Lough Muckno Road to Recovery Project

Paleolimnological Investigation & Nutrient Loading Assessment of Lough Muckno, Co. Monaghan

Final Report

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HYDREC ENVIRONMENTAL CONSULTING

Comhairle Contae Mhuineacháin
Monaghan County Council

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1.0 INTRODUCTION

1.1 Background & Context

Lough Muckno located on the outskirts of Castleblayney Town, Co. Monaghan is the largest lake in the county. Routinely utilised for activities such as swimming, fishing and boating, the lake provides great amenity value to local and wider communities. A recent study commissioned by the Oriel River Catchments and Coastal Association ('ORCCA) on the biodiversity of Lough Muckno and its environs also highlights the substantial ecological value of the area (JBA, 2024).

However, since the commencement of the Water Framework Directive (WFD) monitoring programme in 2007, the ecological status of the lake has failed to achieve the ‘Good’ status required under the directive. At the outset of the monitoring programme, Lough Muckno was classified as being of ‘Bad’ ecological status (2007 – 2012). In the subsequent monitoring period (2010 – 2015), a ‘Poor’ status was recorded before ‘Bad’ ecological conditions once again prevailed from 2013 – 2018 (O’Boyle and Craig, 2020). Encouragingly the EPA reported an improvement in the lake’s ecological status for the 2016 – 2021 period, assigning a ‘Moderate’ classification (Trodd et al., 2022).

In direct response to concerns raised about the deterioration observed for the 2013 – 2018 period, Monaghan County Council sought to commission a study on the lake and its catchment in an effort to inform on how their WFD obligations could be achieved. The project entitled ‘Lough Muckno’s Road to Recovery’ (2022-2024) consists of both a paleolimnological investigation of the lough’s sediment and additional water quality and hydrometric monitoring of the lake and its contributing tributaries. Hydrec Environmental Consulting were appointed to complete the project, and this report documents the findings of the study.

1.2 Aims & Objectives of Project

- In light of the ‘Bad’ to ‘Moderate’ ecological conditions reported for the Lough (WFD monitoring 2007-2021), the study aims to gain an additional understanding of the historic or reference ecological conditions for the lake;
- As total phosphorus (TP) conditions in the lake are failing to achieve ‘Good’ status, the project aims to estimate historic TP concentrations within the lake;

- The study aims to estimate the external TP load reduction required to restore the lake to estimated historic TP conditions. Additionally, the study aims to calculate nutrient loadings for each of the lake's contributing tributaries so as to identify sub-catchments delivering disproportionally larger quantities of TP to the lough.
- It is aimed that monitoring data (i.e. water quality and hydrometric) will also inform on the orthophosphate (PO4-P) reductions required for the tributaries feeding Lough Muckno to achieve 'Good' status for PO4-P; and
- The project aims to investigate if internal phosphorus loading is occurring within the lake and to what extent such might hinder lake recovery times.

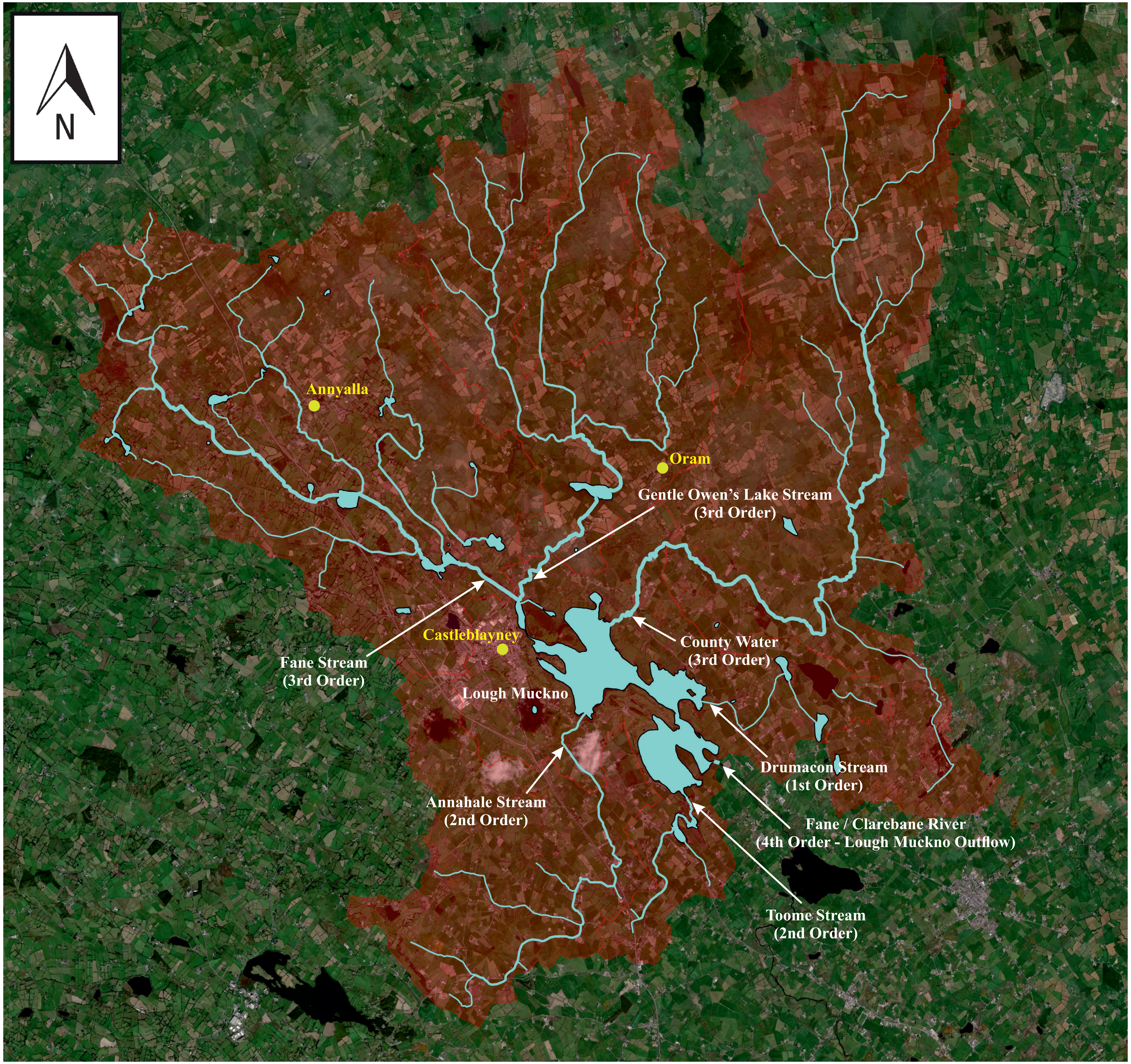
2.0 ENVIRONMENTAL SETTING

2.1 Study Site

Lough Muckno is a large inter-drumlin lake located in County Monaghan in the north-east of Ireland and is situated within the Newry, Fane, Glyde and Dee WFD catchment. The lake comprises of three main basins (i.e. western, centre and southern) and spans a total area of 3.5km^2, hence the large classification. The lake has a mean depth of 5.4m, with a maximum depth of c. 30m found in the southern basin. Horkan and Toner, (1984) reported that the lake was monomictic in nature, typically stratifying during the summer months (May to October) and mixing during winter (November to May). With moderate alkalinity conditions (i.e. 20 – 100 mg/l $CaCO_3$) and accounting for the lake's depth and size, Lough Muckno is categorised as a Type 8 lake, according to the EPA's typology classification (Free et al., 2006).

Lough Muckno's contributing catchment covers an area of 167.5km^2 and is drained by six main fluvial channels that flow into the lough (See Figure 1). Two of these watercourses namely the County Water and Gentle Owen's Lake Stream rise in Northern Ireland thus meaning the lake's catchment is transboundary in nature. A series of smaller lakes are located throughout the catchment with Milltown Lough (aka Muckno Mill Lough), Laragh Lough, Killygola Lough and Drumillard Lough the largest of such.

In board terms, the bedrock type found in the northern portion of the catchment predominately consists of massive sandstone and microconglomerate (i.e. Lough Avaghon Formation and Oghill Formation) with fine to coarsely grained turbidites located to the east and west of the lough (Shercock Formation). At the southern end of the catchment, turbidite, massive sandstone and siltstone belonging to the Taghart Mountain Formation are found. Relatively narrow bands of black shale and tuff transect the catchment (i.e. north-eastern to south-western orientation) directly to the north and south of the lough. Across the entirety of the catchment, a Pl - Poor Aquifer – with Bedrock which is Generally Unproductive except for Local Zones exists. Throughout the catchment, bedrock is predominately overlain by TLPSsS – clayey sandstone and shale till, with areas of Cut – cutover peat and A – glacial alluvium found to flank certain watercourse channels. Grassland dominates the land cover in the catchment, with some areas of wetland, forestry, semi natural vegetation and sport and leisure facilities (e.g. Concra Wood golf course to the west of the lough) also present. The principle built up / urban areas consist of Castleblayney Town, Annyalla and Oram Villages (see Figure 1).



LEGEND

- Lough Muckno Catchment
- Lough
- 1st Order Stream
- 2nd Order Stream
- 3rd Order Stream

HYDREC
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PROJECT:

Lough Muckno's Road to Recovery Project

TITLE:

Lough Muckno Catchment

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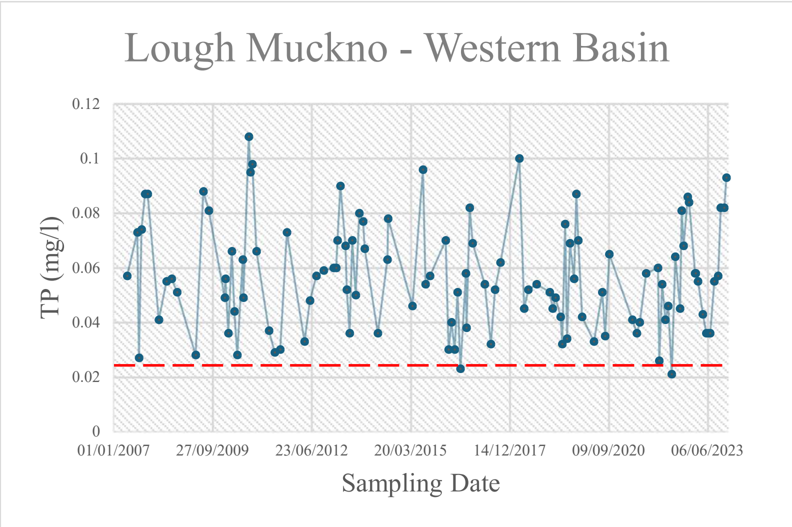
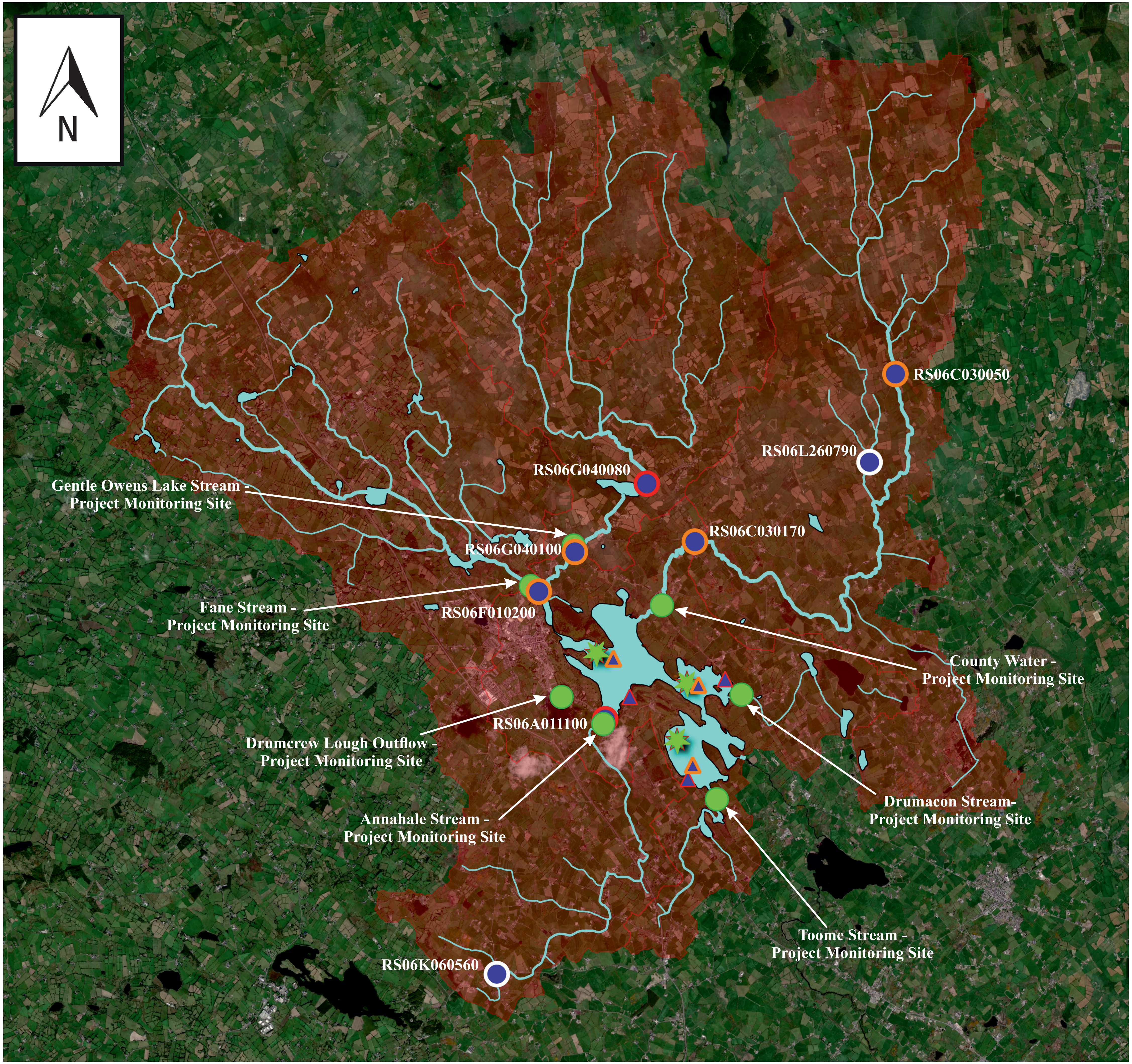
2.2 Nutrient Conditions of Lough Muckno & Tributaries

2.2.1 TP concentrations (Lough Muckno)

Since 2007, as part the EPA's WFD surveillance monitoring, TP concentrations have been monitored at each of the lough's three deepest basins. Depending on the year, sample resolution ranged from 3 to 12 times per annum. During COVID-19, sampling for each basin was completed at surrogate shoreline sites (namely 1A, 2A, 3A) (see Figure 2). Graphs 1 – 3, show the TP monitoring results across the lake. As can be seen from Graphs 1 – 3, TP concentrations ranged from 0.021 – 0.108 mg/l TP for the western basin, 0.019 – 0.114 mg/l TP for the central basin and from 0.017 – 0.097 mg/l TP for the southern basin. Annual average concentrations ranged from 0.042 – 0.68 mg/l TP for the western basin, 0.034 – 0.061 mg/l TP for the central basin and from 0.026 – 0.054 mg/l TP for the southern basin. Consequently, the environmental quality standard (EQS) for 'Good' condition (i.e. 0.025 mg/l TP (annual average)) was exceeded each year at each monitoring location.



Graph 1. Total Phosphorus concentrations recorded within Lough Muckno's western basin (2007 – 2023). The dashed red line represents the annual average EQS of 0.025mg/l. Note, samples taken from shoreline surrogate site (2020 – 2022) also included.



LEGEND

- WFD Monitoring Station
- Monaghan CoCo Investigative Station
- Active Pre -WFD Monitoring Station
- Lough Muckno Road to Recovery - Monitoring Sites
- Lake - WFD Monitoring Station
- Lake - WFD Surrogate Station
- Sediment Coring Location

HYDREC ENVIRONMENTAL CONSULTING

PROJECT:
Lough Muckno's Road to Recovery Project

TITLE:
Orthophosphate monitoring locations in Lough Muckno catchment 2022-2023 (n >4) with Lough Muckno TP monitoring stations 2007 - 2023 included. 2022 coring sites also included.

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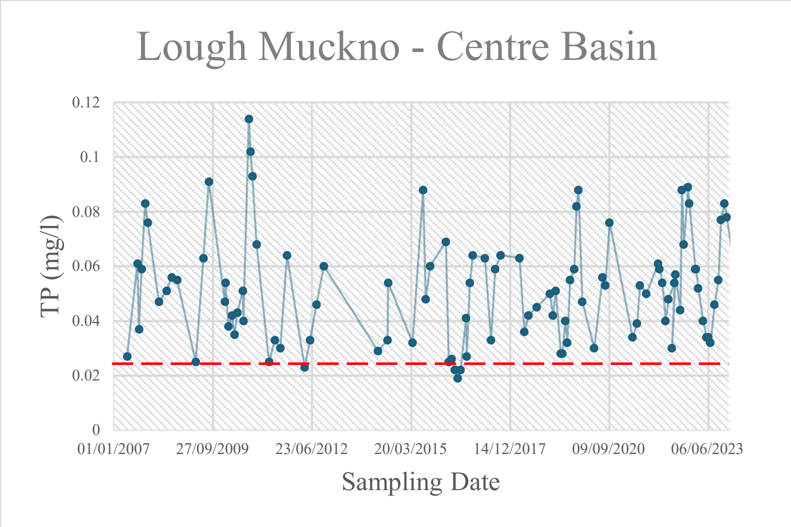
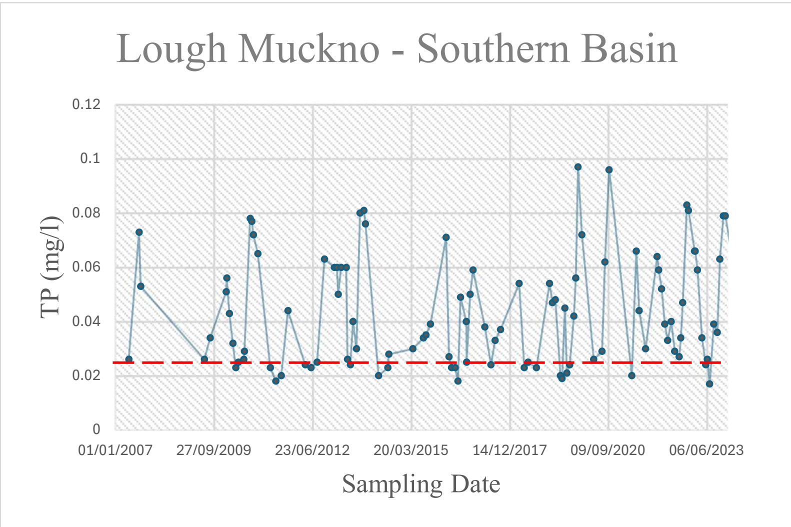


Graph 2. Total Phosphorus concentrations recorded within Lough Muckno's central basin (2007 – 2023). The dashed red line represents the annual average EQS of 0.025mg/l. Note, samples taken from shoreline surrogate site (2020 – 2022) also included.



Graph 3. Total Phosphorus concentrations recorded within Lough Muckno's southern basin (2007 – 2023). The dashed red line represents the annual average EQS of 0.025mg/l. Note, samples taken from shoreline surrogate site (2020 – 2022) also included.

2.2.2 Orthophosphate & TP concentrations (Lough Muckno Tributaries)

Of the six recognised WFD watercourses flowing into Lough Muckno, four are classified as being of 'Poor' water quality status, two of which the Fane Stream (3rd Order) and Annahale Stream (2nd Order) were assessed through direct monitoring, whilst the 'Poor' statuses assigned to the Drumacon Stream (2nd Order) and Annalittin / Toome Stream (2nd Order) were based on a modelling assessment.

Figure 2 highlights the various monitoring locations within the catchment whereby orthophosphate (PO4-P) was monitored in 2022. This includes a combination of pre-WFD, WFD operational / surveillance and investigative monitoring points. Table 1 includes the monitoring data for 2022 at all monitoring sites whereby samples were taken at a minimum of 4 times per annum.

Despite the County Water (3rd Order) achieving a QV4 score (i.e. representative of 'Good' ecological status) at monitoring station RS06C030170 (i.e. Bridge upstream from Wallace's Bridge), nutrient conditions were only at 'Moderate' (annual average = 0.052mg/l). Conversely the orthophosphate concentrations that were recorded on the Fane Stream (i.e. Derrycrevy Stream) were within the 'Good' EQS (annual average = 0.032mg/l), however the Q-Value (QV3) recorded at the site rendered the watercourse to be of 'Poor' status. Both nutrient conditions and the Q-Value (QV3-4) recorded at station RS06G04010 (bridge 1.5km downstream of Muckno Mill Lough) represented a 'Moderate' classification for the Gentle Owen's Lake Stream (3rd Order). Monitoring station (Bridge d/s Fincarn - RS06K060560) is located on the Lisagore Stream (1st Order) which discharges into the Annahale Stream further downstream. The annual average (aa) orthophosphate concentration at said location did not exceed the 'Good' EQS in 2022 (aa = 0.025mg/l), thus representing a stretch of headwaters where excessive orthophosphate loading does not appear to be occurring.

2.3 Existing Hydrometric Data

There is currently one active hydrometric station within the Lough Muckno catchment. This station is situated on the southern shore of Lough Muckno and measures the water levels on the lake. The gauge was originally installed to monitor the Lough's water levels due to downstream water abstractions from Lough Ross and the River Fane at Stephenstown, Co. Louth. Additionally, a hydrometric station owned by the OPW is located c. 1.3km downstream from the outflow of Lough Muckno on the River Fane. The station is named the Clarebane Station (06012) and monitors both water levels and flow. Based on the area and mean water depth of Lough Muckno (see Plate 1) in combination with utilising the annual flow data obtained from the aforementioned hydrometric station, a lake retention time of 45 days is calculated for the lough (i.e. lake flushing rate of 0.12 yrs).

Table 2 outlines the locations where gauges have previously been active or whereby the location of spot flow measurements are recorded on https://gis.epa.ie/EPAMaps/.

Table 1. Results of Orthophosphate (PO4-P) monitoring completed within the Lough Muckno catchment 2022

Sampling Location	Station Name	Sub-Catchment	Monitoring Station Type	S.I. No. 272 of 2009 (as ammended) EQS Value	Sampling Date & OrthoP Results										Annual Average
					Feb-22	Apr-22	Apr-22	Jun-22	Aug-22	Sep-22	Oct-22	Nov-22	Nov-22	Dec-22	
Bridge d/s Fincarn	RS06K060560	Annahale Stream	Investigative	0.035	0.012	0.022	0.017	0.034	0.037	-	0.029	-	-	0.024	0.025
ANNAHALE STREAM - Br u/s L. Muckno	RS06A011100	Annahale Stream	Active Pre WFD	0.035	-	0.019	-	0.019	0.043	-	0.083	0.036	-	0.019	0.037
Skerrymore trib	RS06L260790	County Water	Investigative	0.035	0.024	0.018	-	0.029	0.058	-	0.058	-	-	0.027	0.036
County Br	RS06C030050	County Water	WFD Operational	0.035	0.044	0.031	-	0.064	0.063	-	0.057	-	-	0.051	0.052
Br u/s Wallace's Br	RS06C030170	County Water	WFD Operational	0.035	0.064	0.005	-	0.037	-	0.064	-	0.088	-	-	0.052
GENTLE OWEN'S LAKE STREAM - Br u/s Muckno Mill Lough	RS06G040080	Gentle Owen's Lake Strean	Active Pre WFD	0.035	0.029	0.036	-	0.048	0.097	-	0.069	-	-	0.043	0.054
Br 1.5km d/s Muckno Mill L	RS06G040100	Gentle Owen's Lake Strean	WFD Operational	0.035	-	-	0.005	0.033	0.041	-	0.083	0.082	-	0.096	0.057
Derrycreevy Br	RS06F010200	Fane	WFD Operational	0.035	0.039	0.033	-	0.032	-	0.026	-	0.027	0.032	0.037	0.032

-	No sampling / analysis completed
0.005	Where result was below the limit of detection (i.e. <0.01mg/l) a concentration of 0.005mg/l is included
0.036	Annual Average concentration above the 'Good' EQS for Molybdate Reactive Phosphorus

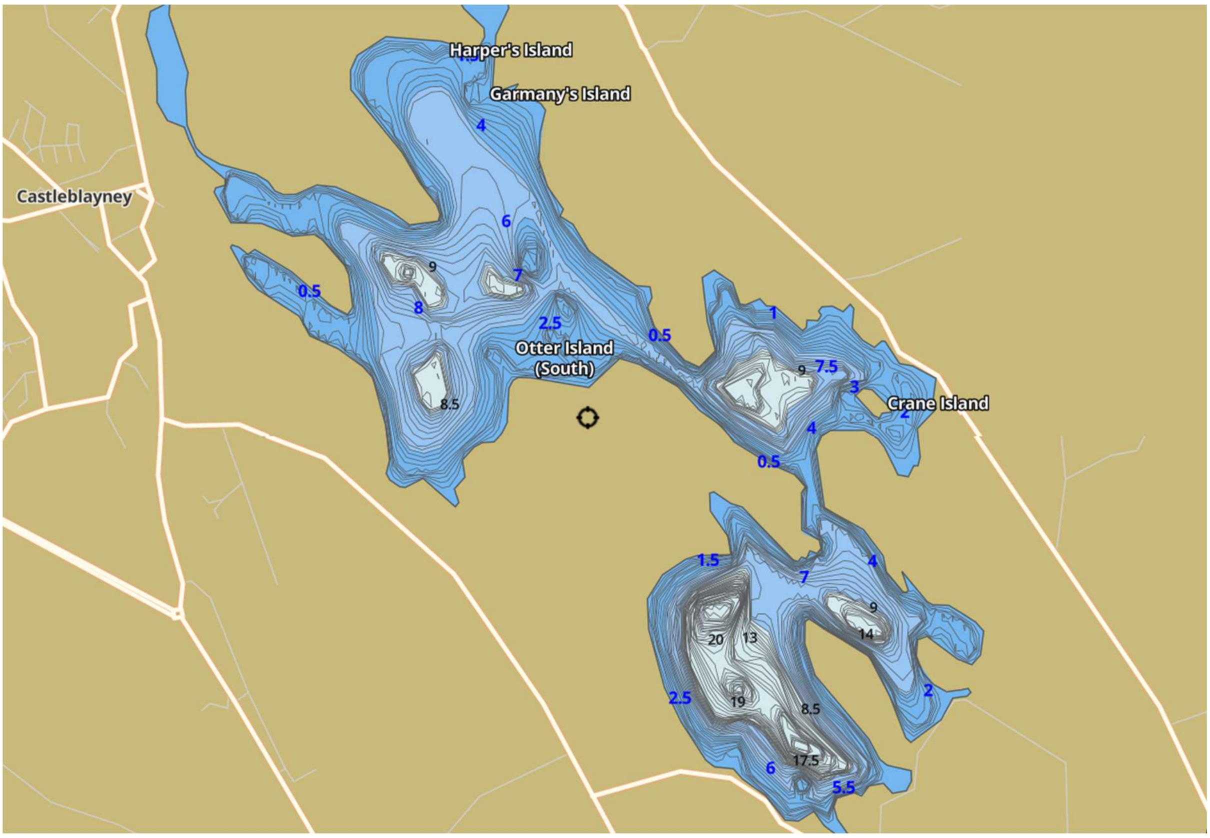


Plate 1. Bathymetric map of Lough Muckno sourced from GPS Nautical Charts.

