads, opening-up lake views, and enabling access to the water. The concentration of species richness in the shoreline zone (Oertli et al., 2002) and the predominance of smaller lakes in the population emphasise the need to focus more research efforts on mapping, monitoring, and evaluating the status of lake shore areas and their potential natural value. An examination of planning applications associated with lakes in County

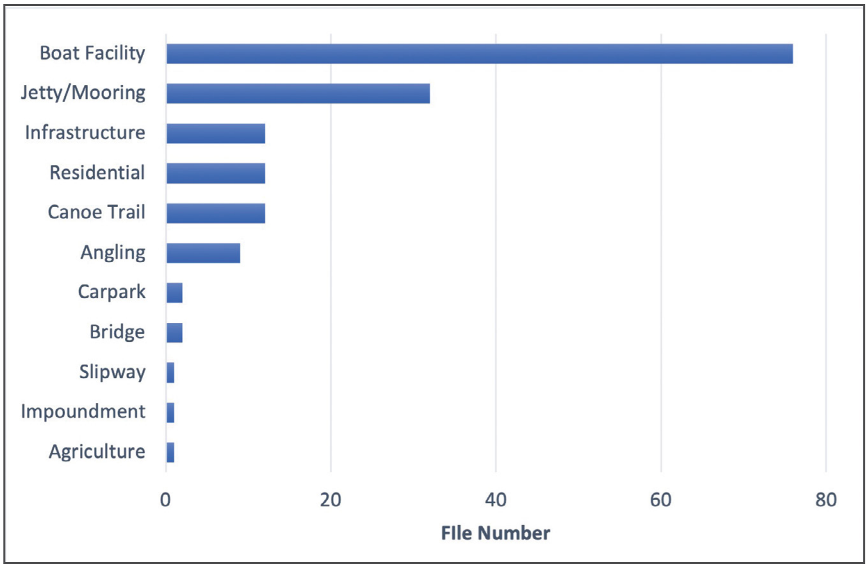

Figure 18.6 County Clare Planning Application (file numbers) associated with lakes (n=158) between 2002 and 2015 (https://www.eplanning.ie/ClareCC/searchtypes)

Clare demonstrated that most applications for development or retention focussed on boating facilities (boat houses/sheds) and jetty/moorings (Figure 18.6). It must be noted that applications for residential dwelling developments adjacent to lakes are greatly underestimated and a more accurate measure of this development pressure is warranted.

Infrastructure developments take up riparian habitat and can interrupt ecosystem dynamics (e.g. bat foraging if trees are removed and/or permanent lighting is erected) and natural run-off patterns (e.g. natural buffer reduced and sediment loads increased). Lakes used for water sports can have negative impacts on the wildlife that depend on these habitats (Schafft et al., 2021). For example, activities such as boating can disrupt nesting and feeding areas for waterbirds, causing flight reactions (escape behaviour) in birds and boat wakes/waves cause flooding of nests. Wintering ducks, geese and swans are very susceptible to disturbance, particularly the Red Throated Diver. Boaters and kayakers value to indicate shallow waters during summer low waters. However, when these are left in the lake overwinter, while not hazardous in themselves, they decrease the wilderness value.

Recreational fishing and even catch and release angling can cause reductions in species and prey populations and disturbance of species, while boats, engines, and wading with nets are additional pressures. Introductions of high-angling value non-native fish species (pike, perch, dace) have consequences for native species (salmon, trout, and lamprey) with dragonflies and damselflies also affected. Fish welfare concerns include damage from hooks, and fish stress from being caught and released. Bankside damage by anglers, broken and discarded line, tackle, lead weights, and hooks can cause problems for birdlife and swimmers.

The presence of invasive species such as Quagga mussels and Curly water weed (*Lagarosiphon*) disrupt the entire aquatic ecosystem and displace native fish species (see Chapter 13). While boats are key vectors, invasives can also be spread on fishing equipment, waders, kayaks, canoes, paddle boards, ropes, life jackets, toys, and swimsuits (Anderson et al., 2015). Melly and Hanrahan (2020) found that there was a significantly low level of biosecurity awareness among outdoor recreational tourists and deficient tourism biosecurity awareness and communication at both national and local levels in Ireland. The lack of biosecurity wash-down facilities contributes to this problem.

The impacts of these developments are further magnified by the fact that the provision of facilities attracts more visitors to the area, increasing the recreational pressure (Schafft et al., 2021). Additionally, as most outdoor enthusiasts are not direct water users, they do not need to utilise facilities to enjoy lake waters (Curtis et al., 2017). Unfortunately, by creating a lakeside amenity attraction with parking and other infrastructure this also attracts irresponsible behaviour. An assessment of amenity carrying capacity (Suárez et al., 2020) of lakes (preferences for outdoor recreation, potential supply, capacity, and demand) is a research gap.

Water Quality

Good lake water quality has ecosystem and wildlife benefits but also results in cumulative social and health consequences to the public, for example, angling tourism relies on a quality natural resource base of habitat and fish stock. Current policy, statutory instruments and conservation measures aim to protect water quality and freshwater ecosystems (See Chapter 11). However, over one-third (36%) of lakes are deemed moderate, poor, or bad water quality (EPA, 2022), while none of the 21 lakes monitored in Northern Ireland in 2021 achieved good overall status. Most of the island's unmonitored small lakes are surrounded by agricultural land use, farming, with stock grazing to the water's edge, and the absence of riparian buffers which potentially reduces quality. Fundamental efforts are being made to ensure that water for the ecosystem, recreational and potable use continues (Daly et al., 2017), including payment for ecosystem services through agri-environmental schemes (O'Rourke and Finn 2020). Regardless, lake and river water quality continues to decline (EPA, 2022).

Water quality influences water-based recreational activities, however, water quality measurements are not easily accessible without concerted effort and expertise to retrieve the results (Curtis et al., 2017). Game angling demand is greater where water quality has a good ecological status, while coarse anglers can tolerate lower water quality (Curtis and Hynes, 2017). Kayakers have preferences for natural surroundings depending on skills and experience (Hynes and Hanley 2006). A survey of recreational boaters (Curtis et al., 2017) indicated significant sensitivities to water quality levels in terms of preferred boating locations. Higher levels of recreational demand were found to occur at sites with better water quality, however, WFD ecological status, the gold standard for science, has a limited impact on users (Breen et al., 2018). Water quality is an issue for wild swimmers (Wood et al., 2022) with more than half of the UK survey participants expressing ecosystem concerns related to water quality, litter in water bodies and boat traffic. Measurement of faecal coliforms and pathogenic micro-organisms (from human and animal wastes) is required for a few designated bathing areas but is not a required measurement under statutory WFD monitoring of the wider lake population.

Infrastructure and Management

Lack of facilities was seen as more problematic than water pollution for most users, according to Williams and Ryan (2004), and lakes with recreational boaters are generally the places with the most facilities (Curtis et al., 2017). Recreational users tend to spend more time at sites with toilet facilities (Breen et al., 2018), which provide support for waterway managers for investment in such facilities at recreational sites. Coarse anglers stay longer on sites with good access possibly due to the amount of equipment they carry and thus benefit more from lakeside infrastructure (Curtis and Breen 2017). Non-trailer boaters were less likely to choose lakes with boat slipways, parking, and toilet facilities. The perceived value derived from constructing toilets and other water sports facilities may be overestimated if individuals engaged in activities like walking, cycling, and other land-based recreation show a greater responsiveness to the provision of such amenities compared to those involved in primary contact recreation. In fact, even if recreationists tend to spend, in general, more time at sites with toilet and other facilities, it was shown that recreational walkers in Ireland viewed water negatively, favouring instead other trail endowments such as signage and maps (Kelley et al., 2016).

While some lakes have major problems with invasive species (Corrib - *Lagarosiphon*, Arrow -Nuttalls Pond weed), the need to control lake 'weeds' is often exhorted for the safety of users (e.g., Lannagh, *Mayo Advertiser* July 26, 2013) as they physically impede boating and angling activity. Curtis (2018) evaluated how anglers assess fishing site attributes and found that concerns about *Lagarosiphon* dominated the results indicating how important and impactful this invasive species is on their enjoyment of the lakes. Local authorities and the Office of Public Works (OPW) are entrusted with infrastructure and amenity management and are responsible for a range of local services including planning, litter, and vegetation management. The OPW has a statutory remit for the conveyance of water and drainage maintenance as well as healthy catchments (Brew and Gilligan 2019). Vegetation management (skimming, digging, weed-cutting bucket) is generally focussed on tall reeds, floating and rooted vegetation as well as bankside trees and scrub. There are clear national guidelines on maintenance works and operational procedures which adhere to Birds and Habitats Directives for Salmon designated rivers during fish spawning seasons, and on bird nest sites and mammal habitats. However, few or no local lake management plans exist. Possibly the most relevant documents are the Natura site S.I. conservation objectives – however, these only relate to protected lake sites. The rest of the lake population is indirectly protected via measures under the WFD, EPA, Local Authority Waters Programme (LAWPRO), and IFI. Tidy Towns groups additionally have an important role. Their historical focus was largely on the beautification of an area (litter collection, weeding, planting); however, many groups have moved beyond aesthetics to pursue a more authentically 'green' agenda.

Camlough Lake in Co. Armagh is a rare case of a mid-altitude, mesotrophic lake, and Area of Special Scientific Interest (ASSI), near an urban centre, and is a recreational hub whose popularity partly lies in its untouched landscape that features hills, woodland, scrub, and some agricultural land. Although most of the lakeshore is inaccessible for land-based recreation, two parking areas and a slipway were created to accommodate the needs of swimmers, paddle recreationists, and anglers. The increasing popularity of the lake drove the local council to apply and secure funding to create a multi-use recreation centre (Outdoor Recreation NI 2017). The construction of grey infrastructure will increase potential recreationists, and the placement of visible zoning signs will certainly change the character of the lake.

Figure 18.7
Swans on
Lough Talt.
Photo: Fran Igoe

Sustainability & Stewardship

Outdoor recreation strategies aim to promote a culture of dynamic sustainable recreation and foster environmental stewardship. The primary purpose is growth, development, and increased participation in the outdoors, therefore, the use of lakes as an amenity and recreation resource will inevitably grow. The individual impact of one recreational lake user is small, however, the cumulative effect of all (boaters, anglers, swimmers) becomes extremely important for sustainability. State policy and local authorities are required to ensure the development of these rural outdoor resources in the public interest and to create value for public expenditure.

Given Ireland's commitment to designate 30% of Ireland for nature by 2030, we need to have a measured response for lakes in terms of amenity and recreation development to ensure that naturalness and wilderness attributes are retained. The urgency of climate change, the biodiversity crisis, and the continuing decline in water quality (EPA, 2022), have shifted attention from unidirectional policies to more integrative approaches aiming for the recovery of ecosystems providing services that benefit society and the economy, inclusive of rural economies. For example, the objective of LAWPRO is to coordinate efforts by Local Authorities, public bodies, and other stakeholders to achieve the water quality objectives of the WFD; to support local communities to get involved in caring for their local waters and participate in decision making and river basin management plans; and to identify the issues impacting on water quality and wildlife and refer them for action (Antwi et al., 2021) (Figure 18.7).

Our regulations appear to be robust, with wildlife conservation protection (SPA, SAC, SSSI) and regulations to avoid significant impacts, however irresponsible behaviour and the impracticalities of enforcement are constant challenges. In the absence of a policy to address potential conflicts between conservation and recreation interests, local authorities have occasionally responded to the rising demand for lake recreation by buying adjacent land or by making specific agreements with landowners. Given the escalation in outdoor recreation and multiple user groups, the benefits that we experience from nature's ecosystem services must outweigh some of the more exploitative uses of lake resources. Schafft et al. (2021) recommend that policymakers and conservation managers need to engage in nuanced and contextualized evaluations about the impact of recreation (Table 18.3).

Table 18.3 Lake Recreation Policy Considerations (after Schafft et al., 2021)

- Manage recreation for conservation benefits,
- Zone and reduce recreation access on lake-wide scales,
- Remove recreational access temporarily or permanently,
- Improve recreational infrastructure only in non-Natura lake ecosystems,
- Individual-level conservation for threatened species,
- Conservation of population size, community integrity or habitat status,
- Consider recreational users in the context of other user groups,
- Prioritise habitat, wildlife, and wilderness value,
- Pay for water use.

A key question is whether our amenity, leisure, and recreational pursuits in nature and on lakes make us better environmental stewards. More people accessing lake resources can create challenges, but it can also increase the potential for environmental stewardship and provide early warnings of deterioration in quality (especially since most of our lakes are small). Collectively, our outdoor experiences are important because they influence people's attitudes and behaviour towards nature and nature conservation measures (Doherty et al., 2014; Murphy et al., 2014).

Daly et al. (2017) suggested the need for the integration and participation of local communities, farmers, rural tourism providers, and recreationists, in ensuring and promoting sustainable natural resource use and ecosystem service provision in rural areas. This resonates with the recent efforts by

LAWPRO and Rivers Trust to increase public participation in local catchment stewardship (Antwi et al., 2021; O'Cinnéide et al., 2021). Catchment-based approaches (e.g., Allow, Maigue, Inishowen) promote integrative management of resources via collaborative partnerships and engagement between governmental structures, stakeholders with economic interests, and local communities that rely on the good quality of water for their well-being. Public participation is a fundamental pillar in water management under the WFD, providing the platform to access local knowledge and experience with problems on the ground.

When interest in conservation is aligned with interest in recreational pursuits, environmental stewardship has been shown to promote positive actions. Anglers have a long history of acting as environmental stewards by spotting pollution incidences and providing valuable monitoring information to facilitate the regulation of water quality and secure the viability of their recreational pursuits (Shephard et al., 2022). The Ballindery Rivers Trust, initially formed by angling groups to reverse the dwindling Dollaghan trout population, later assumed a more diverse role in conservation work, an example of which is its involvement in the protection of Freshwater Pearl Mussel (O'Cinnéide et al., 2021). Moreover, the Maigue Rivers Trust was formed by a group of locals in response to a major pollution incident (Weiner et al., 2023). More recently, bathers, water sport groups and members of the public have participated in citizen science monitoring networks, such as WaterBlitz (Hegarty et al., 2021).

CONCLUSION

This chapter has highlighted the need to support habitat ecological and environmental services provided by lakes on the basis that they generally outweigh the view that lakes are socio-economic resources. To some extent, the restrictions of a rural agricultural environment with limited public access have meant that lakes are less heavily used for amenity and recreation, relative to rivers and the sea. This is good news for their natural role as wildlife habitats and especially for breeding birds. However, where use increases, the potential for habitat modification and the creation of hotspots increases with potential tensions between different users. These increases would benefit from all island registers of recreational users, registers of amenity areas, research into lake-carrying capacities, and further evaluation of the status of lakeshore areas.

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Chapter 19

NAVIGATING GOVERNANCE AND STAKEHOLDER ENGAGEMENT IN WATER MANAGEMENT

Triona McGrath, Sarpong Hammond Antwi,
Alec Rolston and Suzanne Linnane

SUMMARY

Many of Ireland's lakes face significant and escalating anthropogenic pressures, including changing land use and land use practices, climate change, and a growing population. The management of lakes is a complex task due to multiple pressures often acting simultaneously, and the type and severity of pressures varying geographically. Cardoso et al., (2009) suggested that organisations and bodies involved in the management of lakes and their catchments may need to define a hierarchy among the pressures to identify priority actions in the appropriate geographical scale. Furthermore, Baker and Newman (2014) concluded that the goals of lake management should not only focus on water quality, but should also consider broader terms, including the impact of invasive organisms, factors associated with fishing quality, aesthetic factors, and even spiritual values. The management of lakes, therefore, requires strong governance structures, with effective stakeholder engagement at national and local scale. In recent years, the deteriorating health of lakes in both the Republic of Ireland and Northern Ireland illustrates the challenges ahead in managing these precious resources.

This chapter presents the current governance structures of lakes in Ireland and delves into how stakeholder engagement can contribute to governance within water resource management. Focus is placed on two specific case studies: 1) An Fóram Uisce - the National Water Forum - as an exemplar of a statutory stakeholder forum advising on national water policy and governance and 2) a case study from the Group Water Scheme (GWS) sector illustrating how well-defined and targeted engagement efforts contribute to improved water quality services at catchment level.

Keywords Lake management, water quality, improved governance, stakeholder engagement

THE STATUS OF IRELAND'S LAKES

The increasing pressure on Ireland's waterbodies, coupled with fragmented governance and limited resources, is evident in the decline in the water quality of lakes in both the Republic of Ireland (RoI) and Northern Ireland (NI) in recent years. The Environmental Protection Agency (EPA) Water Quality Report for Ireland 2016-2021 indicated only 69% of monitored lakes in the RoI are in high or good ecological status, a decline of 2.7% since the 2013-2018 assessment (Trodd et al., 2021) (Table 19.1) (see Chapter 11). The situation is worse in NI, where five of the 21 (24%) monitored lakes were classified as having good overall status in 2015 and 2018, which decreased to 0% (no lakes) achieving good overall status by 2021 (NIEA, 2021), thus illustrating a rapid decline in the quality of lakes in the region.

It is of note, however, that there are more than 12,000 lakes in the RoI, yet only 224 of these (80% of the surface area of lakes) are currently included in the EPA National Lake Monitoring Programme (EPA, 2021b). Dalton (2018) highlighted that estimates of lake numbers in Ireland, particularly small lakes, have generally been under-represented, and an accurate calculation of lake numbers is necessary to determine realistic estimates of their natural capital, including provisioning, regulating, supporting and cultural ecosystem services. Lakes and reservoirs are the main sources of drinking water for two million people in the RoI, however, approximately 50-60% of the smaller lakes used for potable water supply through GWS are not part of the National Lake Monitoring Programme (NFGWS, *pers. comm.*).

Table 19.1 Breakdown and number of water body types, with % of those in 'good' or 'high' ecological status in 2021, figures for RoI as reported in Trodd et al. (2021), along with the % change since the previous water quality assessment period (2013-2018). Figures from NI as reported in NIEA (2021).

	Republic of Ireland (RoI)			Northern Ireland (NI)		
Water body Type	Number of water bodies	% in 'good' or 'high' ecological status in 2021	% change since (2013-2018)	Number of water bodies	% in 'good' or 'high' ecological status in 2021	% change since 2018
River	3192	50%	-1%	450	0%	-31%
Lake	812	69%	-2.7%	21	0%	-24%
Transitional	196	36%	-15.7%	25	0%	-40%
Coastal	112	81%	-9.5%			
Groundwater	514	91%	-0.8%	75	68%	+3%

WATER GOVERNANCE IN THE REPUBLIC OF IRELAND

The governance of lakes in Ireland differs between the Republic and the North of Ireland, adding complexity to the management of lakes, particularly for those in cross-border catchments. The OECD defines water governance as the 'range of political, institutional and administrative rules, practices and processes (formal and informal) through which decisions are taken and implemented, stakeholders can articulate their interests and have their concerns considered, and decision-makers are held accountable for water management' (OECD, 2015).

