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IDENTIFICATION OF REFERENCE-STATUS FOR IRISH LAKE TYPOLOGIES USING PALAEOLIMNOLOGICAL METHODS AND TECHNIQUES

IN-SIGHT

EPA/ERTDI PROJECT # 2002-W-MS-17

FINAL REPORT

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Executive Summary

This is the final report to the Environmental Protection Agency Ireland (EPA) for the EPA/ERTDI-funded research project *Identification of refereNce-Status for Irish lake typoloGies using palaeolimnological metHods and Techniques* (IN-SIGHT, project # 2002-W-LS/7). IN-SIGHT commenced on January 1st 2003 with the aim of assisting the Government of Ireland meet some of its obligations under the EU Water Framework Directive (WFD). In particular, the project aimed, largely on the basis of a palaeolimnological approach and for freshwater lakes in Ecoregion 17, to test the ecological status of a representative selection of Candidate Reference Lakes (CRLs) and to establish biological reference conditions for examples of the main types of impacted lakes. This report comprises four main chapters in accordance with the research program agreed with the EPA; following an introductory chapter outlining the project, chapter two relates to Work Package one (WP1); chapter three is dedicated to Work Package two (WP2); and chapters four and five are concerned with Work Package three (WP3) deliverables.

Palaeolimnology is a well-established science in many European and North American countries, where it is underpinned by an extensive literature. In adopting a palaeolimnological approach, IN-SIGHT utilised diatom (Bacillariophyceae: siliceous algae) remains in lake sediment cores. Diatoms are sensitive to water quality changes and shifts in the diatom community often correspond closely to changes in other taxonomic groups. A number of other proxies that preserve well in lake sediments was also examined, notably sediment chemistry, cladocera (zooplankton) and pollen.

WP1 aimed to review existing relevant information and sediments relating to freshwater lakes in the Irish Ecoregion and to identify a representative selection of CRLs for subsequent palaeolimnological study in WP2. In Ireland, a substantial amount of information relating to current and past conditions in lake ecosystems is available in published and unpublished forms. Of the latter, theses (many based on research carried out in the consortium of universities in Ireland and the UK involved in IN-SIGHT) and consultancy/research reports form a significant part. Samples and data previously collected in conjunction with palaeolimnological research in Ireland also exist. Information obtained from the evaluation of literature and extant data and sediment samples and cores in WP1 informed subsequent work in IN-SIGHT.

WP1 focused on 76 lakes that the EPA had previously identified as potential extant examples of reference condition (the CRLs mentioned above). A representative selection of these was studied in more detail in WP2 (resources were made available for the sampling and analysis of sediments from 35 CRLs). The decision over which 35 CRLs to sample was made first on the basis of a working typology, the physico-chemical and morphological criteria for which were provided by the EPA and comprised alkalinity, area and altitude, and second according to expert advice on a range of factors including, for example, ease of access. The CRLs sampled were divided among the eight most populated of a total of 12 typology classes.

WP2 determined the presence or absence of anthropogenic pressures at the selected CRLs, based on down-core (generally sediment core top sample-bottom sample) differences in proxies of epilimnetic lake water quality (total phosphorus, TP, and pH) and catchment conditions. Sediment cores were obtained from the deepest part of each of the 35 CRLs during the summer 2003 and dated according to down-core variations in spheroidal carbonaceous particle (SCP) concentrations. Sediment core samples were also analysed for their diatom content and chemistry. Squared chord distance (SCD), detrended correspondence analysis (DCA) and Ireland-specific TP and pH transfer functions were applied to diatom assemblages in sediment core samples to assess the nature and degree of biological and chemical changes at each site. The degree of biological change between a core top sample (representing an integration of present-day conditions) and reference (generally a core bottom sample) from each sampled CRL was assessed using a SCD dissimilarity coefficient ranging from 0 (no difference) to 2 (completely different). Following expert advice, a SCD score of 0.40 (approximating to the 2.5 percentile) was used as the basis for verifying or refuting the reference status of a CRL. Sediment chemistry and CORINE land cover data were used to identify possible human-induced drivers, in particular processes of acidification, eutrophication and sediment inwash, in those cases where biologically important floristic changes were evident from the diatom data.

Reference status was confirmed for 11 (32 %) of 34 CRLs for which diatom data were available. WP2 therefore confirmed the reference status of: Barfinnihy (typology class 3); Bunny (typology class 10); Doo (typology class 3); Dunglow (typology class 2); Keel (typology class 1); Kiltooris (typology class 6); McNean (typology class 8); Nahasleam (typology class 1); O'Flynn (typology class 10); Upper (typology class 4); and Veagh (typology class 4). Core bottom samples in four of the 11 CRLs dated to *c.* 1850 or before (Bunny, Keel, Nahasleam and Upper). The estimated age of core bottom samples from the other seven sites was *c.* 1850 to *c.* 1950 (Doo, Dunglow, Kiltooris, McNean and Veagh), or was impossible to determine (Barfinnihy and O'Flynn). Twenty-three (68 %) of the CRLs sampled showed biologically important deviations from reference condition, with acidification and nutrient enrichment seemingly the main causes of change. Catchment disturbance, notably peat erosion and possibly linked to recent afforestation, also appeared to have been a factor in some cases, while recent climate changes may also have had an impact.

WP3 demonstrated the value of a multi-proxy palaeolimnological approach for defining site-specific ecological reference conditions at lake ecotypes where reference sites do not exist at present, and examined the potential of analogue matching as a technique for identifying restoration targets for lakes impacted by eutrophication. Analyses of sediment chemistry and fossil remains (diatoms, cladocera and pollen) were carried out on sediments obtained from seven lakes (Atedaun, Ballybeg and Inchiquin in County Clare; Egish and Sillan in County Monaghan; Mullagh in County Cavan; and Crans in Co. Tyrone) following a programme of fieldwork in 2004 and were facilitated by chronological control based upon radioactive isotopes. A transfer function developed specifically for WP3 enabled the reconstruction of past epilimnetic TP concentrations. The results indicate that all but one of the study sites currently are in a far more productive state compared with the beginning of the sediment core record and that there has been a shift in the functioning of the lakes from systems characterised by benthic-littoral taxa to those in which planktonic forms are far more prominent. Furthermore, nutrient enrichment has accelerated after *c.* 1980 at five of the lakes (Ballybeg, Crans, Egish, Mullagh and Sillan), while the uppermost samples from the core from Atedaun, for which chronological control is relatively poor, also showed evidence of eutrophication. Two of the lakes studied in WP3 show long-term enrichment, in one case starting in the late 19th century, while both eutrophication and oligotrophication have occurred at three sites. The results obtained in WP2 and WP3 highlight the difficulties in applying a *terminus ad quem* for reference conditions Ecoregion-wide (or a universal temporal end-point for pre-human impact conditions) and demonstrate that lakes in the Irish Ecoregion often have complex and locally specific histories.

An analogue matching training set was used to examine the degree of similarity between modern diatom assemblages in core top samples from lakes sampled as part of WP2 and sediment core bottom samples from WP3 lakes. The analogue matching training set comprised data from surface sediment samples obtained from 13 moderate and high alkalinity CRLs. Sediment core bottom samples from only two of the seven impacted lakes were found to have a close modern analogue among the CRL dataset. The modern analogue approach thus shows some potential, although this potential is currently limited because of the restricted size of the training set and relatively few biological proxies. Future investment aimed at expanding the training set and number of biological proxies should enable the modern analogue approach to make a significant contribution to implementing the WFD.

Chapter 1
Introduction

Directive 2000/60/EC (the EU Water Framework Directive, WFD) established a new legislative framework for European waters. The WFD was agreed by the European Parliament and Council in September 2000 and came into force on December 22nd 2000. All 15 EU Member States in 2000 were expected to incorporate the WFD to national legislation by December 22nd 2003. New EU member states were expected to do the same by the end of their accession period (May 1st 2004) (ECDGE 2004a). According to the ECDGE (2004b), Ireland was one of only five of the 15 Member States to incorporate the WFD to national legislation by the end 2003 deadline, while the WFD had become part of national legislation in 8 of the 10 new EU Member States by the end of their accession period. The fundamental aims of the WFD, to be achieved during the current implementation phase, are the: sustainable use of water resources (coastal, groundwater, lakes, rivers and transitional waters); maintenance of high status waters where they exist and the prevention of deterioration in the existing status of waters; and achievement of at least good status in relation to all waters by 2015.

The adoption of agreed protocols and definitions underpins the implementation phase of the WFD. Accordingly, and with specific reference to surface water bodies within River Basin Districts, states are required to identify, delimit and differentiate water bodies and to establish hydromorphological, physiochemical and biological type-specific reference conditions (Anon 2000: L327/27). According to Table 1.2, Annex V, of the WFD and to REFCOND (2003: 5), biological reference conditions equate to high ecological status and show no or very minor deviation from natural, or pre-human impact, conditions as a result of human activity.

Biological reference conditions can be established through several pathways: (1) spatially, through comparisons with extant, reference examples of the same type of water bodies; (2) modelling, using predictive or hindcasting methods and historical, palaeoecological or other available data; (3) a combination of (1) and (2); and (4) expert judgment (Anon 2000; Andersen *et al.* 2004). In the absence of long-term data, the WFD states that reference conditions based on modelling may be derived using hindcasting methods, and palaeolimnology, the reconstruction of past water quality and catchment condition based on lake sediment records, is given as one such technique (Anon 2000). Specifically annex II of the WFD requires the identification of candidate reference lakes (CRLs) or lakes that may represent type reference conditions; and annex V, the development of tools for determining reference conditions and current status.

In Ireland, where some parts of the country continue to be associated with relatively low levels of human activity, it is conceivable that some surface water bodies at present show no more than very minor deviations from pre-human impact conditions, and therefore that it is possible to adopt, at least in part, a spatial approach in establishing biological reference conditions. Following this logic, the Environmental Protection Agency Ireland (EPA) nominated 76 lakes as CRLs (Appendix 1). The intention is that those CRLs that have their reference status confirmed will provide a benchmark for the restoration of lakes of the same type that currently exhibit more than slight human impacts.

Sediments can provide a record of the past biology and chemistry of water bodies. Diatoms (Bacillariophyceae: single-celled, siliceous algae) are commonly used as limnological indicators of change because of their sensitivity to a wide variety of environmental variables and their good preservation in sediments (Stoermer and Smol 1999). Acidification (Flower *et al.* 1994; Battarbee *et al.* 1999, 2001; Stoermer and Smol 1999) and eutrophication (Anderson 1997; Hall and Smol 1999) are the main processes for which diatoms have proven useful indicators. This role has been enhanced through the development of transfer functions that enable the reconstruction of water quality parameters, notably epilimnetic total phosphorus (TP) and pH, from the remains of diatoms found in sediments (Ramstack *et al.* 2003; Reid 2005). Weighted averaging (WA) regression and calibration (ter Braak and van Dam 1989) and its extension WA partial least squares (WA-PLS) (ter Braak and Juggins 1993) are the most widely used techniques for reconstructing past environmental variables in this way (Birks 1998).

Of the biological elements relevant to the WFD, diatoms represent components of both the phytoplankton and phytobenthos, but importantly shifts in the diatom community often correspond closely to changes in other biological groups (e.g., see Kingston *et al.* 1992). The diatom record is a potentially useful tool, therefore, for assessing water quality and defining lake reference conditions, both chemical and ecological (e.g., Kauppila *et al.* 2002). There are, however, a number of other biological groups that preserve well in lake sediments, representing a range of biological elements relevant to the WFD. For example, cladocera are microscopic crustaceans (zooplankton) that are represented by a variety of body parts, while pollen and spores can be used to assess vegetation change, both in the lake and more widely in the catchment. Sediment chemistry can also be used to support microfossil-based interpretations, and to provide information on catchment processes, such as soil erosion and sewage discharges. These proxies can be efficiently and effectively used within either, or both, high resolution or low resolution (top-bottom) sediment sampling approaches. In the latter, proxies in the upper (0-0.5 cm) lake sediment sample represent an integration of present-day conditions, while those in the bottom sediment sample, depending on the rate of sediment accumulation, are assumed to represent pre-human disturbance or natural conditions (Cumming *et al.* 1992; Smol and Cumming 2000). For the purposes of the WFD, lake reference conditions may be interpreted as being those existing before the onset of intensive agriculture or forestry and before large-scale industrial disturbances. The *terminus ad quem* of reference conditions, or the date of the onset of significant human impacts, is therefore likely to vary geographically.

This is the final report to the Environmental Protection Agency Ireland (EPA) for an EPA/ERTDI-funded research project (# 2002-W-LS/7, *Identification of refereNce-Status for Irish lake typoloGies using palaeolimnological metHods and Techniques,* IN-SIGHT) that aimed to assist implementation of the WFD in Ireland. Focusing on freshwater lakes, adopting a palaeolimnological approach, and divided into three work packages (WP), IN-SIGHT aimed to summarise existing knowledge and data for CRLs (WP1); to test the reference status of a representative selection of CRLs (WP2); and to determine the recent histories and reference conditions for a selection of impacted lakes for which there are currently no extant examples of reference conditions (WP3).

Chapter 2

Identification of CRLs for subsequent detailed analysis, based on expert knowledge and a review of existing information and sediments

2.1 Introduction

The content of this chapter is mainly concerned with WP1, the main aims of which were to collate and evaluate literature, data sets and sediment core samples relating to the 76 CRLs nominated by the EPA, to classify the 76 CRLs in a working typology based on hydromorphological and physico-chemical criteria supplied by the EPA, and to select 35 CRLs (as a representative subset of the total) for sampling and analysis as part of WP2.

2.2 Review of existing literature and information

A substantial amount of information relating to current and past conditions in lake ecosystems in Ireland is available in published and unpublished forms. Of the latter, theses and consultancy/research reports form a significant part (Table 2.1). Several of the 76 CRLs, however, have not been the focus of previous studies, or if they have information from the studies is not readily available (Table 2.2). Samples and data previously collected in conjunction with palaeolimnological research in Ireland also exist (e.g., from the EU-FLAME project, Table 2.3). Appendices 2 and 3 contain a list of references of published material, reports and theses relating to aspects of the physical morphology, chemistry and biology of the CRLs. The references are divided into studies where individual CRLs are the focus of the study (Appendix 2) and multiple lake studies that include CRLs (Appendix 3).

Forty-eight lakes were sampled throughout Ireland as part of EU-FLAME. Of these, ten are among the 76 CRLs nominated by the EPA. Stored samples from nine EU-FLAME lakes were retrieved (material from Anure was missing), prepared for examination (top and bottom samples) and evaluated (Table 2.3). Most of the samples analysed showed mechanical breakage of the diatom frustules, presumably as a result of storage.

Table 2.4 contains information on dated lake sediment cores. Published sediment accumulation rates are summarised in Table 2.5 and are ordered from lowest (Lough Bray Lower 0.31 mm y^{-1}) to highest (Kellys Lough 17 mm y^{-1}). Anderson and Battarbee (1994) state that an accumulation rate of >5 mm yr^{-1} is indicative of a eutrophic lake system or a system with high allochthonous inputs. As is clear from Table 2.5, a large proportion of published sediment accumulation rates for Ireland are indicative of eutrophication and/or sediment inwash.

2.3 Selection of CRLs for sampling

Sufficient funds were made available to IN-SIGHT to enable the collection and analysis of sediment cores from 35 CRLs. Selection of these 35 CRLs followed three steps. First, a working typology of CRLs was established based on criteria and data provided by the EPA (Figure 2.1). Second, principal components analysis (PCA) was used to identify CRLs that most clearly represented the typology class to which they had been assigned (i.e. those CRLs located centrally on PCA axes one and two). Third, expert advice was obtained on, for example, accessibility of a particular site and the real likelihood of a CRL actually being in reference state at present.

The criteria underpinning the working typology were measurements of alkalinity (< 20 mg L^{-1} $CaCO_{3,}$ 20-100 mg L^{-1} $CaCO_{3,}$ > 100 mg L^{-1} $CaCO_3$), average water depth (< > 4m) and lake area (< > 50ha) provided by the EPA. All of the 35 CRLs selected were oligotrophic or meso-oligotrophic and most were located in the western part of Ireland at altitudes of less than 300m asl (Table 2.6). The 35 CRLs cored were divided amongst eight of the total of 12 typology classes: 1) low alkalinity, shallow, small lakes; 2) low alkalinity, shallow, large; 3) low alkalinity, deep, small; 4) low alkalinity, deep, large; 6) moderate alkalinity, shallow, large; 8) moderate alkalinity, deep, large; 10) high alkalinity, shallow, small; and 12) high alkalinity, deep, large lakes. The eight typology classes tended to be the most populous in terms of the total number of CRLs within each.