Given the ungauged nature of the streams flowing into Lough Muckno, the EPA have estimated river flows for a number of watercourses within the Lough Muckno catchment and for a range of flow duration percentiles (i.e. Q1 – Q99). These flows were modelled using the Qube model (formerly known as the Hydrotool) and represent flows that could be expected under naturalised conditions (i.e. they do not take account of artificial influences, such as water supply abstractions or wastewater discharges). Upon inspection, stream/river flows do not appear to be estimated for the County Water, Drumacon Stream or Annalitten/Toome Stream.

Table 2. Locations of historic water level / flow monitoring stations in Lough Muckno Catchment

Station Name	Station Status	Waterbody	Location	Owner	Available Data
Annadrumman	Inactive	Annalitten Stream	E: 285524 N: 316347	Monaghan Co.Co	Spot flow measurements only - No continuous water level or flow records available.
Dromore	Inactive	Drumacon Stream	E: 286500 N: 318800	Monaghan Co.Co	Spot flow measurements only - No continuous water level or flow records available.
Concra	Inactive	Annahale Stream	E: 283968 N: 318378	Monaghan Co.Co	Spot flow measurements only - No continuous water level or flow records available.
Wallace's Bridge	Inactive	County Water	E: 284971 N: 320439	Monaghan Co.Co	Spot flow measurements only - No continuous water level or flow records available.
Derrycreevy	Inactive	Fane Stream (Inflow)	E: 282735 N: 320704	Monaghan Co.Co	Spot flow measurements only - No continuous water level or flow records available.
Drumaliss	Inactive	Gentle Owens Lake Stream	E: 282735 N: 320704	Monaghan Co.Co	Spot flow measurements only - No continuous water level or flow records available.
Drumleek	Inactive	Gentle Owens Lake Stream	E: 284609 N: 322927	Monaghan Co.Co	Water level & flow data available from 2007 – 2021.

2.4 Previous Paleolimnological Studies within the Catchment

Past paleolimnological investigations on Lough Muckno are confined to studies by Douglas et al. (1978), Chique et al. (2017) and Chique et al. (2018). Additionally, a study on Milltown Lake (i.e. lake located within the Lough Muckno catchment) was conducted by Carson et al. (2014).

Chique et al. (2017) conducted a high-resolution palynological analysis on a single sediment core obtained from the western basin of the lough. They inferred the first occurrence of human activity and agriculture during the Early Neolithic (ca. 3870–3500 B.C.). After a period of undiscernible human activity of ~900 years, farming was once again found to commence during the Early Bronze Age (ca. 2600 B.C.). Thereafter, a continuous human presence on the landscape was evident albeit with fluctuating levels of intensity.

By assessing non-pollen palynomorphs (NPPs) and chironomid records in addition to pollen analysis, Chique et al. (2018) attempted to track changing lake conditions as a consequence of human impacts over a c. 223-year period (i.e. more modern sediments). Five distinct periods of change were reported including:

- A productive lake state in an agricultural setting (c. 1790–1840);
- Reduced activity and potential lake amelioration (c. 1840–1897);
- Increase in livestock grazing and lake eutrophication (c. 1897–1954);
- Agricultural modernization and further lake deterioration (c. 1954–1991); and
- Discrete lake improvement (c. 1991–2013).

The aforementioned study represented the first attempt in the Irish Ecoregion to gain insights into Water Framework Directive (WFD) reference conditions based on palaeolimnological analysis of chironomid community structure. Attempts at hindcasting past ecological reference conditions using diatom assemblages is more common in an Irish context, if not yet extensive (Leira et al., 2006, Taylor et al., 2006, O'Dwyer et al., 2013). As diatoms can live in a variety of habitats (i.e. in open water (planktonic), mobile or immobile on the bottom (benthic), attached to plants (epiphytic) or attached to rocks (epilithic)), assessment of their assemblages within sediment records have been used to describe wider ecosystem change (Round *et al.*, 1990, Dixit et al., 1992). Additionally, as individual species have relatively narrow optima and tolerances for nutrient conditions, numerous applications have been developed in an effort to infer / predict past nutrient concentrations (Anderson et al., 1993, Bennion et al., 1996). For instance, diatom-based total phosphorus (TP) transfer functions can provide quantitative estimates of historical phosphorus concentration from the sedimentary composition of diatoms. Chen et al. (2008) developed a diatom based total phosphorus (TP) transfer function for the Irish Ecoregion whereby the response of surface sediment diatom assemblages to measured environmental variables were examined using a 72-lake training set. Lough Muckno was included as one of the lakes used in the study.

Other studies have demonstrated that past lake water TP concentrations can be reconstructed from lake sediment TP data (Moyle and Boyle, 2021, Boyle et al., 2023). However, in such example's phosphorus supply was dominated by external loads, the sediment P profile was stable and internal loading was deemed to be insignificant. The study conducted by Douglas et. al (1978), provided evidence that nutrient loading in the form of sedimentary P release during periods of anoxia was occurring in Lough Muckno. Hence predicting past TP concentrations from the sedimentary TP record in the lake could be problematic.

Whilst diatom inferred total phosphorus (DI-TP) concentrations can provide a potential restoration target condition, internal phosphorus loading may continue to delay improvements in lake water quality even after external loading is reduced (Sondergaard et al., 2003). Thus, for restoration targets to be realistic, account of the timescale for the reduction in internal P loading to occur should be factored into any management plans. Estimations of lake recovery lag times as a consequence of internal P release is understood to be limited in an Irish context to a number of sites including those investigated by Rippey et al (2021). The aforementioned study used the Lewis/Penn model to predict the timescale of reduction of long-term phosphorus release from the sediment of four Irish lakes with the view to predicting timescales for recovery. The model used by Lewis et al. (2007) can be described as a box (Continuously Stirred Tank Reactor) model of the rate of change of labile P in an active layer of sediment where labile P is taken to be responsible for the long-term release of P from sediment. It describes the diagenesis and burial of P with the diagenesis rate constant estimated using the concepts and methods of Penn et al. (1995).

The Rippley et al. (2021) study estimated that a 75% reduction of labile P in the active layer of Lough Ramor and Lough Neagh would take 33 and 41 years respectively. For both lakes internal P release was deemed to be an important component of the lake's phosphorus budget. A survey of long-term data from 35 lakes in Europe and North America concluded that internal release of phosphorus typically endured for 10–15 years after internal loading reduction (Jeppesen et al. 2005). Whilst Sondergaard et al. (2003) showcased how internal release in some lake may last longer than 20 years. Conversely, in lakes with limited summer P release and shorter hydraulic residence times, lake recovery times are anticipated to be within a few years, as is estimated to be the case in Lough Sheelin and Lough Melvin (Rippley et al., 2021).

3.0 Materials & Methods

3.1 Sediment Core Extraction

3.1.1 Long Cores

In total four sediment cores were obtained from the three deepest basins (see Plate 1) of the lough in May 2022 with a Usinger piston corer (Mingram et al., 2007). The corer was deployed from a floating pontoon which was anchored to the bed of the lough (see Plate 2). The positioning of the pontoon was achieved with the assistance of boats and personnel from Monaghan County Council and the Monaghan Civil Defence. Coring was led by Dr. Aaron Potito, Dr. Karen Molloy and Dr. Carlos Chique of the Ryan Institute, University of Galway with all cores transported to the facility for storage upon completion. Subsequently, each core with the exception of LMV was sub-sampled into 1cm slices by Patrick McCabe of Hydrec Environmental Consulting and Donna McEvoy, Executive Scientist, Monaghan County Council in the laboratories of the Ryan Institute.

Plate 2. Photo of assembly of sediment coring pontoon on Lough Muckno May in 2022.

Given that the Ryan Institute had previously carried out a paleolimnological study of the lough in 2013 (Chique et al., 2017), whereby two cores were extracted from the western basin (LM I – II), the naming convention of the four long cores extracted as part of this study followed in a sequential order (LM III–VI). Each core was 3m in length, with the exception of LMV where some losses of sediment occurred during the retrieval process. Hence, no further analysis on core LMV was completed. Core LMVI was used to represent the southern basin. It was understood from the sedimentation rates reported by Chique et al. 2017 for Lough Muckno (i.e. 0.98cm/yr or 9.8mm/yr) that efforts at hindcasting the conditions of the lough, preceding the Irish famine would require core lengths in excess of the capacity of gravity coring devices (i.e. typically 50cm – 100cm). Thus, the 3m cores retrieved from the piston coring apparatus were used in the sediment dating and diatom analysis.

3.1.2 Short Cores

In November 2023, Patrick McCabe of Hydrec Environmental Consulting, Donna McEvoy of Monaghan County Council and Dr. David O'Connell of Trinity College, Dublin, retrieved a short sediment core (25cm in length) from the deepest point of the central basin of the lough using a Kajak gravity corer Ø60 (i.e. supplied by KC Denmark A/S). The core was sectioned into 1cm slices under nitrogen (N_2) atmosphere at the lake shore. Each sample was then placed into 50ml centrifuge tubes and topped up with N_2 gas. Samples were transported to the laboratories of Trinity Colleague Dublin with pore waters and solids separated by centrifugation on the same day as sampling. These samples were subsequently analysed for a number of different P fractions (see Section 3.6.1).

3.2 Sediment Dating

In total 71 samples from cores LMIII, LMIV and LMVI were submitted to Raddec International Ltd. based in the University of Southampton for radiometric dating. Each sample was freeze dried at the laboratory, transferred and weighed into 20ml scintillation vials and counted (80,000 seconds) for their gamma radioactivity (^{210}Pb and ^{137}Cs) using Canberra HPGe well-type gamma spectrometers. Analysis of the gamma spectra was made using Fitzpeaks spectra deconvolving software (JF Computing, UK). All analyses were completed by Dr. Ian Croudace (see methodology outlined in report included in Appendix 1).

3.3 Diatom Slide Preparation & Identification

Sediment samples from two of the Lough Muckno cores (LMIII & LMIV) were prepared for diatom analysis. Samples were prepared by Dr. Ben Goldsmith of Goldsmith Ecology using standard techniques after Batterbee et al. (2001) with the cleaned material mounted in Naphrax onto permanent microscope slides. All slides were labelled with the core code, date and sediment depth. Diatom counts and identification was completed by Patrick McCabe of Hydrec

Environmental Consulting with at least 300 valves counted for each sample using oil immersion objective and phase contrast microscopy (X1250). Diatoms were identified using standard floras (Krammer & Lange-Bertalot 1986–2000). Five slides were counted per core and were targeted following sight of the dating results. For instance, slides coinciding with the timing of pre/post Irish Famine, turn of the 20th century, pre-Irish agricultural intensification, period after the onset of agricultural intensification and recent depositions were selected. Diatom stratigraphy graphs were produced using C2 software (Juggins, 2007) which aided in the visual representation of changes in the diatom assemblages over time. Changes in diatom assemblages were interpretated to inform on wider ecological change in the Lough.

3.4 Diatom Transfer Function

The calibration models for the diatom based total phosphorus (TP) transfer function developed for the Irish Ecoregion was developed using the weighted averaging (WA) method, were data manipulation showed strong influences on model performances (Chen et al., 2007). The optima WA models based on 70 lakes produced a jack-knifed coefficient of determination (r^2_{jack}) of 0.74 and root mean squared error of 0.21 ($\log_{10}$ µg/l^{-1}) for TP.

The diatom assemblage data collected as part of this study was provided to Prof. Chen (i.e. original developer of the Irish DI-TP model) in a format suitable for application with the model. Subsequently, Prof. Chen applied the DI-TP model to the Lough Muckno diatom data and historical TP concentrations were then estimated[1]. A summary of the model outputs is included in Appendix 2.

3.5 Calculation of TP & PO4-P Loadings

3.5.1 Additional Surface Water Sampling & Analysis

During 2023, Lisa Smith and Shane McBrien (Environment Section of Monaghan County Council) took monthly samples from the hypolimnion zone (i.e. 1m from the base of the lake) at each of the three basins within Lough Muckno. Sampling was completed at the deepest point of each basin using a Van Dorn Sampler (supplied by Royal Eijkelkamp). In addition, monthly water quality sampling of the Lough's tributaries was coordinated by Martina Smith, Executive Scientist, Monaghan County Council. As part of the programme seven locations within the catchment were monitored (see Figure 2). Said monitoring locations were positioned on the six fluvial inflows with the final monitoring location situated on the channel that flows out of Drumcrew Lough and into Lough Muckno (see Photos in Appendix 3). Monitoring locations were dictated by accessibility but were positioned as close as possible to the location were the watercourse discharges into the lake. Both orthophosphate (PO4-P) and total phosphorus (TP) were analysed on all samples by CLS Laboratories.

[1] *Weighted average with inverse deshrinking used*

During each lake monitoring event, Monaghan County Council carried out temperature and dissolved oxygen (DO) profiling at the three lake basins using a Hach HQ40d multi parameter probe. Temperate and DO readings were taken at 1m depth intervals.

3.5.2 Additional Hydrometric Montoring

In October 2022, Patrick McCabe of Hydrec Environmental Consulting and Martina Smith, Monaghan County Council, installed a Rugged TROLL 100 data logger at each of the seven additional water quality monitoring stations. A Rugged Baro TROLL was also installed in the catchment to log barometric pressure and temperature to compensate for water level changes due to barometric fluctuations. Data loggers were installed within vertical perforated standpipes erected by Kearns Engineering Services Ltd. The data loggers were used to monitor water levels at each station every 15 minutes for the duration of 2023.

During low, mid and high flow conditions, Patrick McCabe of Hydrec Environmental Consulting carried out velocity readings at each monitoring location. Readings were taken at a number of intervals across each channel cross section using an OTT electromagnetic streamflow gauging meter. Using the measured velocity data and associated water depths a rating curve was developed for each monitoring location. This allowed for the calculation of the flow rates at times of sampling and the Q_{30} flow rate across the entirety of the monitoring period.

3.5.3 Phosphorus Loadings

Annual mean fluvial input and fluvial output orthophosphate and total TP loads were calculated using Method 5 in Johnes (2007), whereby the sum of total loads over sampling days multiplied by the annual mean discharge as a proportion of the total discharge over the sampling day:

$$\text{Load} = \frac{K\sum_{i=1}^{n}(C_i Q_i)}{\sum_{i=1}^{n} Q_i}\overline{Q_r}$$

K = conversion factor to take account of period of record
C_i = instantaneous concentration associated with individual samples (mg l^{-1})
Q_i = instantaneous discharge at time of sampling ($m^3 s^{-1}$)
$\overline{Q}_r$ = mean discharge for period of record ($m^3 s^{-1}$)
$\overline{Q}_{pi}$ = mean discharge for interval between samples ($m^3 s^{-1}$)
$\overline{C}_m$ = mean monthly concentration (mg l^{-1})
$\overline{Q}_m$ = mean monthly discharge ($m^3 s^{-1}$)
n = number of samples

Plate 3. Extracts from Johnes 2007, detailing the formula used to calculate phosphorus loadings.

Model 28 of Khorasani and Zhu (2021) was used to estimate the inflow phosphorus concentration (Cext) that supports the targeted lake TP concentration:

$$\text{Predicted C} = \text{CF x } \frac{-1+\left(1+4\times 0.095\times tw^{0.489}\times Cext^{(-0.333+1)}\times z^{0.288}\right)^{\wedge 0.5}}{2\times tw^{0.489}\times Cext^{-0.333}\times z^{0.288}}$$

Where:

- CF = Correction Factor is 1.159 (Sprugel, 1983);
- tw = Annual mean hydraulic residence time;
- z = Mean depth (m);
- C*ext* = Annual volume-weighted average total phosphorus concentration in the inflow(s). Cext = Lext/qs, where Lext, g P m^{-2} yr^{-1} is the annual average areal external total phosphorus load;
- qs (m yr^{-1}) = Annual hydraulic load, qs = z/tw

3.6 Lake Recovery Prediction Model

3.6.1 Sequential Phosphorus Extraction and Analysis

A 0.5g of freeze dried, sieved sediment was weighed out into acid washed centrifuge tubes. Five sediment samples (0-1cm, 4-5cm, 9-10cm, 14-15cm, 18-19cm) from the short core retrieved in November 2023 were extracted sequentially using a modified SEDEX protocol (O'Connell et al., 2020). Samples were extracted and analysed in duplicate.

The P extraction scheme used here yielded the following operationally defined P fractions: easily exchangeable (P_{Ex}, 1 M MgCl2), humic bound (P_{Hum}, 1 M NaHCO3), Fe-oxide bound (P_{Fe}, CDB), CaCO3 bound (P_{CFA}, 1 M acetate, pH 4), detrital apatite/other inorganic P (P_{Detr}, 1 M HCl), and organic P (P_{Org}, 1 M HCl after washing at 550°C).

3.6.2 Estimating Timelines for Recovery

Lake recovery predictions for Lough Muckno have been estimated following a modification of the Lewis/Penn Model as previously applied on Irish Lakes by Rippley et al. (2021) and outlined on Plate 4. As part of this study, Fraction A and Fraction B concentrations were calculated from extractions using the modified SEDEX protocol presented in O'Connell et al. (2020). Where:

<u>Fraction A</u>

- P_{Ex} – $MgCl_2$
- P_{Hum} – $NaHCO_3$
- P_{Fe} – CDB
- P_{CFA} – Acetate

Fraction B

- P_{Detr} – HCL
- P_{Resi} – HCL after ashing at 550 °C.

The time for the labile P concentration in the active sediment layer to reach 90% (t_{90}) of the way to a new steady-state through diagenesis and burial is determined by the overall rate constant and values included in Chapra (1997). For example, the time taken for the concentration to reach 90% was calculated using $t_{90} = 2.30\ \tau_w$.

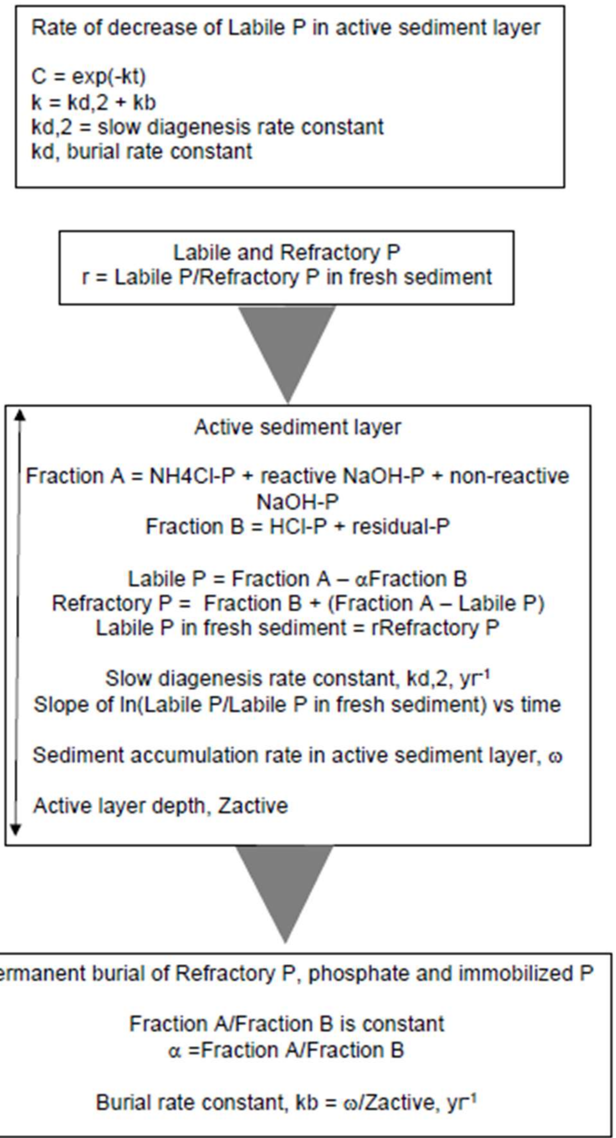
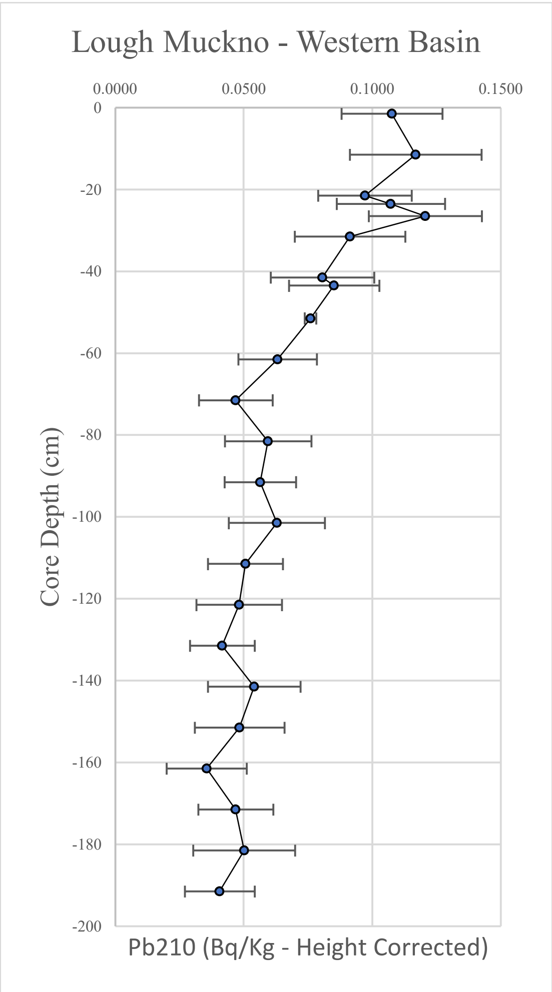


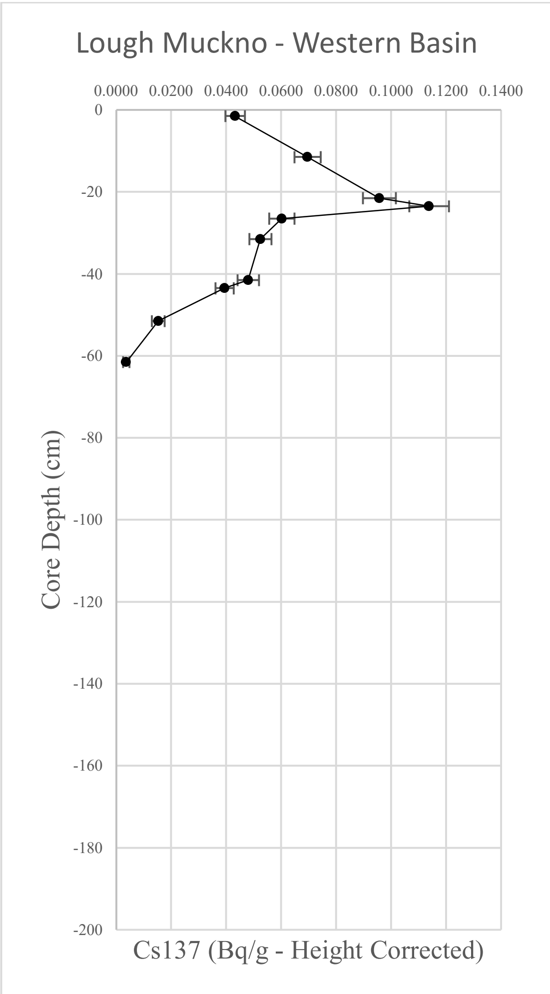
Plate 4. Extract from Rippey et al., 2021 detailing Lewis/Penn Model.

4.0 RESULTS

4.1 Sediment Chronology

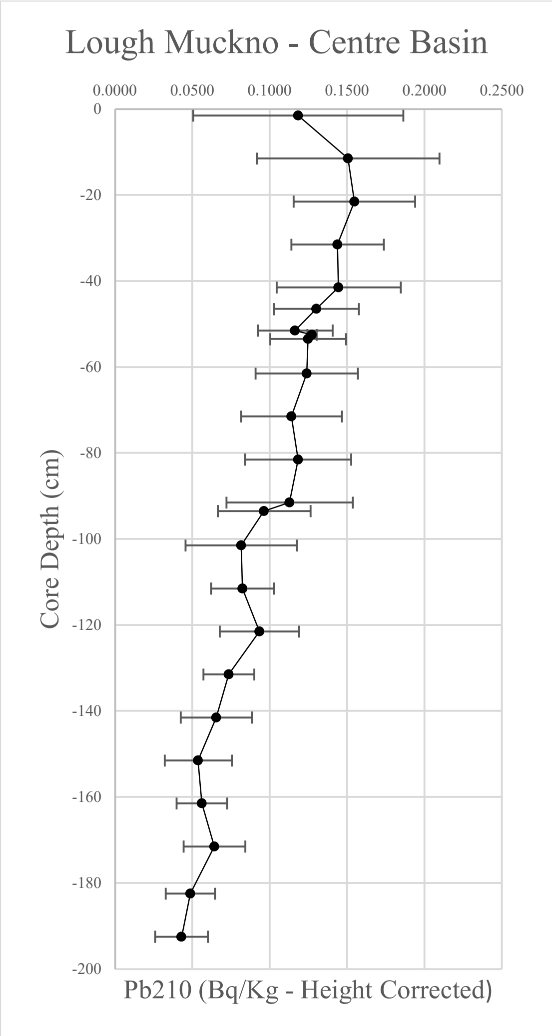
The radio-chronological data and profiles for LMIII and LMIV show distinct features in the down core profiles for ^{137}Cs which are readily attributable to the first onset of the American atmospheric thermonuclear weapons testing in the Pacific Ocean in 1954, the 1963 'bomb peak' and the 1986 Chernobyl nuclear disaster peak (see Graphs 4 - 7). Concentrations of 0.004 Bq/g ^{137}Cs and 0.003 Bq/g ^{137}Cs were attributed to the onset of the weapons testing in cores LMIII and LMIV respectively. The data reveals a consistent age depth relationship in each core, signifying that the sediment accumulation rates to be uniform within the western and central basins. Whilst the rates of accumulation were found to be uniform, the accumulation rates differed in both cores. ^{137}Cs derived sediment accumulation for core LMIII and LMIV were calculated at 8.9mm/yr and 17.2mm/yr respectively.

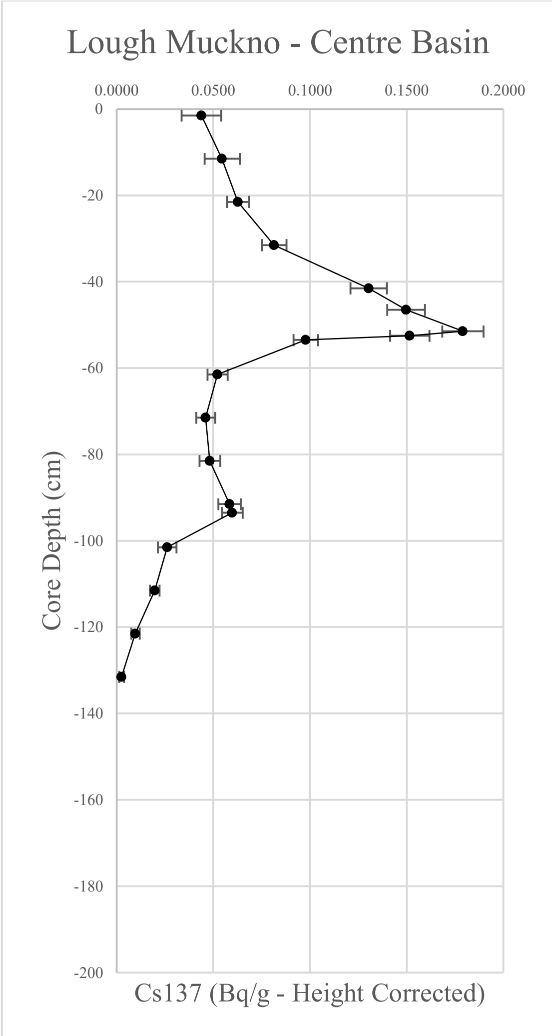




Graph 4 (Left). Downcore distributions of ^{210}Pb activities in Core LMIII. Graph 5 (Right) Downcore distributions of ^{137}Cs activities in Core LMIII.

