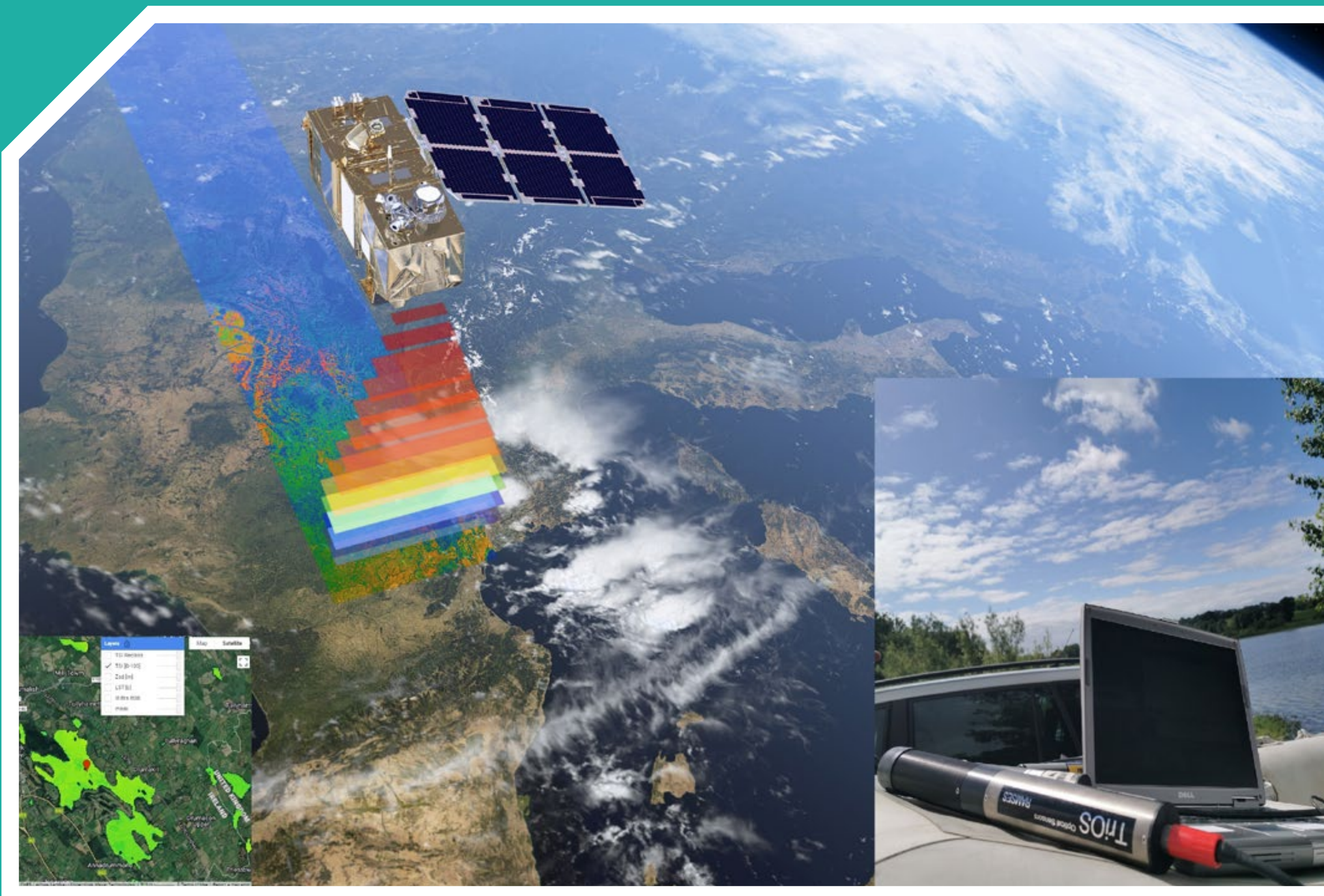
epa Research

Report No.443

# Remote Sensing of Irish Surface Waters

Authors: Conor Delaney, Valerie McCarthy, Kevin French, Sita Karki, Vicky Veerkamp, Moataz Ahmed Abdel Ghaffar, Jenny Hanafin, Alastair McKinstry, Eleanor Jennings and Aaron Golden.



www.epa.ie

Rialtas na hÉireann
Government of Ireland

# Environmental Protection Agency

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

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

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

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

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

## Our Responsibilities Include:

### Licensing

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

### National Environmental Enforcement

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

### Waste Management and Chemicals in the Environment

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

### Water Management

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

### Climate Science & Climate Change

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

### Environmental Monitoring & Assessment

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

### Environmental Research and Development

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

### Radiological Protection

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

### Guidance, Awareness Raising, and Accessible Information

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

### Partnership and Networking

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

## Management and Structure of the EPA

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

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

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

# Remote Sensing of Irish Surface Waters

Authors: Conor Delaney, Valerie McCarthy, Kevin French, Sita Karki, Vicky Veerkamp, Moataz Ahmed Abdel Ghaffar, Jenny Hanafin, Alastair McKinstry, Eleanor Jennings and Aaron Golden.

## Identifying pressures

Lakes, estuaries and coastal waters are crucial for human well-being. Lakes are critical sources of drinking water, and support irrigation, fisheries and aquaculture activities. These waters are also important for recreation and tourism, and support high levels of biodiversity. These natural resources are under anthropogenic pressures from eutrophication, inorganic pollution, acidification, invasive species, extraction of upstream water and climate change. Proper management and maintenance of these resources are essential for society, but are also a requirement under national and EU legislation. The number and diversity of water bodies in Ireland makes regular in situ monitoring an acute challenge for regulatory authorities. This project attempts to determine if the use of freely available Earth observation data from both the Copernicus and Landsat Earth observation programmes could offer a cost-effective and evidence-based means of remotely monitoring such water bodies in Ireland for stakeholders. This report concludes that such monitoring is indeed possible, although complicated by regular cloud cover and high numbers of small, shallow and high-colour lakes that are difficult to survey remotely using existing Copernicus assets.

## Informing policy

A means of improving lake, estuary and coastal water monitoring capacity and frequency on the island of Ireland would significantly aid in the protection and provision of good-quality water resources and increase our understanding of water quality dynamics. In turn, this would improve the management and mitigation of impacted sites, supporting the provision of ecosystem services and ecosystem ecological function. Such a monitoring regime would be invaluable for both policymakers and legislators and enable Ireland to meet its obligations under national and EU legislation.[1]

## Developing solutions

A campaign of ground truth observations of various water quality parameters at selected water body locations, coincident with passes of the Copernicus programme's Sentinel-2 Earth observation satellites, was implemented. This resulted in the development of an Irish-specific data reduction platform yielding mapped estimates of chlorophyll a and water turbidity, both indicators for water quality, directly from this satellite imagery. The performance is consistent with other European initiatives to assess water quality from orbit. The platform increases the EPA's potential ability to monitor ~70% of Irish lakes remotely and better optimise existing sampling programmes. This platform uses newly released Sentinel-2 data for Ireland and updates a monitoring map accessible online. Overall, this demonstrated the efficacy of such an Earth observation-based system to monitor Irish lakes, estuaries and coastal water bodies. Satellite observations can, therefore, complement traditional freshwater monitoring in an essentially automatic and cost-effective manner, permitting the optimal use of in situ monitoring logistics to identify and investigate specific sites in a more controlled and evidence-based fashion.

1 European Communities (Water Policy) Regulations, 2003 (S.I. No. 722 of 2003); European Union (Drinking Water) Regulations 2014 (S.I. No. 122 of 2014); European Communities Environmental Objectives (Surface Waters) Regulations, 2009 (S.I. No. 272 of 2009); European Communities Environmental Objectives (Groundwater) Regulations, 2010 (S.I. No. 9 of 2010); European Communities (Good Agricultural Practice for Protection of Waters) Regulations, 2010 (S.I. No. 610 of 2010); European Communities (Technical Specifications for the Chemical Analysis and Monitoring of Water Status) Regulations, 2011 (S.I. No. 489 of 2011); and EU directives [Water Framework Directive (2000/60/EC), Groundwater Directive (2006/118/EC) and Marine Strategy Framework Directive (2008/56/EC)].

**EPA RESEARCH PROGRAMME 2021–2030**

# Remote Sensing of Irish Surface Waters

## (2017-W-MS-30)

## EPA Research Report

Prepared for the Environmental Protection Agency

by

University of Galway, Dundalk Institute of Technology and Irish Centre for High-End Computing

**Authors:**

**Conor Delaney, Valerie McCarthy, Kevin French, Sita Karki, Vicky Veerkamp, Moataz Ahmed Abdel Ghaffar, Jenny Hanafin, Alastair McKinstry, Eleanor Jennings and Aaron Golden**

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

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

## ACKNOWLEDGEMENTS

This report is published as part of the EPA Research Programme 2021–2030. The EPA Research Programme is a Government of Ireland initiative funded by the Department of the Environment Climate and Communications. It is administered by the Environmental Protection Agency, which has the statutory function of co-ordinating and promoting environmental research.

The authors would like to acknowledge the members of the project steering committee, namely Gary Free (Consiglio Nazionale delle Ricerche), Tiit Kutser (University of Tartu), Kevin Lydon (EPA) Joe Silke (Marine Institute), Patrick Morrissey (EPA), Gavin Smith (EPA), Deirdre Tierney (EPA) Cecilia Hegarty (Research Project Manager on behalf of the EPA) and Anne Mason (Research Project Manager on behalf of the EPA). We also would like to thank Martin Hollan from Dundalk Institute of Technology, who assisted with field sampling.



This report is based on research carried out/data from March 2018 to October 2021. More recent data may have become available since the research was completed.

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

**EPA RESEARCH PROGRAMME 2021–2030**

Published by the Environmental Protection Agency, Ireland

ISBN:978-1-80009-138-2

November 2023 Online version

Price: Free

# Project Partners

**Dr Conor Delaney**
School of Mathematics & Statistical Sciences
University of Galway
Galway
Tel.: +353 85 8050616
Email: conor.delaney@gmail.com

**Professor Aaron Golden**
School of Natural Sciences
University of Galway
Galway
Tel.: +353 91 492327
Email: aaron.golden@universityofgalway.ie

**Dr Valerie McCarthy**
Centre for Freshwater and Environmental Studies
School of Health and Science
Dundalk Institute of Technology
Dundalk
Tel.: +353 42 937 0200 ext. 2843
Email: valerie.mccarthy@dkit.ie

**Kevin French**
Centre for Freshwater and Environmental Studies
School of Health and Science
Dundalk Institute of Technology
Dundalk
Tel.: +353 42 937 0200
Email: kevinjpfrench@gmail.com

**Dr Vicky Veerkamp**
Centre for Freshwater and Environmental Studies
School of Health and Science
Dundalk Institute of Technology
Dundalk
Tel.: +353 42 937 0200 ext. 2838
Email: vicky.veerkamp@dkit.ie

**Professor Eleanor Jennings**
Centre for Freshwater and Environmental Studies
School of Health and Science
Dundalk Institute of Technology
Dundalk
Tel.: +353 42 937 0200 ext. 2804
Email: eleanor.jennings@dkit.ie

**Dr Jenny Hanafin**
Irish Centre for High-End Computing
University of Galway
Galway
Tel.: +353 91 397 851
Email: jenny.hanafin@ichec.ie

**Dr Sita Karki**
Irish Centre for High-End Computing
University of Galway
Galway
Tel.: +353 91 397 853
Email: sita.karki@ichec.ie

**Moataz Ahmed Abdel Ghaffar**
Irish Centre for High-End Computing
University of Galway
Galway
Tel.: +353 1 524 1608
Email: moataz.ahmed@ichec.ie

**Alastair McKinstry**
Irish Centre for High-End Computing
University of Galway
Galway
Tel.: +353 91 397 868
Email: alastair.mckinstry@ichec.ie

# Contents


**Acknowledgements** **ii**

**Disclaimer** **ii**

**Project Partners** **iii**

**List of Figures** **vii**

**List of Tables** **ix**

**Executive Summary** **xi**

**1 Introduction** **1**

1.1 Objectives 1

1.2 Surface Water Bodies in an Irish Context 1

1.3 Remote Sensing of Surface Water Bodies 2

**2 Review of *In Situ* Data and Available Sentinel-2 Imagery** **9**

2.1 *In Situ* Data 9

2.2 Match-up Between Satellite Imagery and *In Situ* Data 9

2.3 Field Validation Methodologies for Surface Waters 9

**3 Field Calibration and Atmospheric Correction Methodologies** **13**

3.1 Aims and Objectives 13

3.2 Overview of Field Sites for Calibration 13

3.3 Atmospheric Correction Methodology 13

3.4 *In Situ* Water Sample Collection and Analyses 15

3.5 Summary of *In Situ* Water Quality 17

**4 Remote Sensing of Surface Waters using Sentinel-2 Imagery** **18**

4.1 Data Acquisition 18

4.2 Selection of Image Processor for Sentinel-2 Data 18

4.3 Atmospheric Correction Performance Evaluation 19

4.4 Water Quality Parameter Validation 19

4.5 Model Optimisation 20

4.6 Model Validation with Historical Data 21

4.7 Remote Sensing for Continuous Monitoring 23

4.8 Earth Observation Platform 25

**5 Data Mining the Landsat Archives for Cloud-free Observations of Irish Lakes 27**

5.1 Open Data and Cloud Computing for Earth Observation 27

5.2 Processing Landsat Imagery using Google Earth Engine 27

5.3 Curating the Landsat Image Archive for an Irish Context 27

5.4 Estimated Overlap of Archival Landsat Imagery and *In Situ* Lake Monitoring 29

5.5 Software and Data Availability on GitHub 34

**6 Conclusion and Recommendations 36**

**References 38**

**Abbreviations 40**

# List of Figures


| | | |
|---|---|---|
| Figure 1.1. | Spatial extent of the Landsat-8, Sentinel-2 and Sentinel-3 over Ireland | 4 |
| Figure 1.2. | Demonstration of spatial resolution in the visible spectrum over Lough Corrib in Co. Galway with (2) Sentinel-3 (300 m), (3) Landsat-8 (30 m) and (1) Sentinel-2 (10 m) | 4 |
| Figure 1.3. | Example of reflectance spectra from a very clear mine pit lake in northern Minnesota, USA, with the corresponding available spectral bands from the Sentinel-2 and the Landsat 8 spacecraft | 5 |
| Figure 2.1. | (Left) Distribution of the 21 lakes for which data were collated for this study; blue polygons denote the lakes designated under the WFD. (Right) Distribution of TRAC samples in purple from 35 TRAC locations across Ireland; blue polygons denote the WFD transitional water bodies | 10 |
| Figure 2.2. | Overlap between the historical lake samples and the Sentinel-2 scenes | 10 |
| Figure 2.3. | Seasonal trends in the collected field samples and Sentinel-2 scenes for lakes | 11 |
| Figure 2.4. | Overlap between historical TRAC samples and Sentinel-2 dates at each TRAC location | 11 |
| Figure 2.5. | Seasonal trends in the collected field samples and Sentinel-2 scenes for TRAC waters | 12 |
| Figure 3.1. | TriOS RAMSES ARC-VIS radiance sensor with a TriOS RAMSES ACC-VIS irradiance sensor used to collect upwelling radiance ($L_u$) and downwelling irradiance ($E_d$), respectively | 15 |
| Figure 3.2. | Measurements of $L_u/E_d$ (blue) and corrected $L_u/E_d$ (red) using the glint removal procedure of Kutser *et al*. (2013) for Lough Muckno, 9 December 2019 | 15 |
| Figure 3.3. | TriOS ARC-VIS RAMSES radiometric sensor showing the original black 5 cm tube and the newly fabricated 12 cm tube | 16 |
| Figure 3.4. | Field radiometry locations and dates (left); Mr Kevin French from DkIT obtaining radiometric data (right) | 16 |
| Figure 4.1. | Steps adopted to develop the optimised integrated workflow to process Sentinel-2 data suitable for comparison with ground truth field data | 18 |
| Figure 4.2. | Comparison of atmospheric correction results and field radiometer data for Lough Owel (a) and Lough Sillan (b) | 19 |
| Figure 4.3. | Turbidity (FNU) and TSM ($g\,m^{-3}$) computation results from ACOLITE and C2RCC, respectively | 20 |
| Figure 4.4. | Chlorophyll *a* ($mg\,m^{-3}$) computation results from ACOLITE and C2RCC, respectively | 20 |

| | | |
|---|---|---|
| Figure 4.5. | Chlorophyll *a* ($mg\,m^{-3}$) and turbidity (FNU) computation results from coupled technique | 21 |
| Figure 4.6. | The distribution of lakes considered for validation (left) and the distribution of TRAC water bodies considered for validation (right) | 22 |
| Figure 4.7. | Chlorophyll *a* ($mg\,m^{-3}$) concentration computed from Sentinel-2 using coupled algorithm (*y*-axis) compared with the field measurements for eutrophic (13 samples), mesotrophic (12 samples), oligotrophic (31 samples) and all lake types | 22 |
| Figure 4.8. | Chlorophyll *a* ($mg\,m^{-3}$) concentration computed from Sentinel-2 using coupled algorithm (*y*-axis) compared with the field measurements for eutrophic (five samples), intermediate (26 samples), unpolluted (10 samples) and all TRAC types | 23 |
| Figure 4.9. | Predicted chlorophyll *a* ($mg\,m^{-3}$) concentrations for Lough Mask, Lough Sillan and Lough Muckno using the coupled remote sensing workflow developed as part of this project | 24 |
| Figure 4.10. | Chlorophyll *a* ($mg\,m^{-3}$) results from the coupled technique for Lough Egish using the Sentinel-2 images acquired from January to November 2020 | 24 |
| Figure 4.11. | Turbidity (FNU) results from the coupled technique for Lough Egish using the Sentinel-2 images acquired from January to November 2020 | 25 |
| Figure 4.12. | Screen capture of the EO platform showing chlorophyll *a* ($mg\,m^{-3}$) and turbidity (FNU) products from Sentinel-2 near Portumna, Co. Galway, in the summer of 2021 | 26 |
| Figure 5.1. | The browser view using GEE | 28 |
| Figure 5.2. | Graph of a simple count of Landsat scenes featuring parts of Ireland | 28 |
| Figure 5.3. | Summary statistics of cloud cover in Landsat scenes that contain observations of Ireland | 29 |
| Figure 5.4. | Demonstration of actual cloud coverage | 29 |
| Figure 5.5. | The GEE interface showing a graph over times of cloud cover statistics for Lough Allen (green) and for the scenes containing Lough Allen (blue) | 30 |

# List of Tables


| | | |
|---|---|---|
| Table 1.1. | Parameters included in the WFD operational and surveillance monitoring programme for lakes and TRAC water bodies | 3 |
| Table 1.2. | Optical typologies of inland water | 6 |
| Table 3.1. | Summary of main characteristics of lakes used for calibration in this study | 14 |
| Table 3.2. | Mean ± standard error (SE) and sample size (*n*) of water quality parameters measured at each of the lakes sampled for field calibration (September 2019–August 2020) | 17 |
| Table 5.1. | Summary statistics of the set of images where cloud cover over the lake is <25% | 31 |
| Table 5.2. | Landsat 5 observations of lakes with <25% cloud cover occurring with 2 weeks of EPA *in situ* observations data (±14 days) | 32 |
| Table 5.3. | Landsat 8 observations of lakes with <25% cloud cover occurring with 2 weeks of EPA *in situ* observations data (±14 days) | 33 |
| Table 5.4. | Summary of the Landsat 5 and Landsat 8 observations of lakes with <25% cloud cover occurring with 2 weeks of EPA *in situ* observations data (±14 days) | 34 |
| Table 5.5. | Landsat 5 observations of lakes with <25% cloud cover occurring with 2 weeks of *in situ* observations data (±14 days) by Inland Fisheries Ireland and Sligo County Council | 34 |

# Executive Summary

The main objective of the INFER project was to examine the potential of freely available Earth observation data for monitoring water quality in Irish lakes and transitional and coastal (TRAC) waters and to determine if prevailing weather conditions compromise the effective use of such remotely sensed data in an Irish context. Images from the twin Sentinel-2 satellites were used to estimate water quality parameters from a set of calibration lakes from which *in situ* water quality and atmospheric correction data were collected at times that coincided with satellite passes or were within a reasonable timeframe compared with ground truth acquisition.

Field radiometry measurements were taken alongside water quality data to coincide with satellite imagery, which allowed glint-free reflectance from the water bodies to be determined. Based on the calibration with these field data, a coupled technique was developed to atmospherically correct and estimate chlorophyll *a* using two processers, C2RCC and ACOLITE, and this coupled technique was validated using historical water quality data collected for a range of lakes of different trophic status. A 'real-time' web-hosted platform was then developed that automatically ingests Ireland-specific Sentinel-2 data, processes the data based on the regionally optimised coupled approach that was developed, and renders predicted chlorophyll *a* and turbidity water quality maps for examination.

A historical analysis of Earth observation data from the archived Landsat program, freely available from Google Earth Engine, was also conducted for 21 lakes regularly monitored by the EPA and local authorities. Observational data from 1984 to 2021 were reviewed, a statistical assessment of cloud coverage occurrence was determined, and those cloud-free observations matching *in situ* sampling events were curated. In all cases, while the spatial resolution of the Earth observation platforms was suitably high (for Sentinel-2, ~10 $m^2$) to resolve and map water quality for the majority of water bodies of interest, the challenging meteorological environment – principally the excessive cloud cover – complicates the use of both the Sentinel-2 and the Landsat platforms, neither of which can see through cloud, limiting the availability of usable images that, in ideal conditions, could be taken as frequently as every 5 days (the Sentinel-2 constellation has a 5-day revisit time).

Taken together, the findings of this project demonstrate the potential use of Earth observation imagery to estimate water quality in surface waters with the implementation of the coupled processor workflow found to be optimal for Irish conditions. The results show that the technique developed can be used to get a snapshot of water quality across the spatial scale to provide general guidance on trophic status. The results also show the need for additional work targeting the application of algorithms for different trophic statuses so that the algorithms are directly applicable to Water Framework Directive (WFD) monitoring. However, further calibration and validation work is needed, particularly in refining this work to take account of various lake typologies, trophic status and optical properties.

# 1 Introduction

## 1.1 Objectives

This report details the results of a medium-scale project whose goal was to determine the efficacy of using freely available Earth observation (EO) imaging data to remotely assess the water quality conditions of Irish surface waters, specifically lakes and transitional coastal waters, and to assess this approach in the context of ongoing water quality assessment and monitoring programmes, such as those associated with the implementation of the European Union (EU) Water Framework Directive (WFD; 2000/60/EC). While both regulatory and local authorities have a legal obligation to comprehensively assess the status of freshwater bodies in Ireland, the number, density and intrinsic diversity of these on the island, combined with Ireland's complex typology, make traditional 'hands-on' monitoring difficult and necessitate the exclusion of certain sites in remote or difficult-to-access settings. Therefore, the possibility that locations of concern could be identified remotely, which would allow resources to be deployed more strategically, was a motivation driving this project.

In this report we detail the results of a coordinated monitoring campaign that involved directly sampling several water bodies representative of the Irish context, and assessing their water quality at those sampling times coincident with EO imagery obtained by the active Sentinel-2 remote sensing satellites, which were funded by the European Commission and are operated by the European Space Agency. The aim here was to use these ground truth data to inform the development of a water quality prediction model that would be able to remotely infer a given water body's chlorophyll *a* and turbidity – both recognised measures of water quality – remotely within a defined confidence range. While such an approach is not new, its application in an Irish context is novel, given the island's distinct meteorological, climatic and surface water environment, as we describe later. A particular goal was to determine the extent to which weather conditions, and in particular cloud cover, would have an impact on the acquisition of useful satellite data, given the days between subsequent imaging opportunities from orbit.

