IN-SIGHT EPA/ERTDI Project # 2002-W-LS/7

Work Package (WP) 3 (months 21-36)

Final Report

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Executive Summary

The *EU Water Framework Directive* (WFD, Directive 2000/60/EC) requires member states to describe ecological reference conditions for impacted lake types. This project examines seven case study lakes from six lake typology classes that are known to have experienced disturbance in their recent history primarily due to nutrient enrichment.

The seven case study lakes include Loughs Atedaun, Ballybeg, Crans, Egish, Inchiquin, Mullagh and Sillan. All are productive systems characterised by plankton-dominated communities associated with nutrient rich, alkaline waters and the presence of nutrient tolerant aquatic macrophytes. Sediment cores from these lakes were examined in detail in terms of their palaeoecological condition. The extracted cores represent an average age of 130 years (minimum 60 years; maximum 237 years) estimated by radiometric dating. Sediment accumulation rates ranged from lows of 0.017 g cm^{-2} yr^{-1} at Egish to a maximum of 0.12 g cm^{-2} yr^{-1} at Inchiquin. Sediment chemistry was measured on 1 cm sample intervals while biological fossils (diatoms, cladocera and pollen) were examined in terms of top (current condition) and bottom (reference condition) samples and intervals in between.

Stratigraphic plots and top and bottom comparisons enable descriptions of pre-impact or reference conditions, onset and speed of disturbances and a description of impacted conditions for the upper and more recent sediments. The results for the reference samples indicate that more diverse diatom and cladocera communties, and assemblages typical of relatively nutrient poor, medium and high alkalinity lakes. Application of the diatom transfer function enables inference of a range of likely reference epilimnetic TP concentrations of between 10 and 20 μg TP l^{-1} for the test lakes.

The diatom assemblage changes show rapid and recent increases (post 1980) in DI-TP in the case study sediment cores from Atedaun, Ballybeg, Egish, and Mullagh. More longterm (post 1850s) and slower rates of change was indicated in cores from Crans and Sillan. In Crans, and to a lesser extent Sillan, the onset of sudden eutrophication as indicated at the base of the core appears more likely to have been driven by catchment clearance or some other disturbance. An apparent recovery post 1920 is probably offset by the increasing transfer of P from land to water from diffuse agricultural sources and has maintained this lake in a hypertrophic state. Diatom-inferred TP at Inchiquin suggests that the lake has been mesotrophic throughout its recent history with slight nutrient enrichment post-1990. Changes in the cladocera assemblages between the reference and surface sediment samples are consistent with the diatom-inferred increases in lake nutrient levels.

An analogue matching training set was developed comprising 13 lakes in good reference condition. The training set samples were matched with the reference samples of the seven test lakes. The squared chord distance dissimilarity coefficient was employed to determine the best modern analogues for the ‘reference’ assemblages. Good modern analogues are achieved for two of the seven WP3 lakes (Ballybeg and Egish). These analogues can potentially act as target restoration conditions for the impacted systems.

1. Context

In accordance with its obligations under the WFD Ireland is committed to ensuring that all of the nation's water bodies will meet the criteria for *good* ecological status by 2016 (Anon, 2000). The aim of the EU WFD is to maintain and improve ecological status (defined in the WFD as the expression of the quality of the structure and functioning of aquatic ecosystems) in EU surface waters and groundwaters. In order to achieve this aim, the WFD requires "good surface water status" to be defined for a particular body of surface water. "Good" is subsequently defined in Table 1.2, Annex V, as "showing low levels of distortion resulting from human activity [and] deviate only slightly from those normally associated with undisturbed conditions." An important component of the WFD is therefore the establishment of reference biological community conditions in anthropogenically-impacted lakes and rivers that are characteristic of Europe's 25 Ecoregions for freshwater bodies.

1.1 Workpackage 3 in the context of IN-SIGHT

The IN-SIGHT project (Identification of reference status for Irish lake typologies using palaeolimnological methods and techniques) commenced in January 2003 is an EPA research project (# 2002-W-LS/7) funded under the ERTDI programme 2000-20006. The project has a three-tiered structure in the form of three work packages. Work package 1 (WP1) identified, collated and evaluated existing published and unpublished literature, data sets and core samples relating to lakes for the Irish Ecoregion in 0-6 months of the project. Work package 2 (WP2) determined the presence or absence of anthropogenic pressures at 35 example Candidate Reference Lakes (CRL) from a range of lake typologies, using palaeolimnology to compare differences in proxies of lake water quality (nutrient content and pH) and catchment conditions between core top and core bottom samples during 7-20 months. The third and final phase of the project, work package 3 (WP3) months 18-36 constitutes the basis of this final report.

Work Package 3 follows on from the WP1 literature review and the broad-based geographical examination of lake typologies in WP2 and aims to provide relatively detailed information on biological reference conditions for a smaller sub-set of lakes. These case study lakes were selected based on the criteria that they constitute lake types in which no or relatively few candidate reference sites exist. These 'impacted' lakes were then examined for the form and timing of anthropogenically-induced pressures using palaeolimnological reconstructions. The ultimate aim being to evaluate the nature of change and establish pre-impact ecological conditions and finally contribute knowledge for restoration targets for certain biota and ecosystem functions.

The multi-proxy approach adopted comprises analyses of diatoms, cladoceran pseudofossils, pollen, sediment lithology and geochemistry. An accurate and precise chronology based upon gamma analysis and related isotopes is employed to allow full interpretation of the multi-proxy data. Reconstructions of reference conditions, changes in water quality and the degree of catchment disturbance is based upon the application of this multi-proxy approach.

The target lakes for examination in this work package include Loughs Atedaun, Inchiquin and Ballybeg in Co. Clare, Loughs Egish and Sillan in Co. Monaghan, Mullagh in Co. Cavan and Crans Lough in Co. Tyrone. These lakes are representatives of six lake typology classes (5, 6, 7, 8, 9 and 12) some of which have no candidate reference lakes and others where determination of CRL status was problematic (as determined in WP2).

2. Aims of WP3

The primary aim of Work Package 3 was to use multi-proxy palaeolimnological techniques to establish and describe biological reference conditions for those EPA typology classes for which no reference sites exist at present. Two key deliverables were agreed with the EPA:

1. Descriptions of ecological reference conditions for lake typologies with no existing reference conditions, based on palaeolimnological data
2. Contribute to knowledge for the identification of restoration targets.

3. Methods

3.1 Study Sites

Seven lakes were selected for sediment coring and study within WP3. Lake locations are illustrated in Figure 3.1. Physical and chemical information is provided in Table 3.1 and Table 3.2. Information on landuse in the catchment for each lake, in the form of 1990 and 2000 CORINE data, was also obtained from the EPA (Table 3.3). The study lakes were selected based on lake typology classes with few or no existing examples of lakes in reference condition, knowledge of nutrient enrichment, expert judgment and following consultation with EPA staff.

As part of WP2 lake typologies for which there are no extant examples of reference conditions were identified. This included EPA typology classes 5 (moderate alkalinity, shallow, small), 7 (moderate alkalinity, deep, small), 9 (high alkalinity, shallow, small) and 11 (high alkalinity, deep, small). The seven lakes selected for WP3 represent six lake typology classes (Figure 3.2), 3 of which have no extant examples of reference conditions (Mullagh = class 5, Crans = class 7, Sillan = class 8 and Ballybeg and Atedaun = class 9). Three additional lakes, Egish, Sillan and Inchiquin (classes 6, 8 and 12, respectively), were also included as these EPA typology classes (sampled in WP2) yielded cores in which diatom preservation and/or the spheroidal carbonaceous particle (SCP)-based chronologies were found to be problematic. In addition the inclusion of Crans, Co. Tyrone contributes to cross border collaboration.

3.2 Fieldwork and coring

The study lakes were surveyed and cored during August and September 2004 as part of WP3. Three sediment cores were extracted from the deepest point (determined via bathymetric surveys) in each lake to ensure sufficient material for analyses.

3.2.1 Lake bathymetries

Bathymetric surveys were conducted for six of the lakes using a portable depth sounder and handheld GPS (Table 3.4). A bathymetric map for Ballybeg was available in Wemaere (2001). The GPS had a positional accuracy of between 5-10 m. An average of 2.2 depth measurements per lake hectare was achieved in the WP3 lakes surveyed. Geo-coded depth data were inputted as (x,y) data into ArcMap 8.0 along with digitized lake boundaries. Bathymetic maps were produced using surface interpolation (Spline) with the Spatial Analyst extension. The depth class interval varies between 1-3 metres and the strongest colour represents the deepest waters. Bathymetric data for Crans Lough is illustrated using Grapher.

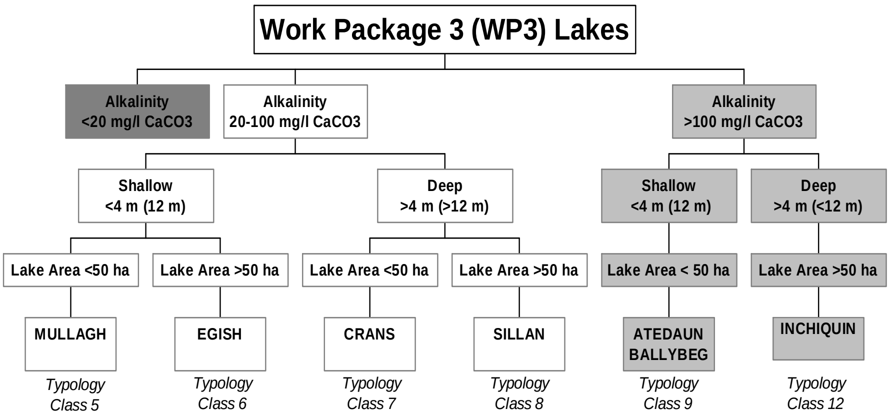


Figure 3.2: *EPA Lake typology classification of WP3 study sites.*

Figure 3.1: *Location of IN-SIGHT work package 3 lakes cored during August and September 2004.*

Table 3.1: *Summary of locational information and physical characteristics for WP3 lakes cored as part of IN-SIGHT WP3. Information was provided by the EPA Ireland.*

Lake	County	Grid Ref.	Geology	River Catchment	Altitude (m)	Mean depth (m)	Lake area (ha)	Catchment area (km^2)	EPA Typology Class
Atedaun	Clare	R297885	Limestone	Fergus	22	1.43	37.99	282.50	9
Ballybeg	Clare	R331738	Limestone	Fergus	10	2.69	19.73	4.14	9
Crans	Tyrone	H711568	Limestone & Shale	Oona	95	6.67	8.50	n/a	7
Egish	Monaghan	H794134	Ordovician Shale & Quartzite	Erne	162	3.32	121.74	7.84	6
Inchiquin	Clare	R270896	Limestone	Fergus	35	10.15	115.67	147.14	12
Mullagh	Cavan	N677854	Silurian Quartzite	Boyne	120	2.33	35.07	1.14	5
Sillan	Monaghan	H709630	Silurian	Annalee	94	5.98	172.00	n/a	8

Table 3.2: *Summary of chemical characteristics for WP3 lakes cored as part of IN-SIGHT.*

Lake	Sample Date	pH	Cond. µScm	Alkalinity mg l^{-1} $CaCO_3$	TP µg l^{-1}	Chl *a*	Colour PTCo	Reference
Atedaun	2000	8.01	279	135.4	36.7	15.5	31	Wemaere, 2001
Ballybeg	2001	7.94	n/a	128.0	84.3	n/a	n/a	Wemaere, 2001
Crans	1989/1990	8.82	316	*2.5	89.0	48.0	n/a	Gibson, 1991
Egish	01/10/1996	7.25	246	78.6	675.0	3.2	35	Irvine *et al*., 2001
Inchiquin	2001 1996/1997	8.21 8.22	n/a 354	161.8 140.0	19.3 21.0	n/a 4.5	n/a 28	Wemaere, 2001 Irvine *et al*., 2001
Mullagh	24/07/1996	7.61	187	58.4	57.0	8.1	29	Irvine *et al*., 2001
Sillan	01/10/1996	6.98	170	37.6	141.0	9.3	36	Irvine *et al*., 2001

**Alkalinity measured as HCO_3*

Table 3.3: *Summary information of percentage of land cover in catchment for lakes cored as part of IN-SIGHT WP3. Land cover information is from the CORINE (1990 & 2000) databases and was provided by the EPA Ireland.*

Lake	Urban		Forestry		Pasture		Agriculture		Bogs		Other	
	1990	2000	1990	2000	1990	2000	1990	2000	1990	2000	1990	2000
Atedaun	0	0.26	1.01	0.80	40.02	38.40	9.90	11.34	3.92	3.07	45.14	46.13
Ballybeg	0	10.90	15.71	22.62	70.94	53.66	0	4.05	0	0	13.35	8.77
Crans	n/a	0	n/a	15	n/a	85	n/a	0	n/a	0	n/a	0
Egish	0	2.74	0	0	89.34	86.35	10.66	10.91	0	0	0	0
Inchiquin	0	0	6.84	5.63	4.57	5.10	2.73	2.64	77.79	82.71	8.07	3.92
Mullagh	0	0	0	0	97.80	95.70	0.33	4.30	0	0	1.87	0
Sillan	0	1.27	0	0	99.63	79.81	0.37	17.98	0	0	0	0.94

3.3 Laboratory analyses

3.3.1 Core extrusion and sediment analyses

Three cores of sediment were taken from the deep basin of each lake, using a gravity corer (a Renberg corer; HTH Teknik, Vårvågen 37, SE-951 49 Luleå) (Renberg, 1991), and were subsampled in the field immediately following collection. Sediment cores were subsampled at 0.5 cm intervals for the upper 5 cm, and at 1 cm intervals thereafter. Sediment core samples were bagged in zip-lock bags, labeled and transported in a cool box to the laboratories. Core 1 was sent to the University of Ulster, Coleraine (UUC) for lithostratigraphic and chemical analyses, Core 2 to Trinity College Dublin (TCD) for diatom and pollen analyses, and to the University of Limerick for cladocera analyses and Core 3 to University College Dublin for radiometric analyses (see Table 3.5).

3.3.2 Radiometric analyses

Cores for radiometric dating were sub-sampled at 1 cm intervals and prepared for radiometric analysis by gamma-spectrometry. A sample from the deepest part of the sequence (where $^{210}Pb_{excess}$ or ^{137}Cs will not have penetrated) was used to estimate background concentrations. Bulk (wet) density and porosity of the samples were used to aid application of models for reconstructing sedimentation history. Chronologies were constructed based on the history of isotope input to sediments from nuclear bomb test fallout, and from relative concentrations of ^{210}Pb (a naturally occurring isotope) and ^{137}Cs, ^{241}Am in the sequences. Six samples from each core were analysed in order to estimate accumulation rates.

Core chronologies were derived from comparison of ^{137}Cs, constant rate of supply (CRS) and constant initial concentration (CIC) lake models. The ^{137}Cs chronology was derived using three reference dates where possible (the sampling date (2004), the Chernobyl incident (1986) and maximum weapons fallout deposition (*c.* 1963)) and the cumulative dry deposition to account for sediment compaction. Different lake models used to allow for varying sediment accumulation rates, sediment compaction, dry mass and slumping or sediment mixing. Only one of the three cores collected was dated by ^{210}Pb and this chronology transferred to other longer cores using basal stratigraphic correlation of dry weight and organic matter content profiles and extrapolation of basal sediment accumulation rates (See Appendix 1).

3.3.3 Lithostratigraphic analyses

Density of wet sediment (g cm^{-3}) was determined from the final weight of extruded sediments of known volume (less the mean bag weight). Percentage water content (as dry weight (DW) density) was determined thermogravimetrically (105°C) on each whole extruded sediment slice (Hilton *et al.*, 1986). Percentage organic content (loss on ignition (LOI) technique; Dean, 1974) of the sediment from cores was measured at 1 cm intervals by thermogravimetry.

3.3.4 Sediment chemistry

Total sediment chemistry concentrations of phosphorus (P) iron (Fe), manganese (Mn), calcium (Ca), sodium (Na) and potassium (K) were assessed using ICP-OES following sequential acid digestion (Bock, 1979; Jordan *et al.*, 2001). Additionally, uranium (U), cadmium (Cd) and boron (B) were determined in Crans and Ballybeg. Sedimentary P was analysed to support the diatom ecological interpretation and the major cations were included to support interpretations of major phases of catchment inwash (Fe, Mn, Ca, Na, K) and internal cycling (Fe and Mn) (Mackereth, 1966; Engstrom and Wright, 1984). Uranium and Cd were included as proxies linked to signals of inorganic fertiliser inputs (Zielinski *et al.*, 1997) and B as a chemical proxy linked to sewage discharge inputs to freshwater (Neal *et al.*, 2005). These chemical parameters were determined on every 1 cm sediment samples except for U, B and Cd, which were determined on every other sample.

Table 3.4: *Bathymetry Data.*

Lake Name	No. measurements	Mean Depth (m)	Max Depth (m)	Area (ha)	Approx. lake volume (m3)
Atedaun	55	2.3	7	338.0	87
Ballybeg*	n/a	2.7	5-6	19.7	n/a
Crans	65	6.7	12	8.5	57
Egish	100	5.0	12	121.7	607
Inchiquin	162	12.2	31	115.7	1411
Mullagh	54	2.9	8	35.1	102
Sillan	99	6.1	13	172.0	1049

**data from Wemaere (2001)*

Table 3.5: *WP3 lake sediment core details.*

Lake Name	Wet Density, DW, LOI Sediment Chemistry	Diatoms, Pollen Cladocera	Radiometric Dating
	Core 1 (cm)	Core 2 (cm)	Core 3 (cm)
Atedaun	43	40	23
Ballybeg	31	30	29
Crans	40	39	31
Egish	33	31	31
Inchiquin	39	41	27
Mullagh	32	38	28
Sillan	39	38	29

In association with radiometrically dated chronologies, chemical accumulation rates were generated based on the product of chemical concentration (mg/g) and dry mass accumulation rate (DMAR g/cm^2/yr) and multiplying by ten to express in units of g/m^2/yr. Quality control was assured by repeat digests in each core and the use of a batch digest method that was validated using certified reference material.

3.3.5 Biological Fossil Groups

Analytical sample resolution for diatoms, pollen and cladocera were completed on the basis of a maximum of 10 samples per core for diatoms and 2 samples per core (core top and bottom) for pollen and cladocera.

3.3.5.1 Diatoms

Samples from each core were prepared and analysed for diatoms using standard methods (Battarbee *et al.*, 2001). In general, sediment core samples contained abundant, well-preserved diatom frustules. At least 300 valves were counted from each sample using an Olympus BX40 with a 100x oil immersion objective and phase contrast. The relative abundance of all species (including unidentified forms) was determined as the percentage of the total count. Principal floras used in the identification were (Krammer and Lange-Bertalot, 1986, 1988, 1991a, b).

All diatom taxa present in all seven cores were assigned to habitat groups using contemporary diatom data derived from literature sources (e.g. Van Dam *et al.*, 1994). Total diatom numbers were also expressed as diatom concentration (cells g^{-1}) and sediment accumulation rate was used to calculate diatom accumulation rates (cells cm^{-2} yr^{-1}).

The Shannon diversity index (H) was used to characterize species diversity in a community (Pielou, 1975). Shannon's index accounts for both abundance and evenness of the species present. The proportion of species i relative to the total number of species (p_i) is calculated, and then multiplied by the natural logarithm of this proportion ($\ln p_i$).

$$H = -\sum_{i=1}^{S} p_{\mathrm{i}} \ln p_{\mathrm{i}}$$

Taxonomic diversity (distinctness) was calculated estimate differences between species and functional variability among species in a community (Clarke & Warwick 1998) for a more direct comparison with nutrient enrichment. This index emphasizes the average taxonomic relatedness between species in a community. Average taxonomic distinctness is defined as:

$$\Delta^{+} = [\Sigma\Sigma_{i>j}\omega_{ij}]/[s(s-1)/2]$$

where s is the number of species present, the double summation is over $\{i = 1, \ldots s\ ; j = 1, \ldots s$, such that $i < j\}$, and ij, is the 'distinctness weight'.

3.3.5.2 Cladocera

Top (sediment surface) and bottom (reference) samples from each sediment core were prepared and analysed for cladocera using a slightly modified version of the standard method described by Frey (1986). Wet sub-samples of approximately 5 g were deflocculated in 50 ml 10% potassium hydroxide (KOH) at 65-70°C. Five ml of 10% HCL was added to remove calcareous sediments. The samples were then filtered through a 53 µm mesh screen to retain exoskeletal fragments. Remains were preserved using a few drops of 100% formaldehyde. Quantitative slides were prepared by transferring volumetric aliquot (0.05 ml) of the well-shaken concentrate to a microscope slide through a precision pipette. Glycerin jelly was mixed with the sample residue and Gram's safranine solution was used to stain and mark the fragments. Cladoceran remains were identified and enumerated at x250 to x400 magnification on a Meijii 2100 compound microscope with phase contrast. Taxonomy of the remains followed Frey (1959, 1960, 1962a, 1962b, 1964), Goulden & Frey (1963) and Alonso (1996). Counts of remains were adjusted to represent individuals as one individual cladocera has two shells, one headshield and one postabdomen. As well as counting the often more abundant pelagic specimens at least 70-100 benthic (chydorid) individuals were counted for each sample. These hard-shelled specimens are considered more sensitive to nutrient levels than their planktonic counterparts. In most cases 2-6 slides of sediments were counted to collect around 100 chydorid individuals, except for the surface sediments of Crans, Inchiquin and Egish which required 32, 24 and 17 slides respectively due to the lower abundance found at these sites. Cladoceran counts for all samples are listed in Appendix 2. The Shannon diversity index (H) was also used to characterize chydorid species diversity

3.3.5.3 Pollen

The concentration of pollen and spores in sediment core samples of 1 cm^3 followed the standard laboratory protocol described in Bennett & Willis (2001). One tablet of *Lycopodium* spores was added to each sample, prior to preparation (each tablet contains *c.* 11,350 spores), in order to facilitate expression of the counts in absolute form. Pollen and spores were enumerated using a light microscope at x400 and x1000 (oil immersion) magnifications and type material belonging to the School of Natural Sciences, Trinity College, University of Dublin. Pollen and spore data are available for a total of 15 sediment core samples (Appendix 3). Preservation was generally adequate for all samples. Problems in extracting sufficient quantities of pollen and spores from core top samples were experienced on occasion thus the uppermost samples analysed for their pollen and spore content in the sediment cores from Crans, Egish, Mullagh and Sillan were, respectively, 10-11, 5-6, 10-11 and 15-16 cm.

The raw pollen and spore counts were converted to both percent and absolute form. Two sums were used in percent calculations: total, which excludes damaged and partially concealed grains but which includes unknowns, and tree, which comprises pollen from arboreal taxa (including *Pinus*-type [comprising pollen from *Pinus* and presumably also from other conifers, such as *Picea,* producing morphologically similar pollen]). Estimated rates of sediment influx and volumes of sediment sample analysed were used to convert raw pollen and spore counts into absolute data. For all but one site, absolute data are expressed as number of grains cm^{-3} year^{-1}. As the sediment influx data for Atedaun are relatively poor, absolute counts from this site are expressed in terms of number of grains cm^{-3}.

3.4 Data analyses

Differences in water quality and biological community composition between pre-anthropogenic impact and impact conditions are assessed using techniques of multivariate data analysis; (i) stratigraphic plots; (ii) ordination techniques (DCA); (iii) diatom inferred chemistry, and; (iv) analogue matching using the squared chord distance as a dissimilarity meassure (Overpeck *et al.*, 1985). Diatom and cladocera data were expressed as precentage relative abundances in all analyses.

3.4.1 Stratigraphy

Summary biostratigraphic diagrams of the diatom and cladocera changes (showing only selected taxa) were produced for individual cores using C^2 (Juggins, 2003). Only one core for each site was dated by radiometric analysis and this chronology was transferred and extrapolated to the other lake cores by stratigraphic correlation of basal dry weights and organic matter and extrapolation of sediment accumulation rates.

3.4.2 Ordination

Detrended correspondence analysis (DCA) (Hill & Gauch, 1980) was performed using CANOCO version 4.5 (ter Braak & Šmilauer, 2002) to assess the direction and magnitude of floristic change at each site. Analysis was carried out on square root transformed diatom data and only taxa present with a relatuve abundance of >2% in at least two samples were included. Analyses were carried out on surface sediment and downcore data of the study lakes, and a subset of INSIGHT WP2 samples containing surface sediment samples of medium and high alkalinity lakes.

3.4.3 Diatom transfer function

In order to quantify the changes in the sediment core diatom assemblages was made using a diatom inferred-total phosphorous (DI-TP) transfer function. The development of weighted averaging (WA) regression and calibration statistical techniques (ter Braak & van Dam, 1989) has enabled quantitative estimates of past water chemistry changes from diatom sedimentary records. Diatom-inferred total phosphorus (DI-TP) is an estimate of epilimnetic phosphorus concentration at the time the diatoms in an assemblage were living.

The diatom-TP transfer function was derived from an Irish Ecoregion training set (Leira & Chen, unpublished) of 73 lakes (range in measured TP = 0-675 µg TP l^{-1}, mean = 33 µg TP l^{-1}, median = 10 µg TP l^{-1}) using the standard numerical technique of weighted averaging (WA) (Birks *et al.*, 1990a&b) and the computer software package C2 version 4 (Juggins, 2003). The best performing WA model used has two components with an r^2_{jack} of 0.55 and RMSEP of 0.31 µg log TP l^{-1}, and a maximum bias of 1.1 µg log TP l^{-1}. Diatom transfer functions were applied to down-core diatom data following taxonomic harmonisation between the surface sediment training sets and the fossil data. All reconstructions were performed using C2 (Juggins, 2003).

3.4.4 Modern Analogue Technique (MAT)

The Modern Analogue Technique (MAT) (Juggins, 1994) was devised to examine the floristic similarities between modern diatom assemblages (e.g. Flower *et al.*, 1997) but it is also useful for comparison of surface sediment (modern) and fossil or pre-disturbance (reference) assemblages. This space-time substitution approach can be adapted to incorporate information on contemporary water quality. The modern analogue technique requires modern and fossil data-sets resulting from surface sediment and sediment core analyses. The degree of similarity (or dissimilarity) in the diatom communities between each reference sample and every sample in the modern analogue training set can then be calculated using the squared chord distance (SCD) (Overpeck *et al.*, 1985; Gavin *et al.*, 2003; Wahl, 2004):

$$d^2_{ij} = \Sigma\, [(Y_{ik\,k})^{0.5} - (Y_{jk})^{0.5}],$$

where the SCD between the *i*th and *j*th samples (d^2_{ij}) is the sum of the squared differences between the square root of the proportion of taxon *k* in samples *i* and *j*. The SCD attempts to emphasise the signal or pattern in the data at the expense of the noise or random variation in species abundances. Similarity (SCD) scores range from 0 to 2, with 0 indicating that two samples have exactly the same composition, and 2 that their compositions are entirely different. The degree of floristic difference can be determined at the 1st, 2.5th, 5th and 10th percentile depending on the degree of rigour required by the study. Random permutations generated the following percentile scores for the CRL lakes in WP2 - 1% = 0.13; 2% = 0.19; 5% = 0.49; 10% = 0.71. Generally, a SCD score less than the 5th percentile indicates that the difference between two samples is statistically insignificant (Simpson *et al*., 2005).