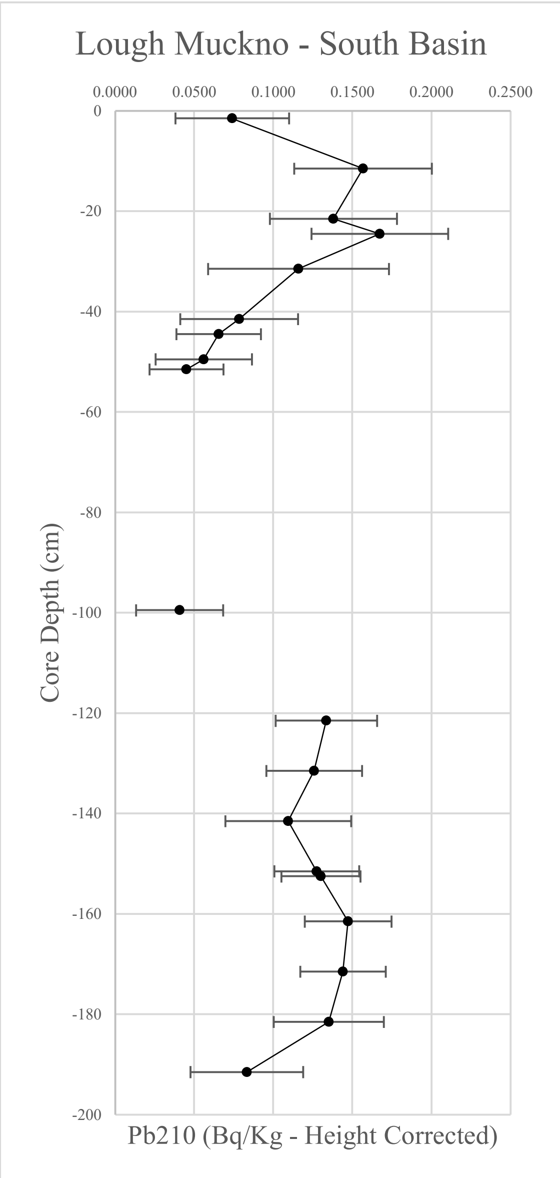
The ^{210}Pb data produce relatively straight log-linear regressions (LMIII R^2 = 0.996, LMIV R^2 = 0.993). However as documented in the analysis report (see Appendix 1), the organic-rich nature of the sediment leads to relatively low activities due to the modest amount of minerogenic material in the sediment. Hence this leads to larger uncertainties than that are seen in the Cs-137 profiles. The ^{210}Pb profiles would suggest a sedimentation accumulation rate of 10mm/yr for core LMIII and 16mm/yr for core LMIV. However, given the larger uncertainties associated with the ^{210}Pb data, the accumulation rates derived from the ^{137}Cs approach (i.e. based on more independent criteria/events) was used as the chronology for this study.

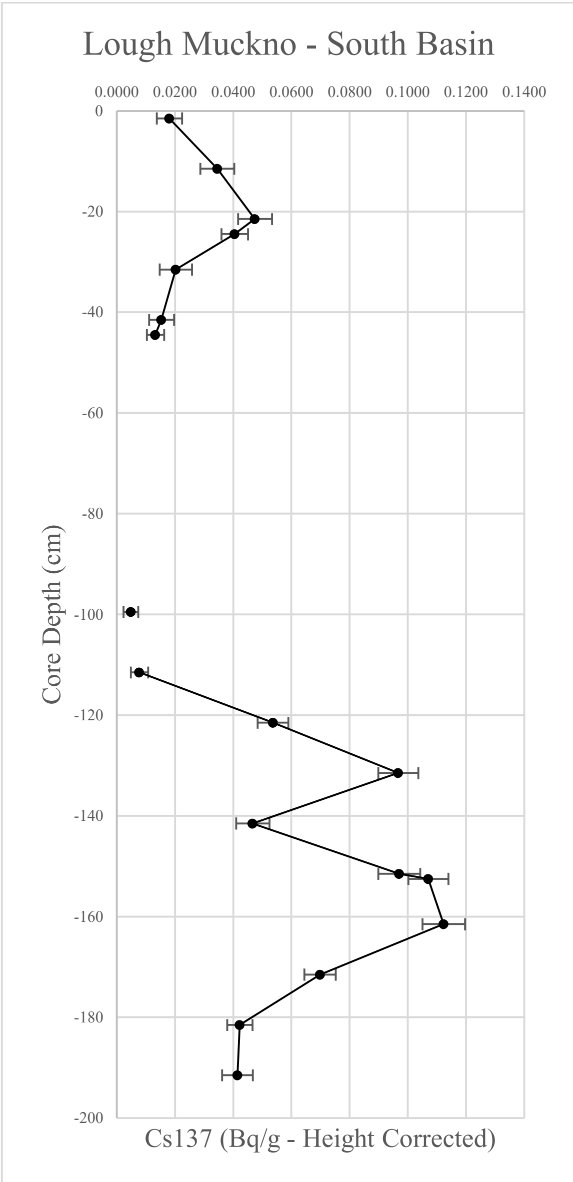




Graph 6 (Left). Downcore distributions of ^{210}Pb activities in Core LMIV. Graph 7 (Right) Downcore distributions of ^{137}Cs activities in Core LMIV.

As mentioned in Section 3.1.1, accurate sediment accumulation rates could not be estimated for core LMVI. As can be seen from Graphs 8-9, a maximum ^{137}Cs of 0.112 Bq/g was recorded at a core depth of 161.5cm. A smaller peak of 0.048 Bq/g ^{137}Cs was recorded at a core depth of 21.5cm. Typically, the larger of the two ^{137}Cs peaks in Irish sediment lakes is found closest to the top of the core and attributed to the Chernobyl accident of 1986 (Taylor et al., 2006, O'Reilly et al., 2011). In this instance, the opposite occurs. This would signify two distinct ^{137}Cs populations in the core. Such a phenomenon can occur when modern heavier sediments originating from activities adjacent to the lake's edge can become buried/deposited below older sediments 'i.e. known as 'slumping'. Plates 5 & 6 shows a distinct transition in the material/sediment type found at c. 110cm deep from core LMVI. Diagonal layering is also evident within the core. Such visual indicators would support this hypothesis.





Graph 8 (Left). Downcore distributions of ^{210}Pb activities in Core LMVI. Graph 9 (Right) Downcore distributions of ^{137}Cs activities in Core LMVI.


Plate 5 (Left) & Plate 6 (Right). Photos of sediment extracted from 1m – 2m below top of lakebed from the southern basin of Lough Muckno. Changes in sediment composition can be observed. (Photos courtesy of Dr. Karen Molloy, Ryan Institute, University of Galway).

4.2 Diatom Identification & Inferred TP Concentrations

4.2.1 Core LMIII (Western Basin)

The diatom assemblage attributed to c.1830 (i.e. pre famine) in the western basin was dominated by *Tabellaria flocculosa* (31% relative abundance (RA) with *Achnanthidium minutissimum* (RA 8%) and *Eunotia incisa* (7%) found to be subdominant (see Graph 10). A number of *Stauroseira spp.* were found in relatives abundances ranging from 2% - 5% namely, *Stauroseira pinnata (*5%), *Staurosira construens* (3%) and *Staurosira construens var. venter* (2%). Four different *Cyclotella spp*. were recorded c. 1830 with *Cyclotella radiosa* recorded in greatest RA (3%).

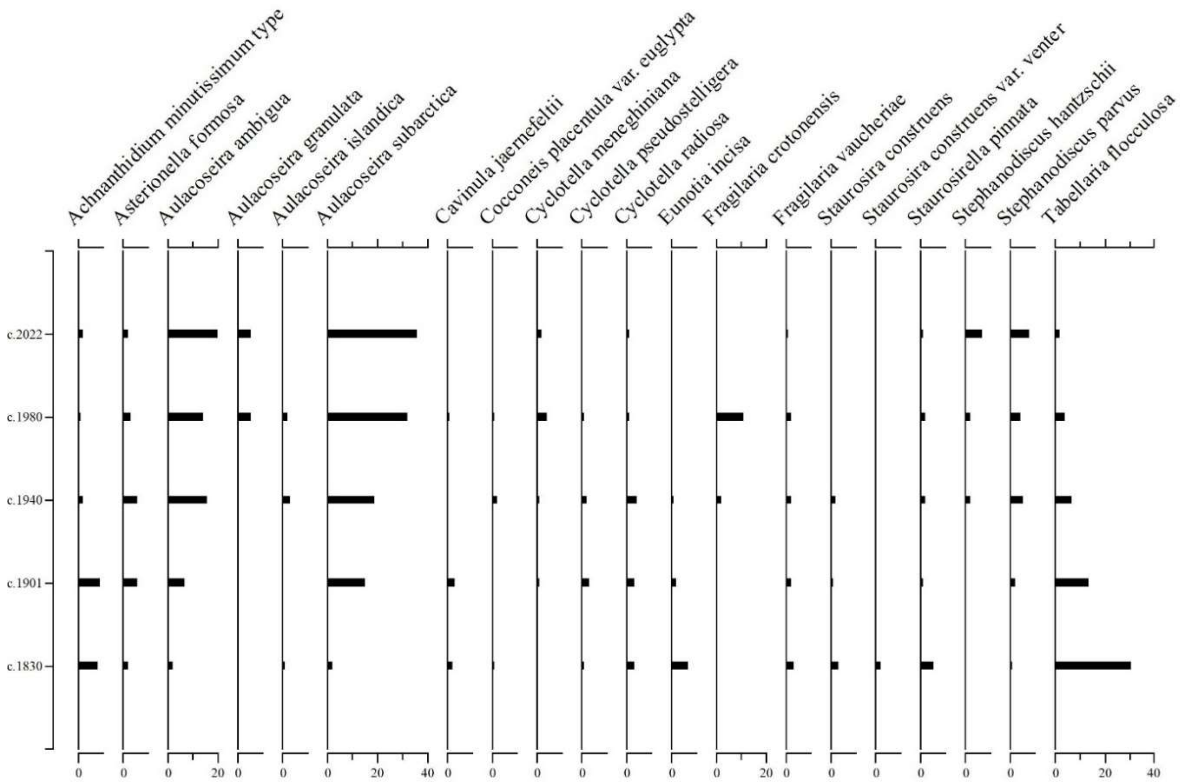
By 1901 a substantial reduction in the relative abundance of *Tabellaria flocculosa* (14%) was observed. Similarly, a reduction in *Eunotia incisa (*2%) was found whereas a slight increase in the RA of *Achnanthidium minutissimum* occurred (8%). At this juncture *Aulacoseira subarctica* (15%) was found to co-dominate, with *Aulacoseira ambigua* (7%) and *Asterionella formosa* (6%) sub-dominant.

Aulacoseira subarctica (19%) was found to be dominant by 1940 with a substantial increase in *Aulacoseira ambigua* (16%) also evident. Additionally, there was an increase in the RA of *Aulacoseira islandica* (3%). *Asterionella formosa* (6%). *Cyclotella radiosa* (4%) and

Fragilaria vaucheriae (2%) were recorded in similar relative abundances, however a further reduction in the *Tabellaria flocculosa* (7%) RA occurred. The RA of the small centric diatom *Stephanodiscus parvus* increased to 5% at this stage.

By 1980, the RA of *Aulacoseira subarctica* increased to 32% with similar relative abundances to that found in 1940 for *Aulacoseira ambigua* (14%) and *Aulacoseira islandica* (2%) recorded. Additionally, the relative abundances of *Stephanodiscus parvus* (4%), S*tephanodiscus hantzschii* (2%) and *Fragilaria vaucheriae* remained similar. *Aulacoseira granulata* (i.e. species not observed in the preceding samples) was recorded at this horizon at a RA of 5%. Whereas the RA of *Tabellaria flocculosa* (4%) continued to reduce. A reduction in the relative abundances of *Asterionella formosa* (2%) and *Cyclotella radiosa* (1%) also occurred. A distinct increase in the RA of *Fragilaria crotonensis* (11%) was evident.

Top of core (i.e. 2022) *Aulacoseira subarctica* (36%) and *Aulacoseira ambigua* (20%) were still found to be dominant and sub-dominant with increases in their relative abundances observed. The relative abundances of both *Stephanodiscus parvus* (8%) and S*tephanodiscus hantzschii* (7%) also increases. At this stage *Fragilaria crotonensis* reduces to <1% RA whilst the reduction in *Tabellaria flocculosa* continues to 2% (i.e. lowest RA for species found in the core).



Graph 10. Stratigraphic diagram showing changes in relative abundance (%) of selected diatom taxa (>2% RA) from Core LMIII

4.2.2 Core LMIV (Centre Basin)

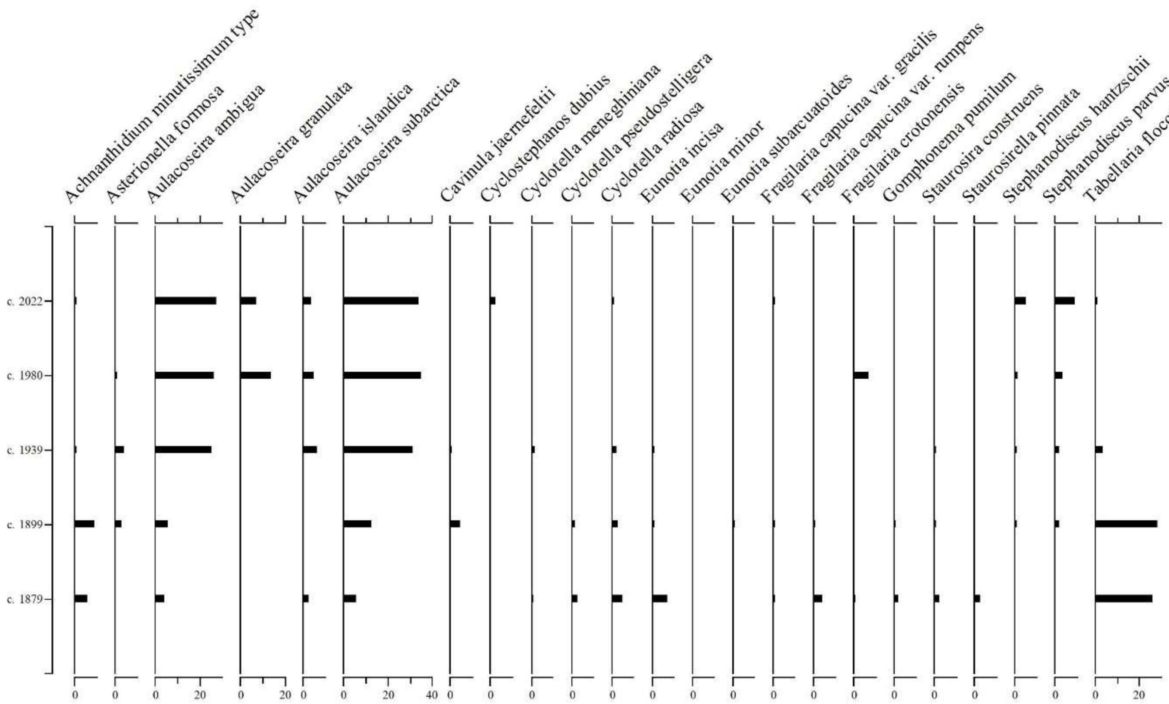
The diatom assemblage attributed to c.1879 in the centre basin was dominated by *Tabellaria flocculosa* (26% relative abundance (RA) with *Eunotia incisa* (RA 7%) and *Achnanthidium minutissimum* (6%) found to be subdominant (see Graph 11). *Fragilaria capucina var. rumpens* was recorded at a RA of 4%. A number of of *Aulacoseira spp.* were found in relative abundances ranging from 2.5% - 6% namely, *Aulacoseira Subartica* (6%), *Aulacoseira ambigua* (4%) and *Aulacoseira islandica* (2.5%). Two *Stauroseira spp.,* namely *Stauroseira pinnata* and *Staurosira construens* had a RA of 2.5% recorded. Four different *Cyclotella spp*. were recored c. 1879 with *Cyclotella radiosa* recorded in greatest RA (5%).

By 1899 a small increase in the relative abundance of *Tabellaria flocculosa* (28%) and *Achnanthidium minutissimum* occurred (9%). In addition, increases in the RA of Cavinula jaernefeltii (5%) and *Asterionella formosa* (3%) were also recorded. Conversely a reduction in the *Staurosira spp, Eunotia incisa (*1.5%)*, Fragilaria capucina var. rumpens* (1.5%) and *Cyclotella radiosa* (3%) was recorded. At this juncture *Aulacoseira subarctica* (13%) was found to co-dominate, with an increase in *Aulacoseira ambigua* (6%) also found.

Aulacoseira subarctica (32%) was found to be dominant by 1939 with a substantial increase in *Aulacoseira ambigua* (25%) and *Aulacoseira islandica* (6%) also evident. Additionally, there was a slight increase in the RA of *Asterionella formosa* (4%). *Stephanodiscus parvus* was recorded at a similar RA (2%) to the assemblage associated with 1899. However, a substantial reduction in the RA of *Tabellaria flocculosa* (4%) occurred.

By 1980, the RA of *Aulacoseira subarctica* further increased to 35%. Similar relative abundances to that found in 1940 for *Aulacoseira ambigua* (26%) and *Aulacoseira islandica* (5%) were recorded. Additionally, the relative abundances of *Stephanodiscus parvus* (4%), slightly increased. *Aulacoseira granulata* (i.e. species not observed in the preceding samples) was recorded at this horizon at a RA of 14%. Whereas the RA of *Tabellaria flocculosa* continued to reduce to >1% RA. A reduction in the relative abundances of *Asterionella formosa* (1%) also occurred. Like Core LMIII, a distinct increase in the RA of *Fragilaria crotonensis* (7%) was evident at this layer.

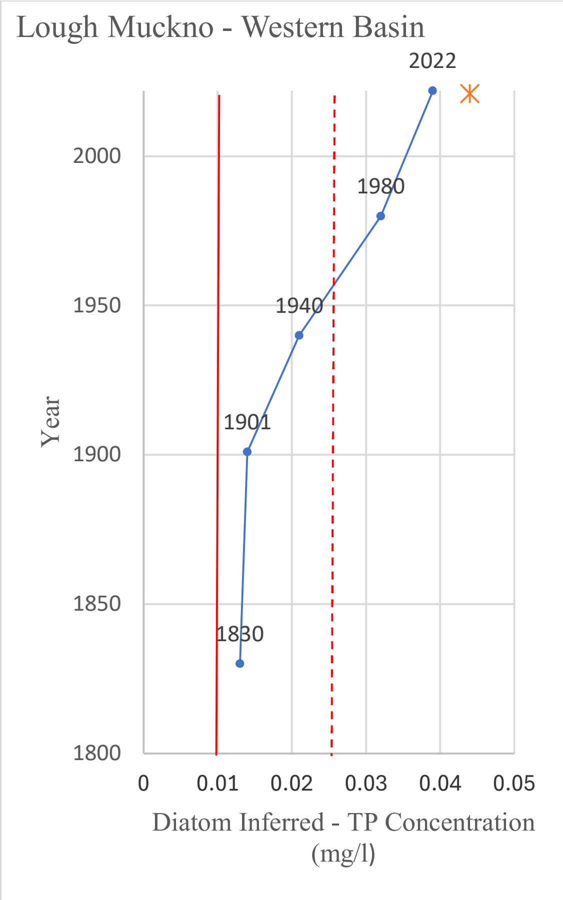
Top of core (i.e. 2022) *Aulacoseira subarctica* (34%) and *Aulacoseira ambigua* (27%) were still found to be dominant and sub-dominant. The relative abundances of both *Stephanodiscus parvus* (9%) and S*tephanodiscus hantzschii* (5%) also increases, whilst a similar RA of *Tabellaria flocculosa* was recorded (1%). *Fragilaria crotonensis* was not recorded at this horizon.

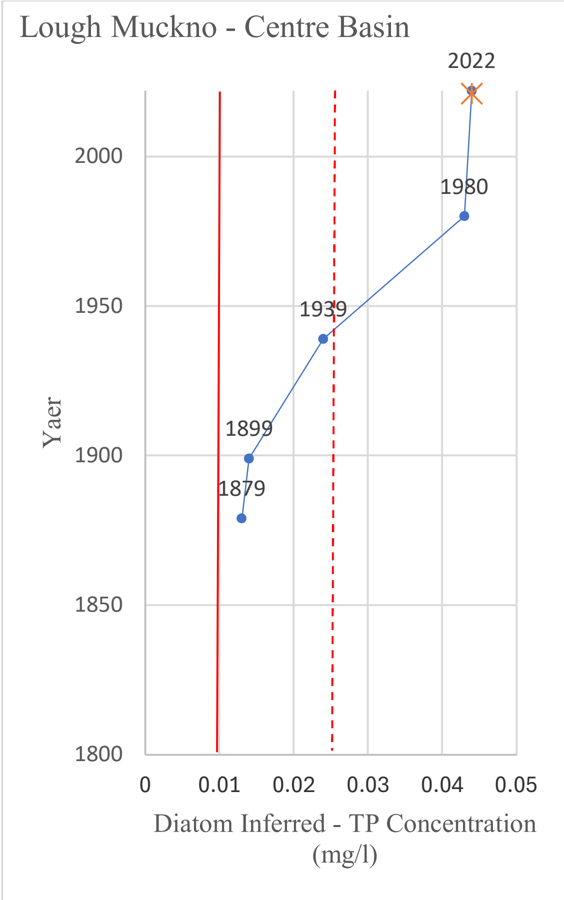


Graph 11. Stratigraphic diagram showing changes in relative abundance (%) of selected diatom taxa (>2% RA) from Core LMIV

4.2.3 Historic TP Concentrations

The results of the diatom inferred total phosphorus (DI-TP) modelling are demonstrated on Graphs 12 & 13. A TP concentration of 0.013mg/l was predicted for 1830 in the western basin with an identical concentration estimated for 1879 for the central basin. Similarly, an identical concentration of 0.014mg/l was predicated for the period 1899-1901 for the two basins. For the year 1940, a TP concentration of 0.021mg/l was predicted for the western basin, with a slightly higher concentration of 0.024mg/l estimated c. 1939 for the centre basin. TP concentrations continued to increase by 1980 whereby TP concentrations of 0.032mg/l and 0.043mg/l were estimated for the western and centre basins respectively. The highest TP concentrations amongst the samples assessed were predicted at the top of the core (i.e. most recent sediment deposition – 2021/2022). A concentration of 0.039mg/l was estimated for the western basin, with a concentration of 0.044mg/l predicted for the centre basin. These predicted values show a strong agreement with the annual average TP concentrations measured as part of the WFD operational monitoring (see Graphs 12 & 13).





Graph 12 (Left). Diatom inferred total phosphorus reconstruction for Core LMIII. Graph 13 (Right). Diatom inferred total phosphorus reconstruction for Core LMIV. Solid red line represents 'High' EQS threshold of 0.01mg/l, dashed red line represents 'Good' EQS threshold of 0.025mg/l, red star signifies the annual average TP concentration recorded as part of the WFD monitoring programme.

4.3 External Phosphorus Loadings & Target Reductions

4.3.1 Phosphorus Concentrations - Lough Muckno Tributaries 2023

Table 3 includes the results of the monthly PO4-P analysis completed on the seven monitoring points included as part of the project in 2023, whilst Table 4 details the total phosphorus results. As can be seen from Table 3, the average annual PO4-P concentration exceeded the associated river EQS (0.035mg/l) for 'Good' status at four of the stream watercourse sampling points. The highest annual average concentrations were recorded on the Gentle Owen's Lake Stream (0.045mg/l) and the County Water (0.044mg/l) with concentrations of 0.039mg/l and 0.037mg/l recorded on the Drumacon Stream and Toome Stream respectively. Annual average concentrations were within the 'Good' status threshold for the Annahale Stream (0.030mg/l), Drumcrew Lough outflow (0.027mg/l), Fane Stream (0.016mg/l) and the Clarebane Stream (0.024mg/l). Similarly, the highest annual average TP concentrations were recorded on Gentle Owen's Lake Stream, County Water, Drumacon Stream and Toome Stream whereby concentrations ranged from 0.109mg/l to 0.119mg/l. The lowest TP concentrations were recorded for the Clarebane Stream (0.090mg/l), Fane Stream (0.084mg/l) and Annahale Stream (0.081mg/l).

4.3.2 Hydrometric Data - Lough Muckno Tributaries 2023

The water levels/depths recorded every 15 minutes at the seven monitoring stations in 2023 are presented within the graphs included in Appendix 4. As can be seen from Graph A4.2 and Graph A4.5 in Appendix 4, watercourse flashiness was greatest for the County Water and Gentle Owen's Lake Stream, with water levels rising and failing quickest in response to catchment input. Table 5, details the calculated water flows at each monitoring station for each sampling event. The estimated Q_{30} flows for 2023 are also included. Of Lough Muckno's tributaries, the highest Q_{30} flow of $1.73m^3/s$ was calculated for the Gentle Owen's Lake Stream with the lowest Q_{30} flow (i.e. amongst the WFD channels) estimated for the Toome Stream ($0.22m^3/s$).

4.3.3 Phosphorus Loadings & Target Reductions - Lough Muckno Tributaries 2023

The OrthoP and TP loadings calculated for each of Lough Muckno's inflowing tributaries for 2023 are detailed on Figure 3 (Johnes, 2007). Additionally, the annual TP loading estimated for the Uisce Eireann WWTP discharge is also included. As annual average PO4-P concentrations were found to be in excess of the 'Good' status EQS in 2023 for the Gentle Owen's Lake Stream, County Water and Toome Stream, the PO4-P load reduction required to lower annual averages to below 0.035mg/l PO4-P for these watercourses has also been calculated. Loading reductions of c. 21.7%, c.55% and c.9.4% were estimated to be required for the Gentle Owen's Lake Stream, County Water and Toome Stream in 2023 respectively.

Table 6. details the results of the modelling applied to predict the external TP loading reductions required to support target lake TP concentrations (Khorasani and Zhu, 2021). Target TP concentrations of 0.024mg/l (pre 1950s) and 0.013mg/l (1800s) as inferred from the diatom transfer function application were utilised. Based on the external TP loading estimated for 2023, an inflowing concentration (C_{ext}) of 66 mg P m^3 is required to achieve a lake TP concentration of 0.024mg/l. This represents a 55% external TP reduction requirement. Whereas an inflowing concentration of 29 mg P m^3 is needed to restore concentrations to c. 0.013mg/l, necessitating an 80% reduction.