Like the rest of Europe, the management of lakes and other waterbodies in the RoI, comes under the remit of the Water Framework Directive (WFD; 2000/60/EC), which was adopted by the European Union (EU) member states in 2000. The WFD provides an overarching ecosystem approach to water management, with the overall objective that EU Member States must protect and restore all waterbodies (rivers, lakes, groundwater, transitional and coastal waters) to good ecological status by 2027. The WFD requires that all lakes over 50 hectares (0.5 km^2) in surface area are reported on, along with smaller lakes associated with protected areas or drinking water abstraction. The WFD has transformed water governance in the RoI and across Europe through the adoption of this integrated strategy for river basin management that relies on ecological rather than political borders to manage water (Hesse et al., 2023).

In the RoI, the relevant governance structures are defined and implemented through Ireland's River Basin Management Plans (RBMPs) which are

Table 19.2 The three-tier structure for implementation of the second River Basin Management Plan (adapted from DHLGH, 2018).

Tier	Leading Body	Responsibilities
Tier 1: National Management and Oversight	Minister for Housing Local Government and Heritage	Policy, necessary legislation and resourcing of the plan. Supported by the Water Policy Advisory Committee.
Tier 2: Technical Implementation and Reporting	Environment Protection Agency (EPA)	Catchment characterisation process, overseeing the national monitoring programme, chairing the National Technical Implementation Group and assisting and advising the Minister.
Tier 3: Regional Implementation	Local Authorities and Local Authority Waters Programme (LAWPRO)	Coordinating the implementation of measures on the ground and the local knowledge required to deliver many potential measures successfully.

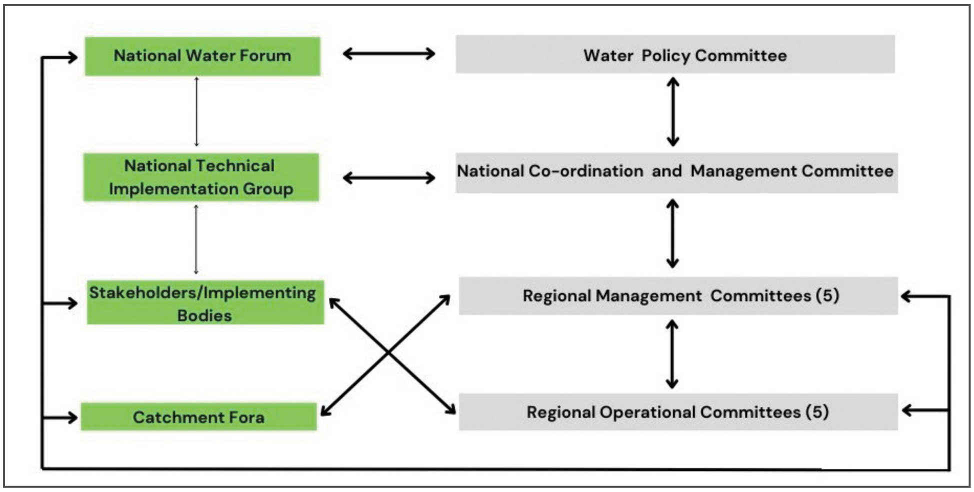

Figure 19.1 Governance structures of the second cycle River Basin Management Plan in the Republic of Ireland (adapted from DHLGH, 2021).

a requirement under the WFD. The Department of Housing, Local Government and Heritage (DHLGH) is the leading government department responsible for the development and implementation of RBMP. The second RBMP involved a complete change in river basin management planning and governance structures relative to the first cycle, where a three-tier structure of governance was adopted (Table 19.2) (DHLGH, 2018).

The second RBMP also introduced an implementation structure for governance at local, regional and national levels (Figure 19.1).

The Water Policy Advisory Committee (WPAC) provides high-level policy direction to the development and oversight of the implementation of the RBMP. WPAC is convened to provide policy advice and assistance to the Minister for Housing, Local Government and Heritage on implementing the WFD and broader water resource issues.

- Membership of the WPAC consists of nominees of:
- Department of Housing, Local Government and Heritage
- Department of Agriculture, Food and the Marine
- Department of Environment, Climate and Communications
- Geological Survey Ireland
- Department of Culture, Heritage and the Gaeltacht
- Department of Health
- Health Services Executive
- County and City Managers' Association (from both Water and Environment Committees)
- Environmental Protection Agency

- Office of Public Works
- Commission for Regulation of Utilities
- Uisce Éireann (formerly Irish Water)
- Inland Fisheries Ireland
- Local Authority Waters Programme

The National Coordination and Management Committee (NCMC) was established under the WPAC to ensure the effective oversight, management and delivery of the RBMPs and to provide the necessary coordination between the Local Authority sector, the EPA and the Department of Housing, Local Government and Heritage. The purpose of the NCMC is to support plan delivery at a national level by sectoral bodies such as Uisce Éireann, the Department of Agriculture, Food and Marine, Forestry Service, and others.

The National Technical Implementation Group (NTIG) oversees the technical implementation of the RBMP at a national level. The purpose of this group is to provide an overarching coordination role for dealing with cross-cutting technical and scientific issues that may arise. It facilitates regular exchange of information and knowledge between the agencies involved in operational, technical and scientific implementation issues. The EPA chairs the NTIG, and membership includes all relevant implementation bodies of the RBMP. The Northern Ireland Environment Agency (NIEA) attends the group's meetings to provide updates on progress within NI and also contributes to any discussions on cross-border catchment issues.

In addition to overseeing the national monitoring programme, the EPA coordinates the tracking of the implementation of actions, undertakes the assessment of effectiveness and is statutorily responsible for reporting on the WFD to the European Commission. This includes assessment and actions for lakes. The third tier of regional implementation is supported by five Local Authority regional committees, whose purpose is to coordinate and implement measures locally. The LAWPRO plays a significant role in the implementation of the RBMP by coordinating the response from Local Authorities and relevant public bodies and by supporting communities and stakeholders to become actively engaged in water protection and restoration (see Chapter 20). LAWPRO have a key role in catchment management, carrying out detailed assessments at the water body scale in priority areas for action and providing advice on targeted measures to protect and restore water bodies.

WATER GOVERNANCE IN NORTHERN IRELAND AND SHARED RIVER BASINS WITH THE REPUBLIC OF IRELAND

Following its departure from the EU in January 2020, NI is no longer under the remit of the WFD, creating challenges for the management of lakes in cross-border catchments(see Highlight Box at the end of this chapter). However, in an attempt to continue the catchment-based approach of the WFD, the Water (Amendment) (Northern Ireland) (EU Exit) Regulations 2019 was published, which indicates how the Water Framework Directive (as transposed) and the various supporting pieces of water legislation, continue to operate in the Region after the exit from the EU. In line with the RoI, the 3rd RBMP for NI (2021-2027) underwent a public consultation in 2021, however, unlike the RBMPs for mainland Britain, the NI plan is still not published.

Ireland shares two river basin districts (RBD) with NI, the Neagh Bann International RBD (35 shared waterbodies) and the North Western International RBD (85 shared waterbodies). Substantial areas lie within cross-border river basins in Ireland, with waters in each jurisdiction flowing into or through the other jurisdiction. Both NI and the RoI each carry full responsibility for ensuring the implementation of all measures in their national territory, including any part of an International River Basin District that lies within their national territory (DHLGH, 2022). The Department of Housing Local Government and Heritage in the RoI stated that coordination with NI is ongoing during the development and implementation of the third RBMP.

Overall coordination for the implementation of the WFD within NI is still undertaken on a bilateral basis through the Department's North-South Water Framework Directive Coordination Group. NIEA and the Loughs Agency are members of the Border Region Operational Committee, which provides a forum to enhance interagency networking and allow for operational staff to share knowledge and seek opportunities to maximise outcomes for cross-border waters. There are several other initiatives and projects to enhance cross-border management, such as the North West Water Forum which includes representatives from the Lough's Agency, the LAWPRO, members of the project board of Source to Tap (Interreg project), Inland Fisheries Ireland, Members of the project board of Catchment CARE (Interreg project), Teagasc, Coillte and the National Parks and Wildlife Service (DHLGH, 2021, 2022a).

One of the key actions for the 3rd RBMP for the RoI is to 'In cooperation with our northern colleagues, DHLGH […] prepare a "shared waters" document that will outline the water bodies that flow into or through both jurisdictions and the work to be undertaken to ensure they meet their environmental objectives as reported in the River Basin Management Plans for Ireland and Northern Ireland.'

Despite these cross-border initiatives and obligations of the WFD, the decline in satisfactory water quality for lakes and other freshwaters in both the RoI and NI reflects the failure of the measures implemented through the first two RBMPs, with insufficient protection of those waterbodies already at good or high status, and a failure to restore other waterbodies to satisfactory conditions (see Chapter 12).

THE NEED TO REVISE EXISTING WATER GOVERNANCE

Each cycle of the RBMP and its associated Programme of Measures, provides an opportunity to review and improve the governance structures that support the WFD water quality objectives. In 2021, the Institute of Public Administration completed an assessment of water governance in the RoI using the OECD Water Governance Indicator Framework to review the implementation of the 2nd RBMP for Ireland 2018-2021 (O'Riordan et al., 2021). This indicated that the governance structures put in place during the 2nd cycle were successful in significantly achieving the objectives of the Water Governance Indicator Framework. They found that the three-tier structure developed in the second cycle (Figure 19.1) represented substantial innovation and was an improvement over the governance arrangements in place for the 1st cycle of the RBMP. This study also revealed a number of areas for improvement and presented a series of recommendations around adapting and improving the operation of the governance structures.

One significant gap highlighted in O'Riordan et al. (2021) is specifically related to insufficient financial resources to deliver the requirements of the WFD. Indeed, the inability to apply or enforce measures that have been decided on is often due to limited financial and human resources dedicated to controlling their application (Bondarouk and Mastenbroek, 2018; Hudson et al., 2019). To effectively implement the RBMP, finances are required to support the implementation process and the administrative costs at organisations/agencies for implementing the proposed measures. The need to adequately resource the 3rd RBMP in Ireland was raised as an issue by many stakeholders during the consultation of the 3rd RBMP (DHLGH, 2022b), highlighting the urgency of addressing the water crisis, along with the climate and biodiversity crises.

The draft plan for the 3rd RBMP includes a proposed measure to 'Explore the feasibility of establishing a high-level interdepartmental group to develop a comprehensive financing strategy to support the implementation of measures to deliver on the ambitious Water, Climate, and Biodiversity objectives committed to in the Programme for Government.' The implementation of this measure would be a significant step towards a holistic, integrated approach. An international example of such policy coherence is Germany, which created a "Super Ministry" for economics and climate protection which can veto any legislation incompatible with the 2015 Paris Agreement (Maublanc, 2022). The initiation of such an interdepartmental group in Ireland would also allow for the identification of synergies in proposed measures across the different components, thereby avoiding duplication and making better use of resources. It would also allow for the identification of trade-offs across the water, biodiversity, and climate components, where they may be required.

In fact, there is a growing realisation that if Ireland is to achieve its water objectives under the WFD, along with its targets for climate and biodiversity, coherence in policy will need to radically improve to ensure that one section of government does not undermine what another is trying to achieve. Maublanc (2022) in an assessment of policy coherence and environmental management, stated that this requires an evolution of the processes and approaches to policymaking, with greater emphasis on seeking their convergence and developing synergies, while also acknowledging trade-offs in a transparent and effective manner. While the term policy coherence has been getting more attention in environmental policy and management in recent years, there is little guidance on how countries should integrate their policies into practice (Stafford-Smith et al., 2017). An existing challenge for environmental policy coherence and improved management of lakes in Ireland is related to the siloed structures of the government departments, whereby water management and the WFD are the responsibility of the Department of Housing, Local Government and Heritage, while Agriculture, a significant pressure on waterbodies in Ireland, is under a different government department. Furthermore, climate action is getting increasing attention and resources in recent years and is addressed through the Department of Environment, Climate, and Communications, and is often not sufficiently aligned with the requirements of the WFD. The EPA has stated that 'the absence of an overarching national environmental policy position is negatively affecting integration and progress across multiple environmentally related strategies, plans and programmes: the sum of the parts do not make up a coherent whole' (EPA, 2020). Changes in government structures may be required to achieve greater coherence, where environmental protection could become, along with fiscal responsibility, a cross-cutting issue (Maublanc, 2022).

STAKEHOLDER ENGAGEMENT

Due to the myriad of pressures impacting lakes in Ireland, effective management requires input from multiple stakeholders. According to the OECD, stakeholder engagement is a critical enabler of improved regulatory quality, where stakeholders can bring their own perspectives and learnt experiences to help shape solutions and avoid costly mistakes. Stakeholders also possess a potential wealth of data on actual impacts incurred, thus providing governments with valuable information to help improve estimations of likely regulatory impacts.

In Ireland, there has been a growing scientific inquiry into the role of stakeholders in water resource management and governance (Antwi et al., 2021; Bresnihan and Hesse, 2019; Rolston and Linnane, 2020). There are, in fact, a range of policies and procedures in place for the participation of local communities in water and sanitation management (DHLGH, 2020). These inquiries and increased policy discourse point to the significance of stakeholder engagement in achieving transformative change in environmental management and in meeting ambitious national water, climate, and biodiversity targets in Ireland. While these efforts collectively reflect the growing concern and interest in stakeholder engagement, a critical question remains: which aspects of water resource management require stakeholder engagement? In addition, the extent to which engagement should improve decision-making for water quality policies remains uncertain.

Case Study 1:
Water governance for future-proofing and the role of An Fóram Uisce

To facilitate stakeholder input to water policy development in Ireland, An Fóram Uisce, The Water Forum, was established in 2018 as the national statutory body representative of stakeholders interested in the quality of Ireland's water bodies, including lakes. An Fóram Uisce currently comprises 26 members from 16 different sectors (Table 19.3), representing a wide range of organisations with direct connections to water quality and managing Ireland's water resources.

As outlined in An Fóram Uisce's Strategic Plan (2022-2027), the vision of the Forum is that 'Ireland's waters are clean, healthy and life-enhancing, supporting biodiversity and providing the basis for community wellbeing and economic sustainability' (An Fóram Uisce, 2021). The role of the Forum is to strengthen stakeholder input into decision-making regarding water policy and water management by providing a platform for stakeholders to meet, engage and debate all matters relating to water as an environmental, economic and social asset. The Forum has a legal role in advising the Minister for Housing, Local Government and Heritage on issues relating to water services and water quality in Ireland. Under the Water Services Act 2017, the Forum has an advisory role on water conservation, rural water services, and the interests of public water consumers. The Forum also has an advisory role to the Water Policy Advisory Committee in relation to the RBMP and the WFD. This unique platform of national stakeholders brings together expertise and different perspectives on managing Ireland's water resources.

To support the wide remit of the Forum's advisory roles, two sub-committees of Forum members were established. The first is the Water Services Standing Committee, which focuses on water policies related to water and wastewater services, rural water, and water conservation. The second, the Catchment Management Standing Committee, focuses on catchment management issues at a national, strategic policy level, particularly focusing on the WFD and Ireland's RBMPs.

An Fóram Uisce as a statutory forum interacts directly with various stakeholder bodies across the three tiers of governance of Ireland's RBMP, including WPAC, the EPA and LAWPRO (Figure 19.1). The Forum has played a significant advisory role in providing stakeholder input to the development and finalisation of the 3rd RBMP. During the six-month consultation period which was launched in September 2021, the Forum met monthly with the Water Advisory Unit of the Department of Housing, Local Government and Heritage to facilitate discussion with Forum members on key areas of the third plan, including governance, agriculture, hydromorphology, forestry and urban wastewater. During each session, relevant officials from government departments and state bodies were invited to present at the Forum to ensure members were knowledgeable on specific topics before positions of the Forum were discussed and agreed upon. In 2022, the Forum subsequently developed a significant submission (AFU,

Table 19.3 Representation of sectors and organisations on the Water Forum (An Foram Uisce), with 26 Members from 16 different sectors. Details are available on An Fóram Uisce (https://thewaterforum.ie/)

Sector	Representative Organisation (# Members)
Chairperson	Independent Ministerial Appointment
Agriculture	Irish Creamery Milk Suppliers Association - ICMSA (1)
	Irish Farmers Association - IFA (1)
	Macra Na Feirme (1)
	Irish Co-Operative Organisation Society - ICOS (1)
Angling	The Angling Council of Ireland (1)
Business	Irish Business & Employers Confederation – Ibec (1)
Community & Voluntary	Irish Rural Link IRL (1)
	Community & Voluntary Pillar (1)
Education	Technological Higher Education Association – THEA (1)
Environment	Sustainable Water Network - SWAN (3)
	Irish Environmental Network – The Environmental Pillar (2)
Fisheries	Fisheries Sectoral Bodies (1)
Forestry	Forestry Sectoral Organisations (1)
Domestic Water Consumer	Public Water Consumer c/f from former Public Water Forum (2)
Recreation	Water Recreational Sector (1)
Rivers Trusts	The Rivers Trusts in Ireland (1)
Rural Water	National Federation of Group Water Schemes - NFGWS (2)
Social Housing	Irish Council for Social Housing (1)
Tourism Sector	Tourism Sectoral Organisations (1)
Trade Union	Irish Congress of Trade Unions – ICTU (1)
Youth/ Interests of Third Level Students	National Youth Council of Ireland (1)

2022), which included 106 recommendations for inclusion in the 3rd RBMP. Recommendations were grouped into four key areas: (1) an outcomes-based approach that focuses on waterbodies as the management unit (2) improved governance, (3) improved public participation in the implementation of the RBMP, and (4) pressures, with specific recommendations around individual pressures on water quality.

In its submission to the Third RBMP, An Fóram Uisce emphasised the need for transparency across all levels of governance of the RBMP; including decision-making, monitoring and evaluation, and access to data and documentation. The Forum also raised concern over insufficient engagement between the three tiers of governance and called for more structured, transparent engagement going into the 3rd cycle. One of the key recommendations was the need for a full-time project management secretariat to support the governance arrangements, to focus on programme management, implementation, reporting, and developing relationships with stakeholders, in line with findings by Boyle et al. (2021). The lack of project management specific to the RBMP is evident with yet another significant delay of over one and a half years for the finalisation and publication of the third plan, which will shorten the third cycle from six to four years. This, therefore, may create challenges regarding the timely implementation of proposed measures in the new RBMP and the likelihood of achieving significant improvements in ecological status is lessened. Considering the evolving and growing environmental targets across government departments, a project management secretariat would support continuous engagement within and between government departments to support policy coherence and the identification of co-benefits across water, climate and biodiversity.

To better integrate water management with biodiversity and climate change action, An Fórum Uisce adopted the Framework for Integrated Land and Landscape Management, (FILLM), as a framework for environmental management to address the interconnectedness of natural systems (Water Forum, 2021). FILLM (Figure 19.2) promotes the management of all components of the environment (air, water, ecosystems, soils, rocks, land, and landscapes) holistically, thereby connecting relevant policies such as the WFD, Urban Wastewater Directive, Habitats Directive, Floods Directive, Drinking Water Directive, Common Agricultural Policy, Climate Action Plan and climate change adaption. FILLM recommends that measures required for sustainable management of water resources, biodiversity management and climate change adaptation and mitigation should be developed and implemented in an integrated manner. Many of the environmental issues are complex or 'wicked' problems, involving multiple pressures acting in combination, and therefore, require action with multiple sectors, in partnerships at international, national and local levels.