4. Results

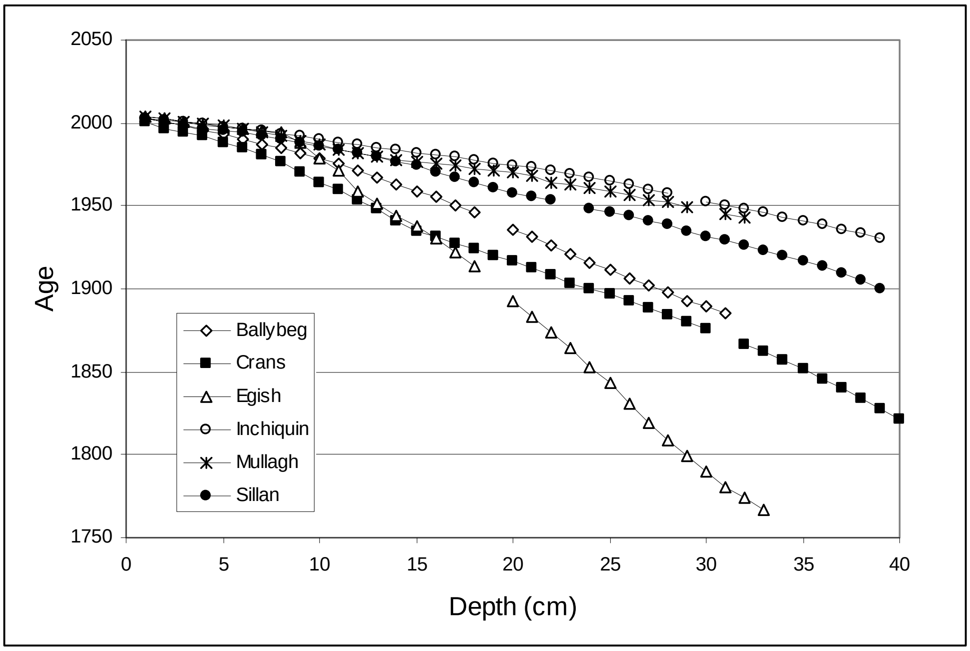
4.1 Radiometric dating

Summary chronologies and estimated sediment accumulation rates for all WP3 cores, based on radiometric dating methods are outlined in Table 4.1 and Figure 4.1. In general, there was good agreement between results of the CRS, CIS and ^{137}Cs-based analyses, with estimated rates of sediment accumulation varying from 0.017 ± 0.004 g cm^{-2} yr^{-1} (Egish) to 0.12 ± 0.02 g cm^{-2} yr^{-1} (Inchiquin). Estimated ages of core bottom samples range from the late 18th century (Egish) to the late 20th century (Atedaun) The core chronology, lithostratigraphy, sediment chemistry and biological profile are reported separately for each lake in the following section and this is followed by a synthesis and discussion of the results.

Table 4.1: *^{210}Pb$_{excess}$ supply rates, ^{137}Cs inventories and estimated sediment accumulation rates for IN-SIGHT WP3 cores.*

Lake	Length of core (cm)	^{210}Pb$_{excess}$ (Bq m^{-2} y^{-1})	^{137}Cs (Bq m^{-2})	Estimated sediment accumulation rate g cm^{-2} yr^{-1}	Estimated sediment accumulation rate cm yr^{-1}	Estimated age of core base (Core 3)	Extrapolated dates for base of adjacent deeper cores (Cores 1 & 2)
Atedaun	23	>83	>5200	n/a	~0.45	<1954	n/a
Ballybeg	29	90	784	0.026	0.28	1900	1885
Crans	31	51	3500	0.028	0.20	1850	1822
Egish	31	66	1400	0.017	0.33	1911	1767
Inchiquin	27	320	2960	0.120	0.60	1950	1931
Mullagh	27	90	1600	0.040	0.50	>1950	n/a
Sillan	23	120	2600	0.053	0.46	1954	1900

Figure 4.1: *Age-depth profiles for six WP3 sediment cores. Gaps in the profiles represent the point where extrapolation was employed for proximate longer cores.*



4.2 Atedaun

Lough Atedaun (R297885) (Figure 4.2) is a 38 ha lake located in the Fergus river catchment in County Clare. Atedaun is classified as an EPA typology class 9 lake and has a high alkalinity (135 mg l^{-1} $CaCO_3$), is the shallowest of the WP3 lakes (mean depth 1.4 m) and is small in size (< 50 ha) (Table 3.1 & 3.2). The catchment bedrock is mainly composed of carboniferous limestone. The karstic nature of the bedrock facilitates groundwater connections to the surface drainage network and greatly influences the lake hydrology and water chemistry. A very fast flushing rate and short water retention time of less than one day was calculated for Atedaun based on net precipitation, catchment area and lake size (Wemaere, 2005). A wastewater treatment plant, catering for a population equivalent of 400, discharges primary treated water directly to the lake. This discharge combined with pressures from a large resident swan population has resulted in nutrient enrichment of the lake. Atedaun had a measured TP of 37 µg l^{-1} in 2000 and is classed as mesotrophic/eutrophic (Wemaere, 2001).

4.2.1 Core chronology

An irregular ^{210}Pb concentration profile was measured for the Atedaun sediment core thus precluding use of the CRS and CIC lake models to estimate chronology. The ^{137}Cs profile shows no evidence of peaks or fall-offs in activity also precluding chronology estimation. The latter, however, suggests that the base of the core (at 23 cm) is younger than the onset of weapons fallout (1954), which translates into a sedimentation rate of at least 0.45 cm yr^{-1} (Table 4.1 and Appendix 1).

4.2.2 Lithostratigraphy

Description of the composition and physical properties of cores of lake sediment provide information the origin and rate of deposition of sediments. The results of sediment density (wet density g/cm3), percentage water content (measured as % dry weight density) and percentage organic content determined via loss-on-ignition analysis for Atedaun are plotted against depth of sediment in Figure 4.3. Sample density varied from 1.25 g/cm^3 at the core base to 0.5 g/cm^3 at the surface. The dry weight data exhibit relatively similar profiles for all lake sediment cores, with higher dry weight densities towards the base of the cores reflecting compaction and decreasing toward to the surface sediments. Increasing up-core organic content was found at Atedaun ranging from lows of 15% LOI, to highs of 20% with a sharp peak evident at *c*. 6 cm.

4.2.3 Sediment Chemistry

The chemistry concentration profiles for Atedaun could not be used to estimate accumulation rates owing to the poorly resolved ^{210}Pb dating profile. The main features in the concentration profiles were noted towards the top of the core at ~5-10 cm (Figure 4.4). Here a decrease in the TP profile was matched with similar decreases in Fe, Na and K, hinting at a change in sediment type. The concurrent increases in Mn at the same depth are matched by a peak in the LOI profile and a decrease in dry weight (Figure 4.3). The Mn changes could be interpreted as internal mobilisation and a build-up at sediment depths <15 cm (internal diagenesis). While this is likely to be occurring to some extent, it is also likely that the changes across the chemical and physical parameters are due to local exogenic sediment changes. The TP concentration profile appears to show variation associated with these other chemical changes.

4.2.4 Biological Fossils

Diatoms

Diatom preservation was good throughout the core. A total of 182 taxa was observed, 27 of which were present with a relative abundance of >2% (Figure 4.4a). A full list of diatom names and their taxon authority is presented in Appendix 2. Diatom species were assigned to habitat (benthic, epiphytic, aerophilic and planktonic) groups using contemporary data derived from different literature studies, but mainly Van Dam *et al.*, (1994) (Figure 4.4a). There has been little change in the diatom species composition over the period represented by the record. Small, non-planktonic taxa, especially *Cocconeis placentula* var. *placentula* and *Amphora pediculus*, taxa generally found in eutrophic waters, have dominated the assemblages. *Achnanthidium* *minutissimum*, a non-planktonic species found in a wide range of waters from low to high nutrient content, was also frequent throughout the core. The presence of non-planktonic taxa reflects the shallow nature of the lake and the high proportion of ephiphytic taxa suggests the presence of macrophytes. The diatom inferred-total phosphorous (DI-TP) model results indicate that Atedaun has been a mesotrophic lake for the whole period covered by the diatom record with signs of recent slight enrichment. The values produced by the model were 16 μg TP l^{-1} for the base of the core (40 cm) increasing to 40 μg TP l^{-1} in the top sample.

Cladocera

Chydorid taxa, which prefer the littoral areas of lakes, were dominant among the cladoceran remains for both surface and bottom sediment samples in Atedaun (Figure 4.6). A full list of the species counts is presented in Appendix 3. Of the 18 species and 1 species group (*Alona guttata/rectangular*) of chydorids recorded, 10 occurred with a relative abundance of greater than 5% at least once. The dominant taxa *Alonella exigua* and *Graptoleberis testudinaria* are typically found in mesotrophic lakes with abundant macropyhtes. *Chydorus sphaericus* can tolerate a wide range of conditions but shows a preference for eutrophic lakes. The increase of *Chydorus sphaericus*, together with the decrease of *Alonella exigua* and *Graptoleberis testudinaria* between the reference and surface samples, may indicate nutrient enrichment in association with a decrease in macrophyte cover. A reduction of macrophyte cover may support less plant-associated chydorids. Planktonic cladocerans were less abundant than chydorids, however, they show an increase in the surface sample.

Pollen

Pollen data summaries are illustrated in Appendix 4. The abundances of *Corylus* and *Pinus*-type pollen increased between the core bottom and top samples (although a proportion of the *Pinus*-type pollen is likely to be of long distance dispersal), while the proportion of pollen from Poaceae, *Quercus* and *Ulmus*, declined. Pollen spectra indicate an expansion of open-canopy hazel (*Corylus*) woodland in the catchment, possibly together with an increased prominence of conifers, apparently at the expense of closed-canopy oak-elm (*Quercus*-*Ulmus*) woodland. A decline in abundance of Poaceae pollen may also represent increased grazing pressure (see Appendix 4).

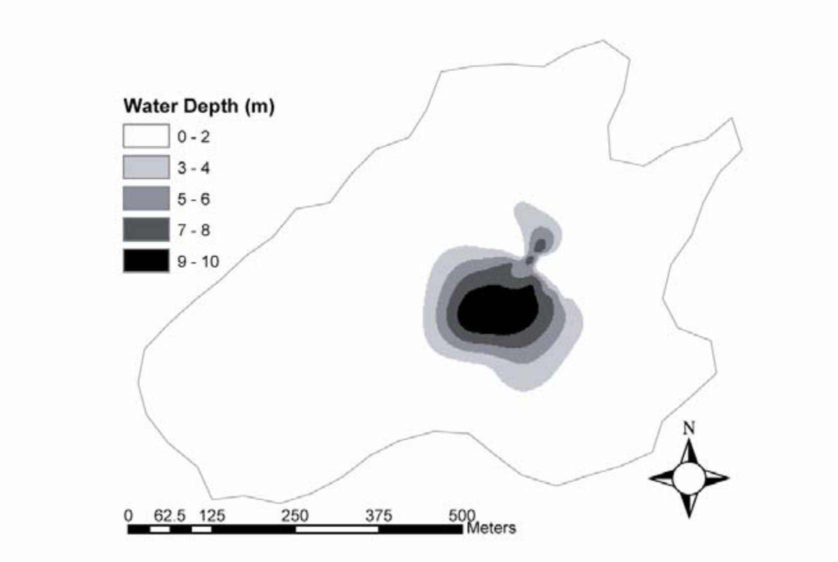


Figure 4.2: *Lake Bathymetry Lough Atedaun*

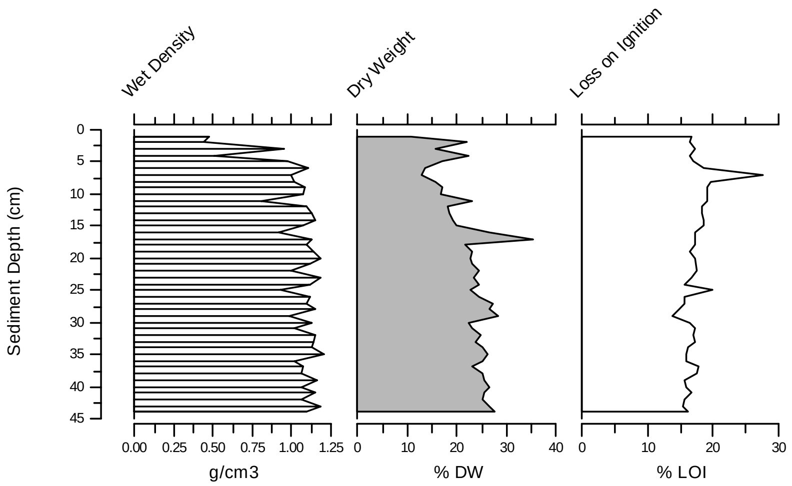


Figure 4.3: *Atedaun - Density of wet sediment (g/cm3), Water content (as % DW) and organic content as loss on ignition (%LOI).*

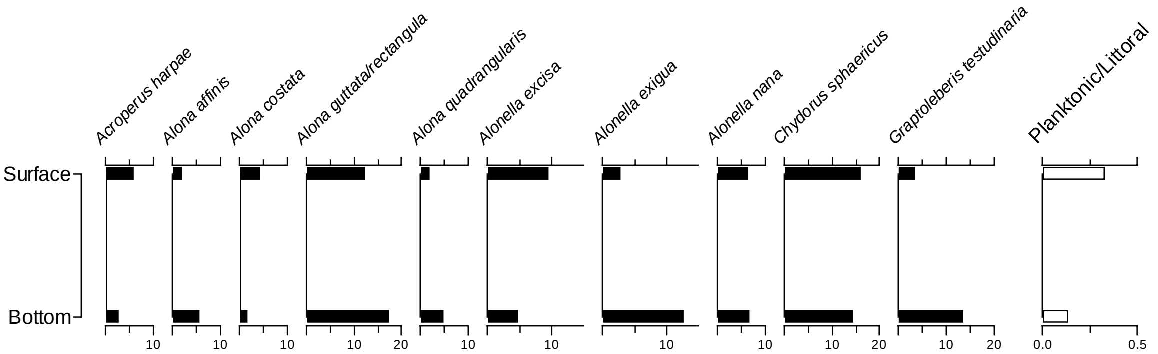


Figure 4.6: *Relative abundance of selected chydorid species in bottom (reference) and surface (c. 2004) sediment samples for Atedaun.*

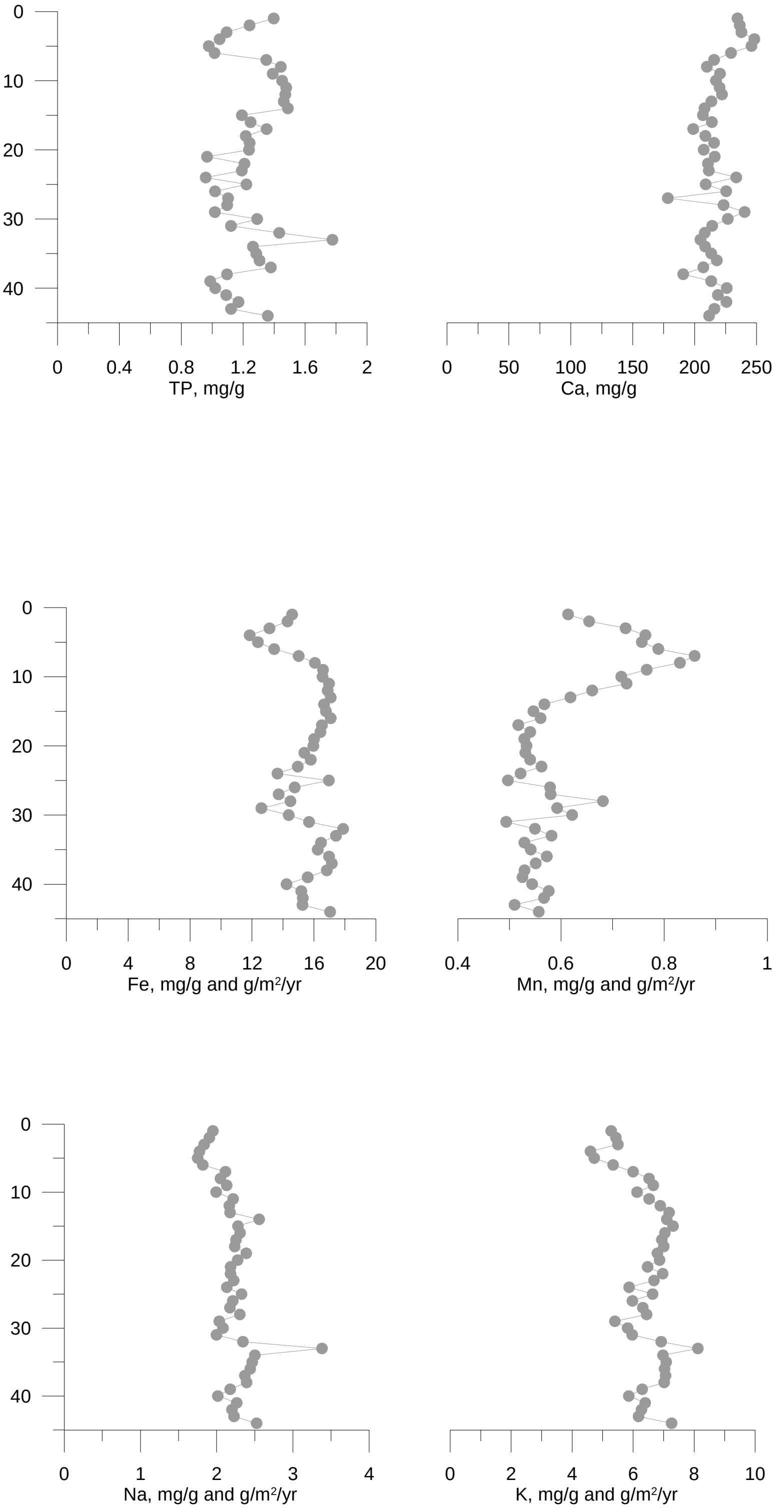


Figure 4.4. *Sedimentary chemistry profiles (grey circles) of P, Ca, Fe, Mn, Na and K from Atedaun Lough. In the top left, the white circles are DI-TP concentrations. Diatom-inferred TP (DI-TP) is presented with chemistry profiles to aid interpretation. Data are plotted on a depth (cm) scale.*

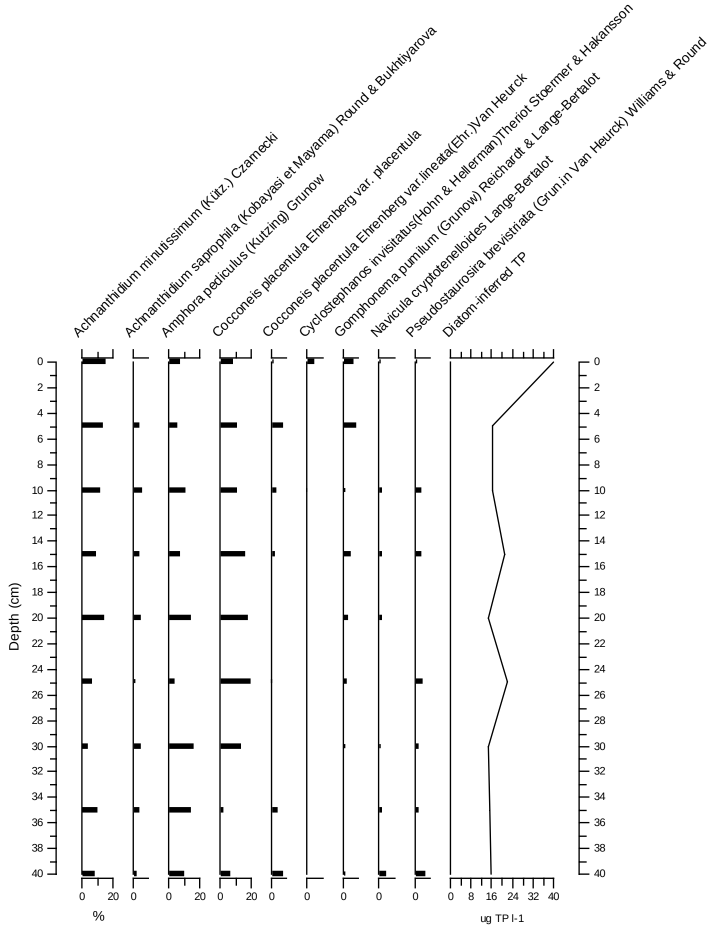


Figure 4.5a: *Diatom stratigraphy (for selected taxa) and diatom-inferred TP from Lough Atedaun. Data are plotted on a depth scale*

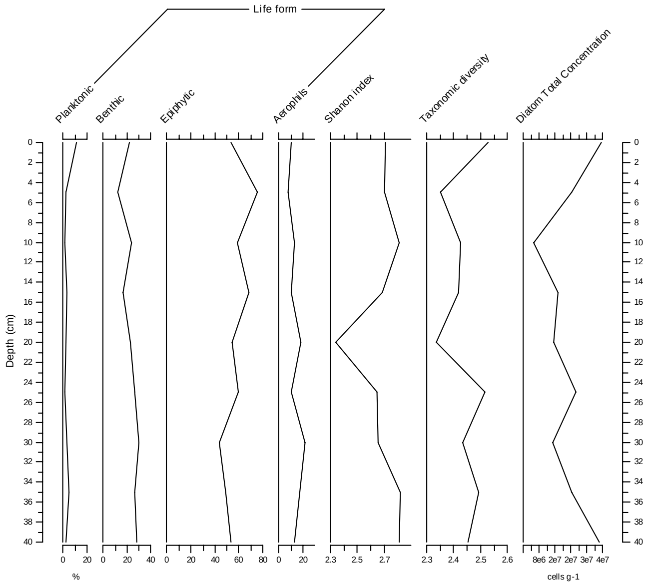


Figure 4.5b: *Life form, diversity, concentration and accumulation rate of diatoms from Atedaun Lough. Data are plotted on a depth scale.*

4.3 Ballybeg

Ballybeg lake (R331738) (Figure 4.7) is in County Clare and is located adjacent to Ennis town. Ballybeg is in EPA lake typology class 9, has high alkalinity (128 mg l^{-1} $CaCO_3$), is shallow (mean depth 2.7 m) and has a surface area of 19.7 ha (Table 3.1 & 3.2). Land cover information from CORINE indicated substantial changes in the catchment between 1990 and 2000 with increased urbanisation and decreased pasture (Table 3.3). This is reflected in high population densities (human and cattle) per hectare relative to the other WP3 study sites. Urbanisation and associated sewerage has impacted the Ballybeg catchment over the last two decades, with several houses now located close to the lakeshore. The Ballybeg catchment contains a substantial proportion of broadleaf forestry (*c.* 25%). Summer stratification, oxygen depletion of the hypolimnion and algal blooms has been documented (Wemaere, 2005). Ballybeg had a measured TP of 75 µg l^{-1} in 2000 and is classed as eutrophic/hypertrophic (Wemaere, 2001).

4.31.1 Chronology

The Ballybeg core shows a very clear exponential decline in $^{210}Pb_{excess}$ and an accumulation rate estimate of 0.026 ± 0.002 g cm^{-2} yr^{-1} (0.28 cm yr^{-1}) (Table 4.1 and Appendix 1). The ^{137}Cs data fit well with this. Close agreement was found in the chronologies estimated from the different lake models. Using a constant sedimentation accumulation rate, as derived from the CRS model, the base of the core at 29 cm, can be dated to 1900 (Table 4.1). A longer core (31 cm) collected adjacent to the radiometrically data core is estimated to extend to 1885 AD following lithostratigraphic correlation.

4.3.2 Lithostratigraphy

A highly variable %LOI profile is evident in the sediment core from Ballybeg. High levels of organic content (*c.* 40% LOI) are present at the base and surface of the core with peaks and troughs evident up through the sediment profile conincident with high levels of %DW (Figure 4.8).

4.3.3 Sediment Chemistry

Sedimentary concentration and accumulation rate profiles for Ballybeg are shown in Figure 4.9. The main feature in the concentration profile is the increase in TP concentration from *c.* 1960 (14 cm) that is matched by a similar increase in Fe, Mn, Na and K. These increases are also matched with an increase LOI (Figure 4.8). Similarly, U and Cd indicate slight increases from approximately 1960. In the absence of independent catchment cation indicators, the TP, Mn and Fe profiles could be interpreted as a process of concurrent solubilisation in deeper anoxic sediments and build-up towards the sediment-water interface. Similar to Atedaun, this process cannot be discounted although it also appears likely that changes in sediment source and/or type has occurred post 1960 and this has changed the trophic status of the lake from meso-trophic to hypertrophic from *c.* 1975. Boron concentration does not increase at the same rate as U, Na and K despite the lake receiving wastewater effluent. In this lake at least, B appears not to be a reliable sewage effluent indicator.

4.3.4 Biological Fossils

Diatoms

Diatom preservation was also good in the core from Ballybeg. A total of 102 taxa were observed in the seven samples analysed, 19 of which were present with a relative abundance of >2% (Figure 4.10 a&b). The record shows a shift from an oligo-mesotrophic benthic dominated assemblage (e.g. *Pseudostaurosira brevistriata*, *Staurosira construens*, *Gomphonema pumilum*, *Gomphonema lateripunctatum*) to an assemblage comprised of taxa more typically found in meso-eutrophic waters (*Stephanodiscus parvus*, *Stephanodiscus hantzschii*, *Asterionella formosa* and *Aulacoseira subarctica*). These changes in the diatom record provide evidence of nutrient enrichment. The diatom-inferred TP value for the bottom (reference *c.* 1890) samples was ~ 16 µg l^{-1} compared to a value for the surface sample of ~ 112 µg l^{-1}. The TP reconstruction of Ballybeg indicates that the lake was mesotrophic until *c.* 1980 (10 cm). Concentrations increased to 35 µg

TP l^{-1} by *c.* 1995 (5 cm) and then rose significantly and rapidly to *c.* 112 µg TP l^{-1} into the hypertrophic range over the last few years. This increase in DI-TP concentration is related to the high percentage of *Stephanodiscus hantzschii* and *Stephanodiscus parvus*, two small, centric planktonic diatoms commonly observed in highly enriched lakes.