Our field work campaign is outlined with the associated methodologies used, and this is complemented with information on the Sentinel-2 data products used, their analysis, and the means of utilising the ground truth data to develop the water monitoring infrastructure currently in operation, which is accessible via a dedicated web portal[1]. We also assessed the potential use of historical EO data going back almost four decades, courtesy of the United States Geological Survey's (USGS) Landsat programme, freely available for examination and processing using Google Earth Engine. Using a subset of water bodies that have been part of long-term monitoring programmes in Ireland, we document how we curated those data products coincident with historical sampling, providing a basis for future work to study long-term trends in water quality for these well-characterised locations.

## 1.2 Surface Water Bodies in an Irish Context

### *1.2.1 Census of water bodies and regulatory requirements*

Ireland has over 12,000 lakes covering a total area of approximately 1200 km$^2$. Lakes greater than 50 ha in area, those used for the abstraction of > 100 m$^3$ per day for drinking water, and those designated as protected areas under the Habitats (92/43/EEC) or Birds Directive (2009/147/EC) fall under the WFD (2000/60/EC) (EPA, 2017), yielding 812 sites that require WFD monitoring. For the period 2019–2021, 224 of these lakes were monitored, accounting for only 30% of WFD-designated lakes and less than 2% of the total number of lakes in Ireland. The deficit in the number of monitored lakes compared with those defined under the WFD is addressed by extrapolating the ecological status of the unmonitored water bodies based on land use, hydrogeomorphological data and expert judgement, which currently represents

1 https://eoplatform.ichec.ie/infer/

the best means of resolving this shortcoming. Most Irish lakes, however, are less than 5 ha in size, with almost 70% less than 1 ha in extent (which also includes ponds) – none of these are monitored directly. In addition, Irish transitional and coastal (TRAC) waters cover approximately 14,000 $km^2$ (transitional waters, 844 $km^2$; coastal waters, 13,325 $km^2$) and include water bodies such as lagoons, estuaries, large coastal bays and exposed coastal stretches. Among these, approximately 84 transitional water bodies and 47 coastal waters were also monitored in the 2019–2021 period and have been carefully chosen to best represent the overall status of TRAC waters. Nevertheless, while specific TRAC water bodies are regularly monitored, the majority are assessed intermittently, with a greater focus on local authorities fulfilling obligations as regards water quality for bathing during the summer season, and, as with lakes, the statuses of unmonitored systems are estimated through extrapolation.

### *1.2.2* In situ *monitoring activities*

Conventional water quality monitoring is both time-consuming and labour intensive. Additionally, data collection is often carried out at a small subset of spatially distributed sites or at a single point (e.g. the deepest point) in a lake, which may not necessarily be representative of the entire water body, and, being primarily based around grab samples, it in effect provides only a snapshot assessment at the time of sampling. A typical methodology usually involves at least two people who have a vehicle with a trailer and the necessary instrumentation travelling from lake to lake, assuming that the lakes are accessible by vehicle; several lakes have been removed from the WFD programme during its lifetime owing to accessibility issues (Tierney *et al*., 2015). Some measurements are carried out *in situ*, with additional water samples taken to a laboratory for analyses. Primary production measurements and other water chemistry analyses may take between 2 hours and 1 day to complete, depending on the parameter of interest. Table 1.1 summarises the parameters monitored as part of WFD implementation in Ireland. Very few lakes are monitored at the frequency required to capture the dynamics of the parameters of interest (Marcé *et al*., 2016), as many lake processes, particularly planktonic and microbial, occur over a much shorter time frame of between hours and days. Large-scale monitoring over wide areas, such as that required as part of WFD implementation, could benefit from more cost-effective approaches, such as the use of remote sensing observations, that could help address some of the spatial and temporal limitations of traditional monitoring.

## 1.3 Remote Sensing of Surface Water Bodies

Remote sensing consists of the acquisition of image data usually taken at specific spectral bands spanning the optical and infrared regions of the electromagnetic spectrum. Such bands are typically selected based on their known sensitivity to either emission or absorption signatures in reflected sunlight associated with specific surface or atmospheric properties. These range from water vapour, ice and aerosol content to arguably one of the most important reflectance signatures, that associated with the fluorescence of the pigment chlorophyll, in particular chlorophyll *a*. Images of various extent and spatial resolution are typically taken simultaneously in multiple spectral bands at the top of the atmosphere, and, by means of determining the aerosol and atmospheric opacity for that image stack, an estimate of the initial surface reflectance can be made. Manipulation of the resulting corrected multi-spectral images allows researchers to create maps that accentuate those regions corresponding to a particular reflectance signature associated with a specific surface property. These maps can then be analysed to characterise the spatial extent and flux response of these regions, in essence both mapping and quantifying a surface entity remotely. For this project we explored the use of freely available remotely sensed imagery from both the Sentinel and Landsat EO programmes. While both have slightly different configurations as regards multispectral imaging, both can provide data products amenable to assessing water quality remotely. While all EO satellites fundamentally sample the same approximate spectral bands, the most significant differences between those currently in operation come down to the regularity with which a given point on the planet's surface is imaged (also known as cadence), the spatial extent and resolution of each image taken, the status of the obtained image data (raw, pre-processed, analysis-ready), and access. In this report we will work with freely available data from the two global leaders in

**Table 1.1. Parameters included in the WFD operational and surveillance monitoring programme for lakes and TRAC water bodies**

| Parameter | Lakes | TRAC water bodies |
|---|---|---|
| Phytoplankton | Twice per year<br>Chlorophyll *a* as per physico-chemical | Four times per year (transitional)<br>Every 3 years (coastal) |
| Aquatic plants | Every 3 years | Every 3 years (every 6 years for saltmarsh) |
| Macroalgae | n/a | Every year (for opportunistic algae); every 3 years (RSL) |
| Phytobenthos | Twice per year every 3 years | n/a |
| Macroinvertebrates | Every 3 years | Every 3 years |
| Fish | Every 3 years | Every 3 years |
| Hydromorphology | Every 6 years | Every 6 years |
| Physico-chemical | Approximately four, six or eight times per year (OM)[a]<br>For SM, 12 times per year every 3 years or as per OM frequency in the other years | Four times per year |
| Priority substances | 12 times per year every 6 years | 12 times per year every 6 years |

**[a]The frequency at which data on some parameters are collected depends on whether the water body is in the OM or SM programme.**

**n/a, not applicable; OM, operational monitoring; RSL, reduced species list; SM, surveillance monitoring.**

observation, namely the EU's Sentinel programme and the United States' Landsat programme.

### *1.3.1 The Sentinel and Landsat missions*

As previously stated, while both satellite systems employ similar imaging technology, the immediate differences in imaging extent and resolution are apparent in Figures 1.1 and 1.2, and we discuss these in the following subsections.

#### *Sentinel missions*

The European Commission's Copernicus programme constitutes the development and operation of a suite of EO platforms that will ultimately number 12 distinct Sentinel mission types in total, of which the image-based Sentinel-2 and Sentinel-3 satellites are most relevant to this project, with the key difference being the former's high-resolution imaging capability and greater cadence, consequently making it the focus of our interest. Sentinel-2 currently comprises two EO satellites in Sentinel-2A and -2B, both of which travel in a sun-synchronous orbit (a third satellite is scheduled to be launched in 2024). Combined, they provide a revisit time on average of every 3–5 days for Ireland, with a swath coverage of 290 km. The MultiSpectral Instrument (MSI) on board both satellites provide high-quality data simultaneously in 13 bands, with a spatial resolution of 10 m/pixel in the visible passbands. Operated by the European Space Agency on behalf of the European Commission, all data obtained from the Sentinel-2 mission have been freely available since the launch of the first satellite in 2015. Given Sentinel-2's higher-resolution image data and its more regular cadence, with passes occurring over the same location several times a month, we proposed to assess the use of these data products in a 'real-time' monitoring capacity.

#### *Landsat programme*

The Landsat programme, a joint venture between the USGS and NASA, began operation in 1972.

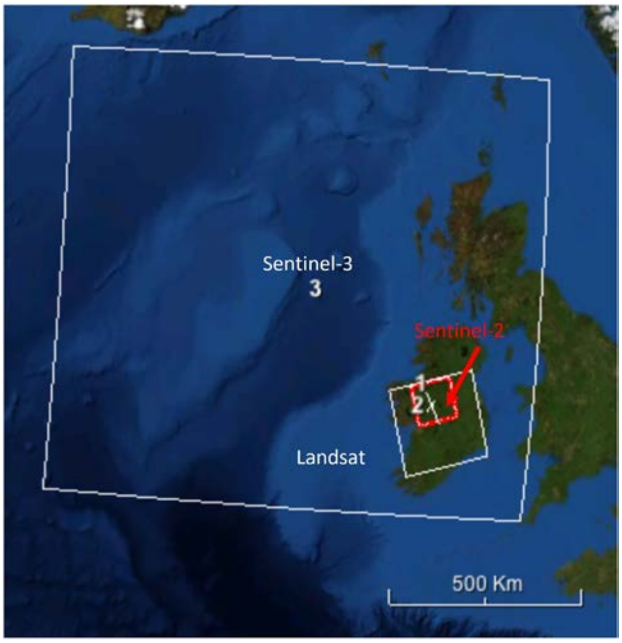



**Figure 1.1. Spatial extent of the Landsat-8, Sentinel-2 and Sentinel-3 over Ireland. The outermost frame (3) represents the Sentinel-3 footprint, the middle frame (2) represents Landsat-8 and the innermost (1) represents Sentinel-2.**

Since then, nine Landsat spacecraft have been launched into a sun-synchronous orbit, ensuring that at least one Landsat spacecraft is always operational during this time, with the most recent spacecraft, Landsat 9, launched in September 2021. While imaging instrumentation has evolved since the start of the Landsat programme, the same fundamental multi-spectral-band-based systems have been used, covering specific passbands in the optical and the infrared. For both Landsat 8 (launched in 2013) and Landsat 9, the instrumentation suite based around the operational land imager (OLI) and thermal infrared sensor (TIRS) covers 11 bands and has a spatial resolution of ~30 m/pixel. The entire planet is imaged every 16 days with a swath width of 185 km, and all data are freely available for analysis. Landsat offers poorer image resolution and cadence than the Sentinel-2 mission; its strength lies in the almost five decades of observational data accrued since its inception, and the fact that the entire petabyte archive is freely accessible from Google Earth Engine's Cloud infrastructure. Given that several water bodies have been regularly and consistently monitored over this timescale, we attempted to assess the viability of using the Landsat archive from a historical perspective to study long-term changes in water quality at these locations.

### *1.3.2 Remotely observed water properties*

The reflectance properties of water are arguably significantly more complex than those of dry land. While the full optical-to-infrared spectral response can

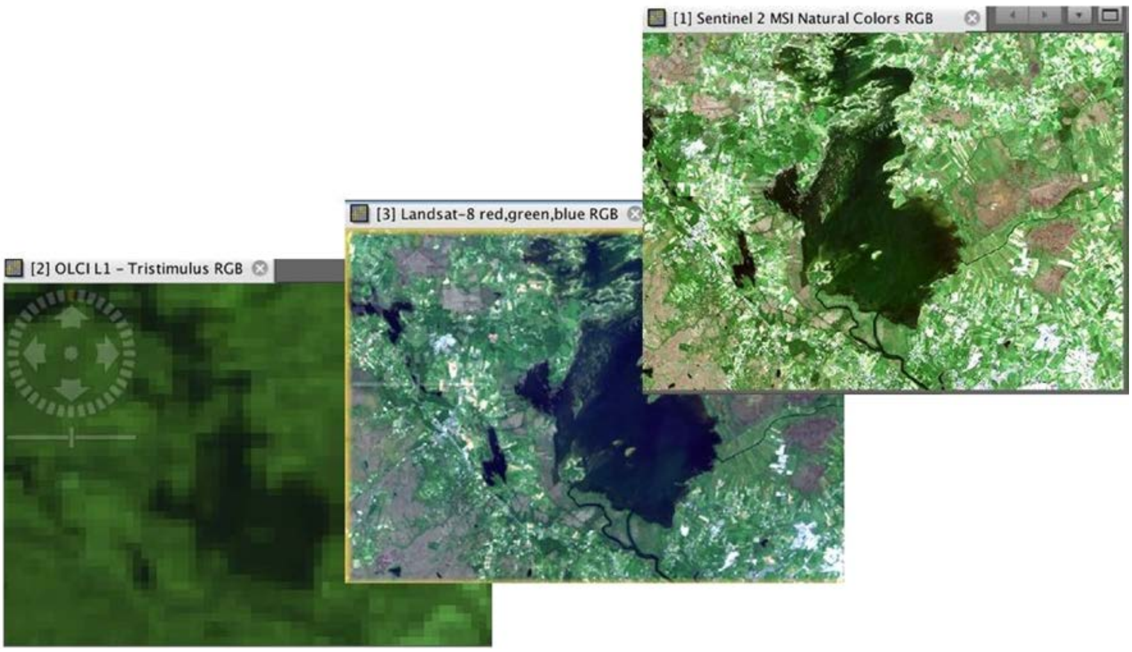



**Figure 1.2. Demonstration of spatial resolution in the visible spectrum over Lough Corrib in Co. Galway with (2) Sentinel-3 (300 m), (3) Landsat-8 (30 m) and (1) Sentinel-2 (10 m).**

be exploited for land remote sensing, this is not the case for water, which strongly absorbs infrared light. The ability to discern suspended matter within a given water column to a specific depth is a strong function of many parameters, and this is further complicated by the highly localised and complex atmospheric conditions near the water interface, a consequence of local temperature, pressure, wind conditions and subsurface activity. So, while scientists have excellent-quality data on the ideal spectral reflectance response of coloured dissolved organic matter (CDOM), blooms of autotrophic phytoplankton (whose response is dominated by chlorophyll *a* fluorescence) and suspended particulates (see, for example, Figure 1.3), actual spectral responses vary between water types and contexts. The ability to accurately characterise these proxies for overall water quality is critically dependent on being able to model both these close-water atmospheric effects and the underlying reflectance response from Irish lakes and coastal waters.

For the totality of a given water body's quality to be fully characterised, it is also necessary that its distinct spatial contexts can be resolved, such as variations in depth and associated subsurface composition, bulk water flows due to wind or inflow/outflow contexts, and biogeochemical status. This is constrained by the widely accepted rule of limiting the examination of remotely sensed data from a given water body by at least 1 'pixel' from the lake shore to obviate signal contamination by littoral effects. This has an immediate impact on the utility of the Landsat imagery, as ~70% of Irish surface bodies are less than 104 $m^2$ in extent, so a boundary limitation of ~30 m (the size of a typical Landsat pixel) would make most, if not all, lakes of this size unsuitable for monitoring from orbit.

### *1.3.3 How remotely observed data are used to determine water quality*

The application of remote sensing to aquatic research started with the availability of NASA's Coastal Zone Colour Scanner (CZCS) data. Chlorophyll *a*, temperature, turbidity and CDOM were the first sets of variables to be measured using remote sensing (Jerlov, 1968, 1976; Gordon and Morel, 1983; Morel, 2001). Research in bio-optical modelling developed to allow physical and biological ocean parameters to be retrieved from purely optical observations. It was rapidly recognised that oceanic (case 1 or clear waters) retrievals were much more straightforward

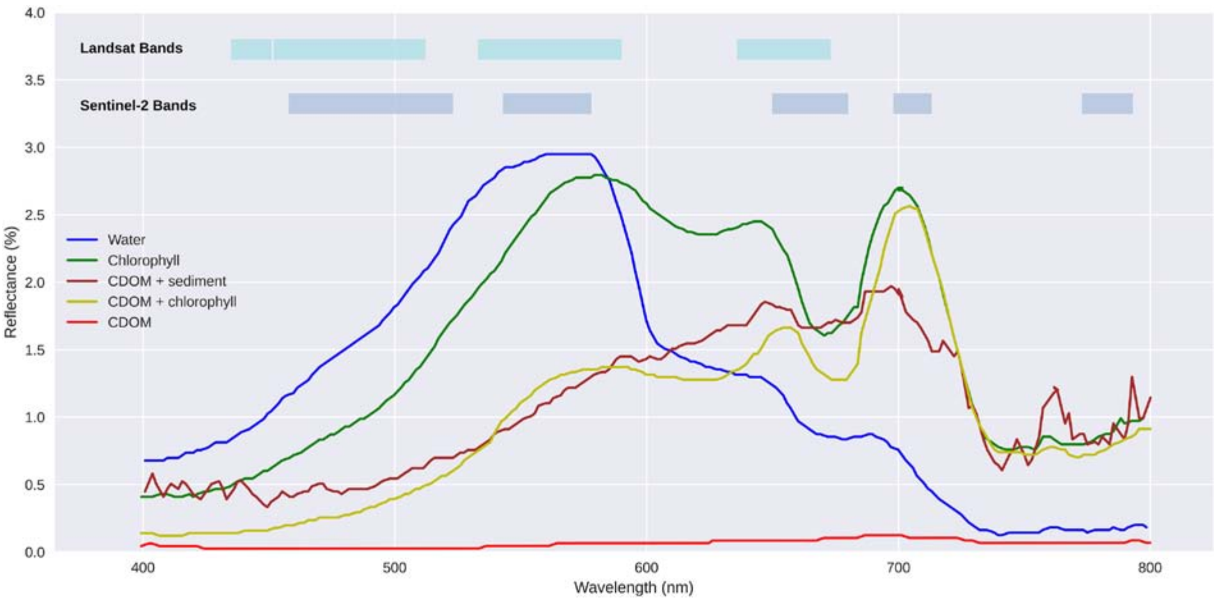



**Figure 1.3. Example of reflectance spectra from a very clear mine pit lake in northern Minnesota, USA, with the corresponding available spectral bands from the Sentinel-2 and the Landsat 8 spacecraft. Specific reflectance spectral responses are displayed for various water quality conditions, with the differences in measured reflectance apparent within each satellite's spectral band channels. By exploiting these differences from given pixel values from a water body, it is possible to discern likely water quality properties remotely (adapted from https://water.rs.umn.edu/lwc).**

than in coastal (case 2 or complex waters) areas or indeed for inland waters, applications of which were limited for many years owing to the absence of appropriate satellite sensors (Palmer *et al*., 2015). The complexity of using remote sensing for inland waters and coastal areas arises from both biological and physical processes. Inland and coastal ecosystems are much more diverse and variable, and physical processes such as river runoff, wave action and tidal action introduce more sediment and other material into the water column. For inland water bodies, the ecosystem and physical processes depend very much on the locality, and so these can vary from one water body to the next.

The first attempt to formally classify water bodies into case 1 and case 2 was found to be ineffective when dealing with inland waters, as almost all inland waters fall into the case 2 category, even if those waters are also dominated by phytoplankton, and the presence of these multiple constituents makes using remote sensing for the monitoring of inland water quality more complex (Ogashawara *et al*., 2017). More recent studies have, therefore, attempted to differentiate inland water types into optically complex categories using *in situ* and/or satellite-derived reflectance data (Spyrakos *et al*., 2017). Optical water types (OWTs) are defined as different water masses with a collection of similar optical characteristics that result in similar reflectance (Vantrepotte *et al*., 2012). By classifying lakes based on OWTs, it is possible to empirically retrieve water column constituents or parameterise bio-optical models (Botha *et al*., 2020). Therefore, the effectiveness of remote sensing techniques varies depending on the optical type of the inland water body in question. The diversity and range of optical properties of different types of inland water types necessitates the development of a robust method of classifying OWTs. Owing to the range of bio-optical properties within these waters, however, this can often be challenging. The recent development of the Copernicus Global Land Cover (C-GLOPS) maps approach, which clusters lakes into 13 different classes or OWTs (Table 1.2; Spyrakos *et al*., 2017), is one such optical classification technique formulated at a global scale. Examples of regionally adapted classification systems have also been developed, such as the classification system based on 11 OWTs, which was recently proposed by Botha *et al*. (2020) for Australian inland and coastal waters.

The measurable physical quantity used for water quality parameters in remote sensing, such as chlorophyll *a*, total suspended material, CDOM and transparency, is reflectance and, in particular, remote sensing reflectance ($R_{rs}$), which in an apparent optical property (AOP). An AOP is a spectral quantity that depends on the concentration of optically reactive substances in the euphotic zone (Cazzaniga, 2018). The $R_{rs}$ spectrum is the result of the interaction of the signal with the water itself and its constituents, including phytoplankton, organic matter and dissolved substances. A processing chain is required to retrieve this information from the remote sensor, which involves the removal of signals that do not contribute anything to the measurement of the parameter of

**Table 1.2. Optical typologies of inland water (adapted from Spyrakos *et al*., 2017)**

| OWT | Dominant characteristics |
|---|---|
| OWT1 | Hypereutrophic waters with scum of cyanobacterial bloom and vegetation-like $R_{rs}$ |
| OWT2 | Common case waters with diverse reflectance shape and marginal dominance of pigments and CDOM over inorganic suspended particles |
| OWT3 | Clear waters |
| OWT4 | Turbid waters and high organic content |
| OWT5 | Sediment-laden waters |
| OWT6 | Balanced effects of optically active constituents at shorter wavelength |
| OWT7 | Highly productive waters with high cyanobacteria abundance and elevated reflectance at red/near-infrared spectral region |
| OWT8 | Productive waters with cyanobacteria presence and with $R_{rs}$ peak close to 700 nm |
| OWT9 | Optically neighbouring to OWT2 waters but with higher $R_{rs}$ at shorter wavelengths |
| OWT10 | CDOM-rich waters |
| OWT11 | Waters high in CDOM with cyanobacteria presence and high absorption efficiency by non-algal particles |
| OWT12 | Turbid, moderately productive waters with cyanobacteria presence |
| OWT13 | Very clear blue waters |

interest. When sunlight reaches a water body, some of it is reflected directly off the surface; however, most of the light penetrates the water column and interacts with dissolved or suspended organic and inorganic material in the water column, which are known as optically active constituents (OACs) and cause the light to be absorbed or scattered. These inherent optical properties (IOPs) are generally unique and measurable. The application of analytical methods to retrieve environmental parameter data from remote sensing data is driven by an understanding of the relationship between IOPs and water-leaving radiative signals, which are what is detected by the satellite sensor (Preisendorfer, 1976). The properties of water that determine remote sensing capacity include water irradiance reflectance (R), above and below water remote sensing reflectance ($R_{rs}$ or $r_{rs}$, respectively) and various diffuse attenuation functions (K), in addition to absorption (a) and scattering (b) coefficient properties, which vary based on the composition of the water body. OACs in the water body are often divided into four main groups: (1) pure water, (2) phytoplankton (measured by pigments such as chlorophyll *a*, (3) non-algal particles, which include both organic and inorganic material, and (4) CDOM. These constituents determine the spectral shape of the light scattered upwards at the air–water interface (water-leaving radiance, $L_w$), which is what is detected by satellite sensors. Typical inland waters have absorption peaks due to constituents such as CDOM and chlorophyll *a* (Ogashawara *et al*., 2017). The most notable absorption feature is in the blue region due to the absorption from CDOM and chlorophyll *a,* and another is located in the red region around 675 nm (Gurlin, 2012). Bio-optical modelling utilises the reflectance and absorption features of these constituents in different regions of the electromagnetic spectrum to quantify their presence. Because of the complex nature of absorption and reflection by these constituents in the blue and green bands (Gurlin *et al*., 2011), longer bands such as red and near-infrared (NIR) have been used for areas where chlorophyll *a* concentration is higher than 10 µg/L (Gitelson and Kondratyev, 1991; Mishra and Mishra, 2012).