Aligning action for climate, water, and biodiversity would also benefit communities, making environmental management more understandable, less fragmented, and thus more achievable. This integrated approach facilitates the identification of co-benefits of various measures to ensure optimum benefits for water, climate, and biodiversity for efforts and resources used,

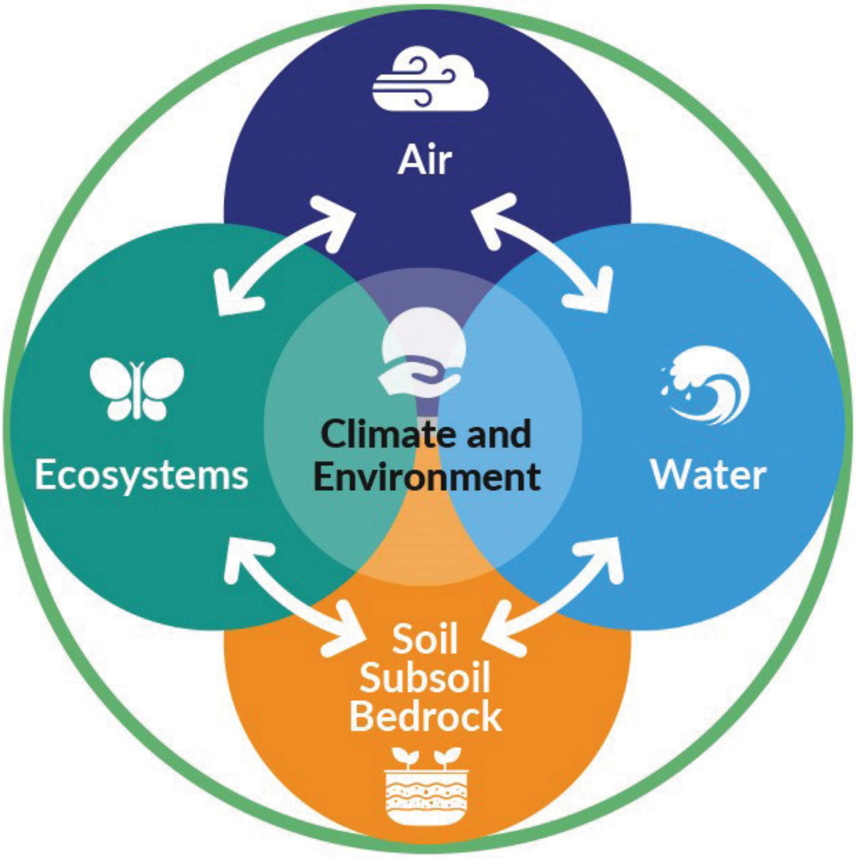

Figure 19.2 Illustration of the whole of environment concept and interlinkages taken from the Water Forum's adopted policy, a Framework for Integrated Land and Landscape Management (FILLM) (AFU, 2022).

while also supporting decision-making around trade-offs, where required. Catchments are traditionally viewed 'as an area formed by topography that supplies water to a river and its tributaries, with all of the water ultimately flowing to a single outlet'. FILLM defines catchments in a much larger and more meaningful fashion; 'a multi-functional, topographically based, dynamic, multiple-scale socio-biophysical system; defined by over ground and underground hydrology; connecting land, water, ecosystems, geosystems, atmospheric systems, and people; and used as the basis for environmental analysis, management, and governance' (Water Forum, 2021). By utilising this concept and this understanding of our ecosystems, the catchment can become an appropriate and effective landscape unit for environmental management and land-use planning. However, in the RoI, current governance structures and implementing agencies (e.g. local authorities) generally act within administrative boundaries, creating challenges for the transboundary management of water resources. While LAWPRO attempts to facilitate better transboundary management through the catchment-based approach, it remains that the catchment is not currently the administrative management unit in Ireland. The 3rd RBMP is proposing the development of detailed Catchment Management Plans for each of the 46 WFD catchments in the RoI, with clearly defined targets for each waterbody, along with co-benefits of water-focused measures on climate and biodiversity. This approach has the potential to improve the management of waterbodies at catchment level.

Case Study 2:
The Group Water Scheme Sector (GWS) and the National Federation of Group Water Schemes (NFGWS)

Consumers in the RoI receive their potable water from one of five types of water supplies, i.e., public water supplies; private wells in areas without piped water supplies; GWS sourced from public supplies; privately sourced Group Water Schemes; and small private supplies (EPA, 2021a). GWS are independent, community-owned entities made up of two or more homes that provide piped, treated drinking water to rural communities, primarily from lakes and reservoirs. With 1.74 million people residing in rural areas, the RoI has a sizable rural population, approximately 38% of the total population. This is higher than the average European rural population of 28%. In the RoI, almost 20% of homes get their drinking water from sources other than public water supplies. The GWS sector provides drinking water to over 69,000 rural households across the state, approximately 6% of the population (Figure 19.3), and must adhere to the drinking water standards outlined in the EU Drinking Water Directive (98/83/EC). The majority of GWS (91%) that abstract from surface waters serve a population of less than 3,000 people, with 94% supplying less than 1500 m^2 of water. Domestic and non-domestic (mostly agricultural, but also some business) consumers are also served by GWS (Rolston and Linnane, 2020) community-led Group Water Schemes (GWS.

Despite challenges, the GWS sector has significantly enhanced water availability and equity, particularly among rural consumers, in the last seven decades. The GWS governance structure focuses on community members' inclusive and participatory engagement in managing schemes. Each scheme is managed by employed or voluntary managers and committee members who are known and trusted within their communities. The GWS model is unique in Ireland and an exemplar for other countries. The activities of the schemes are regulated by the NFGWS, while monitoring of drinking water

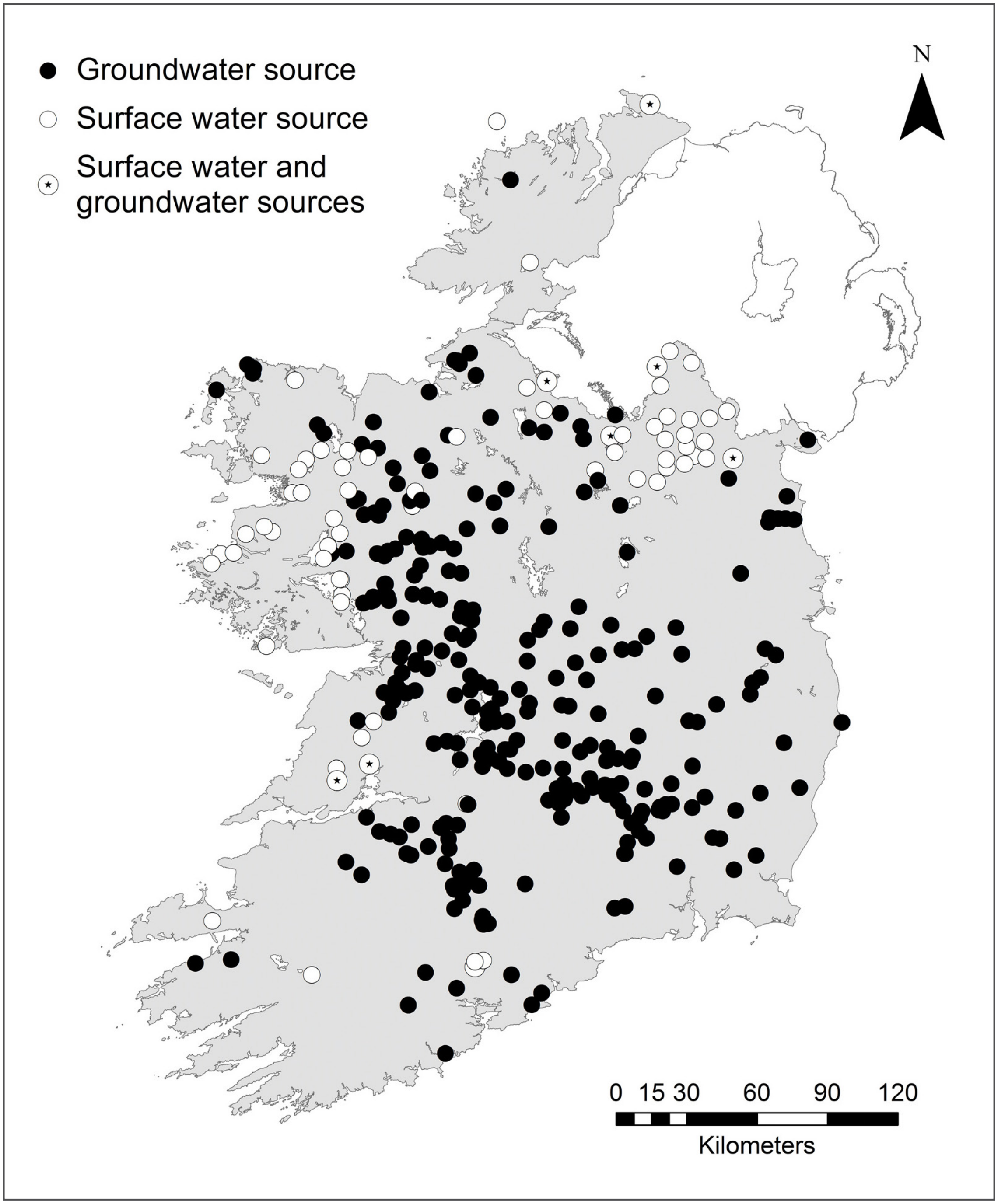

Figure 19.3 Location of and raw water source type for privately sourced GWS that supply 4.4% of the total population of the Republic of Ireland (Source: Rolston and Linnane, 2020) community-led Group Water Schemes.

quality of GWS is carried out by Local Authorities. The GWS structure can be considered a model of effective and sustained stakeholder engagement in rural Ireland, specifically in relation to the governance of water resources, including the delivery of safe potable water, land-use management, and source protection. The development and evolution of the GWS sector across rural Ireland, increasing rural water supply from 3% to 6% of the population, and now supplying water via community-owned schemes to approximately 300,000 citizens is a noteworthy achievement (Deane and MacDomhnaill, 2021).

To deal with the complexities for local communities in managing their water supplies, the rural water sector was transformed and the NFGWS was founded in 1997. The NFGWS quickly gained recognition as the representative organisation for privately owned and part-privately owned GWS in Ireland. This recognition led to the incorporation of the Federation as a cooperative society in 1998 and has since been the umbrella organisation for the GWS sector (EPA, 2022; NFGWS, 2019a). Until the 1950s piped water supplies were virtually unheard of outside of Ireland's towns and cities. County Boards of Health and Public Assistance established in the 1920s had begun the process of providing a public water supply in rural areas through the erection of village pumps. Under the County Management Act (1940. Since its inception, the NFGWS has been working with local authorities, government agencies, and stakeholders to achieve water quality standards in rural water supplies.

First and foremost, the obligation of the GWS sector is to deliver potable drinking water that meets the standards of the World Health Organisation and the EU Drinking Water Directive. The GWS sector has led the way in catchment-based approaches to source protection, to avoid relying solely on end-of-pipe treatment. It has implemented a multi-solution strategy to lower the risk of declining raw water quality, and long advocated the provision of drinking water services through the 'source-to-tap' approach. They recognise that while source protection of drinking water is key to human health, it also provides a sustainable and affordable means of ensuring a safe and sustainable supply of potable water. In order to support each GWS in creating and overseeing its own scheme-specific source protection plan, the NFGWS created a comprehensive strategy for source-protection planning for the privately sourced GWS in 2012. While initial preliminary source protection assessments were started in 2009, most assessments began from 2014 onwards once funding from the Irish Government's Rural Water Programme was made available to individual GWS.

Catchment actions that have mutual benefits for biodiversity and climate change, along with water quality, are highly valued by the sector. Collaboration is key to success and the GWS sector regularly collaborates with other key stakeholders including the Agricultural Sustainability Support and Advisory Programme (ASSAP), LAWPRO, Forestry and Inland Fisheries Ireland, along with State Departments and Uisce Éireann. The systematic approach taken by the GWS sector for the sustainable implementation of Integrated Catchment Management Plans is an excellent model, as is their approach to source protection planning through community and stakeholder engagement. The sector recognises that source water protection is complex with the status of waterbodies determined by the interplay between natural environmental features including bedrock, soil type, weather, etc., and by land use practices and policies. In an attempt to understand and evaluate the efficacy of source protection measures, the first GWS source protection assessment carried out was on Milltown Lake between 2006 and 2011 in Co. Monaghan known as the National Source Protection Pilot Project (NSPPP) (Linnane et al., 2011). This extensive pilot project advocated that a successful source protection approach must start with a sound scientific evaluation of a system, that determines its status (including the trophic status of surface waters) and the pressures on the lake water quality and drinking water source and their root causes. Through a combination of continuous stakeholder engagement and scientific monitoring of the catchment and its waterbodies, management recommendations and strategies were made, to address contamination of the lake that had been caused by current and historic human activity, remediating damage done, where possible, and avoiding further damage. To be truly effective and fully capable of replication, the NSPPP recommended that any similar strategies developed must also be based on scientific monitoring and evaluation as well as on a clear recognition that source protection will require a fundamental shift in attitudes and behaviour towards our water resources. Following on from the NSPPP, the GWS sector has completed source protection assessments of each of their schemes, where the 'Right measure in the right place' approach is adopted through targeted mitigation actions, coupled with meaningful and sustained stakeholder engagement throughout all stages of the plan.

An example of the 'Right measure in the right place' approach employed by the GWS sector is that of Stranooden GWS in County Monaghan, where Phase II of the Source Protection Pilot Project and maintenance of a source protection plan is underway to ensure that water abstracted from the source is of quality standards and safe for usage (Stranooden GWS, n.d.). There are twelve GWS located across County Monaghan that source, treat, and deliver potable water to approximately 60% of the county's population. Despite significant upgrades of their treatment facilities through the Rural Water Programme, the provision of end-of-pipe treatment has no benefit on the quality of the raw water sources, many of which saw deterioration in their water quality through agricultural intensification. White Lough (Figure 19.4), from which Stranooden GWS abstracts its water supply, is one of the most impacted lakes in the region, with both urban and rural pressures from agriculture, and municipal and domestic sources. A Preliminary Report on Source Protection for Stranooden GWS delineated the White Lough catchment and identified possible pressures contributing to the lake's deteriorating water quality status (Rolston, 2014). The scheme supplies approximately 1,100 domestic connections and 400 agricultural and commercial connections making it one of the largest schemes in Ireland. The lake and its tributaries also have unacceptably high levels of herbicide, in particular MCPA (pesticide) contamination. An additional challenge is that much of the catchment of White Lough is outside of the piped water supply area. The project methodology followed a structured approach including extensive raw water analysis, detailed delineation and characterisation of the catchment, identification of critical source areas and extensive stakeholder engagement with all relevant stakeholders, including the agricultural community, schools and consumers. A variety of initiatives were trialled under the expert guidance of multi-agency advisory and steering committees. Following a desktop study and detailed field investigations, and through direct engagement with landowners, farmers, schools, local organisations and businesses, several initiatives were implemented to protect and restore the water quality of the lake. Specifically, measures included the installation of 12,920km of fencing, 4,335km of mixed species hedging, approximately 2km of bank restoration measures and in excess of 5,000m^2 of willow buffer. In addition, the "Let it Bee" initiative is part of the NFGWS pilot water source protection programme run by the Corracreigh GWS to raise local awareness of environmental protection and the dangers of pesticides to honey bees, the local drinking water source, and biodiversity. Also, as part of its efforts to engage the public, including primary school students, the Stranooden GWS re-evaluated its pesticide contamination strategies through the 'Let it Bloom' campaign to end pesticide contamination and encourage pupils to plant trees at home. Other initiatives such as the 'I've planted a tree garden is pesticide-free' initiative are designed to inspire schoolchildren across the country and engage adults through their children on the dangers of pesticides on water sources and biodiversity. These initiatives have resulted in local-level engagement and awareness creation on source protection among the public. In addition, while there have been some early indications of load reductions to phosphate and MCPA loadings across the catchment (but not necessarily MCPA levels in White Lough) there is a commitment to continue to increase efforts to implement mitigation actions and behavioural changes and to assess if additional factors (e.g. climatic causes) are stronger drivers of change (NFGWS, 2021). The NFGWS guidance document entitled 'A Framework for Drinking Water Source Protection' produced as part of this project provides a methodical approach to analysing pressures on water quality within a drinking water catchment/zone of contribution (NFGWS, 2019b). This allows for an educated choice on whether 'protection' or 'improvement' is required. It also highlights the significance of prioritising contamination concerns so that a targeted approach can be taken, which is accessible to the stakeholders, learning from other published measures/actions. Finally, given that the Stranooden GWS catchment is located at the top of the larger cross-border Erne catchment, the Source Protection Pilot Project is advocating strongly for formalised inclusion of the cross-border portions of the catchment, even though they do not impact directly on the GWS's water quality. There is a genuine desire to engage collaboratively going forward, if appropriate governance structures can be agreed upon (NFGWS, *pers. comm.*)

CONCLUSION

Protecting and restoring water quality is essential to both human health and environmental protection. Despite improvements in governance in recent years, the quality of lakes in both the RoI and NI is declining. The need for adequate resourcing to meet WFD objectives has been highlighted by many stakeholders, along with the need for an inter-departmental financing strategy to better align resources for water, climate and biodiversity actions. Increased transparency in evaluation and decision-making has been recommended for the 3rd RBMP, along with improved structured engagement between the tiers of governance. Stakeholder engagement has been identified as a critical component of water resource management, to incorporate different interests and perspectives to better address the growing

Figure 19.4
White Lough,
Monaghan.

water-related pressures. The establishment of An Fóram Uisce as the statutory body to facilitate stakeholder input to national water policy in the RoI has provided a benchmark for other jurisdictions of best practices in stakeholder engagement and water governance. In addition, the GWS sector in the RoI is an excellent example of how communities can come together to manage

their local water source through cooperation, mutual trust and adaptivity. The success of the GWS sector as a vehicle to represent the agreed collective views of the local community should be recognised as a model for meaningful stakeholder engagement and governance of local water resources.

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Highlight Box

ALL ISLAND WATER GOVERNANCE

Catherine Dalton

The island of Ireland includes two international river basin districts (RBD), 11 cross-border river basins (Newry, Fane, Glyde, Dee, Neagh, Lower Bann, Erne, Foyle, Swilly, and Donagh-Moville), 120 river waterbodies, 34 transboundary aquifers, and at least 57 lakes and ponds which straddle this international border. Waters in each jurisdiction flow into and through the other jurisdiction with shared environmental challenges, risks, and opportunities for cooperation (Brennan et al., 2023) (see Chapter 19). Lake water quality is in decline across the island of Ireland with 30% of lakes in the Republic of Ireland (RoI) and no lakes in Northern Ireland (NI) achieving good status.