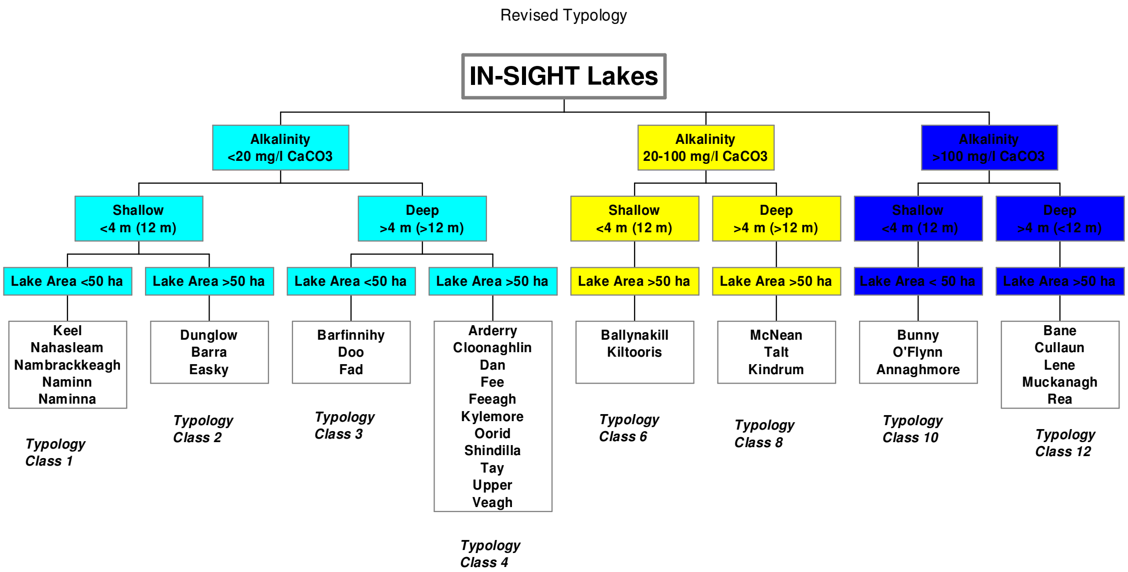


Figure 2.1 Working typology of CRLs sampled as part of IN-SIGHT, based upon criteria and data provided by the EPA

	Primary focus	**Part of multiple lake study**
Published material	46	21
Reports	11	-
Ph.D. Theses	12	4
M.Sc. Theses	9	3
Undergrad Theses	4	-
Total	82	28

Table 2.1 Summary of published and unpublished material relating entirely or in part to the 76 CRLs nominated by the EPA (information is accurate up to 2003)

Lake Name	County	Lake Name	County
Annaghmore	RN	Glenawough	MO
Ballynakill	GY	Hibbert	GY
Bane	WH	Inchiquin	KY
Barra	DL	Kiltooris	DL
Coumalocha	WD	McNean Upper	LM
Coumduala	WD	Nafooey	GY
Coumfea	WD	Nahasleam	GY
Craghy	DL	Nalughraman	DL
Crottys	WD	Namanfin	DL
Fad Inishowen East	DL	Nambrackkeagh	GY
Fad Inishowen West	DL	Naminn	DL
		Waskel	DL

Table 2.2 CRLs without published or unpublished studies (information is accurate up to 2003).

Candidate Reference Lake	**Status**
Anure	No material from this core available to evaluate.
Bafinnihy	*Cyclotella comensis* and *c. comta* are the most abundant diatom species. However the abundance of other diatom species could have been underestimated because of their poor preservation.
Barra	Diatom valves badly preserved. *Eunotia* spp in high abundance.
Dan	*Eunotia pectinalis* spp. dominated both top and bottom samples.
Dunglow	Well preserved centric diatoms belonging to the genus *Aulacoseira*, *Aulacoseira lacustris* is the most abundant species. Other species abundant in the bottom sample are *Cymbella* and *Eunotia*.
Keel	Broken pennate diatoms (*Asterionella, Fragilaria*, *Synedra*). *Cyclotella* spp. well preserved, although some specimens show evidence of dissolution.
Nahasleam	Diatom species belonging to genus *Cyclotella* (*C. comensis*, *c. comta*) share dominance in the top sample. Fragments of *Eunotia* spp. and *Pinnularia* spp. are common in the bottom sample.
Mourne	Valves showed physical damage in the top sample. Assemblages dominated by diatoms from the genera *Eunotia*, *Frustulia* and *Tabellaria*. The bottom sample is characterized by the presence of *Cyclotella* species and *Eunotia faba*. Other diatom species are also present but very badly preserved showing clear evidence of mechanical fracture.
Nakirka	Fragmented material with dominance of *Eunotia* spp.
Nammina	*Cyclotella comensis* and *c. comta* are very abundant throughout all the samples.

Table 2.3 Current (i.e. as of 2003) quality of preservation of diatoms in lake sediment samples collected as part of EU FLAME (Rose *et al.* 1998)

Lake name	^{210}Pb	^{137}Cs, ^{241}Am	^{14}C	SPI	SCP	Pollen	Mag-netics	Reference
Augher	√	√						Patrick 1986
Ballydoo	√	√		√	√	√	√	O'Connell *et al* 2001
Ballywillan	√	√						Gallagher PhD in progress
Borheen	√		√					Leira *et al* 2003
Bray Lr.	√	√						Linnane and Murray 2001
Carra	√							Donahue, unpublished
Castlewellan	√	√						unpublished
Conn	√	√		√	√	√	√	O'Connell *et al* 2001; O'Connor 1998; Murray (pers. comm.); Nowlan *et al* 2000
Cullin				√				O'Connor 1998
Dan	√	√						Murray (pers. comm.); Nowlan *et al* 2000
Derg	√	√						Linnane and Murray 2002
Diheen	√		√					Leira *et al* 2003
Ennell	√	√						Murray and Douglas 1976; O Ravera (pers. comm.)
Erne	√	√						Battarbee 1984; Oldfield *et al* 1978
Garadice	√	√				√		Wood *et al* 1996
Gill	√	√						Murray (pers. comm.); Nowlan *et al* 2000
Glendalough Lr	√	√						Cox and Murray 1991
Kellys Lough	√	√						Leira *et al* 2003
Lavey	√	√						Williams 2000
Leane	√	√						Douglas and Murray 1987
Loch Mor			√			√		O'Connell *et al* 2001
Loughaunyella	√	√	√					Dalton 1999
Maam	√	√			√			Flower *et al* 1994
Mask				√				O'Connor 1998
Maumeen	√	√	√	√	√	√	√	Huang 1994
Maumwee	√	√			√			Flower *et al* 1994
Muck	√	√			√			Flower *et al* 1994
Mullagh	√	√						Murray (pers. comm.); Nowlan *et al* 2000
na Beac	√	√						Unpublished
Neagh	√	√						Gallagher PhD in progress
Owel		√						Murray and Douglas 1976; O Ravera (pers. comm.)
Portmore	√	√						Unpublished
Ramor	√	√						Murray (pers. comm.); Nowlan *et al* 2000
Ree	√	√						Murray (pers. comm.); Nowlan *et al* 2000
Veagh	√	√			√			Flower *et al* 1994
White Lough	√	√						Rippey *et al* 1997

Table 2.4 Dated Sediment Cores from lakes in the Irish Ecoregion (information is accurate up to 2003)

Lake name	**mm yr $^{-1}$**	**g cm^{-2} yr^{-1}**	**Reference**
Bray (Lr.)	0.31	0.02	Nowlan *et al* 2000
Glendalough (upper) pre 1945	1.40		Cox 1989
Glendalough (lower)	1.44		Farrell 1996; Murray and Cox 1991
Loughaunyella	1.60-4.00	0.026	Dalton 1999
Glendalough (Lower)	1.90	0.03	Nowlan *et al* 1998
Bray (Lr.)	2.50		Linnane 1997
Lavey	2.50	0.03	Williams 2000
Dan	2.90		Nolan 1997
Neagh pre 1960*	2.9-9.10		Battarbee 1978
Maam	<3.00	0.08-0.14	Flower *et al* 1994; Duigan 1993
Maumwee	<3.00	0.027	Flower *et al* 1994
Muck	<3.00	0.013-0.021	Flower *et al* 1994
Veagh	<3.00	0.014	Flower *et al* 1994
Conn (south basin)	3.25		Connolly 1997
Dan	3.50	0.03	Nowlan *et al* 2000
Conn	3.80	0.04	Nowlan *et al* 2000
Mullagh	4.00		O'Brien 1995
Owel	4.00		Murray and Douglas 1976
Gill (west)	4.03		Murray 1998
Neagh	4.4-7.4		Rippey *et al* 1982
Garadice	4.80	0.15-0.75	Wood *et al* 1996
Gill 1 Gill 2	4.80 4.90	0.10 0.15	Nowlan *et al* 2000
Glendalough (upper) post 1945	5.70		Cox 1989; Cox and Murray 1991
Mullagh	5.70	0.03	Nowlan *et al* 2000
White Lough	6.60	0.03-0.06	Rippey *et al* 1997
Neagh post 1960*	7.3-11.00		Battarbee 1978
Ramor	7.40	0.18	Nowlan *et al* 2000
Ennell	7.50		Iribas 1996; Murray and Douglas 1976
Augher	8.00		Anderson 1989
Leane	8.00		Douglas and Murray 1987
Gill (east)	8.07		Murray 1998
Derg	8.50	0.15	Linnane and Murray 2002
Diheen	12.00		Leira *et al* 2003
Derg	13.00		Nolan 1993
Ree	14.00		Martin 1994
Ree	13.00	0.15	Nowlan *et al* 2000
Borheen	15.00		Leira *et al* 2003
Kellys Lough	17.00		Leira *et al* 2003

Table 2.5 Sediment accumulation rates (ordered in terms of mm yr $^{-1}$) for lakes in the Irish Ecoregion

Lake name	Irish Grid Ref.	Lake code	Typology class	Altitude (m amsl)	Lake area (ha)	Max. depth (m)	pH	Conductivity (µS cm^{-1})	Alkalinity (mg l^{-1}CaCO$_3$)	TP µg l^{-1}	% land cover in catchment					
											URBAN	FORI	PASTURE	AGRICULT	BOGS	OTHER
Annaghmore	M 900 837	ANN	10	46	53.1	5.7	8.46	351	159.4	6	0.00	0.00	91.44	0.00	0.00	8.56
Arderry	L 995 457	ARD	4	37	81.1	11.6	6.33	84	6.14	6	0.00	9.51	0.00	0.00	90.49	0.00
Ballynakill (Gorumna)	L 856 225	BAL	6	13	23.9	16.4	7.1	244	20.02	5	-	-	-	-	-	-
Bane	N 550 712	BAN	12	112	75.4	16.9	8.43	297	132.5	5	0.00	0.00	94.94	4.68	0.00	0.39
Barfinnihy	V 850 768	BAF	3	249	13.6	16.7	6.84	56	4.2	4	0.00	0.00	0.00	0.00	95.30	4.70
Barra	B 935 120	BAR	2	90	62.6	6.0	6.31	54	3.80	5	0.00	0.00	1.78	0.00	62.04	36.18
Bunny	R 375 967	BUN	10	17	102.9	11.6	8.47	361	156.2	5	0.00	0.00	36.70	0.74	1.22	61.33
Cloonaghlin	V 610 709	CLO	4	109	127.7	29.4	6.82	62	2.0	5	0.00	0.00	0.00	0.00	70.41	29.59
Cullaun	R 315 905	CUL	12	16	49.7	20.1	8.40	393	172.0	6	0.00	0.00	72.15	5.44	0.41	22.01
Dan	O 150 40	DAN	4	200	102.9	33.5	5.11	42	-0.1	6	0.00	8.75	1.01	0.00	51.79	38.45
Doo	C 359 394	DOO	3	283	9.0	6.8	5.88	78.1	2.05	12	0.00	0.00	0.00	0.00	100.00	0.00
Dunglow	B 782 117	DUN	2	13	61.2	6.1	5.73	100	59.63	6	0.00	0.00	1.31	4.37	93.83	0.49
Easky	G 442 225	EAS	2	180	119.2	11.0	6.53	48	4.04	7	0.00	0.00	0.00	0.00	100.00	0.00
Fad Inishowen East	C 539 439	FAD	3	233	12.3	13.6	6.35	80.9	5.02	7	0.00	0.00	0.00	0.00	49.08	50.92
Fee	L 790 613	FEE	4	47	173.7	31.5	6.55	62	3.06	9	0.00	14.02	0.00	0.00	72.46	13.51
Feeagh	F 965 000	FEA	4	11	394.8	43.0	7.39	86	9.60	8	0.00	22.69	0.10	1.62	63.95	11.65
Keel (Rosses)	B 847 162	KEE	1	136	11.4	10.5	5.3	135	2.4	8	0.00	0.00	0.00	0.00	99.91	0.09
Kiltooris	G 676 972	KIL	6	7	43.5	13.5	7.18	205	27.43	14	0.00	0.00	47.87	10.73	17.97	23.42
Kindrum	C 185 430	KIN	8	8	60.8	11.0	8.27	318	69.47	11	0.00	0.00	18.49	22.16	59.34	0.00
Kylemore	L 770 552	KYL	4	35	132.2	25.1	6.59	72	6.99	6	0.00	11.87	0.00	0.24	66.61	21.28
Lene	N 510 685	LEN	12	93	416.2	19.7	8.46	250	104.9	6	0.00	0.00	78.92	11.62	0.00	9.46
McNean	H 040 400	MCN	8	50	977.8	16.9	7.60	116	23.6	17	0.00	13.39	26.36	20.64	22.72	16.89
Muckanagh	R 370 925	MUC	12	17	96.1	17.8	8.53	462	208.6	5	0.00	0.00	55.29	9.18	21.74	13.79
Nahasleam	L 971 244	NAH	1	33	28.1	1.4	6.5	100.8	9.59	7	0.00	5.86	0.00	0.00	92.75	1.39
Nambrackkeagh	L 821 603	NAB	1	65	6.7	8.8	5.98	101	2.26	10	0.00	44.21	0.00	0.00	53.32	2.47
Naminn	C 396 419	NAM	1	150	15.0	7.8	6.55	112	7.0	10	0.00	0.00	0.00	0.00	100.00	0.00
Naminna	R 176 710	NAN	1	169	20.2	8.4	6.02	77	0.7	8	0.00	36.55	0.00	0.00	63.45	0.00
O'Flynn	M 585 795	OFL	10	77	137.5	3.4	8.51	333	138.9	10	0.52	0.00	54.12	0.00	42.04	3.32
Oorid	L 930 460	OOR	4	45	60.5	12.0	6.40	65	8.06	7	0.00	3.10	0.00	4.73	92.17	0.00
Rea	M 615 155	REA	12	81	301.1	20.9	8.54	308	128.5	6	3.07	0.00	86.73	10.20	0.00	0.00
Shindilla	L 960 460	SHI	4	38	70.2	23.0	6.45	73	6.17	4	0.00	5.69	0.00	0.00	94.31	0.00
Talt	G 398 150	TAL	8	130	97.3	23.0	8.01	190	85.09	8	0.00	0.81	26.12	0.00	73.07	0.00
Tay	O 160 75	TAY	4	250	50.0	32.8	5.12	40	-0.3	8	0.00	0.58	0.00	0.00	59.09	40.34
Upper	V 900 817	UPE	4	18	169.9	36.1	6.41	58	2.8	5	0.00	6.30	0.44	2.50	83.72	7.04
Veagh	C 022 215	VEA	4	40	260.9	28.0	6.30	33	2.16	0	0.25	3.15	0.00	0.00	65.19	31.41

Table 2.6 Summary of locational, hydromorphological and physico-chemical information provided by the EPA of Ireland for 35 CRLs selected for coring as part of WP2. Water quality data were provided by the EPA and are annual means.

Chapter 3

Determination of presence or absence of anthropogenic pressures on CRLs

3.1 Introduction

The proposed reference status of a representative selection of CRLs (35 in total) was tested in WP2 through a palaeolimnological approach. WP2 also included an evaluation of the main drivers of any deviations from reference conditions. This mainly involved the analysis of sediment core top and bottom samples, although sediment cores from some sites were analysed at a higher resolution. The sediment core top-bottom approach has been used recently in Canada (Reavie *et al.* 2002), the UK (Bennion *et al.* 2004a,b) and the US (Dixit *et al.* 1999). It provides a relatively efficient and effective means of establishing changes based on sedimentary records from a large number of sites, as it involves the analysis of only two samples per sediment core (Cumming *et al.* 1992; Cumming and Smol 2000; Leira *et al.* 2006). The approach is based on the assumption that sediment core top and bottom samples represent an integration of conditions, respectively, at the time of coring and pre-human impact (i.e. reference or natural). One problem with the technique is geographic variations in both rates of sediment accumulation (and therefore the age of a core bottom sample) and the onset of significant, localised human impact. Several scientists have proposed *c.* 1850 as a suitable reference date for the assessment of human impacts on lakes in the UK (Battarbee 1999, Fozzard *et al.* 1999, Bennion *et al.* 2004a,b). 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 mid-19th century (e.g., Bradshaw 2001).

In WP2 of IN-SIGHT, *c.* 1850 was used as a tentative reference benchmark where it could be established. For those cases where the sediment core bottom sample was thought to post-date *c.* 1850, *c.* 1950 was used as a secondary reference benchmark, because this date was assumed to approximate in Ireland to the onset of increased urbanisation, major aforestation and agricultural intensification.

3.2 Methods

Field-based techniques

Cores of sediment, generally 20-40cm long, were collected from the deepest part of each of the 35 CRLs selected using a gravity (Renberg) corer (Renberg 1991) during summer 2003 and were subsampled in the field immediately (Figure 3.1). Coring of the selected CRLs generally followed an extensive bathymetric survey (Appendix 4). Sediment cores were subsampled in the field 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, labelled and transported in a cool box to the laboratories of the University of Ulster Coleraine (UUC) for lithostratigraphic and chemical analyses.

Laboratory analyses

Division of sediment core samples

Selected sediment samples were subsequently transferred to Trinity College Dublin (TCD) and to University College London (UCL) for analyses of, respectively, diatoms and SCPs. The aims of laboratory-based analyses of sediment core samples in WP2 were three-fold: 1) to establish chronological control; 2) to determine down-core variations in diatoms and lake water and sediment chemistry as means of establishing the degree of deviation of present day conditions from reference conditions; and 3) to assist in the identification of possible causes of biologically important variations (e.g., acidification, eutrophication and/or catchment disturbance).