Table 3. Results of Orthophosphate (PO4-P) monitoring completed within the Lough Muckno catchment 2023 (As part of Lough Muckno Road to Recovery Project)

Watercourse	Sampling Location (ITM)	River Waterbody	S.I. No. 272 of 2009 (as ammended) EQS Value	Sampling Date & OrthoP Results												Annual Average
				09/01/23	09/02/23	28/03/23	25/04/23	16/05/2023	28/06/2023	26/07/2023	24/08/23	21/09/23	23/10/23	13/11/23	12/12/23	
Annalittin / Toome Stream	(685936, 816895)	Fane_020	0.035	0.036	0.031	0.005	0.013	0.005	0.143	0.005	0.122	0.118	0.056	0.039	0.035	0.037
Drumcrew Lough Outflow	(686378, 818823)		0.035	0.005	0.026	0.026	0.005	0.005	0.043	0.072	0.072	0.044	0.059	0.013	0.005	0.027
Drumacon Stream	(683111, 818755)	Fane_020	0.035	0.016	0.017	0.005	0.015	0.005	0.215	0.03	0.02	0.015	0.022	0.046	0.03	0.039
Annahale Stream	(683891, 818350)	Annahale Stream_010	0.035	0.045	0.05	0.012	0.021	0.005	0.033	0.039	0.05	0.041	0.031	0.038	0.04	0.030
County Water	(684931, 820445)	County Water_010	0.035	0.026	0.028	0.029	0.045	0.019	0.075	0.068	0.075	0.051	0.053	0.122	0.08	0.044
Fane Stream	(682691, 820696)	Fane_010	0.035	0.014	0.022	0.005	0.011	0.005	0.021	0.03	0.051	0.035	0.028	0.018	0.02	0.016
Gentle Owens Lake Stream	(683343, 821437)	Gentle Owens Lake Stream_010	0.035	0.043	0.025	0.038	0.056	0.043	0.044	0.053	0.057	0.038	0.072	0.044	0.04	0.045
Clarebane Stream (Muckno Outflow)	(687277, 816788)	Fane_020	0.035	0.038	0.031	0.025	0.021	0.005	0.011	0.005	0.011	0.011	0.041	0.04	0.04	0.024

0.01	Where result was below the limit of detection (i.e. <0.01mg/l) a concentration of 0.005mg/l is included
0.036	Annual Average concentration above the 'Good' EQS for Molybdate Reactive Phosphorus

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Table 4. Results of Total Phosphorus (TP) monitoring completed within the Lough Muckno catchment 2023 (As part of Lough Muckno Road to Recovery Project)

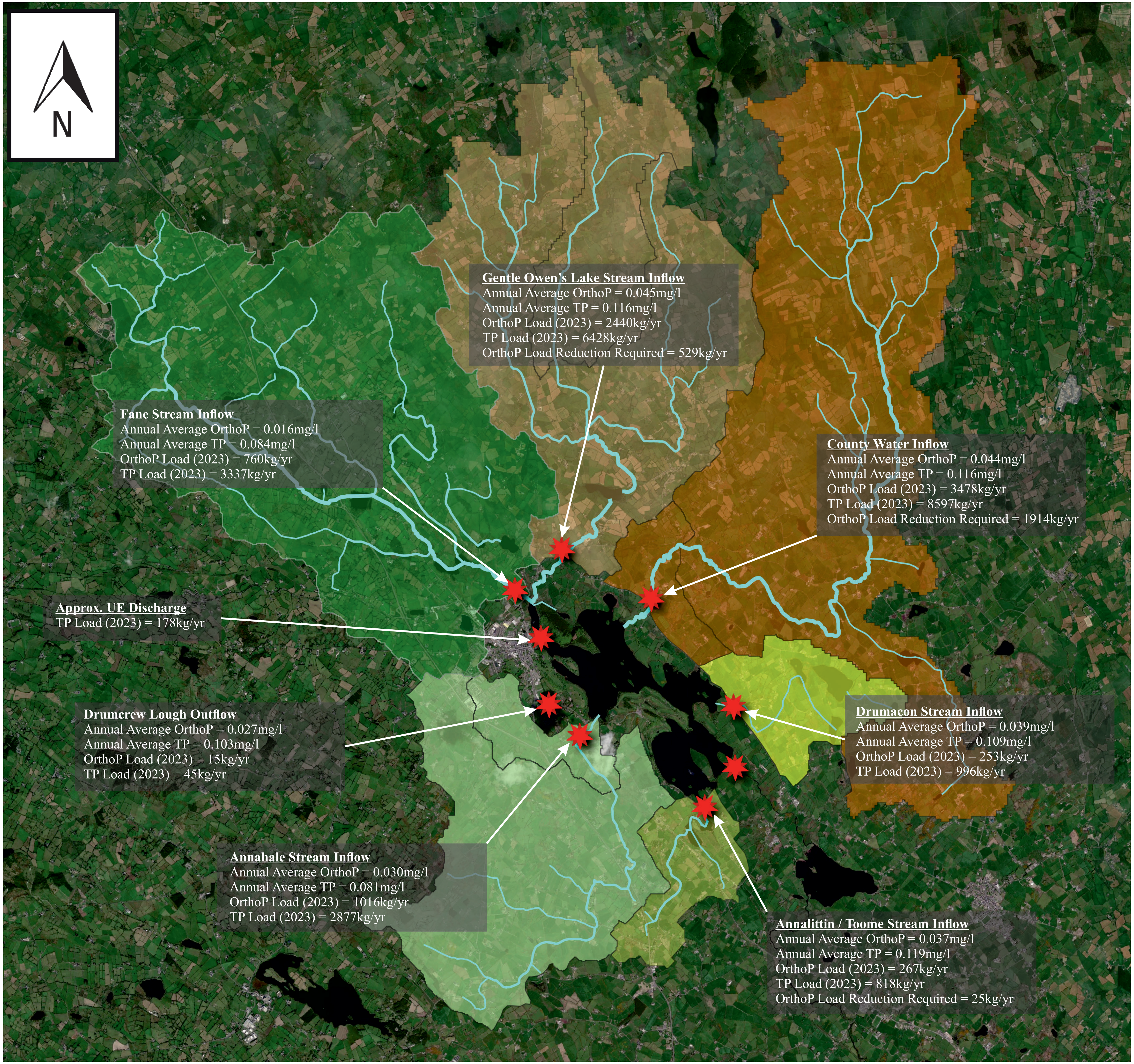
Watercourse	Sampling Location (ITM)	River Waterbody	Sampling Date & TP Results												Annual Average
			09/01/23	09/02/23	28/03/23	25/04/23	16/05/2023	28/06/2023	26/07/2023	24/08/23	21/09/23	23/10/23	13/11/23	12/12/23	
Annalittin / Toome Stream	(685936, 816895)	Fane_020	0.136	0.102	0.074	0.078	0.148	0.216	0.197	0.236	0.149	0.1	0.082	0.1	0.119
Drumcrew Lough Outflow	(686378, 818823)		0.089	0.129	0.07	0.052	0.067	0.282	0.111	0.187	0.114	0.073	0.080	0.05	0.103
Drumacon Stream	(683111, 818755)	Fane_020	0.106	0.082	0.061	0.061	0.08	0.322	0.113	0.108	0.087	0.059	0.106	0.1	0.109
Annahale Stream	(683891, 818350)	Annahale Stream_010	0.076	0.082	0.053	0.054	0.068	0.102	0.096	0.116	0.103	0.069	0.143	0.14	0.081
County Water	(684931, 820445)	County Water_010	0.105	0.119	0.09	0.082	0.081	0.128	0.120	0.158	0.124	0.093	0.243	0.23	0.116
Fane Stream	(682691, 820696)	Fane_010	0.099	0.088	0.058	0.077	0.115	0.085	0.116	0.145	0.125	0.088	0.084	0.06	0.084
Gentle Owens Lake Stream	(683343, 821437)	Gentle Owens Lake Stream_010	0.12	0.096	0.097	0.12	0.135	0.114	0.151	0.154	0.141	0.149	0.117	0.1	0.116
Clarebane Stream (Muckno Outflow)	(687277, 816788)	Fane_020	0.128	0.095	0.083	0.085	0.096	0.063	0.075	0.110	0.106	0.072	0.108	0.1	0.090

0.01	Where result was below the limit of detection (i.e. <0.01mg/l) a concentration of 0.005mg/l is included

Table 5. Flows calculated for sampling events on the six fluvial inflows to Lough Muckno 2023.

Watercourse	Sampling Location (ITM)	River Waterbody	Flows at Sampling Date (m3/s)												Q30 Flows (m3/s)
			09/01/23	09/02/23	28/03/23	25/04/23	16/05/2023	28/06/2023	26/07/2023	24/08/23	21/09/23	23/10/23	13/11/23	12/12/23	
Annalittin / Toome Stream	(685936, 816895)	Fane_020	0.26	0.05	0.26	0.09	0.09	0.02	0.14	0.09	0.09	0.24	0.24	0.33	0.22
Drumacon Stream	(683111, 818755)	Fane_020	0.45	0.15	0.45	0.23	0.22	0.02	0.30	0.24	0.24	0.39	0.47	0.56	0.35
Annahale Stream	(683891, 818350)	Annahale Stream_010	1.16	0.36	1.17	0.59	0.55	0.08	0.79	0.60	0.67	1.07	1.30	1.58	0.95
County Water	(684931, 820445)	County Water_010	3.92	0.23	1.15	0.64	0.38	0.08	0.75	0.41	1.41	1.16	8.23	12.21	1.42
Fane Stream	(682691, 820696)	Fane_010	1.23	0.74	1.23	0.89	0.87	0.34	1.00	0.90	0.89	1.20	1.18	1.42	1.14
Gentle Owens Lake Stream	(683343, 821437)	Gentle Owens Lake Stream_010	1.67	0.07	1.42	0.55	0.49	0.03	1.62	0.69	2.45	1.90	3.99	9.90	1.73
Clarebane Stream (Muckno Outflow)	(687277, 816788)	Fane_020	8.79	1.66	8.68	2.86	2.95	0.58	5.01	3.60	4.64	8.29	8.34	11.18	6.93

HYDREC
ENVIRONMENTAL CONSULTING



LEGEND

Monitoring Point

Lough

1st Order Stream

2nd Order Stream

3rd Order Stream

HYDREC ENVIRONMENTAL CONSULTING

PROJECT:
Lough Muckno's Road to Recovery Project

TITLE:

Orthophosphate and Total Phosphorus loadings from within Lough Muckno's Catchment with estimated PO4-P load reductions for 2023.

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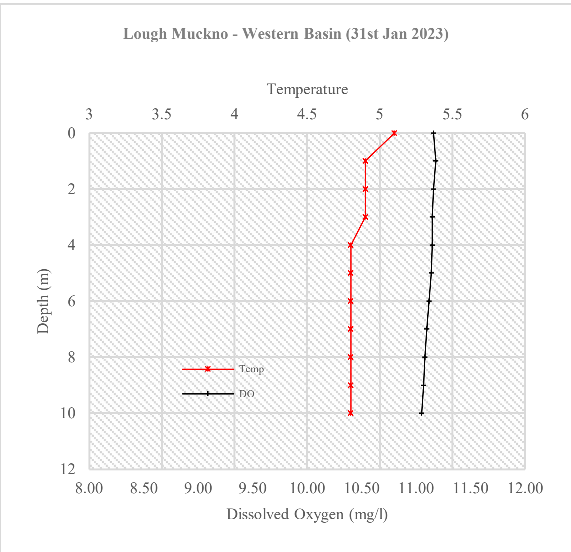
DRAWING NO: Figure 3.	REV. 0

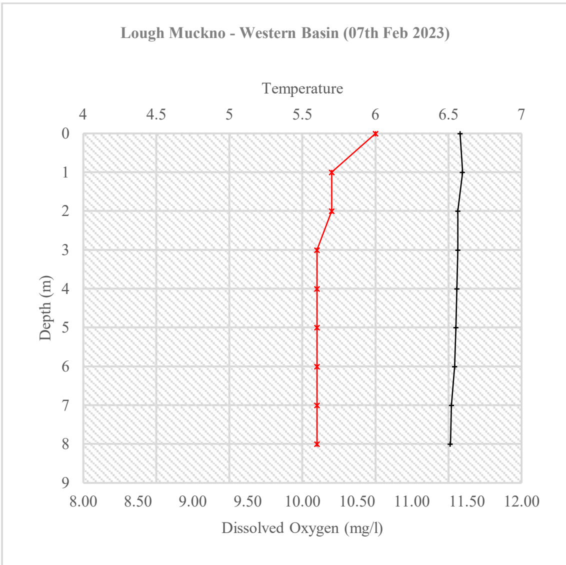
4.4 Estimation of Lake Recovery Times

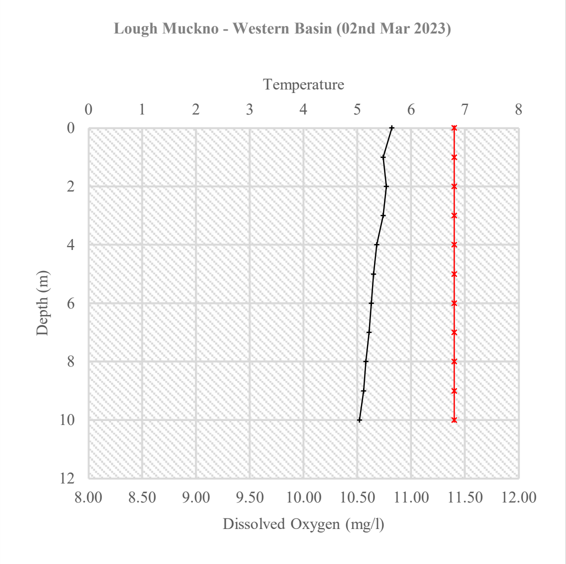
4.4.1 Temperature & Dissolved Oxygen Profiles – Lough Muckno 2023

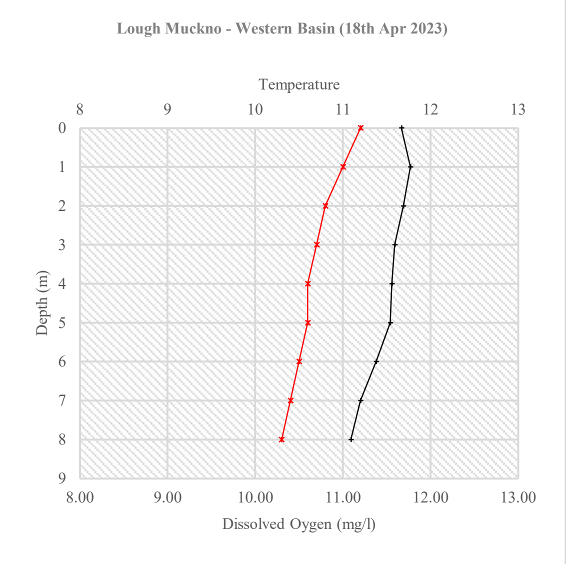
Graphs 14 to 24 represent the monthly temperature and dissolved oxygen (DO) readings taken throughout the water column of the western basin of Lough Muckno. Temperature and dissolved oxygen profiles were found to be relatively stable from January 2023 – April 2023 which would indicate full mixing throughout the basin. By May 2023 thermal stratification had ensued where a thermocline layer is observed c. 5m – 8m deep. The lake continued in a stratified state in June 2023 before a period mixing appears to have occurred in July 2023. By August 2023, thermal stratification has once again developed (i.e. thermocline - 4m – 8m) with temperatures in the metalimnion layer ranging from 5.26ºC to 8.77ºC. Lake overturn occurred in September 2023 with full vertical mixing observed by December 2023. Graphs 22 and 23 would indicate anoxic conditions at the sediment water interface for September and October 2023.

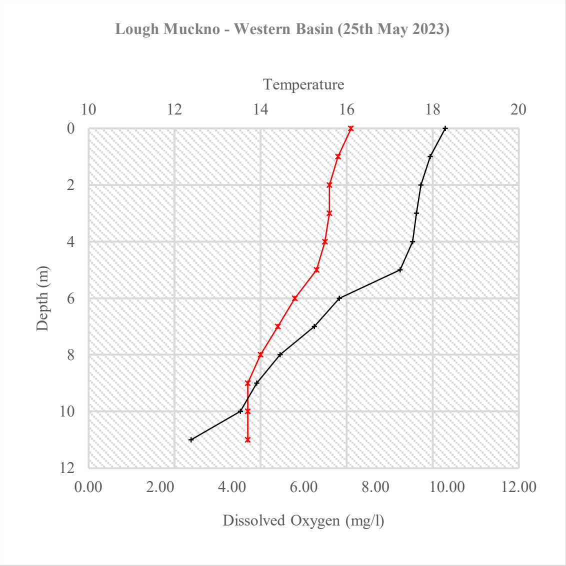
The temperature and DO profiles for the centre and southern basins are included in Appendix 5. The profiles for the central basin follow very similar trends to that of the western basin whereas the onset of thermal stratification was observed earlier in the southern basin (i.e. April 2023). Furthermore, the southern basin was found to be fully stratified in July 2023 indicating a stronger level of stratification to that of the northern and central basins. Similarly, though lake overturn occurred in September 2023 with full mixing observed by December 2023.

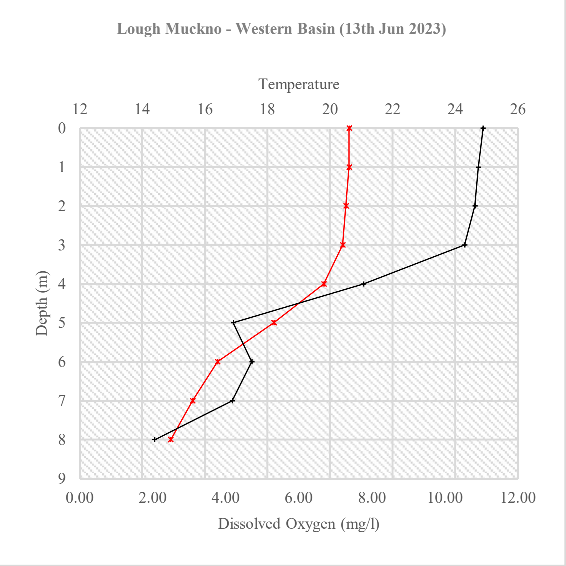


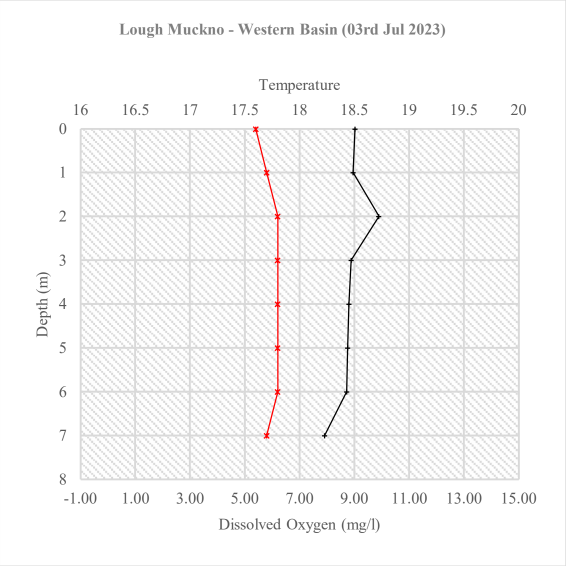


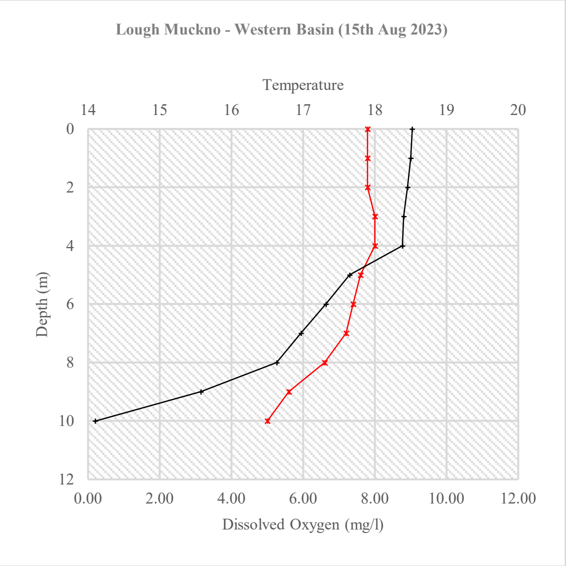

Lough Muckno - Western Basin (02nd Mar 2023)
Temperature
0 1 2 3 4 5 6 7 8
Depth (m)
0 2 4 6 8 10 12
8.00 8.50 9.00 9.50 10.00 10.50 11.00 11.50 12.00
Dissolved Oxygen (mg/l)

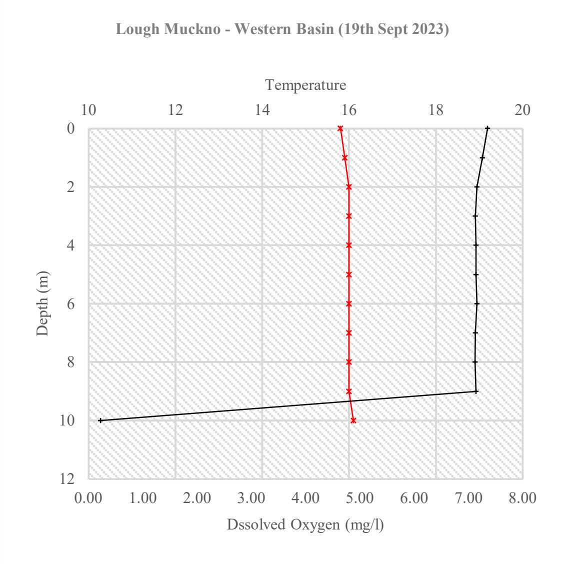

Lough Muckno - Western Basin (18th Apr 2023)
Temperature
8 9 10 11 12 13
Depth (m)
0 1 2 3 4 5 6 7 8 9
8.00 9.00 10.00 11.00 12.00 13.00
Dissolved Oygen (mg/l)

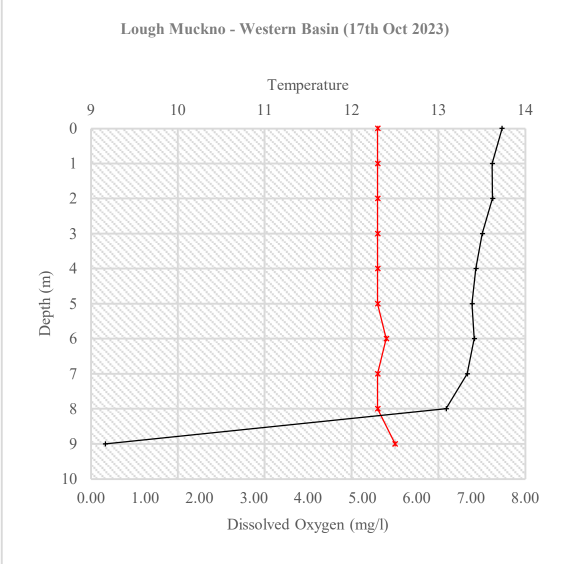

Lough Muckno - Western Basin (25th May 2023)
Temperature
10 12 14 16 18 20
Depth (m)
0 2 4 6 8 10 12
0.00 2.00 4.00 6.00 8.00 10.00 12.00
Dissolved Oxygen (mg/l)

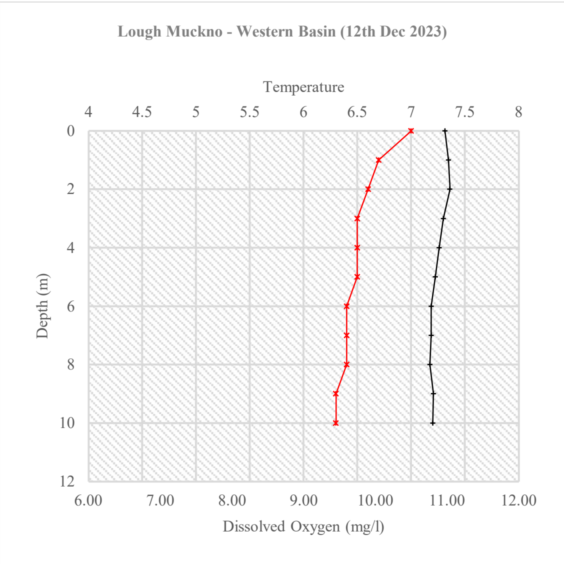

Lough Muckno - Western Basin (13th Jun 2023)
Temperature
12 14 16 18 20 22 24 26
Depth (m)
0 1 2 3 4 5 6 7 8 9
0.00 2.00 4.00 6.00 8.00 10.00 12.00
Dissolved Oxygen (mg/l)


Lough Muckno - Western Basin (03rd Jul 2023)
Temperature
16 16.5 17 17.5 18 18.5 19 19.5 20
Depth (m)
0 1 2 3 4 5 6 7 8
-1.00 1.00 3.00 5.00 7.00 9.00 11.00 13.00 15.00
Dissolved Oxygen (mg/l)


Lough Muckno - Western Basin (15th Aug 2023)
Temperature
14 15 16 17 18 19 20
Depth (m)
0 2 4 6 8 10 12
0.00 2.00 4.00 6.00 8.00 10.00 12.00
Dissolved Oxygen (mg/l)



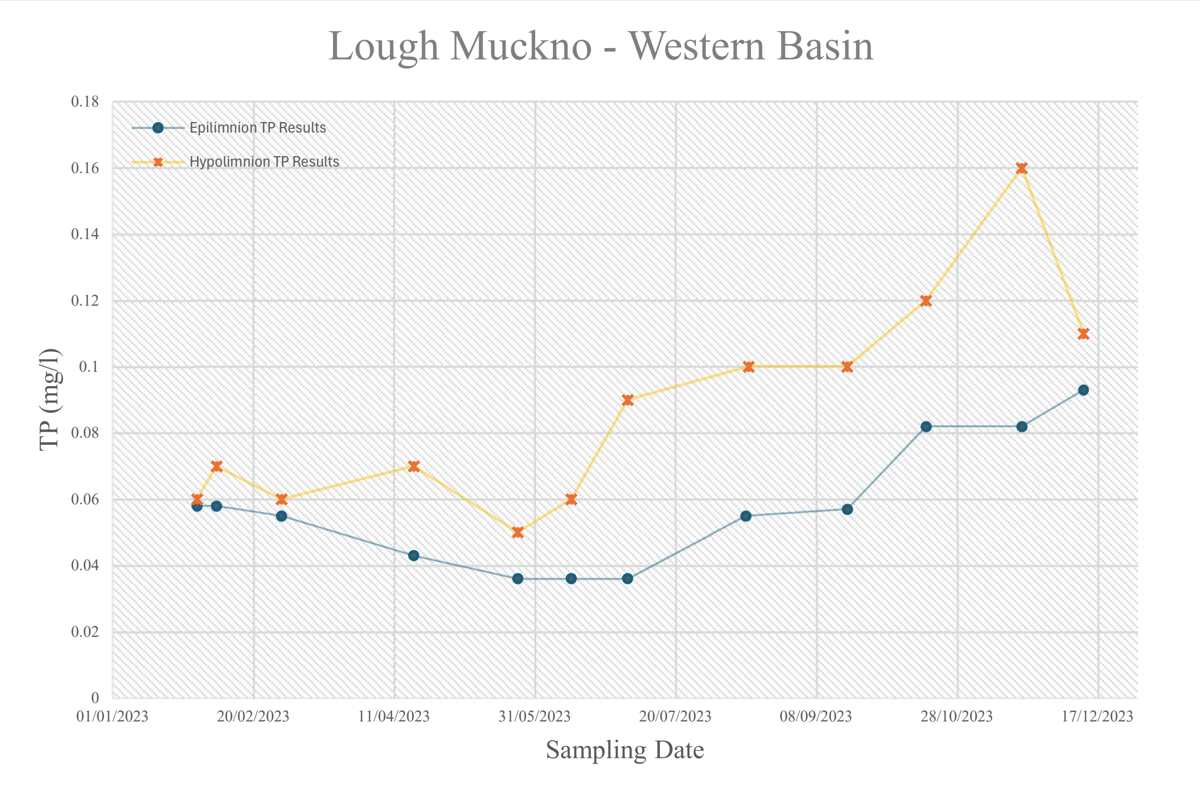




Graphs 14 - 24. Monthly temperature and dissolved oxygen profiles generated for the western basin of Lough Muckno, 2023. (No readings taken in November 203)