Brexit has meant complications to the progress made under the Water Framework Directive (WFD). Water catchments, water quality, pollution, regulation, river basin management, and flood regulations were areas of pre-existing North-South environmental cooperation but are not covered by the NI Protocol which is core to the EU-UK withdrawal agreement (Brennan et al. 2023). The Water (Amendment) (NI) (EU Exit) Regulations 2019 was published to ensure that water legislation under the WFD continues to operate post-Brexit. Formal structures, implementation bodies and areas of cooperation for all-island water are outlined in Figure 1. Similar to the RoI, the 3rd RBMP for Northern Ireland (2021-2027) underwent a public consultation, however, the plan is still not published in contrast to the rest of the United Kingdom. The 3rd RBMP for the RoI has recently been published (DHLGH, 2024).

Potential changes in environmental legislation in NI could be detrimental to lakes and their catchments. Fraser et al. (2020) note that NI has two environmental legislative options post-Brexit; 1. to uphold the WFD or, 2. to replace the WFD with new domestic environmental legislation. The latter requires an international agreement between NI and the RoI to ensure no negative transboundary impacts. Consideration of the island of Ireland as a single river basin district has also been proposed (NESC, 2021). To effectively address common challenges related to water quality, all opportunities must be seized to share information and knowledge in order to connect the natural environment of the whole island.

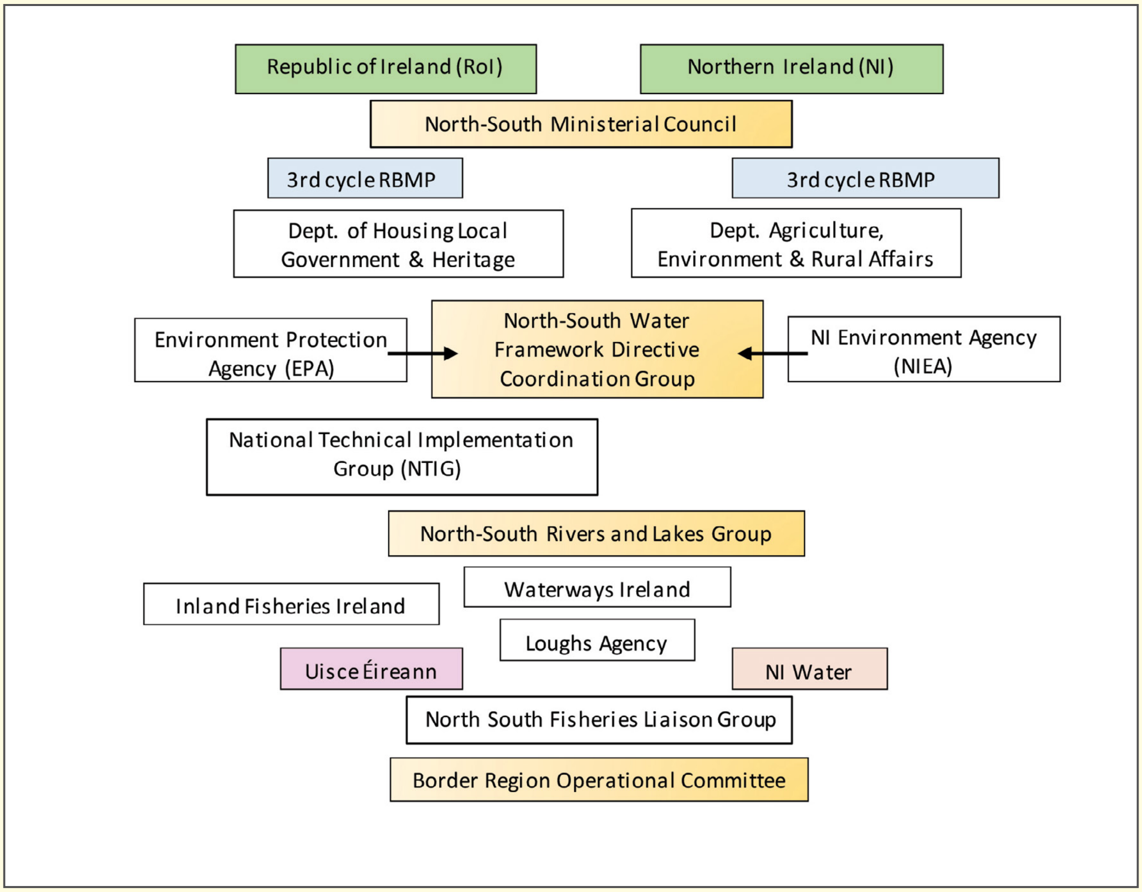

Figure 1 Formal structures, implementation bodies and areas of cooperation for all-island water

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Chapter 20

DIVE IN
ENGAGING PUBLIC PARTICIPATION IN WATER STEWARDSHIP

Fran Igoe and Bernie O'Flaherty

SUMMARY

The Local Authority Waters Programme (LAWPRO) (formerly the Local Authority Waters and Communities Office) was established in 2016 to support community participation in river basin management planning. This chapter outlines some of the workings, experience of, and learnings of LAWPRO from the 2nd cycle (2018 to 2021) of the River Basin Management Plan (RBMP). The chapter draws from current and previous community-led or participatory initiatives focusing on lakes as we enter the 3rd RBMP cycle (2022 to 2027) at draft stage, as of February 2024.

Keywords Lakes, Water Framework Directive, catchment management, river basin management plan, citizen science, community participation, collaboration.

INTRODUCTION

The EU Water Framework Directive (WFD) is implemented in Ireland by a series of River Basin Management Plans (RBMPs) in six-year cycles. In a review of the first cycle RBMP (2009 to 2015), several weaknesses were identified in governance and oversight, public participation and the need to strengthen the science. Therefore, the 2nd RBMP (2018 to 2021) provided for a new approach to catchment management (Integrated Catchment Management (ICM)), new governance arrangements (see Chapter 19) and more effective public participation (DHLGH, 2019).

RBMPs are water quality road maps, they identify the significant pressures impacting water quality and outline a programme of measures (POMs) to support the protection and restoration of water quality status. A key measure of the 2nd RBMP was the establishment of the Local Authority Waters and Communities Offices (LAWCO) in 2016 to drive public engagement, consultation and participation with communities and stakeholders, in line with the ICM approach and philosophy (EPA, 2020). LAWCO was subsequently superseded in 2018 by the Local Authority Waters Programme (LAWPRO) with additional functions in the delivery of a programme of catchment assessment in priority areas for action (PAAs) and the coordination of these activities across 31 local authorities.

Information is key to participation and a further element of the new approach saw the Environmental Protection Agency (EPA) develop and maintain a networking and information-sharing catchment website as part of a collaborative initiative with the Department of Housing, Local Government and Heritage (DHLGH) and LAWPRO. The public information portal www.catchments.ie is a valuable resource to help communities understand the science behind catchment management. This initiative is supplemented by a *Catchments Newsletter* that highlights science and stories from local communities around Ireland. The stories in the newsletter show how local community researchers, government departments, state bodies and others can all have a role to play in working together to protect Ireland's environment.

ENGAGING COMMUNITIES IN WATER MANAGEMENT

Public consultation and engagement, early experience

Strengthening a combination of bottom-up and top-down approaches to water management required new thinking. Understanding how the public interacts with water and perceives water quality was an important first step in planning for the public participation and consultation process for the 2nd cycle RBMP. In his address to the International Association of Hydrologists conference in 2013, Bob Harris discussed some of the challenges of participation suggesting that the essential starting point in public participation is the range of common issues that communities can identify with (Harris, 2013).

The theme selected for the 2016/2017 local public consultation meetings organised by LAWCO was 'What does your river mean to you?' In the interest of simplicity, the term river in the public consultation represented a river catchment and includes all water body types, including lakes.

The diversity of public opinions and values around water was clearly identified during the public consultations for Ireland's 2nd RBMP (2018-2021) and subsequently for the 3^{3d} RBMP (2022-2027) (DHLGH, 2021). During these consultations, it was evident that the public's relationship with Ireland's natural waterbodies, including lakes, is complex.

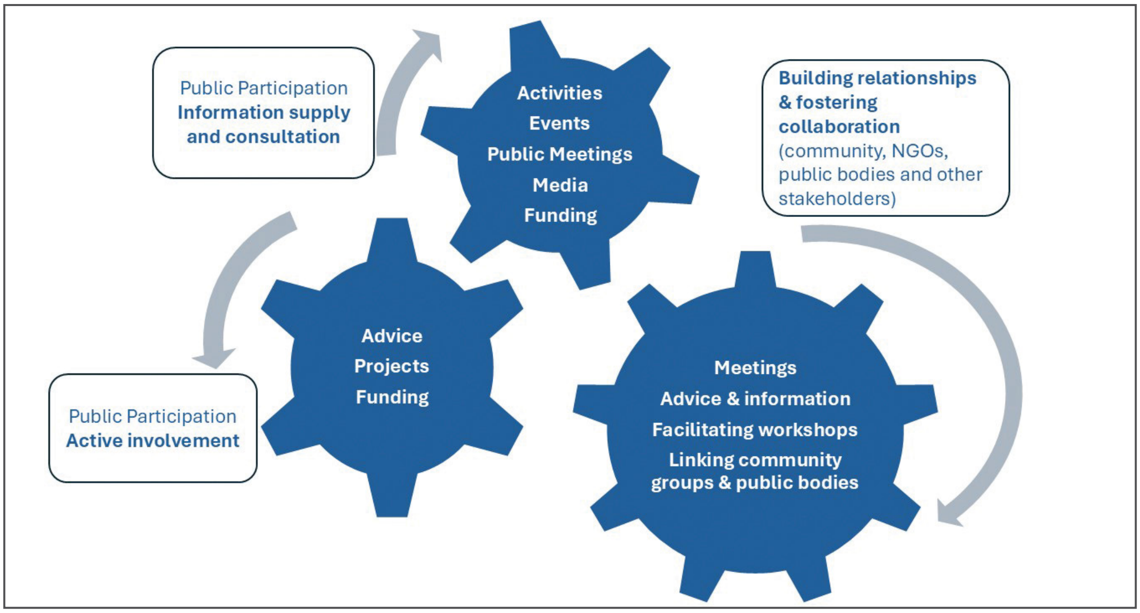
Community Themes

Themes that communities identify with can be summarised as follows: culture and heritage, local information and local benefits, amenity and recreation, health and wellbeing, pride of place, and community wellbeing.

Early community engagement and feedback informed the approach of the LAWPRO work programme. Engagement processes highlighted the importance of local communities and local champions as advocates and guardians of their local waterbodies. Going forward, the team recognised the need to work closely with the community sector, including the EU LEADER programme network. In 2018, a dedicated fund, Community Water Development Fund (CWFD), was established to provide support for water-related community-led projects and additional funding was made available for local awareness initiatives. The establishment and support of locally-led catchment partnerships (ranging from Rivers Trusts, catchment associations, or a 'just coming together' of the range of community groups living within a catchment area) was also viewed as necessary to realise greater water quality impact at the catchment scale.

It is important to note that LAWPRO works with the full range of groups across the capacity spectrum including individual waterbody champions, informal community groups, established community groups and networks (such as Angling groups, Tidy Towns, and Group Water Schemes) in addition to the formally established catchment focused River Trusts and Associations.

Figure 20.1 Community Water Officers and support staff offer a comprehensive range of supports to inform and involve communities and promote collaborative working. (Image credit: Bláithin Ní Aínin, LAWPRO).



Active involvement of communities

At the heart of LAWPRO's community engagement programme is the Community Water Officer (CWO) team hosted in several Local Authority offices throughout the country. Their key function is the promotion of community participation by providing information, organising meetings and supporting the community across a wide range of activities. The team aims to create a broader understanding of the issues impacting local water bodies and to identify groups interested in improving the condition of the water environment. CWOs give practical assistance with funding, project applications, and relationship-building with other stakeholders and public bodies.

Local knowledge supplementing the science

Community involvement is essential for Ireland to deliver on its WFD commitments. According to the EPA 2021 Water Quality Report (EPA 2022), water quality data shows that only 49.5% of our lakes are reaching their objectives of good of high status. However, maintaining even good status can be a challenge as the range of pressures is often multiple, complex and difficult to resolve. In some instances, it may not be immediately clear, what the driver of the decline is, and local knowledge can be essential to understand the actual causes.

Priority Areas for Action (PAA) are identified in the RBMP, therefore, in advance of the catchment assessment team entering a PAA, LAWPRO arranges a local community information meeting to facilitate participation, and, where possible, build in local knowledge in the generation of local catchment assessment reports. Public body representatives and other relevant stakeholders are also invited to these local-focused meetings. In addition, LAWPRO engages with the elected members through the Local Authority Council meetings and/or strategic policy committee (SPC) meetings, presenting the catchment science and the actions needed.

Community engagement tools

In line with WFD's ambition to increase public participation and active involvement around water management, LAWPRO's programme is evolving and expanding. It continues to develop its expertise, techniques and resources to help grow communities that care for water. LAWPRO collaborates with other public bodies and organisations in their outreach initiatives. The tools of engagement include:

- Community Water Development Fund (projects relevant to water quality)
- Local Awareness Initiative (low-cost initiative fund)
- Working with Water, Biodiversity and Climate: A guide for community groups (publication and available online (LAWPRO, 2020a)
- Support for The Rivers Trust (partnership agreement and funding support)
- Work with the Local Authority Community Sector and the Public Participation Networks (PPN).
- Community training through the LEADER Programme
- Riverside workshops – Citizen Science
- Water Heritage Day and collaborative actions with the Heritage Council and local Heritage Officers
- Celebrate World Days e.g. World Wetlands Day, Biodiversity Week, Science Festivals and local festivals
- Promote Tidy Towns involvement through the Waters and Communities Tidy Towns Award (an initiative between, Inland Fisheries Ireland (IFI), Waterways Ireland and LAWPRO)

CAPTURING THE IMAGINATION OF LOCAL COMMUNITIES

The role of citizenry is important in highlighting and prioritising the need to cherish, protect and restore our waterbodies. Community champions who tirelessly work to keep this focus alive are essential in an already congested advocacy space, competing for peoples' time and attention, including that of our politicians and government departments.

Active communities can undertake a range of practical interventions from litter cleanups to more complex projects such as habitat restoration. Community activities may also include:

- Engagement initiatives through the arts: Engage local communities in their local lakes through community initiatives via arts, folklore and storytelling.
- Networking and sharing of science: Develop a deeper understanding of the value of a lake through information gathering – oral history, surveys, and citizen science.
- Lobbying: Advocacy on behalf of the lake to improve water quality protection or sustainable use, e.g., wastewater treatment, abstraction, and access.
- Restoration: Hands-on water protection measures in partnership with responsible stakeholders and agencies

In terms of waterbody types, lakes offer a wide range of ecosystem services including bathing areas, water supply, fishing, water sports, wildlife habitats and general amenity areas (see Chapter 18). Such tangible community benefits are a good starting point for conversations about the value of healthy waters that, in turn, can lead to conversations around more detached or complex water quality issues such as phosphorus loss, the impacts of nutrients, and pesticides (Harris, 2013).

There are various levels of community participation from the lowest level of information supply to more sophisticated social learning processes where communities learn together to manage together (Daly et al., 2016). The initiatives and projects described below, demonstrate the valuable work undertaken by lake communities both in terms of their active involvement and influencing public bodies. The ambition of a community group can vary from getting to know a lake to creating awareness using a range of mediums, from the arts to litter cleanups. At the other end of the spectrum, community groups can have a more involved role in the active management and restoration of lakes (see Chapter 21).

Engagement initiatives through the arts

Lickeen Lough is a 2.5 km long and 0.5 km wide lake located in the Burren of County Clare (Figure 20.2). It is a key water supply to Ennistymon and a locally important fishery. Arctic char were recorded from the lake up until 1992 and their disappearance heightened local interest in the need to protect the lake. In May 2021, the Creevagh Art and Archaeology Collective developed

Figure 20.2
Lickeen Lough, Clare.
Photo: Ruairí Ó Conchúir

an online participatory rural community-based arts project fostering creative responses to Lickeen Lough. The project highlighted the cultural, ecological, and mythological significance of the lake and its catchment area. The project working with artists developed a series of performance-based workshops for local schools to mark the International Day of Biodiversity with a performance in 2023, coinciding with World Day of Audiovisual Heritage. The project highlighted the importance of the lake through folklore and the arts.

Citizen science

Citizen science actively involves citizens in science that generates new knowledge or understanding. Experience by LAWPRO in the 2nd RBMP cycle has shown that it engages people and by involving the public in the monitoring of waterbodies, it increased local knowledge and potential for data. Key benefits include recording wildlife, habitat and issues impacting them through a network of trained volunteers, engaging people with biodiversity and water facilitating a greater appreciation and understanding of protection needs. Direct funding for citizen science training and the provision of equipment is provided through the CWDF.

The WaterBlitz is a co-created research project between Dublin City University Water Institute and citizen scientists in Ireland in partnership with Earthwatch Europe. This project aims to investigate how public engagement can facilitate water restoration by measuring nitrate and phosphate levels in freshwater. These measurements provide a snapshot in time of the water quality in the waterbodies sampled. In 2022, 8.9% of samples submitted by the public were from lakes (Hegarty et al., 2023).

The National Biodiversity Data Centre facilitates the recording of the range of biodiversity found in lakes in Ireland, with data available to researchers, environmental organisations and other users (NBDC, 2022).

Lake buddies

One interesting lake-focused citizen science project developed from the public consultations on the RBMP in 2018. Anglers in the border region expressed a desire for more monitoring of their lakes (McVeigh et al., 2020). After researching the potential for LAWPRO funding for a citizen science monitoring project, the border CWO team approached the EPA, Local Authorities, Northern Ireland Environment Agency and IFI about a potential project and funding from LAWPRO was awarded. As the project ambition was to cover different lakes along the border region (Sheelin, Cavan;

Melvin, Leitrim and Fermanagh; and Eske, Donegal) a methodology for data collection was developed and ArcGIS Survey123 was used to record the lake water quality and other data (wind speed, presence of algae, dissolved oxygen (mg/l) pH, electrical conductivity, temperature, Secchi Disc depth (a proxy for water clarity), total dissolved solids (TDS) and observations at sample location.

The project has been successful in generating a greater appreciation amongst participants of the various parameters examined in the lake water quality assessment and the variability in these parameters that can occur across these large waterbodies. The data generated has been used by LAWPRO catchment science teams in the Sheelin and Melvin catchments to fill in data gaps and give a steer in data-deficient waterbodies.

Lough Derg Native Fish Biodiversity

The Lough Derg Native Fish Biodiversity project was a citizen science initiative focusing on Lough Derg and its tributaries within the River Shannon catchment. The project began in 2006, initiated by local anglers, who wanted to gain a better understanding of the native fish in the lake and determine what could be done to protect them. Key questions that the local anglers wanted to answer related to the heritage aspects of the Lough Derg fish community.