Cladocera

Seven of the observed 18 chydorid species and species groups occurred in abundances greater than 5% in at least one sample (see Figure 4.11). *Chydorus sphaericus* was dominant in both top and bottom samples. The main changes of note in the Ballybeg samples are an increase in *Chydorus sphaericus* from 30% to 40% in the surface sample relative to the reference sample, and a concomitant decrease in mesotrophic species *Acroperus harpae* from 13% to 2%. This may reflect an increase in nutrient availability. No major shifts were obvious in other chydorid species. Planktonic cladocera were more abundant than littoral chydorids in both the top and bottom samples (see Appendix 3).

Pollen

A decline in pollen from deciduous woodland taxa (*Alnus* [alder], *Corylus, Fagus* [beech], *Quercus, Salix* [willow] and *Ulmus*) is concomitant with a substantial increase in the abundance of *Pinus*-type pollen. Of the non-arboreal types recorded, levels of Poaceae pollen show a clear fall. A decrease in the extent of deciduous woodland cover, possibly with a concomitant increase in the presence of conifers in the catchment is inferred. Declines in abundance of Poaceae pollen may represent increased grazing pressure or increased urbanisation and declines in pasture (Appendix 4).

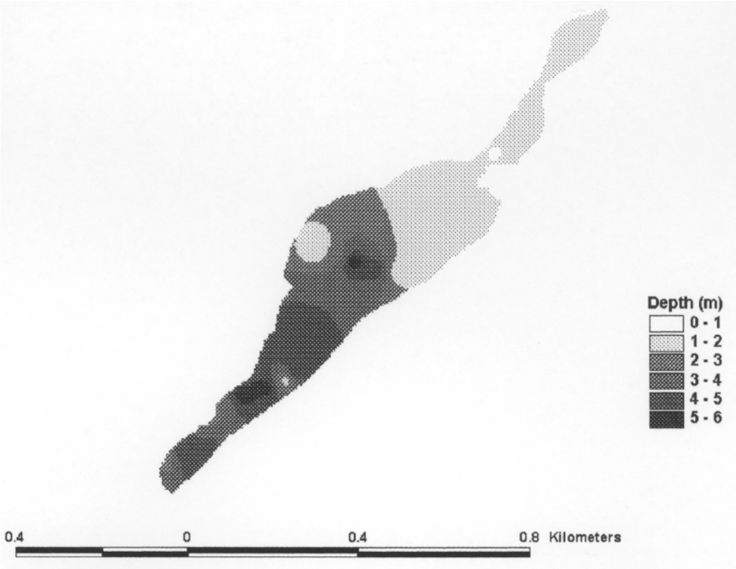


Figure 4.7: *Lake Bathymetry Ballybeg (source Wemaere, 2001)*

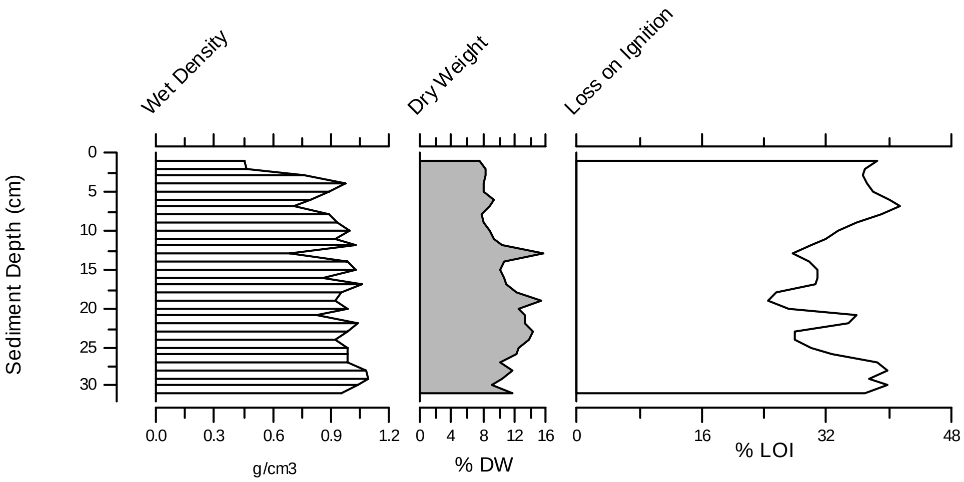


Figure 4.8: *Ballybeg - Density of wet sediment (g/cm3), Water content (as % DW) and organic content as loss on ignition (%LOI).*

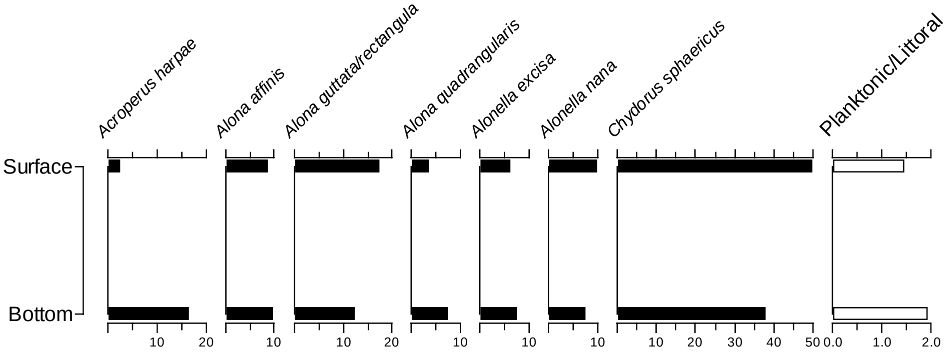


Figure 4.11: *Selected chydorid species in bottom (reference) and surface (c. 2004) sediment samples for Ballybeg.*

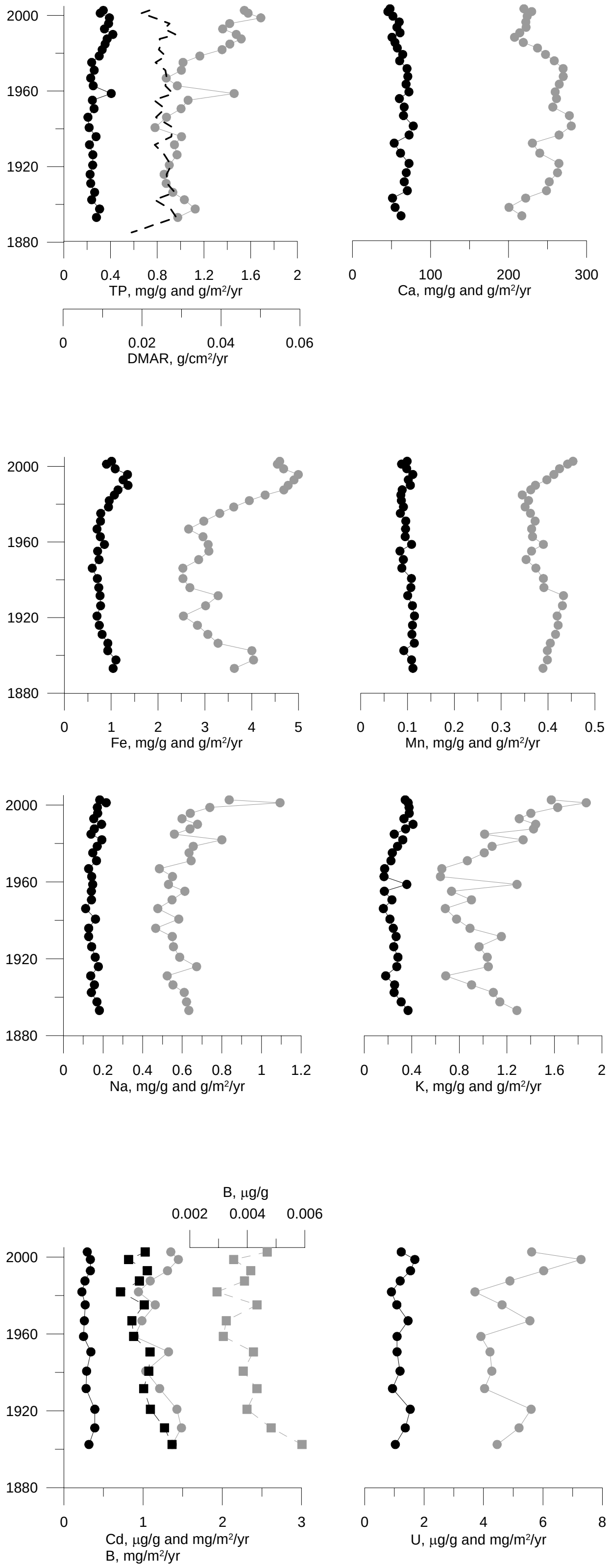


Figure 4.9. *Sedimentary chemistry profiles of P, Ca, Fe, Mn, Na, K, Cd, B and U from Ballybeg Lough. Grey circles (and grey squares - B only) are chemical concentrations; black circles (and black squares - B only) are chemical accumulation rates. In the top left, the dashed line is DMAR; and the white circles are DI-TP concentrations. Data are plotted on an age scale.*

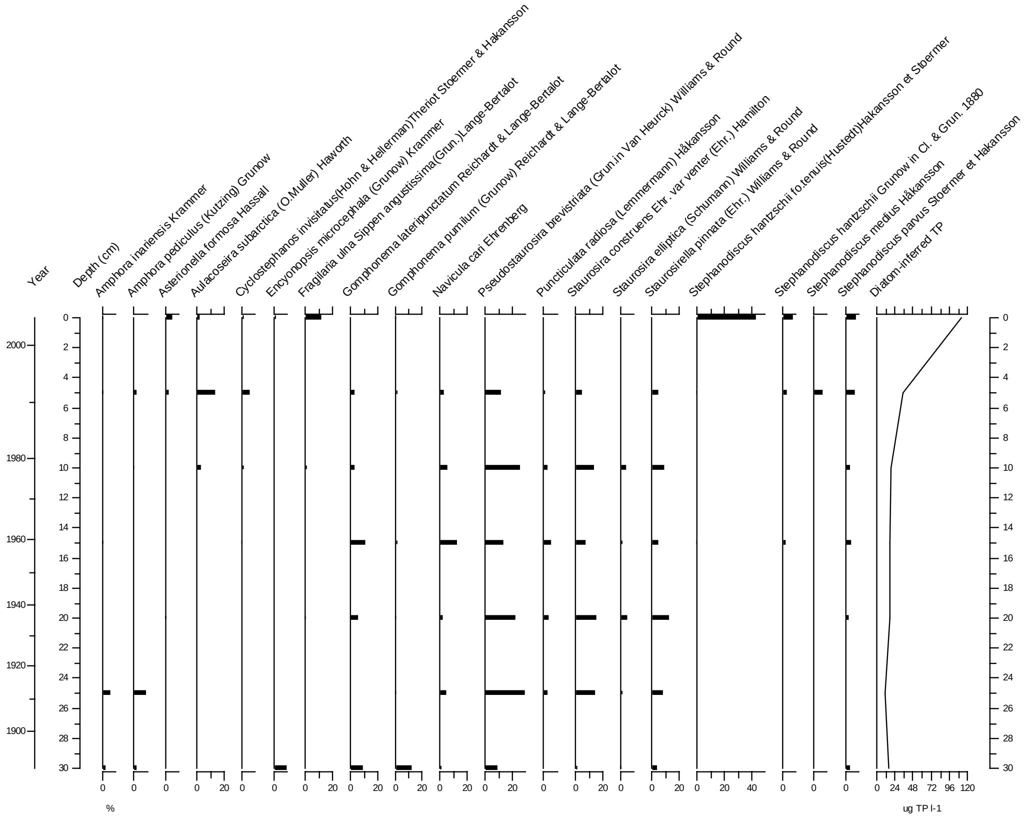


Figure 4.10a: *Summary plots of the common diatom taxa in Ballybeg and diatom-inferred TP. Data are plotted on a depth and age scale.*

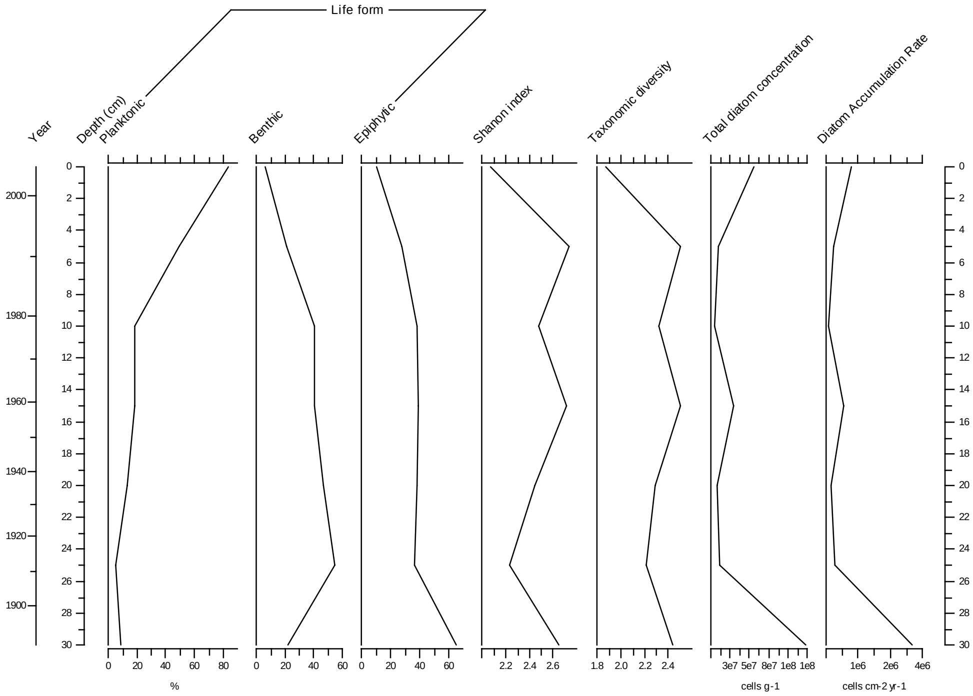


Figure 4.10b: *Life form, diversity, concentration and accumulation rate of diatoms from Ballybeg Lough. Data are plotted on a depth and age scale.*

4.4 Crans Lough

Crans Lough (H711568) is in County Tyrone. The lake bathymetry is shown in Figure 4.12. Crans Lough is classified as EPA typology class 7 with moderate alkalinity, deep waters and small lake size. Average water depth is 6.7 m and the lake area is approximately 8.5 ha and is the smallest of the WP3 lakes (Tables 3.1 & 3.2). Alkalinity levels of 2.45 mg l^{-1} HCO_3 and 89 µg l^{-1} TP were recorded for Crans in 1989/1990 (Gibson, 1991). CORINE data suggest that the catchment landuse is 100% pasture however Landcover 2000 data give a more detailed breakdown including 60% improved grass, 20% calcareous grassland, 5% neutral grass and 15% broadleaf woodland. The catchment for this lake was included in a major arterial drainage development scheme constructed in the 1980s (Anon, 1997).

4.4.1 Chronology

The 31 cm depth core from Crans Lough is estimated to have relatively uniform sediment accumulation 0.028 ± 0.007 g cm^{-2} yr^{-1} (0.20 cm yr^{-1}) over the past 50-60 years. Well-resolved peaks of ^{137}Cs are evident at 6.5 and 14.5 cm depth. Good agreement was found between the three lake models following adjustment to the CRS to correct for errors in measured and interpolated radionuclide concentrations. When these models are extrapolated to the base of the core this suggests that the 31 cm of sediment has accumulated over the past 150 years. Correlation and extrapolation gives an adjacent core basal (and thus reference) date of 1820 AD (Table 4.1).

4.4.2 Lithostratigraphy

The wet density profile for Crans Lough is relatively uniform whereas declines in %DW and increases in %LOI are evident at the base of the core (*c.* early-mid-1800s) (Figure 4.13). A more stable profile is evident above *c.* 25 cm.

4.4.3 Sediment Chemistry

The chemical and accumulation rate profiles for Crans Lough are shown in Figure 4.14. The DMAR indicates a largely decreasing input of sediment that stabilises to approximately 0.025g cm^{-2} yr^{-1} post-1900. The largest changes are at the base of the core (during the dated period) and show rapid increases in TP, Ca and Mn concurrent with lithostratigraphic changes (Figure 4.13). These are mirrored by rapid decreases in Na, K, U and Cd (B below the limits of detection). Notwithstanding the link between the Mn profile with the P profile as might be anticipated with solubilisation, mobilisation and precipitation (internal diagenesis), it seems that a more plausible interpretation is one of changes in sediment type/source, i.e. erosive events from different parts and strata of the catchment.

4.4.4 Biological Fossils

Diatoms

A total of 95 taxa were observed in the 8 samples analysed, 11 of which were present with a relative abundance of >2% (Figure 15a&b) All samples show a similar assemblage with a plankton dominated flora comprised of taxa associated with meso-eutrophic waters, such as *Aulacoseira subarctica*, *Aulacoseira ambigua*, *Asterionella formosa* and a variety of small *Stephanodiscus* spp. typical of very eutrophic conditions. The basal/reference sample (*c.* 1825) comprised a mixed assemblage with abundant non-planktonic taxa (~ 25%) and planktonic diatoms including *Aulacoseira subarctica* and *A. ambigua*. The diatom data indicate that the lake has always supported a planktonic diatom community since at least ~ 1825 AD, but the planktonic forms have expanded at the expense of epiphyte and benthic taxa. The DI-TP results show that Crans has always had high TP concentrations during the period covered by the diatom profile. The lowest DI-TP of 19 µg l^{-1} recorded in Crans sediments was at the base of the core (40 cm), and it appears that the sudden changes in sediment type, including mass chemical input changes, transformed the status of this lake from mesotrophic to hypertrophic during the late-1800s with concentrations always in excess of 100 µg TP l^{-1}. The model infers that TP concentrations remained high through to the mid-1900s then declined slightly by the 1970s. DI-TP appears to increase again in the 1980s and continued to do so to the present day.

Cladocera

The most obvious characteristic of the cladoceran assemblages in the sediment core from Crans is the dominance of the planktonic community in the surface sample compared to the bottom sample (see Figure 4.16). The increase of meso-eutrophic *Chydorus sphaericus* and the decrease of mesotrophic *Alonella nana* between reference and surface samples reflect a possible enrichment. However, very low abundance of chydorids in the surface sample may obscure the comparison with the chydorid assemblage in the reference sample. The dominance of planktonic taxa (*Daphnia* and *Bosmina*) in the surface sample may indicate a shift away from littoral species coincident with a decrease in suitable littoral habitat (Appendix 3).

Pollen

Declines in pollen from deciduous woodland taxa (*Betula* [birch], *Corylus* and *Fagus*) partially mask an increase in pollen from *Alnus, Fraxinus* [ash], *Quercus* and *Salix*. Levels of Poaceae pollen show a significant increase (>50% increase in abundance). Overall the extent of deciduous woodland declined, while cover of grassland increased over the *c.* 180 years represented by the sediment core (Appendix 4).

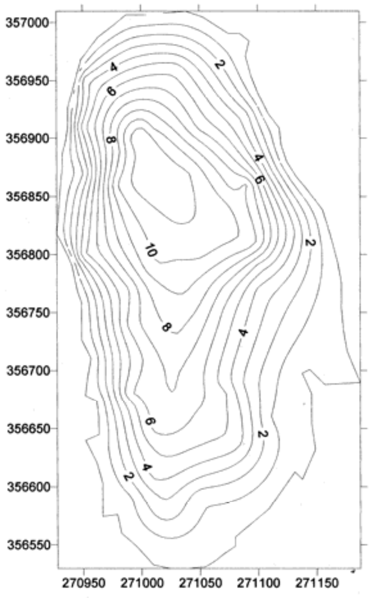


Figure 4.12: *Lake Bathymetry Crans Lough.*

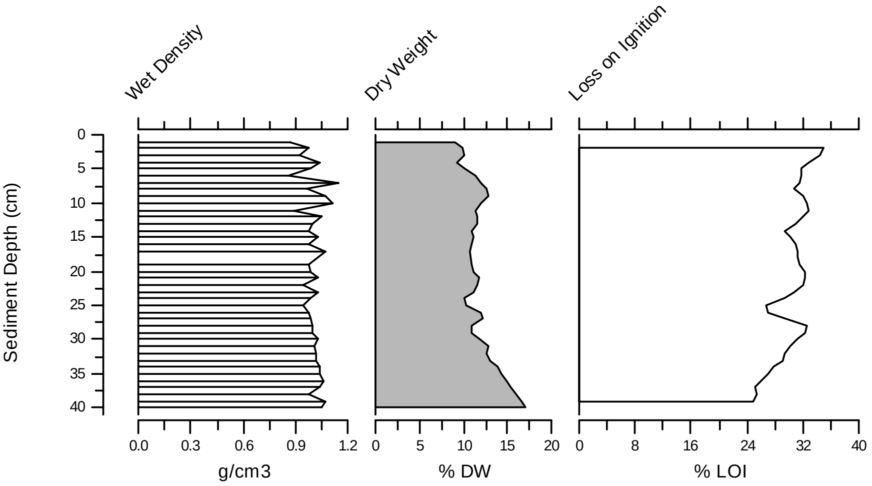


Figure 4.13: *Crans - Density of wet sediment (g/cm3), Water content (as % DW) and organic content as loss on ignition (%LOI).*

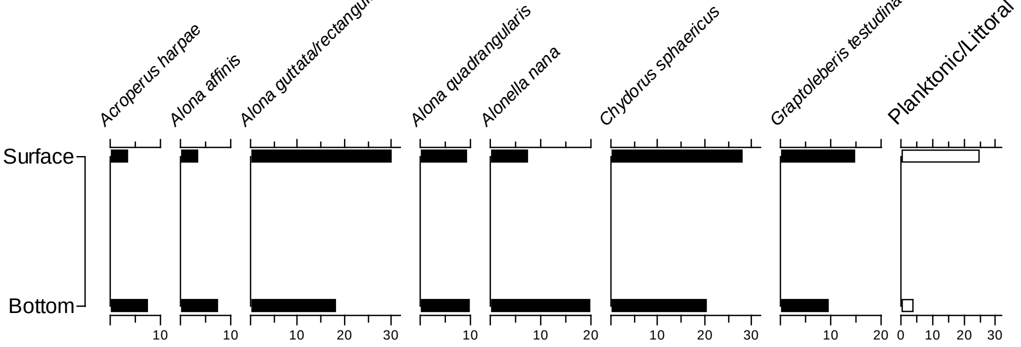


Figure 4.16*: Relative abundance of selected chydorid species in bottom (reference) and surface (c. 2004) sediment samples for Crans.*

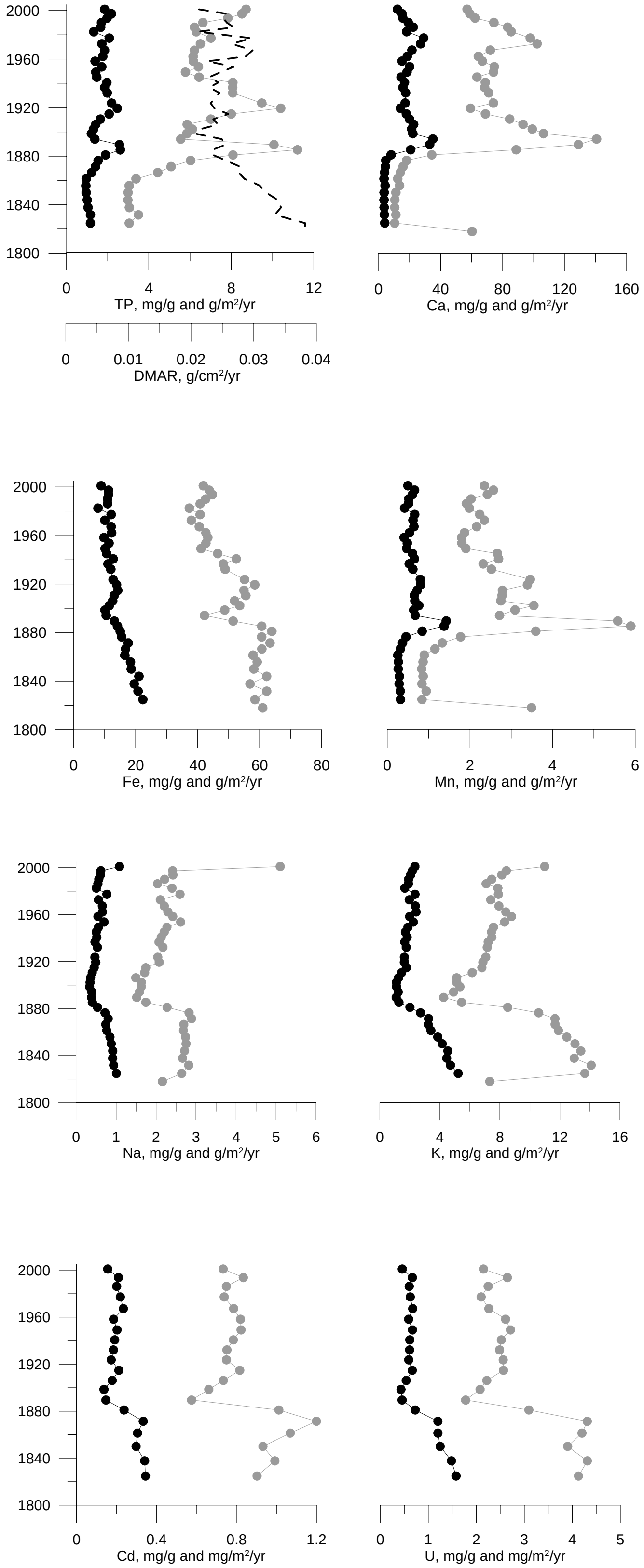


Figure 4.14 *Sedimentary chemistry profiles of P, Ca, Fe, Mn Na, K, Cd and U from Crans Lough. Grey circles are chemical concentrations; black circles are chemical accumulation rates. In the top left, the dashed line is DMAR; and the white circles are DI-TP concentrations. Data are plotted on an age scale.*