The water depth at which the satellite-derived imagery is capable of penetrating is dependent on the wavelength of the light received (e.g. blue and green light penetrates further than red light) and the composition of the water in which the light is travelling. Therefore, in highly turbid waters, sunlight will not be able to penetrate beyond the top few centimetres of the water column, whereas in more optically clear waters, several meters' depth can be illuminated. Consequently, bottom substrate reflectance can become an issue in shallow, clearwater lakes. It may be possible in such lakes to estimate submerged vegetation and water depth from remotely sensed data (Free *et al*., 2020).

Having transitioned the water surface boundary, the water-leaving radiation is also affected by absorption and scattering in the atmosphere. Even on a clear day, this will generally account for 90–98% of the signal obtained by a satellite remote sensor and contains no information about the water body itself (Gitelson and Kondratyev, 1991; Kutser *et al*., 2013). Consequently, it is important to remove these effects to accurately estimate water quality parameters. This has been a problem throughout the history of remote sensing for aquatic systems and particularly so for optically complex inland waters (Ogashawara *et al*., 2021). Because of the effects of turbidity and sun glint and adjacency effects from the surrounding landscape, atmospheric correction is an important processing step in the estimation of water quality parameters from inland and coastal waters.

Atmospheric correction is the process of removing the contributions to the signal that arise from sources other than the water column, such as suspended aerosols. The signal measured by the sensor (top of atmosphere radiance, TOA) is the sum of the various components, as in Equation 1.1:

$$L_{TOA} = L_a + L_r t_r + L_w t_w \qquad (1.1)$$

where:

$L_a$ = atmospheric path radiance

$L_r$ = specular radiance from the water surface

$t_r$ = transmittance of the specular radiance through the atmosphere

$L_w$ = water-leaving radiance

$t_w$ = transmittance of the radiance from water sensor

$L_a$ and $L_r$ = non-water components that atmospheric correction aims to remove (Moses *et al*., 2017).

Aerosols often present a greater problem in inland waters than over the open ocean owing to the presence of greater concentrations of airborne pollutants such as dust particles from industrial and agricultural activities. Consequently, aerosol scattering is likely to make a far greater contribution to the TOA and reduction of the water-leaving signal reaching the sensor. To correct for this atmospheric scattering, detailed atmospheric profiles, which are not generally available at most target sites, are required. Adjacency effects are also problematic in inland and coastal areas and can be particularly difficult for smaller water bodies surrounded by vegetation or hillsides, a not uncommon occurrence in the Irish context. It is estimated that the adjacency affect may be relevant up to 30 km from the shoreline; this can also depend on vegetation type. Various methods have been proposed for correcting for the adjacency effect (Kiselev *et al*., 2015); however, the effectiveness of these methods needs to be carefully assessed and calibrated.

Specific algorithms to correct for the effects of the atmosphere have their basis in the physics of radiative transfer; however, their actual implementation is typically optimised using empirically derived heuristics such as the so-called ‘black pixel’ heuristic, which has been used for the open ocean, whereby the near-infrared band reflectance is used to model atmospheric attenuation. The algorithm then extrapolates the spectral dependence of aerosol reflectance to the visible wavelengths based on the modelled spectral dependence of the identified aerosol type. However, this approach is not valid for turbid coastal and inland waters (Siegel *et al*., 2000). As previously stated, several of the multi-spectral imaging bands on EO platforms are used to guide such model fitting as their response is dominated by aerosol, dust and the water vapour column. How these data are interpreted is encapsulated in many atmospheric correction algorithms typically developed for use with specific imaging instruments. In the case of remote observation over water, and in particular the more complex TRAC and inland water contexts, several such algorithms are in use and have been validated, such as the ACOLITE (Vanhellemont and Ruddick, 2018) and C2CRR (Brockmann *et al*., 2016) processors. While these processors are designed to solve the same problem, each adopts a completely orthogonal means of doing so: the ACOLITE processor implements a modified radiative transfer-based correction based around estimates of Rayleigh and aerosol scattering directly, whereas the C2CRR processor uses a pre-trained neural network infrastructure to infer these corrections from the same multi-spectral data. Both processors have been demonstrated to show equivalent performance in quantifying water quality proxies (i.e. phytoplankton pigments, total suspended matter and CDOM) from both Sentinel-2 MSI and Landsat OLI image data. Both processors are available as stand-alone Python-based modules or integrated into the European Space Agency’s STEP analytics ecosystem. Actual validation of the performance of any processor used to estimate the actual surface reflectance from a given water body is critically dependent on comprehensive ground truth data to assess the expected signal against that actually determined. The goal here is to directly test specific water quality estimates that can be derived from the remotely sensed data and to determine how best these water quality proxies – chlorophyll *a*, turbidity, CDOM – capture the range of directly measured properties obtained *in situ*. Through a coordinated campaign of joint sampling of water quality parameters, *in situ* atmospheric correction data acquisition and the collection of remote satellite observations across a range of surface water types in differing seasonal contexts, it is possible to constrain those free parameters that form part of the image processing workflow so as to yield remotely sensed water quality estimates with some confidence.

# 2 Review of *In Situ* Data and Available Sentinel-2 Imagery

## 2.1 *In Situ* Data

Historically available *in situ* datasets were reviewed to understand the recent trends in sampling with respect to available Sentinel-2 (2015 onwards) satellite coverage. This step was important to understand the seasonal and geographical coverage of these data. The subsequent review of the data provided an evidence-based means of recommending suitable techniques for field data collection and to target the sampling location accordingly to optimise the overlap between field samples and Sentinel-2 overpass. The Dundalk Institute of Technology (DkIT) and Irish Centre for High-End Computing (ICHEC) compiled all the samples previously collected from individual lakes and TRAC waters. The historically collected, and later compiled, samples consisted of information about date, time, depth and location (latitude and longitude), in addition to water quality parameters such as chlorophyll, colour, turbidity, transparency, dissolved organic carbon (DOC) and temperature. Although the collected samples provide a large range of parameters, not all of the above listed parameters were collected from each location. These data will be made available to interested parties on SAFER, the EPA research data portal.

### *2.1.1 Data for lakes and for transitional and coastal waters*

A total of 4472 data points were collected from 21 preselected lakes from 2013 (8 January) to 2017 (12 December). Figure 2.1 shows the distribution of these lakes, most of which are concentrated in the northern half of the country. The lakes selected were of various sizes; the majority were greater than 5 ha in extent, with, in some cases, several stations per study site being used, ranging from two (Lough Derg in Donegal) to 17 (Lough Derg in Tipperary). Altogether data were available from 138 stations for lakes where field sampling was carried out regularly. A total of 8926 data points were collected from 35 TRAC locations from 2013 (14 January) to 2017 (16 November). Figure 2.1 shows the samples collected from TRAC locations distributed approximately uniformly across the country. Altogether we compiled data from 360 stations for TRAC where field sampling was carried out regularly.

## 2.2 Match-up Between Satellite Imagery and *In Situ* Data

### *2.2.1 Data overlaps for lakes*

The dataset was examined to identify those *in situ* sampling dates that coincided with archived Sentinel-2 images. These overlaps or match-ups between samples collected from lakes and Sentinel-2 images and *in situ* samples occurred only for around one-third (based on data availability) of the samples, as shown in Figure 2.2. A seasonal analysis was carried out to observe the trends in data collection overlaps. It could be seen that most of the field data collection was concentrated around the summer months, but many of the overlaps occurred in late summer. Among those matching, we filtered out the scenes (i.e. complete images) with ≥75% cloud cover. The details about the seasonality of the overlap are presented in Figure 2.3.

### *2.2.2 Data overlaps for transitional and coastal waters*

The overlap between TRAC waters and Sentinel-2 occurred for only around one quarter of the samples collected, as shown in Figure 2.4.

As with lakes, seasonal analysis was carried out for TRAC samples in order to observe overall trends and the seasonality of the overlaps. Unlike lakes, most of the data collection as well as overlap occurred during the summer months for Sentinel-2. The lack of data for late summer does not allow us to draw any conclusions. The details about the seasonality of the overlap are presented in Figure 2.5.

## 2.3 Field Validation Methodologies for Surface Waters

We employed historical field (back to 2013) samples to determine the best practices for sampling to optimise the temporal and spatial matchups between *in situ* lake measurements and satellite imagery. Historical

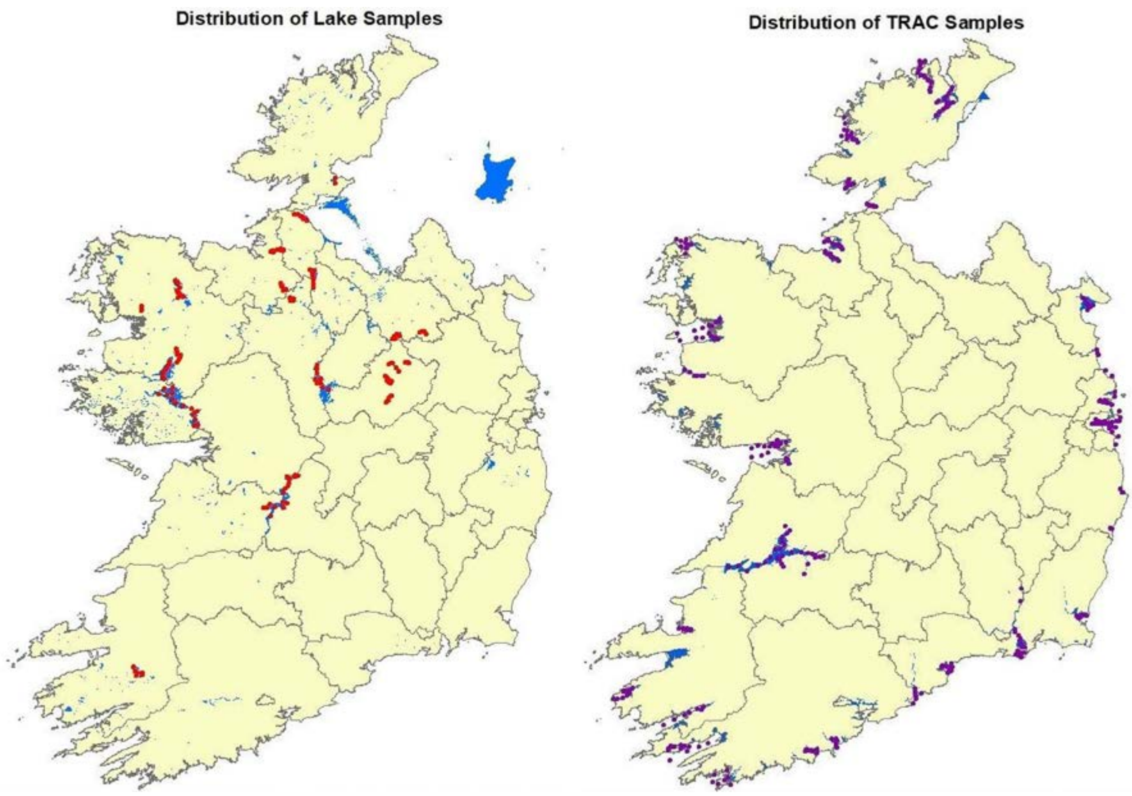



**Figure 2.1. (Left) Distribution of the 21 lakes for which data were collated for this study; blue polygons denote the lakes designated under the WFD. (Right) Distribution of TRAC samples in purple from 35 TRAC locations across Ireland; blue polygons denote the WFD transitional water bodies.**

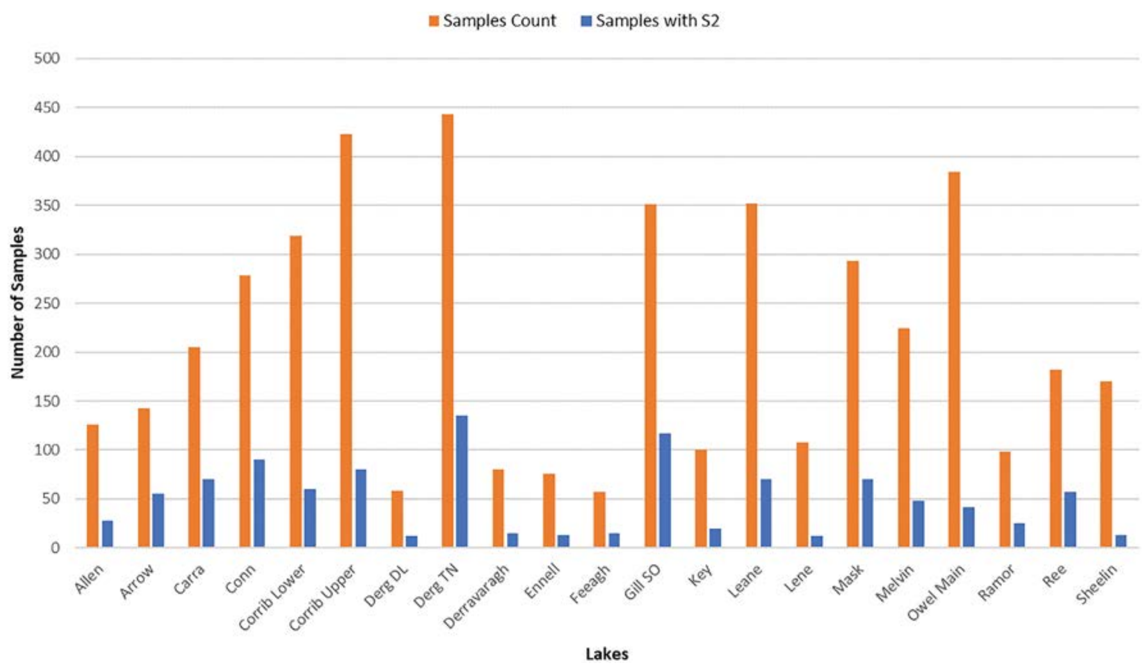



**Figure 2.2. Overlap between the historical lake samples and the Sentinel-2 scenes. The overlap varied for different lakes.**

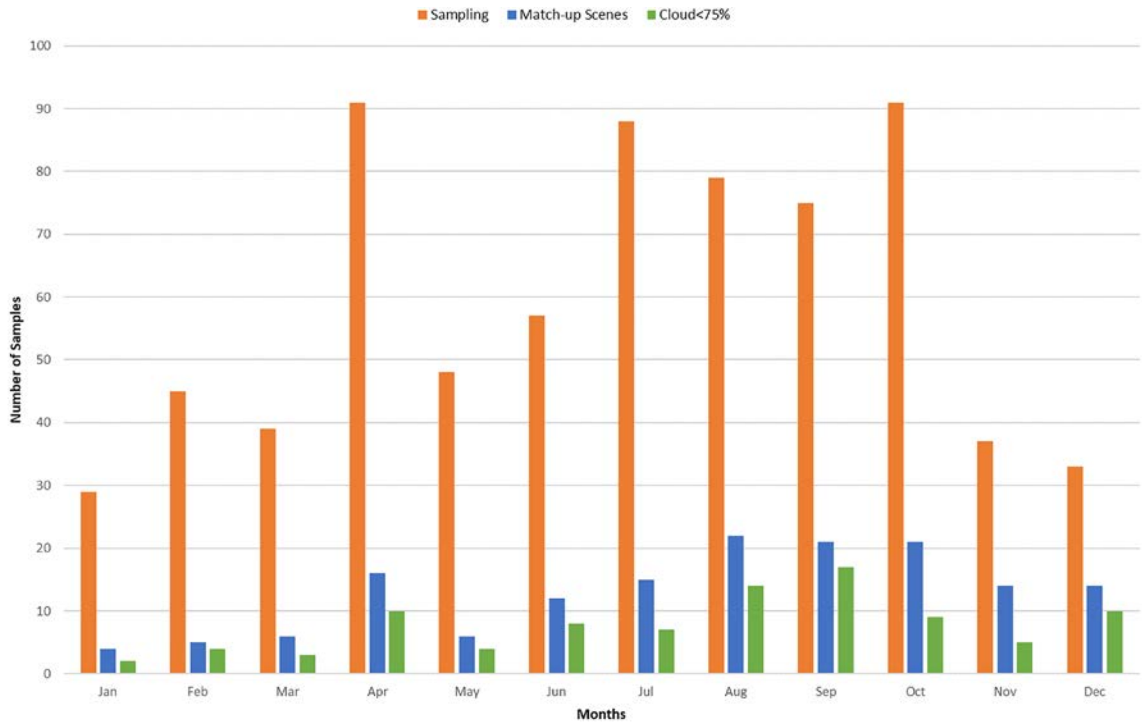



**Figure 2.3. Seasonal trends in the collected field samples and Sentinel-2 scenes for lakes. The number of match-ups after the removal of cloudy scenes (cloud cover <75%) is also displayed.**

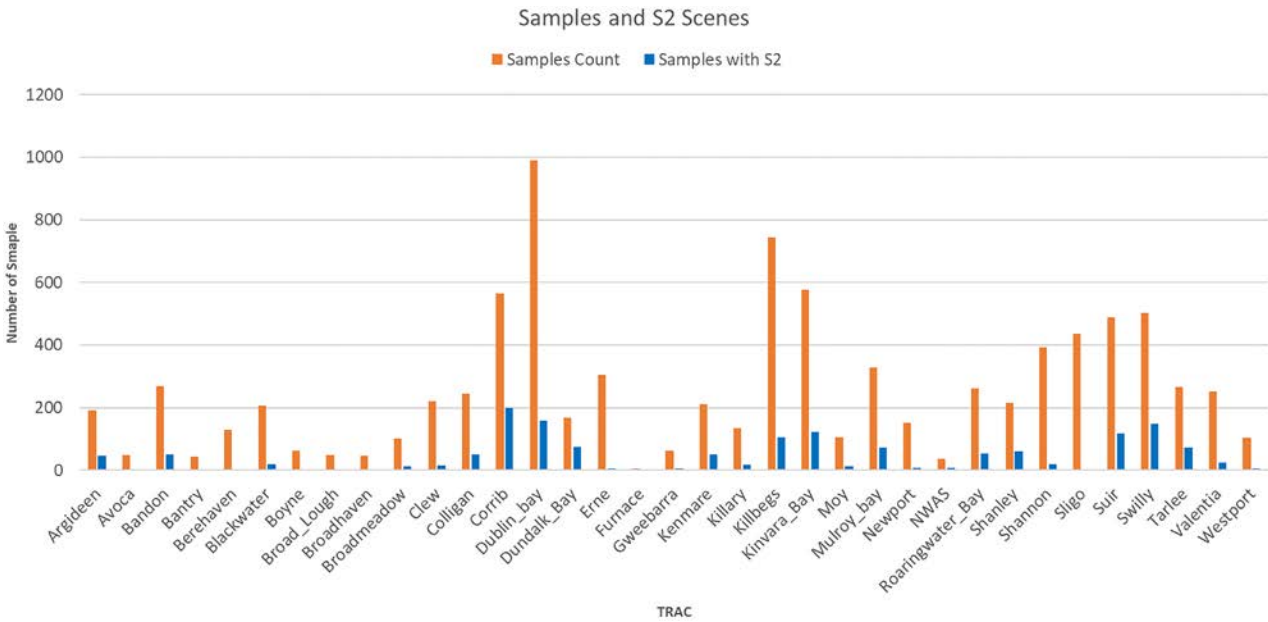



**Figure 2.4. Overlap between historical TRAC samples and Sentinel-2 dates at each TRAC location.**

*in situ* data together with bathymetry survey data were analysed to determine the influence of topographical lake conditions (e.g. bottom reflectance, adjacency) on the magnitude of reflectance. Additionally, the adjacency issue arises due to reflection of land radiance into nearby water pixels, impacting the accuracy of the top of the atmosphere radiance measured. Because of the relatively small size of inland water bodies, the adjacency problem also needs careful consideration. The objective of the adjacency correction algorithm is to quantify the noise from the surrounding pixels and to remove its interference into the target pixel. Every lake has a unique bathymetry and associated littoral zone, but these measures were

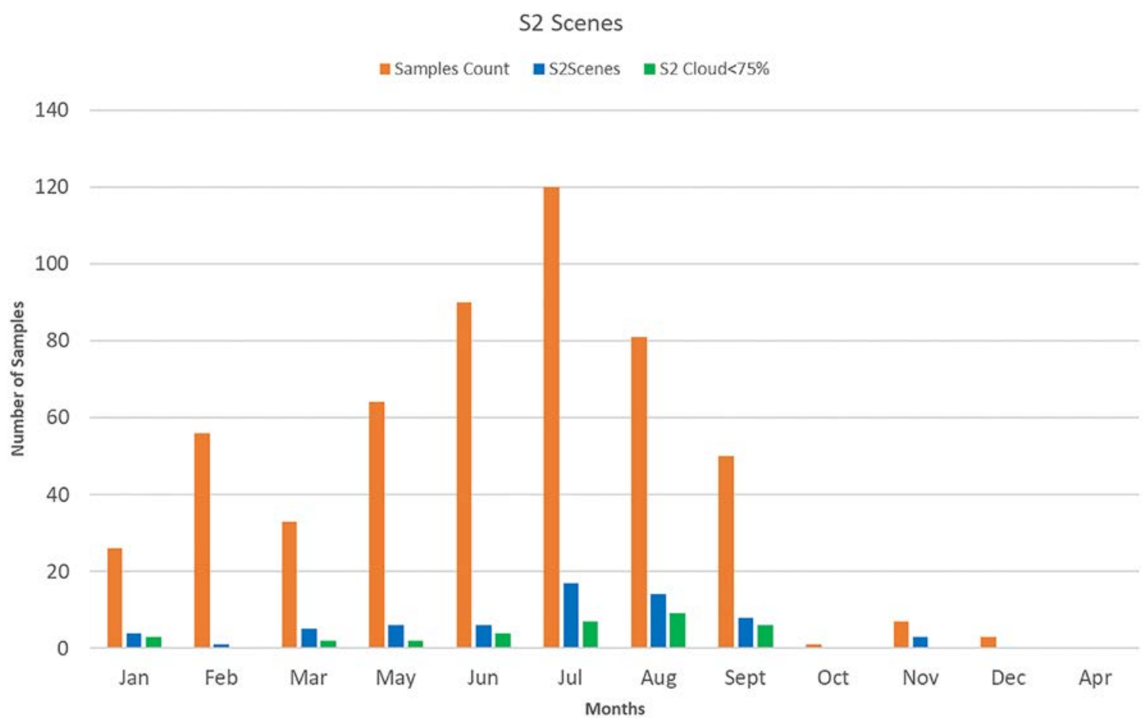



**Figure 2.5. Seasonal trends in the collected field samples and Sentinel-2 scenes for TRAC waters. The number of match-ups after the removal of cloudy scenes (cloud cover <75%) is also displayed.**

followed to minimise the potential effect of bottom reflectance and signal mixing, which is common in small and shallow lakes. Based on the analysis of the historically collected data from lake and TRAC waters, recommendations were made that the planned sampling efforts for the acquisition of field samples and atmospheric correction data collected at a time to correspond directly to a satellite overpass should be concentrated as much as possible to:

1. collect samples at least 10 m from shorelines to minimise the adjacency effect;
2. collect samples from water bodies at a depth of >6 m.

Additional recommendations regarding the collection of samples in the days of clear sky and optimal weather conditions were also made. These conditions were largely based on the need for calm lake surface in order to more easily acquire the necessary radiometric measurements using the methodologies deployed in this project (discussed in detail in section 3.3). These considerations helped to achieve better overlap between the field samples and EO data, enabling better calibration of the water quality algorithms.

# 3 Field Calibration and Atmospheric Correction Methodologies

## 3.1 Aims and Objectives

This section aims to provide an overview of the field methodology put in place to collect *in situ* water chemistry and atmospheric correction data for the calibration of proposed remote sensing models. This work proposed to provide the data that will optimise EO algorithms against new satellite data arising from Sentinel-2 satellites.