Chronological control

Chronological control for sediment cores obtained as part of WP2 was provided by down-core variations in concentrations of SCP. Concentrations of SCP in samples of lake sediments provide a record of the impact of fossil fuel combustion in the region, and down-core variations in these have been shown to provide a reliable and relatively cheap dating method (Rose *et al.* 1995). The start of the SCP record in lake sediments at many sites across Europe is *c.* 1850, while *c.*1950 marks the start of a rapid increase in concentrations, resulting from increased electricity generation, which peaked some two to three decades later. There is some uncertainty attached to the precise dating of variations in SCP concentrations in Ireland, because few studies have been carried out locally. However, separate studies in the northwest and north of Ireland dated the peak in SCP concentrations to, respectively, 1981 ± 2 and 1980 ± 3 (Rose 2001). In the current study, the estimation of SCP concentrations in five sediment samples per core followed the method outlined in Rose and Theophile (2004). SCP were counted at x 400 magnification under a light microscope and concentrations expressed as numbers of SCP per gram dry mass of sediment (g DM^{-1}). Although estimates of sediment age and accumulation rates based on such coarsely resolved analyses have to be treated with caution, there was some evidence to validate the approach. Thus, the estimated accumulation rate for Dan, one of the CRLs sampled in the current study, corresponds closely with published ^{210}Pb-based data for the same site (Nowlan *et al.* 2000), while the accuracy of the SCP-based chronology for Nambrackkeagh was confirmed using newly available ^{210}Pb-based accumulation rate data (McGee unpublished data). Chronological control for CRLs sampled as part of WP2 was based on the: start of the SCP record, 1850±25 years (*c.* 1850); rapid increase in SCP concentrations, 1950±10 (*c.* 1950); and the peak in SCP concentrations, 1980±3 (*c.* 1980) (Rose *et al.* 1995). In addition, the top 0.5cm thick slice of sediment in a core (the core top sample) was assumed to date to the year of coring (i.e., date to 2003).

Diatoms

Sediment core samples were prepared and analysed for diatoms (Bacillariophyceae) using standard methods (Battarbee *et al.* 2001). The remains of diatoms preserved in sediments have been widely used as biological indicators of water quality (Battarbee *et al.* 2001), an approach that utilises robust relationships between diatom assemblages and parameters such as pH (Battarbee 1984; Jones *et al.* 1989; Anderson and Korsman 1990) and TP (Hall and Smol 1992; Bennion *et al.* 1996). At least 300 diatom valves were counted for each sample using oil immersion objective and phase contrast microscopy. The relative abundances of all species (including unidentified forms) were determined as percentages of the total count (Battarbee *et al.* 2001). Diatoms were identified using standard floras (Krammer & Lange-Bertalot 1986, 1988, 1991a,b).

Two levels of resolution were employed: two samples (top and bottom) per core were analysed for 28 of the cores, with the age of the core bottom sample where possible estimated based on the SCP profile; a higher resolution (four or five samples per core, including top and bottom samples) was adopted for cores where there was particular interest in the magnitude, rate and direction of change from the core bottom sample and where the SCP-based chronology was most robust (seven sites in total). At least one example from each of the major types of CRLs was analysed at higher resolution. Generally, core samples contained abundant, well-preserved diatoms, although poor preservation and low concentrations of diatom frustules characterised core samples from the higher alkalinity lakes Bane, Cullaun, Lene, McNean and Rea. In those cases where a core bottom sample was found to contain insufficient abundances of well-preserved diatoms, the stratigraphically contiguous sample was analysed in its place. Only in one case (Fad East, Donegal) were fossil diatoms absent throughout the core from below the upper 2cm, thereby precluding a top-bottom comparison.

Lithostratigraphy and sediment chemistry

Wet sediment density and percentage water content were determined on core samples as a preliminary stage in sediment chemistry analyses. Wet sediment density was determined from the weight of known volumes of fresh sediment samples, while percentage water (as dry weight density) content was established thermogravimetrically (Hilton *et al.* 1986). Total sediment concentrations of P, iron (Fe), manganese (Mn), calcium (Ca), sodium (Na) and potassium (K) were also assessed. Dry weight and density measurements are important for the interpretation of sediment chemistry data, aiding the calculation of sediment and chemical areal accumulation rates, and were obtained for all core samples. Levels of sedimentary TP were used to assist interpretations of changes in diatom assemblages (Rippey and Anderson 1996), while those of Na, K and Ca could indicate periods of catchment erosion. Fe and Mn in sediments are indicators of fine sediment ingress to lakes but can also be vectors for mobilisation of TP in anoxic sediments (Mackereth 1966).

Sediment chemistry in each core was determined in the majority of cases on the top five 0.5 cm- and the bottom five 1 cm-thick slices. Additional sediment samples were analysed between the uppermost and lowermost sets of samples in cores of sediment that had relatively robust SCP-based chronological control and that represented the major types of CRLs (32 CRLs in total). Following Boyle (2001), dried sediments were disaggregated by pestle and mortar and, after further drying, 0.3 g of the dried sediment was added to Teflon beakers. Sediment samples were sequentially digested with concentrated hydrofluoric (HF), nitric (HNO_3) and perchloric ($HClO_4$) acids at temperatures from 40-60 °C and preserved as acidified 25 ml solutions; 30 samples were digested at a time and a blank, certified reference material (CRM) and repeat digest were included for quality control in each run of measurements (Appendix 5). Chemical concentrations (mg g^{-1}) were determined in diluted HNO_3 using an ICP-OES (Jordan *et al.* 2001), and were also transformed to an accumulation rate (mg cm^{-2} yr^{-1}) form using SCP-based estimates of sediment accumulation rate and measurements of sediment dry density.

Data analyses

Analyses of diatom data involved samples from 34 CRLs, because of the poor preservation of diatom remains in samples from below 2cm in the core from Fad East. As SCP-derived chronologies were most problematic for Lene, O'Flynn and Tay, analyses of down-core variations in sediment chemistry were restricted to the 32 CRLs for which there was relatively tight chronological control.

The degree of change between diatom assemblages in core top and bottom sediment samples was assessed using the squared chord distance dissimilarity index (SCD). SCD emphasises the pattern in the data at the expense of the random variation in species abundances (Overpeck *et al.* 1985). The SCD technique was recently used as a basis for quantifying the degree of floristic change between diatom assemblages in sediment core top and bottom samples in a palaeolimnological study of 26 lochs in Scotland (Bennion *et al.* 2004a,b) and for defining reference conditions for acidified waters in the UK (Simpson *et al.* 2005). SCD scores range from 0 to 2, with 0 indicating that two samples have exactly the same species composition, and 2 that their compositions are entirely different. A SCD score 0.4 (approximating to the 2.5 percentile) was used in WP2 to define sites with low floristic change between the bottom and top sample.[H1] This is more stringent than the 5th percentile used by Bennion *et al.* (2004a,b) and in the original report for IN-SIGHT WP2, and reflects revised thinking about what constitutes biologically important change at a site following closer examination of sediment sample data from over 200 UK lake cores held in the AMPHORA database (Environmental Change Research Centre, UCL). Unimpacted lakes in this database typically have SCD scores of ≤ 0.4.

Detrended Correspondence Analysis (DCA) (Hill and Gauch 1980) was used to identify the main patterns of variation in the diatom data, and to establish the directions and magnitude of changes in biological conditions at each coring location. Version 4.5 of CANOCO was employed in the DCA-based ordination of diatom data (ter Braak and Šmilauer 2002). Prior to all analyses, diatom abundances were square root transformed in order to stabilise variance, and rare species were down-weighted.

Diatom-inferred pH and TP (DI-pH and DI-TP) were established using standard weighted averaging (Birks *et al.* 1990,b; Korsman and Birks 1996; Koster *et al.* 2004) in order to quantify any changes in nutrient status and acidity. All diatom-inferred values were established using the computer software package C2 (Juggins 2003). In the absence of a diatom assemblage-water quality training set specific to the Irish Ecoregion, DI-pH and DI-TP were determined using a training set designed specifically for CRLs sampled as part of WP2. The training set comprised diatom counts for surface sediment samples and several years of measurements of lake water quality by the EPA. Levels of acidity ranged between pH 5.11 and pH 8.54 and had a median value of 6.5 pH units. The resultant weighted averaging partial least squares two-component (WA-PLS2) model (r^2 = 0.84) had a root mean squared error of prediction (RMSEP) of 0.43 pH units. The training set for TP included additional information from 10 nutrient-enriched lakes in Ireland so as to extend the TP gradient. TP values in the training set were in the range 0 to 2.55 log10 µg TP l^{-1}, and had a median value of 0.90 log10 µg (8.0 µg) TP l^{-1}. The resultant WA-PLS2 model (r^2 = 0.64) generated a RMSEP = 0.202 log10 µg TP l^{-1}. The difference between current DI-TP and reference DI-TP was used to derive a qualitative estimate of degree of change, with a difference in DI-TP greater than the RMSEP deemed biologically important.

A comparison of the models used in the current research to derive pH and TP from diatom assemblages with other transfer functions recently developed for Northern Ireland and for Europe is presented in Table 3.1. In general, the statistical performance of the predictive models used in WP2 compared well with other diatom-TP and pH transfer functions.

3.3 Results

Approximate sediment chronologies for CRLs

Down-core variations in SCP concentrations allowed estimation of the age of the sediment core bottom sample in 18 of 35 CRLs (Rose and Theophile, 2004 – and see Appendix 6), with rates of sediment accumulation in these 18 cores varying widely, from a low of 0.09cm yr^{-1} (Dunglow) to a high of 0.58cm yr^{-1} (Kiltooris) (Table 3.2). Apparently discontinuous or incomplete SCP profiles precluded the precise dating of core bottom samples – and therefore the estimation of sediment accumulation rates - for the remaining 17 CRLs, although it was possible to gain some idea of the approximate period of time covered by the sediment core record in many of these cases.

Down-core variations in sediment chemistry and diatom data

Figure 3.2 illustrates down-core variations in dry weight and wet density: all cores analysed generally show a decrease in dry weight towards the sediment surface. Down-core differences in sediment chemistry concentrations and accumulation rates between mean reference (average measurements for the lowermost 5cm of sediment in a core), 2003 (core top sample) and mean present-day (average measurements for the uppermost 2.5cm in a core) are shown in figures 3.3a-c, 3.4a,b and 3.5. In order to facilitate assessment of the deviation of present-day diatom assemblages from reference conditions, diatom data from core bottom, present-day and, in some cases, mid-core samples from each lake were combined on the same DCA ordination biplot (Figure 3.6). Down core variations (generally core top-bottom comparisons) in diatoms are summarised in Table 3.3: SCD scores between diatom assemblages in core top and bottom samples ranged from 0.05 (Upper) to 1.77 (Feeagh). Eleven (32 %) of the 34 sites for which top-bottom comparisons in diatom assemblages were possible generated SCD scores < 0.4, indicating little or no change. These 11 cases were distributed among the different CRL typology classes, although none were in typology class 12 (deep, large, high alkalinity). Aside from CRLs in typology class 12, where differential preservation of diatom frustules may have been a factor influencing the results, large, deep, low alkalinity lakes (typology class 4) most consistently showed biologically important differences between core top and bottom samples, i.e. deviation from reference. Eighty-two percent of CRLs within this class generated SCD scores > 0.4. Many of the moderate to high alkalinity CRLs studied were also shown to have experienced important biological changes, based on the SCD scores, although differential preservation of diatom frustules may have been an important factor influencing the results in some cases.

In general, the sediment chemistry accumulation rate data do not indicate increasing catchment (exogenic) inputs, with only Talt showing increases in Ca, Na and K accumulation rates, which is consistent with increased sediment dry weight towards the top of the core. Stable or falling exogenic inputs of sediment to the CRLs studied are also evident when the sediment chemistry data are expressed in concentration form. Manganese accumulation rates increase in some lakes where there are no other cation increases, which is indicative of mobilisation and accretion at a redox boundary (Davison 1993). Increases in Mn are also apparent when the data are expressed in concentration form. Again, Talt is an exception where Mn and Fe increases are also likely to be dependent on exogenic inputs consistent with increased dry weights. Total P accumulation rates indicate a decrease from reference rates for all lakes, with the exception of Cullaun and Talt. It is likely that increased TP accumulation rates at Talt are linked to evidence of inwash, while a link between increased Ca and TP accumulation rates at Cullaun may be due to co-precipitation of TP with $CaCO_3$ (Jager and Rohrs 1990). There is, however, a caveat on the interpretation of these sediment chemistry data. First, the calculation of dry mass sediment accumulation rates using SCP chronologies may introduce an error because the model assumes a linear accumulation rate between estimated dates. The level of error, however, is likely to be minimized in the current study because of the relatively low levels of human activity (and therefore rates of erosion) in the catchments for many of the CRLs cored. Second, and especially with regard to the sedimentary P profiles, chemicals may become concentrated at the sediment-water interface due to diagenesis and mobility. According to the concentration data, this does not appear to be a problem, however. Even in the low alkalinity lakes, where diagenetic mobilisation would be expected to occur (as a result of exogenic Fe and Mn inputs from acid soils) and where changes in the Fe and Mn profiles indicate mobilisation, only a minor concurrent increase in the sedimentary P concentration profiles is evident. Except for Arderry and Fee, by far the largest increases in sedimentary P concentration are in the high alkalinity lakes, where there are no indications of Fe and Mn mobilisation and where these elements would be supply-limited from calcareous catchment soils.

The full, formal names (including authorities) for all diatoms encountered in IN-SIGHT with an abundance > 2% in a sample are listed in Appendix 7, while the main down-core differences in diatom assemblages for the CRLs studied in WP2 are summarised in Appendix

8. Relatively slight differences are apparent from comparisons between the diatom contents of core bottom and top samples from most of the shallow acid lakes (typology classes 1 and 2). There were some exceptions to this, however. At Nambrackkeagh (EPA typology class 1) a change from a *Cyclotella*- (planktonic) to an *Achnanthidium*-dominated (benthic) diatom community was not associated with a change in trophic status in the lake, as the TP accumulation rate profile was largely stable through the whole sediment record obtained. Naminn (typology class 1) experienced a shift from a *Eunotia-Achnanthidium* (benthic) assemblage to one characterised by *Staurosira*. Small benthic *Staurosira* are considered pioneering taxa and have been related to disturbance events within a lake catchment and increased weathering; their abundance at Naminn would thus suggest anthropogenic disturbance although there are no chemical indicators to support this assertion. At Keel (typology class 1), diatom assemblages in a sediment core sample dated *c.* 1850 show a only small deviation when compared with the top (surface) sample from the same site, according to both the DCA ordination results and the SCD score. However, while the *c.* 1850 and core top samples from Keel were characterised by a diatom assemblage comprising planktonic forms typical of nutrient rich waters (e.g. *Asterionella ralfsii*), a pre- *c.* 1850 sample from the same core contained a much more diverse diatom community typifying oligo-mesotrophic conditions, suggesting eutrophication began during the early part of the 19th century. The ordination scores for Easky (typology class 2) suggest only a small degree of floristic and trophic changes, from an assemblage characterized by *Cyclotella* to one characterized by *Staurosira*. Both assemblages suggest mesotrophic conditions.

Core bottom samples from deep acidic lakes (typology classes 3 and 4), in contrast to shallow lakes, largely comprised planktonic diatoms, such as *Cyclotella comensis* and *Cyclotella krammeri*. Sediment core top samples from small deep acidic lakes (Barfinnihy and Doo, typology class 3) showed little deviation in diatom assemblages compared with core bottom samples, according to SCD scores and the DCA plot. The core bottom sample for Doo dates to shortly prior to *c.* 1950, which could account for the relatively small intra-core differences for this site, although a small increase in abundances of *Asterionella ralfsii* towards the top of the core suggests slight enrichment. Comparisons between the content of core bottom and top diatom assemblages from Arderry, Cloonaghlin, Fee and Feeagh (all typology class 4) show similar trajectories of change towards assemblages characteristic of more nutrient-rich conditions.

Diatom communities in which *Aulacoseira ambigua* was abundant replaced planktonic assemblages at Arderry and Fee. The SCD scores for these lakes (ranging from 0.86 to 1.77) suggest moderate to high floristic turnover. Intra-core comparisons between bottom and top samples for Cloonaghlin resulted in a SCD score of 1.60, due largely to an increased abundance of a single diatom species (*Cyclotella stelligera*). Oorid (typology class 4) showed only a small degree of floristic change according to the DCA plot, while its SCD score (0.99) indicates a much more significant change, owing to the increased prominence of *Cyclotella comensis*. The core bottom diatom asssemblage for Kylemore (typology class 4) is closer in composition to those associated with the moderate alkalinity lakes (typology classes 6 and 8); the SCD score (1.04) reflects a biologically important deviation towards less alkaline conditions. The SCD score for Tay (1.17) also indicates a substantial difference in diatom assemblages in the core top and bottom samples from this site, characterised by the increased abundance of *Achnanthidium* and other non-planktonic taxa, and towards conditions similar to Dan at the present time. Dan and Tay are geographically proximate, and both were originally grouped in typology class 4. In both cases, the sediment records indicate inwash as a result of disturbances in their catchments. SCD and ordination scores for samples from Shindilla, Upper and Veagh (all typology class 4) indicate comparatively low levels of floristic change.