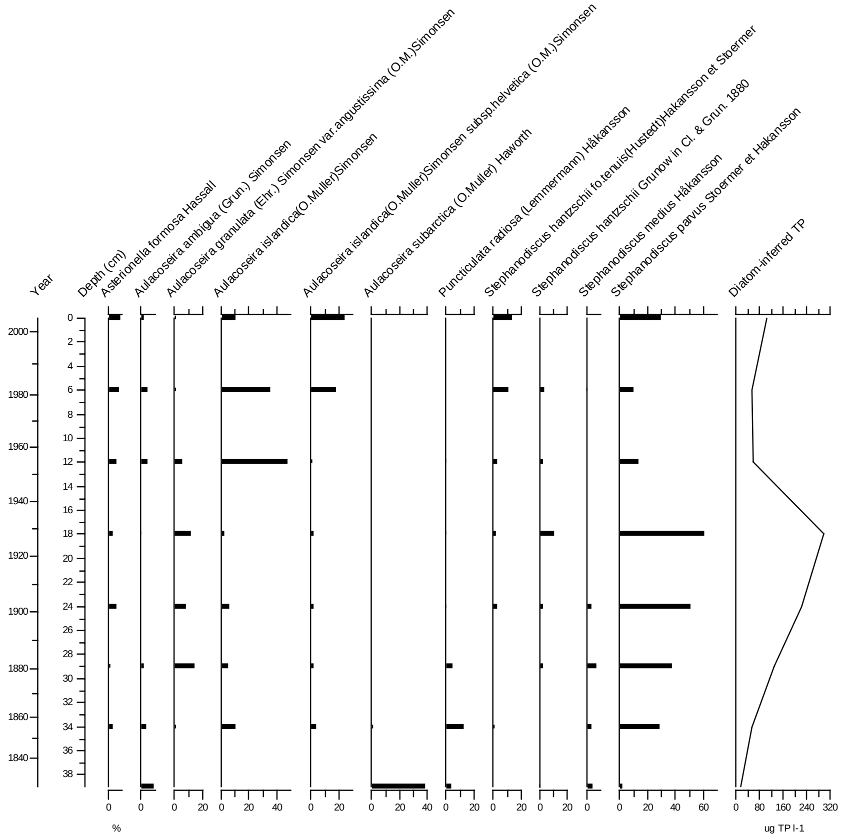


Figure 15a: *Summary plots of the common diatom taxa in Crans and diatom-inferred TP. Data are plotted on a depth and age scale.*

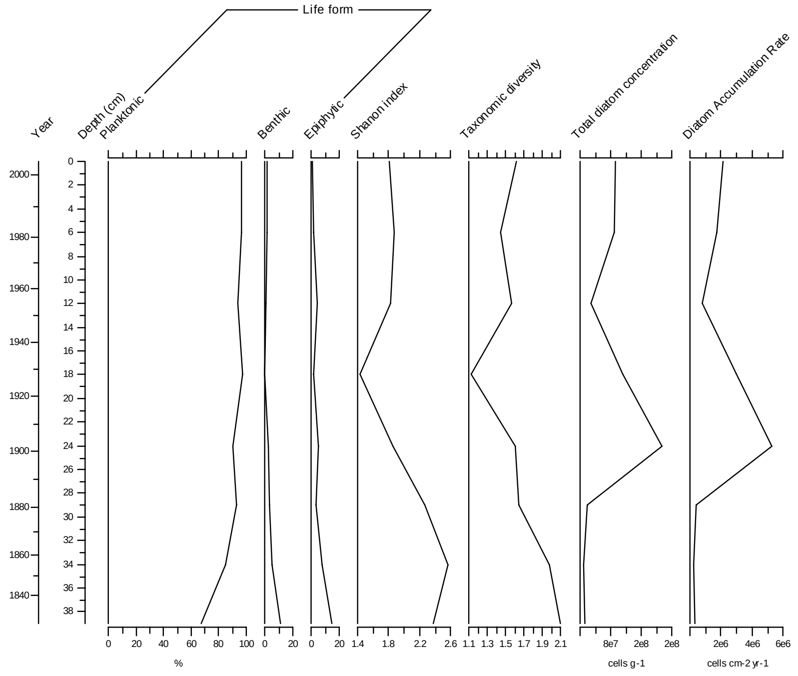


Figure 15b: *Life form, diversity, concentration and accumulation rate of diatoms from Crans Lough. Data are plotted on a depth and age scale.*

4.5 Lough Egish

Lough Egish is part of the Erne river system in County Monaghan (H794134) and is an EPA typology class 6 lake with moderate alkalinity (79 mg l^{-1} $CaCO_3$), shallow water depth (mean depth 3.3 m) and is large in size (122 ha) (Figure 4.17). The catchment geology is predominantly Silurian quartzite. Cattle density of 1.68/ha and sheep density of 0.24/ha was calculated by Irvine *et al.* (2001) from 1990 CSO data representing a two-fold increase since 1920. Industrial developments have also encroached upon the Egish catchment in the form of a creamery established in the early 1900s and an agriculture feed mill in the 1990s. A highly enriched and productive lake experiencing algal blooms was documented by the early 1970s in Flanagan & Toner (1975) and Champ (1977) with extremely high phosphate concentrations (410-1100 µg l^{-1} TP). Catchment land use over the period 1990-2000 has seen a small decline in pasture and an increase in urban landuse (Table 3.3). Egish has been classed as hypertrophic with levels of TP in excess of 600 µg l^{-1} recorded in recent years (Irvine *et al.*, 2001).

4.5.1 Chronology

The ^{210}Pb profiles show a clear hiatus in the sequence between the 6.5-8.5 cm depth, which could arise from physical disturbance of the sediment (slumping), but could also result from changes in the sedimentation regime at the sampling location (Appendix 1). The ^{210}Pb data shows a logical profile above and below this disruption and the CRS model is able to accommodate the hiatus. The change in sedimentation regime could also explain the presence of two ^{137}Cs peaks, which might otherwise be a blended broad peak (comprising both the Chernobyl and weapons fall out signal). Sediment deposition rates of 0.017 ± 0.004 g cm^{-2} yr^{-1} (0.33 cm yr^{-1}) were calculated for the majority of the core. A basal age of 1911 AD is estimated for the dated core at 31 cm depth. This was extrapolated to 1767 for the adjacent deeper cores (Table 4.1).

4.5.2 Lithostratigraphy

A highly variable %LOI profile was found in the sediment core from Lough Egish similar to that from Ballybeg (Figure 4.18). High levels of organic content (*c.* 35-40% LOI) are present at the base of the core with peaks and troughs evident up through the sediment profile. The sediment slumping event or change in sedimentation regime suggested by the ^{210}Pb concentrations coincides with a sharp decline in %LOI and decreases in %DW.

4.5.3 Sediment Chemistry

The sedimentary chemistry for Egish is shown in Figure 4.19. The DMAR changes noted in the ^{210}Pb chronology show a rapid increase post 1970 (*c.* 10 cm) and this is matched by increases in the TP and Mn concentration profiles. Iron shows a less marked increase and is mostly correlated with the Ca concentration profile suggesting scavenging of Ca by ferric hydroxides in the water column; both these are inversely correlated with the Na and K concentration profiles at the base of the core during the dated period which suggests a small change in the sediment source/type during the 1930s. In the absence of a coincidental DMAR, the TP and Mn profiles might be attributed to internal diagenesis. This is likely to be occurring although it seems that changes in sediment type and delivery is at least an equally valid interpretation when considering the abrupt DMAR increases at similar sediment depths.

4.5.4 Biological Fossils

Diatoms

The percentage relative frequencies of most common diatom taxa in the eight levels analysed of the Egish sediment core are shown in Figure 4.20a and life form and accumulation rates in Figure 4.20b. A total of 182 taxa were observed, 25 of which were present in an abundance >2% in the eight samples analysed. The Egish diatom record shows an initial assemblage dominated by periphytic diatom species, mainly small *Fragilaria* and *Achnanthes*, and a few planktonic species, e.g. *Aulacoseira subarctica*. Increases in a number of planktonic taxa are found since ~ 1970. The main increases are in *Stephanodiscus* *parvus*, a late-winter associated taxa typical of very eutrophic conditions, and *Cyclostephanos dubius*. There are also low percentages of *Asterionella formosa* and *Aulacoseira subarctica*. Egish has experienced a strong eutrophication over the last three decades, switching from a mesotrophic lake to a hypertrophic one. The results show that the baseline DI-TP concentrations at the beginning of the record (*c.* late 19th century) were approximately 16 µg l^{-1} TP. The levels rose to levels >200 µg l^{-1} around 10 cm depth (post 1970), an increase that is related to the high abundance of *Stephanodiscus parvus* and concurrent with increases in diatom accumulation rates. This long term stability followed by a recent increase in productivity is also confirmed by the ^{210}Pb profile, which suggests a rapid increase in sediment accumulation rate dating to the late 1980s (to values >0.15 g cm^{-2} y^{-1}), which progressively relaxes to values around 0.05 g cm^{-2} y^{-1} for the surface layers.

Cladocera

The cladoceran assemblages in the Lough Egish sediments changed completely from littoral (chydorid) species in the bottom sample to planktonic (*Daphnia* and *Bosmina*) species in the surface sample (see Figure 4.21 and Appendix 3). Species shifts within in the chydorids over the period represented by the core include a major decline (from 53% to 10%) in *Alona rustica*. This species is normally common in dystrophic waterbodies and is generally absent in enriched environments. Meso-eutrophic species *Chydorus sphaericus* increased from 6% to 21% and *Alona quadrangularis* increased from 1% to 22% between bottom and surface samples. These species changes reflect major nutrient enrichment in Egish during the sedimentation period.

Pollen

The abundances of pollen from deciduous woodland taxa decline overall (although *Betula, Quercus* and *Ulmus* pollen increases). The abundance of *Pinus*-type pollen shows a moderate increase, while that of Poaceae shows a much more marked increase. Ericaceae pollen, presumably from heathers such as *Calluna*, is relatively common in the core bottom sample, while levels of *Myriophyllum* pollen in both of the samples analysed from this site are also notable. The overall extent of deciduous woodland declined, especially more open-canopy forms characterised by hazel. Grassland cover expanded during the same time period, while the abundance of Ericaceae pollen in the core bottom sample may represent peat inwash. Levels of *Myriophyllum* pollen may indicate nutrient enrichment.

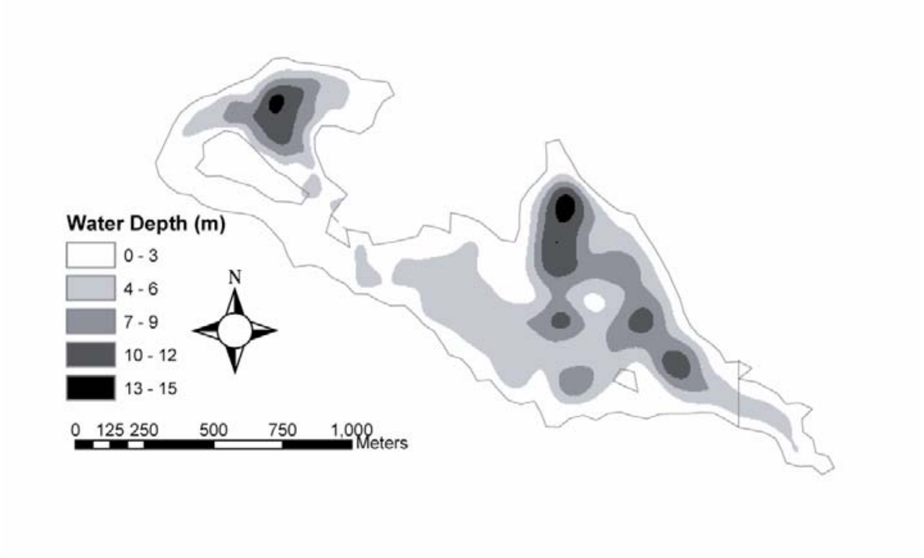


Figure 4.17: *Lake Bathymetry Lough Egish*

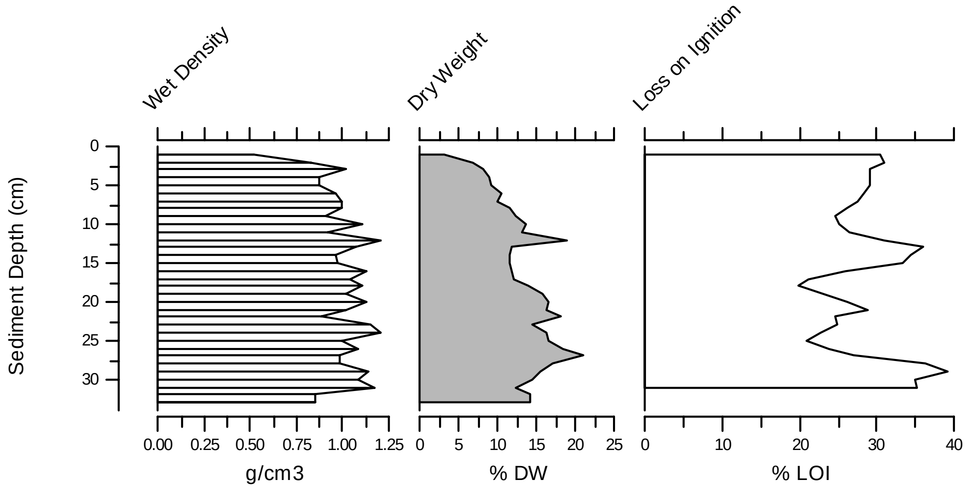


Figure 4.18: *Egish - Density of wet sediment (g/cm3), Water content (as %DW) and organic content as loss on ignition (%LOI).*

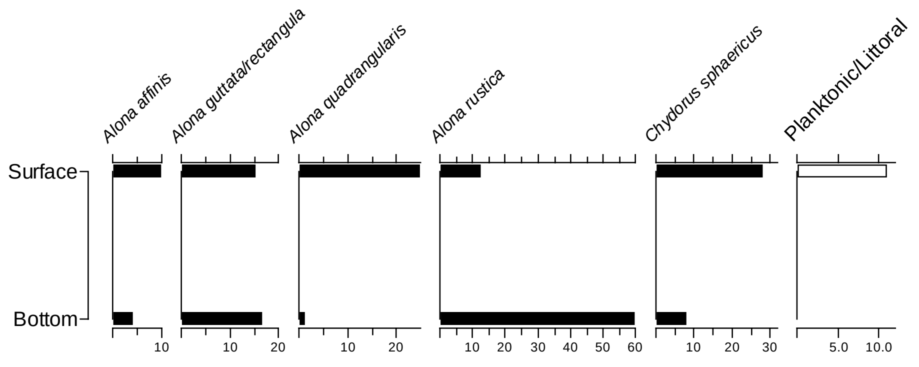


Figure 4.21: *Relative abundance of selected chydorid species in bottom (reference) and surface (c. 2004) sediment samples for Egish.*

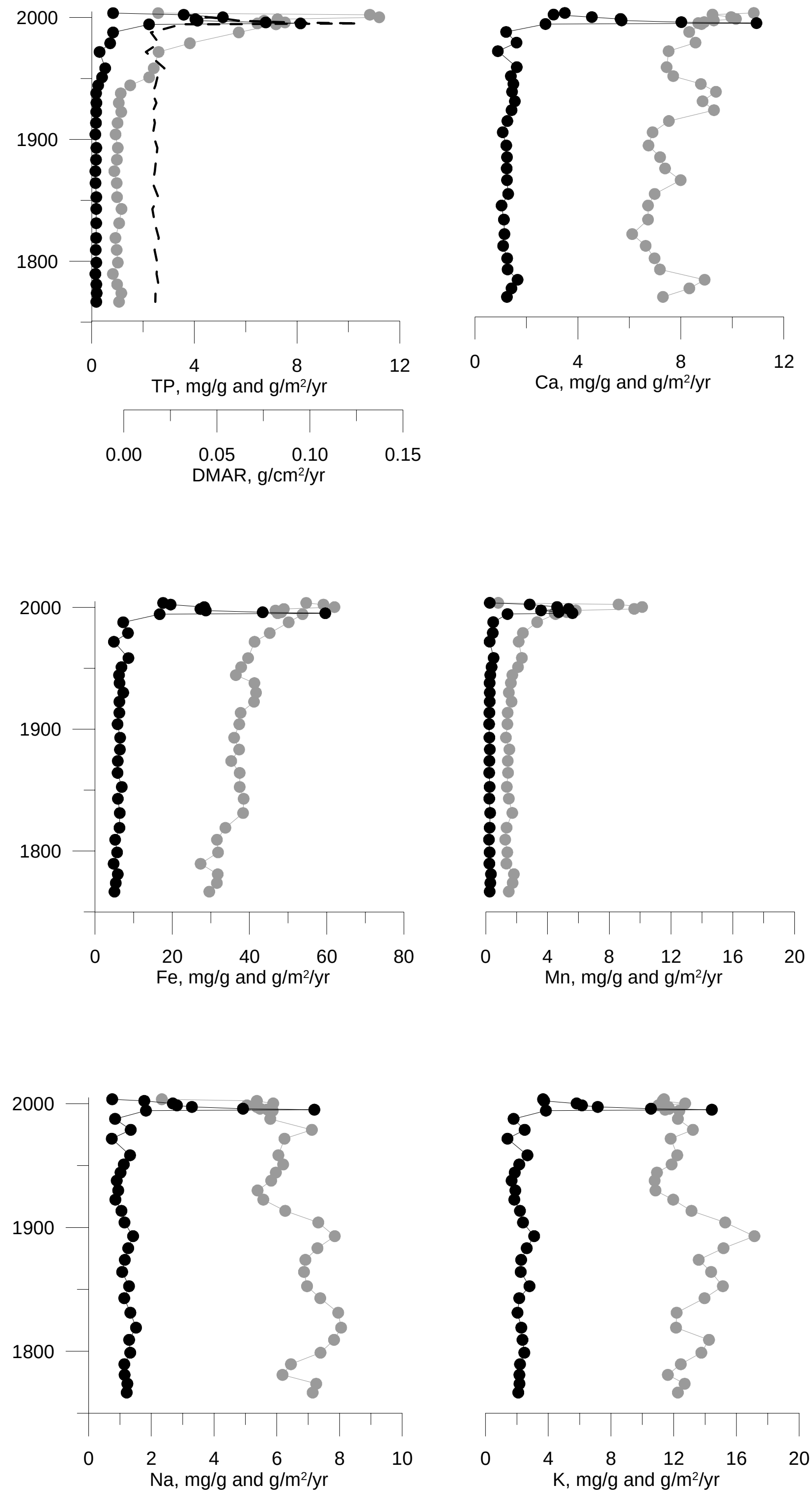


Figure 4.19. *Sedimentary chemistry profiles of P, Ca, Fe, Mn, Na and K from Egish Lough. Grey circles are chemical concentrations; black circles are chemical accumulation rates. In the top left, the dashed line is DMAR; and the white circles are DI-TP concentrations. Data are plotted on an age scale.*

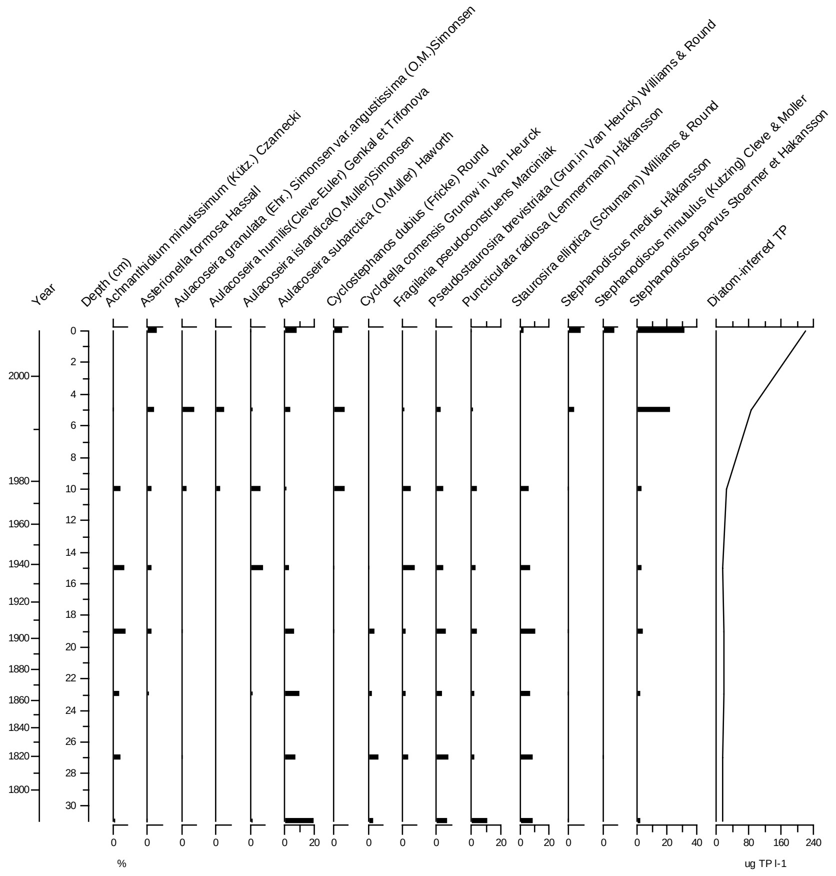


Figure 4.20a: *Summary plots of the common diatom taxa in Egish and diatom-inferred TP. Data are plotted on a depth and age scale.*

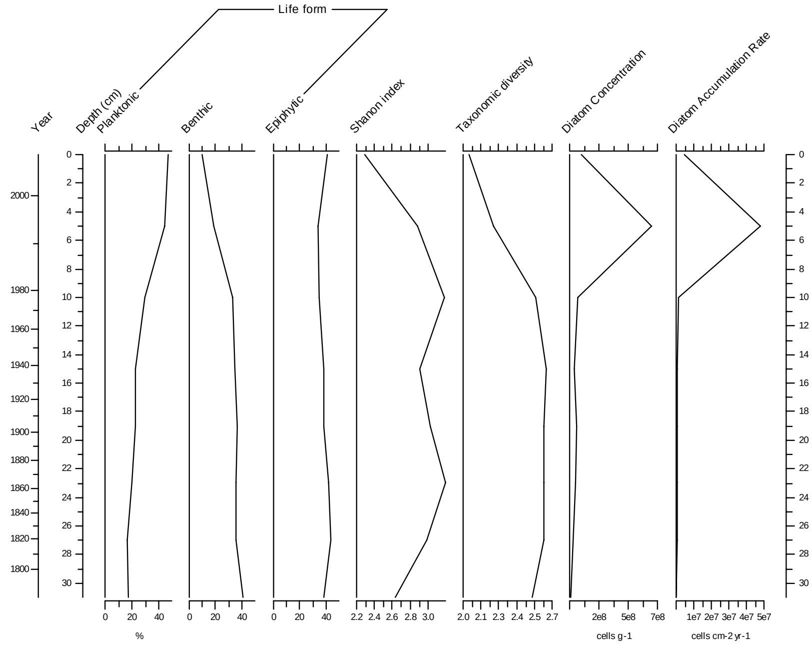


Figure 4.20b: *Life form, diversity, concentration and accumulation rate of diatoms from Egish Lough. Data are plotted on a depth and age scale.*

4.6 Inchiquin

Lough Inchiquin (R270896) in County Clare is also part of the Fergus river system along with Lough Atedaun. Inchiquin has the highest alkalinity (161 mg l^{-1} $CaCO_3$) of the WP3 lakes reflecting the carboniferous limestone bedrock. The lake has moderate water depth (mean depth 10 m), is 116 ha in lake surface area and therefore belongs to EPA typology class 12 (Tables 3.1, 3.2 and Figure 4.22). The land cover in the Inchiquin catchment is largely dominated by peatlands, along with deciduous woodland and conifer plantations. Agriculture and human population census data indicate very low population densities (<1 per hectare) in the catchment (Wemaere, 2005). A wastewater treatment plant at Kilfenora dischanges wastewater following secondary treatment to groundwaters in the Inchiquin catchment potentially affecting Inchiquin. Water is abstracted at a rate of 454 m^3 day^{-1} to supply the town of Corofin (Wemaere, 2005). A water residence time of 33 days (0.09 years) was calculated for Inchiquin by Allott *et al*., (1998). Evidence of substantial nutrient enrichment ranging from 85 to 380 µg l^{-1} TP was documented by Flanagan & Toner (1975) and Champ (1977) with depletion of dissolved oxygen levels. Examination of the algal species composing the phytoplankton during 1975 also suggested that Inchiquin was eutrophic (Champ, 1977). Irvine *et al.,* (2001) classed Inchiquin as mesotrophic and observed oxygen depletion in the hypolimnia during summer stratification.

4.6.1 Chronology

The ^{137}Cs chronology, obtained using three reference dates (the sampling date of 2004, the Chernobyl event in 1986 and maximum weapons test fallout in 1963) is in good agreement with the ^{210}Pb chronology and suggests that the base of the 27 cm Inchiquin core dates to the mid-to late 1950's. A relatively fast accumulation rate of 0.12 ± 0.002 g cm^{-2} yr^{-1} (0.60 cm yr^{-1}) is therefore estimated for the past 49 years. A 39 cm length core collected in close proximity to the dated core gives an estimated extrapolated date of 1930 AD (Table 4.1).

4.6.2 Lithostratigraphy

The lithostratigraphy of the Inchiquin core exhibits steady declines in %DW and increases in %LOI from mid-way through the profile at approximately 20 cm (*c.* early 1970s) (Figure 4.23).

4.6.3 Sediment Chemistry

The TP profile from Inchiquin (Figure 4.24) generally increases post 1960 and appears to follow the Mn profile but with no similar DMAR trend at the same depths. The rapid increase in DMAR post 1960 to *c.* 1990 is not matched in magnitude by any of the chemical profiles. There are similarities between Mn, Na and K concentration although the strongest correlation is between Na and K (r = 0.95). The TP concentration profile indicates a stepped increase post 1980 (12 cm) and this is matched by the Mn profile and Fe profiles (r = 0.80). In this core, P and Fe appear to follow the same deposition concentration and this does indicate the possibility of internal diagenesis. There are some similarities, however, with Na and K at least at certain change points in the profile and this also suggests changes in sediment source or type.

4.6.4 Biological Fossils

Diatoms

The diatom stratigrapic profile for Inchiquin is shown in Figure 4.25a and 4.25b. A total of 137 diatom taxa were identified in the eight samples analysed, of which 27 were >2% in at least two samples. The diatom record from Inchiquin shows a succession from a periphytic dominated assemblage to a mixed community comprising planktonic and non-planktonic forms. The upper part of the diatom record shows increasing percentages of small *Stephanodiscus* and *Cyclotella*, and a drop in the abundance of periphytic *Amphora pediculus*. The DI-TP reconstruction shows that Inchiquin has been a mesotrophic lake for the whole of the period from around 1930 to 2004. TP reconstructed values ranged from 15 μg to 23 μg l^{-1}, showing a slight increase to the top of the record (post 1990).

Cladocera

No obvious shift in dominant species can be observed within the chydorid assemblage between the reference and surface core samples from Inchiquin, nor were there major changes in the relative abundances of the chydorid species (see Figure 4.26). The dominance of meso-eutrophic *Chydorus sphaericus* and mesotrophic *Alona guttata/rectangular* indicate a meso-eutrophic condition in Inchiquin for both top and bottom samples. However, the ratio of planktonic/littoral cladocera increased from less than 1 to more than 5 between the bottom and surface sample, indicating an increased importance of planktonic assemblages within the cladoceran community.

Pollen

Only relatively slight changes in levels of tree (including *Pinus*-type) and non-tree pollen are evident between the core bottom and uppermost samples analysed from Inchiquin. Generally there is stable vegetation cover in the catchment, although minor changes in woodland composition and a small increase in grassland cover are indicated (Appendix 4).