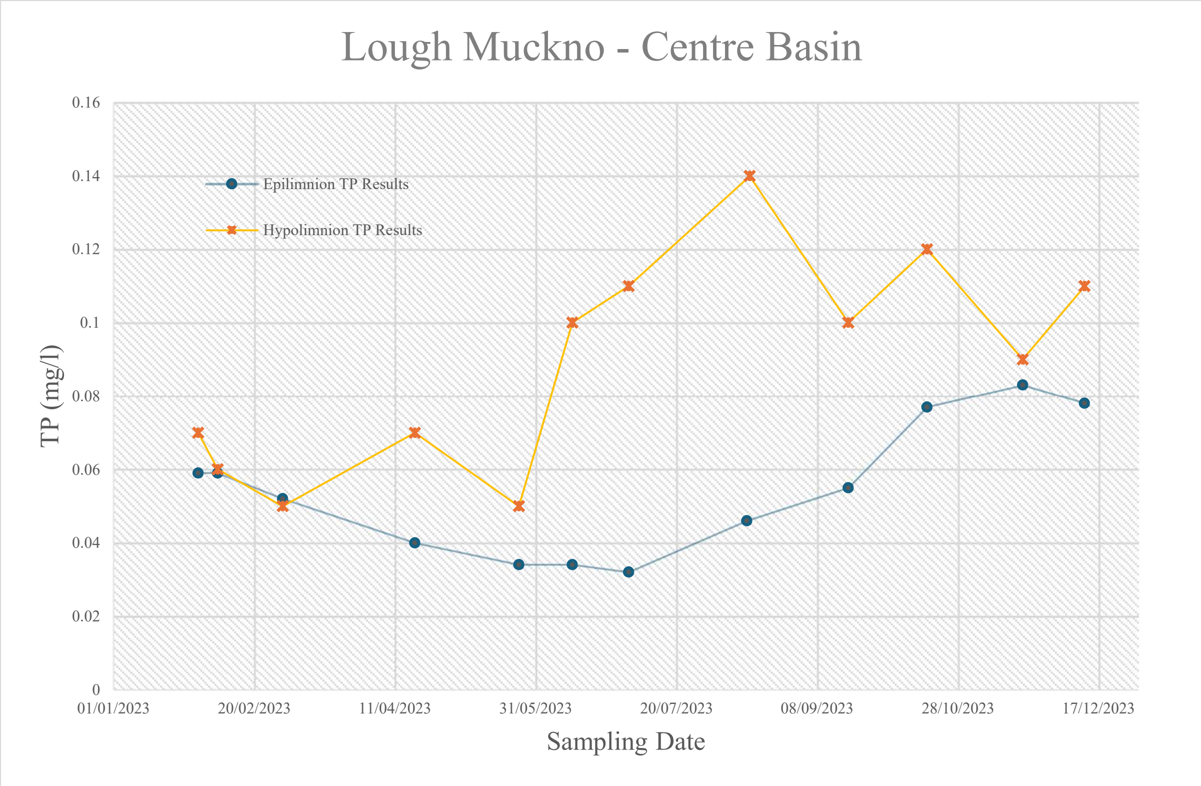
4.4.2 Epilimnion and Hypolimnion TP Results – Lough Muckno 2023

Samples taken from the epilimnion and hypolimnion of the western basin during January – March 2023 would indicate a similar concentration of TP throughout the column (Graph 25). For instance, in January 2023 concentrations of 0.058mg/l and 0.060mg/l were recorded for the epilimnion and hypolimnion respectively. In February 2023, concentrations of 0.058mg/l and 0.070mg/l were recorded with concentrations of 0.055mg/l and 0.060mg/l recorded in March 2023. From April onwards the difference in epilimnion and hypolimnion concentrations increased, where hypolimnion concentrations were found to range from 0.05mg/l to 0.16mg/l. This separation in the TP profiles coincided with stratifying conditions. It's also apparent from the results that epilimnion TP concentrations increased in October (0.082mg/l) and November (0.082mg/l) following the commencement of the autumn turnover. In December, the difference between the epilimnion (0.093mg/l) and hypolimnion (0.11mg/l) TP concentrations were less pronounced.



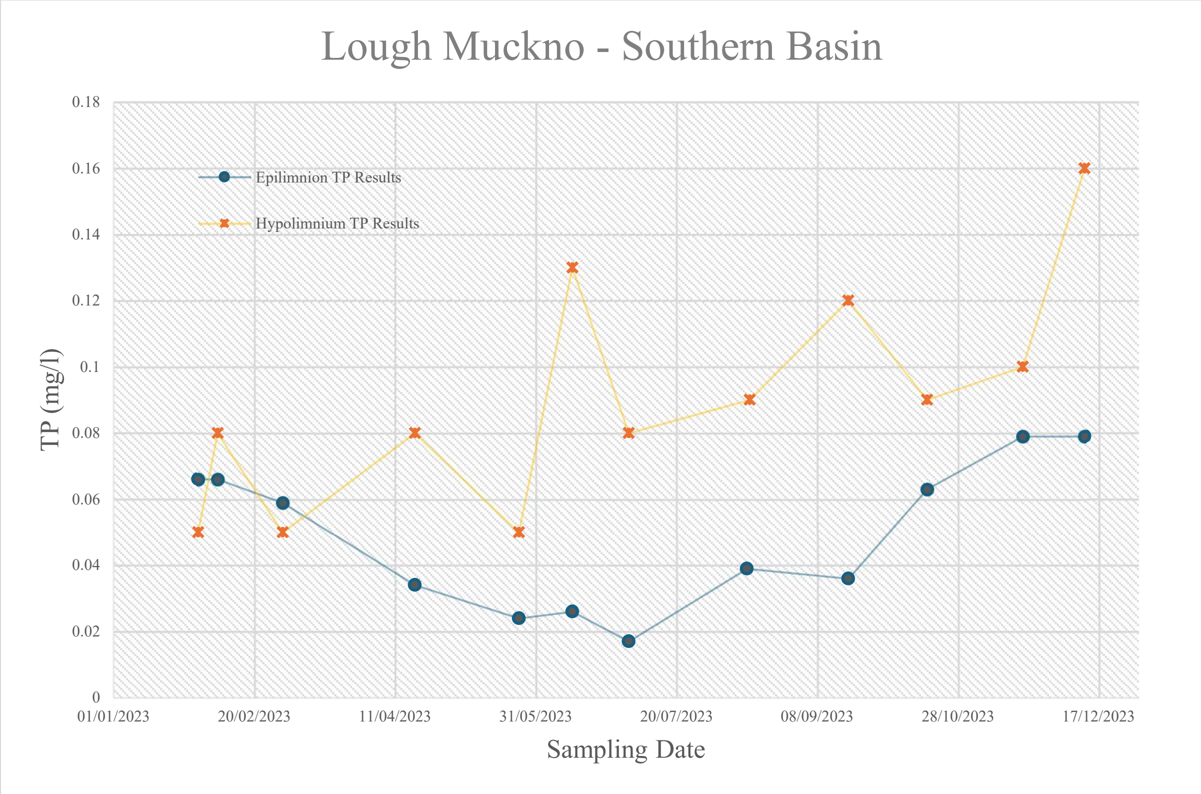
Graph 25. TP concentrations recorded in the epilimnion and hypolimnion of Lough Muckno's western basin throughout 2023.

Similarly, samples taken from the epilimnion and hypolimnion of the central basin during January – March 2023 would indicate a similar concentration of TP throughout the column (Graph 26). For instance, in January 2023 concentrations of 0.059mg/l and 0.070mg/l were recorded for the epilimnion and hypolimnion respectively. In February 2023, concentrations of 0.059mg/l and 0.060mg/l were recorded with concentrations of 0.052mg/l and 0.050mg/l recorded in March 2023. From April onwards the difference in epilimnion and hypolimnion concentrations increased, where hypolimnion concentrations were found to range from 0.05mg/l to 0.14mg/l. This separation in the TP profiles coincided with stratifying conditions. It's also apparent from the results that epilimnion TP concentrations increased in October (0.077mg/l) and November (0.083mg/l) following the commencement of the autumn turnover. Similar to the western basin, in November, the difference between the epilimnion (0.083mg/l) and hypolimnion (0.09mg/l) TP concentrations were less pronounced.



Graph 26. TP concentrations recorded in the epilimnion and hypolimnion of Lough Muckno's centre basin throughout 2023.

Samples taken from the epilimnion and hypolimnion of the southern basin during January – March 2023 would indicate a similar concentration of TP throughout the column with epilimnion concentrations exceeding that of the hypolimnion on occasion (Graph 27). For instance, in January 2023 concentrations of 0.066mg/l and 0.050mg/l were recorded for the epilimnion and hypolimnion respectively. In February 2023, concentrations of 0.066mg/l and 0.080mg/l were recorded with concentrations of 0.059mg/l and 0.050mg/l recorded in March 2023. From April onwards the difference in epilimnion and hypolimnion concentrations increased, where hypolimnion concentrations were found to range from 0.05mg/l to 0.16mg/l. This separation in the TP profiles coincided with stratifying conditions. It's also apparent from the results that epilimnion TP concentrations increased in October (0.063mg/l) and November (0.079mg/l) following the commencement of the autumn turnover. In December, the difference between the epilimnion (0.079mg/l) and hypolimnion (0.16mg/l) TP concentrations were at their greatest across the three basins for the month.



Graph 27. TP concentrations recorded in the epilimnion and hypolimnion of Lough Muckno's southern basin throughout 2023.

4.4.3 Sediment Phosphorus Fractions, Model Coefficients, Rate Constants & Timescale for Recovery

The concentrations of measured P_{Ex}, P_{Hum}, P_{Fe}, P_{CFA}, P_{Detr} and P_{resi} are included in Table 6 with PO4-P to sediment mass ratio results included in Appendix 6. The P_{ex} (i.e. easily exchangeable) concentrations were very small across the five samples ranging from 0.003 – 0.024 mg PO4-P/g. Other extraction concentrations namely, P_{Hum}, P_{Fe}, P_{CFA} and P_{resi} decreased with depth. Similarly, total phosphorus concentrations generally decreased down core where concentrations of TP from 1cm to 15cm ranged from 1.794– 1.033 mg P/g. A slight increase from the concentration recorded at 15cm was observed at 19cm (1.103 mg P/g) which coincides with an increase in P_{Detr} (0.229 mg PO4-P/g), the extraction which represents detrital apatite and other inorganic forms of P.

As referenced in Rippley et al. (2021) the key P fraction used in the Lewis/Penn model is the variation with depth of Fraction A as a percentage of the TP concentration. For the Lough Muckno Core, the depth of the Zactive layer was taken as 19cm. Whilst concentrations below the 19cm depth interval haven't been established, Fraction A concentrations of 0.44 mg PO4-P/g and 0.42 mg PO4-P/g were measured at a depth of 15cm and 19cm respectively. Consequently, Fraction A equates to 42.6% and 38.3% of TP at 15cm and 19cm respectively.

Similarly, the Fraction A % of TP has previously been found to range from c. 38% - 42% from the cores analysed from Lough Ramor, Lough Melvin and Lough Neagh (Rippley et. al 2021).

Table 6. Results of phosphorus sequential extraction analysis from short core taken from Lough Muckno's centre basin, November 2023. Also included are the sediment accumulation rate, active sediment layer depth (Zactive), calculated slow diagenesis rate constant (kd, 2), burial rate constant (kb) and overall rate constant (k) and time to reduce liable P by 90% (t_{90}, yr).

Core Depth (cm)	Fraction A				Fraction B		Total P (mg PO4- P/g)
	P_{ex}	Phum	P_{fe}	P_{cfa}	P_{detr}	P_{resi}	
1.00	0.012	0.304	0.555	0.228	0.120	0.575	1.794
5.00	0.010	0.259	0.490	0.093	0.094	0.543	1.489
10.00	0.005	0.168	0.425	0.092	0.160	0.505	1.355
15.00	0.003	0.148	0.199	0.090	0.089	0.050	1.033
19.00	0.024	0.145	0.169	0.084	0.229	0.452	1.103
Sediment Acc Rate, cm yr-1			**Zactive (cm)**	**kd, 2, yr^{-1}**	**kb, yr^{-1}**	**k, yr^{-1}**	**t_{90}, yr**
1.72			19	0.1	0.091	0.190	12

Based on the basin's sedimentation rate and defined depth of active sediment (i.e. Zactive), a burial rate constant (kb) of 0.091 yr^{-1} was estimated (see Table 6) whereas a slow diagenesis rate constant (kd, 2) of 0.1 yr^{-1} was calculated. Hence the overall rate constant (k) which is the sum of kb and kd,2 was estimated at 0.190 yr^{-1}. It was found that both burial and diagenesis play an important role in the loss of labile P from Lough Muckno's active sediment layer. For instance, the relative contribution of burial to the total loss of labile P (kb/k) was estimated at 47.5%. Using t_{90} as an indicator for the time in which long term sediment release becomes inconsequential to the Lough's P budget, a period of 12 years is predicted.

5.0 DISCUSSION

5.1 Lake Sedimentation Rates

Sedimentation rates for the western basin of Lough Muckno were previously estimated at 9.8mm/yr by Chique et al. (2017). Hence, the sedimentation rate derived from this project for the western basin (i.e. 8.9mm/yr) is consistent with that of the previous investigation. As part of this project a sedimentation rate for the centre basin of the Lough was also established (i.e. 17.2mm/yr). The aforementioned sedimentation rate is understood to be approaching that of the highest deposition rate recorded in an Irish context (Taylor et al., 2006, O'Dwyer and Taylor 2010, Rippey at al., 2021) and similar to that recorded by Carson et al (2014) for Milltown Lough (17.1mm/yr) upstream of Lough Muckno. Comparatively high sedimentation rates have also previously been recorded in other lakes situated within the Irish drumlin belt (Anderson & Rippey, 1994, Nowlan et al., 2000). As described by Chique (2017) high rates of material export would be expected in lakes with a large catchment to lake area drainage ratio, as is the case with Lough Muckno. Correspondingly other inter drumlin lakes with small contributing catchments such as Namachree Lough and Lough Egish in Co. Monaghan and Crans Lough, Co. Tyrone were found to have sedimentation rates ranging from 0.13cm/yr – 0.25cm/yr or 1.3mm/yr 2.5mm/yr (Taylor et al., 2006, O'Dwyer et al., 2013). Further studies have demonstrated how sedimentation rates were found to increase across a eutrophic gradient (Fiskal et al., 2019). Hence, the high sedimentation rates recorded in Lough Muckno are attributed to a combination of factors including, catchment topography, catchment size and lake productivity.

5.2 Past Ecological and Nutrient Conditions

Previous efforts at establishing ecological baseline conditions for Irish lakes have examined the suitability of using c. 1850 AD as a suitable reference date for the assessment of anthropogenically driven aquatic impacts (Leria et al., 2006). The oldest sediments assessed as part of this study have been attributed to time periods either side of this date. Whilst species abundance varied across both basins assessed, epilithon and epipelon benthic taxa were found to be common and diverse in both. For instance, *Tabellaria flocculosa* was found to dominate with *Achnanthidium minutissimum* subdominant. Such species have been found to dominate the oligotrophic reference assemblages of other Irish and Scottish lakes (Bennion and Simpson 2004, Taylor et al., 2006b). The diversity and abundances of epiphytic diatoms such as *Eunotia incisa*, *Staurosira elliptica* and *Staurosirella pinnata* for the period would suggest a more extensive macrophyte cover than compared with today. Lough Mullagh and Lough Sillan in Co. Cavan has also both experienced a more recent reduction in epiphytic communities from that of historic conditions (Taylor et al., 2006). Diatom inferred total phosphorus (DI-TP) concentrations for this period were predicted at 0.013mg/l, which based on current Environmental Quality Standards (EQS) is within the boundary of 'Good' water quality status.

Around the turn of the 20th century, benthic taxa were still found to dominate with *Tabellaria flocculosa* again most abundant. A loss in abundance of epiphytic taxa corresponded to an increase in planktonic diatoms such *Aulacoseira subartica, Aulacoseira ambigua* and *Asterionella formosa*. Again, whilst species abundance differed, the trend in changes between both basins were broadly similar notwithstanding that the increase in *Aulacoseira subartica* was more pronounced in the central basin. This increase in planktonic taxa could be taken as indicative of the onset of nutrient enrichment. Just like Chique et al. (2017) had attributed the period from 1840-1897 in Lough Muckno to reduced activity/potential lake amelioration, they also associated the period thereafter with an increased level of enrichment. Whilst some Irish lakes were already found to have deteriorated to an established eutrophic state by this period (Taylor et al., 2006) others situated within the Irish Drumlin Belt, namely Lough Namachree, County Monaghan (O'Dwyer et al., 2013), Lough Herron, Co. Down (Anderson, 1997) and Lough Sillan (Taylor et al., 2006) have also observed the beginning of enrichment at this juncture.

Some studies have utilised c. 1950 as a secondary target reference condition date for lake restoration (Leira et al., 2006). This period predates an Irish wide increase in agricultural intensification and fertiliser use (Tunney, 1990). Previous paleolimnological studies on some Irish lakes such as Friary Lough, Co. Tyrone (Jordan et al., 2002), Lough Creeve, Co. Tyrone and Lough Corbet, Co. Down (Anderson, 1997) provide evidence of rapid deterioration post 1950. The diatom assemblages c. 1939/1940 across both basins in Lough Muckno shows the abundance of the previously dominate taxa *Tabellaria flocculosa,* reduce dramatically with the mesotrophic planktonic species *Aulacoseira subartica* now dominant (Gibson et al., 2002). DI-TP concentrations were still found to be at 'Good' status ranging from 0.021 – 0.024mg/l. Conversely, by 1980 eutrophic conditions had established in the lake with further increases in the abundance of *Aulacoseira subartica,* a continued sub dominance of *Aulacoseira ambigua* and an increase in the more eutrophic *Aulacoseira granulata* found (Lepisto et al., 2006, Bennion et al., 2012*).* Inferred TP values ranged from 0.032mg/l – 0.043mg/l which are congruent with conditions outside of 'Good' water quality conditions. A notable increase in the abundance of *Fragilaria crotonensis* was observed in the 1980 assemblages and subsequently found to disappear in the modern sediment assemblage. Given that *Fragilaria crotonensis* is a taxa known to depend on a sufficient silica supply (Saros et al., 2005) it is plausible that silica limiting conditions in the lough has resulted in the species reduction thereafter. Silica limitation was also identified through paleolimnological investigation to have occurred in a number of lakes in Northern Ireland as a result of increased TP loading (Ryves et al., 2013).

Further periods of enrichment have been discovered in some Irish lakes post the 1980's (Taylor et al., 2006). For example, DI-TP concentrations in Lough Egish, Co. Monaghan were found to rise from c. 0.032mg/l to c. 0.079mg/l from 1980 to 2004. Hypereutrophic conditions do not manifest in Lough Muckno, with modern sedimentary diatom assemblages found to be very similar to those recorded in 1980. Whilst an increase in the relative abundance of the small centric diatom, *Stephanodiscus parvus* was observed in recent sediments, it did not dominate as was characteristic of other hypereutrophic settings (Anderson 1997, Taylor et al., 2006). Additionally, annual average TP concentrations recorded through monitoring in 2021/2022 in the western and central basins (0.044mg/l) are similar to those inferred through the diatom transfer function modelling.

5.3 Predicted Timescales for Lake Recovery

The active sediment layer in four other studied Irish lake sediments was found to range from 8cm to 29cm in depth (Rippey et al., 2021). The assumed Lough Muckno Zactive depth was within this range (19cm) and is similar to the depth of the layer of diagenesis of labile P found in other lake sediments (Carignan and Flett, 1982, Nembrini et al., 1982). Similarly, a study by Carey and Rydin (2011), found that the concentration of P stabilised / become permanently buried at a depth of 16cm for half of the eutrophic lakes investigated in the 94-lake study.

In relation to the model coefficients, the diagenesis rate constant of labile P (kd,2) calculated by Rippey et al., (2021) for Lough Melvin, Lough Ramor, Lough Sheelin and Lough Neagh was found to be wide ranging (0.0155 – 0.383 yr^{-1}). The kd,2 rate estimated for Lough Muckno as part of this study is within this range and found to be mid-range of the rates presented on other international sites by Penn et al. (1995) whereby kd ranged from 0.007 – 0.20 yr^{-1} with lowest rates generally found at lakes with lower TP concentrations. Given Lough Muckno's meso / eutrophic history, the kd rate appears to be comparable with other settings.

Taking a reduction of 90% (t_{90}) of labile P in the active sediment layer representing a steady-state value, Rippey el al. (2021) predicated lake recovery times of 5 to 100 years for the four Irish lakes investigated. It was also identified that only Lough Ramor and Lough Neagh showed evidence of internal phosphorus loading with their t_{90} values calculated from 49 – 76 years. It is noted that both lakes have substantially lower sedimentation rates and greater superficial sedimentary TP concentrations. Elsewhere Lewis et al., (2007) determined a t_{90} value of 16 years for Onondaga Lake, New York, whereas Katsev et al., (2006) estimated recovery timescales of 10 to 20 years based on their modelling work. Whilst Horppila et al. (2017) predicted that substantial internal loading would continue for c. 25 years in the shallow Lake Tuusulanjarvi, Sweden, the aforementioned lake was found to be hypereutrophic in nature. Considering Lough Muckno's nutrient status, the t_{90} value of 12 years estimated as part of this study align with recovery times reported elsewhere.

6.0 CONCLUSIONS & RECOMMENDATIONS

Since the commencement of WFD monitoring in Lough Muckno in 2007, mean annual total phosphorus (TP) concentrations have exceeded the associated 'Good' environmental quality standard (EQS) each year without exception. Reconstructed historic TP concentrations at Lough Muckno have identified periods where concentrations are within the boundary for 'Good' TP conditions. For instance, pre / post c.1850 a TP concentration of 0.013mg/l has been inferred, whilst c. 1940 (i.e. pre agricultural intensification / increased fertiliser usage) concentrations of 0.021mg/l – 0.024mg/l were estimated. Both dates have previously been attributed as potential restoration targets for lake recovery in Ireland. Whilst the concentrations inferred for both these periods in Lough Muckno are found at either end of the 'Good' status spectrum, concentrations associated with 'High' status conditions were not predicted.

With increasing TP concentrations, diatom assemblages would also indicate a shift from clear-water, plant dominated conditions, through more mesotrophic to current day meso / eutrophic conditions. Efforts to restore Lough Muckno should initially focus on reducing the external TP loading to the lake. Given that annual average orthophosphate (PO4-P) concentrations exceeded the 'Good' environmental quality standard (EQS) for the Gentle Owen's Lake Stream, County Water, Drumacon Stream and Annalittin / Toome Stream, the reductions required to achieve the river water body EQS for PO4-P in these sub-catchments could form the initial focus for mitigation. Ultimately, the required reductions in PO4-P in these watercourses would also contribute to the TP load reduction required for Lough Mucko. Said reduction in PO4-P would have resulted in a c.11% reduction in TP loading to the lough in 2023. Thus, measures targeted at additional TP reductions are necessary. Notwithstanding this, measures aimed at reducing PO4-P at sites within the aforementioned sub-catchments could be designed to deliver greater reductions in TP also. It is noted that annual average TP concentrations were elevated throughout Lough Muckno catchment, hence it is envisaged that there is substantial opportunity in the other sub-catchments to also deliver TP load reductions. Conversely a preliminary assessment of the TP loading from the Uisce Eireann discharge to the lough is estimated to account for less <1% of the lake's TP budget.

In order to identify critical source areas (CSAs) within the sub-catchments proposed for source protection works, additional surface water monitoring within such would be advantageous. For example, taking the annual average concentrations recorded at the Skerrymore Trib monitoring station (RS06L260790) within the County Water catchment and extrapolating stream flows from the data recorded within the County Water catchment 2023, it was estimated that c. 2.5% of the PO4-P loading within the County Water catchment derived from the portion of the catchment upstream of monitoring station RS06L260790, whilst the said area covers c. 11% of the sub-catchment. Furthermore, additional hydrometric monitoring within the catchment should be considered so that nutrient loadings can be calculated from future water quality sampling conducted as part of further catchment characterisation efforts and/or measurement of mitigation effectiveness. Additionally, the duration of hydrometric monitoring could be extended to a number of years so that more robust rating curves could be developed.

Given the evidence for internal TP loading within the Lough, it was estimated that a lag time of c. 12 years for lake recovery subsequent to external load reduction applies to Lough Muckno. This estimated timescale could be further refined via additional spatial and temporal analysis of the lough's sedimentary phosphorus. However, recovery times for the Lough have been found to be in line with the one-to-two-decade timeframe broadly applied elsewhere. Nevertheless, it is recommended that this timescale for recovery should also be monitored directly as loadings are reduced.