## 3.2 Overview of Field Sites for Calibration

Regardless of the algorithm or approach taken (empirical, semi-empirical or semi-analytical), the calibration and validation of remote sensing products utilising site-specific data collected in the field is an important step in the process of assuring that the satellite products are adapted to regional conditions or the particular characteristics of a lake under investigation. Field validation and calibration data can include water quality measurements and *in situ* radiometric data, which can be used to regionally adapt chosen bio-optical and atmospheric correction models and to assess their performance.

A site selection process was undertaken during the spring of 2019 to shortlist appropriate sites for field calibration of satellite-derived products. Field data collection included a range of *in situ* water quality parameters and the acquisition of atmospheric correction data. In total, 11 lakes and one TRAC site were sampled. Sites were selected based on several criteria such as size, depth, trophic status and WFD status, in addition to location and ease of access. Owing to the need to sample during clear days and at times that coincided with Sentinel-2 passes, it was necessary to focus on sites closest to the laboratory facilities for ease of deployment and immediate return to analyse samples.

A timetable for proposed sampling was established by drawing up a schedule of Sentinel-2 satellite overpasses starting from summer 2019, but this was dependent on weather conditions, with cloud-free, relatively calm conditions required to facilitate data acquisition for atmospheric correction. Sampling took place between July 2019 and August 2020, with a large disruption between February and June 2020 owing to the COVID-19 pandemic.

A summary of the sites sampled and their key characteristics is provided in Table 3.1. The lakes in the field campaign were divided between those that were part of the EPA WFD monitoring programme (seven lakes) and those that were unmonitored (four lakes). Some lakes were sampled on numerous occasions during this period. At least five sampling locations in each lake were selected on each sampling occasion and taken, where possible, at >6 m depth and more than 10 m from shore. The planned sampling of TRAC waters, which was to coincide with the WFD monitoring programme, was disrupted owing to the COVID-19 lockdown. Consequently, only a limited number of samples from Dundalk Bay were collected, and these were insufficient to use as calibration data, with the added complication of significant cloud cover on the sampling days.

## 3.3 Atmospheric Correction Methodology

The collection of *in situ* data from handheld radiometric devices can be considered free from atmospheric effects since the path from the sensor to the surface is negligible (Warren *et al*., 2019). These measurements can then be used to calibrate and validate atmospheric correction data of satellites. Numerous handheld and portable devices are available that can be used on boats, jetties and buoys (Groetsch *et al*., 2014; Charria *et al*., 2016) and either fixed in place to gather point measurements or used on boats to measure transects. All of these instruments measure radiance (measure light in a narrow angle) or irradiance (collect data from the hemisphere), which are incorporated into water-leaving reflectance measurements to remove variation in light conditions during the measurements (Ligi, 2017).

**Table 3.1. Summary of main characteristics of lakes used for calibration in this study**

| Lake (number of sampling occasions) | Coordinates | Surface area ($km^2$) | Maximum depth (m) | WFD typology class | WFD status (2015–2018) |
|---|---|---|---|---|---|
| Muckno (7) | 54.09821, –6.69117 | 3.57 | 30 | 8 | Poor |
| Sillan (3) | 54.00732, –6.92715 | 1.62 | 15 | 8 | Poor |
| Sheelin (1) | 53.81458, –7.32010 | 18.15 | 15 | 12 | Good |
| Owel (2) | 53.5749, –7.3926 | 10.22 | 22 | 8 | Good |
| Derravaragh (1) | 53.65828, –7.36587 | 9.14 | 23 | 10 | Good |
| Gill, Sligo (2) | 54.25036, –8.38203 | 13.81 | 31 | 8 | Moderate |
| Monalty (1) | 53.96718, –6.68070 | 15.3 | ~6 | 9 | Poor |
| Capragh (2) | 53.99525, –6.67989 | 0.12 | 12 | – | – |
| Corstown (1) | 53.86712, –6.64390 | 0.12 | 8.5 | – | – |
| Barnagrow (1) | 54.00964, –6.97682 | 0.39 | 15 | – | – |
| Whitewood (2) | 53.83734, –6.79529 | 0.35 | > 10 | – | – |

**Typology 8 = mean depth > 4 m, > 50 ha and moderate alkalinity (20–100 mg/$CaCO_3$).**
**Typology 9 = mean depth < 4 m, < 50 ha and high alkalinity (> 100 mg/$CaCO_3$).**
**Typology 10 = mean depth < 4 m, > 50 ha and high alkalinity (> 100 mg/$CaCO_3$).**
**Typology 12 = mean depth > 4 m, > 50 ha and high alkalinity (> 100 mg/$CaCO_3$).**

In this study, field hyperspectral radiometers were used to collect *in situ* radiometric data. A TriOS RAMSES ARC-VIS radiance sensor was used, which has a 256-channel silicon photo diode array detector that covers a spectral range from 320 to 950 nm. The pixel dispersion is 3.3 nm and the wavelength accuracy is 0.3 nm (Ligi, 2017). The field of view is 7° in the air and accuracy is better than 6%. This was used in conjunction with a TriOS RAMSES ACC-VIS irradiance sensor, which is similar to the radiance sensor but has a cosine collector and accuracy of 6–10% (Ligi, 2017). A two-sensor set-up was used, with an irradiance sensor ($E_d$) looking directly upwards and a radiance sensor looking directly downwards ($L_u$) (Figure 3.1).

A glint-free measurement technique described by Kutser *et al*. (2013) was used, which contrasts with the system used by Mobley (1994) that deploys an irradiance sensor looking directly upwards and two radiance sensors looking 42° from nadir and zenith, respectively, which aims to minimise sun glint from the surface as much as possible. However, this set-up is not considered ideal for inland waters, particularly in smaller lakes, where adjacency effects from nearby forests, or buildings in an urban setting, may interfere with the upwelling radiance sensor reading. Consequently, Kutser *et al*. (2013) proposed a method that allows glint-free reflectance to be measured without actual glint-free measurements. This is achieved by using a 5 cm black plastic tube attached to the Ramses radiance sensor. A second set of measurements is taken in addition to the upwelling ($L_u$) and downwelling ($E_d$) measurements, in which the Ramses irradiance sensor is held just above the water surface and the radiance sensor is held just below the water surface, allowing it to measure the actual water-leaving signal but without glint ($L_w$). Using this methodology, reflectance with no glint is measured ($L_w/E_d$) in addition to reflectance that does contain glint ($L_u/E_d$). A corrected spectrum is then obtained by subtracting the glint spectrum from the reflectance ($L_u/E_d$) (Kutser *et al*., 2013; Figure 3.2). This methodology, although more suited for inland water, is difficult to perform in rough conditions.

Between July 2019 and August 2020, *in situ* radiometric measurements were timed for selected field sites to match a satellite overpass in clear sky conditions, with as little cloud cover as possible. Initial trials using the glint-free measurement technique described by Kutser *et al*. (2013) were not successful. Even under what would be considered relatively calm conditions in Ireland, the water was consistently ‘choppy’ so that it was not possible to prevent the radiance sensor becoming completely submerged in water during glint-free measurements. Consequently, a number of different tube lengths were trialled in the laboratory to establish the longest length possible without interfering with the operation of the sensor. Following these trials, a 12 cm tube length was considered optimal, and a tube of this length was

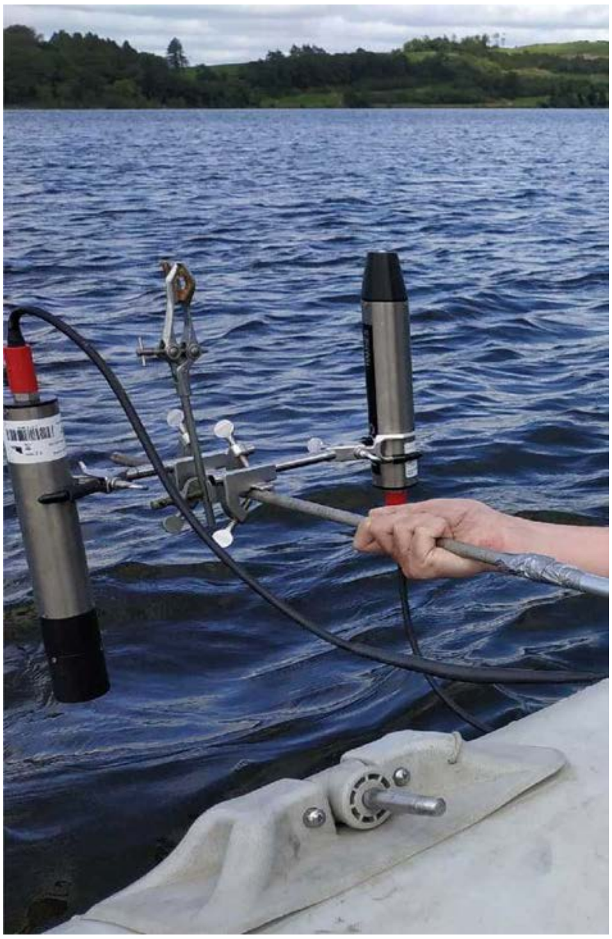


**Figure 3.1. TriOS RAMSES ARC-VIS (Rastede, Germany) radiance sensor with a TriOS RAMSES ACC-VIS irradiance sensor used to collect upwelling radiance ($L_u$) and downwelling irradiance ($E_d$), respectively.**

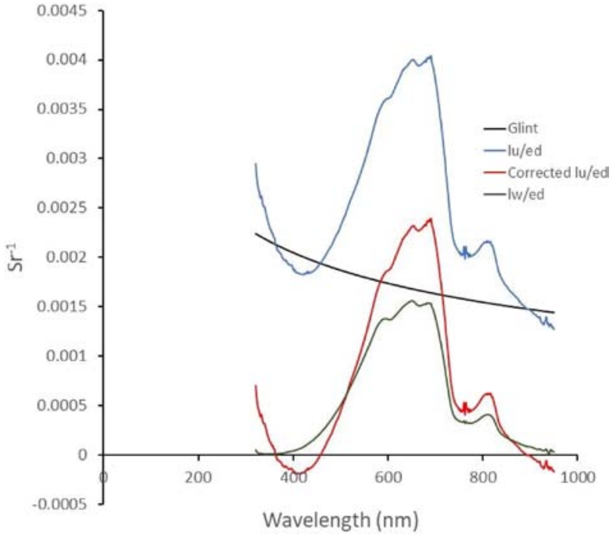



**Figure 3.2. Measurements of $L_u/E_d$ (blue) and corrected $L_u/E_d$ (red) using the glint removal procedure of Kutser *et al*. (2013) for Lough Muckno, 9 December 2019. $L_u$ = upwelling radiance; $E_d$ = downwelling irradiance; $L_w$ = water-leaving signal but without glint; $L_w/E_d$ = reflectance with no glint; $L_u/E_d$ = reflectance with glint.**

fabricated using 3D printing and successfully deployed thereafter (Figure 3.3).

Altogether, six data points from four different lakes were collected. The actual number of field campaigns and the dates and locations of radiometry are shown in Figure 3.4.

## 3.4 *In Situ* Water Sample Collection and Analyses

A GPS and a depth sounder (Hondex PS-7) were used to locate sampling sites. Water samples were collected for a range of water quality parameters that had the potential to be examined or to interfere with satellite remote sensing observations. Secchi depth transparency was measured by lowering a Secchi disk on the shaded side of the boat and recording the depth at which the disk was no longer visible, to the nearest 0.1 m ($d_1$). The disk was then slowly hauled up, and the depth at which the disk reappeared was again recorded to the nearest 0.1 m ($d_2$). The Secchi disk transparency was calculated by taking the arithmetic mean of these two measurements ($d_1$ and $d_2$). Dissolved oxygen, conductivity, pH and temperature were taken using a YSI 556 MPS multi-probe (Yellow Springs, OH, USA). Samples for assessing water chemistry were collected in 2 L pre-acid-washed high-density polyethylene bottles (HDPB), pre-rinsed with lake water prior to sample collection. All water samples were kept in the dark at 4°C until further analyses, which were carried out within 24–48 hours of collection. On-site unfiltered lake water was placed into 120 ml amber glass bottles and preserved with Lugol’s iodine solution to preserve phytoplankton for later identification and enumeration if necessary.

A subsample of water was filtered through Whatman 0.45 µm membrane filters to carry out full UV-Vis spectrophotometer scans and fluorescence excitation-emission matrices (EEMs). DOM absorbance was measured using a UV-Vis spectrophotometer (UV-1800, Shimadzu, Japan) to carry out full scans across wavelengths from 200 to 900 nm using a 1 cm glass cuvette and Milli-Q water as blank.


**Figure 3.3. TriOS ARC-VIS RAMSES radiometric sensor showing the original black 5 cm tube and the newly fabricated 12 cm tube, which was found to be more effective under the normally relatively windy conditions often experienced in Ireland.**

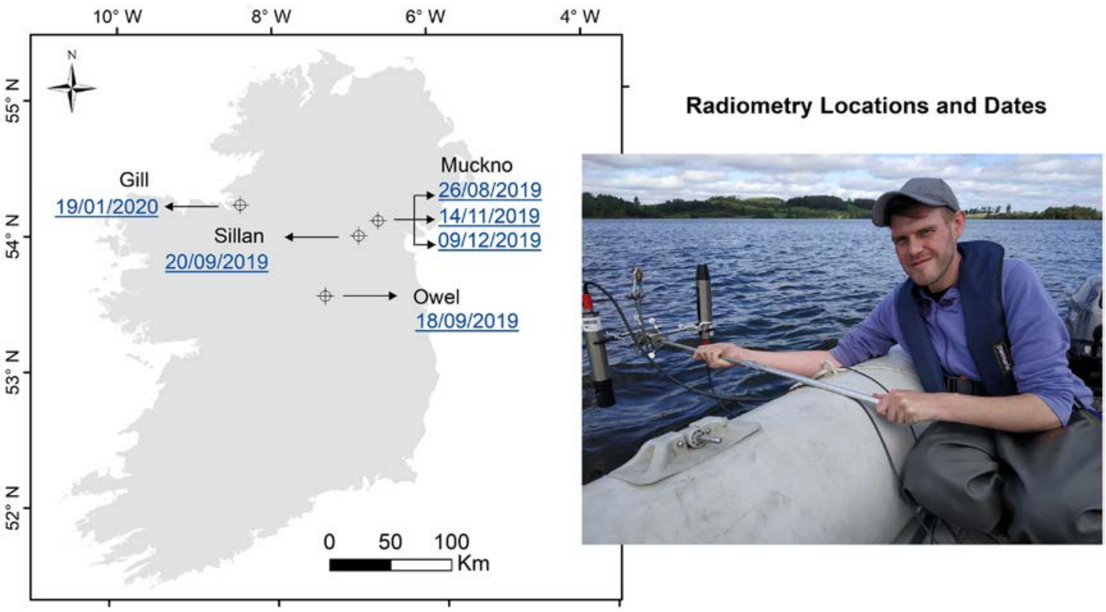



**Figure 3.4. Field radiometry locations and dates (left); Mr Kevin French from DkIT obtaining radiometric data (right).**

Absorbance units measured at 420 nm were used to characterise water colour (Weyhenmeyer *et al*., 2016). Fluorescence EEMs were characterised using a fluorescence spectrophotometer (Varian Cary Eclipse, Agilent Technologies, Santa Clara, CA, USA) in a 1 cm quartz cuvette. Fluorescence intensities were measured at excitation wavelengths ranging from 220 to 450 nm (at 5 nm increments) and emission wavelengths ranging from 240 to 600 nm (at 2 nm increments).

Chlorophyll *a* analyses were carried out on 1 L triplicate samples, filtered through Whatman GF/C filters on site and extracted with methanol (Standing Committee of Analysts 1980) with absorbance read in a spectrophotometer at 665 and 750 nm in a 5 cm cell. Alkalinity was analysed in a 50 ml unfiltered sample of lake water by Gran titration according to Mackereth *et al*. (1978). DOC was analysed in Whatman 0.45 µm membrane filtered water using a Sievers M5310 C Total Organic Carbon Analyser (range 4 ppb to 50 ppm, accuracy ±2% or 5% ppb). Suspended solids were measured by passing 1 L of water through a pre-combusted and weighted GF/F filter, which was dried at 105º C for 24 hours and re-weighed. The same filter was then combusted at 550ºC for 2 hours and re-weighed for the estimation of organic matter based on the loss-on-ignition method following Allen (1989).

## 3.5 Summary of *In Situ* Water Quality

Water chemistry data collected and analysed as part of the field calibration are summarised in Table 3.2. The highest concentrations of chlorophyll *a* were recorded in Lough Muckno, with a maximum value of 31.5 mg m$^{-3}$. The lowest mean chlorophyll *a* value was found in Lough Gill, with a mean ± SE of 0.40 ± 0.05 mg m$^{-3}$. The low values in Lough Gill are likely to be related to the time of the year, with one sampling trip in late November and the other in late January. The highest DOC, colour and total suspended solids (TSS) were recorded in Lough Muckno, although the lowest Secchi transparency was recorded in Lough Gill, as were the highest colour concentrations.

**Table 3.2. Mean ± standard error (SE) and sample size (*n*) of water quality parameters measured at each of the lakes sampled for field calibration (September 2019–August 2020)**

| Lake | Conductivity (µS cm$^{-1}$) | DO (mg L$^{-1}$) | Chlorophyll *a* (mg m$^{-3}$) | Colour (mg PtCo L$^{-1}$) | Secchi depth (m) | TSS (mg L$^{-1}$) | DOC (mg L$^{-1}$) |
|---|---|---|---|---|---|---|---|
| Muckno | 320.3 ± 23.8 | 10.37 ± 0.33 | 9.53 ± 1.31 | 42.1 ± 2.66 | 1.20 ± 0.07 | 4.62 ± 0.43 | 11.96 ± 1.03 |
| Mean ± SE<br>Range (*n*) | 209.3–500 (25) | 7.46–12.70 (25) | 1.62–31.56 (38) | 17.0–73.0 (38) | 0.7–2.10 (30) | 0.50–14.50 (33) | 3.90–24.60 (33) |
| Sillan | 413.4 ± 71.9 | 9.27 ± 0.61 | 9.03 ± 1.27 | 16.9 ± 4.56 | 1.23 ± 0.10 | 5.83 ± 0.64 | 8.97 ± 0.27 |
| Mean ± SE<br>Range (*n*) | 228–810 (10) | 6.68–11.4 (10) | 4.48–14.18 (10) | 1.0–34.0 (10) | 0.8–2.0 (10) | 2.10–8.20 (10) | 7.40–9.82 (10) |
| Sheelin | 617.6 ± 11.1 | 10.61 ± 0.26 | 4.35 ± 0.34 | 12.8 ± 1.28 | 3.69 ± 0.34 | 1.06 ± 0.34 | 8.07 ± 0.14 |
| Mean ± SE<br>Range (*n*) | 583–646 (5) | 9.93–11.19 (5) | 3.15–4.90 (5) | 9.0–16.0 (5) | 3.0–4.5 (5) | 0.30–2.30 (5) | 7.75–8.57 (5) |
| Owel | 378.6 ± 14.1 | 10.17 ± 0.17 | 2.28 ± 1.28 | 3.86 ± 1.06 | > 5 (7) | 3.26 ± 1.35 | 9.48 ± 0.98 |
| Mean ± SE<br>Range (n) | 316–413 (7) | 9.72–10.90 (7) | 0.31–8.88 (7) | 1.0–8.0 (7) | | 0.60–8.80 (7) | 5.68–12.0 (7) |
| Derravaragh | 387.4 ± 2.66 | 8.43 ± 0.12 | 5.80 ± 1.19 | 22.4 ± 0.24 | 3.80 ± 0.24 | 2.20 ± 0.44 | 8.43 ± 0.06 |
| Mean ± SE<br>Range (*n*) | 381–396 (5) | 8.05–8.68 (5) | 2.55–9.45 (5) | 22.0–23.0 (5) | 3.0–4.5 (5) | 1.00–3.30 (5) | 8.30–8.58 (5) |
| Gill, Sligo | 208.6 ± 0.91 | 11.09 ± 0.05 | 0.40 ± 0.05 | 103.7 ± 0.90 | 0.92 ± 0.03 | 1.05 ± 0.08 | 10.7 ± 0.14 |
| Mean ± SE<br>Range (*n*) | 204–214 (10) | 10.84–11.30 (10) | 0.20–0.66 (10) | 98–108 (10) | 0.8–1.1 (10) | 0.60–1.40 (10) | 10.15–11.37 (10) |
| Monalty<br>Range (*n*) | n/a[a] | n/a[a] | 13.1–14.9 (2) | 34–36 (2) | 1.00–1.25 (2) | 2.60–3.00 (2) | n/a[a] |
| Capragh | n/a[a] | n/a[a] | 8.93 ± 0.05 | 56.3 ± 9.85 | 1.56 ± 0.06 | 3.18 ± 0.49 | n/a[a] |
| Mean ± SE<br>Range (*n*) | | | 5.28–12.09 (4) | 35–74 (4) | 1.50–1.75 (4) | 2.20–4.20 (4) | |
| Corstown<br>Range (*n*) | n/a[a] | n/a[a] | 14.50–19.0 (2) | 35–49 (2) | 1.50 (2) | 1.9–2.2 (2) | n/a[a] |
| Barnagrow | n/a[a] | n/a[a] | 13.52 | 62 | 0.75 | 3.3 | n/a[a] |
| Whitewood<br>Range (*n*) | n/a[a] | n/a[a] | 12.5 (2) | 35–51 (2) | –1.25 (2) | 3.1–4.0 (2) | n/a[a] |

**[a]YSI probe and DOC analyser were malfunctioning during July and August 2020.**

# 4 Remote Sensing of Surface Waters using Sentinel-2 Imagery

## 4.1 Data Acquisition

The Sentinel-2 archive was scanned for cloud-free views of the sampled locations during the field campaign (September 2019–August 2020). Considering the fast-changing and unpredictable weather conditions prevalent in Ireland, it was difficult to obtain the exact overlap between cloud-free Sentinel-2 acquisition and a corresponding *in situ* water quality measurement. The goal was to get those imaged locations with a minimum number of days between a clear view from orbit and *in situ* sampling, but only 59 data points were useful, and the rest were discarded as no corresponding clear scenes (devoid of cloud or cloud shadow) were found. Almost half of the data had same-day acquisition, whereas an additional 25% of the data points had corresponding acquisition within 2 weeks.