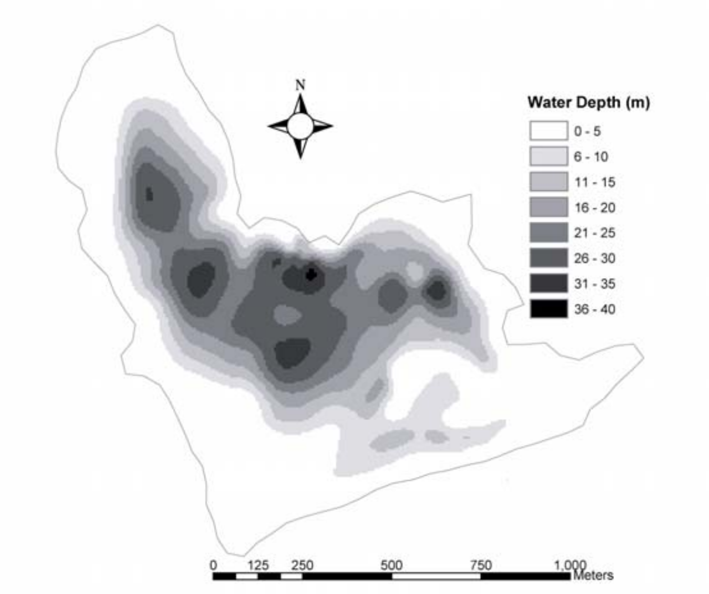


Figure 4.22: *Lake Bathymetry Lough Inchiquin*

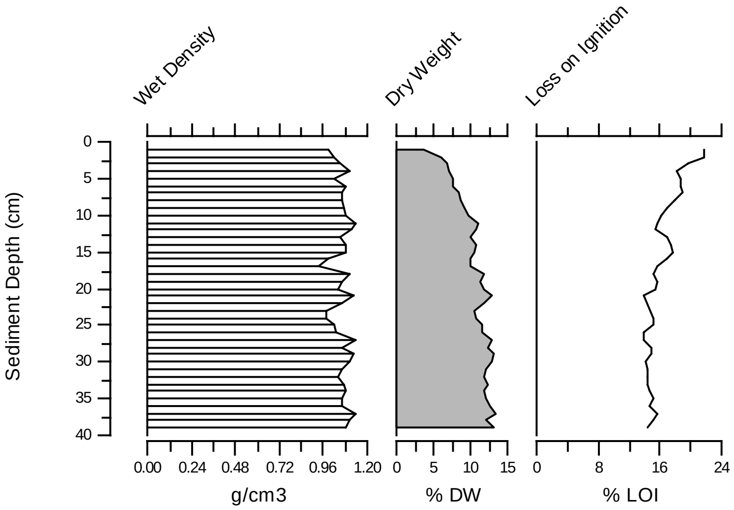


Figure 4.23: *Inchiquin - Density of wet sediment (g/cm3), Water content (as % DW) and organic content as loss on ignition (%LOI).*

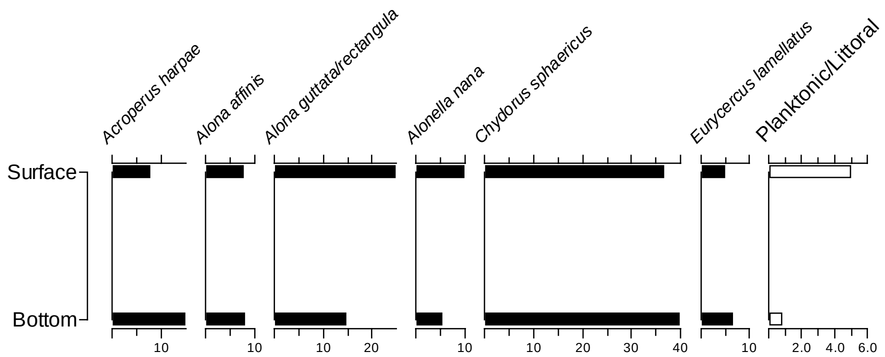


Figure 4.26: *Selected chydorid species in bottom (reference) and surface (c. 2004) sediment samples for Inchiquin.*

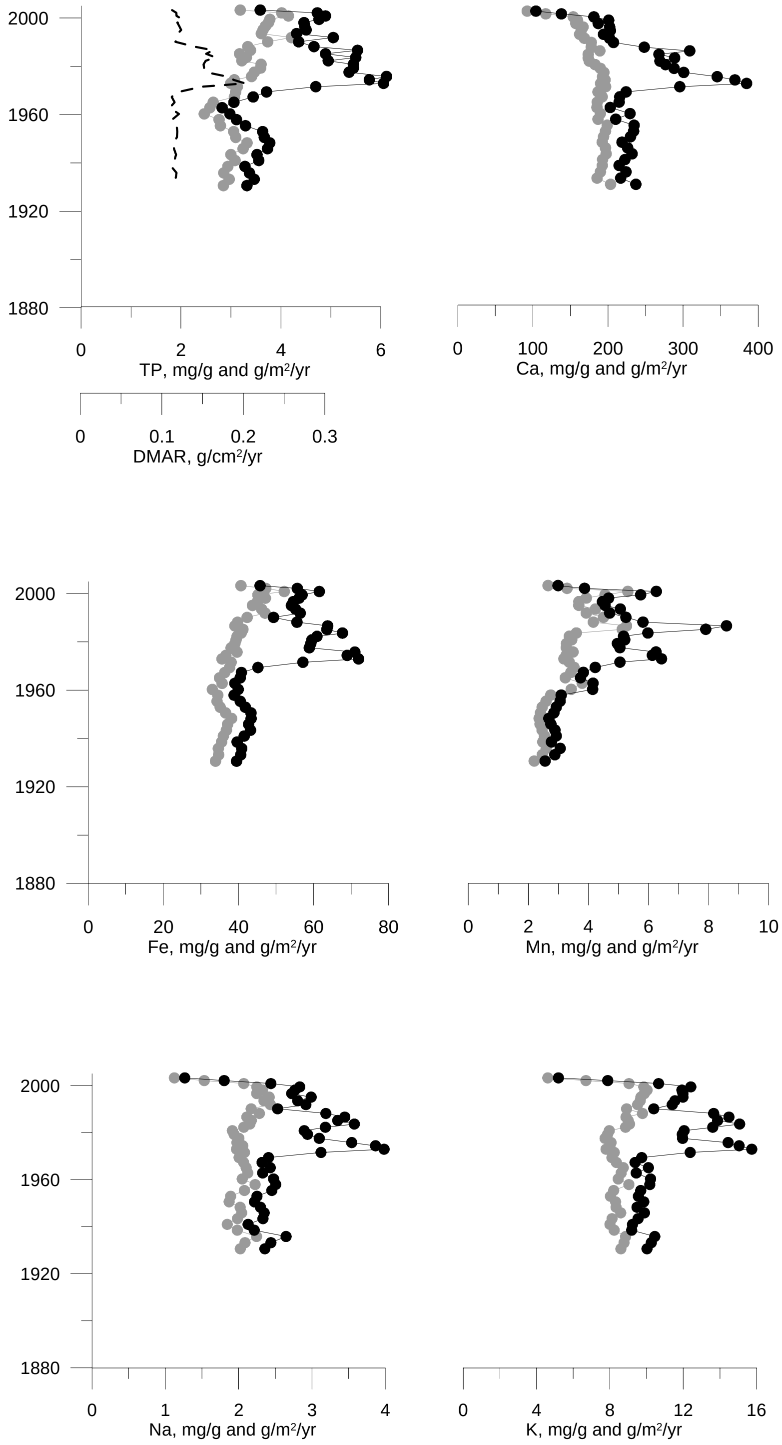


Figure 4.24. *Sedimentary chemistry profiles of P, Ca, Fe, Mn, Na and K from Inchiquin Lough. Grey circles are chemical concentrations; black circles are chemical accumulation rates. In the top left, the dashed line is DMAR; and the white circles are DI-TP concentrations.Data are plotted on an age scale.*

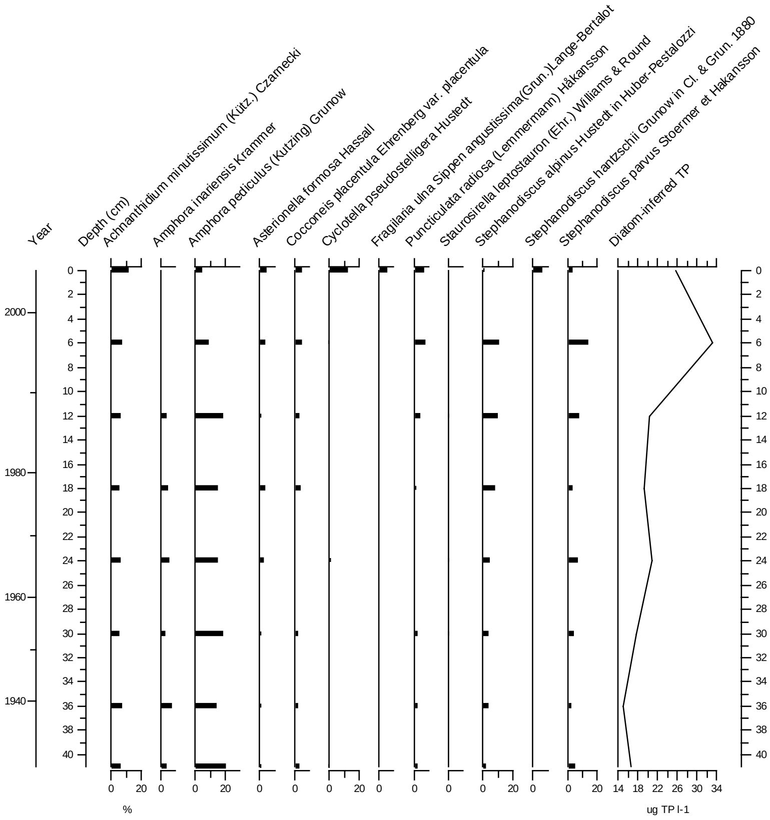


Figure 4.25a: *Summary plots of the common diatom taxa in Inchiquin and diatom-inferred TP. Data are plotted on a depth and age scale.*

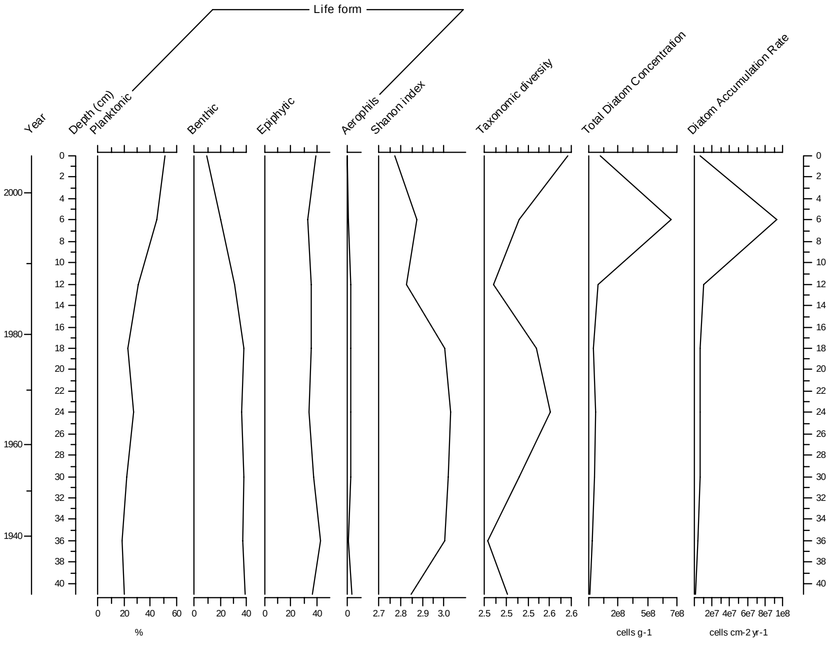


Figure 4.25b: *Life form, diversity, concentration and accumulation rate of diatoms from Inchiquin Lough. Data are plotted on a depth and age scale.*

4.7 Mullagh

Mullagh lake in County Cavan (N677854) is part of the Boyne river catchment which is underlain by Silurian quartzite geology. The lake is in EPA typology class 5 having moderate alkalinity (58 mg l^{-1} $CaCO_3$) shallow water depth (mean 2.3 m) and a relatively small lake area (35 ha) (Tables 3.1, 3.2 and Figure 4.27). A lake water residence time of 1.34 years was calculated by Allot *et al.*, (1998). Mullagh is subject to intense agricultural activities. Catchment land use is predominantly pasture with a high cattle density of 2.85/ha and sheep density of 0.83/ha according to 1990 CSO data (Irvine *et al.*, 2001). Cattle numbers have doubled since the 1920s. Mullagh is classed as a eutrophic lake with TP of 57 µg l^{-1} (Irvine *et al.*, 2001). Macrophyte cover was extensive and well developed at the time of sampling.

4.7.1 Chronology

A broad subsurface peak is evident in the ^{137}Cs data from the Mullagh sediment profile (Appendix 1). It is likely to result from a blend of the Chernobyl and weapons fallout signals and post-depositional mobility (similar to that found at Lough Egish) and is associated with high organic content. Insufficient reference points therefore preclude estimation of a ^{137}Cs chronology. The CRS lake model estimates the core base of 27 cm to date to *c.* 1950. The flattening of the ^{210}Pb profile towards the top of the core suggests significantly increased sedimentation in recent years (5 cm+). The model estimates that accumulation is at the rate of 0.035 ± 0.007 g cm yr^{-1} (0.60 cm yr^{-1}) for the lower section of the core. An increased accumulation rate at the bottom of the core makes extrapolation below 30 cm depth (1950) inappropriate (see Appendix 1).

4.7.2 Lithostratigraphy

The lithostratigraphic profile for the Mullagh sediment core is relatively stable (Figure 4.28). The only point of change is identified at 12 cm where %DW declines more sharply and declines in %LOI are reversed and a steady incline is evident. There are notably higher levels of organic content (>35% LOI) throughout the profile relative to the other WP3 lake sediment cores.

4.7.3 Sediment Chemistry

The Mullagh chemistry profiles are illustrated in Figure 4.29. The TP concentration profile similarly increases from a stable background of less than 2 mg/g to over 6 mg/g following the 1990s. The large DMAR feature observed during the 1970s is matched by Na and K increases and to a lesser extent Fe. This indicates a rapid change in sediment type/source. In this core, however, it is likely that the TP profiles are linked to some extent to sedimentary diagenisis with Fe and especially Mn that show a similar profile across the dated period and that are not matched by any of the other catchment cation profiles.

4.7.4 Biological Fossils

Diatoms

The percentage of relative frequencies and concentrations of the major diatom taxa in 9 levels of the sediment core from Mullagh analysed are illustrated in Figure 4.30 (a&b). Diatom preservation was good throughout the core. A total of 114 taxa was observed, 21 of which were present in at least 2 samples with an abundance >2%. The diatom stratigraphy (Figure 4.30a) shows a marked change in the diatom species composition from 15 cm, dated to *c.* 1975, following a long period of relative stability. The lower samples (pre-1975) were all dominated by oligo-mesotrophic taxa, particularly *Staurosirella pinnata*, *Staurosira elliptica*, *Pseudostaurosira brevistriata* and *Fragilaria pseudoconstruens*. The uppermost samples (post-1975) were markedly different with the decline of periphytic, oligo-mesotrophic species and their replacement primarily by *Aulacoseira granulata*, *A. ambigua*, *Asterionella formosa* and small centrics *Cyclotella* and *Stephanodiscus*.

The diatom flora of Mullagh suggest that the lake has become more nutrient rich in recent years. The values produced by the DI-TP model ranged from *c.* 16 µg l^{-1} TP for the lower part of the core (38 cm), increasing to 78 µg l^{-1} TP for the 2004 sample. The increase in DI-TP from meso-trophic to eutrophic concentrations post-1970s is concurrent with a large DMAR peak (Figure 4.29) indicating a rapid change in sediment type/source. The high DI-TP value for the surface sample is explained by the higher relative abundance of *Aulacoseira granulata* var. *angustissima*, which has a high TP optimum.

Cladocera

The relative abundance of littoral chydorid species show little change in a comparison of reference and surface samples from Mullagh (Figure 4.31). Some change is evident in the dominant species *Chydorus sphaericus* and *Alona affinis* where there are slight increases in relative abundance in the surface sample while oligo-mesotrophic species *Chydorus piger* displays a decreased abundance. However, a four-fold increase in the ratio of planktonic to littoral species is evident between the bottom and surface samples.

Pollen

The abundances of pollen from deciduous woodland taxa declined between bottom and surface samples from Mullagh. The abundance of *Pinus*-type pollen remained more-or-less constant, while that of Poaceae and *Myriophyllum* increased markedly. The overall extent of deciduous woodland declined, while grassland cover expanded. Levels of *Myriophyllum* pollen in the uppermost sample analysed may indicate nutrient enrichment.

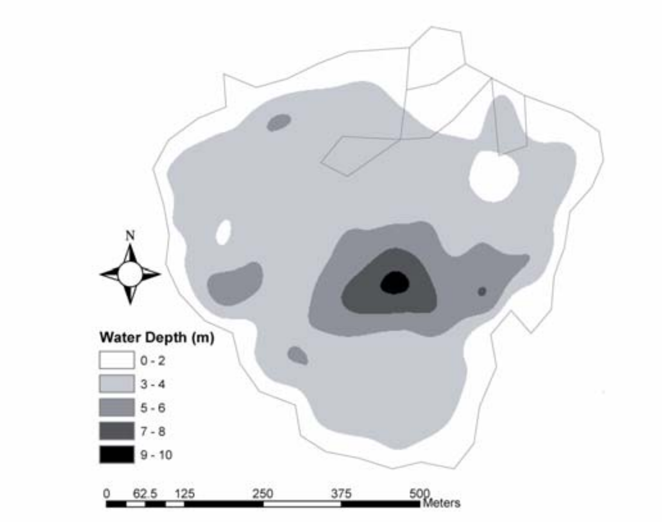


Figure 4.27: *Lake Bathymetry Mullagh Lough*

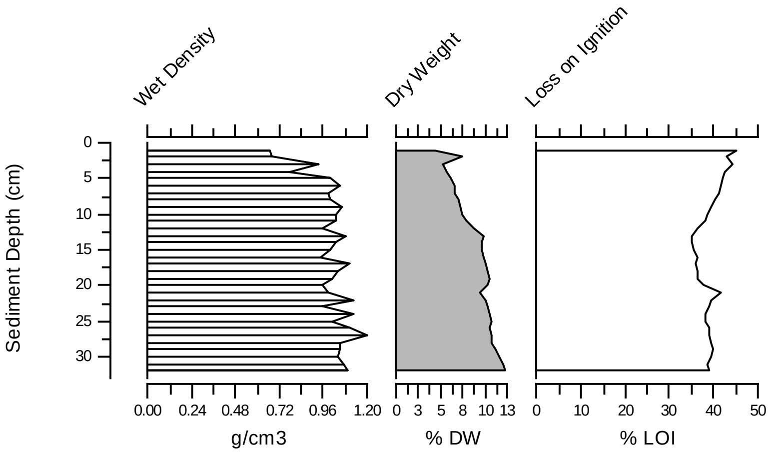


Figure 4.28: *Mullagh - Density of wet sediment (g/cm3), Water content (as % DW) and organic content as loss on ignition (%LOI).*

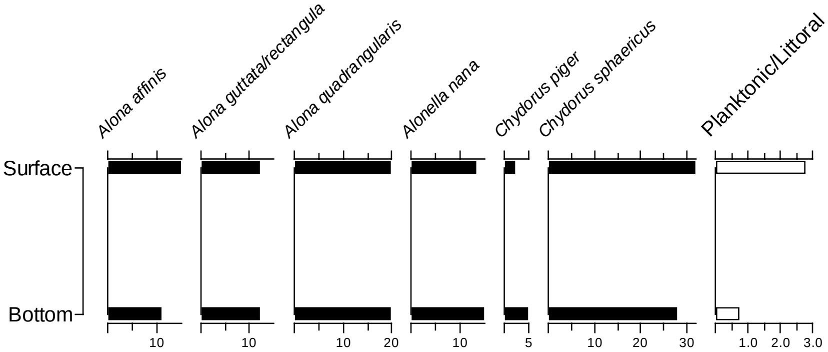


Figure 4.31: *Selected chydorid species in bottom (reference) and surface (c. 2004) sediment samples for Mullagh.*

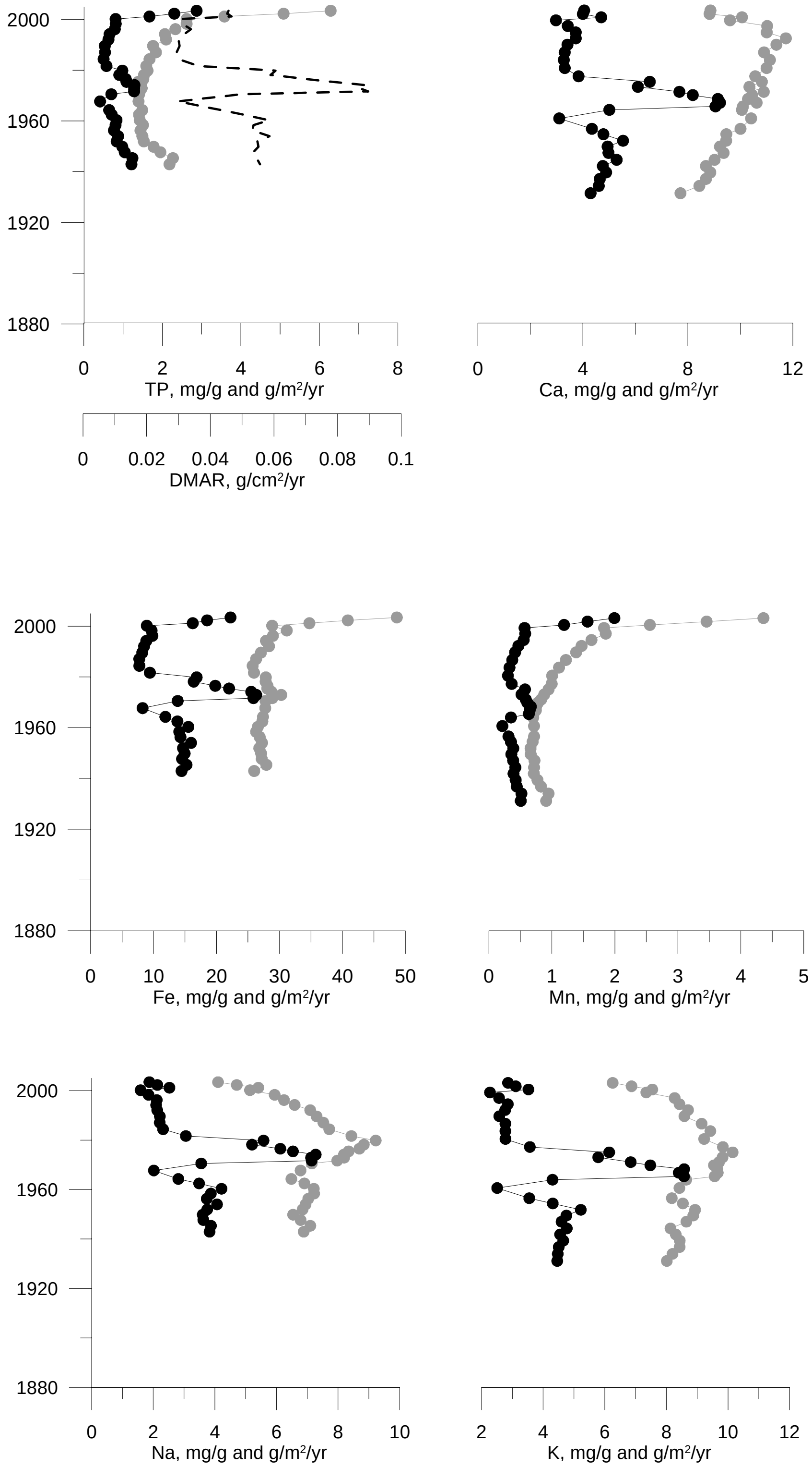


Figure 4.29. *Sedimentary chemistry profiles of P, Ca, Fe, Mn, Na and K from Mullagh Lough. Grey circles are chemical concentrations; black circles are chemical accumulation rates. In the top left, the dashed line is DMAR; and the white circles are DI-TP concentrations. Data are plotted on an age scale.*

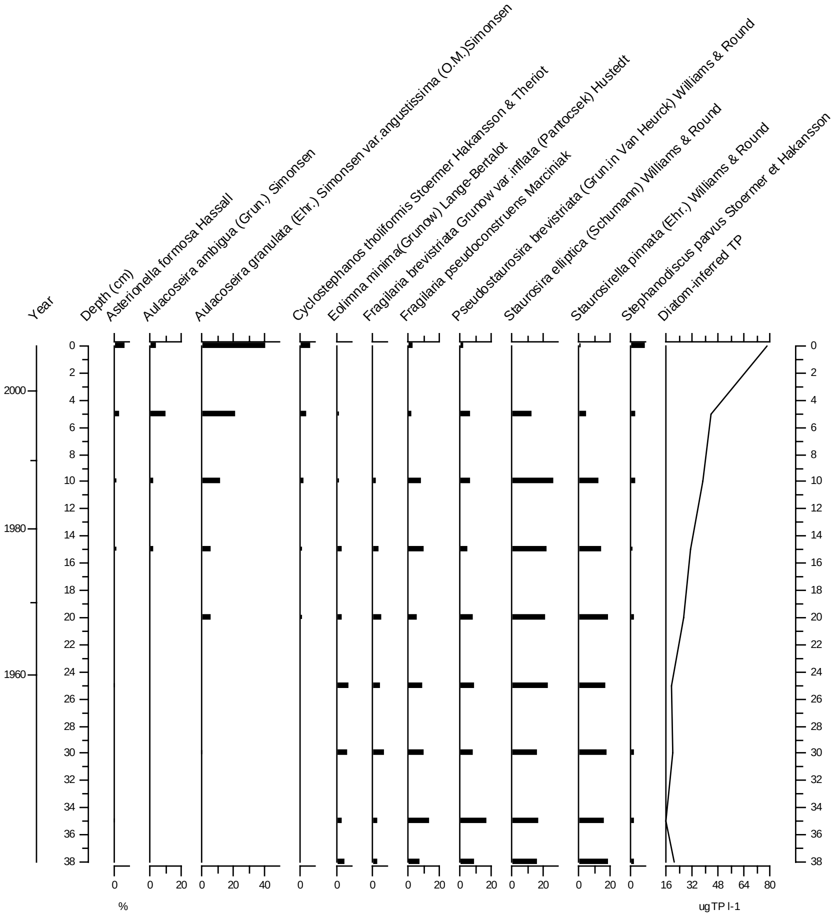


Figure 4.30a: *Summary plots of the common diatom taxa in Mullagh and diatom-inferred TP. Data are plotted on a depth and age scale.*

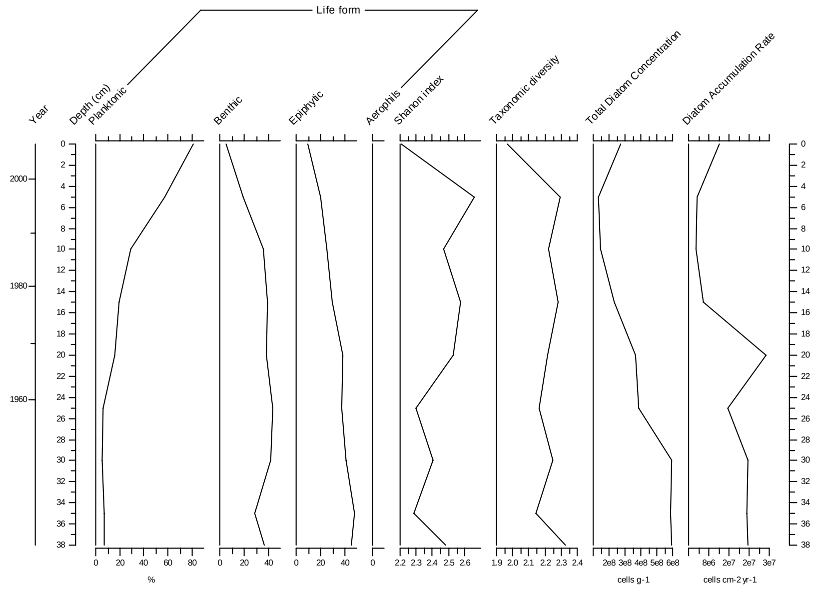


Figure 4.30b: *Life form, diversity, concentration and accumulation rate of diatoms from Mullagh Lough. Data are plotted on a depth and age scale.*

4.8 Sillan

Sillan lake in Co. Cavan (H709630) beside the town of Shercock is the largest of the WP3 lakes (172 ha) and belongs to EPA typology class 8. Sillan has a mean depth of 6 m (Figure 4.32), medium alkalinity levels (37.6 mg l^{-1} $CaCO_3$) and a TP of 141 µg l^{-1} (Irvine *et al.*, 2001). The presence of point sources of pollution in the form of a chicken processing factory and treated sewage from Shercock have been documented in the past (O'Connor & Bracken, 1978). In addition, a caravan site is located close to the north shoreline of Sillan. Physico-chemical monitoring the 1970s indicated TP levels ranging from 90-870 µg l^{-1}, elevated concentrations of nitrogen, ammonia and seasonal release of sediment phosphorus while examination of littoral, sublittoral and profundal fauna enabled classification of the lake as moderately eutrophic (Flanagan & Toner, 1975; Champ, 1977; O'Connor & Bracken, 1978).