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APPENDIX 1

RADDEC INTERNATIONAL – RADIOMETRIC SEDIMENT DATING REPORT

Raddec International Ltd.,
Unit 46, Romsey Industrial Estate,
Romsey, SO51 0HR, United Kingdom
Tel: (+44) 07305 094753
Email: sales@raddec-int.com

Date: 28th June 2023

REPORT

Radiometric dating of sediment cores from Lough Muckno, Co. Monaghan, Ireland

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Consultant Analyst:
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CONTENTS

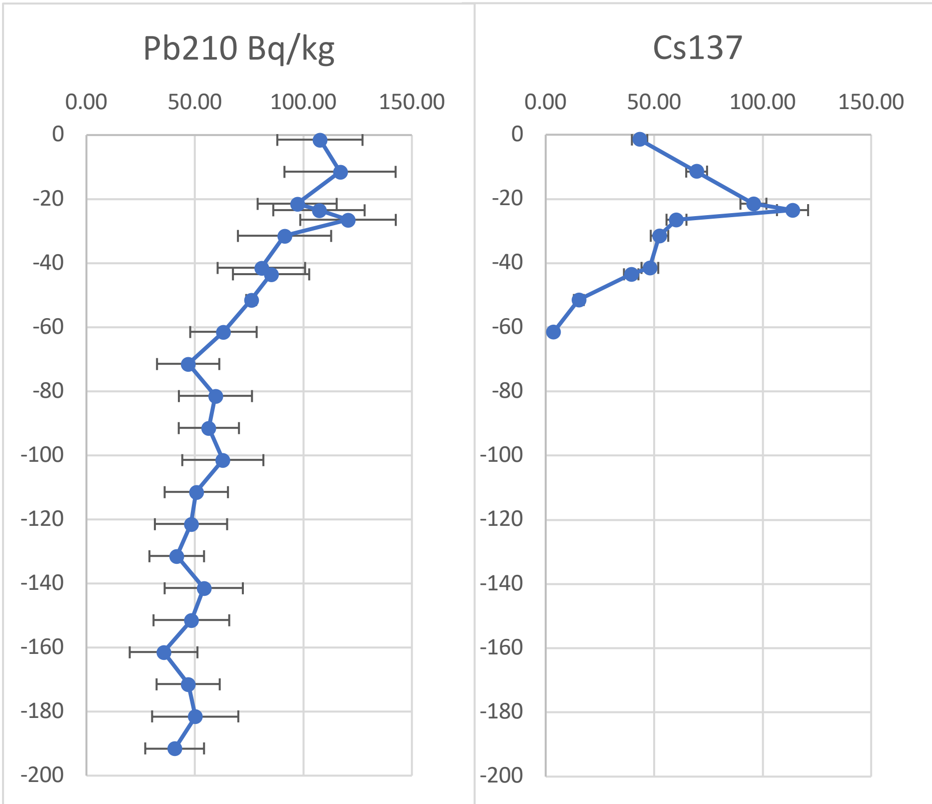
Dating of sediment cores from Lough Muckno (Co Monaghan)

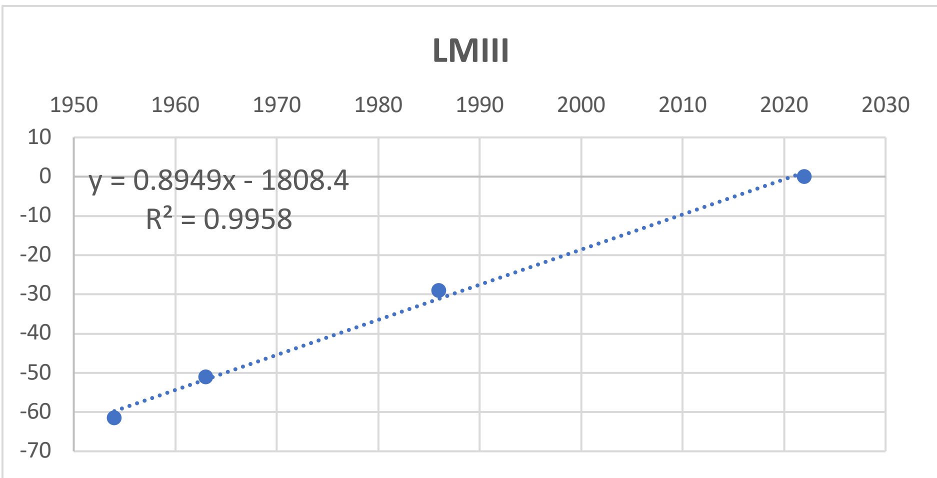
Methodology

Three cores were collected by the customer and dissected at 1.0 cm increments and placed wet into zip-seal plastic bags. The samples were delivered to Southampton (Raddec Labs) and showed some evidence of leakage on arrival. The leakage was of no analytical consequence. Seventy-one sub-samples were supplied wet and were freeze-dried at the laboratory. The dried sub-samples were then fully transferred and weighed into 20 mL scintillation vials and counted (80,000 seconds) for their gamma radioactivity using Canberra HPGe well-type gamma spectrometers. Analysis of the gamma spectra was made using Fitzpeaks spectra deconvolving software (JF Computing, UK).

Results

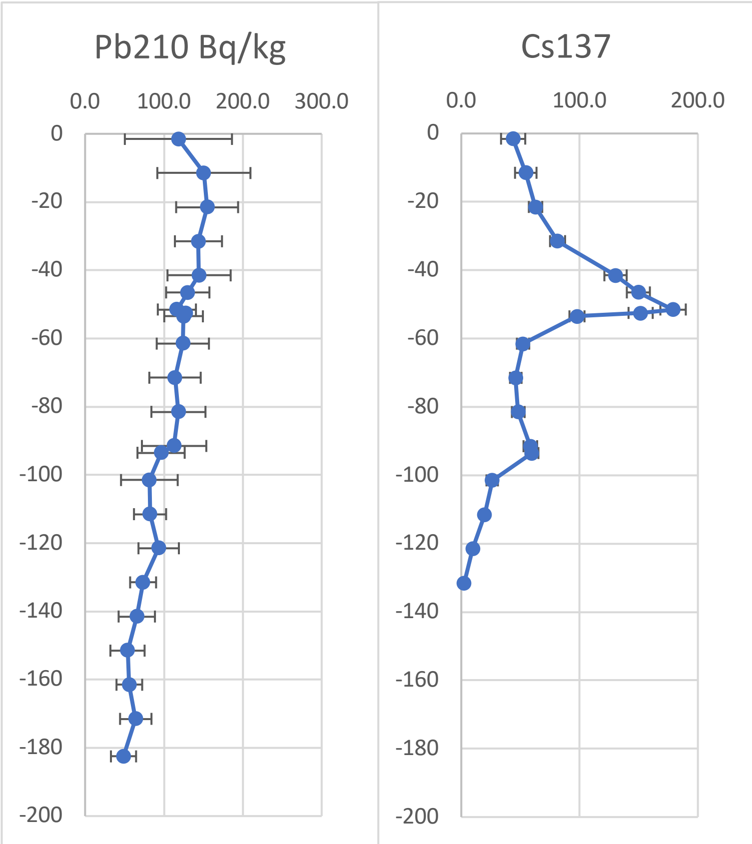
Radioanalytical data are recorded in the Appendices and presented in graphical form below.
Data are presented as initial activities (Bq/gram) and then corrected for the sample height in the vial which follows a systematic relationship. These data are presented as Bq/kg.

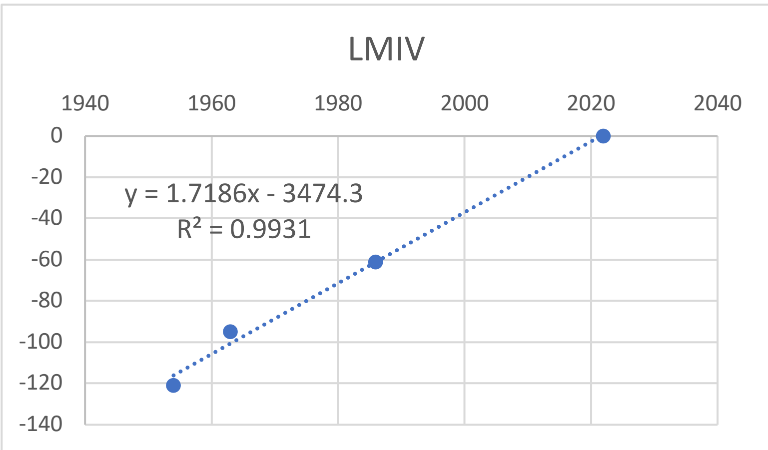




Year	Event in Core LM III	Depth of indicator (cm)
1954	Onset of atmospheric nuclear weapon tests	-61.5
1963	Bomb peak maximum	-51
1986	1st appearance of Chernobyl fallout	-29
2022	Date of core collection	0

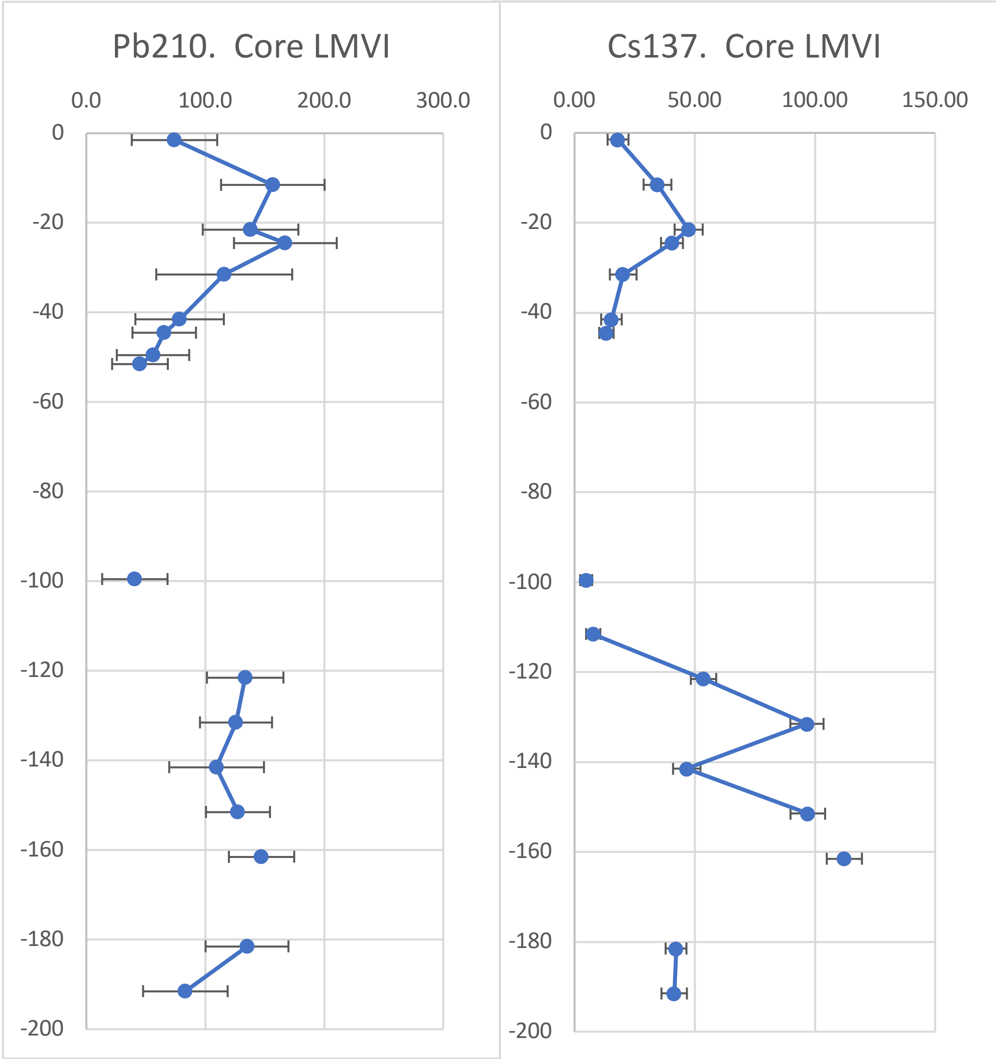
Core LM III **Cs-137 Accumulation rate** **8.9** **mm/yr**





Year	Event in Core LM IV	Depth of indicator (cm)
1954	Onset of atmospheric nuclear weapon tests	-121
1963	Bomb peak maximum	-95
1986	1st appearance of Chernobyl fallout	-61
2022	Date of core collection	0

Core LM IV   Cs-137 Accumulation rate   17.2   mm/yr



Problems with Core LM VI:

- Physical disturbance from boats, people, bioturbation, coring artefacts (slumping)
- Introduction of a sedimentary event involving dumping of organic rich sediment onto the sediment

The Customer reflected on the unusual data seen for Core VI. Following an inspection of their field records / photos etc. it appeared that slumping may have occurred (i.e. diagonal layering was evident). The coring also occurred in relatively close proximity to the edge of the deep basin.

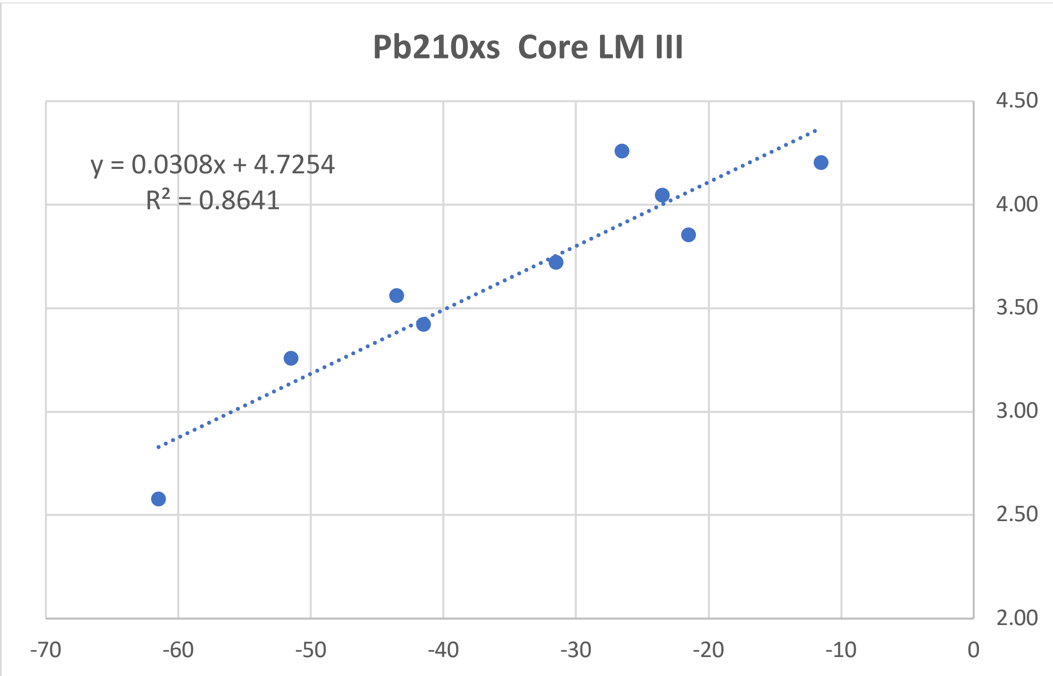
Sediment accumulation rates for Cores LM III and LM IV

Cs-137 Profiles

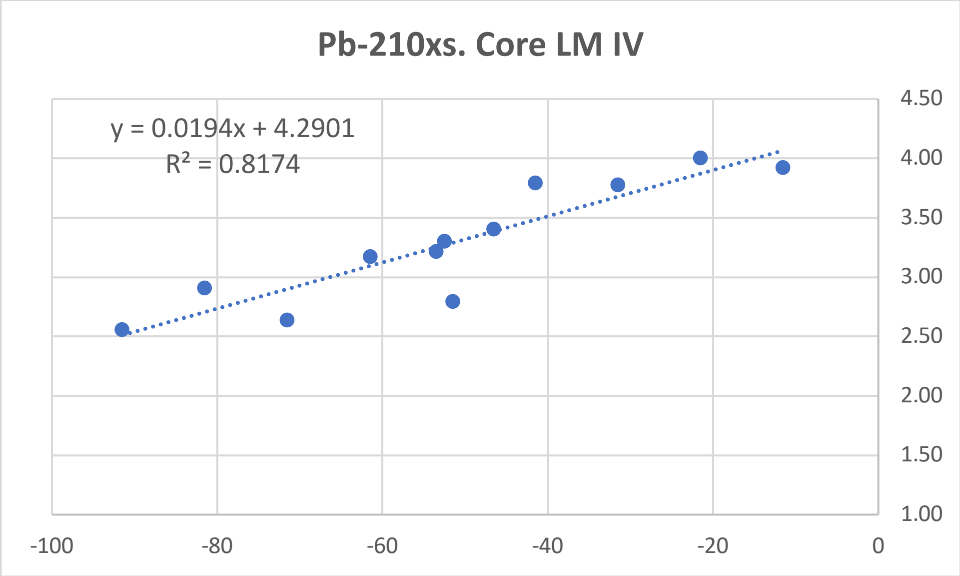
The radiochronological data and profiles show distinct features in the down core profiles for ^{137}Cs which are readily attributable to the first onset of the atmospheric testing of thermonuclear weapons, the 1963 'bomb peak' and the 1986 Chernobyl peak. The data reveal a consistent age-depth relationship that shows the sediment accumulation rates to be uniform (but different for LM III and LM IV) over the whole length of the cores.

Pb-210 Profiles

The ^{210}Pb data produce relatively straight log-linear regressions. However, the organic-rich nature of the sediment leads to relatively low activities due to the modest amount of minerogenic material in the sediment. This leads to larger uncertainties that are seen in the Cs-137 profiles. The larger uncertainties explain the variation in Pb-210 dating assessments. **Note: In the calculation the estimated Supported Pb-210 contributions are: 50 Bq/kg for LM III and 100 Bq/kg for LM IV.**



Pb-210 (Simple Method) 10.9 mm/yr for LM III



Pb-210 (Simple Method) 15.95 mm/yr for LM IV

Conclusion

Summary Table of sediment accumulation rates

	Cs-137 mm/year	Pb-210 mm/year
LM III	8.9	10.0
LM IV	17.2	16.0

The correspondence between the two dating approaches is clearly consistent. The Cs-137 approach is based on more independent criteria (events).

References supporting the methodological approach

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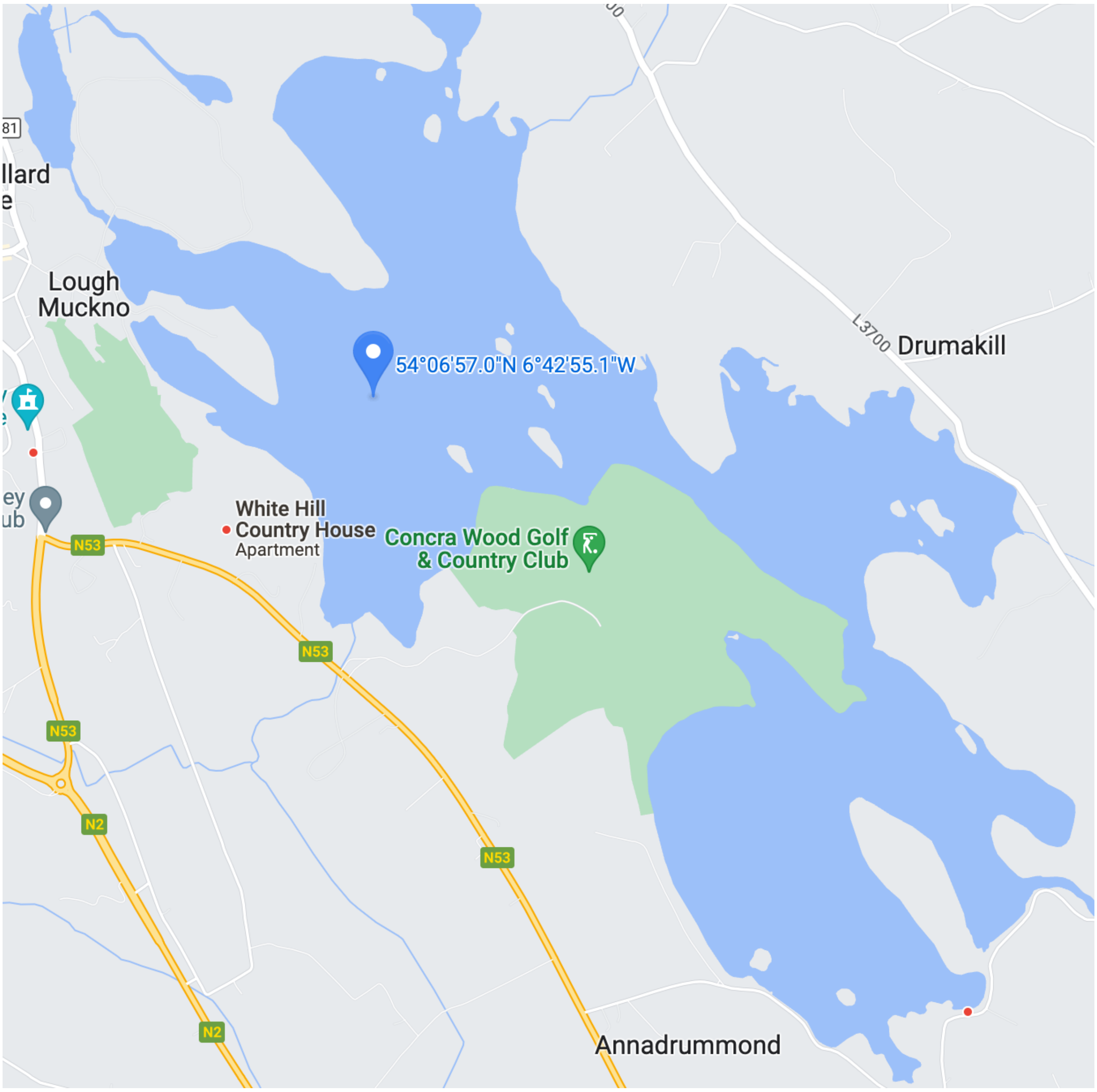
Sample Location (courtesy Google Maps)



Appendices: Radioanalytical Data Tables

Core LM III		Raw (Bq/g)			
Depth midpt (cm)	Vial height (mm)	Pb210	+-	Cs137	+-
-1.5	20	0.137	0.025	0.0551	0.0045
-11.5	22	0.146	0.032	0.0869	0.006
-21.5	30	0.112	0.021	0.1104	0.0069
-23.5	39	0.112	0.022	0.1189	0.0075
-26.5	39	0.126	0.023	0.063	0.0048
-31.5	33	0.102	0.024	0.0586	0.0045
-41.5	31	0.092	0.023	0.0548	0.0044
-43.5	36	0.092	0.019	0.0426	0.0036
-51.5	35	0.083	0.0025	0.0167	0.0025
-61.5	39	0.066	0.016	0.0038	0.0012
-71.5	39	0.049	0.015	<0.003	
-81.5	42	0.06	0.017	<0.0021	
-91.5	36	0.061	0.015	<0.0026	
-101.5	28	0.074	0.022	<0.0031	
-111.5	29	0.059	0.017	<0.0031	
-121.5	31	0.055	0.019	<0.0041	
-131.5	40	0.043	0.013	<0.0025	
-141.5	29	0.063	0.021	<0.0034	
-151.5	21	0.061	0.022	<0.0045	
-161.5	30	0.041	0.018	<0.0041	
-171.5	23	0.058	0.018	<0.0038	
-181.5	38	0.053	0.021	<0.0036	
-191.5	40	0.042	0.014	<0.0029	

Height corrected (Bq/kg)				
Pb210 Bq/kg	+-	Ln(Pb-210)xs	Cs137	+-
107.61	19.64	4.05	43.3	3.5
116.88	25.62	4.20	69.6	4.8
97.13	18.21	3.85	95.7	5.9
107.17	21.05	4.05	113.8	7.1
120.56	22.01	4.26	60.3	4.5
91.31	21.48	3.72	52.5	4.0
80.62	20.16	3.42	48.0	3.8
85.10	17.57	3.56	39.4	3.3
75.93	2.29	3.26	15.3	2.2
63.15	15.31	2.58	3.6	1.1
46.89	14.35			
59.46	16.85	2.25		
56.42	13.87	1.86		
62.87	18.69	2.55		
50.64	14.59	-0.45		
48.20	16.65			
41.62	12.58			
54.07	18.02	1.40		
48.37	17.45			
35.56	15.61			
46.88	14.55			
50.14	19.87	-1.99		
40.65	13.55			

Core LM IV		Raw (Bq/g)					Height corrected (Bq/kg)				
Depth midpt (cm)	**Vial height (mm)**	**Pb210**	**+-**	**Cs137**	**+-**		**Pb210 Bq/kg**	**+-**	**Ln(Pb-210)xs**	**Cs137**	**+-**
-1.5	12	0.162	0.093	0.06	0.014		118.33	67.93	2.91	43.82	10.23
-11.5	16	0.199	0.078	0.072	0.012		150.63	59.04	3.92	54.50	9.08
-21.5	20	0.197	0.05	0.0799	0.0072		154.74	39.27	4.00	62.76	5.66
-31.5	20	0.183	0.038	0.1036	0.0081		143.74	29.85	3.78	81.38	6.36
-41.5	20	0.184	0.051	0.166	0.012		144.53	40.06	3.80	130.39	9.43
-46.5	32	0.147	0.031	0.169	0.011		130.19	27.46	3.41	149.68	9.74
-51.5	33	0.13	0.027	0.2	0.012		116.37	24.17	2.80	179.04	10.74
-52.5	20	0.162	0.0038	0.193	0.013		127.25	2.98	3.30	151.60	10.21
-53.5	24	0.153	0.03	0.1198	0.0078		124.89	24.49	3.21	97.79	6.37
-61.5	38	0.131	0.035	0.0552	0.0055		123.92	33.11	3.17	52.22	5.20
-71.5	34	0.126	0.036	0.0509	0.0054		114.02	32.58	2.64	46.06	4.89
-81.5	24	0.145	0.042	0.059	0.0066		118.36	34.28	2.91	48.16	5.39
-91.5	22	0.141	0.051	0.0729	0.0072		112.88	40.83	2.56	58.36	5.76
-93.5	37	0.103	0.032	0.0639	0.0058		96.34	29.93		59.77	5.43
-101.5	31	0.093	0.041	0.0298	0.0055		81.50	35.93		26.12	4.82
-111.5	32	0.093	0.023	0.0222	0.0028		82.37	20.37		19.66	2.48
-121.5	35	0.102	0.028	0.0106	0.0023		93.31	25.62		9.70	2.10
-131.5	40	0.076	0.017	0.0026	0.0013		73.56	16.46		2.52	1.26
-141.5	32	0.074	0.026	<0.0054	-		65.54	23.03			
-151.5	30	0.062	0.025	<0.0056	-		53.77	21.68			
-161.5	34	0.062	0.018	<0.0036	-		56.10	16.29			
-171.5	34	0.071	0.022	<0.0032	-		64.25	19.91			
-182.5	32	0.055	0.018	<0.0034	-		48.71	15.94			
-192.5	FULL	0.043	0.017	<0.0036				0.02			

Core LM VI		Raw (Bq/g)			
Depth midpt (cm)	Vial height (mm)	Pb210	+-	Cs137	+-
-1.5	17	0.097	0.047	0.0237	0.0057
-11.5	15	0.209	0.058	0.046	0.0077
-21.5	12	0.189	0.055	0.065	0.008
-24.5	20	0.213	0.055	0.0516	0.0058
-31.5	24	0.142	0.07	0.0248	0.0068
-41.5	23	0.097	0.046	0.019	0.0053
-44.5	23	0.081	0.033	0.0164	0.0037
-49.5	22	0.07	0.038	<0.0081	-
-51.5	30	0.052	0.027	<0.0067	-
-61.5	17	<0.12	-	<0.014	-
-71.5	20	<0.084	-	<0.012	-
-79.5	25	<0.071	-	<0.0085	-
-81.5	20	<0.13	-	<0.017	-
-99.5	26	0.049	0.033	0.0058	0.003
-91.5	20	<0.07	-	<0.0088	-
-101.5	24	<0.15	-	<0.02	-
-111.5	22	<0.078	-	0.0097	0.0037
-121.5	25	0.162	0.039	0.0651	0.0064
-131.5	38	0.133	0.032	0.1022	0.0073
-141.5	34	0.121	0.044	0.0516	0.0063
-151.5	30	0.147	0.031	0.1119	0.0083
-152.5	full	0.13	0.025	0.107	0.0069
-161.5	35	0.161	0.03	0.1227	0.008
-171.5	full	0.144	0.027	0.0698	0.0054
-181.5	28	0.159	0.041	0.0497	0.0051
-191.5	30	0.096	0.041	0.0478	0.0061

Height corrected (Bq/g)				
Pb210 Bq/kg	+-	Ln(Pb-210)xs	Cs137	+-
74.1	35.90	4.3046	18.10	4.35
156.8	43.51	5.0544	34.51	5.78
138.0	40.17	4.9272	47.48	5.84
167.3	43.20	5.1195	40.53	4.56
115.9	57.14	4.7523	20.24	5.55
78.4	37.18	4.3612	15.36	4.28
65.5	26.68	4.1808	13.26	2.99
56.0	30.42	4.0250		
45.1	23.42	3.8075		
40.8	27.47	3.7071	4.83	2.50
			7.77	2.96
133.5	32.15	4.8940	53.66	5.28
125.8	30.27	4.8343	96.68	6.91
109.5	39.82	4.6953	46.69	5.70
127.5	26.88	4.8475	97.04	7.20
				0.01
147.3	27.44	4.9920	112.25	7.32
				0.01
135.1	34.83	4.9054	42.22	4.33
83.3	35.56	4.4212	41.45	5.29