The initiative was a collaboration between the 13 angling clubs within the Lough Derg Angling Federation, the Lough Derg SubAqua Club and the Lough Derg Science Group, the Irish Char Conservation Group, the Shannon Regional Fisheries Board, the Electricity Supply Board (ESB), the University of Waterloo, Canada and Queens University Belfast. Significant funding was accessed through the EU LEADER programme, EPA research funding mechanisms with match funding provided by the Lough Derg Angling Federation, the Irish Char Conservation Group, the Heritage Council and North Tipperary County Council.

The anglers were given specific tasks carry to out, from the collection of fish tissue for genetic analysis, the taking of fish scales for ageing purposes, photographs for morphometric (shape) and meristic (character) analysis and the collection of macroinvertebrate and plankton samples to be processed for stable isotope analysis. The anglers also carried out additional fish surveys which allowed a comparison between current fish stocks with historic figures available prior to the construction of Ardnacrusha Dam at the outflow of Lough Derg (see case study Chapter 4).

Figure 20.3
Lough Derg
Subaqua Club
citizen scientist.

The Lough Derg Subaqua Club divers took benthic samples and the Lough Derg Science Group also took plankton samples and provided identification of macroinvertebrate samples (Figure 20.3).

This project is a great example of a large-scale community-led project working strategically with relevant partners involving citizen scientists at its core, to provide information support for good planning and management. The learnings from the project have not only informed the application of the RBMP 2018-2022 (e.g., selection of PAAs within the catchment (e.g. Ballyfinboy River)) but also the ongoing restoration work of the Lower Shannon Fisheries Partnership. Of course, the information is interesting in its own right and shines an extra light on what is part of the unique natural and cultural heritage of Lough Derg.

Carra LIFE

Lough Carra is a 1,600-ha limestone lake located within the Lough Mask catchment, Co Mayo (see Chapters 10 and 12). The lake is a premier wild brown trout fishery managed by IFI, and as such is an important tourist amenity. It is relatively shallow with an average depth of 1.8 m. Its ecology is unique, supporting marl lake habitat, orchid-rich grasslands, limestone pavement habitat, cladium fen, otters, and lesser horseshoe bats.

LAWPRO started working in the Lough Carra Catchment in 2016. The idea for a community association with a focus on the catchment was already being discussed within the local community. Concerns were being raised about a perceived decline in the water quality of the lake with a view to taking remediation action. The CWO, Mick Kane, met with individuals in the catchment and from there, the seeds for the formation of a formal catchment association focusing on issues impacting the lake were sown. Following this, Lough Carra was included as a PAA under the RBMP (2018-2021) and in January 2018 the Lough Carra Catchment Association (LCCA) was established with financial support from LAWPRO.

Within the RBMP (2018-2021) planning process, a PAA community stakeholder information meeting was organised. Those present included locals, representatives from Mayo County Council, the EPA, angler associations, the Lough Carra Group Water Scheme and third-level institutions. Representation from the agriculture and educational sectors was particularly strong. The PAA process facilitated the articulation of a broad range of questions from the community and these were taken forward by the LAWPRO catchment scientists in their follow-up scientific assessments.

The LCCA recognised the need to bring in large-scale funding to facilitate project actions informed by this scientific work and set about the development of an EU LIFE application focusing on the catchment. Funding through the EU LEADER programme and LAWPRO community funding, facilitated the development of a feasibility study to inform this EU LIFE application. The feasibility study concluded that the focus should be on nutrient reduction and community awareness within the Lough Carra catchment. The bid was developed through a series of meetings with key stakeholders backed by the relevant government agencies. Mayo County Council, the National Parks and Wildlife Service (NPWS) and LAWPRO) were the lead applicants, with support from other agencies and stakeholders which included A Steering Group was formed to help advise and guide on the development of a concept note for the project application submission to the EU LIFE office.

Through great patience and perseverance, the EU LIFE bid (€5m) eventually met with success. This is a credit to all involved, as EU LIFE bids are not for the faint-hearted. They are competitive processes facing strong competition across EU member states. The programme is now being implemented on the ground, with a range of measures taking place across the catchment. These include actions to reduce losses of nutrients and the protection of semi-natural habitats. The project team works with farmers and other stakeholders to achieve this goal.

A collaborative approach was undertaken towards education by working with IFI, NPWS, LAWPRO, Galway and Mayo Institute of Technology (now Atlantic Technological University) and the local school principals. All national schools have been visited by IFI in the delivery of their child-friendly 'Something Fishy' workshop (https://somethingfishy.ie/). In addition, the 'All About Water' workbook (https://nfgws.ie/all-about-water/) was also circulated. Teachers are progressing through the modules with a strong focus on catchment management. Other community outreach opportunities were undertaken during National Heritage Week together with numerous local water quality awareness events, e.g., the Ballinrobe River festival. A video detailing the history and amenity value of the lake was developed by EPA biologist Bryan Kennedy. Further details can be found at https://loughcarra.org/catchment-association/

Lough Muckno – the 'Road to Recovery'

Another example of a local community taking proactive steps based on accessing relevant scientific information is typified by Lough Muckno in Co. Monaghan. Lough Muckno and the surrounding area is of significant amenity value to the local community, described locally as the *'Killarney of the north'*. An EPA report highlighted that Lough Muckno's water quality status was at bad status (WFD status 2013-2018). A local community group, Friends of Lough Muckno, voiced their concerns and this was followed by reporting in the the local press. Local Councillors and other stakeholders also became concerned and wanted the issue addressed.

In response, a number of actions were undertaken. In 2021, Monaghan County Council developed and procured a project titled the Lough Muckno Road to Recovery Project. The council has installed data loggers on all inputting tributaries, taking monthly samples to calculate phosphorus load apportionment. Sediment cores were also taken to track past changes in the lake and identify timescales when the lake was under duress and experiencing improvements.

This community and public body involvement prompted a local councillor to comment on the obvious passion of locals for the lake, he suggested that *'This work will determine the historical status of the lake and will help identify the condition of the lake and more importantly how we can make it better'* (Northern Sound, 2023).

Submissions were made to the draft RBMP to have Lough Muckno included as a PAA under RBMP 2022 -2027. The project has developed with the involvement of IFI and Uisce Éireann.

Small actions still make a difference

Kilkeran Lake is a natural sedimentary lagoon (see Chapter 8) located approximately 6 km southeast of Rosscarbery in Co. Cork. The lagoon is impounded by well-developed sand dunes and is connected to the sea by a narrow, intermittently blocked channel. It is a Natura 2000 site with features of interest including coastal lagoons (site code 1150 under the Habitats Directive), embryonic shifting dunes (code 2110), shifting dunes along the shoreline with *Ammophila arenaria* (Marram or white dunes) (code 2120), fixed coastal dunes with herbaceous vegetation (grey dunes) (code 2130) (Anon. 2013). The lagoon is prone to algal blooms and the once thriving trout fishery has now disappeared. The invertebrate fauna of the lagoon consists of several rare and lagoon-indicator species have been recorded. North-west of Kilkeran Lake are areas of freshwater marsh, swamp and wet grassland are found, following the stream which enters the lagoon. Key stakeholders include farmers, environmentalists, anglers, rowers, surfers and the wider community.

In August 2016, LAWPRO were contacted by a representative of the local community who were interested in exploring options to improve the environmental status of the lake. During a drive around the catchment, it became apparent that Himalayan balsam *Impatiens glandulifera*, a highly

Figure 20.4
Left: Location of discovery of invasive Himalayan balsam planted within Lough Kilkeran catchment. Right: Proximity of Himalayan balsam plants to the feeder stream of Lough Kilkeran, a potential vector of their spread.

invasive plant, had been planted in planters outside the local parish church across the road from a stream channel discharging into the lagoon (Figure 20.4). Due to the proximity of the Himalayan balsam plants to the adjacent stream feeding Kilkeran Lake, these plants posed a potential high risk to the Natura 2000 site.

The community group responded quickly and took practical steps to eradicate the plant, by physically removing plants over the following month, culminating with a presentation of some of the removed plants at a community hall meeting organised to discuss planning for the RBMP.

Stories from the Waterside

Stories from the Waterside is an initiative that LAWPRO set up to engage with the public during the COVID-19 pandemic. The public was invited to submit stories featuring their local waterbody from a range of perspectives including folklore, wildlife, traditions and memories. Over 470 stories were received from across the country. The exercise was a phenomenal success and subsequent feedback indicated that it provided a great support for many of

Figure 20.5 Glendalough, Co. Wicklow.

those who put pen to paper during the first public health lockdown. These stories are published on the website www.storiesfromthewaterside.ie and the winning stories are featured in a publication, published to coincide with Heritage Week 2020 (LAWPRO, 2020b).

Roughly 20% of the stories submitted feature lakes (Figure 20.5). Subsequent follow-up reading sessions were organised with communities into 2023, coinciding with World Wetlands Day and World Water Day, with spinoffs taking place for school children. Polls were carried out to canvass participant views around water. The majority of them agreed that water quality was important to them (96%), with 50% stating that they would be interested in getting involved in local projects.

CONCLUSION

Lakes are an important part of Ireland's heritage, and it is clear from LAWPRO's engagement with the public that they are cherished from a broad range of perspectives. Public participation in water quality management is essential to achieve water quality restoration and protection. Lakes present a range of challenges and opportunities for communities to get involved. The experience to date is that local communities and the wider public are not only important stakeholders as custodians and users of lake environments but can also bring expertise, local knowledge, access to funding and be champions. If community participation is supported by the relevant state agencies and catchment science, appropriate solutions to water quality problems are more likely to follow.

A collaborative approach works best where the community works with local stakeholders, relevant government agencies, universities and any organisation that can assist in their objectives. Catchment partnerships ranging from catchment associations, Rivers Trusts or formal and informal groups living within a catchment area can offer a framework to provide the vision, buy-in and capacity for taking the necessary ICM approach.

However, often catchment or water stewardship initiatives are still too dependent on voluntary champions and wider support is needed. This is where the state can step in and provide some assistance. LAWPRO was set up with that purpose, bridging the catchment science with community support and awareness. As we move into the 3rd RBMP (2022-2027) this ambition will be expanded and it is hoped that even greater support will take place over the coming years.

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Chapter 21

LAKES AND LOCAL COMMUNITIES DEEPER LINKS

Micheál Ó Cinnéide

SUMMARY

This chapter is a case study of a community catchment group in the Galway area, which is dedicated to the protection of Lough Corrib and the sustainable development of the Corrib catchment. It describes the evolution of Corrib Beo since 2019 and its activities in the areas of communications, education, environment, culture and recreation. The challenges faced by the Corrib Beo team and similar Irish catchment groups are assessed. The future aims and aspirations of Corrib Beo are presented, in the context of the draft River Basin Management Plan (RBMP) for Ireland, 2024 to 2027.

Keywords Community, education, environment, governance, heritage, recreation.

INTRODUCTION

The EU Commission published guidance on public participation for the Water Framework Directive (WFD), which encouraged a learning approach to public participation (O Cinnéide et al., 2021).

> A willingness to improve trust, transparency, and a positive attitude to the process of implementing the Directive with stakeholders and members of the public is essential for success. Each can learn much from the others (EU Commission, 2003).

Recent supports have encouraged the establishment of community water groups with a range of water stewardship and citizen science initiatives (Kelly-Quinn et al., 2022; Weiner et al., 2022). Many of these groups work closely with the Local Authority Waters Programme (LAWPRO) community teams (see Chapter 20) and with the Rivers Trust movement in Ireland. The initial phase of catchment groups in river and lake catchments has been marked by strong local enthusiasm but hampered by limited resources. The lessons learned from the efforts of LAWPRO and these recent catchment groups can help to inform governance arrangements for future RBMPs. The level of ambition, pace, scope and scale of LAWPRO/statutory support for catchment groups in the 2024-2027 RBMP will be key influences in the future evolution of these lake and catchment projects. This chapter focusses on the experience of a community catchment group in the Galway area, Corrib Beo, which is dedicated to promoting and facilitating the restoration and enjoyment of Lough Corrib and the wider Corrib catchment through education, awareness and joint actions.

Lough Corrib, a brief profile

Sir William Wilde, in his book *Wilde's Lough Corrib: Its Shores and Islands* (Wilde, 1867) introduced the archaeology and folklore of Lough Corrib, seen as the 'jewel in the crown' of the west of Ireland at the start of the Victorian era. The book has been described as an 'educational vademecum for those who want to explore Lough Corrib and its hinterlands from the safety of the Galway-based steamer, Eglington' (Wilde, 1867).

The Corrib catchment includes Ireland's second largest inland lake, Lough Corrib and drains a total area of 3,112 km^2 (see Map, Figure 21.1). The total population of the Corrib catchment is approximately 116,866. The catchment is characterised by a wide, relatively flat limestone plain occupying the eastern two-thirds of the catchment. This area east of the lake is karstified limestone, with groundwater and surface water highly interconnected (EPA, 2021). The many uninhabited islands of Lough Corrib have long been studied for their vegetation (Roden, 1979, 1998) and Lough Corrib was designated as a RAMSAR site for its internationally important wetland habitats in 1996.

Water quality in the Corrib catchment

At a national level, it is estimated that just 50% of monitored lakes (113) are in a high or good ecological status, based on the EPA monitoring (O'Boyle et al., 2019) (see Chapter 11). The Environment Protection Agency's (EPA's) Catchment report for the Corrib catchment (Hydrometric area 30) in 2021 showed a similarly mixed picture with four waterbodies achieving high status, 89 achieving good status, 24 achieving moderate status, five achieving poor status and two bad status waterbodies (EPA, 2021).

EPA reported that the significant pressures on 'At Risk waterbodies' in the Corrib catchment were: Hydromorphology in 23 water bodies and 2 lakes (the presence of drainage schemes, leading to a significant amount of siltation, especially in the Clare sub-catchments); agriculture in 12 water bodies and one lake body (phosphorus loss, runoff, bank erosion); forestry in 4 water bodies (extensive tree felling, siltation and nutrients), invasive species; urban wastewater treatment in four water bodies, including Moycullen; peat drainage, and extraction in 2 water bodies (EPA, 2021). Roden et al. (2020), in a survey for National Parks & Wildlife (NPWS) rated the underwater vegetation of Lough Corrib as poor due to a shallow depth of vegetation colonization, dark water and other factors.

These technical reports do not fully convey the strongly held views and concerns of local environmental groups and angling clubs about the deterioration in the quality of Lough Corrib and the tributaries that flow into it. The summers of 2021 and 2022 brought green algal conditions to areas of the lake. 'The appalling state of Galway's Owenriff River catchment shows what dumping slurry has done. This river previously held vibrant stocks of salmon, trout and otter and was home to one of the world's largest surviving colonies of freshwater mussels, all protected by EU law' (O'Sullivan, 2022). The Owenriff River, which flows into Oughterard, has been designated a priority area for action by LAWPRO (see Chapter 20). As Cilian Roden, an Irish ecologist, said at a Corrib Beo event in 2023: 'Lough Corrib is a spent land, with cutover bogs, peaty fields, conifers on half drained bog and sad, abandoned houses. If it's so beautiful, why do we thrash it?'

ORIGINS

The Corrib Beo experience

The foundations for Corrib Beo were laid at an event on board the Corrib Princess cruise boat sponsored by LAWPRO in September 2018 and coordinated by Catherine Seale, Community Water Officer for Galway. Participants at the event, representing thirty community, environmental, and angling groups around the Corrib, demonstrated a keen interest in forming a network to share knowledge and ideas. Recurring themes included water quality, protecting biodiversity, ecological corridors and blueways. This event was followed up by a meeting in the Glenlo Abbey Hotel, Galway in October 2018 attended by 15 people where an ad-hoc committee was formed. Corrib Beo was launched publicly in May 2019 (Murphy, 2019) and held its first AGM in Galway in June 2019. The group had its third AGM in November 2022.

Corrib Beo has consciously taken a broad, holistic view of the challenges facing the Corrib since it was established, with a focus on community, nature, culture, and economy. Corrib Beo is registered as a Company Limited by Guarantee (CLG). It has agreed on a set of Memorandum and Articles, which enabled it to raise funds from Galway County Council, LEADER, LAWPRO, Galway Wind Fund and local sponsors. As set out in its constitution, Corrib Beo's objective is:

> To promote a partnership-based approach for the care, protection, restoration and sustainable development of the Corrib catchment and to realise the potential of the Corrib system for the benefit of its communities, environment and lakeside economy. This will be achieved by developing a shared vision for a living, vibrant Corrib, by building alliances of community, state, private and non-governmental groups and by the fostering of collective effort towards promoting the objectives (www.corribbeo.ie, 2019).

ACTIVITIES

Since 2019, Corrib Beo's activities have been aligned with the four pillars in its work plans – Culture, Environment, Recreation, and Education. Taken as a whole, Corrib Beo's advocacy, education and cultural projects have been aimed at building a sense of Corrib identity. These activities are described in more detail in the sections that follow. A summary timetable of the evolution and activities of Corrib Beo since 2018 is given in Table 21.1.

Culture and heritage

There is a growing, shared belief that the Corrib is at risk of serious environmental decline and has gradually lost its identity and its sense of place, as Ireland's second-largest lake, at the heart of Galway life. It is a part of the Corrib Beo analysis that Lough Corrib has been 'hidden in plain sight' in Galway's cultural life. This is in part captured in the curious road signs on the main N59 road, leading west from Galway city through Connemara – at Bushy Park, north of Galway city, the sign proclaims: 'Lough Corrib 26km' when in fact lower Lough Corrib is visible to the east, just a mile from the road. This 'blind spot' was also evident in the publication of a map, *Discover Galway: Things to do in Galway*, by Galway City and County Councils to mark Galway 2020 – out of the 144 'places to see' attractions and centres listed on the map, just three sites (linked to water sports) were associated with the Corrib (Galway County Council, 2020).

Based on this assessment, Corrib Beo focused initially on the cultural heritage of the Corrib as a means of building stronger public awareness of the ecological challenges. One of the first Corrib Beo events was a heritage trip to Inchagoill Island in August 2019. This was a community engagement trip to raise awareness of the rich heritage of the Corrib. Over 200 people, including artists, historians, environmentalists and musicians came to the island and learned about the Corrib.

As with community groups across Ireland, the outreach work of Corrib Beo was restricted due to COVID-19 measures in 2020 and 2021. Corrib Beo had planned a programme of events to spark a public conversation on 'Facing the Future of Lough Corrib' as part of the Galway 2020 cultural festival and National Heritage Week, but this had to be cancelled. Collaborative links included local partners such as Moycullen Heritage, Oughterard Arts Programme, Brigit's Garden and Cnoc Suain, with support from LAWPRO. The aims were to convene a series of discussions, related to the changing uses of the landscape around Lough Corrib since ancient times and the challenges of building a more sustainable future for the communities and unique ecosystems around Lough Corrib.

Corrib Beo worked with twelve community groups to organise a series of heritage events around the Corrib during August 2022, in association with LAWPRO. These events explored ways to re-kindle awareness of the lake (its archaeology, history, nature values, and recreation), promote the cultural identity of the Corrib region and foster/restore a sense of place, for the betterment of its communities. The 'Connecting Corrib Communities - Showcasing Heritage' programme included a media launch with public representatives in Claregalway Castle and 14 coordinated community heritage events during Heritage Week. One of the events, a guided heritage walk on 'Galway's History of Canal Building and Milling' won a Heritage award for Galway City.