4.8.1 Chronology

The ^{137}Cs profile for Sillan shows a broad sub-surface peak extending in the region from about 12 cm to a depth of 23 cm reflecting a merging of Chernobyl and weapons test fallout similar to the sediment cores from Mullagh and Egish (Appendix 1). A core chronology was obtained using a CRS model with an estimated date of 1954 ± 4 at 23 cm depth. The average sediment accumulation rate is estimated as 0.053 ± 0.012 g cm^{-2} yr^{-1} (0.46 cm yr^{-1}). Correlation and extrapolation suggests an estimated age of 1900 AD for an adjacent core (at 39 cm depth) (Table 4.1 and Appendix 1).

4.7.2 Lithostratigraphy

Lithostraphic profiles of wet density, %DW and %LOI for Lough Sillan are illustrated in Figure 4.33. High basal wet densities are coincident with highs in DW and lows in LOI. The most change is evident in the sediment profile below 27 cm depth (pre-1940 AD) where relatively rapid increases in LOI and declines in DW are apparent. Post-1940 (27 cm) the profile is relatively stable.

4.8.3 Sediment Chemistry

The chemistry profiles for Sillan are shown in Figure 4.34 and indicate a rapid increase in DMAR from the 1980s (above 12 cm). The TP concentration profile is closely matched with similar change points in the Mn profile and, with no concurrent changes in DMAR or the other catchment cations, suggesting Mn/P diagenesis.

4.8.4 Biological Fossils

Diatoms

Diatom preservation was good in the sediment core from Sillan. A total of 149 taxa were observed in samples analysed, 17 of which were present with a relative abundance of >2%. The percentage relative frequencies of the major diatom taxa in the eight levels analysed are illustrated in Figure 4.35a and life forms in 4.35b. The diatom stratigraphy shows that there have been slight changes in the diatom taxa composition in terms of relative percentages over the *c.* 100 year period represented by the core. However, there has been no clear species replacement and the assemblages have been dominated by the same planktonic *Aulacoseira* species throughout the core. The only changes were excursions between *Aulacoseira subarctica* and *A. granulata*, and that periphytic taxa accounted for greater relative abundances in the bottom sample than in the upper samples. The DI-TP results show that Sillan has been a eutrophic lake since at least 1915 (35 cm). The model indicates a slight decline in TP concentrations between 12 and 6 cm depth (1980s), increasing again to 65 µg TP l^{-1} in the surface sample. The drop in DI-TP is explained by the higher abundance of *Aulacoseira subarctica.*

Cladocera

The chydorid assemblage in the Sillan reference sample was dominated by *Alona affinis* in contrast to the surface sample where *Alona quadrangularis*, which prefers a higher trophic state, was dominant (Figure 4.36). Relative abundances of oligo-mesotrophic species also decreased between the bottom and the surface sample, indicating possible increased nutrient enrichment during the past decades. An increase in the planktonic/littoral ratio also occurred.

Pollen

A moderate decline in pollen from woodland taxa, including conifers, was concomitant with a rise in Poaceae pollen. Sediment core samples from Sillan also contain pollen from Ericaceae and *Myriophyllum* and *Isoetes* spores. A decline in the overall extent of woodland, while grassland cover expanded is interpreted from the data. The presence of Ericaceae pollen may represent some inwash of peat, which would also explain the relatively abundant *Isoetes* pollen. High levels of *Myriophyllum* pollen in the core bottom sample when compared with the sample from 15-16 cm depth may indicate a weakening of nutrient enrichment and a decline in aquatic macrophytes.

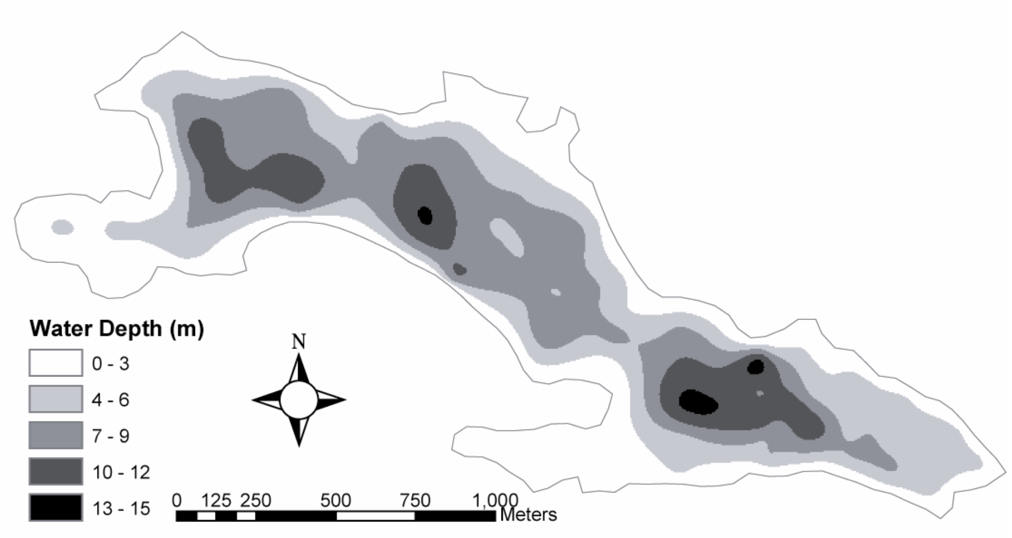


Figure 4.32: *Lake Bathymetry Sillan Lough*

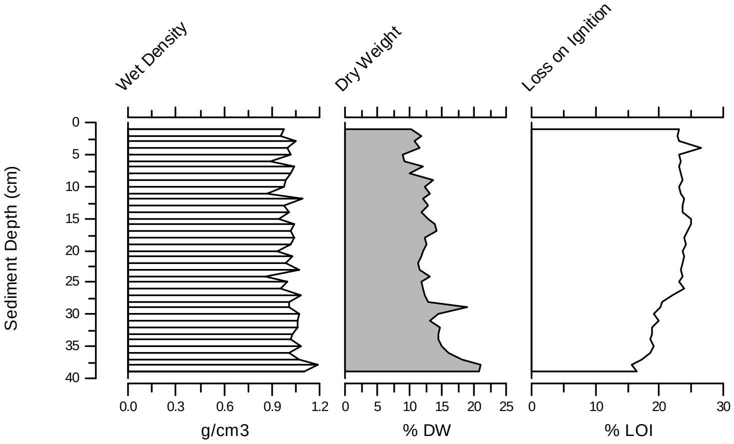


Figure 4.33: *Sillan - Density of wet sediment (g/cm3), Water content (as % DW) and organic content as loss on ignition (%LOI).*

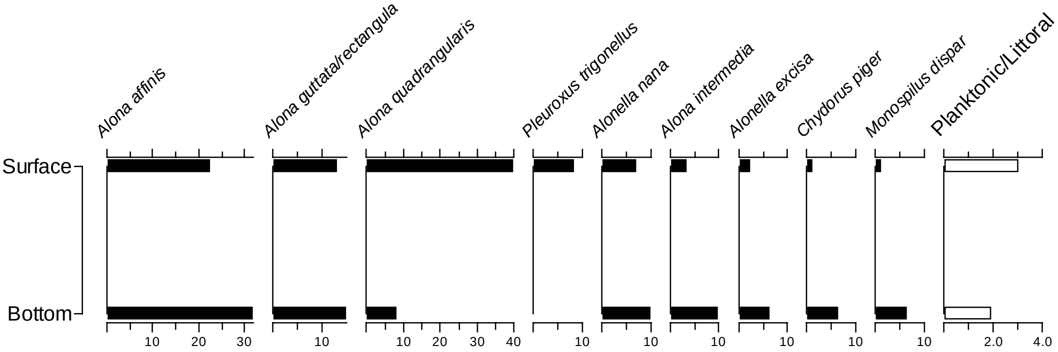


Figure 4.36: *Selected chydorid species in bottom (reference) and surface (c. 2004) sediment samples for Sillan.*

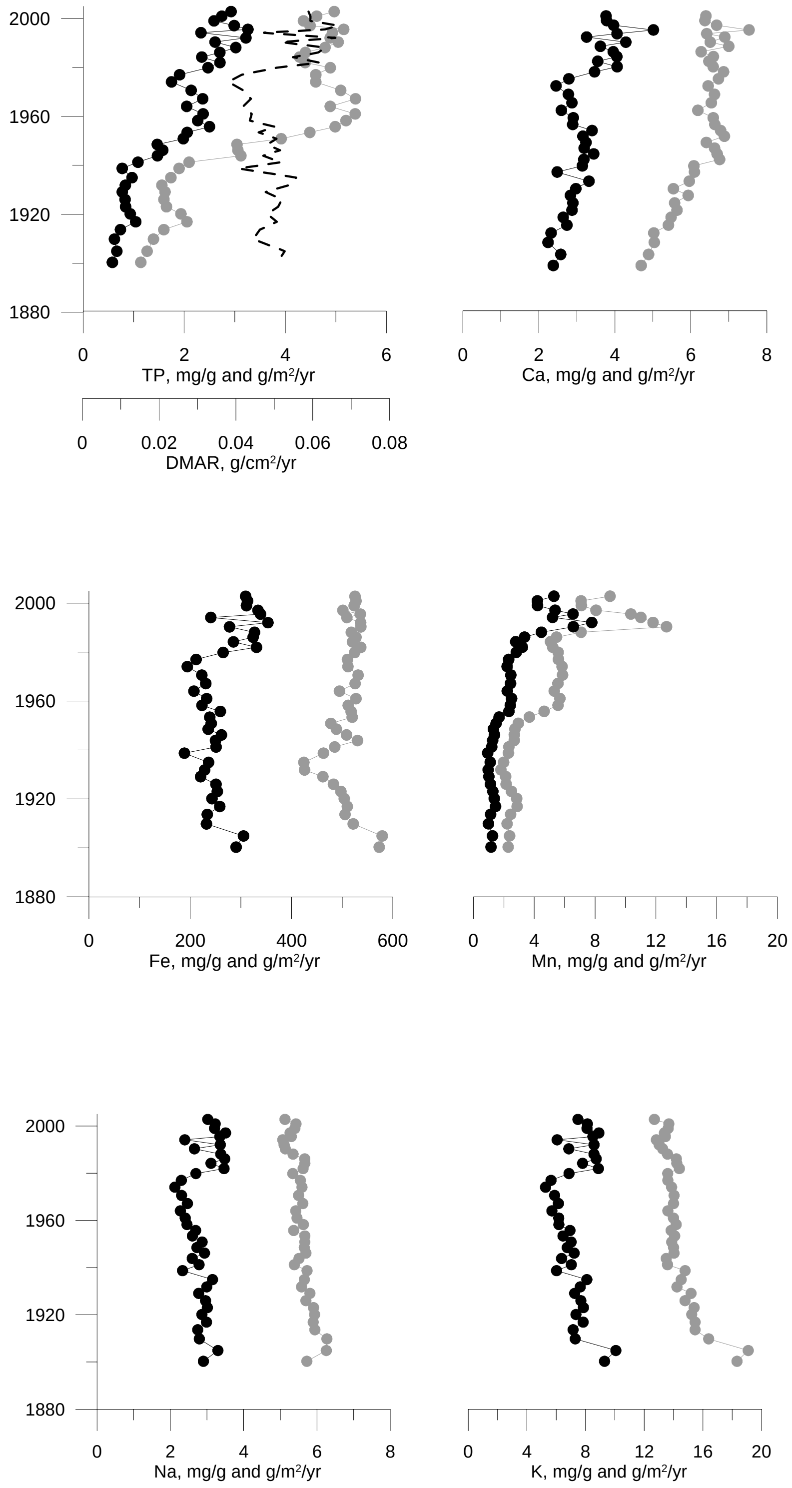


Figure 4.34. *Sedimentary chemistry profiles of P, Ca, Fe, Mn, Na and K from Sillan Lough. Grey circles are chemical concentrations; black circles are chemical accumulation rates. In the top left, the dashed line is DMAR; and the white circles are DI-TP concentrations. Data are plotted on an age scale.*

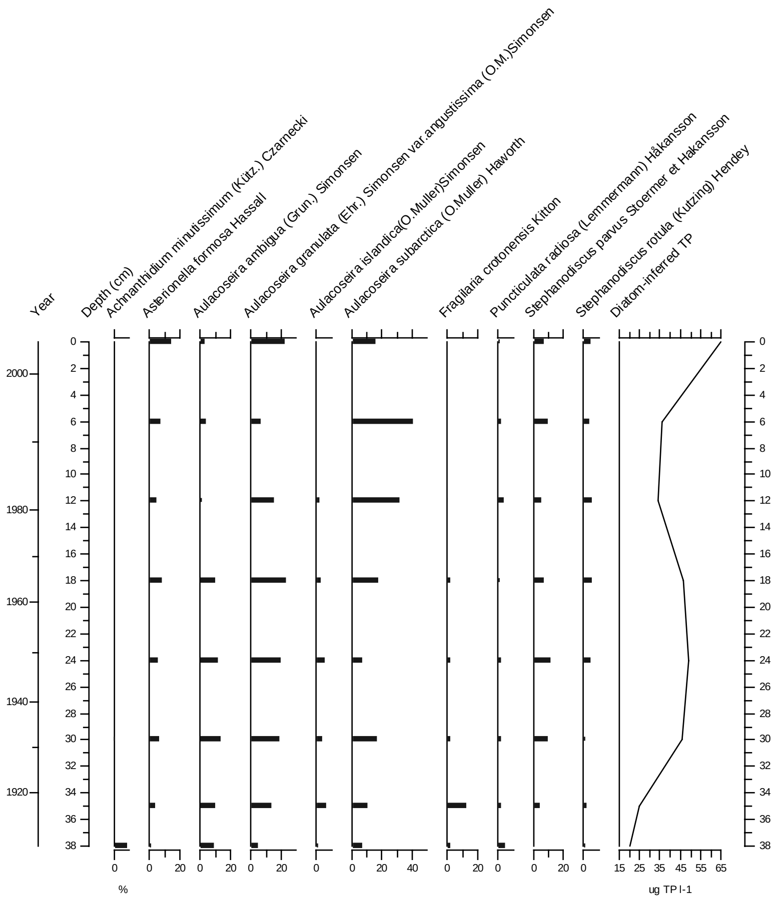


Figure 4.35a: *Summary plots of the common diatom taxa in Sillan and diatom-inferred TP. Data are plotted on a depth and age scale.*

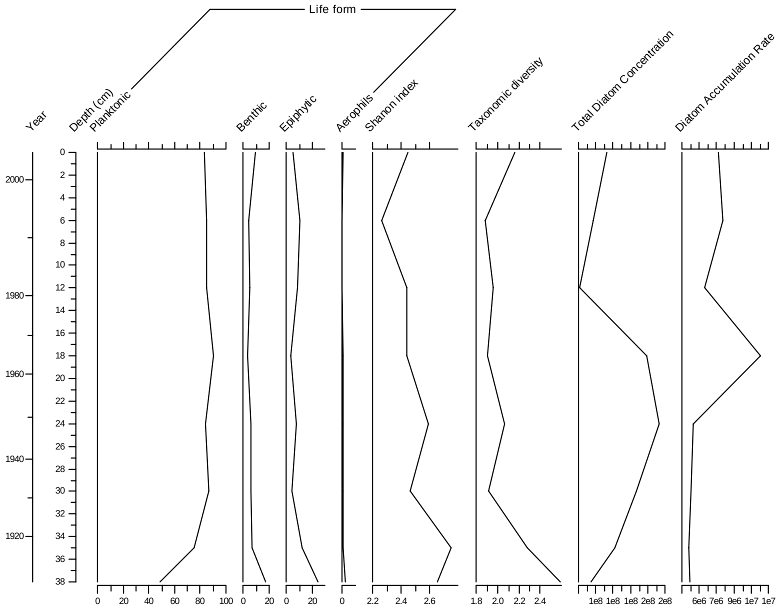


Figure 4.35b: *Life form, diversity, concentration and accumulation rate of diatoms from Sillan Lough. Data are plotted on a depth and age scale.*

5. Synthesis of Results

5.1 Reference time period

The broad geographic range of lake types targeted in WP3 has inevitably resulted in variable sediment accumulation rates. Generally deeper, less productive sites accumulate sediment ~0.2 cm y^{-1} while shallow productive sites range between 0.4-0.5 cm y^{-1}. The seven WP3 lakes have estimated sediment accumulation rates ranging between 0.2 and 0.6 cm y^{-1}. This means that the basal sediment samples have variable reference points as follows: Egish 1766; Crans 1820; Ballybeg 1885; Sillan 1900; Inchiquin 1930; Mullagh <1950 and Atedaun >1950. It has been generally agreed in the UK that *c.* 1850 is a suitable reference date for the assessment of anthropogenically-driven aquatic impacts (Bennion *et al.*, 2004a&b). This date was selected on the basis that any major human impacts occurred after this date (Moss, Johnes & Phillips 1996). However, in many parts of northwestern Europe, including Ireland, profound environmental changes as a result of human activities, such as the impacts of forest clearance, pre-date the 19th century (see, for example, the work of Bradshaw (2001) in Denmark and Leira *et al.* (in press) in Ireland).

The core bottom diatom samples in two of the lakes represent *c.* 1850 AD reference conditions (or before). Core bottom samples for a further four CRLs date to the period between the primary and a possible secondary reference baseline (i.e. *c.* 1850 to *c.* 1950) while one sample is post 1950.

5.2 Down-core variations in sediment chemistry

The sedimentary P chemistry concentrations largely follow the same trend as the diatom-inferred TP profiles. Positive correlations between sedimentary P Fe, and Mn can be linked to solubilisation of Mn and Fe in anoxic sediments, mobility and build-up at the more oxic sediment-water interface boundary (Engstrom and Wright, 1984; Davison, 1993). In such circumstances it can be problematic to interpret increasing TP concentration profiles with increasing exogenic P inputs when the profile might be more related to P/Mn/Fe diagenesis. Boyle (2001) suggested that this movement is more predominant in sediments with extremely low DMAR in the order of 20 $g/m^2/yr$. As DMAR in the WP3 cores are between 200 and 1200 $g/m^2/yr$ (expressed $g/cm^2/yr$ in the Figures), then it is also likely that the Mn, Fe and P profiles are the result of normal deposition processes, at least in some lakes. It is possible that increased water column P concentration from higher P loads to lakes can increase Mn and Fe sedimentation via scavenging (e.g., Mucci *et al.*, 2000). Other work has also shown how P and Mn need not be positively correlated in anoxic sediments (Hongve, 2003). In Atedaun, for example, the build up of Mn towards the sediment surface is not matched with a similar P build-up. The latter is rather more correlated with other indicators of catchment inwash (Fe (in this case), Na and K). It is, perhaps, very difficult, to decouple the effects of redox-driven mobilisation and Mn and P build-up with those of normal deposition processes. Nevertheless, there appears to be some indication of this type of P diagenesis in the P and Mn profiles of Mullagh and Sillan. In other WP3 cores, Mn and P profiles register with other sedimentary profiles that would be independent of redox mobilisation. Increased DMAR in Egish, for example, towards the core surface; increased Ca and concurrent decreases in other catchment cations in Crans at the base of the core; and a positive correlation with P, Mn and K, Na in Inchiquin. These examples all point to changes in sedimentation rate and/or source/type. The very strong link between P, Mn and Fe in Ballybeg is also not independent of other catchment cation indicators and so a definitive link between P and Mn mobilisation remains, at best, loosely deductive and not based on the rest of the data. Mullagh is similar to Crans with an indication of historical mass sediment input changes coincident with the onset of eutrophication (from the DI-TP profiles). The rapid increase in DMAR post 1960 with a concurrent increase in Na, K and Fe does not influence the sedimentary TP profile (which appears to be more related to Mn).

The use of U and Cd, and B as markers for inorganic fertilisers and sewage effluent inputs, respectively, is unresolved in the two lake cores analysed (Crans and Ballybeg). Boron in Crans was not detected by ICP-OES. The Na and K (and Fe, Mn) concentration profiles are similar and may indicate catchment erosion in Ballybeg. In Crans the largest changes in U and Cd concentrations are similarly linked to historical (post 1820) changes in sediment source/type rather than contemporary (post 1950) impacts. The ecological response of the lake (DI-TP) is well synchronised sedimentary P throughout the core history. The decrease in sedimentary P during 1930s to the 19960s in Crans is matched by a concurrent decrease in DI-TP during this period. This decrease is noteworthy in itself as it relates to changing P transfers that are not matched by the loss of other cations that might be expected in terms of changes in hydrological controls (less runoff). Instead it points to changes in P source rather than delivery, but the ecological response is not significant (i.e., it doesn't change trophic state). It is interesting to note that DI-TP in this lake is only in the meso-trophic range at the base of the core (40 cm). This fits with other findings in Northern Ireland where pre-eutrophic conditions have been estimated in the first half of the 19th Century (Anderson, 1997) in dated sediment cores.

5.3 Down-core variations in biological fossils

Diatom preservation was surprisingly good in all seven cores. This was unexpected as analysis of 35 WP2 cores suggested that preservation is often problematic in high alkalinity sites. Figure 5.1 shows a combined plot of all seven lake DI-TP reconstructions while Figure 5.2 illustrates the core samples in ordination (DCA) space to aid in the examination of their floristic status and deviation from reference state. The core bottom samples contain diatom assemblages typical of relatively nutrient poor oligo-mesotrophic conditions. Diatom-inferred TP for the reference samples ranged from 12 to 21 µg l^{-1} (average ~17 µg l^{-1}). The lakes react individually with respect to the onset of nutrient enrichment, although, there is a common pattern of succession of diatom assemblages. The DCA line trajectories for all lake cores follow a similar direction reflecting similar responses to nutrient enrichment (Figure 5.2). All of the cores (with the exception of Atedaun and Inchiquin) show a species succession that represents a clear eutrophication trend. All cores show a shift from a periphytic community to a plankton-dominated one parallel to the increase in diatom-inferred TP. The diatom assemblage changes show rapid and recent increases above 6 cm (post 1980) in DI-TP in the case study sediment cores with the exception of Inchiquin. Both Egish and Ballybeg are known to be impacted by point source effluent discharges (a creamery in Egish and sewage works into Ballybeg), in addition to being situated in agricultural catchments. Enrichment is also evident in levels of sedimentary TP in covariance with DMAR, Fe and Mn. This increase in TP may result from enhanced catchment erosion, increased inputs of soil P and/or in-lake release of sediment P. In addition more long term (post 1850s) and slower rates of change were indicated in cores from Crans and Sillan. In Crans (and to a lesser extent Sillan), the onset of eutrophication as indicated at the base of the core appears more likely to have been driven by catchment clearance or some other disturbance. An apparent recovery in Crans post 1920 is most probably offset by the increasing transfer of P from land to water from diffuse agricultural sources (Jordan *et al.*, 2002) and has maintained this lake in a hypertrophic state. Diatom-inferred TP at Inchiquin suggests that the lake has been mesotrophic throughout its recent history with slight nutrient enrichment post-1990.

Reduced extent of woodland and a concomitant expansion of grass (Poaceae) cover is evident at four of the study sites (Crans, Egish, Mullagh and Sillan) when percent pollen and spore data in the bottom core samples are compared with those in the uppermost core samples analysed. Vegetation in the catchment for Inchiquin appears to have remained relatively stable, with no major changes in the extent of either woodland or grassland cover, whereas woodland cover appears to have increased in the Atedaun and Ballybeg catchments.

The non-tree pollen and spore abundances appear relatively complacent and any differences between core bottom and top/uppermost samples are generally minor, with the exception of Poaceae pollen. This is mainly because of the relatively low abundances of non-tree pollen, once Poaceae pollen has been accounted for, in the sediment core samples analysed. Some of the non-tree data are noteworthy, however: examples include the abundance of Ericaceae pollen in the core bottom sample from Egish, which may indicate peat inwash, and differences between core bottom and top/uppermost samples in levels of *Isoetes* spores and *Myrophyllum* pollen. Species of both *Isoetes* and *Myrophyllum* can be sensitive indicators of water quality: variations in the abundances of *Isoetes* spores can reflect peat inwash, while the abundant presence of *Myrophyllum* could indicate nutrient enrichment and/or increased siltation.