APPENDIX 2

DIATOM INFERRED TP MODEL SUMMARY

ModelSumrBlank
Results for model: DI-TP recon for Muckno

Model name	:	DI-TP recon for Muckno
Description	:	Model 23
Model type	:	Weighted Averaging
Date	:	14 十月, 2024: 18:16:41
Species data	:	Diatom Raw-1%&3 sites
Environmental data	:	EnviDiatTransformed
Environmental variable	:	TP
Total number of samples	:	72
Number of samples in model	:	70
Total number of variables	:	233
Number of variables in model	:	233
Fossil data	:	MUCKNO diatom perc data for recon
Total number of samples	:	10
Total number of variables	:	233
Number of variables in model	:	233

The following training set samples have been excluded from the model:

15 CAR
71 VEA

Taxa with only one occurrence have had their tolerances set to 0.27929

Deshrinking regression coefficients

#	Id	WA_b0	WA_b1	WATOL_b0	WATOL_b1
1	Inverse deshrinking	-0.94697	1.7746	-0.44462	1.4231
2	Classical deshrinking	0.68831	0.4368	0.427	0.60886

Model performance

#	Id	WA_Inv	WA_Cla	WATOL_Inv	WATOL_Cla
1	RMSE	0.19733	0.22413	0.15208	0.16337
2	R2	0.77517	0.77517	0.86647	0.86647
3	Ave_Bias	-5.9476e-016	-5.5987e-016	-1.5067e-016	-1.6653e-016
4	Max_Bias	0.35143	0.19324	0.34337	0.25246
5	Jack_R2	0.64568	0.65009	0.74255	0.74515
6	Jack_Ave_Bias	-0.0082918	-0.010411	0.017799	0.020823
7	Jack_Max_Bias	0.45143	0.30835	0.41096	0.32769
8	RMSEP	0.24794	0.26801	0.21269	0.22447
9	%Change	***	-8.0922	***	-5.5392
10	Rand. t-test	***	0.948	***	0.945

APPENDIX 3

PHOTOS OF LOUGH MUCKNO TRIBUTARIES / SAMPLING SITES

Plate A3.1 Photo of monitoring location on the Fane Stream

Plate A3.2 Photo of monitoring location on the Gentle Owen's Lake Stream

Plate A3.3 Photo of monitoring location on the County Water

Plate A3.4 Photo of monitoring location on the Drumacon Stream

Plate A3.5 Photo of monitoring location on the Toome Stream

Plate A3.6 Photo of monitoring location on the Annahale Stream

Plate A3.7 Photo of monitoring location on the Drumcrew Lough outflow

APPENDIX 4

WATER LEVELS RECORDED IN LOUGH MUCKNO TRIBUTARIES 2023

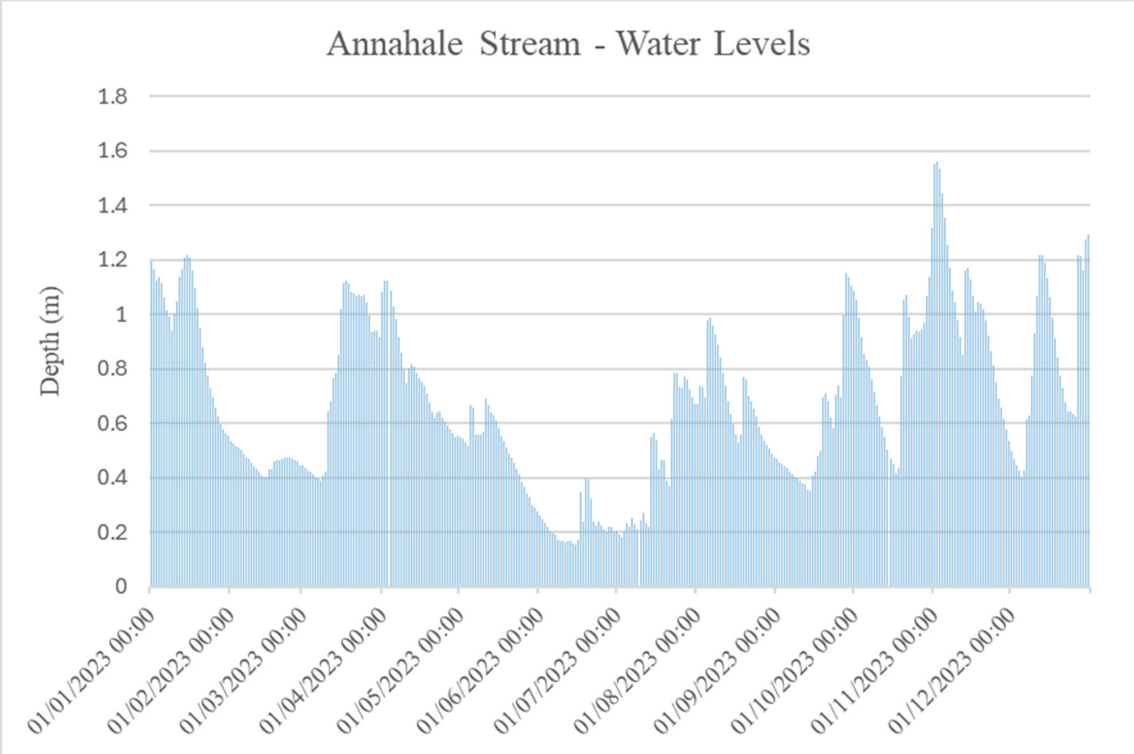


Plate A4.1 Water depths recorded every 15 minutes in 2023 on the Annahale Stream (ITM 683892, 818352)

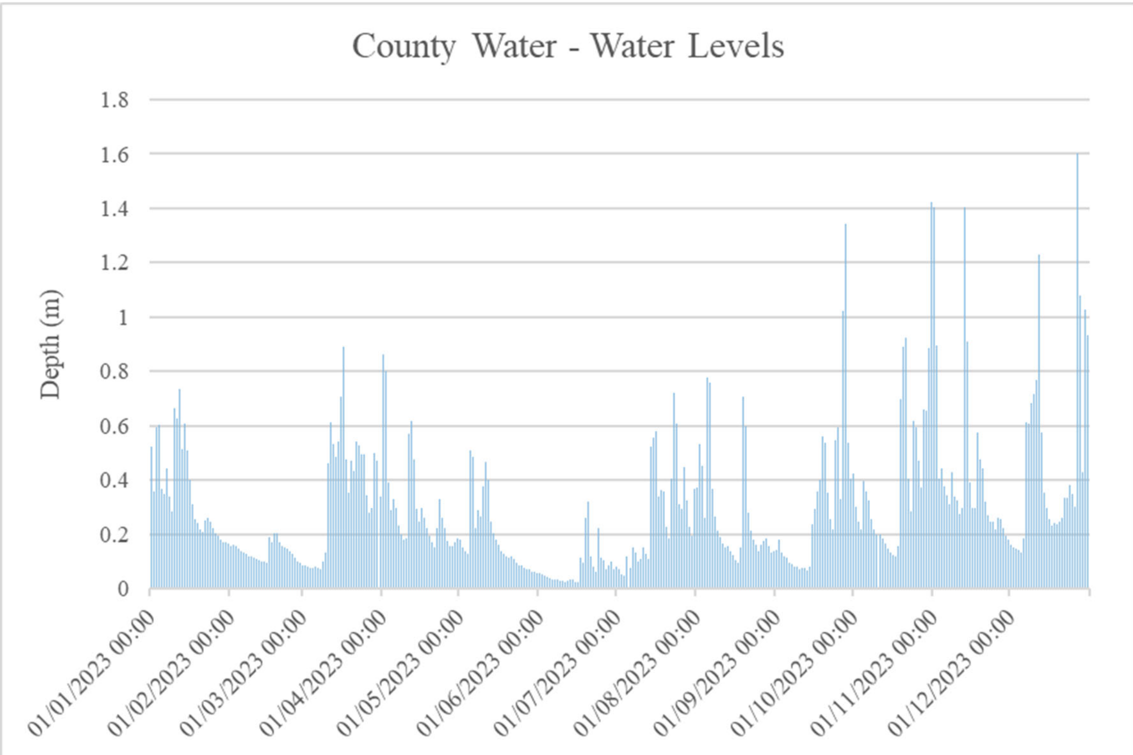


Plate A4.2 Water depths recorded every 15 minutes in 2023 on the County Water (ITM 684931, 820445)

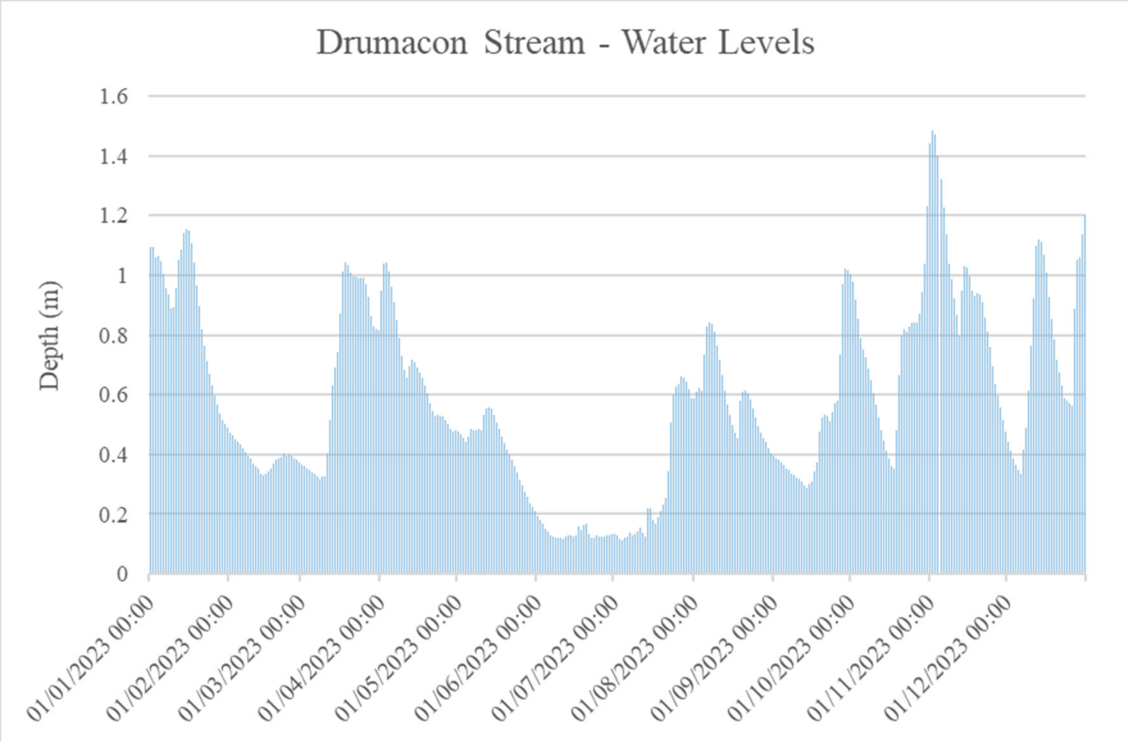


Plate A4.3 Water depths recorded every 15 minutes in 2023 on the Drumacon Stream (ITM 686381, 818818)

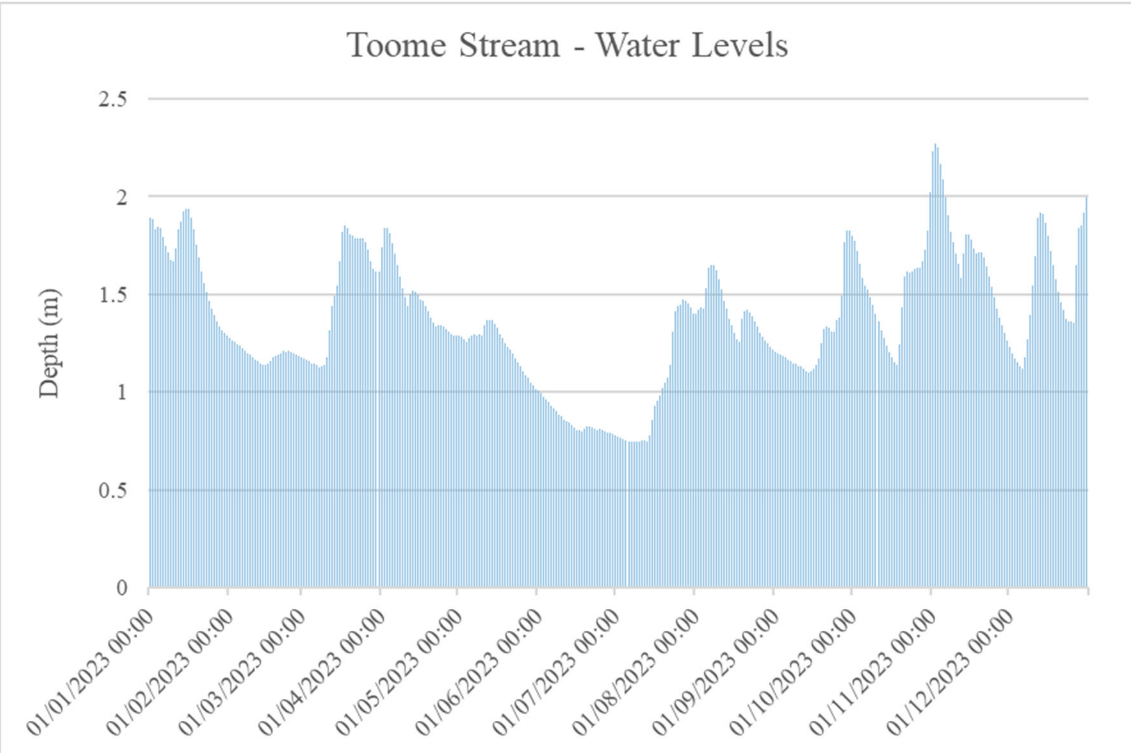


Plate A4.4 Water depths recorded every 15 minutes in 2023 on the Toome Stream (ITM 685936, 816895)

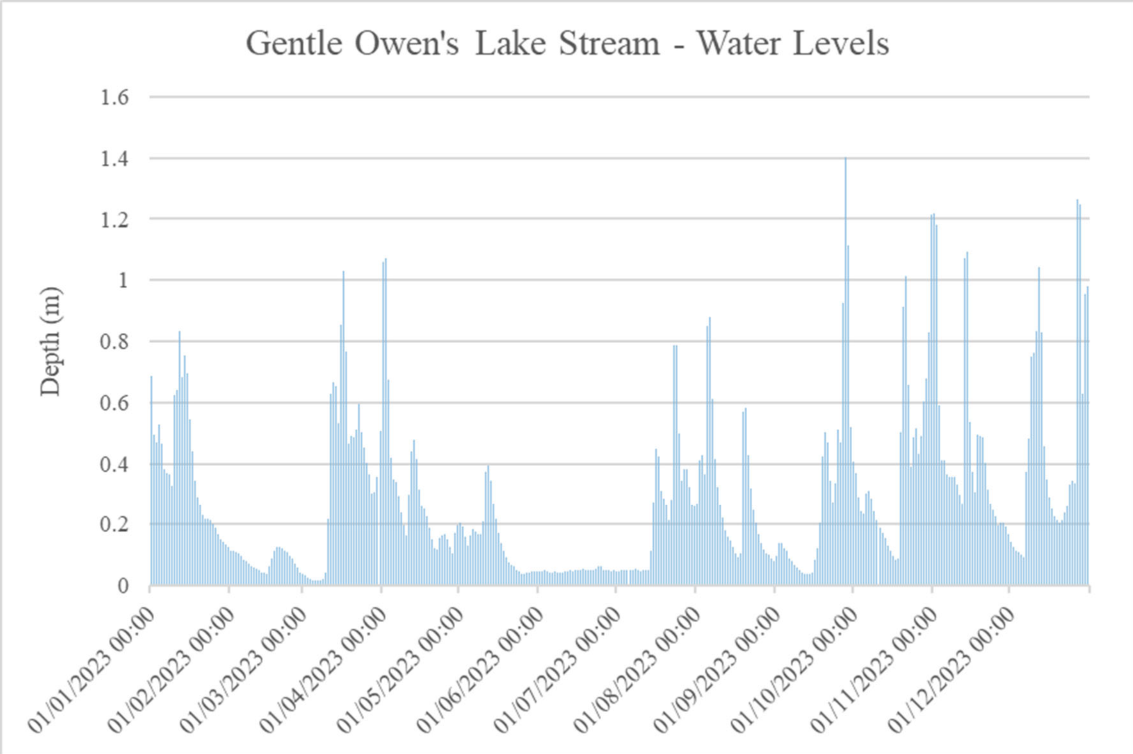


Plate A4.5 Water depths recorded every 15 minutes in 2023 on the Gentle Owen's Lake Stream (ITM 683343, 821437)

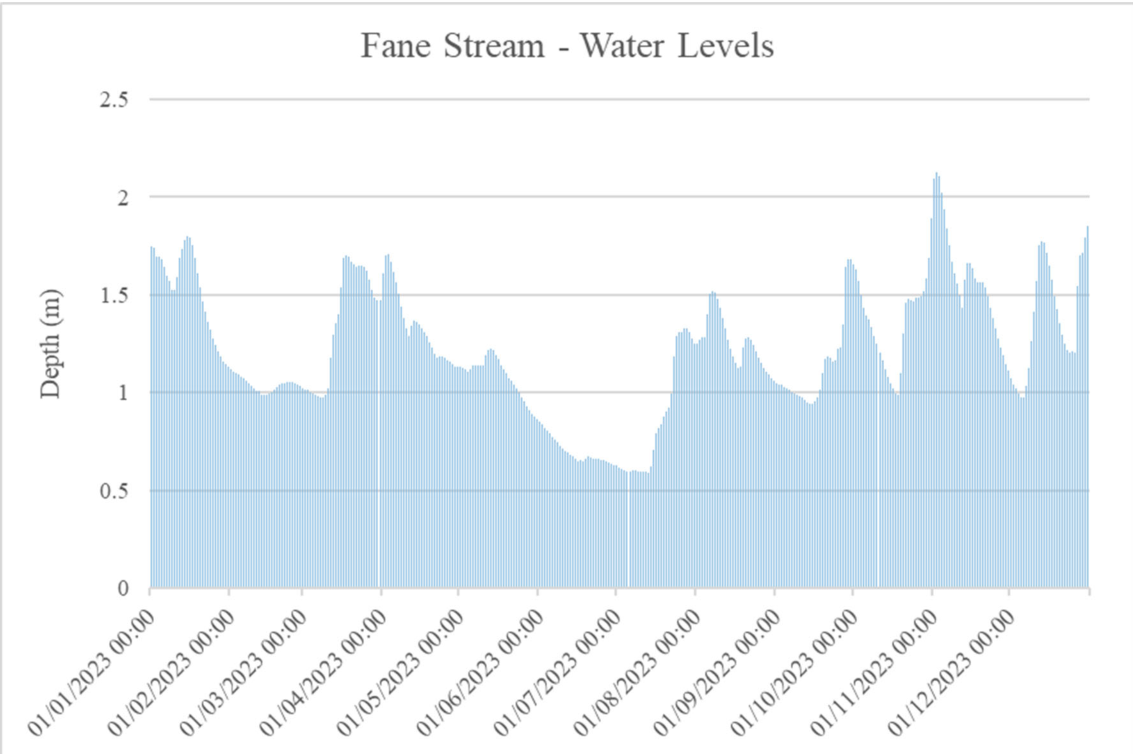


Plate A4.6 Water depths recorded every 15 minutes in 2023 on the Fane Stream (ITM 682691, 820696)

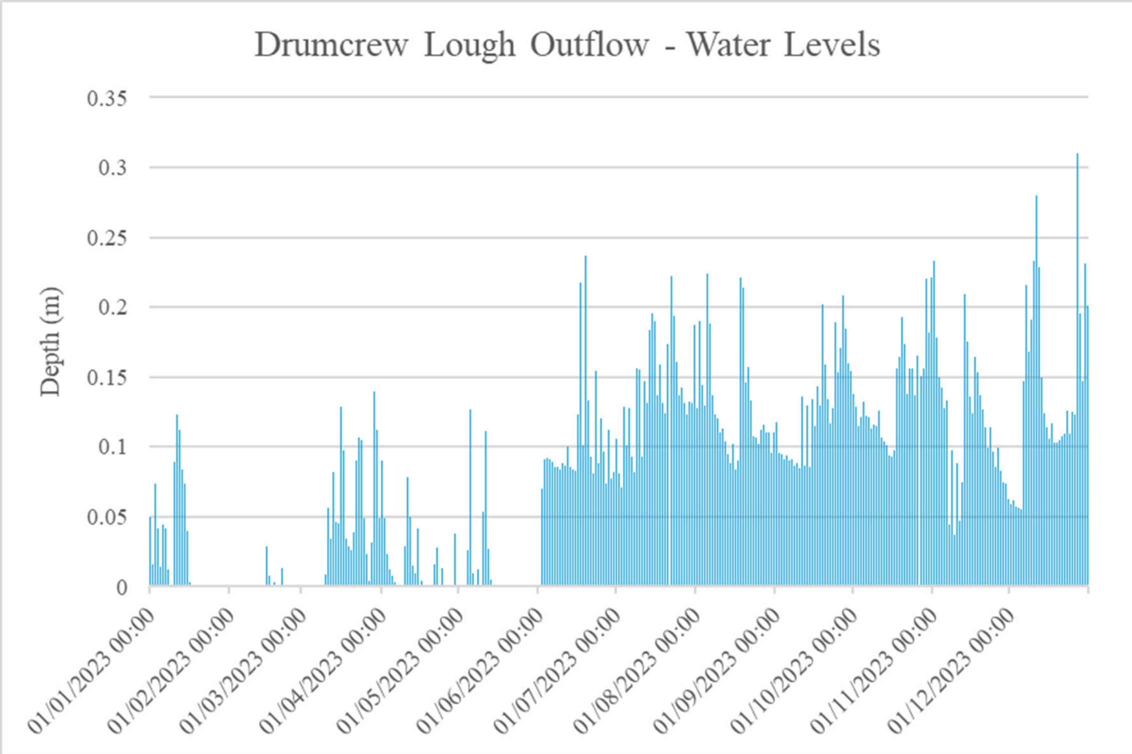
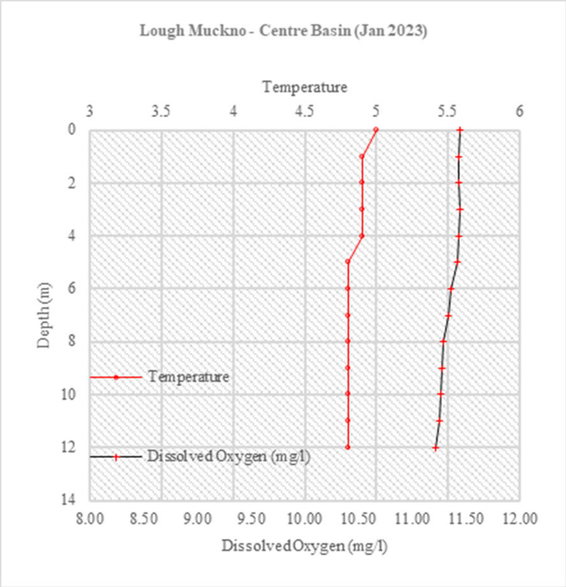
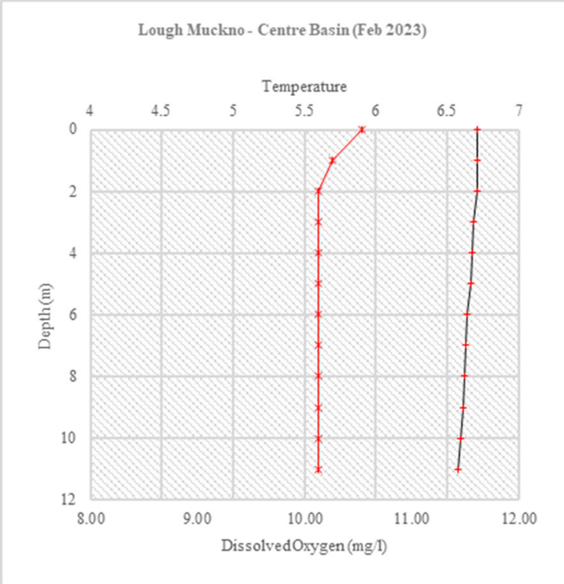


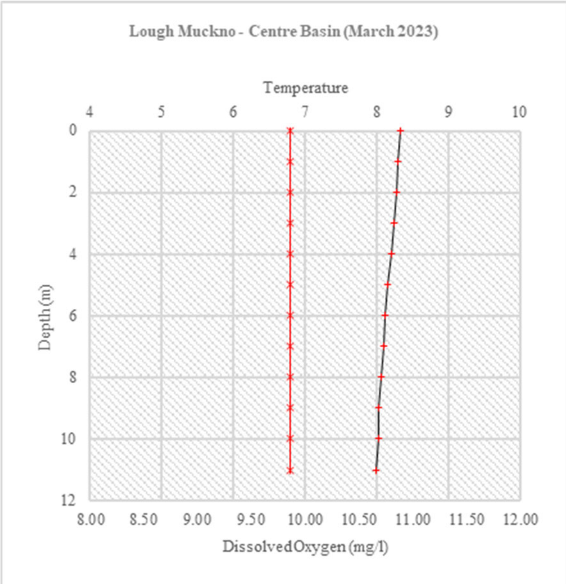
Plate A4.7 Water depths recorded every 15 minutes in 2023 on the Drumcrew Lough Outflow (ITM 683108, 818758)

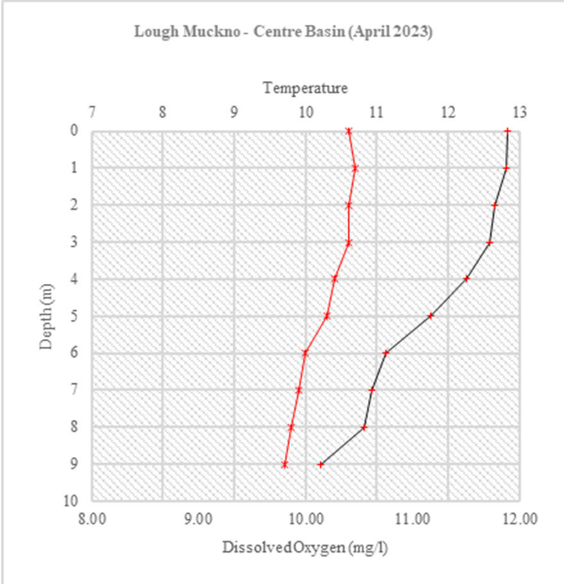
APPENDIX 5

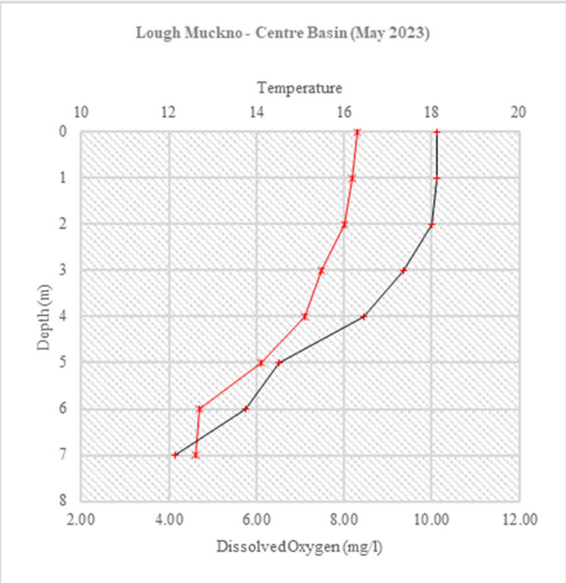
TEMPERATURE & DISSOLVED OXYGEN PROFILES OF LOUGH MUCKNO 2023 (CENTRE & SOUTHERN BASINS)