The DCA results (Figure 3.6) indicate similar trajectories of changes in diatom assemblages between core bottom and top samples for moderate to high alkalinity sites (typology classes 6 to 12). Some lakes (e.g., McNean, typology class 8) appear to have experienced relatively little change, although in some cases this is because the time period between the lowermost samples analysed and the age of the core top sample (*c.* 2003) is comparatively short (about 53 years in the case of McNean.

Core bottom samples from moderate alkalinity, shallow, large lakes (typology class 6, Ballynakill and Kiltooris) were characterised by the benthic diatoms *Achnanthidium minutissimum* and *Cocconeis placentula*. The relatively low SCD scores indicate that these lakes have experienced insignificant levels of floristic change. In contrast, core bottom diatom assemblages from moderate alkalinity, deep, large lakes (typology class 8) were largely characterised by planktonic diatoms (e.g., *Cyclotella comensis*). The DCA ordination plot and SCD score indicate considerable floristic change at Talt (typology class 8), yet *C. comensis* characterised both core bottom and top samples. The upper sediments in this lake were all impacted by recent changes, as is evident in the dry weight profile (Figure 3.2). Some high alkalinity lakes (typology classes 10 and 12) also show major deviations, particularly according to the SCD scores (e.g., the SCD scores for Annaghmore and Cullaun are, respectively, 0.84 and 1.30). Diatom assemblages in which *Amphora pediculus* and *Pseudostaurosira brevistriata* are abundant characterise the core bottom samples of these lakes, which in both cases appear to pre-date *c.* 1850 (Table 3.2). A largely planktonic diatom flora (e.g., *Cyclotella comensis*) has replaced the non-planktonic diatom reference assemblage at Cullaun, while Annaghmore shows a shift from a non-planktonic diatom community, comprising *Eunotia arcus* and *Pseudostaurosira brevistriata*, to a flora characterised by *Amphora pediculus* and *Mastogloia lacustris*. Cullaun was noted as having increased TP accumulation rates, although the absolute rate of 0.007 mg cm^{-2} yr^{-1} is very low.

Down-core variations in diatom inferred pH and TP (DI-pH and DI-TP)

Down-core difference in DI-pH and DI-TP are shown in figures 3.7 and 3.8 and in Table 3.3. These results must be viewed in the context of current limitations in the models used in WP2 to infer pH and TP based on diatom and environmental data for lakes in the Irish Ecoregion. Note that because of the relatively low values involved, and because of known deficiencies in the model used, intra-core differences in DI-TP are reported in Table 3.3 as proportional change. No unambiguous links between DI-pH, diatom assemblages and sediment chemistry, including Ca (the levels of which are an indicator of buffering capacity) and between DI-TP, diatom assemblages and sediment chemistry are evident from the results.

For most of the CRLs, differences exist in DI-pH between core bottom and top samples, although only four lakes (Dan, Easky, Kylemore and Tay, all low alkalinity CRLs) show a decline in pH > RMSEP. Several CRLs appear to have experienced a reduction in DI-TP. However, only in Tay is this reduction significant (> RMSEP). By comparison, two low alkalinity CRLs show an increase in DI-TP > RMSEP between core bottom and present-day conditions: Fee and Feeagh (both typology class 4). Arderry and Cloonaghlin also exhibited a change in DI-TP, although no statistically significant and concurrent increases in TP accumulation rate were evident.

According to results from those lakes where a relatively high temporal resolution was possible, low alkalinity lakes show the most striking changes in DI-pH and DI-TP (e.g., Easky, Keel and Fee, Figure 3.9a,b). All low alkalinity lakes exhibit increases in DI-TP up to *c.* 9 µg l^{-1}. In one of the lakes (Keel) the increase in DI-TP takes place before *c.* 1850, and shows some stability since the mid-19th century. There is also evidence of acidification at Fee, Feeagh and Naminna, although the DI-pH changes, including those for Keel, are not significant. Only relatively small changes in DI-pH and DI-TP between core bottom and top samples are evident at sites within the moderate (e.g., Ballynakill) and high (e.g., Annaghmore and Muckanagh) alkalinity classes (respectively, typology classes 6, and 10 and 12). It should be noted that the estimated ages of the sediment core bottom samples from Annaghmore, Ballynakill and Muckanagh are all pre-*c.* 1850.

3.4 Discussion

According to intra-core comparisons, largely stable ecological conditions were observed for 11 CRLs (32% of those studied) over the period of time represented by their respective sediment cores. A general decline in sedimentary P accumulation rates up-core may be an artifact of the data. Alternatively it may reflect changes in land use and human population levels following the famines in Ireland of the early to mid 19th century, which had their most profound impact (rural depopulation on a massive scale) in the west of the country (Donnelly, 2001). For four of the lakes showing relative biological stability over the time period represented by the sediment core (Bunny, Keel, Nahasleam and Upper) the core bottom sample dated to *c.* 1850 or earlier. Core bottom samples for five (Doo, Dunglow, Kiltooris, McNean and Veagh) of the other seven CRLs dated to the period between the primary and secondary reference baselines (i.e. *c.* 1850 to *c.* 1950). As this period was prior to agricultural intensification and afforestation in much of Ireland, the reference status of these sites would also appear justified. Sediment core bottom samples for the remaining two verified CRLs (Barfinnihy and O'Flynn) proved impossible to date to an acceptable level of certainty using the SCP method. From the SCP data that are available and when compared to the primary reference date, it appears that core bottom samples from these two sites are considerably older (Barfinnihy) and somewhat younger (O'Flynn) than *c.* 1850.

Intra-core comparisons revealed biologically important changes between core bottom and top samples for 23 (68 %) of the CRLs studied. The main drivers of changes at these oligotrophic and meso-oligotrophic lakes appear to be nutrient enrichment and increased acidity. Phosphorus transfer to freshwaters is a major cause of nutrient enrichment in Ireland at present, although no evidence of a link between indicators of the mass transfer of exogenic soil material and those CRLs with increasing TP accumulation was found in the current study. Increased TP transfer is not necessarily linked directly to increased soil loss, however, and both increased discrete point sources, such as those associated with rural dwellings and septic tanks, and diffuse soluble P losses from P-saturated soils or inappropriate slurry spreading (e.g., during wet weather) (Jordan *et al.* 2005), are possible drivers of changes in the diatom assemblages recorded here.

Peat inwash could have influenced the composition at several lakes that experienced biologically important changes in diatom assemblages, but show no major change in the DI-pH and DI-TP profiles, particularly those exhibiting a shift to a benthic diatom assemblage characterised by *Fragilaria* taxa and, in some cases, the loss of planktonic assemblages. Small, benthic *Fragilaria* are considered pioneering taxa and have been related to rapidly changing environmental conditions (e.g., increased turbidity in the water column). Furthermore, diatom-community changes associated with peat inwash are usually characterized by the loss of planktonic assemblages (Jones *et al.* 1989). Peat erosion could have been linked to afforestation, as conifer plantations, many dating to the period following the secondary reference benchmark adopted in the current study (i.e. *c.* 1950), are present in the catchments for many of the CRLs included in WP2.

Of particular note is the comparatively high incidence of important deviations in biological conditions among the low alkalinity, large deep lakes (82 % of CRLs in typology class 4 generated SCD scores > 0.4). Nutrient enrichment does not appear to have been the driver here as increases in DI-TP are relatively minor and are not generally supported in the sedimentary TP data. It could be, however, that epilimnetic TP concentrations are not in balance with sediment-based TP. Moreover, relatively small increases in TP concentrations in P-limited lakes may impact diatom populations before any increases are evident in sediment chemistry: rapid DI-TP change has been found in some historically oligotrophic lakes in Northern Ireland prior to increases in sediment TP (Jordan and Anderson unpublished data). Acidification appears to have been a factor at several of these lakes, however, notably Dan, Kylemore and Tay.

The more finely resolved sediment chemistry and diatom data from Keel and Talt are of particular interest. The sedimentary data for Keel indicate relatively little change between *c.* 1850 and the present-day. The rate of sedimentation at Keel was, however, low (0.19cm yr^{-1}) and the base of the 41cm-long core of sediment obtained dated to the late 18th century, based on an extrapolation of the SCP chronology. Comparisons of diatom assemblages and DI-TP between the core bottom and top samples from this site indicate much larger changes than are evident since *c.* 1850, due to increased abundances of *Asterionella ralfsii* (a taxon that was not recorded in pre-*c.* 1850 sediments). The ecology of this taxon is not well known but appears to be indicative of peatland disturbance and nutrient enrichment (Liehu *et al.* 1986). It could therefore be argued that *c.* 1850 is too late to act as a reference date for Keel and this may also be the case for several other lakes in catchments that until the mid 19th century supported far higher population densities than today. The results from Talt indicate a pattern of change that may be hidden in some of the less finely resolved core datasets. The sediment chemistry for this site indicates catchment disturbance in the form of increases in sediment dry weight and in Ca, Fe, K, Mn, Na and TP accumulation rates between *c.* 1950 and the core top samples. According to the dry weight and sediment chemistry data, the catchment has stabilised since this disturbance event, although diatom communities and pH levels have yet to recover fully.

Analysis of the moderate and high alkalinity lakes (typology classes 6, 8, 10 and 12), where dissolution of silica diatom frustules has caused preservation and therefore interpretation problems, highlights the dangers of relying on diatoms as proxies of overall biological conditions in these systems. As the sedimentary data that are available for sites within these classes show some deviation from reference conditions may have occurred, a separate study should focus specifically on these typology classes using biological indicators other than diatoms (e.g. chironomids, cladocera, ostracods, pigments) that could not be used in WP2 because of limited funding. A further limitation of this investigation was that it was only possible to consider in any detail a restricted range of potential causes of variability, despite the potential role of other important influencing factors, notably climate change (e.g., Smol and Cumming 2000; Lotter *et al.* 2002; Sorvari *et al.* 2002; Hudson *et al.* 2003; Michelutti *et al.* 2003; Rühland *et al.* 2003; Smol *et al.* 2005). A number of lakes in this study have experienced a rise in *Cyclotella* taxa when compared with reference conditions that could not be related directly to human activities. Increased abundances of various *Cyclotella* species have been linked to climate change throughout the Canadian arctic (Karst-Riddoch *et al.* 2005) as well as in temperate regions (Wolin and Stoermer 2005) and climate changes since *c.* 1850 are likely to have impacted oligotrophic and meso-oligotrophic lakes in Ireland.

To conclude, results from WP2 discussed above:

- Indicate that 11 (32 %) of CRLs studied show relatively stable conditions, represented by little deviation between sediment-based proxies in core bottom, or *c.* 1850 where it could be established with some precision, and top samples. For four of these sites (Bunny [typology class 10], Keel and Nahasleam [both typology class 1] and Upper [typology class 1]) the bottom samples from the short sediment cores analysed appeared to date to *c.* 1850 or older.
- Demonstrate that of the CRLs that do not appear to have remained biologically largely stable over the time period represented by the sedimentary sequences analysed, large, deep, low alkalinity lakes in particular (82 % of this type of CRL studied) show biologically important deviation from reference conditions.

- Confirm acidification and nutrient enrichment as important drivers of recent changes, but do not exclude other factors such as catchment erosion and climate change.
- Suggest that *c.* 1850 may not be an appropriate reference baseline in all cases, especially when viewed in the context of the history of rural Ireland.