Cladocerans, or water fleas, are a dominant component of the zooplankton and littoral microcrustacean of standing waters. Members of the Daphniidae and Bosminidae families are more common in the open water, while the Chydoridae family comprises mainly benthic/littoral species. Cladocerans are an important component of most freshwater lakes and occupy an intermediate trophic status in food webs and nutrient dynamics. Cladocera remains, which are generally preserved well in lake sediments, are known to provide good proxy records for reconstructing anthropogenic impacts, including nutrient enrichment (Jeppesen *et al.*, 2001). Preservation of cadoceran remains was generally good in both the surface (modern) and bottom (reference) sediments of the seven WP3 lakes.

The planktonic individuals in the sediments of the seven lakes were mainly composed of *Daphnia* and *Bosmina* species, together with an extremely low abundance and/or rare occurrence of *Ilyocryptus* sp., *Leptodora kindti* and *Sida crystalline* (Appendix 2). The species richness of the fossil planktonic community is difficult to assess because of the taxonomic problem with the incomplete *Daphnia* remains (normally only postabdominal claws are preserved), and the fact that other planktonic species with soft shells are not preserved in lake sediments. Planktonic cladocera predominate in the majority of the samples examined from both reference and modern samples reflecting their high representation. Species richness of identified littoral chydorids ranges from 15 to 19 species/group in all of the samples. *Chydorus sphaericus*, *Alona guttata/rectangular*, *A. quadrangularis*, *A. affinis* and *A. rustica* are the most common and/or dominant species for the seven lakes. *Chydorus sphaericus* was dominant or sub-dominant in all the lakes except in Sillan, where *Alona* species dominated.

Sediment core bottom or reference samples generally provide a high abundance of chydorid individuals with a planktonic/littoral ratio less than 1 in Atedaun, Egish, Inchiquin, and Mullagh (Table 5.1). This relative abundance is substantially altered in the surface samples where higher abundances of planktonic cladocera were found in six of the seven WP3 lakes. Ballybeg is the exception, where a slight decrease in the planktonic/littoral ratio was observed. This change is paralleled by a reduction in chydorid species diversity between bottom and surface samples in all lakes with the exception of Egish and Inchiquin. Low chydorid abundances may account for these exceptions.

The increase in the planktonic assemblages between bottom and top samples may indicate a eutrophication trend. Nutrient enrichment can affect the zooplankton, either directly by affecting physiological processes or indirectly through food web effects or habitat changes (Irvine *et al.*, 2001). Oxygen depletion and the build up of H_2S can create chemical stress in the profoundal zone of eutrophic lakes during the summer stagnation (Lampert & Sommer, 1997). In such conditions the deep-water fauna become impoverished and so the planktonic fauna would be comparatively abundant. Biotic effects including fish predation and primary production complicate the implications of zooplanktonic assemblage change (Irvine *et al.*, 2001). For example, the replacement of the larger *Daphnia pulex* group in the reference sample by smaller *Daphnia longispina* group in the surface sample from Mullagh (Appendix 3) may indicate an increase of predation pressure by fish and invertebrates. A shift from littoral to planktonic species may also reflect a decrease in the suitability of the littoral habitat, for example, loss of macrophytes and an increase in algal blooms (REF).

Increased nutrients into a lake are likely to affect the chydorid community in a number of ways. In the initial stages of nutrient enrichment, an increase in the diversity of the macrophytes (and hence substrate for the chydorids) and increased availability of food as periphyton may produce higher abundances and species richness of chydorids. However with increased eutrophication, a switch from a plant dominated lake to a phytoplankton dominated lake may cause a decrease in the species richness owing to changes in the structure of the littoral zone associated with the loss of macrophytes. Water clarity may decrease which could have implications for the benthic periphyton, and oxygen levels may also fluctuate. The relative abundances of *Chydorus sphaericus* showed a clear increase between bottom and surface sediments in four lakes. It has been widely reported that a high proportion of *C. sphaericus* can indicate eutrophication (e.g. de Eyto *et al.*, 2002). A eutrophic lake in which healthy macrophytes have decreased or died out would favour chydorids with a more planktonic lifestyle such as *Chydorus sphaericus*, which may use agglomerations of phytoplankton as its substrate. *C. sphaericus* grazes cyanobacteria and its population often increases markedly during phytoplankton blooms in eutrophic lakes. REF In Lough Sillan, the dominant species shifted from *Alona affinis* to *A. quadrangularis*, together with an increase of *Leydigia leydigii* which is characteristic of more eutrophic conditions and a decrease of *Chydorus piger* which prefers oligotrophic conditions. However, it is unclear whether chydorids respond to TP directly or they are affected more profoundly by concomitant changes in primary producer communities and habitat availability (Jeppesen *et al.*, 2001). Changes in the invertebrate and vertebrate communites with increased nutrient enrichment would also be likely to have an effect on the chydorid communities.

The chydorid assemblage changes between the reference and surface sediment samples are consistent with an increase in lake nutrient levels and this generally corresponds to the diatom-inferred TP results. The increase in planktonic cladocera also reflects a similar pattern of succession of plankton dynamics shown by diatoms, though the mechanisms driving the planktonic communities remain to be clarified. However, the eutrophication dynamics inferred by diatom analysis could be a potentially significant driving force for planktonic cladoceran assemblage change.

5.4 Modern analogue matching

The modern analogue technique is used here to compare surface sediment (modern) datom and fossil or pre-disturbance (reference) assemblages. Analogue matching is utilised as a form of space for time substitution model. The best surface sediment modern analogues from candidate reference lakes (CRLs) are identified for the pre-disturbance or 'reference' diatom assemblages in the seven WP3 case study lakes. These analogue lakes are assumed to have similar community composition to the impacted lakes prior to disturbance and can then provide information on potential restoration target conditions. In order to make reasonable floristic comparisons between a fossil sample (in a sediment core) from the impacted lakes studied in WP3 and modern (2004 surface sediment) samples, a pre-selection of the most suitable modern examples was made based on data available from the 35 WP2 candidate reference lakes. Lakes of similar type as the WP3 case study lakes (based mainly on alkalinity) were selected to form the analogue match training set. The training set is intentionally biased towards medium and high alkalinity lakes as the WP3 study lakes belong to these types. Thirteen CRL were available for the analogue matching training set from typology classes 6, 8, 10 and 12 (see Appendix 5).

The squared chord distance (SCD) dissimilarity coefficient was used to determine the best modern analogues for the reference assemblages of the WP3 study lakes. In this analysis a perfect match has an SCD score of 0 and samples that are completely different have an SCD score of 2. Good analogues are defined as having a squared chord distance dissimilarity coeffcient of less than the 5th percentile (SCD score <0.49) as determined in WP2. The modern analogue diatom training set is comprised of 13 samples and 367 taxa. The common taxa (>2% in at least 2 samples) comprised 62 taxa. The dataset has reasonable representation of the different assemblages present in standing waters and includes taxa ranging from oligotrophic to eutrophic conditions. The assemblages include the non-planktonic *Fragilaria* spp. and planktonic forms such as *Stephanodiscus parvus* and *Aulacoseira ambigua*. The squared chord distance dissimilarity scores between reference samples and the modern analogue training set samples are illustrated in Table 5.2 and Figure 5.3.

There is no good modern analogue for the Atedaun bottom or 'reference' sample in the analogue training set i.e. no modern analogue sample has an SCD score of <0.49 (Figure 5.2). The best match is Lough Bunny with and SCD score of 0.755 (Table 5.2). Like Atedaun, Lough Bunny is a high alkalinity lake and its modern surface sediment sample contains the non-planktonic *Amphora pediculus* similar to the Atedaun reference sample. However, the modern sample from Lough Bunny does not contain the less dominant taxa (*Achnantidium minutissimum*, *Cocconeis* spp) in the same abundance and thus may account for the relatively high dissimilarity score.

There is a good match between the Ballybeg reference sample and the Lough Bane modern analogue training set sample (SCD score 0.365). These sites both have high alkalinity waters, however Ballybeg is a shallow water lake (<4m) while Bane is a deepwater lake (>4m). The surface sample from Lough Bane contains similar diatom flora to the Ballybeg reference sample with *Pseudostaurosira brevistriata*, *Staurosira construens* var. *venter*, *Amphora pediculus* and *Staurosirella pinnata* dominant in both samples.

The squared chord distance dissimilarity scores for the Crans reference sample and the analogue training set samples show no good analogues. Ballynakill is the best match with an SCD score of 0.684. Like Ballynakill, Crans is a medium alkalinity lake. Ballynakill is a shallow lake while Crans has an average depth greater than 4 m. Both samples are characterised by the presence of the planktonic *Aulacoseira subarctica* a species indicative of low-medium nutrient concentrations and *Puncticulata radiosa*. The differences in their relative abundances (*A. subarctica* is dominant in the Crans reference sample) may account for the high dissimilarity score.

Ballynakill performs better as a good analogue for the reference sample from Lough Egish. The SCD score for Ballynakill is 0.397 while Talt has the next best with a score of 0.755. Ballynakill and Egish both have medium alkalinity levels and are shallow water lakes. Ballynakill is currently a mesotrophic lake. Both samples contain similar species in their diatom assemblages including the non-planktonic *Staurosira elliptica* and *Achnanthidium minutissimum*, and the planktonic *Aulacoseira subarctica* and *Cyclotella comensis*.

The dissimilarity scores between the Inchiquin reference sample and the modern analogue training set show no close analogues. The best matches are Loughs Bunny (0.633) and Annaghmore (0.703). All three lakes have high alkalinity levels. However, Inchiquin is a large deepwater lake while the latter two are shallow and small lakes.

The dissimilarity scores between the Mullagh reference sample and the analogue training set indicate that there is no good or even moderate modern analogue. The best matches are Bane (SCD score 1.021), Ballynakill (1.383) and Muckanagh (1.404). Like Mullagh, Ballynakill is a medium alkalinity lake while Bane and Muckanagh are high alkalinity lakes. The reason for the high dissimilarity scores is that these lakes contain relatively low abundances of *Staurosirella pinnata*, *S. elliptica* and *Pseudostaurosira brevistriata*, compared to the greater numbers found in the Mullagh reference sample.

Ballynakill (with an SCD score of 0.622) is again a poor analogue match for Sillan, although the both have medium alkalinity. Sillan is deep lake while the latter is shallow. Like the Sillan reference sample, the modern Ballynakill sample contains a diatom assemblage characterised by the presence of *Aulacoseira ambigua*, *Achnanthidium minutissimum*, *Aulacoseira subarctica* and *Puncticulata radiosa*. The reason for the relatively high dissimilarity scores is that the training set samples do not contain the relatively high abundance of the planktonic taxa *Aulacoseira granulata* seen in the Sillan reference sample.

In summary, the lower the dissimilarity coefficient the more similarity between the reference and modern assemblages. The minimum acceptable dissimilarity coefficient using the 5th percentile was calculated as 0.49 for the IN-SIGHT dataset to achieve good analogues. With this level of rigour good modern analogues are achieved for two of the seven WP3 lakes (Ballybeg and Egish). No modern analogues were achieved for the other five reference samples using the current 13 sample analogue training set.

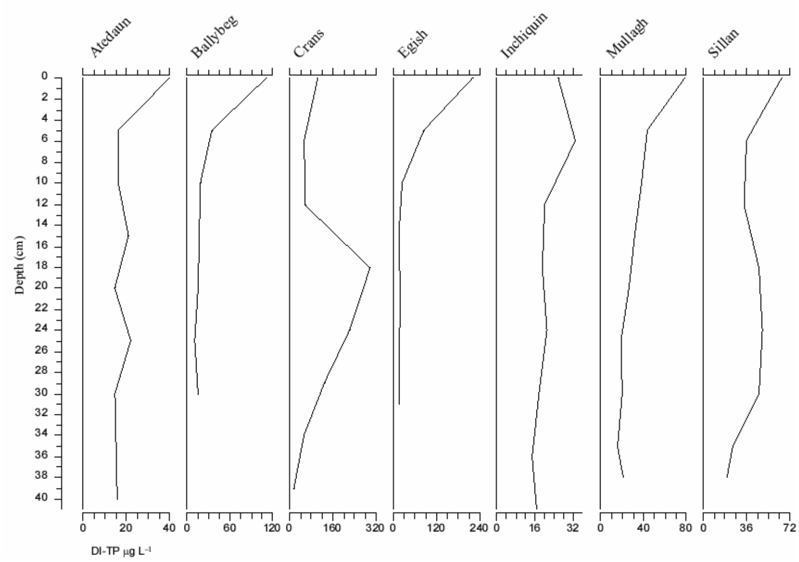


Figure 5.1: *Summary of DI-TP changes in all lakes studied plotted against depth (cm)*

Table 5.1: *Summary of planktonic and littoral cladocera and Shannon Diversity Index (H) of chydorid species for the seven WP3 lakes.*

Lake	Atedaun		Ballybeg		Crans		Egish		Inchiquin		Mullagh		Sillan	
Depth (cm)	**0-1**	**39-40**	**0-1**	**30-31**	**0-1**	**39-40**	**0-1**	**31-32**	**0-1**	**40-41**	**0-1**	**38-39**	**0-1**	**38-39**
% Planktonic	30	12	60	66	96	80	92	14	84	46	74	43	75	66
% Littoral	70	88	40	34	4	20	8	86	16	54	26	57	25	34
Planktonic/Littoral	0.43	0.14	1.48	1.94	25.27	4.12	11.02	0.16	5.07	0.86	2.80	0.75	3.03	1.94
Chydorid diversity (H)	2.44	2.47	2.07	2.36	2.08	2.33	2.26	1.78	2.38	2.25	2.14	2.43	2.41	2.57

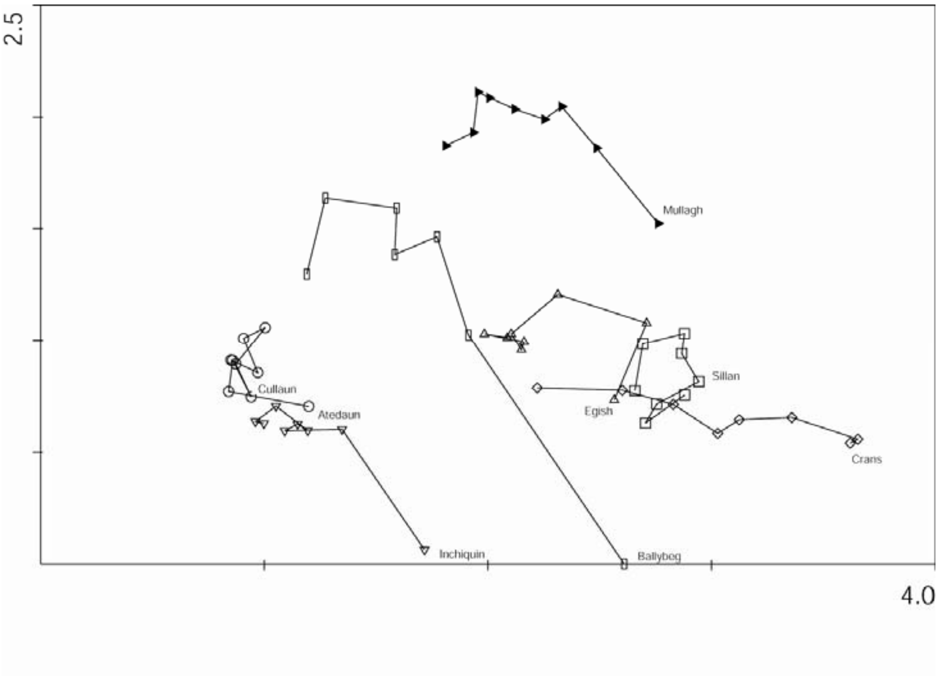
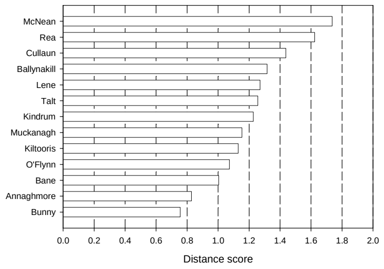


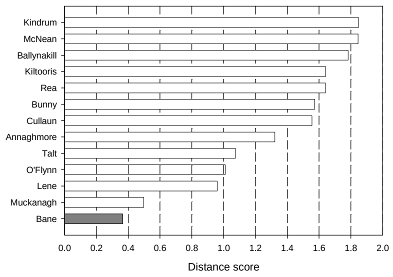
Figure 5.2: *DCA biplot combining all sediment samples from seven WP3 lake. The surface sample (2004) for each WP3 core is labelled and fossil samples from that core are linked with connecting lines.*

Table 5.2: *Summary of square chord distance (SCD) scores for WP3 test lakes (reference sample) and surface and the closest CRL modern analogue (species abundances >2%)*

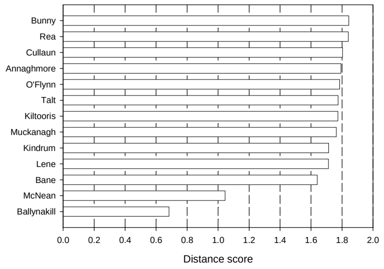
Test Lake	**Closest Modern Analogues**		**Minimum SCD**
	Good SCD <0.49	**Poor SCD <0.71**	
Atedaun			0.755
Ballybeg	Bane	Muckanagh	**0.365**
Crans		Ballynakill	0.684
Egish	Ballynakill		**0.397**
Inchiquin		Bunny/Annaghmore	0.663
Mullagh			1.021
Sillan		Ballynakill	0.623



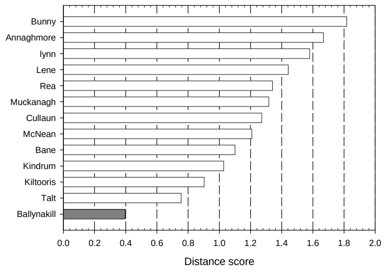
Atedaun



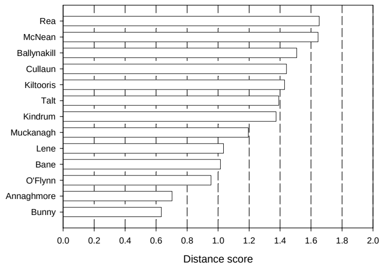
Ballybeg



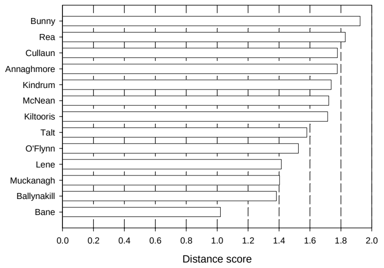
Crans



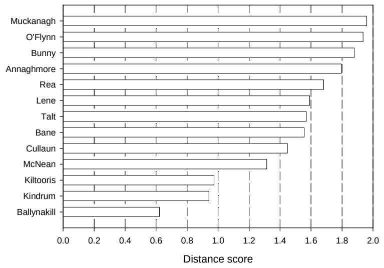
Egish



Inchiquin



Mullagh



Sillan

Figure 5.2: *Histograms of the squared chord distance dissimilarity scores between WP3 reference samples and the modern analogue training set samples. Samples less than the 5th percentile (<0.49) are highlighted..*

6. Discussion

6.1 Ecological reference conditions

A key deliverable in IN-SIGHT work package 3 is to describe the ecological reference conditions based on palaeolimnological data for lake types which have no existing modern examples of existing reference conditions. The seven WP3 lakes represent medium-high alkalinity lake types (EPA typology classes 5, 6, 7, 8, 9 and 12). Typology classes 5, 7 and 9 have no CRLs in the IN-SIGHT project while there were problems in terms of the sediment core chronologies and diatom preservation in 6, 8 and 12.

The reference diatom assemblage (estimated to be post-1950) of Atedaun is dominated by non-planktonic taxa. No chronology was available for the Atedaun sediment core due to a poorly resolved ^{210}Pb dating profile. The most abundant species are *Amphora pediculus* and the benthic *Achnanthidium minutissimum*. The assemblage is very diverse with occurrence of a large number of taxa (77) in relatively low percentages. The assemblage is indicative of waters with low to medium nutrient concentrations. The abundance of *Amphora pediculus* and *Achnanthidium minutissimum* reflects the shallow nature of the lake. The presence of taxa associated with epiphytic habitats suggests that macrophytes were present. These reference conditions are supported by the cladoceran remains where highly diverse hard shelled benthic chydorid taxa predominate in the reference assemblages (88%). The dominance of *Alonella exigua* and *Graptoleberis testudinaria* suggest abundant macrophyte presence and confirms medium nutrient concentrations.

The reference diatom assemblage (*c.* late 1800s) of Ballybeg is relatively diverse with 88 different taxa and is dominated by non-planktonic taxa *Pseudostaurosira brevistriata* and *Staurosira construens*. This assemblage is typical of alkaline, shallow lakes of intermediate nutrient status. These species grow attached to plant surfaces or on the surface sediments. Planktonic cladocera dominate the littoral chydorids in the reference assemblage from Ballybeg (66%:34%). Mesotrophic chydorid species *Acroperus harpae* along with *Chydorus sphaericus* are noticeably dominant in the reference sample.

The diatom flora of Crans is relatively diverse with 99 taxa. The reference assemblage (*c.* early 1800's) and is dominated by the planktonic species *Aulacoseira subarctica*. *Stephanodiscus medius*, a small centric planktonic diatom and *Aulacoseira ambigua*, another planktonic diatom, are also present. These taxa are commonly associated with alkaline, productive waters. A very high cladoceran planktonic/littoral ratio (80%:20%) is evident in the reference sample consisting mainly of *Daphnia*. In the chydorid assemblage there is a predominance of species *Alonella nana*, *Alona guttata/rectangular* and *A. affinis* which have low to moderate TP optima. The presence of these species suggest availability of suitable littoral habitats.

The reference diatom assemblage (*c.* late-1700's) of Lough Egish is dominated by non-planktonic taxa (*c.* 83% of the whole assemblage). The most abundant species are the small, benthic *Staurosira elliptica* and *Pseudostaurosira brevistriata*. The assemblage is very diverse with occurrence of a large number of taxa (72) in low percentages. The planktonic component is represented by *Aulacoseira subarctica*, although in low abundance (7.5%). The asssemblage is indicative of waters with low to medium nutrient concentrations. The importance of the periphytic community indicates the shallow nature of the lake. Epiphytic taxa are present in large numbers (>43%) suggesting an extensive presence of macrophytes. The chydorid assemblage dominates the Egish reference sample with a very high planktonic/littoral ratio (14%:86%). This dominant littoral assemblage also has the lowest diversity of the WP3 samples examined. The reference sample is dominated by *Alona rustica* which has a very low TP optima and tolerance range and can indicate dystrophic conditions.

The diatom flora of Inchiquin (*c.* early 1900s) is diverse with 77 taxa, all present in relatively low percentages, and is dominated by non-planktonic assemblages comprising *Amphora pediculus* and *Achnanthidium minutissimum*. The planktonic component is comprised of *Stephanodiscus* *parvus*, indicative of nutrient enrichment, although in low numbers (*c.* 5%). The planktonic cladocera are proportionally well balanced with the benthic chydorid assemblage (46%:54%) compared to other reference samples. Meso-eutrophic *Chydorus sphaericus* and mesotrophic *Alona guttata/rectangular* indicate meso-eutrophic conditions in these reference assemblages.

The reference diatom assemblage (*c.* mid- 1900s) of Mullagh is similar to that of Egish. It is relatively diverse (83 taxa) and is dominated by the non-planktonic taxa *Staurosirella pinnata*, *Staurosira elliptica*, *Pseudostaurosira brevistriata*, and *Fragilaria pseudoconstruens*. The large numbers of benthic taxa are indicative of shallow waters and the high percentage of epiphytic taxa suggests the abundance of macrophytes. This dominance of benthic diatom taxa is reflected in the cladoceran community structure where the proportion of cydorid species (57%) exceed the planktonic species (43%). High levels of *Alona quadrangularis* and *Chydorus sphaericus* are present reflecting moderate nutrient status.

The reference diatom flora of Sillan (*c.* 1900) is dominated by planktonic taxa (49% of the whole assemblage). The most abundant taxa are *Aulacoseira ambigua*, *A. subarctica*, *A. granulata* var. *angustissima*, *Puncticulata radiosa* and benthic *Achnanthidium minutissimum*. The assemblage is indicative of relatively deep waters with medium to high nutrient concentrations. The abundance of epiphytic taxa (25% of the assemblage) suggests a wider distribution of macrophytes than in the present. The cladoceran planktonic/littoral ratio (66%:34%) in the Sillan reference sample is paralleled by the highest chydorid species diversity for the WP3 reference samples. The reference sample is dominated by *Alona affinis* and various species with oligo-mesotrophic preferences.

In summary, the natural variability of reference-state in lakes is potentially very broad and reflects their different morphometries, range of habitats and the higher alkalinity and productivity of shallow waters. Reference assemblages are dominated by epiphytic diatoms and littoral cladocera who favour abundant macrophyte cover. They indicate healthier systems with more diverse communities.

6.2 Restoration targets and lake management

These data from the WP3 case study lakes provide an indication that a historical reference date of 1850 (e.g., Leira *et al.*, in press) may not be tenable in all situations and that more recent reference conditions (and dates) will be lake and/or catchment specific. In terms of managing lake trophic status under the Water Framework Directive, managing towards a 20-40 year old reference status might seem more appropriate (and achievable) than managing towards a 150 year old standard. In sites that experienced early onset of eutrophication (e.g. Crans and Sillan) the 1850 date may be more appropriate as a reference target while the palaeolimnological data from Egish and Ballybeg suggests that a reference condition (i.e. oligo-mesotrophic) was evident in recent years and attainment of similar reference conditions might be achieved by control of point source discharges.

An analogue matching training set of modern reference samples was developed using the WP2 candidate reference lakes. Just 13 lakes were available for matches in the medium-high alkalinity lake types (similar to the WP3 case study lakes). Selection of sites from the Irish Ecoregion has the advantage of minimising biogeographical differences. The SCD score or dissimilarity coefficient was applied to identify the best matches or modern analogues for the 'reference' assemblages of the seven test lakes. The test procedure identified modern reference samples as close matches for two, and poor analogues for another three of the seven test lakes. These modern analogues can potentially act as physical, chemical and biological target conditions for the impacted system.

The low number of good modern analogues for the fossil reference samples suggest that: a) the reference diatoms are not reflecting these modern conditions; b) the reference conditions are unique; or c) the range of hydrochemical conditions included in the training set is too small. Pre-disturbance assemblages contain higher abundances of benthic diatom assemblages. These species are less well represented in the training set sites. This then constrains the number of good analogue matches for pre-disturbance reference conditions

Other applications of the modern analogue techniques to define reference conditions have benefited from more training set samples. Flower (1997) used a training set of 194 lakes, while Simpson *et al.*, (2005) used 83 lakes. Both of these studies looked at acidic waters. In perhaps the most relevant study Bennion *et al.*, (2004a) utilised a training of 30 lakes to identify modern analogues for lakes impacted by eutrophication. Despite this relatively broad range of training set samples no good analogue matches were found using diatoms for the three test lakes. However the same procedure was then applied to cladoceran assemblages and a combined diatom-cladocera training set and this increased the number of close analogue matches.