## 4.2 Selection of Image Processor for Sentinel-2 Data

The ACOLITE and C2RCC processors were used to perform atmospheric correction and the computation of water quality parameters from the Sentinel-2 imagery. Ground truth data collected from field sampling and *in situ* radiometry were analysed and compared with the results obtained using a water quality processor on the satellite data. Figure 4.1 shows the detailed breakdown of the steps that were determined to yield the best performing data analytics workflow. For atmospheric correction, a dark spectrum fitting technique (Vanhellemont and Ruddick, 2018; Vanhellemont, 2019) was applied in ACOLITE, whereas a neural network-based technique (Brockmann *et al*., 2016) was used in the C2RCC processor to compute chlorophyll *a* and total

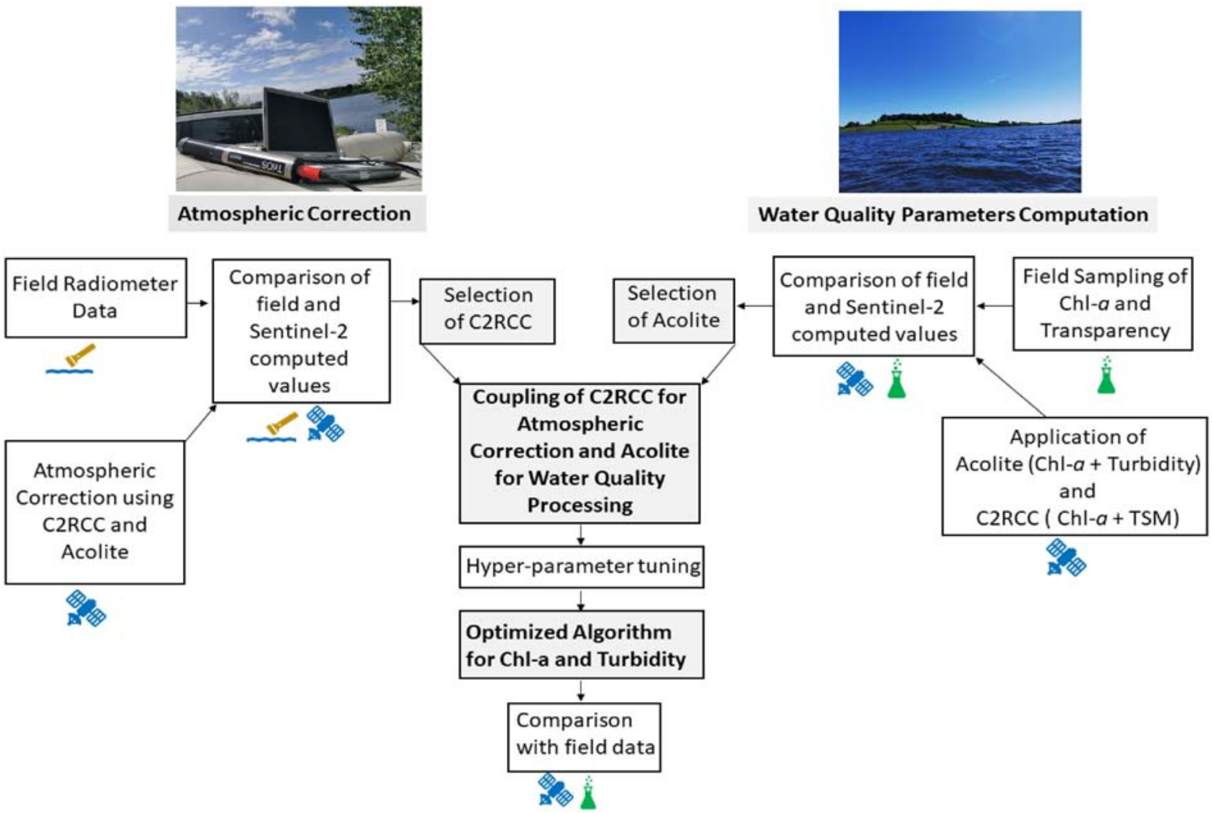



**Figure 4.1. Steps adopted to develop the optimised integrated workflow to process Sentinel-2 data suitable for comparison with ground truth field data.**

suspended matter (TSM). In the ACOLITE processor, different algorithms were analysed, and finally the red edge algorithm by Gons *et al*. (2002) was selected for processing chlorophyll *a* ($mg\,m^{-3}$), with published coefficients and a mass-specific chlorophyll *a* absorption of 0.015 using red edge bands from Sentinel-2. Similarly, the algorithm developed by Nechad *et al*. (2009, 2010) was used to compute turbidity (measured in Formazin Nephalometric Units, FNU) using ACOLITE, which uses the red band from Sentinel-2.

## 4.3 Atmospheric Correction Performance Evaluation

Sentinel-2-derived results were compared with those measured from field radiometry and sampling. The comparison of the field- and satellite-derived results showed that the C2RCC algorithm provided better estimates of atmospheric contribution than the ACOLITE processor. Figure 4.2 shows the measure of upwelling radiance ($L_u$) and downwelling irradiance ($E_d$) taken from the field radiometer at Lake Owel and Lake Sillan on 18 September 2019. The remote-sensing reflectance was then computed, which is the ratio of downwelling irradiance that is incident on the surface of the water to the portion that is returned through the surface. The graphs also show the estimation after the glint had been removed. The top-of-atmosphere reflectance ($R_{toa}$) or the reflectance before the atmospheric correction and the surface reflectance for water pixels ($R_{how}$) derived from both C2RCC and ACOLITE are also shown in the graph. The surface reflectance after atmospheric correction from both processors was compared with the field radiometric measurements. The reflectance for water pixels from C2RCC ($R_{how}$, shown in brown) provides a better approximation of the glint-free ($L_u/E_d$) measurement from the radiometer than the one from ACOLITE ($R_{how}$, shown in black). Based on the similar comparison for all the locations of field radiometry, C2RCC was selected for the atmospheric correction of Sentinel-2 imagery.

## 4.4 Water Quality Parameter Validation

Sentinel-2-derived water quality results were compared with those measured from field sampling. From each sampled location, chlorophyll *a* ($mg/m^3$) and transparency (m) measurements were taken. The C2RCC processor was used to compute chlorophyll *a* and TSM, whereas the ACOLITE processor was able to compute chlorophyll *a* and turbidity.

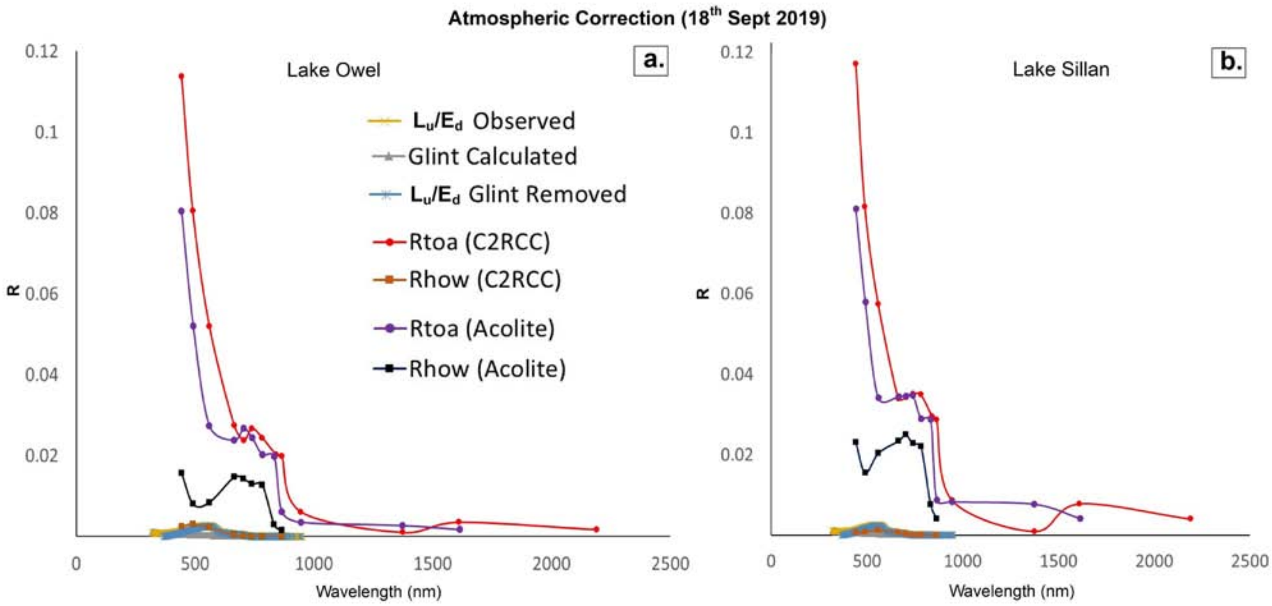



**Figure 4.2. Comparison of atmospheric correction results and field radiometer data for Lough Owel (a) and Lough Sillan (b). Each plot shows the computed top-of-atmosphere reflectance ($R_{toa}$) and surface reflectance for water pixels ($R_{how}$) derived from both ACOLITE and C2RCC processors, as well those derived from the ground truth data.**

Comparing the results for turbidity, TSM and field transparency, the ACOLITE processor showed a better approximation of the field condition than the C2RCC processor, but the relationship between transparency and TSM is not straightforward (inverse relationship between Secchi depth and TSM for water bodies with less CDOM) for Irish lakes and is affected heavily by the presence of CDOM (Free *et al*., 2000). Similarly, the chlorophyll *a* estimation from the ACOLITE processor showed better approximation of the field measurements than that from C2RCC. For both TSM and chlorophyll *a* estimation, the results were concentrated around very low values compared with the field measurements. This observation was not consistent with the behaviour of the C2RCC processor during atmospheric correction, when it performed better than the ACOLITE processor. When comparing the surface reflectance for water pixels ($R_{how}$) from C2RCC and ACOLITE, it is evident from Figure 4.3 that the surface reflectance from C2RCC is closer to the radiometric measurements. This suggests that the sets of trained neural networks used in the model contribute to the better performance of C2RCC regarding atmospheric correction, but not to the water quality parameters as shown in Figures 4.4 and 4.5.

## 4.5 Model Optimisation

Based on the overall results, a coupled approach was developed whereby the atmospheric correction was carried out using the C2RCC and the water quality parameters were computed using techniques adopted in the ACOLITE processor (chlorophyll *a:* Gons *et al*. 2000; turbidity: Nechad *et al*. 2009,

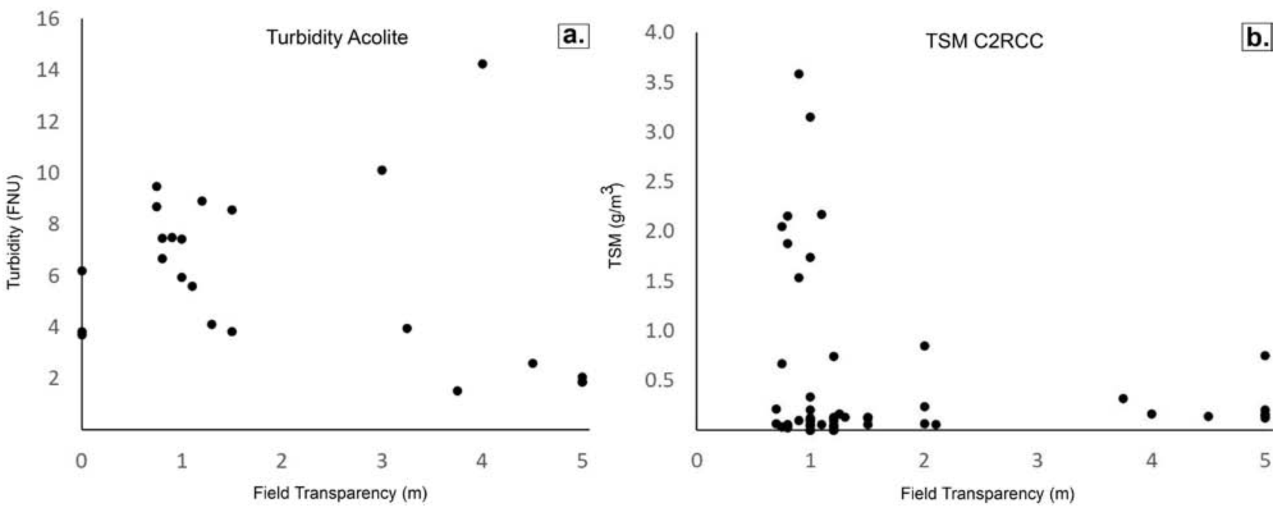



**Figure 4.3. Turbidity (FNU) and TSM (g m$^{-3}$) computation results from ACOLITE and C2RCC, respectively. C2RCC shows the overall underestimation of values.**

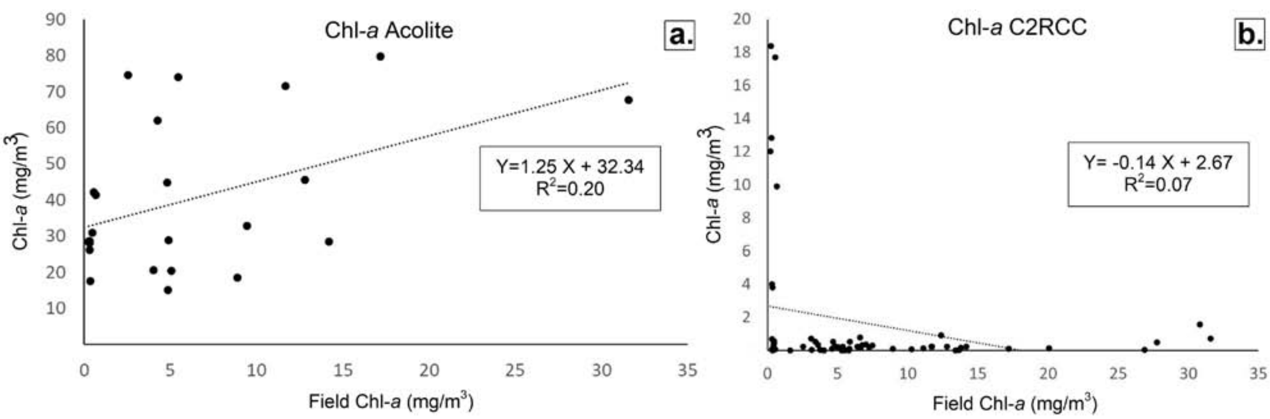



**Figure 4.4. Chlorophyll *a* (mg m$^{-3}$) computation results from ACOLITE and C2RCC, respectively. C2RCC shows the overall underestimation of values.**

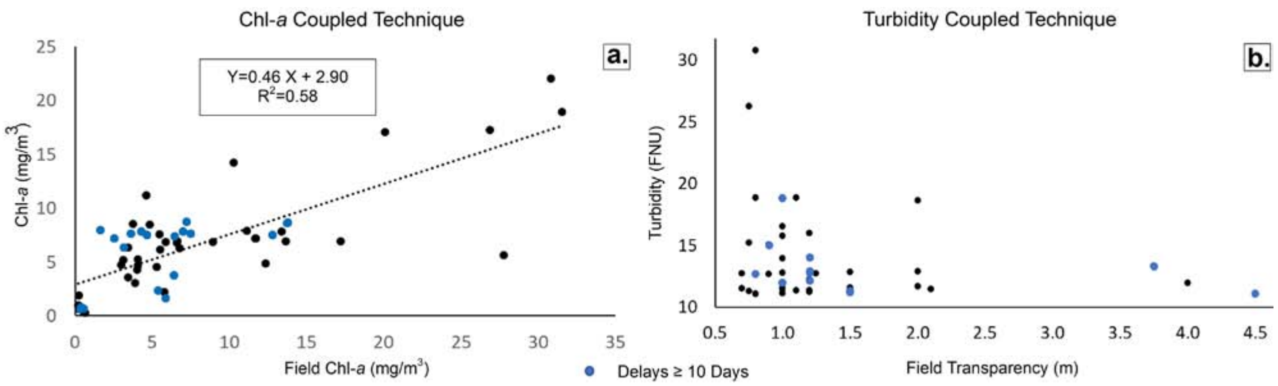



**Figure 4.5. Chlorophyll *a* (mg m⁻³) and turbidity (FNU) computation results from coupled technique. Delays of more than 10 days are shown in blue.**

2010). It is worth mentioning that the ACOLITE processor provides multiple algorithms to choose from [chlorophyll *a*: chl_oc2, chl_oc3 (Franz *et al*., 2015), chl_re_gons, chl_re_gons740 (Gons *et al*., 2000, 2002), chl_re_moses3b, chl_re_moses3b740 (Moses *et al*., 2012), chl_re_mishra (Mishra and Mishra, 2012); turbidity: tur_nechad2009ave, tur_nechad2016, tur_nechad2009 (Nechad *et al*., 2009, 2010), tur_dogliotti2015 (Dogliotti *et al*., 2015)], but the selected options provided the best results for our consideration (sentinel bands, resolution, size of the lakes, etc.).

The parameters were tuned in this coupled algorithm to better reflect the field measured samples, in effect bringing the differences apparent in Figure 4.2 into concordance, and, in so doing, correcting for the local/boundary layer atmospheric effects associated with such water body contexts. The results from the final algorithm are presented in Figure 4.5. The coupled technique showed better approximation of field measurements than each standalone processor. The graph also shows the data points for water quality products with the scene where the time delay (between the Sentinel acquisition and *in situ* measurements) is more than 10 days. The reason for showing these data with long delays was to highlight the complexity of trying to get data with short delays. The data with delays of more than 10 days were thus not considered in validation steps. The figure shows that the results from coupled algorithm for chlorophyll *a* are better than those for turbidity. Additionally, it is important to note that turbidity is affected by phytoplanktonic growth, but it is not entirely reasonable to consider only chlorophyll *a* for water quality since turbidity accounts for non-planktonic contribution. Because of the lack of appropriate field datasets for TRAC on the day of Sentinel-2 acquisition, no TRAC datasets were used in model optimisation. Because of the transitional and turbulent nature of the TRAC water bodies, unlike lakes, TRAC samples require more synchronisation between the field sampling and satellite overpass times. The field data collection efforts for TRAC were highly disrupted by the pandemic, and all the collected data were at least a few weeks apart from a cloud-free overpass and were thus unusable for model optimisation.

## 4.6 Model Validation with Historical Data

For the validation task historical datasets from different lakes and TRAC water bodies were scanned for possible overlap with the Sentinel-2 scenes. Different types of lakes and TRAC water bodies were selected to make the study as comprehensive as possible.

### *4.6.1 Data overlaps for lakes and for transitional and coastal waters*

The validation tasks focused on eutrophic, mesotrophic and oligotrophic lake types. Figure 4.6 shows the types of lakes and sample distribution used for data validation. Figure 4.7 shows the comparison of the historical data with those computed using the coupled technique developed in this project. The maximum time delay between sampling and Sentinel-2 image acquisition was 4 days. The results show good model performance in mapping water quality for oligotrophic and mesotrophic lakes compared with eutrophic lakes. Because of this limitation, although the model at this state cannot be implemented for full-scale WFD monitoring, it can provide general

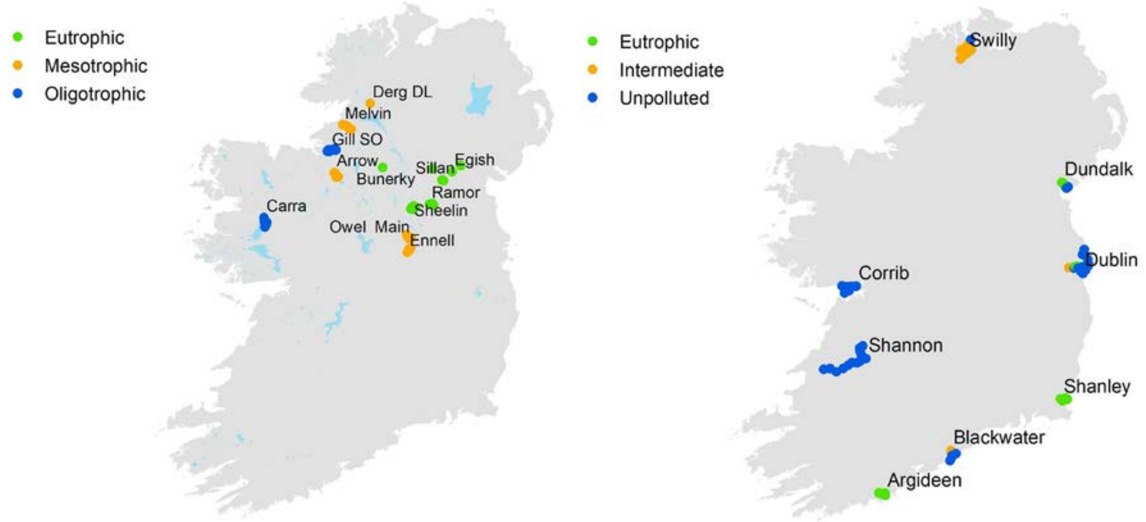



**Figure 4.6. The distribution of lakes considered for validation (left) and the distribution of TRAC water bodies considered for validation (right); both are based on the availability of field data and corresponding Sentinel-2 scenes.**

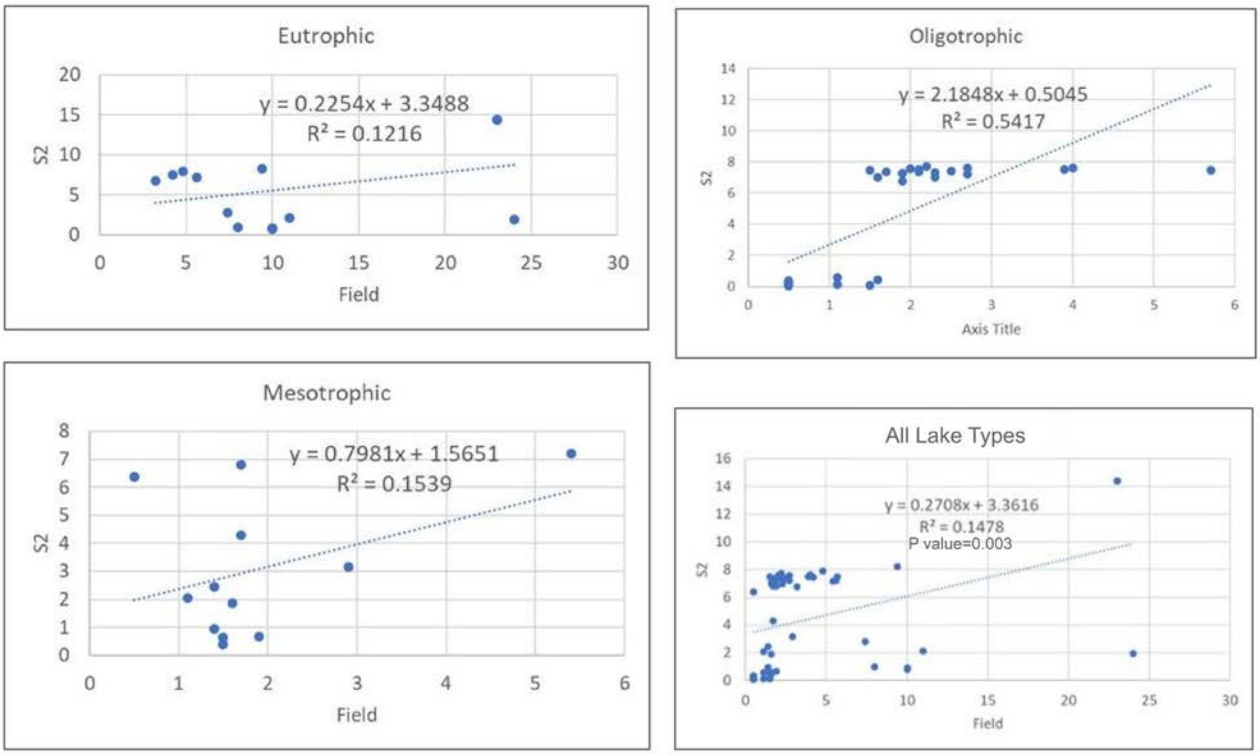



**Figure 4.7. Chlorophyll *a* (mg m$^{-3}$) concentration computed from Sentinel-2 using coupled algorithm (*y*-axis) compared with the field measurements for eutrophic (13 samples), mesotrophic (12 samples), oligotrophic (31 samples) and all lake types. The maximum time delay is 4 days in all cases.**

guidance regarding water quality class and ecological status. Thus, improvements would be expected in the case of synchronised imaging/sampling to better assess the water quality of each lake type. The current investigation relied on limited number of samples from each lake type, and, therefore, additional sampling and validation has the potential to further refine the algorithm.