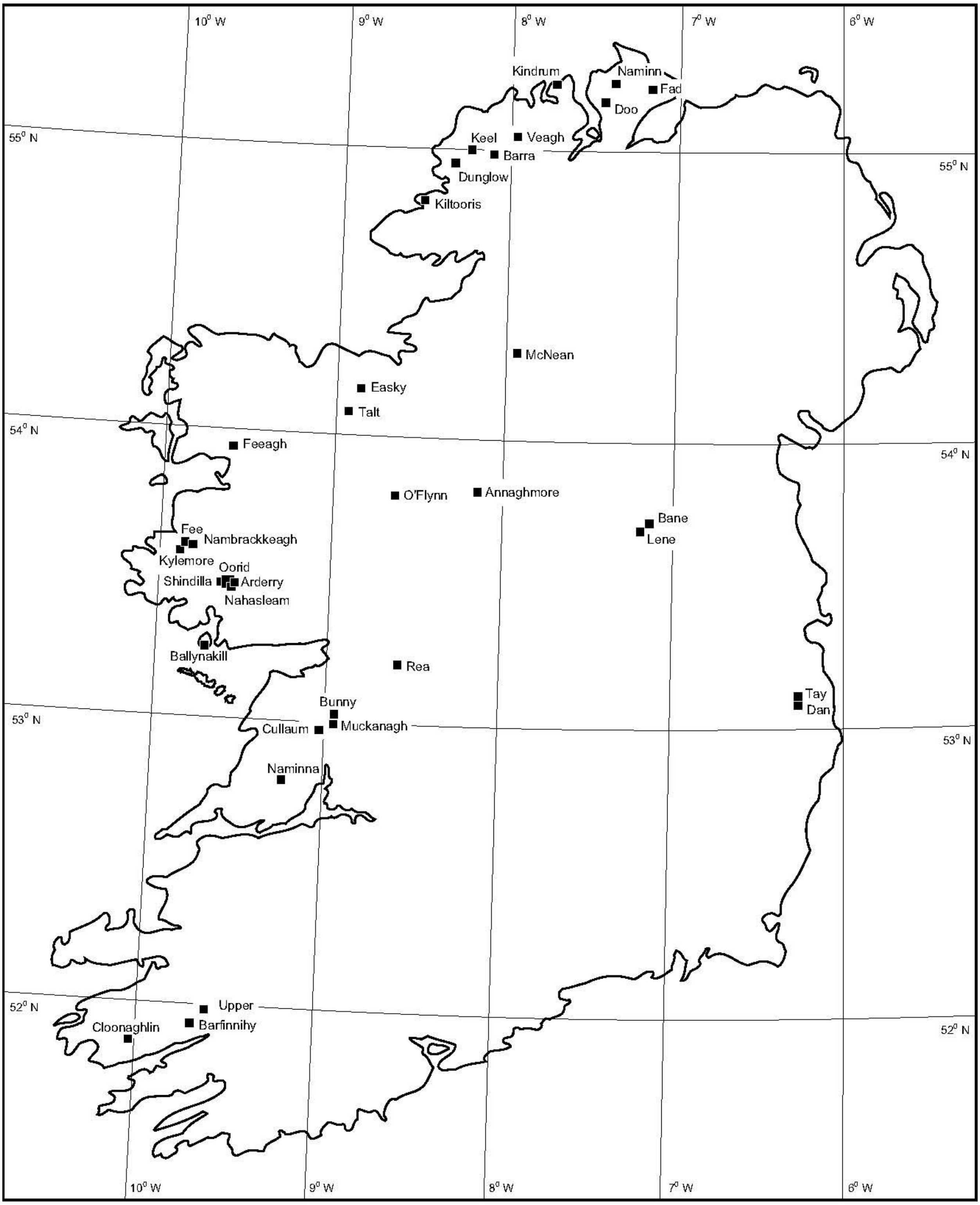


Figure 3.1 Location of the 35 CRLs studied in WP2 of IN-SIGHT

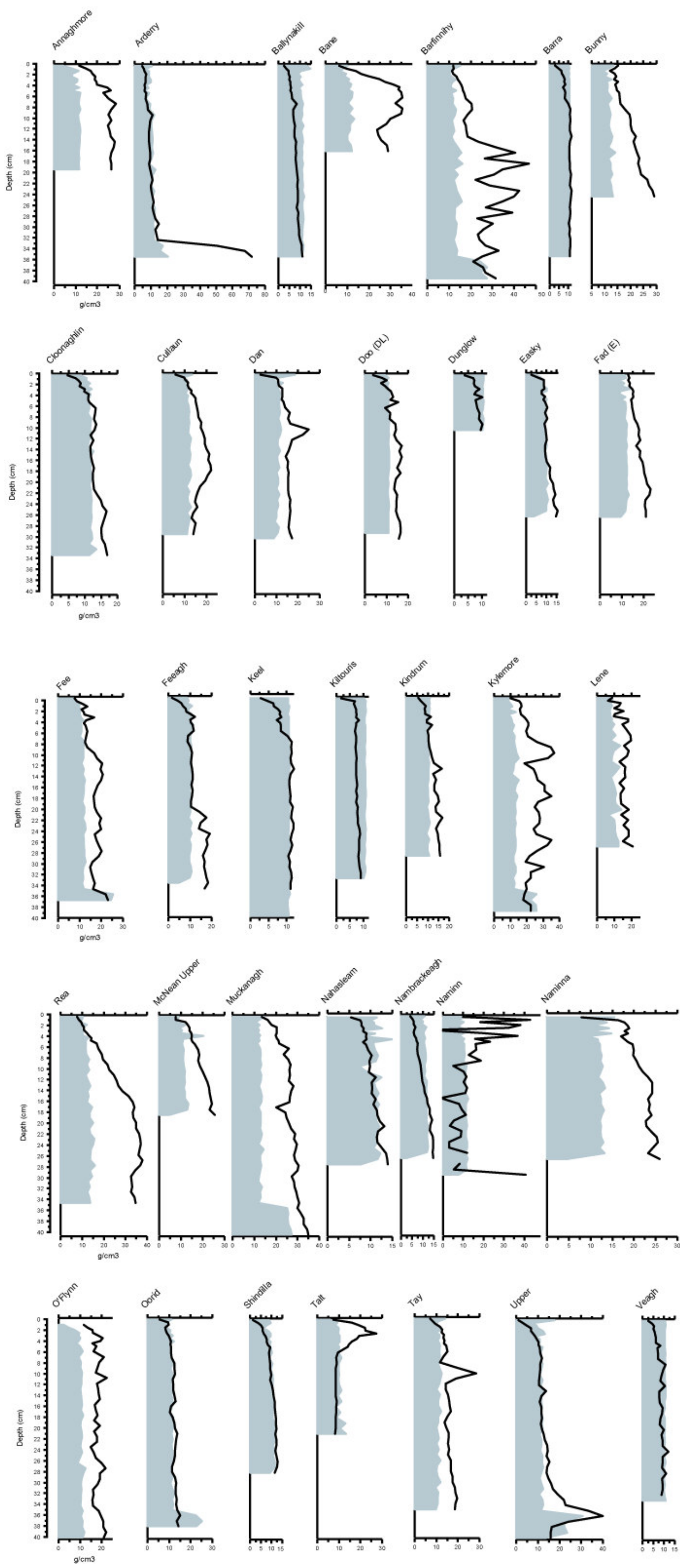
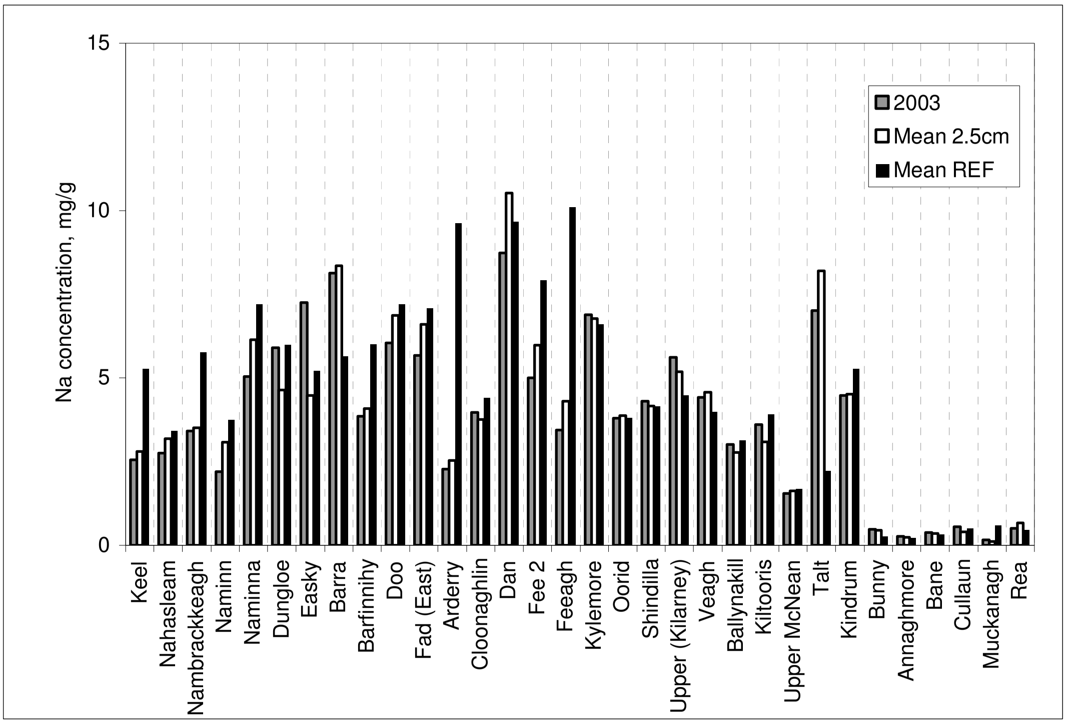


Figure 3.2: Dry weight (black line) and wet density (shaded curve) (both g cm^{-3}) for the CRL cores plotted against depth (cm). Wet density rates are x 10 to facilitate comparison with dry weight.



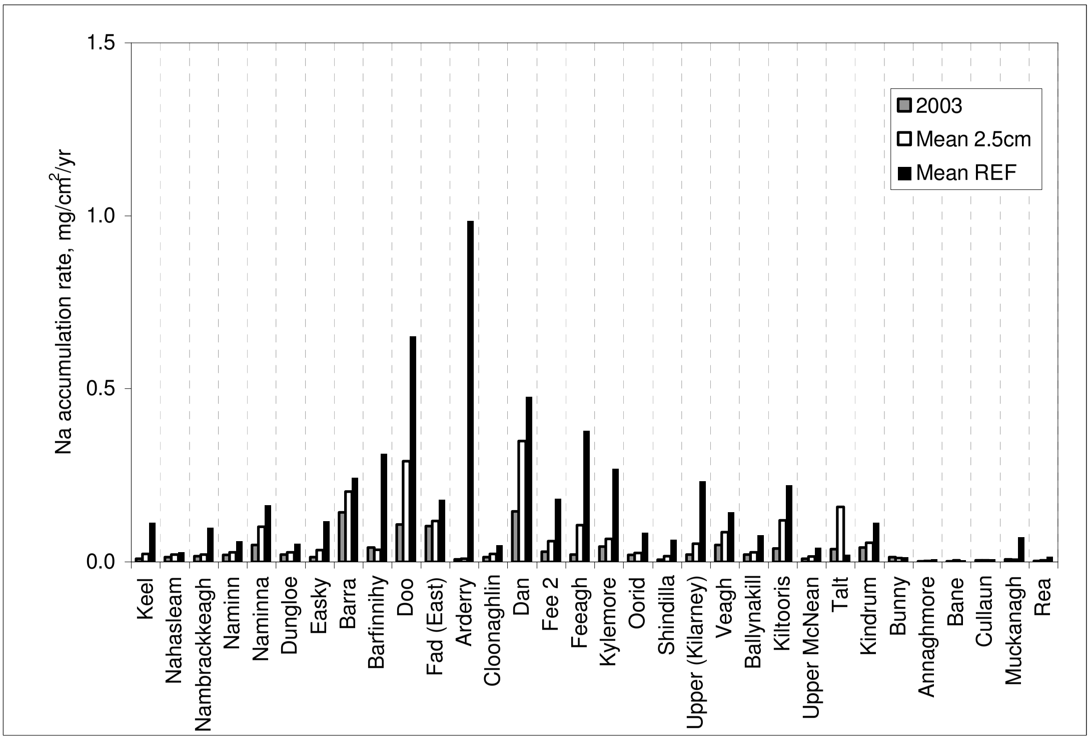


Figure 3.3a Intra-core differences in Na concentrations and accumulation rates for the 32 CRLs sampled for which there is tightest chronological control.

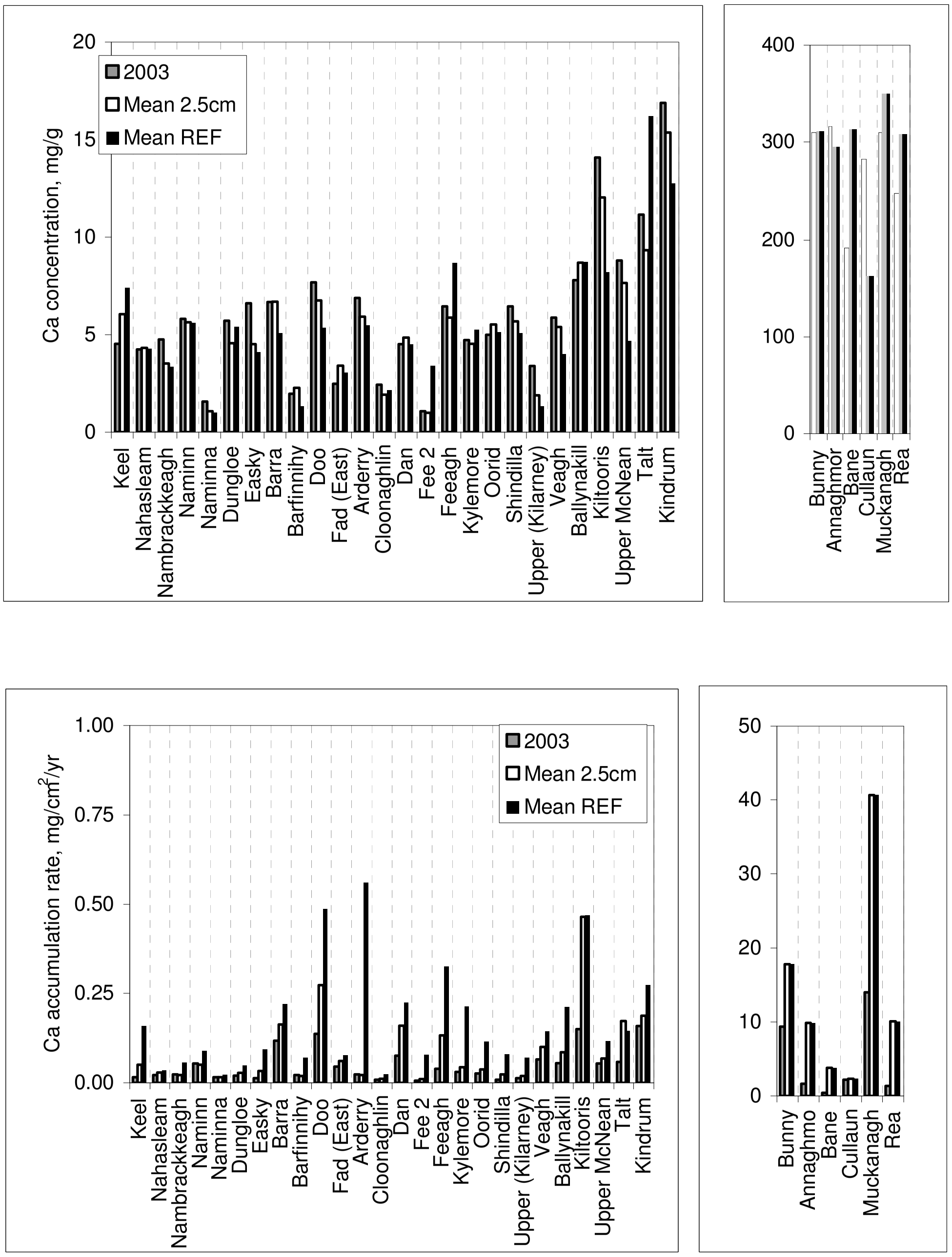
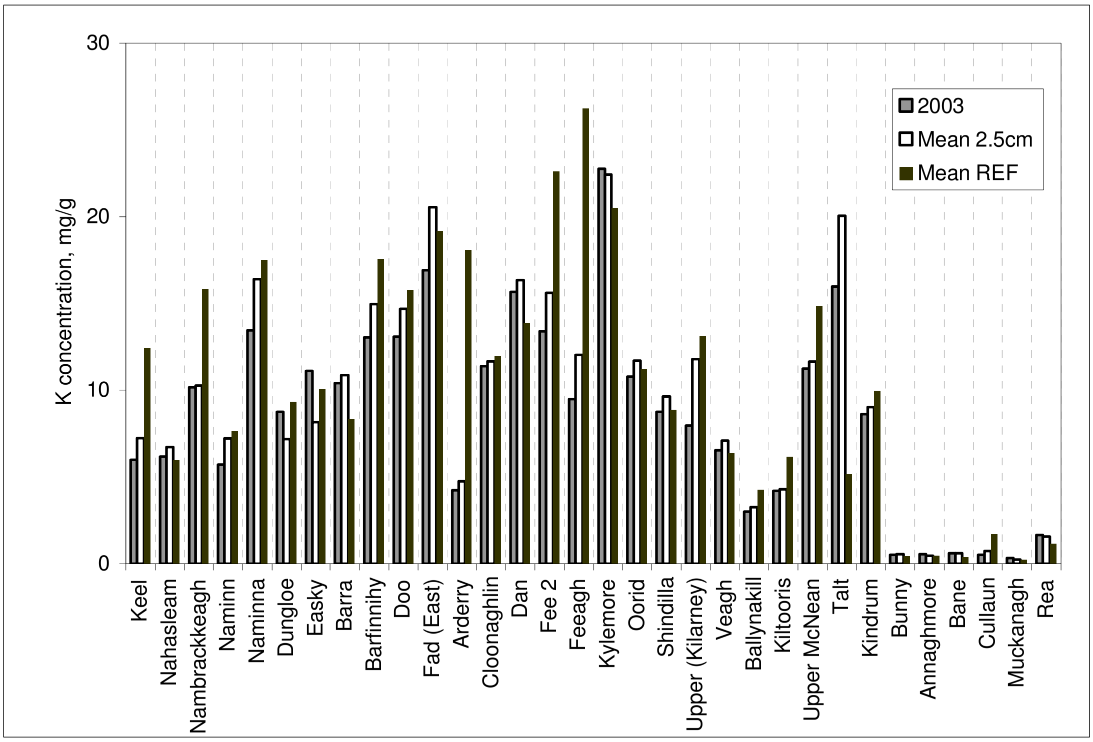


Figure 3.3b Intra-core differences in Ca concentrations and accumulation rates for the 32 CRLs sampled for which there is tightest chronological control.



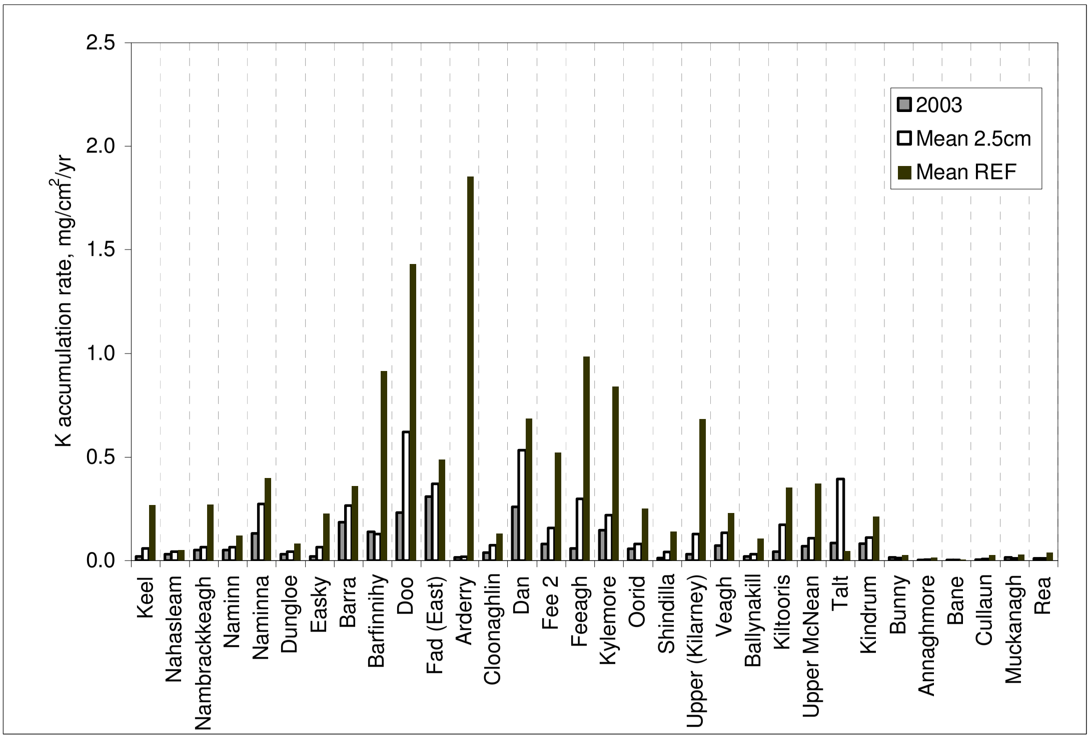


Figure 3.3c Intra-core differences in K concentrations and accumulation rates for the 32 CRLs sampled for which there is tightest chronological control.