Heritage Week 2022 culminated with a Corrib communities' gathering at Knockferry Pier and Kilbeg, which attracted over 400 participants and offered trips across the lake, talks on water quality, music and crafts. The seventy inter-pier ferry crossings evoked memories of links in earlier generations, reconnecting communities with a tradition of lakeshore visits. The events brought positive coverage in the local media, including the *Connaught Tribune*, *Galway Advertiser*, *Tuam Herald*, Galway Bay FM and

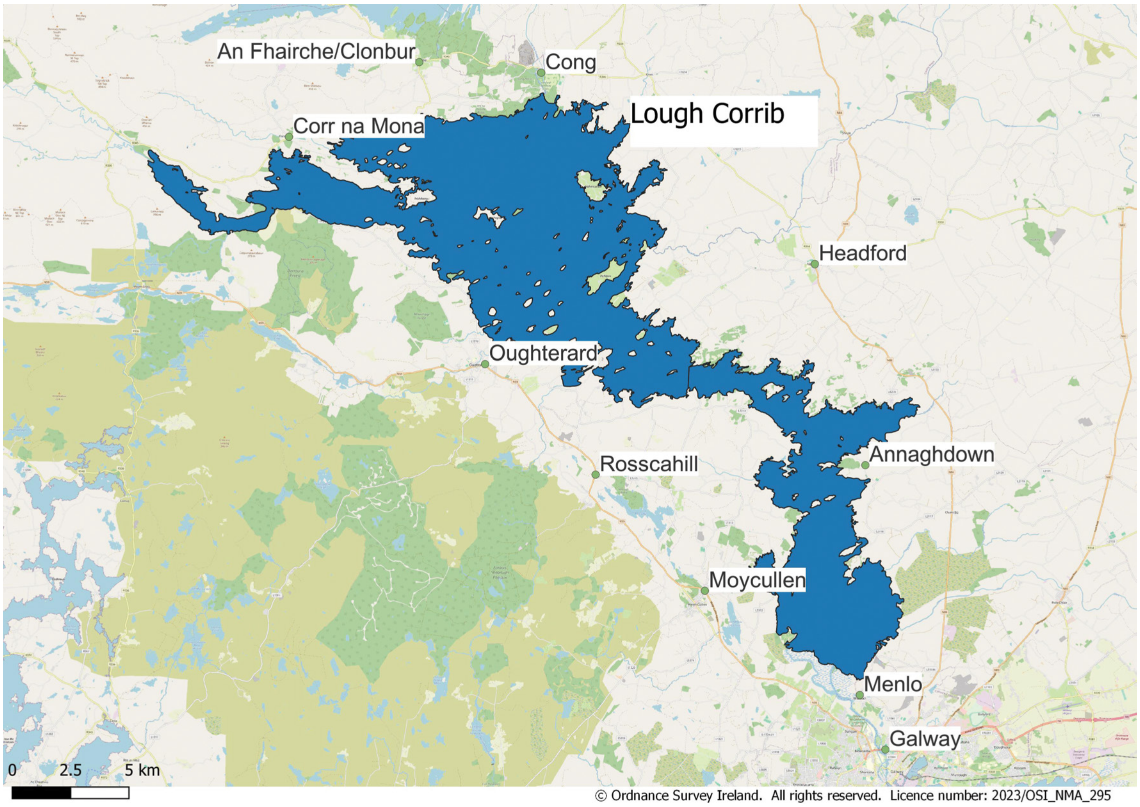

Figure 21.1
Lough Corrib and principal towns and settlements
Map courtesy of LAWPRO.

Nuacht TG4, and focused public attention on the rich heritage and ecology of Lough Corrib.

In August 2023, Corrib Beo continued this pattern of working with communities to arrange a series of cultural and environmental events, including nature walks and talks. One of the highlights of the Corrib Beo events was a lecture by Dr Cilian Roden on the late Tony Whilde, who set up the Corrib Conservation Centre in the 1980s. The talk was entitled 'Is Tony Whilde's vision for the Corrib still relevant?' Kilcummin Church in Oughterard was full and the audience greatly appreciated the session.

The Corrib Beo team, led by Hazel Morrison, worked with local communities around the Corrib to bring together an exhibition: 'Corrib Shores - These are our People' at Galway City Museum in Summer 2023, supported by Galway County Council. This exhibition was a collaboration with 11 community groups, from Máigh Cuilinn, Collinamuck, Oughterard, Corr na Móna, Cong, Headford, Donaghpatrick/Kilcoona, Menlo and Galway. Corrib Beo had worked with the museum, especially with Education Officer, Brendan Mac Gabhann, on project ideas to celebrate the Corrib. Based on the positive reaction, it was seen as the start of a series of events celebrating the cultural identity of the Corrib, including its 5,000-year history, fisheries and natural capital. The Heritage Council, in its most recent strategy, pointed out that 'heritage crosses organisational boundaries; there is a key role for communities to build capacity and share good practice' (Heritage Council, 2023). Corrib Beo is keen to expand on this work, to learn from and work with Corrib communities to promote the cultural and natural heritage of the Corrib.

Environment

Corrib Beo is mindful that the Corrib is the second largest lake system on the island of Ireland (after Lough Neagh), draining an area of 3,112 km^2. This poses a major challenge in terms of water management. In common with most Irish catchments, there is a mosaic of interlocking state agencies and groups with an interest in the Corrib, but a *lacuna* in terms of public participation.

Corrib Beo has adopted a holistic, sustainable, science-based approach to fishing and ecology in the Corrib. The group has recognised that the Corrib is unique in terms of its legacy of fishing and salmonid angling (Figure 21.2). One of Corrib Beo's aims is the restoration of the Corrib's reputation as one of the most attractive fishing destinations in Europe and there are many common concerns regarding the impact of water quality and invasive species. Members of the angling community have engaged with Corrib Beo and the chair of the Lough Corrib Angling Federation was a member of the Board. It is clear that there is a spectrum of opinions in the angling community e.g., on the regulations regarding Salmonid status for the Western lakes, and the merits of cooperation with statutory groups (Figure 21.3).

Corrib Beo worked closely with LAWPRO and local partners since 2019 to build awareness of water quality and environmental issues in the Corrib catchment. This included information on water issues as part of the Inchagoill event in 2019; submissions to Galway City and Galway County Council regarding Corrib water quality issues; submission to the Minister on the draft RBMP, 2021, a focus on water quality in videos, media interviews and in education projects (see below), joint public meetings with Galway Waterways and with the Galway Public Participation Network (PPN) on Corrib water challenges.

The Corrib Beo team worked on two EU LIFE project applications as a mechanism to build momentum for its environmental work. In 2020**,** in partnership with the Galway Waterways Foundation and the Insight Centre

Figure 21.2
Fishing boat on Lough Corrib. Photo: Adobe Stock

Figure 21.3
Anglers tea stop
on Lough Corrib
Photo: Fiona Kelly

for Data Analytics at NUIG, it applied to the Environmental Governance and Information section of the EU LIFE fund. A key aim of the project was to create a Corrib Data Portal as a resource for communities around the Corrib, as well as raising awareness of the state of its water quality, biodiversity, species health, and invasive organisms. By making data more visible and easily accessible, the aim was to mobilise community groups and agencies in actions to restore the Corrib's environmental health. While the 2020 application was scored highly, it did not pass the threshold for EU LIFE funding.

The focus and evolution of catchment groups are strongly influenced by the membership, skills base and assets of the group. If riparian land owners or angling groups are core members, there is a greater potential for physical instream work, which requires access to land, equipment and insurance. The scale of the Corrib catchment has proven a challenge in bringing the widely dispersed stakeholders together to forge a broader Corrib alliance. Members from Corrib Beo took part in the 'Who's Who in the Corrib' event in Autumn 2023 in Claregalway. The Corrib workshop included over 40 representatives from the angling groups, Corrib Beo, Galway City and County Councils, EPA, Inland Fisheries Ireland (IFI), NPWS, the Agri-climate Rural Environmental Scheme (ACRES) team and universities. The workshop discussed the challenges facing Lough Corrib - a loss of water quality, invasive species, climate change, lack of public awareness of the lake and a mosaic of state bodies. Based on the feedback, there was a strong sense that there was a need to mobilise resources towards a common vision for the Corrib. Corrib Beo supports the need for a Corrib Forum, as part of the future evolution of RBMP, to bring together the state agencies and voluntary groups that are working to protect the Corrib. The turnout at the Corrib information day showed a strong level of public interest and a mandate for LAWPRO and groups like Corrib Beo to continue their work with Corrib communities. Corrib Beo is committed to working with LAWPRO and others on this joint Corrib action and is optimistic that the next River Basin Plan will provide a context for such initiatives.

Table 21.1 A selection of Corrib Beo public events (Ev), meetings (M), consultation (C), Exhibition (Exh), Submissions (Sub), Talk (T), between 2018 and 2024.

Date	Event/Meeting	
2018	Foundation Event on board Corrib Princess	Ev
	Ad hoc committee formed	M
2019	Corrib Beo Launch	M
	1st Annual General Meeting (AGM)	M
	Heritage Trip to Inchigoill	Ev
	Registered as a Co Limited by Guarantee	M
2020	Facing the future of Lough Corrib – discussion series	Ev
	Consultation on merits of a Corrib Trails Network	C
2021	Funding application – Corrib Data Portal (EU LIFE)	A
	Submission to the Minister on the draft River Basin Management Plan 2021	C
2022	Connecting Corrib Communities – showcasing heritage events	Exh
	3rd Annual General Meeting (AGM)	M
	Hands around the Corrib at Knockferry – talks, music, boat trips	Ev
	Joint public meeting with Galway Waterways on Corrib water challenges	M
	Submission to Galway City & Galway County Council regarding Corrib water quality issues	Sub
	EcoAvocates and EU+ Erasmus programs launched	Ev
2023	Public Talk – Is Tony Whilde's vision for the Corrib still relevant?	T
	Book Launch - Our Corrib Walks Guidebook	Ev
	Exhibition - Corrib Shores – these are our people	Ev
	Lakeboat restoration project	Exh
	EcoEd talks at Galway Science Festival and Galway Youth Assembly	Ev
	Who's who in the Corrib, Claregalway	Ev
2024	Review of Corrib Beo strategy	M

Recreation

Since its inception, Corrib Beo has set out an objective of promoting greater access to the Corrib's blue and green spaces. During 2020, Corrib Beo consulted with community groups and agencies (Galway City and County Councils, Fáilte Ireland, Forum Connemara) on the merits of a Corrib Trails Network. With the support of Forum Connemara, it commissioned a feasibility study on the Corrib Trails Network, which was completed by the consultancy firm Meehan Tully, Sligo in late-2021. The process included workshops with community groups and agencies to gather data and weave together a network of content-rich walking/cycling Corrib trails and blueways. It was seen that such a Corrib Trail Network had the potential to promote well-being cultural identity and awareness of the Corrib's unique natural capital (Meehan Tully, 2021).

Corrib Beo worked with community groups and State agencies (Coillte, Fáilte Ireland) to promote a series of guided heritage walks in Cloch Breac, Collinamuck, Headford, Cong, Tirellan, and Annaghdown. Corrib Beo sponsored a publication, *Guidebook - Our Corrib Walks* (McGinley and Healy 2023), describing twelve walking trails around the Corrib, which build awareness and appreciation of the Corrib environment. This book was promoted at media events and on RTE radio. Corrib Beo has promoted the creation of the Corrib Beo Cycling Club, which arranged a series of eco-leisure cycles on minor roads along the Corrib.

Environmental education

At the meeting of Corrib stakeholders in Autumn 2023, education and engagement were cited as key opportunities for addressing the challenges of Lough Corrib (Murphy, 2023). A core part of the Corrib Beo initiative has been education, carried out via its partnership with the EcoEd4All team, which has many overlapping members with the Corrib Beo board. EcoEd4All has delivered on the educational pillar for Corrib Beo. The EcoEd4all initiative for environmental education was targeted in its initial phase at transition year students in Irish secondary schools. It set out to make environmental education a cornerstone of the formal second-level curriculum. The EcoEd4All team developed modules and delivered training and webinars with teachers at 16 education centres throughout Ireland. EcoEd4All built up a strategic relationship with Alison, a leading platform for free online education, founded by Mike Feerick in Galway in 2007. EcoEd4All also built a collaboration with Cooperation Ireland (CI) and partnered with CI to support the All-Island Schools for Climate Action. Much of the funding for EcoEd4all has been provided by SSE Renewables, with some revenue from content royalties on the Alison platform. EcoEd4All has published three annual reports and four newsletters (Ecoed4all, 2021, 2022, 2023).

A member of the EcoEd4All team, Jennifer Cunningham, developed the Eco Advocate programme in Galway, adopting EcoEd4All content for outdoor classroom delivery and the Water Sport4Green EU project, which links with partners in five different locations across the EU, Italy, and Portugal. To date, over a thousand students (Transition year) have been through the Eco Advocate program in the Corrib catchment. Once the Irish students have completed an Eco Advocate course, they can apply to continue with the EU Erasmus+ funded project, focussed on testing water quality in the Corrib catchment.

Outreach and relationship building

Since day one, Corrib Beo has worked to build links and partnerships as a means of promoting awareness and collective action for the Corrib. This is a core activity for all the Irish catchment groups. In addition to the 'core' linkages with the LAWPRO team, based in Galway, some of Corrib Beo's key links and partnerships to date are outlined below.

- Galway Waterways Foundation. The Galway Waterways Foundation was founded in 2018 with a focus on the protection and restoration of the waterways' legacy in Galway City. It became an affiliate member of the Rivers Trust network. Corrib Beo joined with Galway Waterways Foundation in a number of actions including meetings with the City Council and public engagement on the recreational needs of Galway waterways users. The two groups merged in 2022 and will continue to play an active part in the evolution of the Irish Rivers Trust movement, which brings together a wide range of catchment groups (see below).
- National Park City Galway was launched in 2020 as a pioneering initiative to promote quality green and blue spaces in Galway city. It brought together over 100 'champions' from various strands of Galway life and Corrib Beo members were listed as supporting champions. President Michael D. Higgins became its founding patron. It set out to promote the UN Sustainable Development Goals 2030 in the city and its subgroups included teams on education, research, green infrastructure, volunteerism and a Green Directory for Galway. While it attracted strong support from environmental groups, schools and corporations,

its efforts to have a 'National Park City' designation for Galway were rejected by the City Council (Smith, 2022; Corrigan, 2022). Corrib Beo continues to support the grassroots activity of the National Park City project, including tree planting, signage, nature walks and advocacy.

- Carra Mask Corrib Water Protection Group Ltd. - this group, based in Headford, County Galway with roots in the angling sector was established in 2000 to raise awareness of the problems of declining water quality in the Western lakes (Figure 21.4). It initiated a prosecution of the Irish government in the European Court of Justice for pollution of lakes and has carried out monitoring work over many years on the Corrib and in the Owenriff River. Since 2022, Corrib Beo members have taken part in joint educational projects with the Group, involving hands-on training for school groups in the catchment.
- East Corrib Alliance (ECA) was formed in 2021 by four angling clubs associated with Lough Corrib and streams on the eastern side of the Corrib. Its stated purpose is 'the restoration and maintenance of spawning habitat, conservation and protection of wild brown trout and salmon in the Corrib System'. The ECA members have worked with farmer-landowners, IFI and the Office of Public Works to carry out instream projects in a number of tributaries east of the Corrib. Corrib Beo has built relationships with members of the ECA and has taken part in joint events, including Heritage Week and LAWPRO meetings.
- Lough Carra Catchment Association (LCCA) – Corrib Beo members have attended meetings of the LCCA in County Mayo. The LCCA has been active as an environmental non-government organisation in highlighting the decline of water quality in the Carra catchment (Huxley, 2015) (see Chapter 20). For several years, the association campaigned to organise an EU Life project designed to improve water quality and nature conservation around Lough Carra. With the support of the EU Commission, Mayo County Council, NPWS, Coillte and other agencies, the Carra LIFE project was successfully established in 2021. www.loughcarralife.ie.
- The Lough Corrib Navigation Trustees (LCNT) were established by the Navigation Act of 1859, made by the Commissioners of Public Works in Ireland. The archives of the Lough Corrib Navigation Trustees are held by Galway City Council, dating from 1857 to date. The Trustees are responsible for the maintenance of navigation aids, a number of piers on the Corrib system and the canal in Galway City. Corrib Beo has built a relationship with LCNT in order to host heritage and recreational events at LCNT piers in Knockferry and Kilbeg, Galway.

Figure 21.4
Lough Mask,
Corrib catchment
Photo: David Taylor

- Inland Fisheries Ireland (IFI) is a key player in Lough Corrib, due to its role in the protection of fish stocks and promotion of angling. In recent years, it has invested over €300,000 per year in an invasive species programme on Lough Corrib, aimed at combatting the spread of *Lagarosiphon major*, the curly-leaved waterweed (O'Donnell, 2023) (see Chapter 13). There has been ongoing engagement with IFI on the potential development of a 'Corrib Centre' beside the river Corrib.
- Coillte owns and operates forests and recreational areas around the shores of Lough Corrib, which provide parking for public access. Corrib Beo has built a relationship with Coillte in order to host heritage events such as visits to Inchagoill Island and Clonbur forest trails.

Other Corrib Beo relationships have included meetings and joint initiatives with Galway City Museum (see Cuture above), Galway Civic Forum, the Headford Lace Trail, Claregalway Castle (which has hosted several Corrib Beo events), Galway City Council, the Western Lakes GeoPark, the Galway Education Board, and schoolteachers across the catchment. The forging of such relationships is a long, slow process, but is an essential aspect of the work of catchment groups. 'Successful ORB [outreach and relationship building] interventions are usually resource-intensive and are more likely to be successful when there is a strong community spirit' (Osawe et al., 2023).

Corrib Beo has played an active part in the evolution of catchment networks in Ireland and has been an active member of the iCatch network since 2021. This network (now hosted by Rivers Trust Ireland) includes most of the pioneering catchment groups such as Inishowen Rivers Trust, Maigue Rivers Trust, East Wicklow Trust, Nore Vision, Boyne Valley Trust and the Lough Carra Catchment Association. As part of the iCatch network, Corrib Beo members took part in a series of training courses and drafted joint submissions on the draft 2023-2027 RBMP.

ASSESSMENT and SYNTHESIS

Based on the Corrib Beo experience to date, some of the key successes and challenges are detailed below.