The validation tasks for TRAC focused on eutrophic, intermediate and unpolluted locations based on formal EPA classifications. Figure 4.6 shows the types of TRAC water bodies and the distribution of samples used for data validation. Figure 4.8 shows the comparison of the historical data with those computed using the coupled technique developed in this project. The maximum time delay was restricted to 1 day because of the turbulent nature of TRAC water bodies. The results show that, unlike with lakes, the model works better for eutrophic and intermediate TRAC locations than for unpolluted locations. Although this is not significant, it allowed the water quality of systems that need frequent monitoring (eutrophic and intermediate compared with unpolluted) to be mapped.

## 4.7 Remote Sensing for Continuous Monitoring

The coupling of atmospheric correction, water quality parameter processing and subsequent hyperparameter tuning as previously described offers a means of implementing a remotely sensed mechanism to infer regional water quality measurements across Ireland and at spatial scales that would be impossible to survey locally. In Figure 4.9 we demonstrate how this methodology may be used to capture water quality estimates at scale for three lakes currently monitored as part of the WFD. In the cases of Loughs Sillan and Muckno, localised 'grab sampling' would not, or would not be likely to, identify the full distribution and extent of chlorophyll *a* concentration for either lake. Using the methodology developed as part of this project, a fuller picture regarding the spatial distribution of the chlorophyll *a* concentration can be provided. While comparing the results from the field observations, one sample at a location might be attributed for a lake, but the map generated from the coupled algorithm shows the spatial distribution across the entire lake area.

In Figures 4.10 and 4.11 we show how the use of remote sensing data offers a powerful means of temporally monitoring the spatial variability of such water bodies. The figures show the chlorophyll *a* and turbidity for Lough Egish with an area of around 1 km² in the Drumlin Belt region close to the border

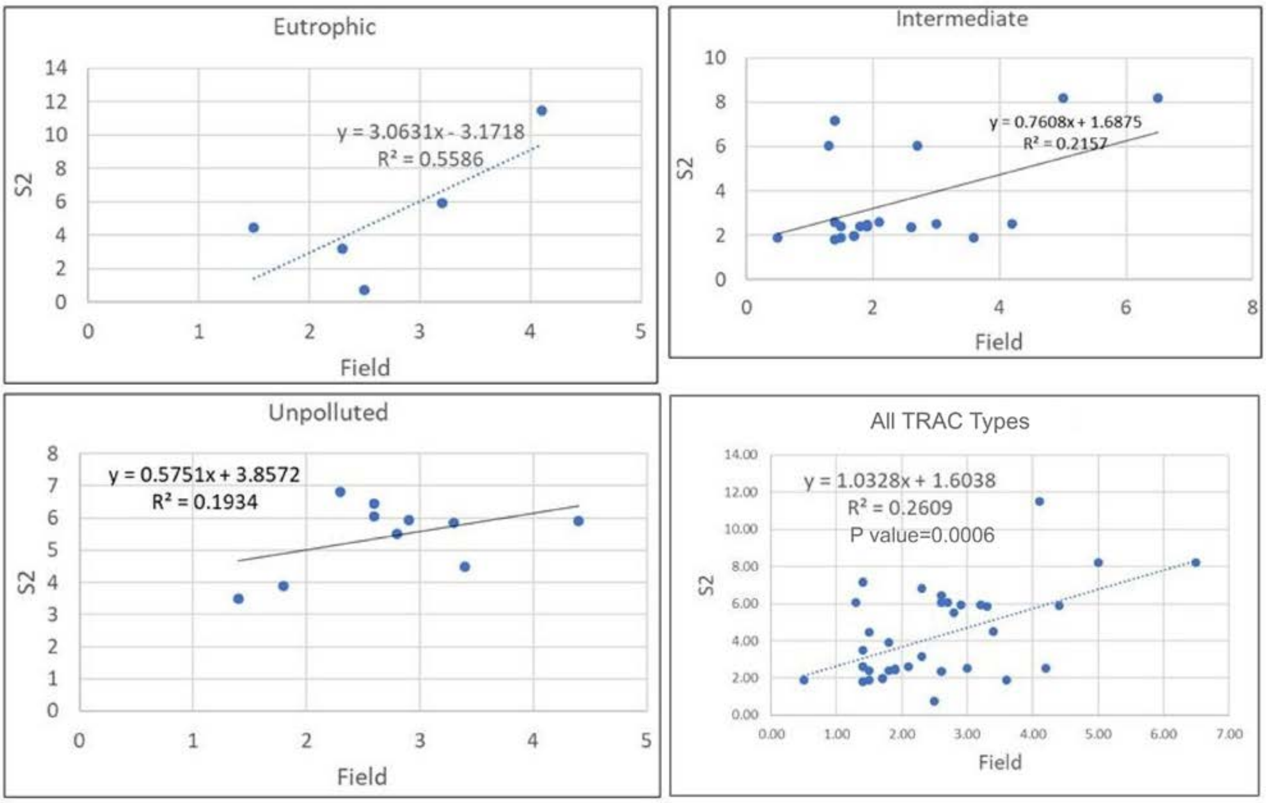



**Figure 4.8. Chlorophyll *a* (mg m⁻³) concentration computed from Sentinel-2 using coupled algorithm (*y*-axis) compared with the field measurements for eutrophic (five samples), intermediate (26 samples), unpolluted (10 samples) and all TRAC types. The maximum time delay is 1 day in all cases.**

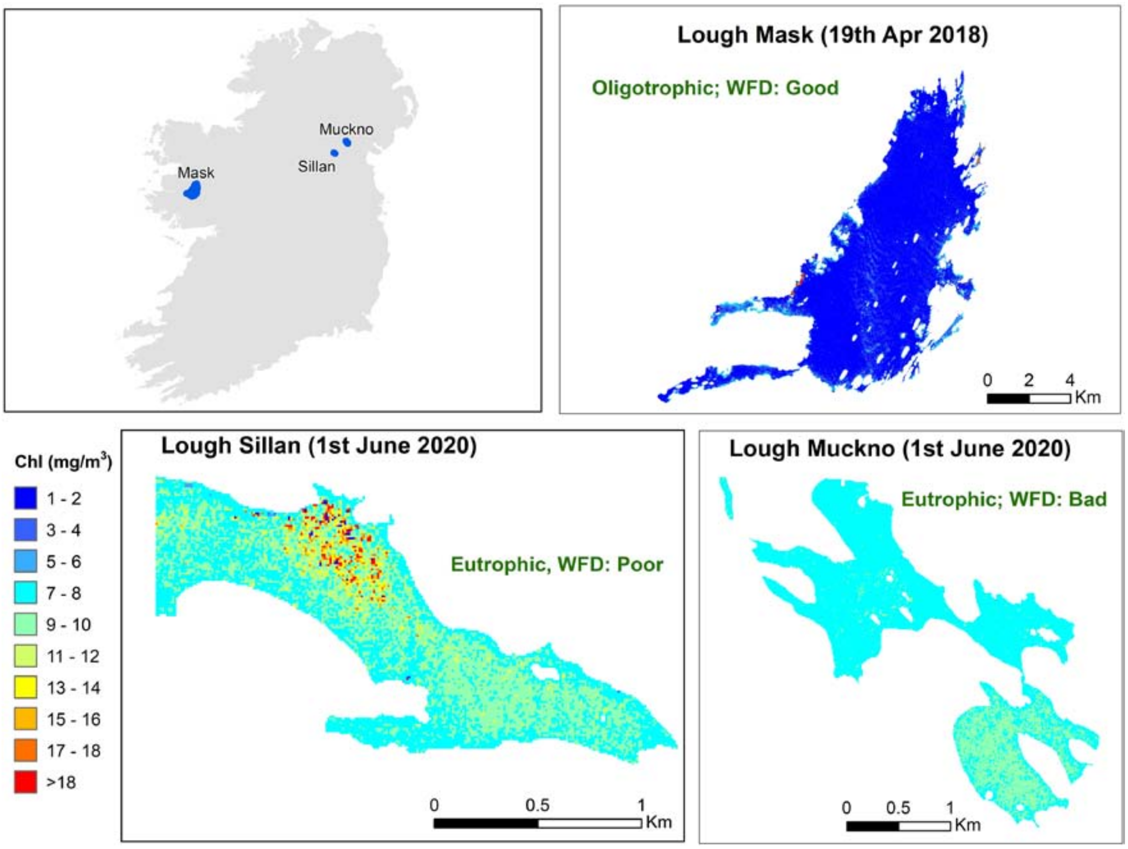



**Figure 4.9. Predicted chlorophyll *a* (mg m$^{-3}$) concentrations for Lough Mask, Lough Sillan and Lough Muckno using the coupled remote sensing workflow developed as part of this project.**

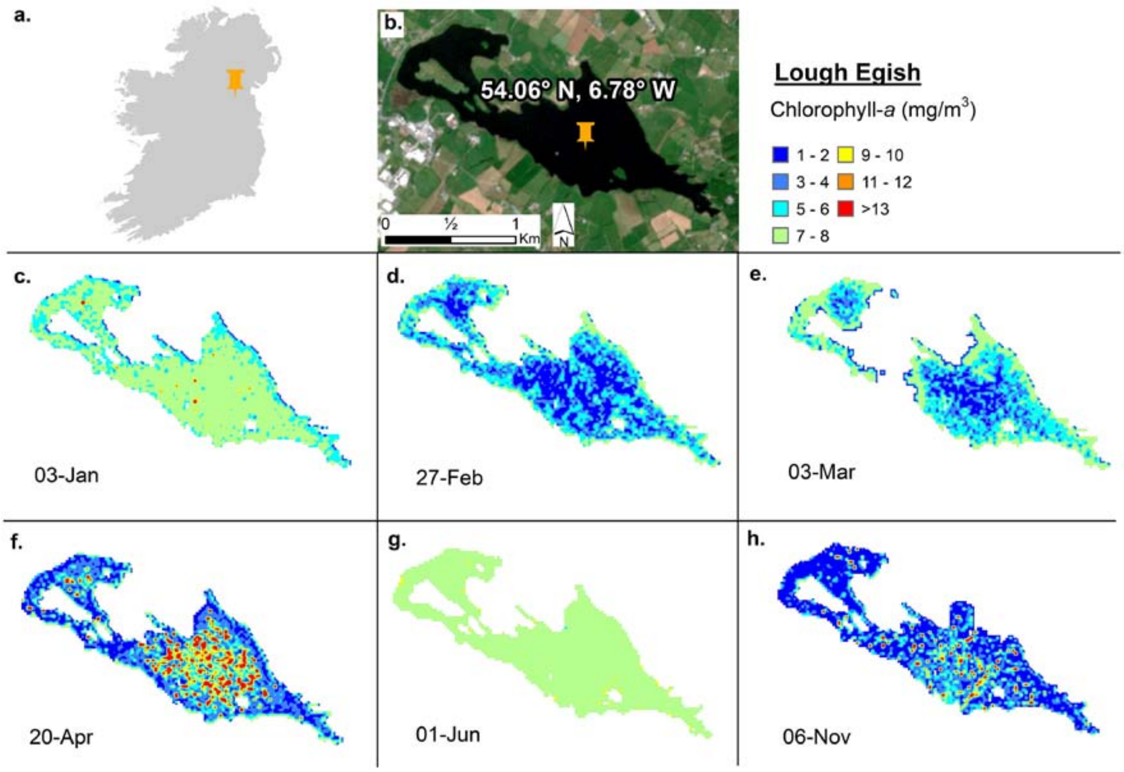



**Figure 4.10. Chlorophyll *a* (mg m$^{-3}$) results from the coupled technique for Lough Egish using the Sentinel-2 images acquired from January to November 2020.**

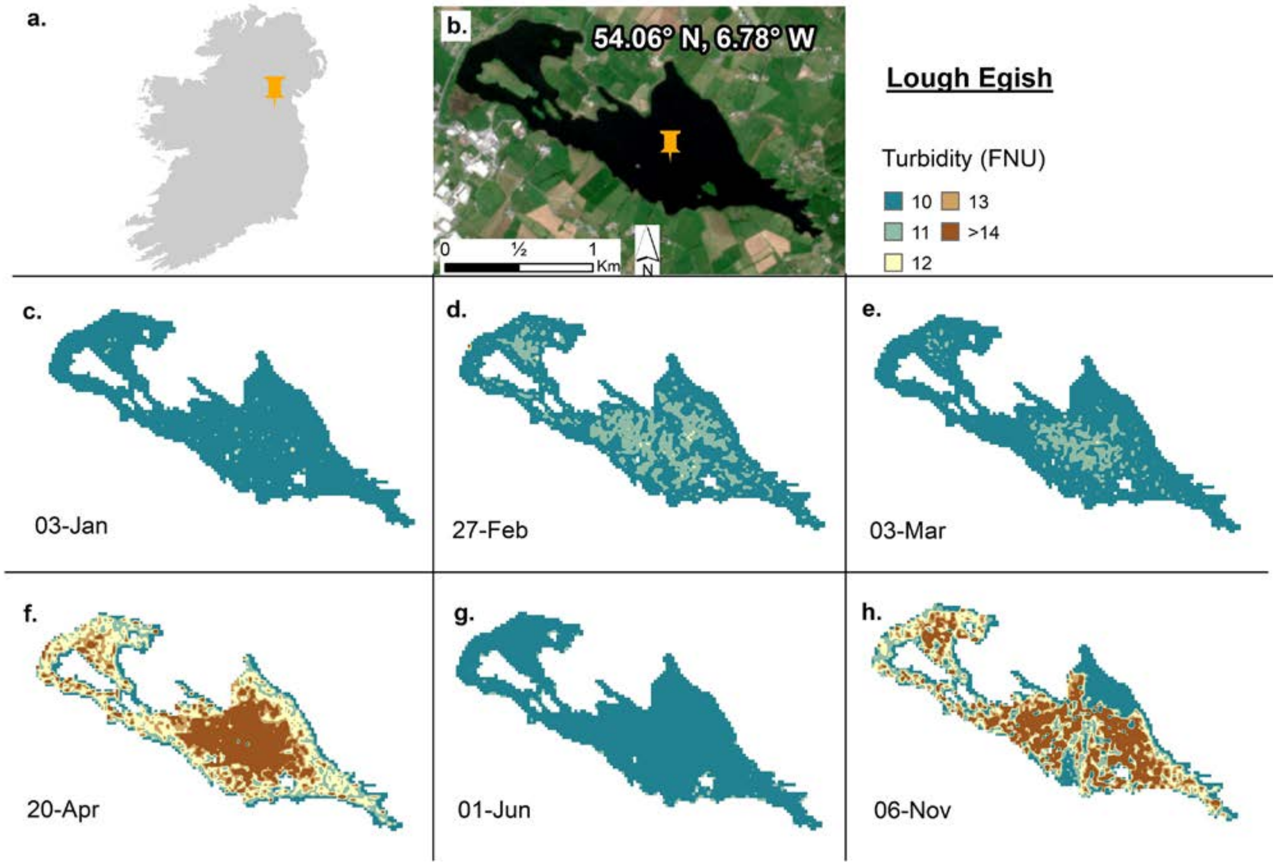



**Figure 4.11. Turbidity (FNU) results from the coupled technique for Lough Egish using the Sentinel-2 images acquired from January to November 2020.**

with Northern Ireland. All the cloud-free scenes available for 2020 were used to monitor water quality for a total of six months (January, February, March, April, June and November). Figure 4.10 shows the seasonal fluctuation of chlorophyll *a* whereby it had lower magnitudes during the winter (early January) and then slowly increased during the spring (April) and decreased again during mid-summer (June). Comparing the results with the values from catchments.ie (https://www.catchments.ie), it was found that the chlorophyll *a* values based on satellite estimates peaked in April, similar to the peak in observed *in situ* values taken that month. Nevertheless, remote sensing estimates remained below those comparable values taken in the field between April and August 2020, indicating a need for further model calibration and validation. (For example, the closest *in situ* value to satellite estimate during this period was taken in April. Maximum satellite-derived estimates on 20 April 2020 ranged from 9 to 12 mg m$^{-3}$; however, *in situ* values taken on 22 April 2022 ranged from 42 to 44 mg m$^{-3}$.) The coupled algorithm enabled the spatial distribution and seasonal trend or short-term variation (for example comparable concentrations in January and June) that can help investigate local conditions. Figure 4.11 shows a similar trend for 2020, with lake turbidity peaking during early spring and autumn (November). Both chlorophyll *a* and turbidity show similar levels of seasonality, as phytoplankton growth is likely to contribute to turbidity concentrations.

## 4.8 Earth Observation Platform

The current system providing water quality (chlorophyll *a* and turbidity) data to the INFER GIS web portal (https://eoplatform.ichec.ie/infer) consists of a series of Python scripts that wrap the different software used to generate the water quality maps. First, the Sentinel-2 data are downloaded from the European Space Agency's SciHub (https://scihub.copernicus.eu) platform when new data over Ireland become available. Then a series of processing scripts using SNAP graph-builder command line capabilities and Quantum GIS (QGIS) toolkits is run on the data to

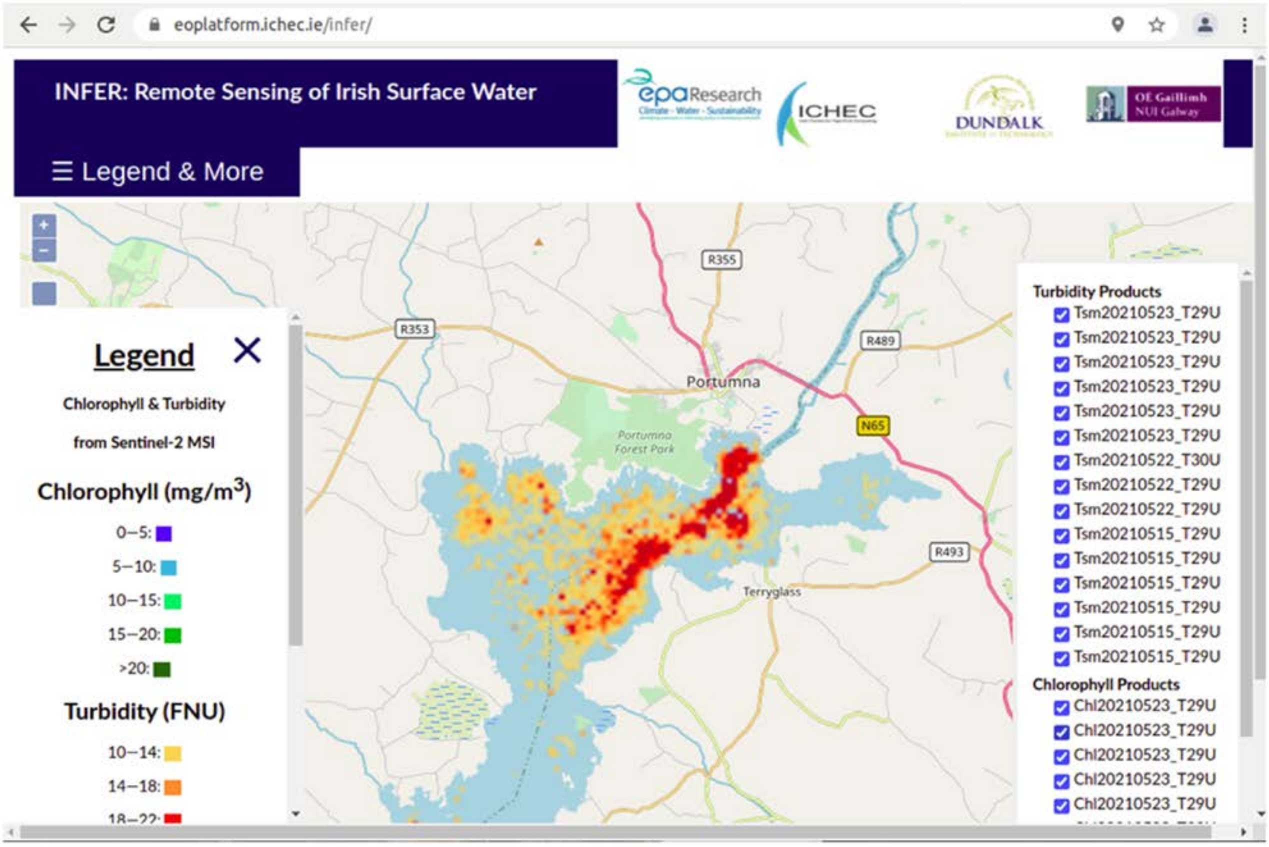



**Figure 4.12. Screen capture of the EO platform showing chlorophyll *a* (mg m$^{-3}$) and turbidity (FNU) products from Sentinel-2 near Portumna, Co. Galway, in the summer of 2021.**

carry out atmospheric correction, scene identification and water parameter estimation. The final products are posted to the web server and displayed using a JavaScript-based platform (see Figure 4.12). The resulting maps of chlorophyll *a* and turbidity can be explored on the platform as shown in Figure 4.12. Currently this is the prototype of the website and displays the water quality products for the last 15 days only.

# 5 Data Mining the Landsat Archives for Cloud-free Observations of Irish Lakes

As explained in previous sections, Landsat data were not used as they were considered inappropriate for the development of a near-‘real-time’ water quality remote sensing infrastructure. Sentinel-2 offers higher image resolution and more frequent passes over Ireland. However, it was also noted that an extensive archive of Landsat imagery covering over four decades is available to researchers, and this offers the possibility of studying and comparing specific lake and TRAC water body locations with existing *in situ* monitoring data. This investigation necessitated the use of free Cloud services to access and analyse the EO data. Subsequently, this presented the opportunity to assess the feasibility of using Cloud-based infrastructure to explore and analyse such data in the context of remotely sensed water quality.

## 5.1 Open Data and Cloud Computing for Earth Observation

In 2008, the USGS adopted an open data policy for all Landsat imagery, making the data freely available to any organisation or individual and thus removing the financial barriers that had previously existed when each image had to be purchased individually. Although accessing images became free, the open data policy did not eliminate the significant costs of storing, processing and computing large collections of Landsat data. However, in recent years there has been a change in thinking about how Landsat and Sentinel-2 datasets are shared, and, consequently, about how such data are analysed. This shift has been brought about by the rise of Cloud computing technologies developed by Google and Amazon. Both Google Cloud Platform[2] and Amazon Web Services[3] have created archives of EO data on their Cloud platforms. These archives are curated and updated with the latest images as soon as these are made available. In addition, numerous tools are provided to help users access and analyse the data. The ability to access petabytes of EO data and to process these in a cost-effective manner remotely has both revolutionised and democratised EO analytics.

## 5.2 Processing Landsat Imagery using Google Earth Engine

To help promote the use of EO for environmental analysis, the Google corporation created Google Earth Engine (GEE), a free-to-use platform for scientific analysis and visualisation of geospatial datasets for academic, non-profit business and government users (Gorelick *et al*., 2017). The interface of GEE (Figure 5.1) is a standard web page with which the user interacts using JavaScript code to process Google’s EO archives within the Google Cloud Platform – access is mediated by the user’s Google account. The results of any deployed scripts, which appear to run on the browser, are displayed on the same page. In Figure 5.1, the GEE web page is divided into three panes: one contains the JavaScript (top left), one contains output (top right) and one contains the EO image (bottom panel). The user writes JavaScript that uses the GEE analysis library to process the EO archive of interest. All Cloud infrastructure resources, such as virtual machines, data assets and storage, are handled automatically by the GEE.