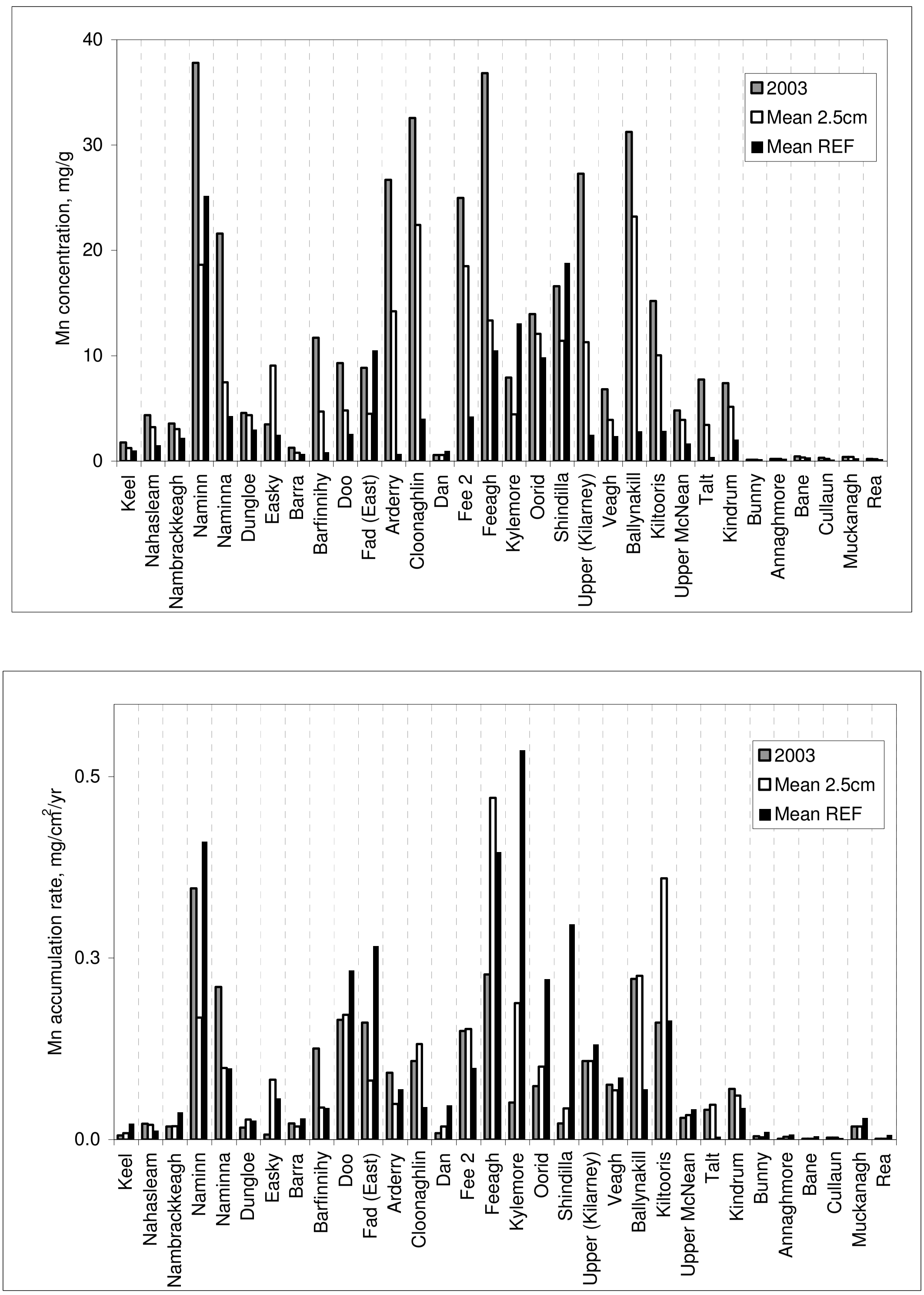


Figure 3.4a Intra-core differences in Mn concentrations and accumulation rates for the 32 CRLs sampled for which there is tightest chronological control.

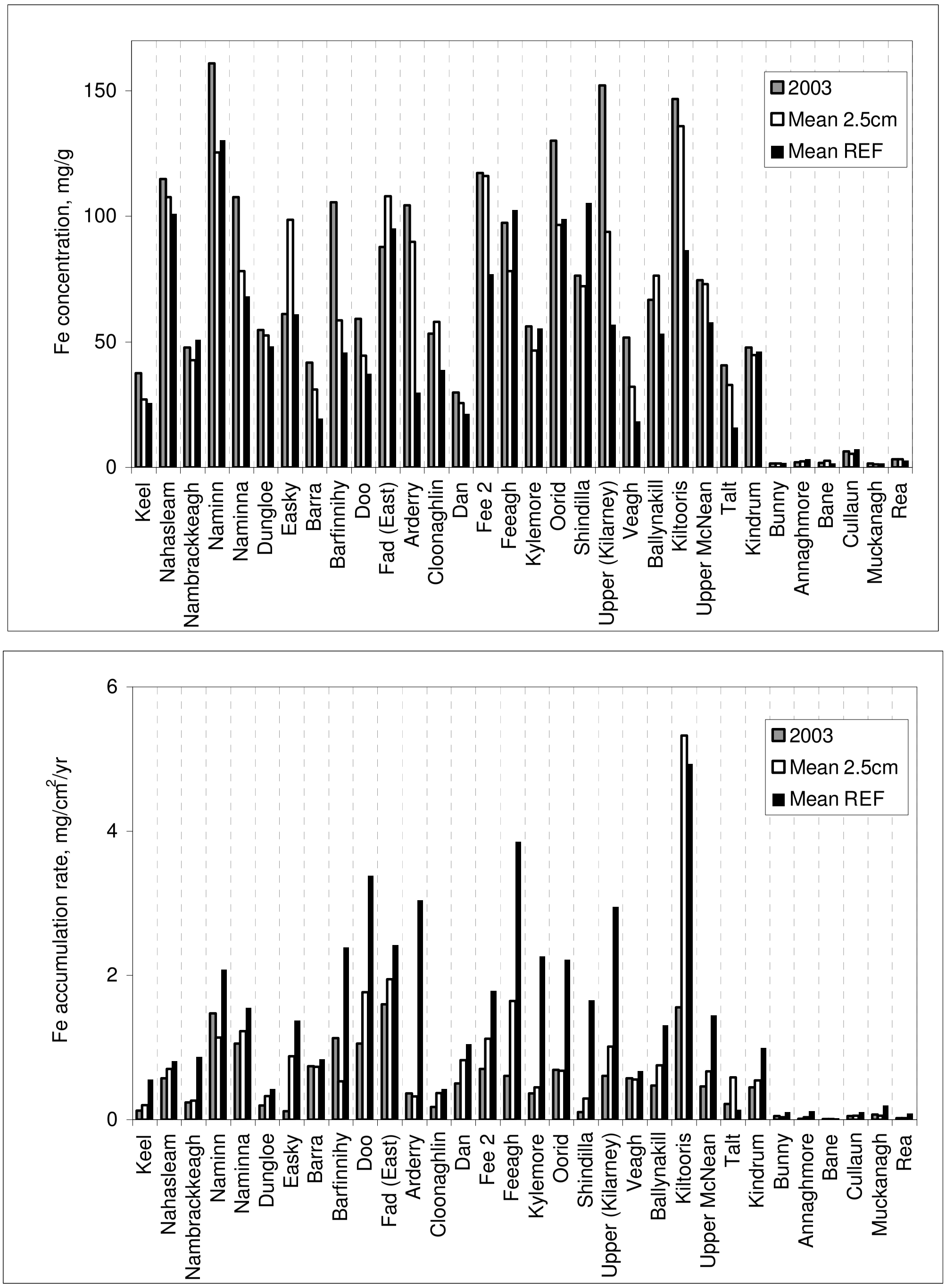


Figure 3.4b: Intra-core differences in Fe concentrations and accumulation rates for the 32 CRLs sampled for which there is tightest chronological control.

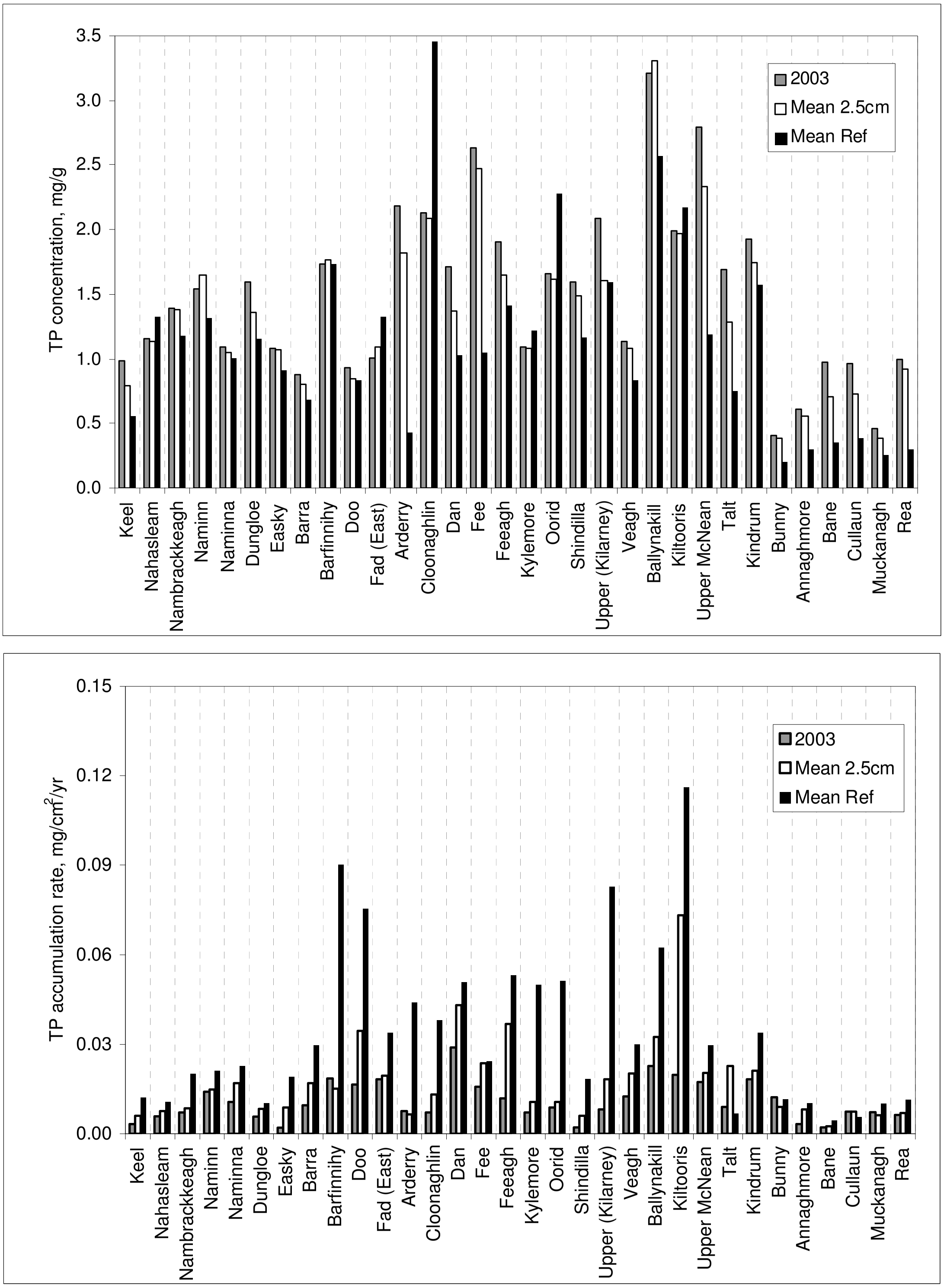


Figure 3.5 Intra-core differences in TP concentrations and accumulation rates for the 32 CRLs sampled for which there is tightest chronological control.

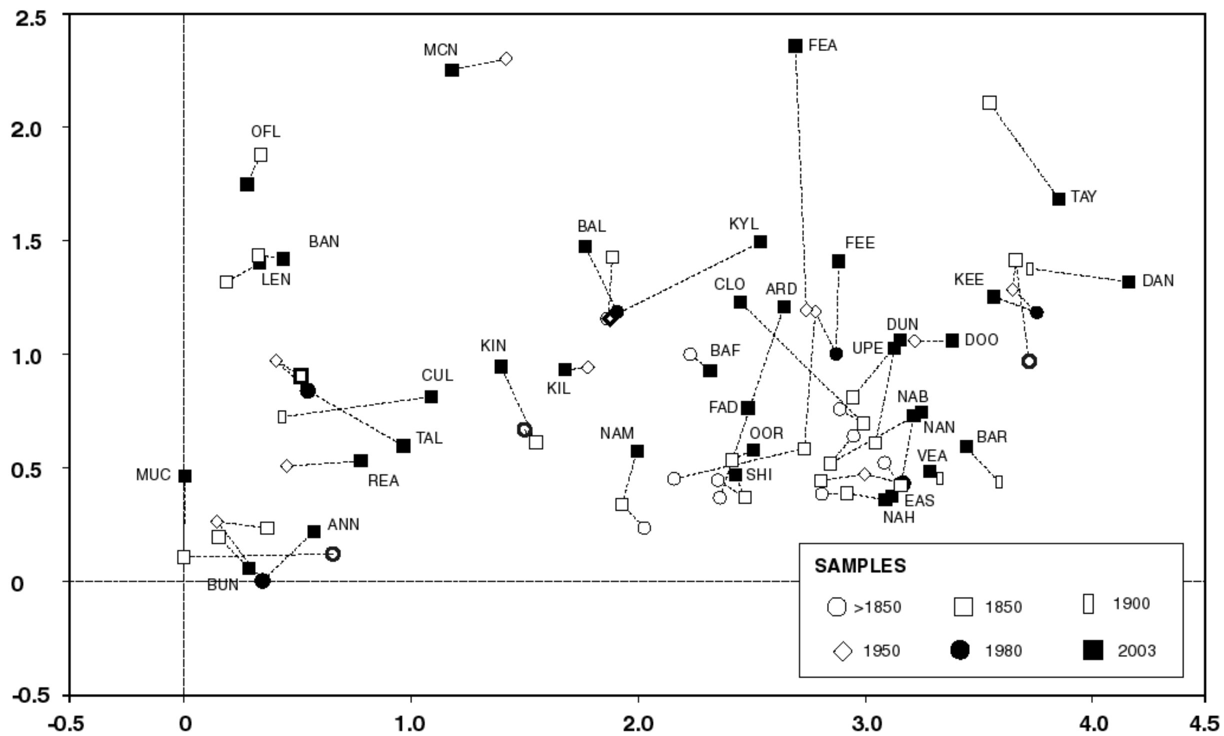


Figure 3.6 DCA biplot combining lake sediment core bottom and top samples, as well as mid-core samples where available. Lines connect samples from the same sediment core. The orientation of the line provides an indication of the direction of floristic change and its length is a measure of floristic difference (species turnover) (units=Hill's SD). See Table 2.6 for explanation of lake codes. Chronological control provided by down-core variations in SCP concentrations – see text and Appendix 6 for details.

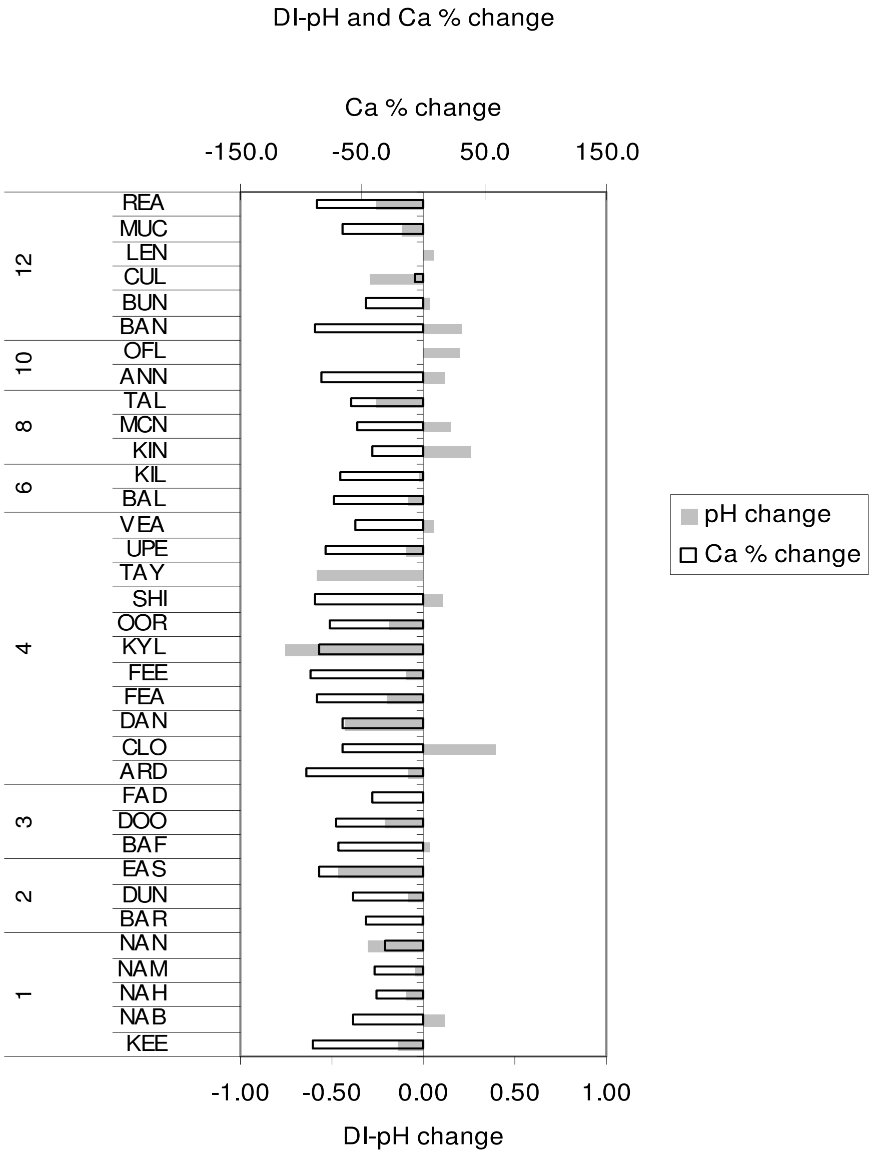


Figure 3.7 Differences in DI-pH (RMSEP = 0.43 pH) and Ca accumulation rate percentages (as an indication of variations in buffering capacity) between core bottom and top samples. See Table 2.6 for an explanation of lake codes. CRLs are ordered according to typology class: from CRLs in typology class 1 at base of figure to CRLs in typology class 12 at the top of the figure.