Successes

- **Personal commitment**: Voluntary groups rely on the personal commitment, time and energies of individual members. As *Habermas* put it, the dominant stance of most citizens in our modern society is one of 'civic privatism' (Habermas, 1987). Voluntary groups are a vital resource in Irish communities, from Tidy Towns to GAA clubs and Men's Sheds, and, in the context of Corrib Beo, there has been a consistent level of support for its work from the founding members and heritage groups in lakeside communities.
- **Relationships**: From inception, the support and seed funding from the LAWPRO team have been vital to Corrib Beo's work. Since 2019, Corrib Beo has sought to build a network of informal and collaborative links with a wide spectrum of public agencies, schools, communities and private sectors in the catchment (as described above) and these partnerships have been integral in the development of the work programme.
- **Environment and Education Partners**: In the area of education, the Corrib Beo and Ecoed4all teams have leveraged the support of Education Centres, University of Galway staff and schoolteachers across the catchment, in other regional centres and in Northern Ireland.
- **Adaptability**: The ability to deal with adversity and to adapt to circumstances has been a recurring feature of Corrib Beo's journey to date. While the Corrib Beo and EcoEd4all teams have submitted a total of seven applications for significant funding that would have enabled the projects to engage staff (eg two to EU LIFE, one ERASMUS+, applications to SEAI and Pobal for Climate Education, the Heritage Council capacity Fund, Galway Wind Park Fund (large scale Projects) without success, the team has continued to forge ahead with its work.

Challenges

- **Scale:** The vast size of Lough Corrib and its hinterland is a formidable challenge for a start-up environmental group such as Corrib Beo. This issue was highlighted at the 'Who's Who on the Corrib?' stakeholder event – 'the Lough is large and this presents challenges for managing effectively as well as communicating across a wide area with a large number of groups' (Murphy, 2023).
- **Contested waters:** Corrib Beo has, since its inception, been mindful that there are long-standing relationships and sensitivities about Lough Corrib, which influence the attitudes and behaviours of groups such as trout and coarse anglers, boat owners, riparian owners and statutory bodies (Buckley, 1992). There is currently no mechanism or Forum for these 'competing rights' to be addressed. As noted also in the marine context, 'local relationships with the natural environment express distinctive cultural values. The importance of taking into account the wider socio-ecological context in order to understand local environmental relations is now widely accepted' (Brennan, 2017).
- **Complex governance:** The experience of Corrib Beo since 2019 has shown the complexity of environmental management in a large Irish lake catchment. There is no single authority which has the responsibility for governance, management protection or restoration of the lake. These roles in the Corrib are divided between at least 10 statutory bodies, including three local authorities (Galway County, Galway City and Mayo); the EPA (water quality assessment); IFI (fisheries protection, water quality); NPWS (nature protection in the Corrib, which is designated as a Special Area of Conservation SAC, and Special Protected Area, SPA); the Office of Public Works (arterial drainage); Lough Corrib Navigation Trust (piers and navigation); Coillte (management of forest holdings); TEAGASC (farm advice) and LAWPRO (catchment science and community engagement). This is a challenging mosaic for the public to navigate (Murphy, 2013).
- **Capacity and resources:** Corrib Beo has, like most catchment groups and regional environmental NGOs, survived on a shoestring. While LAWPRO has provided some project funding, the level of resources has not been sufficient to recruit even a part-time staff member to work with Corrib Beo Directors. The lack of financial support from LAWPRO or other state bodies is seen as an impediment to the continued activity of many catchment groups. The review of structures and policy frameworks for catchment groups in the 2022-2027 RBMP should be accompanied by a commitment to provide a blend of core funding and project support, to ensure a transition to a more sustainable and participative WFD landscape. It is the view of Corrib Beo that the LAWPRO CWDF should be scaled up, to provide for core funding (administration)

and bring an element of continuity for community water groups, based on an annual work programme. As set out by OECD in a seminal Review of Water Governance: 'The development of skills, technical expertise and knowledge are preconditions for effective governance of water policy. Capacity building at all levels is crucial for effective water policies in response to the challenges of the 21st century' (OECD, 2012).

Prospects for Community groups in the next River Basin Cycle, 2024 /2027

The initial phase of catchment groups in river and lake catchments, as set out in the Corrib Beo case study, has been marked by strong local enthusiasm but limited resources. In parallel, water quality trends in Irish rivers and lakes have not shown the recovery that was set out in WFD targets.

LAWPRO published a discussion document on Catchment Community Forums in the context of the new RBMP for Ireland (LAWPRO, 2023). While the discussion document is welcome and the *bona fides* of LAWPRO are evident, there is uncertainty about the roles that are envisaged for the new Catchment Community Fora. There is a risk of a continuing gap between 'grassroots' voluntary groups and the technical work of the statutory bodies. If the rollout of Catchment Plans after the pilot phase in 2024/25 remains circumscribed, it may fall short of the potential impacts set out for catchment planning in Irish and EU policy statements.

Public participation in environmental decision-making is essential if the necessary hard decisions for the future of humanity is to have a sustainable future are to be supported by the wider community (Ewing et al., 2011).

In a wider context, other lake systems can provide a rich source of future learning for the Corrib in terms of governance and restoration challenges. These include Lough Neagh, Ireland's largest lake, where there is a 'widespread public dissatisfaction with the current governance, management and sustainability arrangements' (Burke et al., 2022), and Lake Vesijarvi in Finland (Keto et al., 2012) where the Lake Vesijarvi Foundation had led a major restoration effort since 2007.

Future Evolution

Corrib Beo would like to continue to play an active role in the implementation of the new RBMP, (DHLGH, 2024), which will provide for 46 catchment plans. Following the publication of the RBMP, Corrib Beo will seek to work with relevant groups (LAWPRO, Galway City and County Council, EPA and others) to strengthen the role of public participation in the Corrib environment.

Corrib Beo's vision for the future includes five mutually supporting goals:

1. Corrib Beo will co-design and participate in the establishment and growth of the Corrib Forum, as an integral part of the new RBMP, 2024-2027.
2. Corrib Beo will consult with communities and educational bodies (University of Galway, ATU, the Galway Roscommon Education Board) and seek Irish/EU funding for the design and establishment of a Corrib Studies and Research Centre, on the shores of Lough Corrib, focused on the largest karstic freshwater ecosystem in western Europe, 'A Corrib field station that would research the lake's problems, allow the whole community access its wonders and be a focal point for the debate that must precede answering the unavoidable question: where do we fit in?' (Roden, 2023).
3. Promote the development of a sustainable cross-Corrib ferry for people and bicycles to link communities across the Corrib, using existing piers at Knockferry and Kilbeg, to open up sustainable travel and recreational links around the Corrib. Ideally, this electric ferry would be franchised by Lough Corrib Navigation Trust (who oversee the Corrib piers on both sides) and would restore the former transport links between the east and west shores of the Lake.
4. Have Lough Corrib recognised and promoted as a premier blue destination for 'slow tourism', including water sports and recreation (walking, cycling, swimming, rowing, kayaking, bird watching, angling and sustainable pleasure boating), drawing on the expertise of Waterways Ireland and Fáilte Ireland. As the unique selling point of the Corrib is its wilderness and biodiverse landscape, any tourism developments for greenways/blueways should be ecologically sensitive and in keeping with the natural Corrib environs.
5. The evolution of an All-Ireland Lakes Restoration Network, including links developed with community groups in Lough Carra (LCCA), Lough Mask, Lough Furnace (Marine Institute), the Erne Trust and the Lough Neagh Partnership, to foster mutual learning and collaboration.

Corrib Beo's founders and directors look forward to working with the range of Corrib communities, state and local agencies, educational groups and partners to achieve this vision of a restored Corrib ecosystem – as Sir William Wilde saw it, the 'jewel on the crown' of the west of Ireland.

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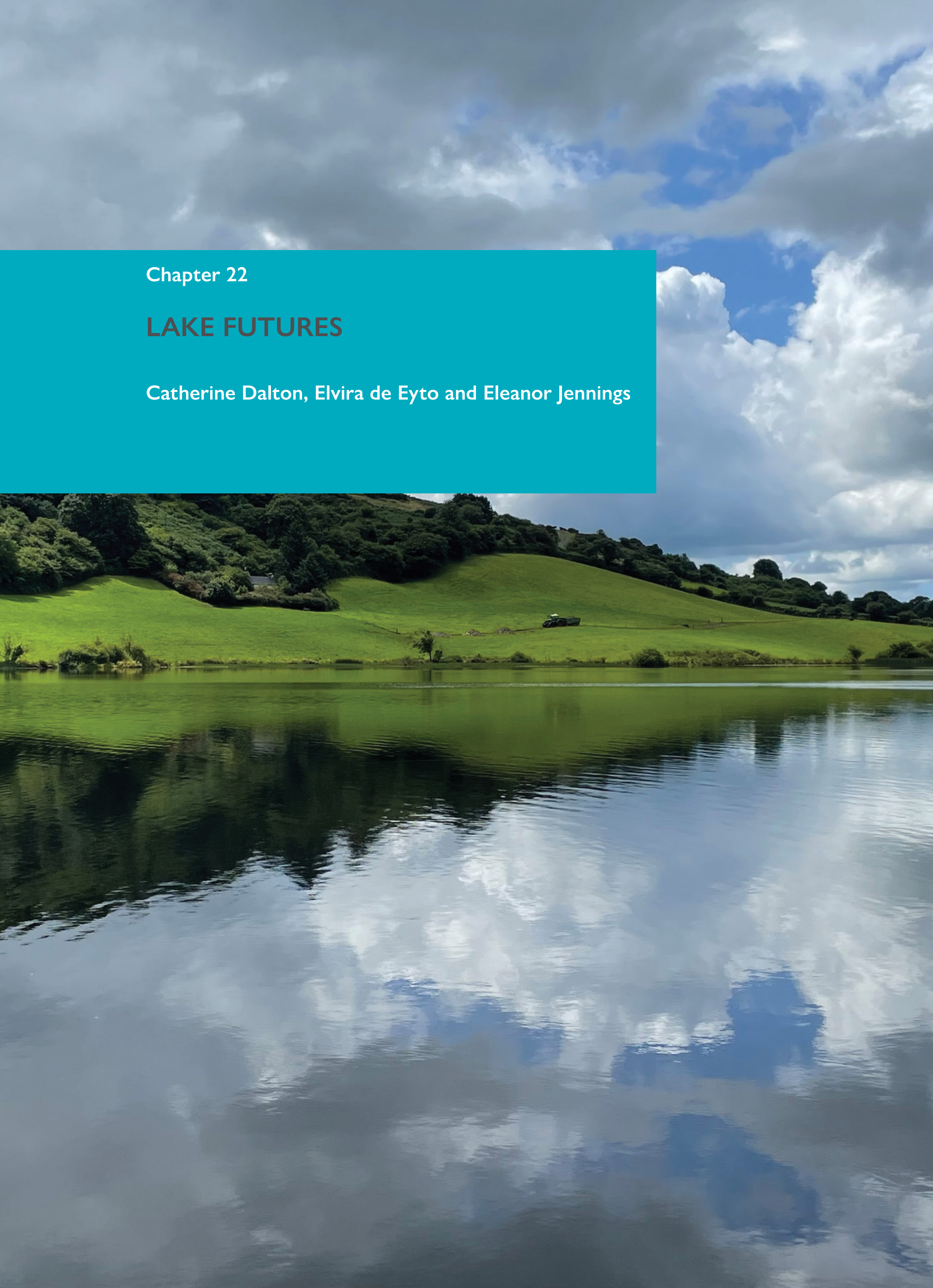
Chapter 22

LAKE FUTURES

Catherine Dalton, Elvira de Eyto and Eleanor Jennings



SUMMARY

This final chapter summarises some of the significant learnings and issues identified by our chapter authors and highlights research gaps about lakes in Ireland. It also includes a collation of key questions and recommendations identified in earlier chapters. These contributions can guide policymakers and those tasked with managing the risks of uncertain lake futures in a time of extreme change.

Keywords Lake research gaps, key questions, recommendations

INTRODUCTION

The island of Ireland is fortunate to have an abundance of lakes. In this volume, we have chronicled their genesis and diversity, explored pressures and threats to their health, and reviewed our interconnections with them. As outlined in Chapter 2 on lake origins (Delaney, 2024) and Chapter 3 on lake archives (Dalton et al., 2024a), this abundance is due to Ireland's past and current climate and to our location on the edge of the Atlantic Ocean. The movement and melting of glaciers across the landscape, together with associated erosion and deposition, first gouged out the depressions that were to become our lakes. The island's temperate climate now ensures that these are constantly replenished with water brought in by Atlantic weather systems. Our lakes are unique ecosystems, home to a wide range of species (Chapter 5; Gray et al., 2024), including culturally and economically important fish species (Chapter 6; Kelly et al., 2024). They have also attracted human settlement for millennia (Chapters 15 and 16; Potterton, 2024a; 2024b) and have been a focus of cultural interactions (Chapter 17; Dalton and O'Brien, 2024). Lakes continue to be a focal point for amenity and recreation (Chapter 18; Dalton et al., 2024b) and community activism (Chapter 21; Ó Cinnéide, 2024) today.

Unlike some of our European neighbours, where extreme drought has reduced many lakes and reservoirs to critically low levels, a lack of water is still relatively rare here. In fact, if anything Irish lakes are more likely to be overflowing (Chapter 4; Irvine and Katsanou, 2024). But this abundance does not mean that all is well. The tragic images of algal blooms on Lough Neagh in 2023 and the desperate calls for action were stark (Chapter 1; Dalton et al., 2024c and Chapter 12; de Eyto et al., 2024). They shone an all too brief media spotlight on pressures that also affect many of our less iconic lakes. Over-enrichment with nutrients, the main driver behind the deterioration in Neagh, was identified as the greatest challenge facing Irish lakes in our review of lakes ecosystem health (Chapter 11; Tierney, 2024). More notably, eutrophication was highlighted in all chapters on rarer and protected lake types: turloughs (Chapter 7; Naughton et al., 2024), coastal lagoons (Chapter 8; Oliver et al., 2024), upland lakes (Chapter 9; Kelly-Quinn, 2024) and lakes classed as European Union (EU) Annex 1 habitats (Chapter 10; Roden and O'Connor, 2024).

Such problems are not, however, new. Their development on the island of Ireland has been traced back over decades using valuable long-term datasets (Chapter 12; de Eyto et al., 2024). But even more concerning is that pressure from eutrophication is not occurring in isolation. The same long-term datasets now show that Irish lakes are warming, an effect of human-induced climate change. Without mitigation, the implications of global warming for lake ecosystems will become even more extreme in the coming decades (Chapter 14; Jennings et al., 2024). At the same time, our authors identified a raft of other challenges, all driven by human behaviour: introduction of invasive species (Chapter 13; Lucy et al., 2024), changes in hydromorphology (Chapter 4; Irvine and Katsanou, 2024), excess abstraction, channelisation and land drainage (Chapter 10; Roden and O'Connor, 2024), and increases in fine sediment and water colour levels (Chapter 9; Kelly-Quinn, 2024). These pressures are fundamentally altering the way in which lake ecosystems function and, therefore, are problematic for the species that inhabit them. And, while we humans benefit culturally from the natural value of lakes (Chapter 17; Dalton & O'Brien, 2024), lakes in turn are also experiencing pressures from our recreational use (Chapter 18; Dalton et al., 2024b; Chapter 21; Ó Cinnéide, 2024).

Maintaining or returning lakes to good ecological status not only preserves their unique biodiversity, described in Chapter 5 (Gray et al., 2024) but also enhances our lives. However, as noted in Chapter 11, achieving this status for lakes in the Republic of Ireland (RoI) before the next Water Framework Directive (WFD) deadline is unlikely (Tierney, 2024). All of our authors have called for a multisectoral and multi-agency approach to lake management. Chapter 4 suggested that the very existence of multiple agencies, legal ambiguities and contradictory remits contributes to non-compliance with environmental objectives (Irvine and Katsanou, 2024). This situation may be compounded by future regulatory divergence on our shared island, now that Northern Ireland is no longer part of the EU (Chapter 19; McGrath et al., 2024). What is not in doubt is that financial and human resources are crucial to support effective management and that decisions that affect lake futures cannot continue to be taken in separate sectoral silos (Chapters 4, 19, 20 and 21). Chapter 19 stressed the need for an inter-departmental financing strategy to better align resources for water, climate and biodiversity actions (McGrath et al., 2024). While initiatives that include communities as well as managers and state agencies are now being promoted (Chapter 20; Igoe and O'Flaherty, 2024 and Chapter 21; Ó Cinnéide, 2024), such community-based protection can only be effective with financial support.

All agreed that action is needed, action that must be bottom-up as well as top-down. Fostering environmental stewardship, and even more importantly, environmental advocacy is the only way to ensure that lakes matter. Below we have collated the main knowledge gaps identified by our co-authors in highlight boxes. Addressing these through new research, policy change and coordinated action will contribute to protecting lakes in Ireland in the coming decades.

LAKES - MIRRORS TO THE PAST

The study of lake sediment deposits has significantly advanced our understanding of the story of lakes and their catchments, including the last glacial period (c. ~70,000-16,000 years ago), Late Glacial (c. ~16,000-11,700 years ago), Holocene (c. 11,700+ years), Industrial (c. AD1750+), and Anthropocene (c. AD1950+) histories. While sedimentary records extending into the Late Glacial and Holocene periods have been examined at multiple sites, the underlying sterile glacial sediments are rarely studied (Delaney, 2024). Studies using bioindicators (e.g. pollen and diatoms) and the geochemistry of organic sediments have predominantly targeted low-altitude and oligotrophic lakes, with investigations of natural and culturally eutrophic lake systems notably underrepresented (Dalton et al., 2024d). A persistent challenge for palaeoecologists involves pinpointing exactly when specific natural events, such as climate fluctuations, and anthropogenic activities, including deforestation and agriculture, began influencing ecosystems and sediment burial on local and regional scales. There is a need also for a more in-depth exploration of the carbon sinks contained in lake sediments, given increasing human pressures on freshwater systems including global warming. Such stores also are of direct relevance for understanding changes in the global carbon cycle.

Historical Context

1. A synthesis of work is needed on the extent of glacial sediments in lake basins.
2. More sediment investigations and reconstructions are required in natural and culturally eutrophic lakes.
3. Sediment core information needs to be collated and stored in publicly accessible databases to enable additional synthesis and added value.
4. Future directions in lake sediment research should address total sediment volumes and carbon accumulation.
5. Further elucidation of regional and national patterns in aquatic system sediment responses is necessary with climate warming and increasing human pressures.

LAKES - REFLECTIONS OF THE PRESENT AND WINDOWS TO THE FUTURE

Lakes play a crucial role in regulating water and nutrient cycles, helping to maintain water quality and supply for human use, agriculture, and other downstream ecosystems.

Hydrology

Lake hydrology or the quantity and dynamics of flow, connection to groundwater, and basin morphology are fundamental components of lakes (Irvine and Katsanou, 2024). Alterations to hydromorphology are often overlooked but are increasingly recognised as a pressure impacting the ecology of lakes. Hydromorphological alterations (river barriers, water abstraction, drainage, land use), especially when coupled with increased nutrient loads, can lead to a disturbance that promotes the expansion of alien invasive species. Moreover, water abstraction from lakes requires regulation and effective management to ensure not only the sustainability of supply but also the protection of ecosystems.