## 5.3 Curating the Landsat Image Archive for an Irish Context

Using bespoke scripts on GEE to query the 1.3-petabyte Landsat archives’ metadata, images were identified from when Landsat’s position coincided with observational images of Ireland from the start of the Landsat programme in 1972. In Figure 5.2, we show the associated incidence of image acquisition following this survey. Summary statistics of the cloud coverage of Landsat scenes that contain Ireland were

2 https://cloud.google.com/storage/docs/public-datasets

3 https://registry.opendata.aws/

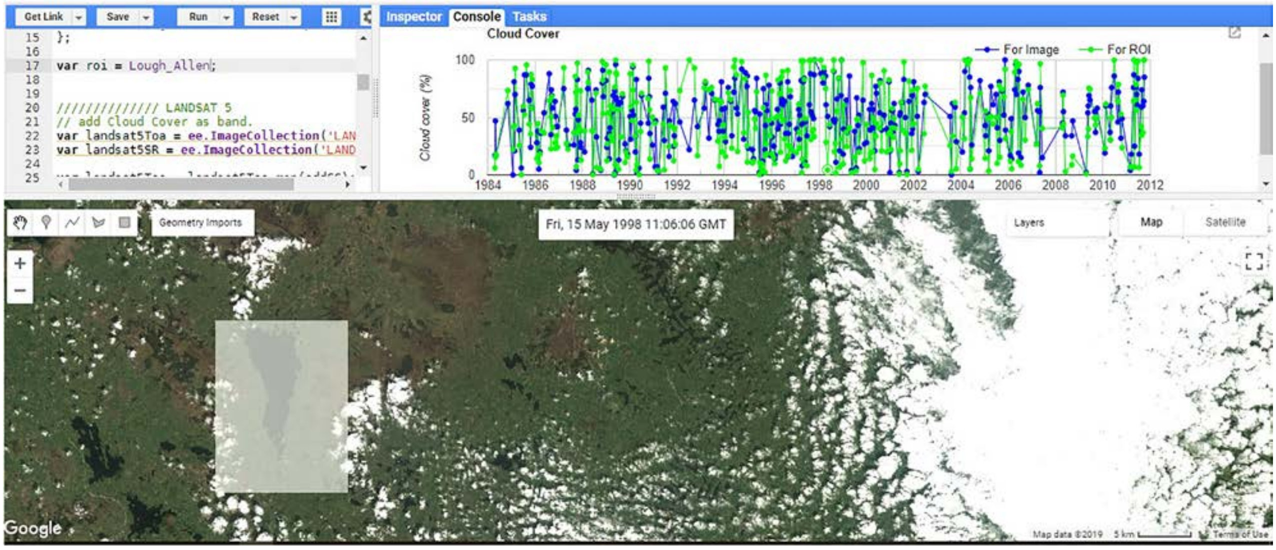



**Figure 5.1. The browser view using GEE. The upper left panel shows the editing area where JavaScript code is produced and deployed; the upper right panel shows a sample time series output of data taken from the area highlighted in the lower panel, which shows EO image data.**

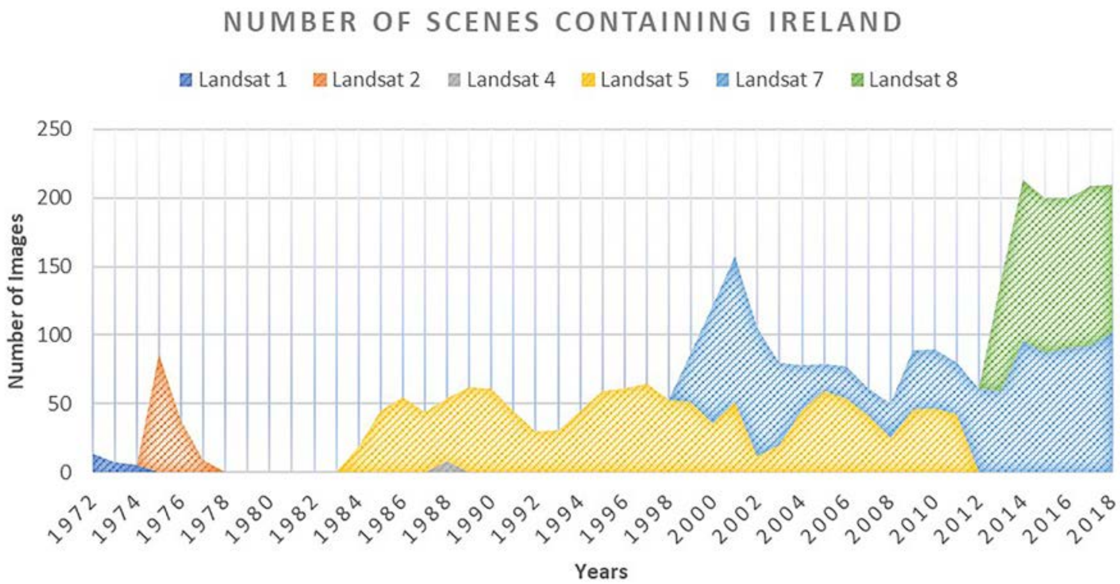



**Figure 5.2. Graph of a simple count of Landsat scenes featuring parts of Ireland.**

produced by applying a filter for Ireland to all relevant imagery data and then aggregating the properties of the resulting data collection, as shown in Figure 5.3. From this figure, it can be seen that the number of scenes with < 25% cloud cover is very small: about 11 per year from 1984 to 2018. This is, however, likely to be a severe underestimation of what is potentially available for scrutiny. For example, in Figure 5.4, the full Landsat image on the left-hand side has 64% cloud cover, while the same image on the right-hand side (via GEE) shows that, in fact, the Pollaphuca Reservoir is cloud free.

Consequently, scalable workflows based around the deployment of specific geospatial queries associated with water bodies of interest against cloud status were developed. These workflows made use of shapefiles containing polygons of lakes used as part of the ongoing WFD monitoring programme provided by the EPA. For this analysis, 21 lakes were assessed against the Landsat archive, although any lake described by the WFD shapefile could be processed

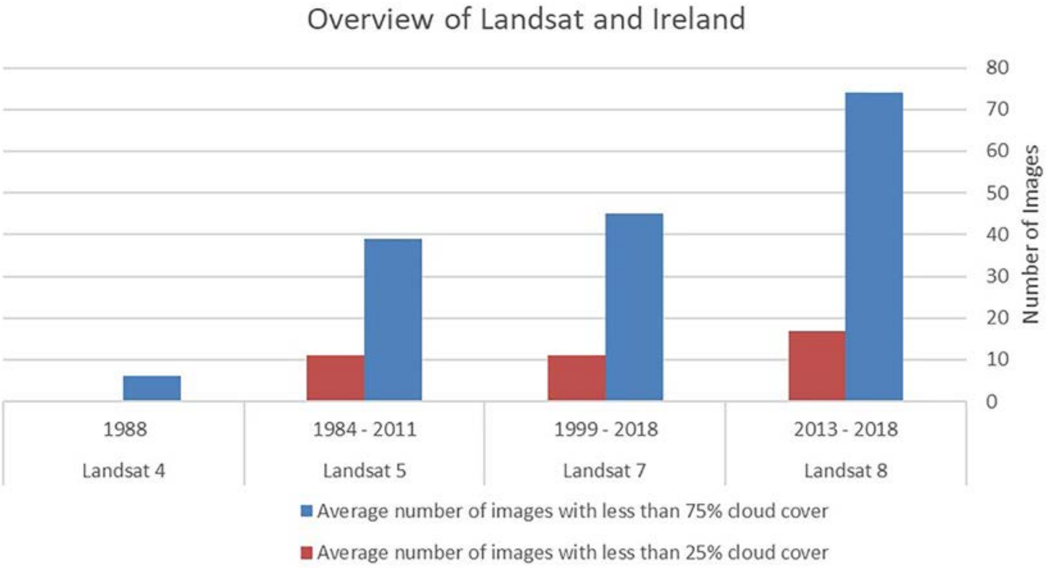



**Figure 5.3. Summary statistics of cloud cover in Landsat scenes that contain observations of Ireland.**

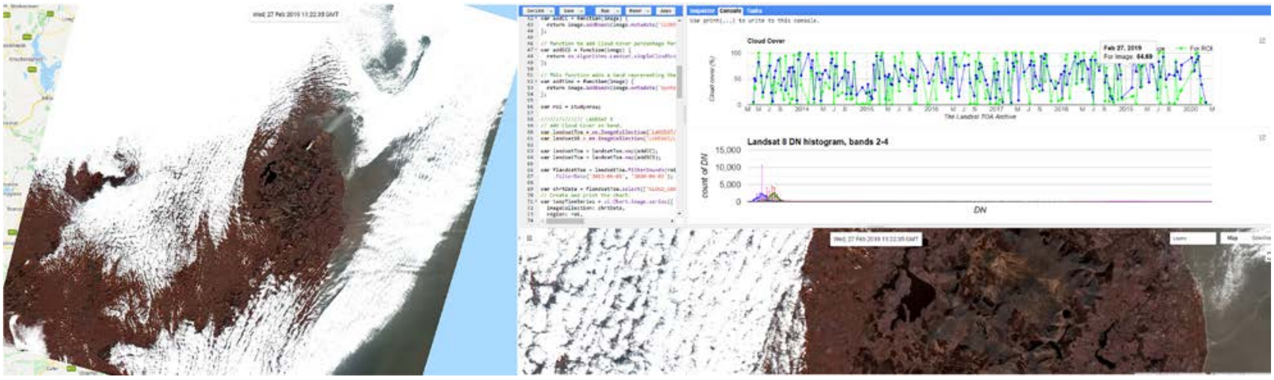


**Figure 5.4. Demonstration of actual cloud coverage. The image on the left has 64% cloud cover. Within the same scene, Pollaphuca Reservoir is cloud free, as seen on the right panel.**

using the same workflow by using the relevant EPA Edencode to reference the lake polygon. Queries take several minutes per lake to run, and some post-processing is then needed to extract the dataset returned by GEE, which is parsed into a desktop file or database for further analysis. A metric of < 25% cloud cover over a lake was chosen; this metric was based on the examination of raw results through the GEE visualisation interface. In Figure 5.5 the results for Lough Allen are displayed, showing a sample image (with the lake shapefile overlaid as a filled black polygon) and a time series yielding cloud cover statistics for this lake between 1984 and 2012. In Table 5.1 the results for all 21 lakes are presented for each individual Landsat mission where it is apparent the Landsat archive becomes a useful observation platform for Ireland from 1984 onwards. By averaging over Landsat 5, 7 and 8 for the years 1984 to 2021 (37 years), we find that there are seven observations per year per lake in the study that have < 25% cloud cover. The average cloud cover over the lakes in this image subset is 7%.

## 5.4 Estimated Overlap of Archival Landsat Imagery and *In Situ* Lake Monitoring

The results from the data mining of Landsat archives were compared with a collection of historical *in situ* water quality observation events for several lakes to see if it was possible to create a set of *in situ* data that could be used to calibrate models built using historical

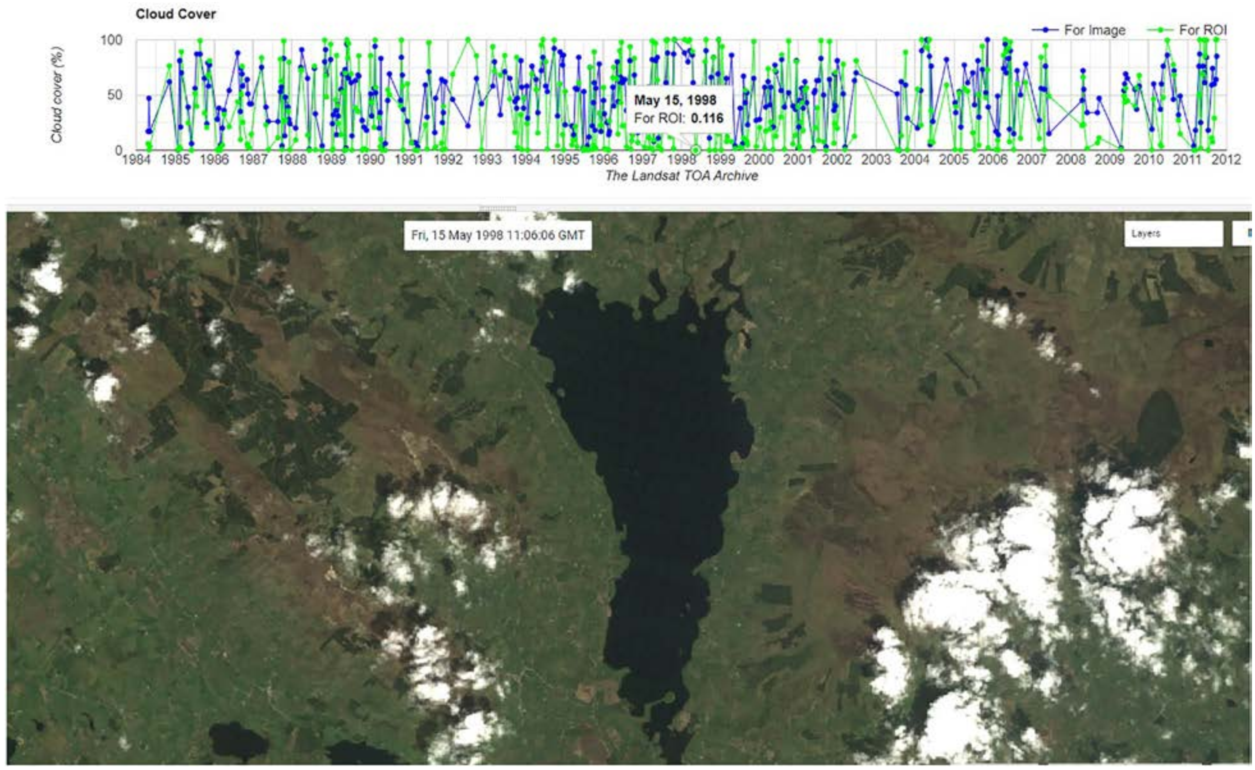



**Figure 5.5. The GEE interface showing a graph over times of cloud cover statistics for Lough Allen (green) and for the scenes containing Lough Allen (blue). In the lower panel is an image corresponding to a selected point in the graph.**

Landsat data. To do this, the following datasets of *in situ* observations were created:

- EPA 2007–2017: This was produced by combining datasets obtained from the EPA.
- Sligo County Council: Lough Gill (1995–1997): 252 observation dates.
- IFI (Inland Fisheries Ireland): Loughs Mask, Ennell and Owel (1984–2015): 632 combined observation events.

The water quality datasets were input into a relational database, and the dates of the observation events for each of the lakes were extracted via an SQL query; these datasets were then imported into a separate database containing the results of the cloud coverage analysis of lakes in Landsat images. More queries were developed to match *in situ* observation dates with Landsat overpasses on the same dates; it was decided to try to match overpass dates with the period of 14 days before or after the *in situ* observation. Using these criteria, Landsat observations that corresponded with *in situ* observations were found for Landsat 5 and Landsat 8, but none was found in the 4 years of Landsat 7 data (see Table 5.1 for the Landsat time ranges used in this project).

Tables 5.2 and 5.3 show the match-up between Landsat 5 and 8 observations of lakes with < 25% cloud cover and the *in situ* observations (±14 days of the observation date) of those lakes. For Landsat 5, the period of matching observations is bounded by the start date of the EPA *in situ* observations (2007) and the end of the Landsat 5 mission (early 2012). For Landsat 8, the period of matching observations is bound by the start date of the Landsat 8 mission (early 2013) and the end of the EPA *in situ* observations (2017). While all 21 lakes listed in Table 5.1 were included in the analysis, only 12 had overlapping *in situ* and Landsat 5 observations and 13 had overlapping *in situ* and Landsat 8 observations. Summary statistics for both Landsat 5 and Landsat 8 are presented in Table 5.4.

To demonstrate the flexibility of this data mining approach, it was extended to non-EPA *in situ* observations. *In situ* observations were obtained from Sligo County Council (Lough Gill, 1995–1997) and Inland Fisheries Ireland (Lough Allen, 1986–2006

**Table 5.1. Summary statistics of the set of images where cloud cover over the lake is <25% (date ranges refer to the time period sampled for this work; see text for more details)**

| Statistics for lakes with <25% cloud cover over lake | Landsat 4: 1/8/1982–31/12/1993 | | | Landsat 5: 1/3/1984–1/6/2012 | | | Landsat 7: 1/1/1999–1/4/2003 | | | Landsat 8: 1/4/2013–1/4/2021 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Number of images where cloud cover over lake <25% | Mean cloud cover over lake | Sample standard deviation from mean cloud cover over lake | Number of images where cloud cover over lake <25% | Mean cloud cover over lake | Sample standard deviation from mean cloud cover over lake | Number of images where cloud cover over lake <25% | Mean cloud cover over lake | Sample standard deviation from mean cloud cover over lake | Number of images where cloud cover over lake <25% | Mean cloud cover over lake | Sample standard deviation from mean cloud cover over lake |
| Muckno (Lough/ Blayney Castle) | 1 | 4.79 | 0 | 171 | 6.2 | 6.49 | 29 | 6.55 | 6.86 | 99 | 6.44 | 6.53 |
| Owel (Lough) | 2 | 12.5 | 2.69 | 153 | 5.2 | 7.08 | 36 | 5.08 | 7.52 | 100 | 5.66 | 7.14 |
| Dan (Lough) | 0 | 0 | 0 | 155 | 5.41 | 6.68 | 36 | 3.34 | 5.12 | 93 | 5.85 | 6.44 |
| Egish (Lough) | 1 | 1.12 | 0 | 177 | 6.85 | 6.33 | 29 | 7.92 | 6.44 | 89 | 7.2 | 6.56 |
| Knockaderry Reservoir | 2 | 20.09 | 0.7 | 261 | 4.11 | 5.87 | 66 | 3.61 | 5.21 | 151 | 3.29 | 5.37 |
| Sheelin (Lough) | 1 | 7.93 | 0 | 171 | 6.07 | 7.32 | 55 | 5.95 | 7.54 | 142 | 5.82 | 6.96 |
| Pollaphuca Reservoir | 1 | 15.09 | 0 | 141 | 5.93 | 6.91 | 27 | 5.75 | 6.31 | 40 | 6.87 | 5.98 |
| Allen (Lough) | 0 | 0 | 0 | 178 | 6.59 | 7.6 | 41 | 6.67 | 6.96 | 83 | 3.12 | 7.37 |
| Currane (Lough) | 1 | 3.48 | 0 | 187 | 5.96 | 7.48 | 51 | 5.16 | 6.83 | 93 | 6.4 | 7.6 |
| Ramor (Lough) | 0 | 0 | 0 | 159 | 5.99 | 7.13 | 37 | 6.06 | 7.36 | 133 | 5.11 | 6.48 |
| Derriana (Lough) | 1 | 7.17 | 0 | 176 | 4.02 | 5.97 | 41 | 5.9 | 7.76 | 92 | 5.19 | 7.04 |
| Gill (Lough) | 0 | 0 | 0 | 172 | 6.46 | 7.05 | 32 | 7.35 | 7.54 | 86 | 6.16 | 7 |
| Feeagh (Lough) | 0 | 0 | 0 | 144 | 5.04 | 7.11 | 38 | 6.04 | 8.02 | 106 | 6.27 | 7.3 |
| Furnace (Lough) | 0 | 0 | 0 | 178 | 4.47 | 5.65 | 61 | 4.67 | 6.31 | 140 | 6.99 | 7.72 |
| Derg (Lough) | 1 | 11.71 | 0 | 108 | 8.12 | 7.61 | 25 | 8.02 | 8.47 | 48 | 8.8 | 8.29 |
| Ree (Lough) | 0 | 0 | 0 | 98 | 7.51 | 7.62 | 18 | 6.67 | 8.16 | 51 | 5.42 | 7.01 |
| Conn (Lough) | 0 | 0 | 0 | 133 | 6.8 | 7.77 | 14 | 6.2 | 6.16 | 38 | 10.69 | 8.7 |
| Mask (Lough) | 0 | 0 | 0 | 147 | 7.18 | 8.02 | 37 | 8 | 8.28 | 40 | 8.53 | 7.26 |
| Corrib Lower (Lough) | 0 | 0 | 0 | 180 | 6.3 | 7.01 | 34 | 6.13 | 7.14 | 105 | 7.55 | 8.22 |
| Corrib Upper (Lough) | 0 | 0 | 0 | 149 | 7.26 | 7.64 | 31 | 6.64 | 7.62 | 38 | 8.49 | 8.06 |
| Leane (Lough) | 0 | 0 | 0 | 170 | 6.47 | 7.43 | 40 | 5.64 | 7.33 | 84 | 5.7 | 7.19 |

**Table 5.2. Landsat 5 observations of lakes with <25% cloud cover occurring with 2 weeks of EPA *in situ* observations data (±14 days)**

| EPA *in situ* (2007 to 2017) overlap with Landsat 5 | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Body of water** | **Number of matched observations** | **Average number of days between matched observations** | **Longest gap between matched observation (days)** | **Average cloud cover over lake** | **Maximum cloud cover over lake** | **Minimum cloud cover over lake** | **Average cloud cover for whole scene** | **First *in situ*** | **Last *in situ*** |
| Knockaderry Reservoir | 38 | 6.32 | 12 | 5.72 | 23.57 | 0.04 | 37.89 | 26 Mar 2007 | 30 Sep 2011 |
| Allen (Lough) | 10 | 5.3 | 14 | 6.05 | 22.19 | 0 | 34 | 24 Apr 2007 | 26 Jul 2011 |
| Currane (Lough) | 20 | 6.3 | 14 | 8.69 | 23.26 | 0 | 42.05 | 16 Jan 2007 | 26 Jul 2011 |
| Dan (Lough) | 15 | 6.87 | 13 | 4.7 | 21.44 | 0.28 | 29.8 | 02 Sep 2007 | 21 Apr 2011 |
| Egish (Lough) | 13 | 6.77 | 14 | 7.79 | 21.68 | 0.69 | 49.62 | 28 Aug 2007 | 17 Oct 2011 |
| Feeagh (Lough) | 6 | 10 | 13 | 8.63 | 24.81 | 0.36 | 45.33 | 21 Apr 2008 | 12 Oct 2011 |
| Gill (Lough) | 20 | 6.55 | 14 | 8.94 | 22.28 | 0.03 | 35.35 | 15 Apr 2008 | 14 Sep 2011 |
| Muckno (Lough/ Blayney Castle) | 14 | 9.29 | 14 | 9.88 | 19.5 | 0.04 | 45.43 | 23 Apr 2007 | 17 Oct 2011 |
| Owel (Lough) | 25 | 6.68 | 14 | 8.92 | 24.46 | 0.03 | 28.04 | 17 Apr 2007 | 27 Oct 2011 |
| Ramor (Lough) | 11 | 7.09 | 14 | 7.9 | 16.42 | 0.17 | 33.45 | 23 Apr 2007 | 26 Oct 2011 |
| Sheelin (Lough) | 30 | 8.03 | 14 | 8.22 | 20.41 | 0.02 | 32.6 | 23 Apr 2007 | 26 Oct 2011 |
| Pollaphuca Reservoir | 22 | 6.73 | 13 | 6.64 | 23.13 | 0.02 | 29.73 | 15 May 2008 | 15 Nov 2011 |