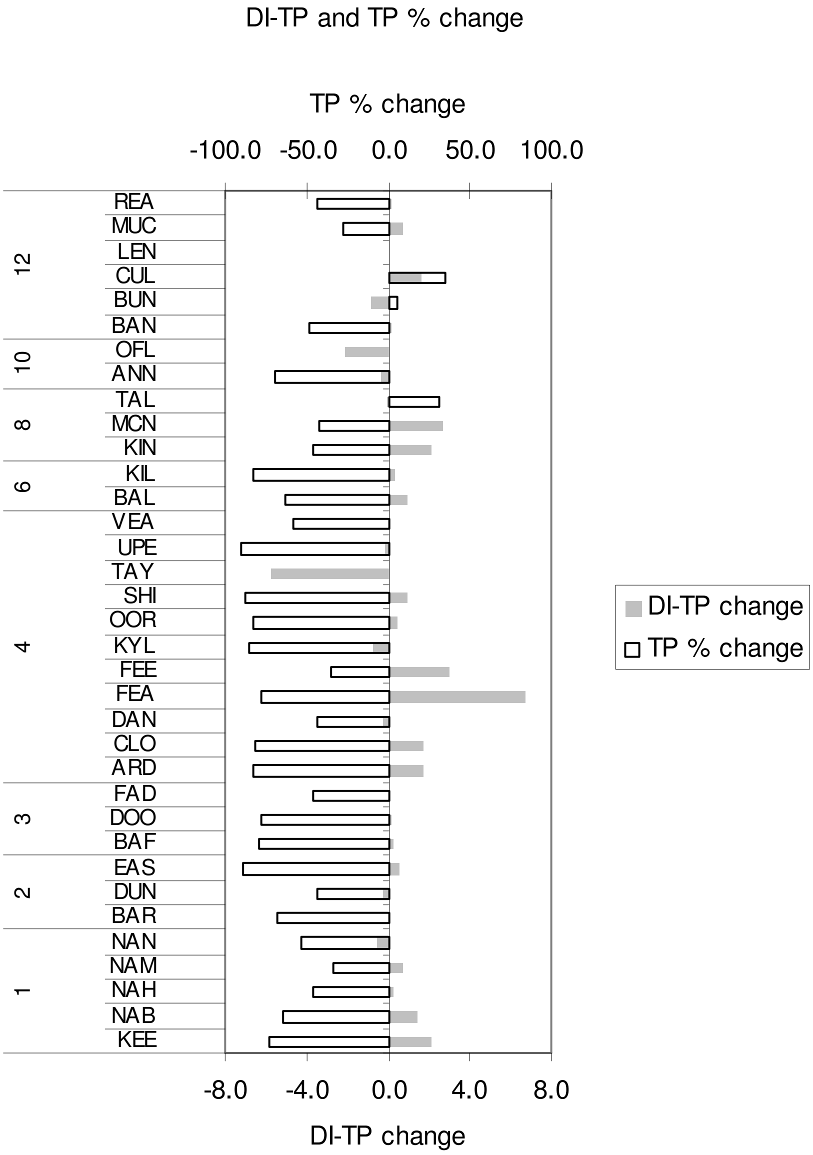
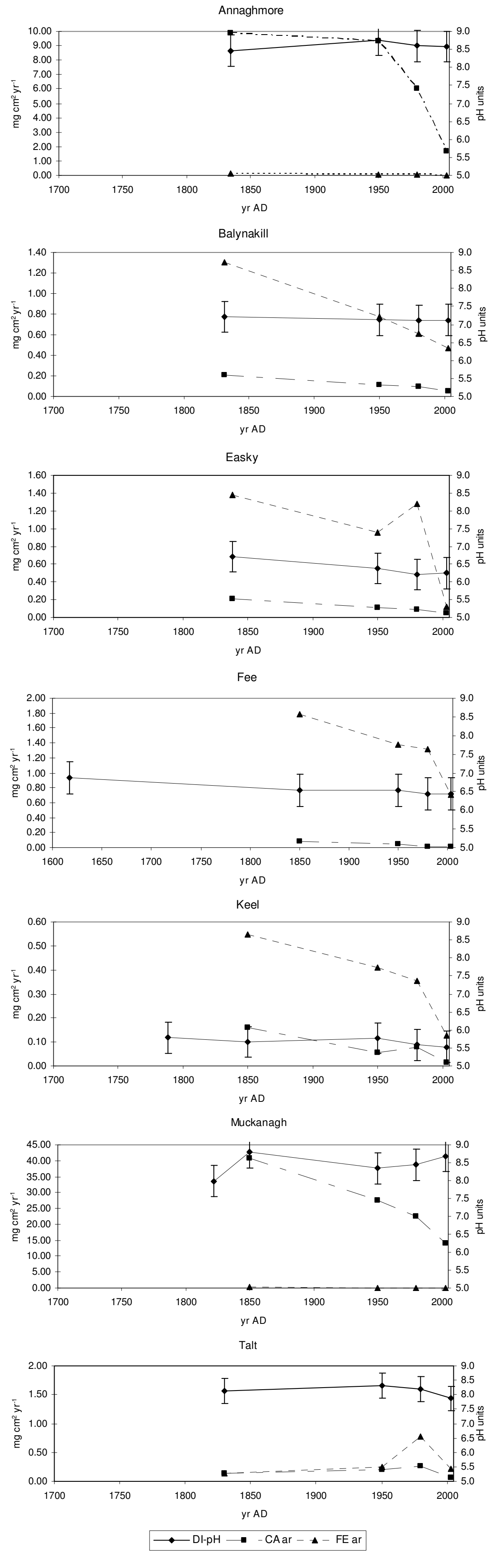


Figure 3.8 Differences between core bottom and top samples in DI-TP (RMSEP = 0.202 log µg TP l^{-1}) and sediment TP accumulation rate changes at the study lakes. See Table 2.6 for explanation of lake codes. CRLs are ordered according to typology class: from CRLs in typology class 1 at base of figure to CRLs in typology class 12 at the top of the figure.


Annaghmore
Balynakill
Easky
Fee
Keel
Muckanagh
Talt
mg cm² yr⁻¹
pH units
yr AD
DI-pH
CA ar
FE ar

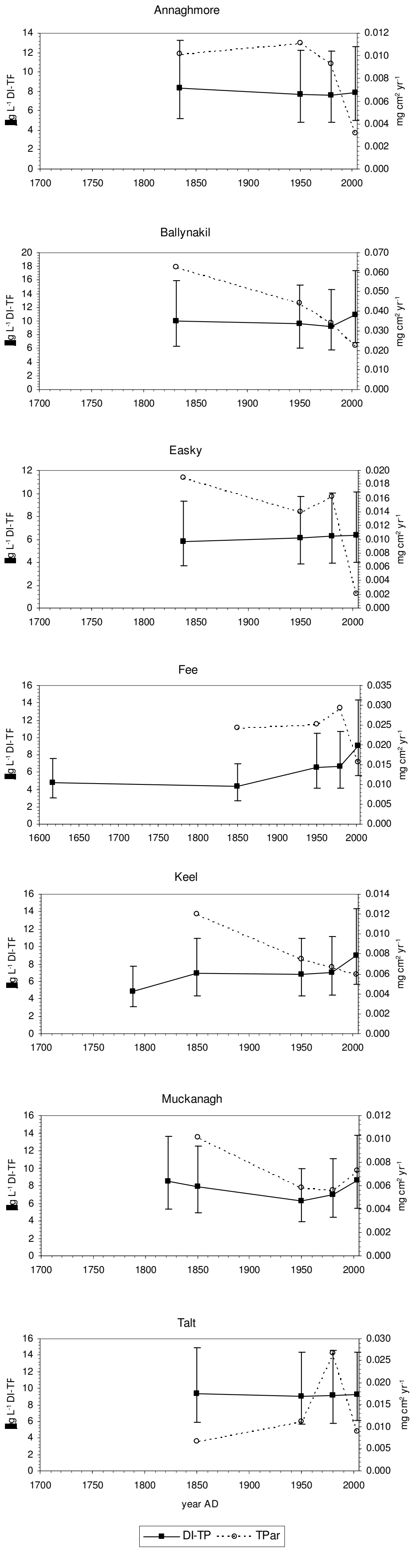

Annaghmore
Ballynakil
Easky
Fee
Keel
Muckanagh
Talt
DI-TF
mg cm2 yr-1
year AD
DI-TP
TPar

Figure 3.9a,b Reconstructions of DI-pH and percentage changes in Fe and Ca accumulation rates and DI-TP (µg l^{-1}*)* for CRLs where there is greatest chronological control (chronological control provided by down-core variations in SCP concentrations – see text and Appendix 6 for details).

Training set reference	Number of lakes	Estimation		Prediction	
		RMSE	r^2	RMSEP	r^2
pH (IN-SIGHT WP2)	35	0.282	0.93	0.427 (jack)	0.86
TP (IN-SIGHT WP2)	45	0.174	0.84	0.202 (jack)	0.64
SWAP pH Birks *et al.* (1990b)	167	0.230	0.91	0.290 (jack)	0.86
AL :PE pH Cameron *et al.* (1999)	118	0.133	0.97	0.326 (jack)	0.82
NW Europe TP Bennion *et al.* (1996)	152	0.150	0.91	0.210 (jack)	na
Northern Ireland TP Anderson *et al.* (1993)	43	0.172	0.75	na	na
SE England TP Bennion (1994)	30	0.160	0.79	0.280 (boot)	na

Table 3.1 Summary performance statistics of published DI-pH and DI-TP transfer functions, showing the statistics of the model developed in WP2. The RMSEP estimates are based on either leave-one-out jacknifing (jack) or bootstrapping (boot).

Lake	Typology class	Length of core (cm)	Estimated depth 1850 (cm)	Estimated depth 1950 (cm)	Estimated depth 1980 (cm)	Estimated age for bottom diatom sample analysed	Estimated sediment accumulation rate (cm yr^{-1})
Annaghmore	10	20	17-19	5-7	2-3	1834	0.12
Arderry	4	36	>9?			<1850?	NA
Ballynakill	6	36	29-35	10-13	4-5.5	1831	0.21
Bane	12	17	4.5-8?	1.5-3?	0.5-1?	<1850	NA
Barfinnihy	3	40	>9?			<1850?	NA
Barra	2	36	50-63	17-22	7.5-9	1905	0.37
Bunny	10	25	21-24	7-8.5	3-4	1833	0.15
Cloonaghlin	4	34	9-17?	3-6?	1-2.5?	<1850	NA
Cullaun	12	31	8-14?	2.5-5?	1-2.5?	<1850	NA
Dan	4	31	43-57	15-20	6.5-8.5	1909	0.33
Doo	3	31	72-86	25-30	10.5-13	1944	0.53
Dunglow	2	11	13-15	4-6	2-3	1885	0.09
Easky	2	27	23-27	8-9	3-4	1838	0.16
Fad	3	27	>27	6-7	2-4	1850-1950	NA
Fee	4	38	10-18?	3.5-6.5?	1.5-3?	<1850	NA
Feeagh	4	36	66-76	23-27	10-12	1926	0.47
Keel	1	41	28-30	11-15	3-4.5	1788	0.19
Kiltooris	6	34	66-110	23-40	10-19	1944	0.58
Kindrum	8	30	20-22	7-8	3-4	1776	0.13
Kylemore	4	40	>10?			<1850?	NA
Lene	12	29	>29			>1850	NA
McNean	8	19	12-14	3.5-5	1.5-2.5	1950	0.36
Muckanagh	12	42	31-40?	10.5-14?	4.5-6?	<1850	NA
Nahasleam	1	27.5	8-14?	2.5-5?	1-2.5?	<1850	NA
Nambrackkeagh	1	26.5	17-21	6-7	2.5-3.5	1789	0.12
Naminn	1	30	22-24	6-7	2.5-3.5	1804	0.15
Naminna	1	26.5	8-15?	2.5-5.5?	1-2.5?	<1850	NA
O'Flynn	10	42	>42			>1850	NA
Oorid	4	39	>10?			<1850?	NA
Rea	12	36	9-17?	3-6?	1-2.5?	<1850	NA
Shindilla	4	29	18-21	6-7	2.5-3.5	1775	0.13
Talt	8	22	18-21	5.5-7	2.5-3.5	1830	0.13
Tay	4	36	>36			>1850	NA
Upper	4	40.5	35-40	11-14	4.5-6	1840	0.25
Veagh	4	34	60	20	9	1850-1950	NA

Table 3.2 Approximate chronologies and estimated sediment accumulation rates for cores from CRLs sampled as part of WP2, based on down-core variations in SCP concentrations (see text and Appendix 6 for further details on this method and the results).

Lakes	Typology class	SCD	SD Hill's units	Change in DI-pH units	Prop. change in DI-TP
Annaghmore	10	0.835	1.118	0.11	0.95
Arderry	4	0.859	1.797	-0.08	1.31
Ballynakill	6	0.509	1.24	-0.09	1.09
Bane	12	0.557	1.112	0.21	1.01
Barfinnihy	3	0.139	0.731	0.03	1.04
Barra	2	0.409	0.986	-0.01	1.01
Bunny	10	0.351	0.94	0.03	0.90
Cloonaghlin	4	1.599	1.416	0.39	1.31
Cullaun	12	1.302	1.376	-0.29	1.18
Dan	4	0.410	0.806	-0.43	0.96
Doo	3	0.259	1.139	-0.21	1.02
Dunglow	2	0.171	1.176	-0.08	0.97
Easky	2	1.034	1.1	-0.47	1.08
Fad	3	-	-	-	-
Fee	4	0.967	1.494	-0.09	2.05
Feeagh	4	1.769	1.822	-0.19	1.89
Keel	1	0.319	1.1	-0.14	1.31
Kiltooris	6	0.288	1.171	-0.02	1.03
Kindrum	8	0.423	1.26	0.25	1.25
Kylemore	4	1.044	1.551	-0.76	0.91
Lene	12	0.478	1.001	0.06	1.01
McNean	8	0.148	1.056	0.15	1.14
Muckanagh	12	0.458	0.884	-0.12	1.10
Nahasleam	1	0.296	0.787	-0.10	1.03
Nambrackkeagh	1	0.75	0.984	0.12	1.25
Naminn	1	0.562	1.205	-0.05	1.09
Naminna	1	0.735	1.123	-0.30	0.92
O'Flynn	10	0.327	1.045	0.19	0.83
Oorid	4	0.987	1.715	-0.19	1.08
Rea	12	0.472	1.554	-0.25	1.02
Shindilla	4	0.416	1.039	0.10	1.20
Talt	8	0.96	1.508	-0.25	0.99
Tay	4	1.169	1.069	-0.58	0.58
Upper	4	0.046	1.019	-0.09	0.98
Veagh	4	0.245	0.923	0.05	1.01

Table 3.3 Summary of down-core variations in biological and inferred parameters for the 35 CRLs studied. Data comprise Squared Chord Distance (SCD) scores for pairs of core bottom and top samples from 34 of the 35 CRLs, along with Hill's SD units and intra-core differences in DI-pH and DI-TP. 'Prop change in DI-TP' = the proportion of change in DI-TP in the core top sample compared with the core bottom, or reference, where for example 0.8 = 20% decrease, 1.2 = 20% increase etc. CRLs that appear on the basis of their SCD scores to have had their CRL status verified in this study (i.e., SCD scores ≤ 0.4) are shaded. NB no SCD score based on an intra-core comparison was calculated for Fad Inishowen East in County Donegal because of an absence of well-preserved diatoms throughout the core (see text for further details).

Chapter 4

Multi-proxy palaeolimnological reconstructions of reference biological communities in anthropogenically impacted lakes

4.1 Introduction

This chapter details the results and conclusions from the part of WP3 of IN-SIGHT. WP3 focused on those types of lakes that belong to the major typology classes for which there are no extant reference sites. This chapter discusses the use of multi-proxy palaeolimnological techniques to quantify the extent and rate that current conditions at impacted lakes have deviated from biological reference conditions and the main pressures that appear to have led to the loss of reference conditions at these sites.

Focusing on sediment cores from impacted lakes, the multi-proxy approach adopted comprised analyses of three types of microfossils (cladocera, diatoms and pollen and spores), lithology and geochemistry. An accurate and precise chronology based upon radiometric techniques was employed to enable a more complete interpretation of the sediment-based data than was possible for WP2.

4.2 Methods

Selection of study sites

Seven lakes were selected for sediment coring and study in WP3: Atedaun, Ballybeg and Inchiquin in County Clare; Egish and Sillan in County Monaghan; Mullagh in County Cavan; and Crans in Co. Tyrone (Figure 4.1, tables 4.1 and 4.2). 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 4.3). The study lakes were selected based on knowledge of nutrient enrichment, lake typology classes, expert-judgment and following consultation with EPA staff, and represented six lake typology classes (Figure 4.2). All of the lakes studied in WP3 were from moderate and high alkalinity typology classes and were generally located within catchments in which improved pasture was the predominant landuse. None of the lakes that had their CRL status verified as part of WP2 were in typology classes 5, 7, 9 and 12. These typology classes, however, include five of the seven impacted lakes studied in detail in WP3. Lakes from typology classes 6 and 8 were also included in WP3 because there were data problems associated with the only two CRLs from these typology classes that, on the basis of intra-core comparisons in WP2, showed relatively small changes in sediment-based proxies.

Thus, diatom preservation was poor for McNean (typology class 8), while on the basis of down-core variations in SCP concentrations the core bottom samples for Kiltooris (typology class 6) and McNean dated to, respectively, *c.* 1944 and *c.* 1950.

Atedaun is located in the Fergus river catchment in County Clare, eutrophic and in typology class 9. 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 high flushing rate and short water retention time (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 of *c.* 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.

Ballybeg, adjacent to Ennis town in County Clare, currently supports high population densities (human and cattle) relative to the other WP3 study sites and is eutrophic. Urbanisation 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. Summer stratification, oxygen depletion of the hypolimnion and algal blooms are all documented for Ballybeg in Wemaere (2005).