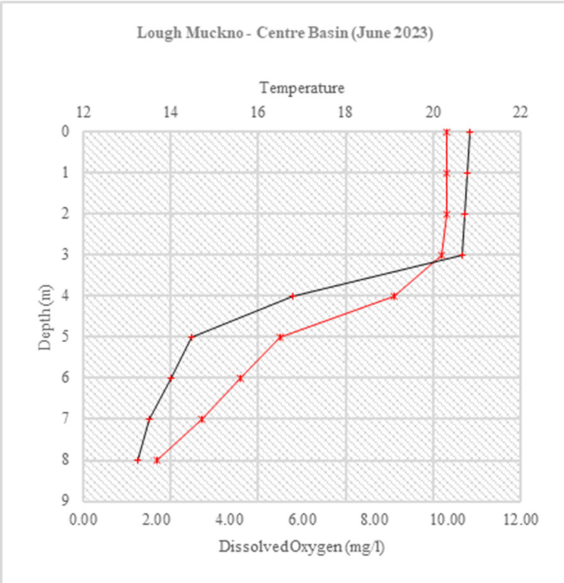

Lough Muckno - Centre Basin (Jan 2023)
Temperature
Depth (m)
Temperature
Dissolved Oxygen (mg/l)
Dissolved Oxygen (mg/l)

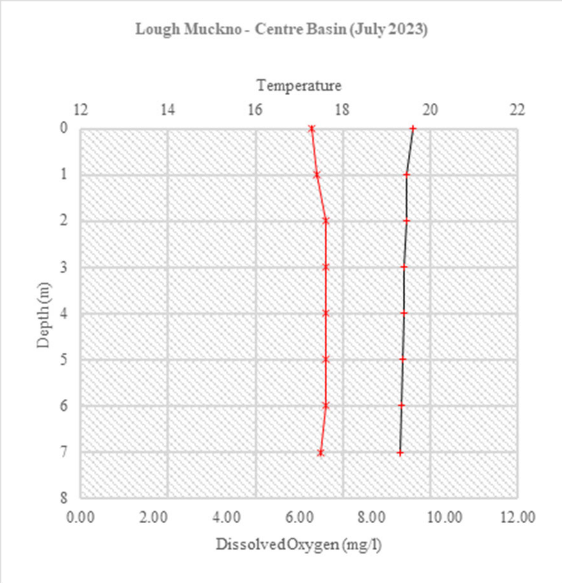

Lough Muckno - Centre Basin (Feb 2023)
Temperature
Depth (m)
Dissolved Oxygen (mg/l)

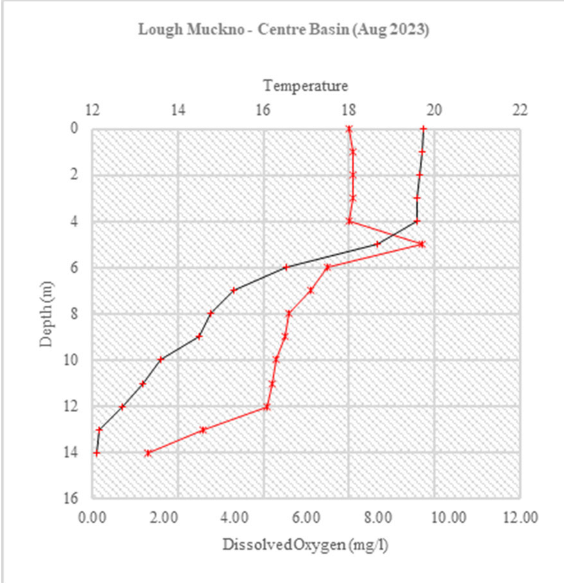

Lough Muckno - Centre Basin (March 2023)
Temperature
Depth (m)
Dissolved Oxygen (mg/l)

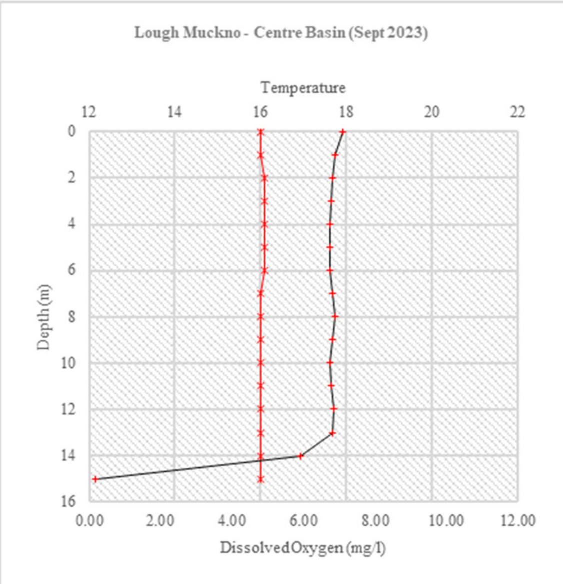

Lough Muckno - Centre Basin (April 2023)
Temperature
Depth (m)
Dissolved Oxygen (mg/l)

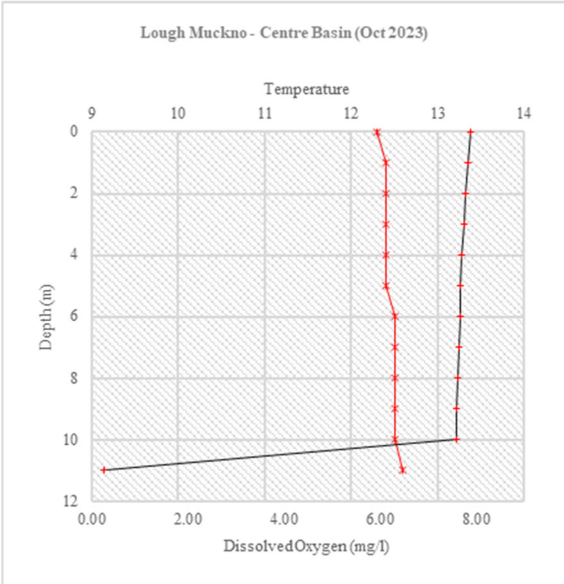

Lough Muckno - Centre Basin (May 2023)
Temperature
Depth (m)
Dissolved Oxygen (mg/l)

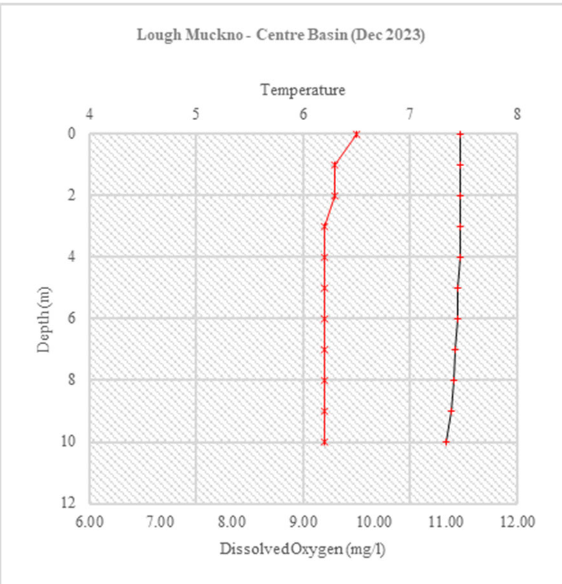

Lough Muckno - Centre Basin (June 2023)
Temperature
Depth (m)
Dissolved Oxygen (mg/l)

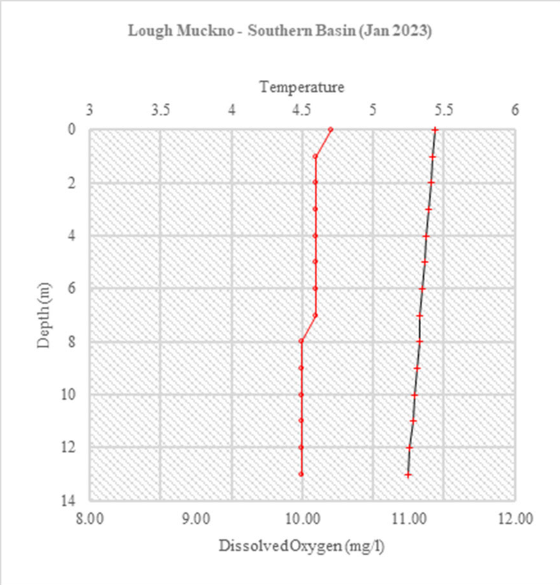

Lough Muckno - Centre Basin (July 2023)
Temperature
12 14 16 18 20 22
Depth (m)
0 1 2 3 4 5 6 7 8
0.00 2.00 4.00 6.00 8.00 10.00 12.00
Dissolved Oxygen (mg/l)

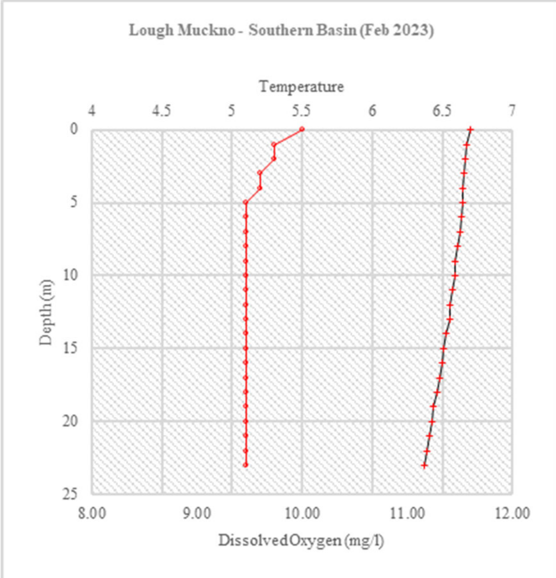

Lough Muckno - Centre Basin (Aug 2023)
Temperature
12 14 16 18 20 22
Depth (m)
0 2 4 6 8 10 12 14 16
0.00 2.00 4.00 6.00 8.00 10.00 12.00
Dissolved Oxygen (mg/l)

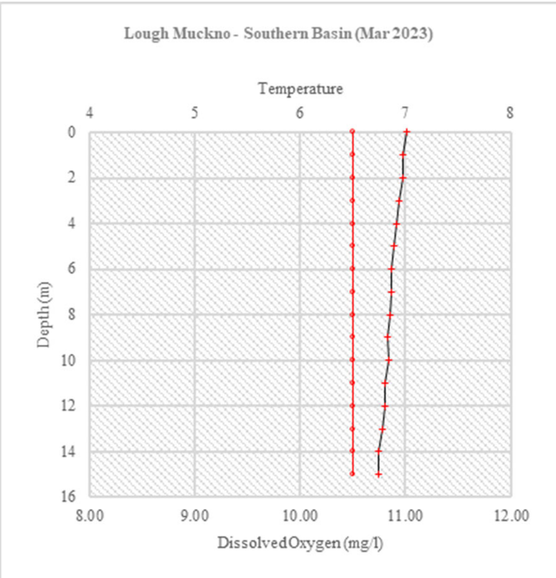

Lough Muckno - Centre Basin (Sept 2023)
Temperature
12 14 16 18 20 22
Depth (m)
0 2 4 6 8 10 12 14 16
0.00 2.00 4.00 6.00 8.00 10.00 12.00
Dissolved Oxygen (mg/l)

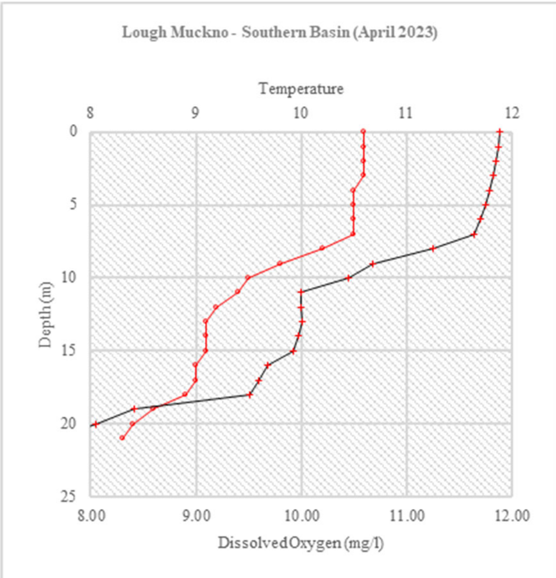

Lough Muckno - Centre Basin (Oct 2023)
Temperature
9 10 11 12 13 14
Depth (m)
0 2 4 6 8 10 12
0.00 2.00 4.00 6.00 8.00
Dissolved Oxygen (mg/l)

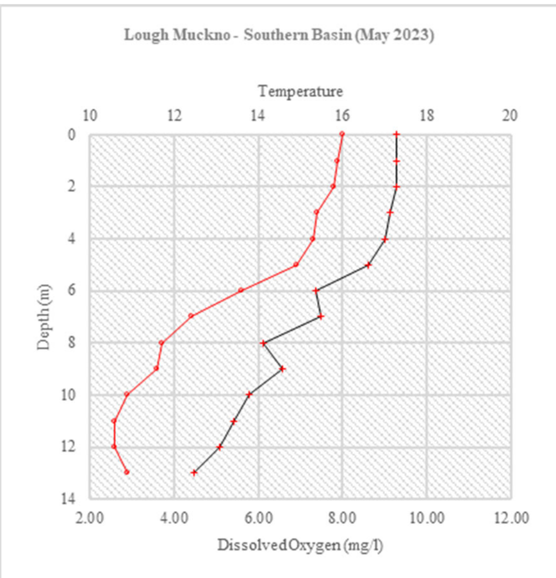

Lough Muckno - Centre Basin (Dec 2023)
Temperature
4 5 6 7 8
Depth (m)
0 2 4 6 8 10 12
6.00 7.00 8.00 9.00 10.00 11.00 12.00
Dissolved Oxygen (mg/l)

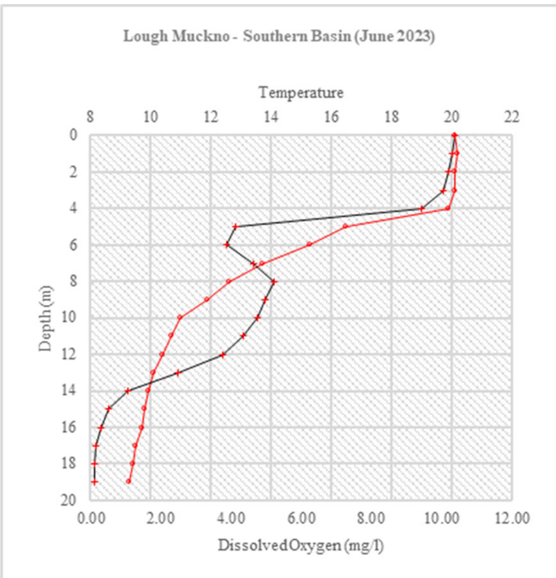

Lough Muckno - Southern Basin (Jan 2023)
Temperature
3
3.5
4
4.5
5
5.5
6
Depth (m)
0
2
4
6
8
10
12
14
8.00
9.00
10.00
11.00
12.00
Dissolved Oxygen (mg/l)

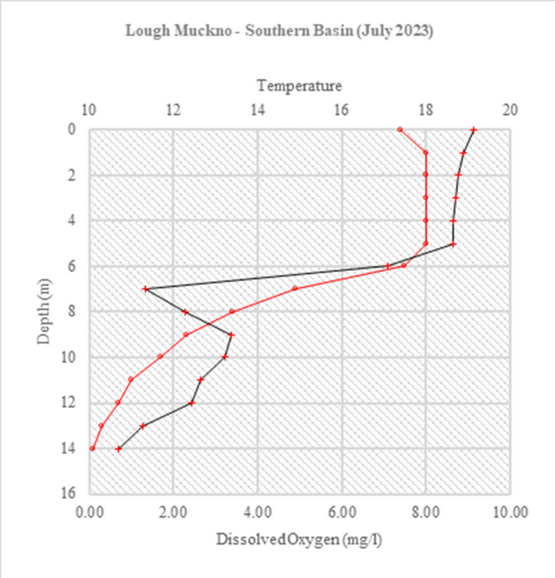

Lough Muckno - Southern Basin (Feb 2023)
Temperature
4
4.5
5
5.5
6
6.5
7
Depth (m)
0
5
10
15
20
25
8.00
9.00
10.00
11.00
12.00
Dissolved Oxygen (mg/l)

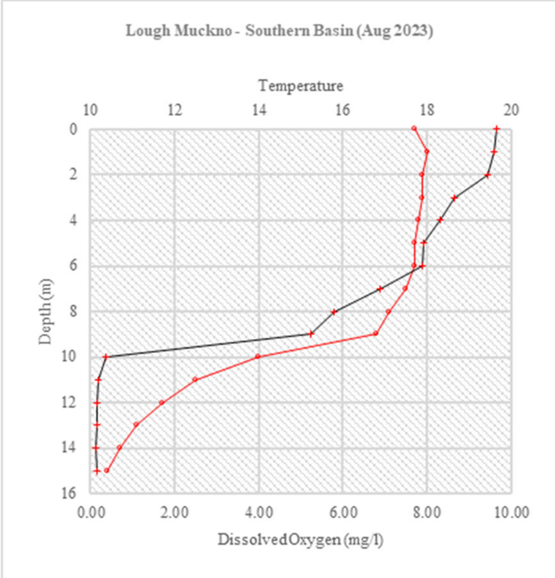

Lough Muckno - Southern Basin (Mar 2023)
Temperature
4
5
6
7
8
Depth (m)
0
2
4
6
8
10
12
14
16
8.00
9.00
10.00
11.00
12.00
Dissolved Oxygen (mg/l)

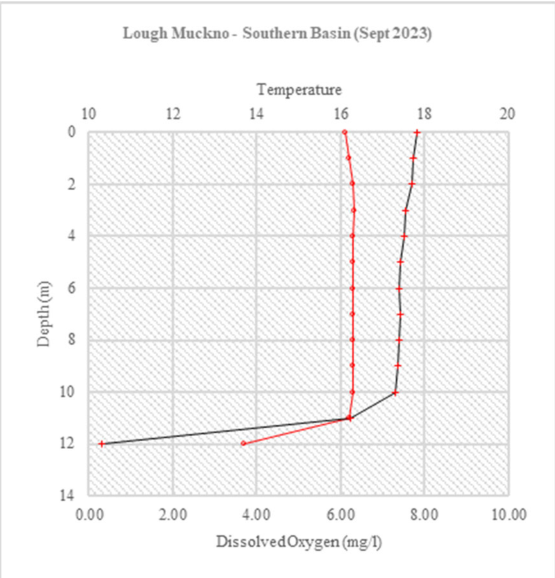

Lough Muckno - Southern Basin (April 2023)
Temperature
8
9
10
11
12
Depth (m)
0
5
10
15
20
25
8.00
9.00
10.00
11.00
12.00
Dissolved Oxygen (mg/l)

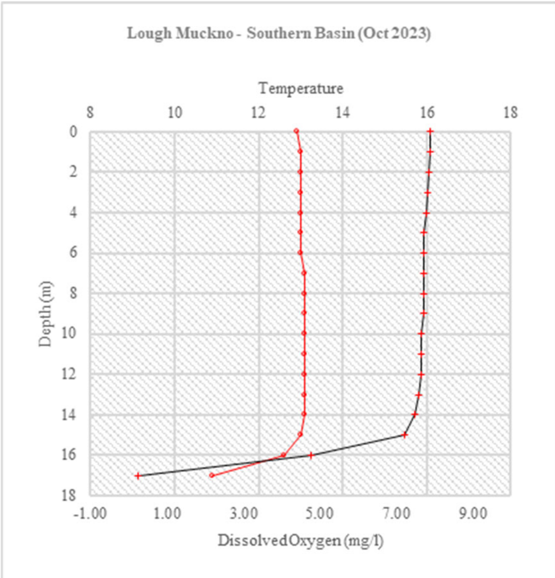

Lough Muckno - Southern Basin (May 2023)
Temperature
10
12
14
16
18
20
Depth (m)
0
2
4
6
8
10
12
14
2.00
4.00
6.00
8.00
10.00
12.00
Dissolved Oxygen (mg/l)

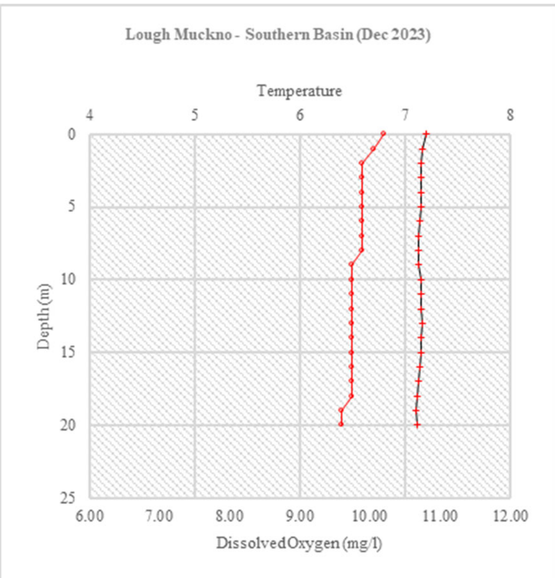

Lough Muckno - Southern Basin (June 2023)
Temperature
8
10
12
14
16
18
20
22
Depth (m)
0
2
4
6
8
10
12
14
16
18
20
0.00
2.00
4.00
6.00
8.00
10.00
12.00
Dissolved Oxygen (mg/l)


Lough Muckno - Southern Basin (July 2023)
Temperature
10
12
14
16
18
20
Depth (m)
0
2
4
6
8
10
12
14
16
0.00
2.00
4.00
6.00
8.00
10.00
Dissolved Oxygen (mg/l)


Lough Muckno - Southern Basin (Aug 2023)
Temperature
10
12
14
16
18
20
Depth (m)
0
2
4
6
8
10
12
14
16
0.00
2.00
4.00
6.00
8.00
10.00
Dissolved Oxygen (mg/l)


Lough Muckno - Southern Basin (Sept 2023)
Temperature
10
12
14
16
18
20
Depth (m)
0
2
4
6
8
10
12
14
0.00
2.00
4.00
6.00
8.00
10.00
Dissolved Oxygen (mg/l)


Lough Muckno - Southern Basin (Oct 2023)
Temperature
8
10
12
14
16
18
Depth (m)
0
2
4
6
8
10
12
14
16
18
-1.00
1.00
3.00
5.00
7.00
9.00
Dissolved Oxygen (mg/l)


Lough Muckno - Southern Basin (Dec 2023)
Temperature
4
5
6
7
8
Depth (m)
0
5
10
15
20
25
6.00
7.00
8.00
9.00
10.00
11.00
12.00
Dissolved Oxygen (mg/l)

APPENDIX 6

PHOSPHORUS EXTRACTION RESULTS (LABORATORY DATA)

(name) EXTRACTION SEQUENCE	(id) SEDIMENT IDENTIFICATION	(name) EXTRACTION FRACTION	average of extraction duplicates (mg PO4-P/L) SPETCTROPHOTOMETRIC CONCENTRATION	(mg PO4-P) MASS OF EXTRACTED PO4-P	(mg PO4-P/g) MASS RATIO
1	Lough Muckno - middle basin - (0-1cm) [22/11/2023]	Pex	0.2137	0.00587675	0.011993367
2	Lough Muckno - middle basin - (0-1cm) [22/11/2023]	Phum	2.978275	0.14891375	0.303905612
3	Lough Muckno - middle basin - (0-1cm) [22/11/2023]	Pfe	7.352625	0.272047125	0.555198214
4	Lough Muckno - middle basin - (0-1cm) [22/11/2023]	Pcfa	4.8092	0.111610325	0.227776173
5	Lough Muckno - middle basin - (0-1cm) [22/11/2023]	Pdetr	4.319375	0.05894805	0.120302143
6	Lough Muckno - middle basin - (0-1cm) [22/11/2023]	Presi	28.185225	0.28185225	0.575208673
1	Lough Muckno - middle basin - (4-5cm) [22/11/2023]	Pex	0.169625	0.004664688	0.00951977
2	Lough Muckno - middle basin - (4-5cm) [22/11/2023]	Phum	2.54295	0.1271475	0.259484694
3	Lough Muckno - middle basin - (4-5cm) [22/11/2023]	Pfe	9.04765	0.23987605	0.489542959
4	Lough Muckno - middle basin - (4-5cm) [22/11/2023]	Pcfa	2.343475	0.0453716	0.092595102
5	Lough Muckno - middle basin - (4-5cm) [22/11/2023]	Pdetr	3.414875	0.0461665	0.094217347
6	Lough Muckno - middle basin - (4-5cm) [22/11/2023]	Presi	26.585825	0.26585825	0.542567857
1	Lough Muckno - middle basin - (9-10cm) [22/11/2023]	Pex	0.10825	0.002584525	0.005274541
2	Lough Muckno - middle basin - (9-10cm) [22/11/2023]	Phum	2.018025	0.0823311	0.168022653
3	Lough Muckno - middle basin - (9-10cm) [22/11/2023]	Pfe	5.6243	0.2080991	0.424692041
4	Lough Muckno - middle basin - (9-10cm) [22/11/2023]	Pcfa	2.0756	0.045078625	0.091997194
5	Lough Muckno - middle basin - (9-10cm) [22/11/2023]	Pdetr	4.820625	0.078104375	0.159396684
6	Lough Muckno - middle basin - (9-10cm) [22/11/2023]	Presi	24.725825	0.24725825	0.504608673
1	Lough Muckno - middle basin - (14-15cm) [22/11/2023]	Pex	0.0456	0.001267138	0.002585995
2	Lough Muckno - middle basin - (14-15cm) [22/11/2023]	Phum	1.498025	0.0722779	0.147505918
3	Lough Muckno - middle basin - (14-15cm) [22/11/2023]	Pfe	3.1353	0.0976575	0.19930102
4	Lough Muckno - middle basin - (14-15cm) [22/11/2023]	Pcfa	2.01065	0.04417925	0.090161735
5	Lough Muckno - middle basin - (14-15cm) [22/11/2023]	Pdetr	3.25535	0.04376625	0.089318878
6	Lough Muckno - middle basin - (14-15cm) [22/11/2023]	Presi	24.705475	0.24705475	0.504193367
1	Lough Muckno - middle basin - (18-19cm) [22/11/2023]	Pex	0.424975	0.011686813	0.023850638
2	Lough Muckno - middle basin - (18-19cm) [22/11/2023]	Phum	1.46895	0.071300925	0.145512092
3	Lough Muckno - middle basin - (18-19cm) [22/11/2023]	Pfe	2.9823	0.08256575	0.168501531
4	Lough Muckno - middle basin - (18-19cm) [22/11/2023]	Pcfa	2.00425	0.041103125	0.083883929
5	Lough Muckno - middle basin - (18-19cm) [22/11/2023]	Pdetr	8.817975	0.11227245	0.229127449
6	Lough Muckno - middle basin - (18-19cm) [22/11/2023]	Presi	22.152075	0.22152075	0.452083163