**Table 5.3. Landsat 8 observations of lakes with <25% cloud cover occurring with 2 weeks of EPA *in situ* observations data (±14 days)**

| Body of water | Number of matched observations | Average number of days between matched observations | Average cloud cover over lake | Maximum cloud cover over lake | Minimum cloud cover over lake | Average cloud cover for whole scene | First *in situ* | Last *in situ* |
|---|---|---|---|---|---|---|---|---|
| Knockaderry Reservoir | 94 | 7.79 | 2.5 | 23.76 | 0 | 39.16 | 31 May 2013 | 7 Nov 2017 |
| Allen (Lough) | 11 | 9.27 | 3.26 | 13.61 | 0.06 | 28.25 | 22 Oct 2013 | 21 Sep 2017 |
| Currane (Lough) | 26 | 7.5 | 5.7 | 22.75 | 0.05 | 46.7 | 16 Jul 2013 | 12 Oct 2017 |
| Dan (Lough) | 36 | 7.28 | 7.09 | 22.41 | 0.03 | 40.49 | 8 Apr 2013 | 7 Nov 2017 |
| Egish (Lough) | 12 | 7.33 | 8.9 | 23.39 | 0.18 | 44.81 | 19 Aug 2014 | 10 Oct 2017 |
| Feeagh (Lough) | 30 | 7.2 | 5.27 | 24.71 | 0.05 | 27.81 | 10 Apr 2013 | 12 Sep 2017 |
| Gill (Lough) | 12 | 8 | 7.51 | 22.64 | 0.57 | 45.68 | 2 Jul 2013 | 27 Apr 2017 |
| Muckno (Lough/ Blayney Castle) | 61 | 6.97 | 4.78 | 20.32 | 0.01 | 38.1 | 19 Jun 2013 | 5 Dec 2017 |
| Owel (Lough) | 35 | 7.31 | 7 | 24.75 | 0 | 32.6 | 29 May 2013 | 12 Sep 2017 |
| Ramor (Lough) | 70 | 6.77 | 5.93 | 24.77 | 0.02 | 40.05 | 25 Mar 2013 | 13 Mar 2017 |
| Sheelin (Lough) | 29 | 6.69 | 9.02 | 24.32 | 0.02 | 34.33 | 25 Apr 2013 | 17 Jul 2017 |
| Pollaphuca Reservoir | 82 | 7.87 | 5.42 | 23.87 | 0 | 36.06 | 15 Apr 2013 | 6 Sep 2017 |
| Knockaderry Reservoir | 82 | 7.07 | 7.09 | 24.93 | 0.03 | 40.56 | 15 May 2013 | 6 Dec 2017 |

**Table 5.4. Summary of the Landsat 5 and Landsat 8 observations of lakes with <25% cloud cover occurring with 2 weeks of EPA *in situ* observations data (±14 days)**

| | Total number of matched observations | Average gap from *in situ* to EO (days) | Average cloud cover over lake | Average maximum cloud cover over lake | Average minimum cloud cover over lake | Average minimum cloud cover over whole scene |
|---|---|---|---|---|---|---|
| Landsat 5 (2007–2011) | 224 | 7.16 | 7.67 | 21.93 | 0.14 | 36.94 |
| Landsat 8 (2013–2017) | 580 | 7.47 | 6.11 | 22.79 | 0.08 | 38.05 |

**Table 5.5. Landsat 5 observations of lakes with <25% cloud cover occurring with 2 weeks of *in situ* observations data (±14 days) by Inland Fisheries Ireland and Sligo County Council**

| Body of water | Total number of matched observations | Average gap from *in situ* to EO (days) | Average cloud cover over lake | Average maximum cloud cover over lake | Average minimum cloud cover over lake | Average cloud cover over whole scene | First *in situ* | Last *in situ* |
|---|---|---|---|---|---|---|---|---|
| Inland Fisheries Ireland *in situ* (1984–2015) overlap with Landsat 5 | | | | | | | | |
| Lough Allen | 33 | 7.64 | 4.9 | 23.05 | 0.04 | 29.52 | 30 Nov 1987 | 18 Sep 2006 |
| Lough Owel | 14 | 6.86 | 2.33 | 12.06 | 0.07 | 34.29 | 1 Apr 1984 | 1 Oct 1992 |
| Sligo County Council *in situ* (1995–1997) overlap with Landsat 5 | | | | | | | | |
| Lough Gill | 19 | 6.53 | 5.33 | 19.31 | 0.02 | 37.58 | 11 Dec 1995 | 22 Oct 1997 |

and Lough Owel, 1984–1992). As before, these observation events were imported into the Landsat observation database. The results of the overlap between *in situ* and Landsat observations are presented in Table 5.5; only Landsat 5 observations were applicable in this case.

## 5.5 Software and Data Availability on GitHub

Software for this Landsat-related activity is available at the following GitHub URL (https://github.com/SnaggyD/INFER).

Contained in this repository are four JavaScript applications that will search Landsat archives on GEE for images containing Irish lakes of interest (specified in the code):

- **shpLandsat4TOACloudBrowseFnl**: For Landsat 4.
- **shpLandsat5TOACloudBrowseFnl**: For Landsat 5, this is the most useful as Landsat 5 had a long operational life.
- **shpLandsat7TOACloudBrowseFnl**: For Landsat 7; only useful up to 2003 due to fault on satellite in that year.
- **shpLandsat8TOACloudBrowseFnl**: For Landsat 8; operational since 2013. The code considers the amount of cloud cover over a lake; for example, the code as presented here returns Landsat images (products) in which the cloud cover over the lake in question is <25%. The cloud cover metric can be edited in the code.

Two results folders are supplied, one with the results in CSV format and the other with the results in XLS (Microsoft Excel) format. These are high-level summary results that are outputs from the INFER project. They provide a useful overview of what can be done with the code supplied. To obtain these results, the data produced by the code were extracted from GEE and put into an SQL database for further analysis. The content of both is identical. The files supplied are as follows:

- **AllLandsatQuery_25_Crosstab**: This is the output of a crosstab query that lists product IDs from 1984 to 2021 of Landsat products that contain observations of the lakes listed in the query where the cloud cover over the lake is <25%. Note that one Landsat product can contain observations of several lakes.

- **OverlapDates_Crosstab**: This is the output of a crosstab query by year and month that lists the number of individual Landsat products that met the criteria of the project. Each Landsat scene contains at least one observation of a lake of interest in which the cloud cover over the lake is <25%.
- **Look_Up_Lakes**: A look-up table of the lakes used for the comparison between EPA *in situ* and EO observations.
- **OverlapwithEPASampling_2007_2017**: This is the list of Landsat products that overlap EPA *in situ* measurements. The dates of EPA water quality *in situ* measurements at lakes in Ireland from 2007 to 2017 were matched with the dates of Landsat observations of the same lakes with <25% cloud cover.

More information on these resources can be found in the ReadMe on the INFER GitHub space (https://github.com/SnaggyD/INFER#readme).

# 6 Conclusion and Recommendations

Images from the Sentinel-2 satellite were used to estimate water quality parameters in Ireland from a set of calibration lakes from which *in situ* water quality and atmospheric correction data were collected at times that coincided with satellite passes. We adapted and validated the atmospheric correction and water quality processor for surface waters in Ireland applicable to Sentinel-2 imagery with the critical use of field data collected to coincide with satellite passes, which provided essential water quality measurements and field radiometry. Field-collected datasets were compared with those computed using the two most widely used algorithms for analysing Sentinel-2 data, namely the C2RCC and Acolite processors. The C2RCC-based processor showed better performance for atmospheric correction, whereas the Acolite-based processor demonstrated enhanced efficacy for chlorophyll *a* and turbidity. By coupling the processors, the advantages of both were combined, yielding an optimal means of inferring regional lake water quality in Ireland using Sentinel-2 data. The resulting workflow was integrated into a web platform facilitating third parties interested in monitoring lake water quality in Ireland.

Although it is challenging to get a long-time series of cloud-free scenes for Ireland due to its temperate maritime climate, we determined that satellite observations can be used to conduct regional monitoring of freshwater quality remotely. In the future, the addition of high-quality data from field measurements can be used for continuous improvement of the model and subsequent validation. The modified method employed in this project to acquire glint-free radiometric measurements for atmospheric correction was found to work well in Irish conditions, with the extended tube used with the TriOS Ramses radiometers enabling measurements to be recorded even in relatively windy conditions. As a result, we have been able to demonstrate that satellite observations can effectively complement traditional freshwater monitoring at regional scales in an essentially automatic manner, permitting the optimal use of *in situ* monitoring logistics to identify and investigate specific sites in a more controlled and evidence-based fashion.

There is promising potential for the successful estimation of chlorophyll *a* in Irish lakes using a coupled approach with the C2RCC and ACOLITE processors, producing an improved product for Irish conditions. However, additional calibration and validation work is needed to further enhance the analytical methods, particularly in refining this work to take account of various lake typologies, trophic statuses and optical properties. Globally, there is currently a need to collect frequent *in situ* radiometric data for atmospheric correction in order to calibrate and validate regionally adapted satellite products. To build on the work of this project, it will be important that more data for atmospheric correction and *in situ* water quality are collected for the Irish region. The methods employed in this project necessitated the use of two TriOS RAMSES radiometers; however, there is a wide range of multi-spectral radiometers on the market that could also be used, and investing in their use in monitoring programmes would increase the reliability and usefulness of water quality estimates based on satellite remote sensing data. There is also clear potential of the analysis of historical Landsat observations using Cloud computing resources to provide insight into the historical status of water quality in Irish lakes.

In this work we have demonstrated that by using the free-to-access EO archives on the Cloud and free-to-use proximity computing (Google Earth Engine in this case) it is possible to generate datasets of cloud-free observations of Irish lakes that are of the maximum possible size. This was achieved by using the metric of cloud cover over a lake to filter the Landsat archives to create lake-specific datasets for analysis. This is a major improvement on the traditional approach of filtering EO data based on cloud cover over the whole scene and is possible only by using big data archives of EO observations and high-performance distributed computing on the Cloud. The traditional approach was taken with the Sentinel-2 datasets used in the project. In the future, the technique used with Landsat could be extended to Sentinel-2, raising the possibility of creating a bigger set of observations from Sentinel-2.

The Landsat observations were matched with historical EPA *in situ* observations from several lakes, and the list of corresponding Landsat images has been made available (GitHub and SAFER[4]) so that future researchers do not have to re-run the big data analysis.

Working with archives of EO and historical *in situ* data is feasible only because of the free resources made available by Google. These resources offer a path to the low-cost analysis of EO data and are preferable to building dedicated infrastructure to achieve the same result but at a higher cost, especially since an international community of practice has grown in support of Google Earth Engine. We recommend that the practice of leveraging free EO data and processing resources be continued.

To build on the techniques and technologies demonstrated here, the EPA should encourage the research and development of EO water quality models that can be verified against the *in situ* record by:

- Encouraging the approach of selecting images for analysis by the metric of cloud cover over a lake rather than cloud cover for the whole image. The product names of such images should be recorded and made available to other researchers as has been done with the Landsat images discovered in this project (see the GitHub details provided in Chapter 5).
- Producing an analysis-ready dataset (ARD) of EPA *in situ* observations. While it is true that the observations are already available on catchments.ie, this ARD would be tailored to data scientists and should include the observation dates, location information and reported water quality parameters. The dataset should be released under an open data licence and made easily accessible to any EO/data scientist.
- Encouraging the development of water quality models based on EO by providing a dedicated GitHub account and/or a dedicated web page on catchments.ie, which will provide data scientists with a focal point for the EPA's many data resources. The datasets and code produced by this project can act as a starting point.
- Continuing the collection of water quality data to coincide with satellite passes where possible, with the intention of utilising these data for the calibration and validation of satellite remote sensing data. The collection of data during good weather conditions, preferably away from shorelines and shallow water, also promotes the usability of such data points for EO validation. The availability of high-frequency (both spatially and temporally) field observations can promote the use of drone acquisition as well as commercial satellite sensors that provide high-resolution imagery.
- Encouraging collaboration between limnologists and remote sensing specialists in order to ensure that developments in the field of EO are fully integrated with surface water research and water management and, in addition, that remote sensing specialists themselves acquire the specific limnological understanding to enable them to fully adapt remote sensing products for specific regional, physical and biological conditions.
- Collecting radiometric measurements for atmospheric correction in conjunction with the collection of water quality data, which would also provide valuable information allowing for the improved application of remote sensing products adapted to Irish conditions. Such data are also vital for efforts globally to improve remote sensing products. The methods used in this project to collect field radiometric data appropriate for remote sensing calibration demonstrate the importance of adapting protocols to suit Irish conditions and the benefit of utilising easily deployed, mobile and flexible methods that can be readily incorporated into traditional monitoring programmes.

4 https://eparesearch.epa.ie/safer/

# References


Botha, E.J., Anstee, J.M., Sagar, S., Lehmann, E. and Medeiros, T.A.G., 2020. Classification of Australian waterbodies across a wide range of optical water types. *Remote Sensing* 12: 3018.

Brockmann, C., Doerffer, R., Peters, M., Stelzer, K., Embacher, S. and Ruescas, A., 2016. Evolution of the C2RCC neural network for Sentinel 2 and 3 for the retrieval of ocean colour products in normal and extreme optically complex waters. In *Proceedings of the ESA Living Planet*, Prague, Czechia 9–13 May.

Cazzaniga, I., 2018. Processing and analysis of latest generation satellite data for monitoring optically complex waters. PhD Thesis, Universitá degli Studi di Milano-Bicocca, Italy.

Charria, G., Lamourox, J. and De Mey, P., 2016. Optimizing observational networks combining gliders, moored buoys and FerryBox in the Bay of Biscay and English Channel. *Journal of Marine Systems* 162: 112–125.

Dogliotti, A.I., Ruddick, K., Nechad, B., Doxaran, D. and Knaeps, E., 2015. A single algorithm to retrieve turbidity from remotely-sensed data in all coastal and estuarine waters. *Remote Sensing of the Environment* 156: 157–168.

EPA, 2017. *Water Quality in Ireland 2010–2015*. Environmental Protection Agency, Johnstown Castle, Ireland.

Franz, B.A., Bailey, S.W., Kuring, N. and Werdell, P.J., 2015. Ocean color measurements with the Operational Land Imager on Landsat-8: implementation and evaluation in SeaDAS. *Journal of Applied Remote Sensing* 9(1): 096070.

Free, G., Allott, N., Mills, P., Kennelly, C. and Day, S., 2000. Colour in Irish lakes. *Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen* 27: 2620–2623.

Free, G., Bresciani, M., Trodd, W., Tierney, D., O'Boyle, S., Plant C. and Deakin, J., 2020. A reference based estimation of lake ecological quality from Sentinel-2 remote sensing imagery. *Hydrobiologia* 847: 1423–1438.

Gitelson, A.A. and Kondratyev, K.Y., 1991. Optical models of mesotrophic and eutrophic water bodies. *International Journal of Remote Sensing* 12: 373–385.

Gons, H.J., Rijkeboer, M., Bagheri, S. and Ruddick, K.G., 2000. Optical teledetection of chlorophyll *a* in estuarine and coastal waters. *Environmental Science and Technology* 34(24): 5189–5192.

Gons, H.J., Rijkeboer, M. and Ruddick, K.G., 2002. A chlorophyll-retrieval algorithm for satellite imagery (medium resolution imaging spectrometer) of inland and coastal waters. *Journal of Plankton Research* 24(9): 947–951.

Gordon, H.R. and Morel, A.Y., 1983. *Remote Assessment of Ocean Colour for Interpretation of Satellite Visible Imagery: A Review*. Springer-Verlag.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D. and Moore, R., 2017. Google Earth Engine: planetary-scale geospatial analysis for everyone. *Remote Sensing of the Environment* 202: 18–27.

Groetsch, P.M.M., Simis, S.G.H., Eleveld, M.A. and Peters, S.W.M., 2014. Cyanobacterial bloom detection based on coherence between ferrybox observations. *Journal of Marine Systems* 140: 50–58.

Gurlin, D., 2012. Near infrared-red models for the remote estimation of chlorophyll-a concentration in optically complex turbid productive waters: from *in situ* measurements to aerial imagery. Doctoral Dissertation. University of Nebraska-Lincoln, NE.

Gurlin, D., Gitelson, A.A. and Moses, W.J., 2011. Remote estimation of chl-*a* concentration in turbid productive waters – return to a simple two-band NIR-red model? *Remote Sensing of the Environment* 115: 3479–3490.

Jerlov, N.G., 1968. *Optical Oceanography*. American Elsevier Publishing Company, Inc., New York, NY.

Jerlov, N.G., 1976. *Marine Optics*. Elsevier Scientific Publishing Company, Amsterdam, The Netherlands.

Kiselev, V., Bulgarelli, B. and Heege, T., 2015. Sensor independent adjacency correction algorithm for coastal and inland water systems. *Remote Sensing of Environment* 157: 85–95.

Kutser, T., Vahtmäe, E., Paavel, B. and Kauer, T., 2013. Removing glint effects from field radiometry data measured in optically complex coastal and inland waters. *Remote Sensing of the Environment* 133: 85–89.

Ligi, M., 2017. Application of close range remote sensing for monitoring aquatic environment. PhD Thesis. University of Tartu, University of Tartu Press, Estonia.

Mackereth, F.J.H., Heron, J. and Talling, J.F., 1978. *Water Analysis: Some Revised Methods for Limnologists*. Freshwater Biological Association Scientific Publication No. 36, Ambleside, UK.

Marcé, R., George, G., Buscarinu, P., Deidda, M., Dunalska, J., de Eyto, E., Flaim, G., Grossart, H.P., Ivanovic, V., Lenhardt, M. and Moreno-Ostos, E., 2016. Automatic high frequency monitoring for improved lake and reservoir management. *Environmental Science and Technology* 50(20): 10780–10794.

Mishra, S. and Mishra, D.R., 2012. Normalized difference chlorophyll index: a novel model for remote estimation of chlorophyll-*a* concentration in turbid productive waters. *Remote Sensing of the Environment* 117: 394–406.

Mobley, C.D., 1994. *Light and Water: Radiative Transfer in Natural Waters*. Academic Press, Inc., San Diego, CA.

Morel, A., 2001. Bio-optical models. In Steele, J.H. (ed.), *Encyclopedia of Ocean Sciences*. Elsevier Academic Press, London, UK, pp. 317–326.

Moses, W.J., Gitelson, A. A., Berdnikov, S., Saprygin, V. and Povazhnyi, V., 2012. Operational MERIS-based NIR-red algorithms for estimating chlorophyll-*a* concentrations in coastal waters – the Azov Sea case study. *Remote Sensing of the Environment* 121: 118–124.

Moses, W.J., Sterckx, S., Montes, M.J., De Keukelaere, L. and Knaeps, E., 2017. Atmospheric correction for inland waters. In Mishra, D.R., Ogashawara, I. (eds), *Bio-optical Modelling and Remote Sensing of Inland Waters*. Elsevier, Amsterdam, The Netherlands, pp. 69–100.

Nechad, B., Ruddick, K. and Neukermans, G., 2009. Calibration and validation of a generic multisensor algorithm for mapping of turbidity in coastal waters. In *Proceedings of SPIE – The International Society for Optical Engineering* 7473: 74730H.

Nechad, B., Ruddick, K. and Park, Y., 2010. Calibration and validation of a generic multisensor algorithm for mapping of total suspended matter in turbid waters. *Remote Sensing of the Environment* 114(4): 854–866.

Ogashawara, I., Mishra, D.R. and Gitelson, A.A., 2017. Remote sensing of inland waters: background and current state-of-the-art. In Mishra, D.R., Ogashawara, I. (eds), *Bio-optical Modelling and Remote Sensing of Inland Waters.* Elsevier, Amsterdam, The Netherlands.

Ogashawara, I., Kiel, C., Jechow, A., Kohnert, K., Ruhtz, T., Grossart, H.-P. Holker, F., Nejstgaard, J.C., Berger, S.A. and Wollrab, S., 2021. The use of Sentinel-2 for chlorophyll-*a* spatial dynamics assessment: a comparative study on different lakes in northern Germany. *Remote Sensing* 13: 1542.

Palmer, S.C., Kutser, T. and Hunter, P.D., 2015. Remote sensing of inland waters: challenges, progress and future directions. *Remote Sensing of the Environment* 157: 1–8.

Preisendorfer, R.W., 1976. *Hydrologic Optics*. US Department of Commerce, Washington, DC.

Siegel, D.A., Wang, M., Maritorena, S. and Robinson, W., 2000. Atmospheric correction of satellite ocean color imagery: the black pixel assumption. *Applied Optics* 39: 3582–3359.

Spyrakos, E., O'Donnell, R., Hunter, P.D., Miller, C., Scott, M., Simis, S.G., Neil, C., Barbosa, C.C., Binding, C.E., Bradt, S., Bresciani, M., Dall'Olmo, G., Giardino, C., Gitelson, A.A., Kutser, T., Li, L., Matsushita, B., Martinez-Vicente, V., Matthews, M.W., Ogashawara, I., Ruiz-Verdú, A., Schalles, J.F., Tebbs, E., Zhang, Y. and Tyler, A.N., 2017. Optical types of inland and coastal waters. *Limnology and Oceanography* 63: 846–870.

Vanhellemont, Q., 2019. Adaptation of the dark spectrum fitting atmospheric correction for aquatic applications of the Landsat and Sentinel-2 archives. *Remote Sensing of the Environment* 225: 175–192.

Vanhellemont, Q. and Ruddick, K., 2018. Atmospheric correction of metre-scale optical satellite data for inland and coastal water applications. *Remote Sensing of the Environment* 216: 586–597.

Vantrepotte, V., Loisel, H., Dessailly, D. and Mériaux, X., 2012. Optical classification of contrasted coastal waters. *Remote Sensing of the Environment* 123: 306–323.

Warren, M.A., Simis, S.G.H., Martinez-Vicente, V., Poser, K., Bresciani, M., Alikas, K., Spyrakos, E., Giardino, C. and Ansper, A., 2019. Assessment of atmospheric correction algorithms for the Sentinel-2A MultiSpectral Imager over coastal and inland waters. *Remote Sensing of the Environment* 225: 267–289.

Weyhenmeyer, G.A., Müller, R.A., Norman, M. and Tranvik, L.J., 2016. Sensitivity of freshwaters to browning in response to future climate change. *Climatic Change* 134: 225–239.

# Abbreviations

| | |
|---|---|
| **CDOM** | Coloured dissolved organic matter |
| **DOC** | Dissolved organic carbon |
| **EO** | Earth observation |
| **EPA** | Environmental Protection Agency |
| **FNU** | Formazin Nephalometric Units |
| **GEE** | Google Earth Engine |
| **ICHEC** | Irish Centre for High-End Computing |
| **IR** | Infrared |
| **S2** | Sentinel-2 |
| **TOA** | Top of the atmosphere |
| **TRAC** | Transitional and coastal |
| **TSM** | Total suspended matter |
| **USGS** | US Geological Survey |
| **WFD** | Water Framework Directive |

# An Ghníomhaireacht Um Chaomhnú Comhshaoil

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

## Is féidir obair na Gníomhaireachta a roinnt ina trí phríomhréimse:

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

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

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

## I measc ár gcuid freagrachtaí tá:

### Ceadúnú

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

### Forfheidhmiú Náisiúnta i leith Cúrsaí Comhshaoil

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

### Bainistíocht Dramhaíola agus Ceimiceáin sa Chomhshaol

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

### Bainistíocht Uisce

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

### Eolaíocht Aeráide & Athrú Aeráide

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

### Monatóireacht & Measúnú ar an gComhshaol

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

### Taighde agus Forbairt Comhshaoil

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

### Cosaint Raideolaíoch

- Monatóireacht a dhéanamh ar leibhéil radaíochta agus nochtadh an phobail do radaíocht ianúcháin agus do réimsí leictreamaighnéadacha a mheas;
- Cabhrú le pleananna náisiúnta a fhorbairt le haghaidh éigeandálaí ag eascairt as taismí núicléacha;
- Monatóireacht a dhéanamh ar fhorbairtí thar lear a bhaineann le saoráidí núicléacha agus leis an tsábháilteacht raideolaíochta;
- Sainseirbhísí um chosaint ar an radaíocht a sholáthar, nó maoirsiú a dhéanamh ar sholáthar na seirbhísí sin.

### Treoir, Ardú Feasachta agus Faisnéis Inrochtana

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

### Comhpháirtíocht agus Líonrú

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

## Bainistíocht agus struchtúr na Gníomhaireachta um Chaomhnú Comhshaoil

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

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

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

EPA Research

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

www.epa.ie