Hydromorphology

6. All lake hydromorphological data (bathymetries, hypsographic curves, groundwater inputs, abstractions) needs collation and public access.
7. There is need for improvement and adoption of a common monitoring methodology for hydromorphological elements and a revaluation of typology (lake type) delineations.
8. Knowledge of the ecological mechanisms that link hydromorphology to biological quality elements, along with the development of new indicators sensitive to hydromorphological alterations is needed.
9. In-depth studies on single lakes are essential alongside WFD assessments.
10. Targets for good ecological potential need clear, evidence-informed definitions and should be waterbody specific.
11. Water abstraction from lakes requires more effective regulation and management.
12. The potential for removal of barriers on rivers and adjacent to lakes needs assessment.
13. More work and investment are needed to build an operational system for all-island lake assessment using remote sensing.

Biodiversity

Ecosystems have numerous natural mechanisms to maintain life, a phenomenon vividly demonstrated in lakes where biota range from microscopic bacteria and phytoplankton to larger organisms like plants, fish, and birds (Gray et al., 2024) (Figure 22.1). However, disruptions to physical processes (sedimentation and stratification) and biological processes (nutrient and decomposition cycles) are jeopardising species' survival in lakes. The global biodiversity crisis is particularly acute in freshwater environments, where species are declining at an alarming rate compared to marine and terrestrial ecosystems. In Ireland, the decline is exacerbated by factors such as urbanisation, eutrophication, overgrazing, peat cutting, afforestation, and the overarching influence of climate change. Habitat loss, disease, and alterations to catchments further jeopardise species' survival. Unfortunately, the significance of biodiversity conservation in small lakes often goes unassessed and unrecognised in legislative and management frameworks (Dalton et al., 2024c).

Figure 22.1
Mare's tail (*Hippuris sp.*) Lough Inchiquin, Clare. Photo: Ruth Little

Lakes in Ireland have low fish biodiversity relative to the rest of Europe. The regions in the northwest, west, and south of Ireland exhibit the most intact native fish populations (Kelly et al., 2024). Introduced fish, including roach and perch, are now the dominant species in many lakes and ongoing dispersal or relocation of species leads to uncertainty regarding their distribution. It must also be noted that most small lakes have yet to undergo scientific surveys. National law primarily focuses on commercially or recreationally valuable fish species (eel, salmon, and brown trout) while conservation measures are required to safeguard certain vulnerable species (e.g. Arctic char). There is a pressing need for comprehensive and ongoing long-term studies to assess the impacts of climate change on fish, including changes in phenology, within all-island lake habitats.

Biodiversity

14. Small lakes need to be incorporated into national monitoring programs.
15. All biological indices need to be applied to help identify sites with conservation significance.
16. Arctic char and various ecotypes of Eurasian trout need protection under national law.
17. Comprehensive monitoring studies are needed to assess climate (temperature tolerance) and phenological (breeding, spawning) changes in fish.
18. The impacts of angling, non-native species introductions, and habitat modifications require continued monitoring.
19. There is a need for an overall audit of species loss/species richness in lakes.

Habitats

Oligotrophic, marl, naturally eutrophic, dystrophic, and lakes with the rare Slender Naiad *Najas flexilis* lakes are lakes of distinction in Europe that are well represented in Ireland (Roden and O'Connor, 2024). Other important lake habitats include turloughs, coastal lagoons and upland lakes. Every six years, the RoI assesses and reports on the conservation status of habitats and species protected under the EU Habitats Directive and recent reports confirm that we are steadily losing many of our most distinctive and conservation-worthy lakes with unfavourable, poor, bad, and deteriorating status being reported. Excess nutrients (phosphorus), strongly coloured inflowing water, and reduced transparency pose a major threat to these priority lakes.

Turloughs and lagoons are very dynamic habitats, the former due to their ephemeral nature (Naughton et al., 2024) and the latter due to their geographical position at the interface between land and sea (Oliver et al., 2024). Historical records of turlough flood patterns have been sparse and discontinuous due to their scattered distribution and temporary nature. Key threats to the integrity of both turlough and coastal lagoon habitats include drainage, eutrophication, and climate change. Activities such as small-scale alterations to turlough overflow channels, surrounding drainage, and swallow holes pose significant threats. Lagoons are a priority habitat in special need of protection because so much of the habitat in Europe has disappeared or been degraded. Projected increases in significant groundwater flooding events, as well as changes in the depth and duration of flooding, are expected to impact

Habitats

20. The steady loss of priority (Annex I) habitats is a red flag for the need for increased protection.

21. More research effort is required to identify naturally eutrophic lakes.

22. Unacceptable human activities (and the level of acceptable disturbance) need to be identified to ensure priority habitat sustainability.

23. Systematic monitoring of turloughs using field instrumentation and Earth observation techniques is imperative given the effects of climate change.

24. Important coastal lagoon habitats can experience multiple pressures and require sustainable management planning.

25. Further genetic analysis can help with fish stock identification and potentially uncover and age unique upland fish populations.

26. The discrepancy between the less stringent measurement of WFD lake ecological status and more stringent assessment of habitat conservation condition needs to be addressed.

27. All lake habitat types require long-term studies to assess ecosystem change.

28. Conservation efforts need to focus on individual bodies, wetlands and the linkages between them in the landscape.

sensitive turlough habitats. Moreover, the management of coastal lagoons is likely to become more controversial in future with the pressures of land use and sea-level rise. The implementation of new and ongoing significant artificial drainage schemes to alleviate flooding is another potential pressure.

Upland lakes constitute only a small proportion of the island's total number of lakes, harbouring relatively low diversity, but collectively making a significant contribution to the ecological landscape (Kelly-Quinn, 2024). These remote small water bodies remain largely understudied. Their fish populations likely possess unique genetic and morphological characteristics with potential conservation significance, underscoring the importance of additional research efforts. Threats to these delicate environments include acid deposition, nutrient enrichment from forestry operations, increased dissolved organic carbon loading and inputs of fine sediment.

Information on vegetation structure and function is key to determining the conservation status of lake habitats. Notably, assessment of lake ecological status, under WFD, is less stringent than assessment of habitat conservation condition, which is a concerning discrepancy for measures under the River Basin Management Plan (Roden and O'Connor, 2024).

Lake Status

Since 2007, 224 lakes have been monitored as part of the national lake monitoring program under the WFD in the RoI, though its implementation poses logistical challenges (Tierney, 2024). Over five cycles of WFD monitoring, there has been minimal change in lake water quality, with approximately half of the lakes maintaining good to high-quality status. However, there is concern over the decline in the number of high-status lakes, and only six lakes are assessed for bathing waters. Water Framework Directive data for Northern Ireland (published in 2021 in line with monitoring timescales) demonstrated that none of the 21 lakes monitored achieved good overall status. The RoI has also faced criticism from the EU Commission for drinking water quality, compliance with WFD regulations regarding water abstraction and impoundments, and shortcomings in addressing invasive species.

Sentinel lakes with sustained high-resolution monitoring integrate signals of land use change, pollution, and climate change impacts. Long-term monitoring of these lakes demonstrates the complexity of lake conservation, and the need to consider multiple stressors alongside natural variability. For example, Sheelin was once renowned for its trout population; Leane has many priority habitats and species in a highly protected catchment; Neagh provides drinking water to almost two million people and supports a commercial eel and pollan fishery; Erne is a heavily modified cross-border water body; Feeagh is a long established monitoring site for its diadromous fish populations; Carra is the largest marl lake on the island (de Eyto et al., 2024). Five of these six lakes have experienced nutrient enrichment, the primary issue of concern in most lakes in Ireland. Despite sustained efforts to prevent phosphorus from entering the lakes, declines in water quality are not being reversed. These issues are now additionally compounded by water quality pressures from global warming.

Lakes also face a higher risk of invasive species compared to terrestrial systems, with pathways linked to recreation, angling, and commercial activity (Lucy et al., 2024). However, there is currently no overarching policy on invasive alien species (IAS) management for the island of Ireland, with EU regulations binding only in the RoI, adding complexity to the issue. An all-island approach, including spot checks, boat certification and contingency plans, is essential, particularly for cross-border lakes (18 of which are monitored under the WFD).

Routine monitoring, led by experts and targeting likely hotspots, is crucial for early detection and rapid response if necessary.

Climate change is already having an impact on Irish lakes, with winter warming being more pronounced than that of summer (Jennings et al., 2024). Climate-induced alterations in water transparency and inflows are anticipated to have significant repercussions for biogeochemical and ecological processes. There is a pressing need to understand the potential future impacts of climate change in lakes of different types, but the scarcity of long-term datasets means that modelling experiments and observational records are limited. In addition, there are notable gaps in understanding lake physics within the context of the Irish climate, particularly across lake types, and in simulating future impacts on lake biota.

Past, present, and future quality

28. More lake-specific catchment management plans are needed as essential tools for improving lake water quality.

30. A unified system is needed to consolidate past data and contemporary lake monitoring efforts collected by various agencies for different purposes.

31. Continuous long-term monitoring of lakes needs to be prioritised to disentangle the effects of human actions from climate change to determine realistic conservation measures.

32. An overarching policy for IAS management is needed for the island of Ireland.

33. An all-island approach is needed for management of the 57+ cross-border lakes and ponds.

34. A greater understanding of lake thermal structure in the context of our Irish climate is needed, especially in studies using high-frequency monitoring.

35. There is a dearth of studies examining the potential impacts of climate change on lake biota, both globally and in Ireland.

36. Assessments of the nutrient input from birds to (small) lakes in Ireland are needed to accurately determine their contribution to the total lake nutrient budget.

37. Adaptive management strategies are needed for lake water bodies in response to more extreme climate events.

PEOPLE AND LAKES – FRIENDS OR FOE

Archaeology offers insight into human interaction with lakes spanning from prehistory to medieval times (Potterton, 2024a; 2024b). Lakes served as essential resources for food (fish, waterfowl, plants), water, raw materials (reeds, clay, stone, ice), transportation, and defence. Artefacts from various prehistoric periods, including the Mesolithic, Neolithic, Bronze, and Iron Ages, offer glimpses into the past. The discovery of approximately 500 log boats in Ireland (the majority recovered from lake settings), sheds light on Bronze Age travel and transport. Today, our archaeological heritage faces threats from industrial development, climate change, and looting, yet advancements in scientific methods, technology, and equipment offer unprecedented opportunities to record and analyse archaeological evidence.

Lakes have played significant roles throughout recent history, evident in mythology, folklore, hydrolatry (or worship of water), pilgrimages, art, and leisure activities (Dalton and O'Brien, 2024). They have also been focal points in the struggle to control water, with the belief that draining water from the land would unlock valuable resources such as arable land, marl for nourishing soil, turf for fuel, and reeds for thatching, as well as facilitating the development of waterpower. Both natural and artificial lakes have been utilised for fishing and industrial purposes. Alterations to land and rivers through drainage schemes have resulted in the extinction of ponds

People and lakes

38. Vigilance is needed to protect archaeological heritage from threats from pillaging, industrial development, and climate change.

39. Historical landscape features (waterlogged lands, natural aquatic boundaries, blind loughs) need further investigation.

40. Discrepancies between the number of lakes with names recorded indicate a need for further efforts to explore the toponymic significance of lakes and ponds.

41. All-island registers of lake recreational and amenity users' (including anglers) need to be established, as well as a mechanism for addressing competing rights.

42. Comprehensive evaluation of individual lake carrying capacities, outdoor recreation demand and other pressures is necessary.

43. Further assessment of the status of lakeshore areas is needed as they experience the most intense pressure from recreational activities.

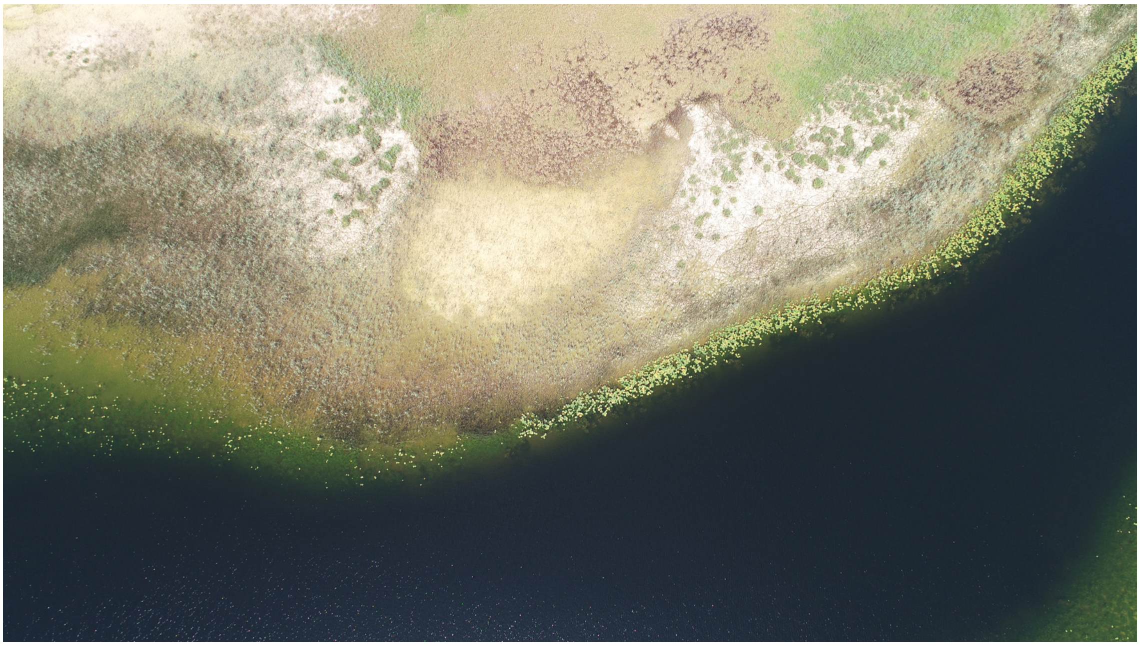


Figure 22.2
Cullaun Lough, Clare. Photo: Ruth Little

and wetlands and the isolation of natural aquatic boundaries by human intervention. Understanding these landscape legacies is crucial, particularly in the context of efforts to restore wetlands and enhance carbon sequestration.

Lakes serve multiple purposes for people, including drinking water supply, waste discharge, angling, and recreation. Amenity and recreation activities interact directly and indirectly with lake waters (Dalton et al., 2024b). Lakes are also crucial habitats for wildlife, spanning shore, shoreline, near-shore, and deep-water regions (Figure 22.2). The primary aim of outdoor recreation strategies is to grow, develop, and increase participation in outdoor activities, thus the utilisation of lakes as recreational resources is expected to expand. This raises concerns about habitat modification and the emergence of conflict among different user groups. Comprehensive evaluations of lake carrying capacity and outdoor recreation demand are crucial.

Water governance structures and international, national, regional, and local implementing agencies, operate within administrative boundaries. As a result, lake catchments are not the management unit in Ireland, despite scientific recommendations (McGrath et al., 2024). The importance of lakes for people is exemplified by the fact that lakes and reservoirs serve as the primary sources of drinking water for nearly 4 million people on the island. While our waters flow through shared cross-border catchments, governance arrangements follow two separate legislative frameworks (Chapter 19; Figure

Figure 22.3
Lough Melvin traverses the north-south border with a quarter of the lake in Fermanagh and three-quarters in Leitrim. Photo Robert Rosell

22.3). Moreover, insufficient financial resources have hindered the fulfilment of requirements outlined in the WFD and exemplified by infringements and fines.

The establishment of Local Authority Waters Programme (LAWPRO) in the RoI marked a significant milestone in fostering community involvement in the management of river basins and was contemporaneous with the establishment of the Rivers Trust in NI (Igoe and O'Flaherty, 2024). Key components of LAWPRO's efforts are Community Water Officers and the Community Water Development Fund. Despite these developments and the significant contributions of voluntary champions, initiatives focused on catchment or water stewardship are often reliant on limited support, in a crowded advocacy landscape where attention is divided among various priorities and political agendas.

Corrib Beo is an example of a community catchment group, and Lough Corrib serves as a model of the diverse state of lakes across Ireland in the early 21st century (Ó Cinnéide, 2024. The group was established in response to growing concerns from local environmental and angling groups regarding declining lake water quality. This group has achieved notable successes through individual activism, implementing educational initiatives, and demonstrating adaptability but has also faced challenges in terms of capacity, limited resources, and failures in funding applications.

Figure 22.4 Drone photo of Lough Atedaun, Clare. Photo: Ruth Little

Governance and communities

44. Water and catchment protection should be a cross-cutting government issue.

45. Governance structures for water need a dedicated supportive secretariat.

46. Adequate state resources must be allocated to effectively address Ireland's declining water quality.

47. Community initiatives focused on catchment or water stewardship require more capacity and resources to sustain public participation and achieve sustainability.

48. Community water groups need support in a crowded advocacy landscape where attention is divided among various priorities.

49. To effectively address common challenges related to all-island water quality, progress made under the WFD must be maintained and augmented to link all-island water environments.

50. If Ireland is to achieve its water objectives under the WFD, along with its targets for climate and biodiversity, coherence in policy will need to radically improve.

CONCLUSION

Engagement with lakes, rivers, and wetlands has changed over time from places of settlement to areas requiring drainage. This book project started with the aim of showcasing lakes in Ireland and highlighting the importance of aquatic biodiversity, water quality, and environmental health. The challenges of climate change, water protection and biodiversity and habitat loss permeate most of the book chapters while the challenge of mitigation and management of lakes is of increasing concern.

One could interpret the current state of lakes in Ireland in several ways 1. Better than our more industrial European neighbours, 2. Maintaining the status quo for the last 50 years or, 3. Lacking progress. The question now centres on how sustainable our lakes are in the longer term. What is not in any doubt from the many examples illustrated in the preceding chapters is the pervasive problem of nutrient enrichment. There is a vital need to radically change our land uses, prioritise lakes for protection, and implement more long-term monitoring. Elements needed for successful restoration include better public, agriculture and industry engagement, wider implementation of nutrient reduction/control measures on a catchment scale, further reductions in point sources and innovation in new measures. A more holistic approach will enable agencies, stakeholders and communities to effectively protect and restore lake ecosystems facing multifaceted threats and guide strategic prioritisation of conservation measures.

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Water is the defining element of Ireland's natural heritage. The mild, wet climate shapes the landscape, endowing the island with an extraordinary number of lakes. This book showcases these lakes, emphasising the importance of aquatic biodiversity, water quality, and environmental health.

Unfortunately, many iconic and less well known lakes face threats from pollution, biodiversity loss, and climate change. Key academics and professionals share knowledge and research experiences on *Lakes in Ireland – Mirrors of Change* in twenty-two chapters. The book highlights the urgent need for radical changes in land use and the prioritisation of lake protection. Key knowledge gaps are identified and chapter authors provide fifty recommendations for research, policy change, and coordinated action to safeguard Ireland's lakes.

Aimed at practitioners, students, decision-makers, and the public, this peer-reviewed, open-access e-book is freely available on the Marine Institute Open Access Repository, thanks to generous sponsors, in particular the National Parks and Wildlife Service (NPWS), the Environmental Protection Agency (EPA), the Marine Institute and Mary Immaculate College.

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