In summary, the results suggest that the analogue matching procedure does have the potential to be a useful tool for identifying appropriate restoration targets for enriched lakes. The present study is limited by the small size of the analogue matching training set. The results suggest that a larger dataset is needed. A logical step for future research is to expand the floristic comparisons by adding more modern reference lakes to the training set and to include faunistic comparisons by applying the same procedure to cladocera and/or other biological fossils.

6.3 Summary and Conclusions

1. Seven lakes covering the main types of mesotrophic to hypertrophic lakes occupying lowland agricultural catchments in the Irish Ecoregion were selected for detailed palaeolimnological analysis.
2. Lithostratigraphic investigations indicated wide variations in the proportions of water content (as %DW) and organic matter (as %LOI) with distinct peaks and troughs. These are generally in phase with sediment geochemistry concentrations and organic content increases with nutrient enrichment.
3. Sediment geochemistry revealed positive correlations between sedimentary P, Fe and Mn and relatively high levels of DMAR were established for the study sites.
4. Chronological control was achieved for six of the seven lakes using radiometric analysis (using the constant rate of supply (CRS) and constant initial concentration (CIC) and verified using measurements of ^{137}Cs activity). Estimated rates of sediment accumulation varied from 0.017 ± 0.004 g cm^{-2} yr^{-1} to 0.12 ± 0.02 g cm^{-2} yr^{-1}.
5. Estimated ages of core bottom samples are lake specific as follows:- Egish 1766; Crans 1820; Ballybeg 1885; Sillan 1900; Inchiquin 1930; Mullagh <1950 and Atedaun >1950.
6. The reference samples show diatom assemblages and cladoceran assemblages typical of relatively nutrient poor oligo-mesotrophic conditions. They indicate a healthier ecosystem with more diverse communities of diatoms, cladocera and vegetation in nearly all cases. Diatom-inferred TP for the reference samples ranged from 12 to 21 µg l^{-1} (average ~17 µg l^{-1}).
7. The diatom and cladoceran fossil assemblages show a shift from benthic to planktonic species dominated production and a less diverse community in a comparison of pre- and post disturbance conditions and are consistent with an increase in lake nutrient levels.
8. Diatom assemblage changes show rapid and recent increases (post 1980) in DI-TP in case study sediment cores from Atedaun, Ballybeg, Egish, and Mullagh. More longterm and slower rates of change was indicated in cores from Crans (post 1850s) and Sillan (post 1900s). No change was determined for the Inchiquin reconstruction but it has experienced a recent (1990s) increase in the abundance of planktonic species at the expense of the benthic assemblages.
9. The Modern Analogue Technique and SCD dissimilarity score proved a useful tool for assessing target reference conditions for lakes impacted by eutrophication. MAT helped determine good analogue matches for two impacted lakes. The approach could be expanded with the inclusion of more modern reference sites and by applying the same procedure to cladocera and/or other biological fossils.
10. The application of multi-proxy palaeolimnological techniques to the seven test lakes illustrates the potential of the sediment record for providing an integrated

ecosystem assessment of reference condition. Whilst the data can be somewhat difficult to interpret due to the complexity of some of these systems, the multi-indicator data reflect a shift in the functioning of most of the lakes from benthic-littoral to planktonic dominated production. The study demonstrates the ability of this tool to provide comprehensive information on the functioning of the system.

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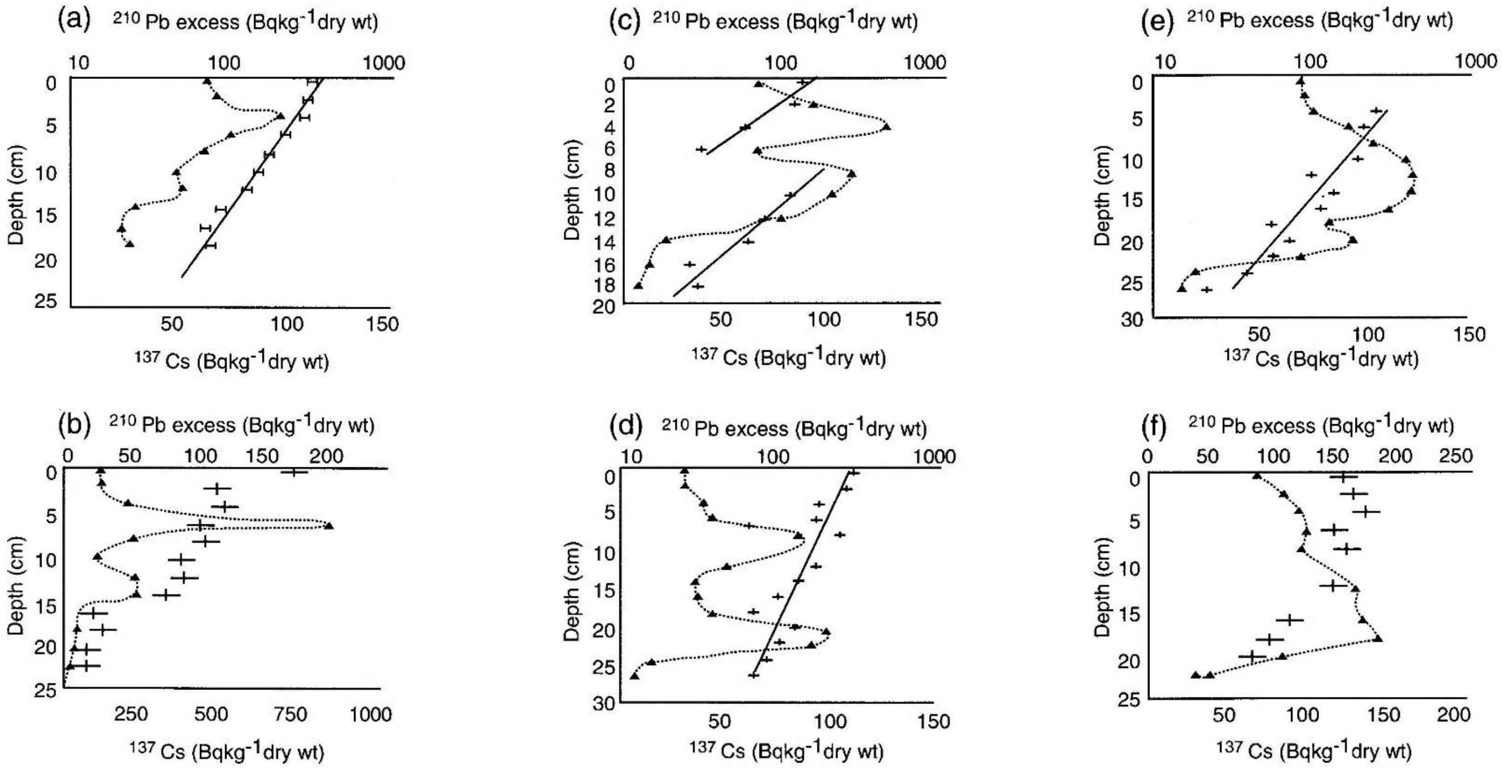
8. Appendices

Appendix 1: Core chronologies
Appenidx 2: Diatom taxa
Appendix 3: Cladocera data summary
Appendix 4: Pollen data summary
Appendix 5: Modern analogue training set details

Appendix 1: *Core chronologies (dated by ^{210}Pb and transferred to other longer cores using basal stratigraphic correlation of dry weight and organic matter content profiles and extrapolation of basal sediment accumulation rate – figures in bold are extrapolations).*

Depth	Ballybeg Year	Crans Year	Egish Year	Inchiquin Year	Mullagh Year	Sillan Year
0-1cm	2002.7	2000.3	2003.6	2003.2	2003.4	2002.8
1-2cm	2001.2	1996.8	2002.3	2002.1	2002.3	2000.9
2-3cm	1998.7	1994.6	2000.2	2000.8	2001.2	1999.0
3-4cm	1995.7	1991.8	1998.7	1999.4	2000.2	1997.0
4-5cm	1992.9	1988.5	1997.4	1998.1	1998.3	1995.5
5-6cm	1990.0	1985.4	1996.0	1996.6	1996.2	1994.1
6-7cm	1987.5	1980.5	1995.2	1995.1	1994.2	1992.0
7-8cm	1984.8	1976.1	1994.4	1993.5	1992.1	1990.3
8-9cm	1981.9	1970.1	1987.8	1991.9	1989.6	1988.1
9-10cm	1978.5	1964.3	1978.9	1990.1	1987.0	1986.1
10-11cm	1975.1	1959.8	1971.8	1988.1	1984.4	1984.2
11-12cm	1971.0	1953.8	1958.4	1986.6	1981.7	1981.9
12-13cm	1966.8	1947.9	1950.9	1985.1	1979.8	1979.8
13-14cm	1962.8	1941.4	1944.4	1983.6	1978.1	1976.9
14-15cm	1958.7	1934.8	1937.8	1982.3	1976.5	1974.0
15-16cm	1955.1	1931.1	1929.9	1980.8	1975.4	1970.6
16-17cm	1950.7	1927.8	1922.5	1979.2	1974.1	1967.1
17-18cm	1946.1	1924.0	1913.5	1977.5	1972.9	1964.0
18-19cm	1940.6	1920.4	1904.1	1975.8	1971.7	1961.0
19-20cm	**1935.9**	1917.0	**1893.0**	1974.4	1970.5	1958.2
20-21cm	**1931.6**	1913.0	**1883.3**	1972.9	1967.7	1955.7
21-22cm	**1926.3**	1908.4	**1873.9**	1971.6	1964.3	1953.4
22-23cm	**1920.8**	1903.5	**1864.1**	1969.4	1962.5	1950.8
23-24cm	**1915.9**	1899.9	**1852.6**	1967.3	1960.3	**1948.5**
24-25cm	**1911.1**	1896.4	**1842.9**	1965.1	1958.4	**1946.1**
25-26cm	**1906.4**	1892.2	**1831.2**	1962.8	1956.3	**1943.8**
26-27cm	**1902.5**	1888.0	**1819.1**	1960.3	1954.0	**1941.2**
27-28cm	**1897.6**	1884.1	**1809.3**	1957.9	1951.9	**1938.7**
28-29cm	**1893.1**	1880.1	**1798.9**	1955.4	1949.8	**1934.9**
29-30cm	**1889.5**	1875.9	**1789.5**	**1952.9**	**1947.7**	**1931.8**
30-31cm	**1885.1**	1871.2	**1780.9**	**1950.6**	**1945.3**	**1929.1**
31-32cm		**1866.6**	**1773.8**	**1948.3**	**1942.9**	**1926.0**
32-33cm		**1861.8**	**1766.6**	**1945.9**		**1923.0**
33-34cm		**1856.7**		**1943.4**		**1920.1**
34-35cm		**1851.3**		**1941.0**		**1916.9**
35-36cm		**1845.7**		**1938.5**		**1913.7**
36-37cm		**1839.9**		**1935.8**		**1909.8**
37-38cm		**1834.3**		**1933.2**		**1904.9**
38-39cm		**1827.9**		**1930.6**		**1900.3**
39-40cm		**1821.6**				

Figure 1: *Down-core variations in ^{137}Cs (dotted line) and ^{210}Pb$_{excess}$ (with 1SD error bars) (a) Ballybeg; (b) Crans; (c) Egish; (d) Inchiqin (e) Mullagh; (f) Sillan.*



Appendix 2: *Diatom Taxa (taxon name and authority)*

Name
Achnanthes conspicua A.Mayer
Achnanthes minutissima Kutzing var. *jackii* (Rabenhorst) Lange-Bertalot
Achnanthes petersenii Hustedt
Achnanthidium alteragracillima (Lange-Bertalot) Round & Bukhtiyarova
Achnanthidium caledonicum (Lange-Bertalot) Lange-Bertalot
Achnanthidium minutissima (Kütz.) Czarnecki var. *affinis* (Grun.) Bukht.
Achnanthidium minutissimum (Kütz.) Czarnecki
Achnanthidium pusillum (Grun. in Cl. & Grun) Czarnecki
Achnanthidium saprophila (Kobayasi et Mayama) Round & Bukhtiyarova
Amphora inariensis Krammer
Amphora pediculus (Kutzing) Grunow
Asterionella formosa Hassall
Asterionella ralfsii W.Smith var. *ralfsii*
Aulacoseira alpigena (Grunow) Krammer
Aulacoseira ambigua (Grun.) Simonsen
Aulacoseira distans (Ehr.)Simonsen
Aulacoseira granulata (Ehr.) Simonsen
Aulacoseira granulata (Ehr.) Simonsen var. *angustissima* (O.M.)Simonsen
Aulacoseira humilis (Cleve-Euler) Genkal et Trifonova
Aulacoseira islandica (O.Muller) Simonsen subsp. *helvetica* (O.M.)Simonsen
Aulacoseira islandica (O.Muller) Simonsen
Aulacoseira subarctica (O.Muller) Haworth
Brachysira brebissonii Ross in Hartley ssp. *brebissonii*
Brachysira exilis Round & Mann
Brachysira garrensis (Lange-Bertalot & Krammer) Lange-Bertalot
Brachysira procera Lange-Bertalot & Moser
Cocconeis neothumensis Krammer
Cocconeis placentula Ehrenberg var. *placentula*
Cocconeis placentula Ehrenberg var. *lineata* (Ehr.)Van Heurck
Cyclostephanos dubius (Fricke) Round
Cyclostephanos invisitatus (Hohn & Hellerman)Theriot Stoermer & Hakansson
Cyclostephanos tholiformis Stoermer Hakansson & Theriot
Cyclotella atomus var. *gracilis* Genkal & Kiss
Cyclotella comensis Grunow in Van Heurck
Cyclotella delicatula Hustedt
Cyclotella distinguenda var. *distinguenda* Hustedt
Cyclotella gordonensis Kling & Håkansson
Cyclotella krammeri Håkansson
Cyclotella ocellata Pantocsek
Cyclotella polymorpha Meyer & Hakansson
Cyclotella pseudostelligera Hustedt
Cyclotella schumanni (Grunow) Håkansson
Cyclotella striata (Kutzing) Grunow 1880 in Cleve & Grunow
Cymbella affinis Kutzing var. *affinis*
Cymbella helvetica Kutzing
Cymbella laevis Naegeli in Kutzing var. *laevis*
Denticula tenuis Kutzing

Encyonema neogracile Krammer
Encyonema perpusillum (A. Cleve) D.G. Mann
Encyonema silesiacum (Bleisch in Rabh.) D.G. Mann
Encyonopsis cesatii (Rabenhorst) Krammer
Encyonopsis microcephala (Grunow) Krammer
Encyonopsis minuta Krammer & Reichardt
Eolimna minima (Grunow) Lange-Bertalot
Eunotia arcus Ehrenberg var. *arcus*
Eunotia implicata Nörpel, Lange-Bertalot & Alles
Eunotia incisa Gregory var. *incisa*
Eunotia pectinalis (Kutz.)Rabenhorst var. *undulata* (Ralfs) Rabenhorst
Eunotia rhomboidea Hustedt
Fragilaria brevistriata Grunow var. *inflata* (Pantocsek) Hustedt
Fragilaria capucina Desmazieres var. *capucina*
Fragilaria capucina Desmazieres var. *vaucheriae* (Kutzing) Lange-Bertalot
Fragilaria crotonensis Kitton
Fragilaria gracilis Østrup
Fragilaria lapponica Grunow in van Heurck
Fragilaria pseudoconstruens Marciniak
Fragilaria robusta (Fusey) Manguin
Fragilaria ulna Sippen *angustissima* (Grun.) Lange-Bertalot
Fragilaria virescens Ralfs
Frustulia erifuga Lange-Bertalot & Krammer
Frustulia krammeri Lange-Bertalot & Metzeltin
Frustulia saxonica Rabenhorst
Gomphonema exilissimum (Grun.) Lange-Bertalot & Reichardt
Gomphonema lateripunctatum Reichardt & Lange-Bertalot
Gomphonema minutum f.*curtum* (Hustedt) Lange-Bertalot & Reichardt
Gomphonema olivaceum (Hornemann) Brébisson var. *olivaceum*
Gomphonema parvulum (Kützing) Kützing var. *parvulum* f. *parvulum*
Gomphonema pumilum (Grunow) Reichardt & Lange-Bertalot
Karayevia clevei (Grun. in Cl. & Grun.) Round & Bukhtiyarova
Karayevia laterostrata (Hust.) Kingston
Mastogloia elliptica (C.A. Agardh) Cleve
Mastogloia lacustris (Grunow) van Heurck
Mastogloia smithii Thwaites
Navicula cari Ehrenberg
Navicula cryptotenelloides Lange-Bertalot
Navicula heimansioides Lange-Bertalot
Navicula radiosa Kützing
Navicula vitiosa Schimanski
Nitzschia bacillum Hustedt
Nitzschia denticula Grunow
Nitzschia perminuta (Grunow) M.Peragallo
Peronia fibula (Breb.ex Kutz.)Ross
Pinnularia irrorata (Grunow) Hustedt
Pinnularia subcapitata Gregory var. *subcapitata*
Planothidium hauckianum (Grun.) Round & Bukhtiyarova
Psammothidium altaicum Bukhtiyarova
Psammothidium oblongellum (Oestrup) Van de Vijver

Psammothidium pseudoswazi (Carter) Bukht. et Round
Psammothidium sacculum (Carter) Bukhtiyarova et Round
Psammothidium subatomoides (Hustedt) Bukht.et Round
Pseudostaurosira brevistriata (Grun.in Van Heurck) Williams & Round
Puncticulata comta (Ehr.)Håkansson
Puncticulata radiosa (Lemmermann) Håkansson
Rhoicosphenia abbreviata (C.Agardh) Lange-Bertalot
Stauroforma exiguiformis Flower Jones et Round
Staurosira construens Ehr. var *venter* (Ehr.) Hamilton
Staurosira construens Ehrenberg
Staurosira elliptica (Schumann) Williams & Round
Staurosira martyi (Heribaud) Lange-Bertalot
Staurosirella pinnata (Ehr.) Williams & Round
Stephanodiscus alpinus Hustedt in Huber-Pestalozzi
Stephanodiscus hantzschii fo. *tenuis* (Hustedt) Håkansson et Stoermer
Stephanodiscus hantzschii Grunow in Cl. & Grun. 1880
Stephanodiscus medius Håkansson
Stephanodiscus neoastraea Hakansson et Hickel
Stephanodiscus parvus Stoermer et Hakansson
Stephanodiscus rotula (Kutzing) Hendey
Tabellaria flocculosa (Roth) Kutzing

Appendix 3: *Cladocera data summary (for surface and bottom sediments of 7WP3 lakes)*

Species-Lake		**Atedaun**		**Ballybeg**		**Crans**		**Egish**		**Inchiquin**		**Mullagh**		**Sillan**	
Depth (cm)		**0-1**	**39-40**	**0-1**	**30-31**	**0-1**	**39-40**	**0-1**	**31-32**	**0-1**	**40-41**	**0-1**	**38-39**	**0-1**	**38-39**
Chydorid (Littoral Cladocera)	*Acroperus harpae*	8	3	2	13	2	7	3	2	6	2	3	1	3	3
	Alona affinis	3	6	7	8	2	7	11	3	6	14	9	19	21	9
	Alona costata	6	2	4	4	1	4		1	4	2	2	2	1	2
	Alona guttata/rectangula	12	18	14	10	16	17	12	12	14	11	10	11	11	10
	Alona intermedia	1	2						3	1		4	3	6	4
	Alona quadrangularis	3	5	3	6	5	10	23	1	4	20	20	34	5	20
	Alona rustica		2		1		3	10	50		1	1	1	1	1
	Alona sp.(small)	5				1	2		1	9					
	Alonella excisa	13	5	5	6			3	3	4		2	2	4	2
	Alonella exigua	4	13	1	2	1	3			1		1	1	2	1
	Alonella nana	9	7	8	6	4	21	3	4	9	12	15	6	6	15
	Alonopsis elongata						1	2		3		1	2	2	1
	Camptocercus rectirostris	2	1		1			1	1	1		3	1	2	3
	Chydorus piger	1	1				1	4	2	1	2	5	1	4	5
	Chydorus Sphaericus	22	15	40	30	15	19	22	6	28	30	23	5	2	23
	Eurycercus lamellatus	4	2	4	3	1	2	3		4	3	2	1		2
	Graptoleberis testudinaria	5	14	3	3	8	9	2	2	2	4	2	3	3	2
	Leydigia leydigii			1	1	1	2	1			2	1	5	1	1
	Monospilus dispar					1	2		1	1	1	1	1	4	1
	Oxyurella tenuicaudis					1		3							
	Phrixura rostrata		1						1				1	3	
	Pleuroxus aduncus			1	3										
	Pleuroxus denticulatus		1												
	Pleuroxus laevis	3		1		1			1	1					
	Pleuroxus trigonellus	2	2	2	3					1	2		7		
	Pleuroxus truncatus			1	1					2					
	Pleuroxus uncinatus										1	4	5	2	4
	Rhynchotalona falcata												1		
	Unknown Chydorid	2	4	1	0	0	3	0	0	0	0	1	1	4	1
Subtotal of Chydorid		**105**	**103**	**98**	**101**	**60**	**113**	**103**	**94**	**102**	**100**	**107**	**110**	**114**	**87**
Planktonic Cladocera	*Bosmina longirostris*		4	123	174	58	381	118	1	6	196	46	103	90	46
	Bosmina longispina		3		1				1	12	8	2	88	32	2
	Bosmina sp.	3	1						1	41					
	Daphnia longispina group	40	5	22	21	1219	79	1012	11	429	94	2	150	45	2
	Daphnia pulex group					239	3	2		29		32	1		32
	Ilyocryptus sp.	1													
	Leptodora kindti							2			1		3		
	Sida crystallina	1					2	1	1		1	1		2	1
Subtotal of Planktonic		**45**	**14**	**145**	**196**	**1516**	**465**	**1135**	**15**	**517**	**86**	**300**	**83**	**345**	**169**
Total		**150**	**117**	**243**	**297**	**1576**	**578**	**1238**	**109**	**619**	**186**	**407**	**193**	**459**	**256**

Appendix 4: *Pollen data summary. (Data underlined are for core bottom samples AT = Atedaun, BA = Ballybeg, CR = Crans, EG = Egish, IN =Inchiquin, MU = Mullagh, SI = Sillan).*

Sample id. & depth (cm)	**Deciduous tree (% sum = total excluding damaged)**	***Alnus* (% sum = tree pollen)**	***Betula* (% sum = tree pollen)**	Corylus *(% sum = tree pollen)*	***Fagus* (% sum = tree pollen)**	***Fraxinus* (% sum = tree pollen)**	***Pinus*-type (% sum = tree pollen)**	***Quercus* (% sum = tree pollen)**	***Salix* (% sum = tree pollen)**	***Ulmus* (% sum = tree pollen)**	**Poaceae *(% sum = total excluding damaged)***	**Ericaceae (% sum = total excluding damaged)**	***Isoetes* (% sum = total excluding damaged)**	***Myriophyllum* (% sum = total excluding damaged)**
AT 00-01	46	5	6	61	1	1	16	5	1	3	23	0	0	0
AT 10-11	43	12	8	48	0	5	9	7	7	2	34	1	0	0
AT 39-40	35	17	5	42	0	0	9	18	3	6	34	3	0	0
BA 00-01	25	8	0	31	0	2	33	25	0	0	30	0	0	0
BA 30-31	30	20	0	33	2	0	6	34	3	2	38	0	0	0
CR 10-11	15	19	0	12	2	2	21	36	5	0	68	4	1	0
CR 39-40	34	15	10	28	7	1	7	28	1	3	41	3	1	0
EG 05-06	47	21	10	38	0	0	7	18	1	5	36	1	1	1
EG 31-32	62	30	6	47	0	0	2	12	1	2	13	7	2	3
IN 00-01	35	6	6	41	0	3	18	23	2	0	37	1	0	0
IN 40-41	36	4	3	48	0	0	16	26	2	1	32	1	0	0
MU 10-11	52	16	7	45	2	0	8	19	0	3	26	2	0	5
MU 38-39	70	16	7	47	0	0	6	20	0	4	15	1	0	1
SI 15-16	41	23	8	32	0	2	9	21	3	2	34	2	5	3
SI 38-39	49	22	7	33	0	0	11	24	0	2	21	2	5	7

Appendix 5: *Modern analogue training set details*

Lake name	**Co.**	**Grid Ref.**	**Altitude (m)**	**Lake area (ha)**	**Catchment area:lake area**	**Max. found depth (m)**	**pH**	**Conductivity (μS cm^{-1})**	**Alkalinity (mg/L^{-1} $CaCO_3$)**	**Colour mg l^{-1} PtCo/ Hazen**	**Chlorophyll *a* ug l^{-1}**	**PO_4-P μg l^{-1}**	**TP μg l^{1}**	**TN mg l^{-1}**
Annaghmore	RN	M 900 837	46	53.1	7.45	5.7	8.46	351	159.4	19	0.4	<10	6	0.48
Ballynakill	CE	L 856 225	13	23.9	5.90	16.4	7.1	244	20.02	20	3.71		5	<1
Bane	WH	N 550 712	112	75.4	6.23	16.9	8.43	297	132.5	1	1.4	<10	5	0.46
Bunny	CE	R 375 967	17	102.9	9.05	11.6	8.47	361	156.2	9	1.4	<10	5	0.37
Cullaun	CE	R 315 905	16	49.7	26.58	20.1	8.40	393	172.0	16	0.8	<10	6	0.53
Kiltooris	DL	G 676 972	7	43.5	12.76	13.5	7.18	205	27.43	33	1.41	<5	14	<1
Kindrum	DL	C 185 430	8	60.8	6.03	11.0	8.27	318	69.47	26	5.52	0	11	<1
Lene	WH	N 510 685	93	416.2	3.11	19.7	8.46	250	104.9	4	3.4	<10	6	0.34
McNean	LM	H 040 400	50	977.8	12.31	16.9	7.60	116	23.6	80	6.9	<10	17	0.45
Muckanagh	CE	R 370 925	17	96.1	23.05	17.8	8.53	462	208.6	26	0.8	<10	5	0.71
O'Flynn	RN	M 585 795	77	137.5	13.35	3.4	8.51	333	138.9	63	0.8	<10	10	0.88
Rea	GY	M 615 155	81	301.1	3.55	20.9	8.54	308	128.5	3	2.4	<10	6	0.50
Talt	SO	G 398 150	130	97.3	5.85	23.0	8.01	190	85.09	15	1.89		8	<1