Crans, a 8.5 ha lake and eutrophic according to unpublished TP data held within the Northern Ireland Lakes Survey Database (Department of Agriculture and Rural Development, Northern Ireland) is located in the Oona river catchment in County Tyrone, which discharges into the Blackwater catchment and eventually into Lough Neagh, and is in typology class 7. A small area of deciduous woodland is located close to the lake. The catchment geology is Lower Carboniferous (Viséan Calp) limestone and shale overlain by glacial till; land within the catchment was included in a major arterial drainage development scheme constructed in the 1980s (Anon 1997).

Egish is part of the Erne river system in County Monaghan and is in typology class 6. The catchment geology is predominantly Silurian quartzite. Densities of 1.68 ha^{-1} for cattle 0.24 ha^{-1} for sheep were 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, which was expanded in the 1970s, a retail park, large pig farm and a feed mill that opened in the 1990s. The creamery may have been a source of pollutants in the 1970s, while the owners of the pig farm were prosecuted for illegal effluent discharges in the 1990s (O'Flaherty pers. comm.). A highly enriched and productive lake with extremely high P concentrations and algal blooms was documented by the early 1970s in Flanagan and Toner (1975) and Champ (1977). Catchment landuse over the period 1990-2000 has seen a small decline in pasture and an increase in urban areas (Table 4.3). 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).

Inchiquin, County Clare, is also part of the Fergus river system (along with Atedaun), has the highest alkalinity (161 mg l^{-1} $CaCO_3$) of the WP3 lakes owing to the carboniferous limestone bedrock, and belongs to typology class 12. Land cover in the Inchiquin catchment is largely peatland, along with deciduous woodland and conifer plantations, and there are relatively low population densities (<1 per ha) of livestock and humans (Wemaere 2005). A wastewater treatment plant at Kilfenora discharges wastewater following secondary treatment to groundwaters in the Inchiquin catchment, potentially affecting the lake. Flanagan and Toner (1975) and Champ (1977) documented evidence of substantial nutrient enrichment and depleted levels of dissolved oxygen. Examination of the algal 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 hypolimnum during summer stratification.

Mullagh, County Cavan, is part of the Boyne river catchment, which is underlain by Silurian quartzite geology, and is in typology class 5. The lake is subject to intense agricultural activities. Catchment landuse is predominantly pasture, with densities of cattle and sheep of, respectively, 2.85 ha^{-1} and 0.83 ha^{-1} reported in 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).

Sillan in County Cavan is located beside the town of Shercock and is the largest of the WP3 lakes at 172 ha. The lake is in typology class 8, and a TP of 141 µg l^{-1}, reported by Irvine *et al.* (2001), indicates hypertrophic conditions. The presence of point sources for pollution, in the form of a chicken-processing factory and treated sewage from Shercock, has been documented in the past (O'Connor and Bracken 1978). In addition, a caravan site is located close to the north shoreline of Sillan. Physico-chemical monitoring in the 1970s revealed elevated levels of TP, nitrogen and ammonia and the seasonal release of sedimentary P, while examination of littoral, sublittoral and profundal fauna enabled classification of the lake as moderately eutrophic (Flanagan and Toner 1975; Champ 1977; O'Connor and Bracken 1978).

Field-based techniques

The seven lakes were surveyed and cored during August and September 2004. Bathymetric surveys were conducted for six of the lakes using a portable depth sounder (> 2 depth measurements per ha) and a handheld GPS with a positional accuracy of 5-10 m (Table 4.4). Geo-coded depth data were inputted as (x,y) data into ArcMap 8.0 along with digitized lake boundaries. Bathymetic maps were generally produced using surface interpolation (Spline) with the Spatial Analyst extension (Appendix 9). A bathymetric map for Ballybeg was available in Wemaere (2001).

Three cores were collected from coring sites *c.* 1 m apart in the deepest part of each lake using a gravity (Renberg) corer (Renberg 1991). Sampling of cores in the field followed the same procedure as outlined in Chapter 3, with samples from the three cores collected from each lake subsequently used separately to determine: (a) the rate of sediment accumulation; (b) lithostratigraphic and sediment chemistry properties; and (c) microfossil content (diatoms, cladocera and pollen).

Laboratory methods

Chronological control

Chronological control for lakes studied as part of WP3 was based upon radiometrically-determined sediment accumulation rates (Robbins *et al.* 1978). Relative concentrations of ^{210}Pb (a naturally occurring isotope) and ^{137}Cs in ten to fourteen sediment samples per core were determined by high-resolution gamma spectrometry. Sediment chronologies and accumulation rates were used to calculate age using the constant rate of supply (CRS) of ^{210}Pb model, and were verified using anthropogenic ^{137}Cs activity profiles. The supported ^{210}Pb was determined from concentrations of ^{214}Pb and ^{214}Bi in each sample. Levels of unsupported ^{210}Pb ($^{210}Pb_{excess}$) were then calculated as the difference between the total and the supported ^{210}Pb concentrations. Limited resources meant that only one core per lake could be dated in this way, with chronological control extended to other cores from the same lake using down-core variations in sediment properties.

Microfossil analyses

Three groups of microfossils (diatoms, cladocera and pollen and spores) were used to hindcast historical lake water quality and catchment conditions. Several species of cladocera that preserve well and reflect the nutrient status and pH of lake water (Irvine *et al.* 2000; de Eyto *et al.* 2002) have been used in the reconstruction of aquatic conditions (Frey 1960;

Parise and Riva 1982): Daphniidae and Bosminidae tend to be planktonic, while the Chydoridae are mainly benthic/littoral. Pollen and spores are commonly used in studies of recent environmental changes (Bennett and Willis 2001) and were used in WP3 to estimate changing terrestrial plant cover (e.g., Edwards and Whittington 2001).

Microfossils were enumerated in seven to nine samples per core for diatoms and, generally, two samples per core for cladocera and pollen and spores. Where possible the microfossil content of core top and bottom samples was established. This approach assumes that the top and bottom samples in a sediment core integrate, respectively, conditions at the time of coring and site-specific reference conditions (Smol 2002, and see Chapter 3). For diatoms, samples were prepared and analysed using the procedures outlined in Chapter 3. For cladocera and pollen and spores, 1 cm-thick samples of core sediment were used. Cladocera were concentrated using a modified version of the standard method described by Frey (1986) and identified following Frey (1959, 1960, 1962a,b, 1964), Goulden and Frey (1963) and Alonso (1996). Pollen and spores were concentrated in unit volumes of sample following the standard laboratory protocol described in Bennett and Willis (2001) and identified through reference to type material. The relative abundances of all diatom and cladoceran species (including unidentified forms) were established on the basis of the total count per sample. Diatom abundances were also expressed in concentration (cells g^{-1}) and accumulation rate (cells cm^{-2} yr^{-1}) forms. Two sums were used in percent calculations for pollen and spores: 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 morphologically similar types from other conifers]).

Lithostratigraphy and sediment chemistry

Wet sediment density and percentage water content were determined on all samples from the cores used for lithostratigraphic and sediment chemistry analyses. As in WP2, wet sediment density was determined from the weight of known volumes of fresh sediment samples, while percentage water (as dry weight density) and organic (loss on ignition (LOI), measured at 1 cm intervals) contents were established thermogravimetrically (Hilton *et al.* 1986). Total sediment chemistry concentrations of Ca, Fe, K, Mn and P were assessed using ICP-OES following sequential acid digestion (Jordan *et al.* 2001). Additionally, uranium (U), cadmium (Cd) and boron (B) were determined for sediments from Crans and Ballybeg. As with WP2, sedimentary P was analysed to support microfossil data, while analyses of major cations (Ca, Fe, K, Mn and P) were included to assist in hindcasting phases of catchment inwash 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 every 1 cm, except U, B and Cd, which were determined every 2 cm. Chemical accumulation rates were generated based on the product of chemical concentration (mg g^{-1}) and dry mass accumulation rate (DMAR) and expressed as g m^{-2} yr^{-1}. Quality control was assured through repeat digests and the use of a batch digest method validated with certified reference material.

Data analyses

Down-core differences in diatom assemblages and water quality were quantified through: reconstructions of DI-TP; indices of diversity; and ordination. DI-TP transfer functions, specific to WP3, were developed using an Irish Ecoregion training set of 73 lakes, the standard numerical technique of weighted averaging (WA) (Birks *et al.* 1990a,b; Korsman and Birks 1996; Koster *et al.* 2004) and the computer software package C2 version 4 (Juggins 2003). The DI-TP transfer functions developed for WP3 data were based on a dataset that incorporated a broader range of measured TP values (range = 0-675 µg l^{-1}, mean = 33 µg l^{-1}, median = 10 µg l^{-1}) when compared with the dataset used in developing the version of the model applied in WP2, because the training dataset for the latter did not extend into the eutrophic and hypertrophic part of the trophic gradient. Reconstructions of DI-TP were based on harmonised data and produced using a WA partial least squares two-component (WA-PLS) model (ter Braak and Juggins 1993; Birks 1995), the performance statistics of which compared well with similar models developed for other parts of Europe (Table 4.5). Two diversity indices - Shannon (Pielou, 1975) and taxonomic distinctness (Clarke and Warwick 1998) - were also calculated (although results from these, as they relate to fossil assemblages of different ages that may have been subjected to differential preservation, have to be treated with caution). DCA (Hill and Gauch 1980) was used to explore changes in diatom assemblages within and between sediment cores using CANOCO version 4.5 (ter Braak and Šmilauer 2002), square root transformed data and down weighting of rare taxa.

4.3 Results

Down-core variations in sediment chemistry and microfossils

Lake sediment cores ranged in length from 27 cm to 41 cm (Table 4.6). In general, there was good agreement between results of the CRS and ^{137}Cs-based age models, 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) and estimated ages of core bottom samples ranging from the late 18th century (Egish) to the early 20th century (Inchiquin, Sillan and possibly Mullagh) (Figure 4.3, Table 4.7). Figure 4.4 illustrates down-core variations in Pb_{excess} and ^{137}Cs for all cores analysed, apart from Atedaun. The Pb_{excess} and ^{137}Cs profiles for Atedaun were too irregular to provide reliable chronological control.

Sediment samples generally contained abundant, well-preserved microfossils. At least 400 valves and 70-100 chydorids were enumerated in each sediment sample analysed for its diatom and cladocera content, respectively. 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). DI-TP and measured TP correlated well (r^2 = 0.67, p value < 0.01), although the model tended to underestimate the high values of TP measured at Egish and Sillan. Most WA models produce DI-TP values that underestimate measured TP in highly productive lakes (Hall *et al.* 1997), possibly because diatom species composition changes little as epilimnetic TP concentration increases above 100-200 $\mu g\ l^{-1}$ (Anderson *et al.* 1993; Bradshaw and Anderson 2001). Furthermore, wide fluctuations in epilimnetic TP concentrations in highly productive lakes (Bennion and Smith 2000; Bradshaw *et al*. 2002) are unlikely to be fully represented in a relatively few field measurements. For ease of interpretation, DI-TP values are discussed below in the context of the OECD (1982) scheme of trophic assessment (oligotrophic 0-10 $\mu g\ l^{-1}$ TP; mesotrophic >10-35$\mu g\ l^{-1}$ TP; eutrophic >35-100 $\mu g\ l^{-1}$ TP; hypertrophic >100 $\mu g\ l^{-1}$ TP).

Cladocera counts usually required 0.1 to 0.3 ml of concentrated sample, although surface samples from Crans, Inchiquin and Egish required far larger volumes owing to low concentrations of chydorids (1.6 ml of concentrate in the case of Crans). Appendix 10 provides a full list of the cladoceran species counts. Counts of identifiable pollen and spores (i.e. excluding those rendered unidentifiable owing to damage or debris on the microscope slide) ranged from 141 to 397 $sample^{-1}$. Preservation was poorest in samples from Ballybeg (material from core top and bottom samples from this site yielded, respectively, 141 and 203 pollen and spores). Problems in extracting sufficient quantities of pollen and spores from core top samples were also experienced on occasion: the uppermost samples analysed for their pollen and spore content in the sediment cores from Crans, Egish, Mullagh and Sillan were, respectively, 10-11 cm, 5-6 cm, 10-11 cm and 15-16 cm (Table 4.8).

Atedaun

An irregular ^{210}Pb concentration profile precluded use of the CRS model to estimate chronology, while an absence of noticeable peaks in the ^{137}Cs profile also prevented the construction of a reliable chronological framework based on radiometric analyses. The absence of a fall-off in the ^{137}Cs profile suggests that the base of the core (at 23 cm) could be younger than the onset of weapons fallout (1954), which translates into a sedimentation rate of at least 0.45 cm yr^{-1}. This rate is higher than many of those listed in Table 2.5.

The results of sediment density, percentage water content and percentage organic content determined via loss-on-ignition analysis for Atedaun are plotted against depth of sediment in Figure 4.5a. 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 profile, with higher dry weight densities towards the base of the cores reflecting compaction and decreasing toward to the surface, is similar to the dry weight profiles for the other WP3 cores. Organic matter content increased up-core, with a sharp peak evident at *c.* 6 cm. Chemistry data could not be expressed in accumulation rate form because of the weak chronological control for sediments from Atedaun. The main features in the concentration profiles were noted towards the top of the core between 5 and 10 cm (Figure 4.6a), where a decrease in the TP profile matched falls in Fe, Na and K and suggests a change in sediment type. Mn increased over the same depth range.

Only relatively minor changes in diatom assemblages are evident over the period represented by the sediment core (Figure 4.7a). Small, non-planktonic taxa, especially *Amphora pediculus* and *Cocconeis placentula* var. *placentula*, generally found in eutrophic waters, characterise 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, while the high proportion of epiphytic taxa suggests the presence of macrophytes. The DI-TP results indicate that Atedaun was mesotrophic up to the most recent period, with DI-TP values ranging from 16 µg l^{-1} for the base of the core (40 cm) increasing to 40 µg l^{-1} in the core top sample. Chydorid taxa, which prefer the littoral areas of lakes, were abundant in both core top and bottom samples (Figure 4.8a). Of the 18 species and one species complex (*Alona guttata/rectangular*) of chydorids recorded, 10 occurred with a relative abundance of greater than 5% in at least one sample. *Alonella exigua* and *Graptoleberis testudinaria* were common, but were less so in the core top sample. These taxa are typically found in mesotrophic lakes with abundant macrophytes (Duignan 1992). *Chydorus sphaericus*, which can tolerate a wide range of conditions but shows a preference for meso-eutrophic lakes (de Eyto *et al*. 2002), increased between the core bottom and top samples. The increase of *Chydorus sphaericus* together with the decrease of *Alonella exigua* and *Graptoleberis testudinaria* may indicate nutrient enrichment in association with a decrease in macrophyte cover. A reduction of macrophyte cover is likely to lead to lower abundances of those chydorids that spend part of their life cycle attached to plants (Jeppesen *et al*. 2001).

Planktonic cladocerans, although less abundant than chydorids, are more abundant in the core top than the bottom sample. The abundances of *Corylus* (hazel) 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 (grass family), *Quercus* (oak) and *Ulmus* (elm) declined (Table 4.8). Pollen spectra indicate an expansion of open-canopy hazel woodland in the catchment, possibly together with an increased prominence of conifers, apparently at the expense of closed-canopy oak-elm woodland. A decline in abundance of Poaceae pollen may also reflect an increase in grazing pressure, with many grasses being consumed or trampled before being able to release pollen.

Ballybeg

An exponential decrease in $^{210}Pb_{excess}$ activity with depth (Figure 4.4a) is consistent with a constant rate of sediment accumulation, while the two peaks in ^{137}Cs concentration are attributable to Chernobyl and weapons fallout. The total inventory for the unsupported ^{210}Pb, at 3000 ± 50 Bq m^{-2}, implies a mean supply rate typical of atmospheric flux in this region (McGarry 1991; Mitchell *et al.* 1992) and that the bulk of the unsupported ^{210}Pb is from atmospheric deposition. The proportion of organic matter was highly variable (Figure 4.5b), whereas DMAR and sediment chemistry accumulation rates showed only minor down-core variations (4.6b). Sedimentary Fe, K, Mn, Na and TP concentrations increased markedly from *c.* 1970, while increases in Cd and U concentrations were later (from *c.* 1980).

Diatom concentrations and accumulation rates are highest in the core bottom and top samples (Figure 4.7b). The top sample had substantially reduced diversity. Changes in diatom assemblages record a shift from an oligo-mesotrophic, benthic-dominated (e.g. *Gomphonema lateripunctatum*, *G. pumilum*, *Pseudostaurosira brevistriata* and *Staurosira construens* to a meso-eutrophic, planktonic (e.g., *Asterionella formosa*, *Aulacoseira subarctica, Stephanodiscus hantzschii* and *S. parvus*) assemblage suggestive of nutrient enrichment. DI-TP was relatively constant and in the mesotrophic range to *c.* 1980, after which date it increased to the extent that the core top sample represents hypertrophic conditions. Increased DI-TP concentrations from *c.* 1980 reflect increasing percentages of *Stephanodiscus hantzschii* and *S. parvus*. Planktonic cladocerans dominate both top and bottom samples, with relative increases of the planktonic *Chydorus sphaericus* and greatly reduced abundances of the benthic *Acroperus harpae* in the core top sample (Figure 4.8b) possibly a response to nutrient enrichment. Pollen from deciduous woodland taxa (*Alnus* [alder], *Corylus, Fagus* [beech], *Quercus, Salix* [willow] and *Ulmus*) was less abundant in the core top than in the core bottom, while the reverse was true for *Pinus*-type pollen (Table 4.8).

Crans

An exponential decline in $^{210}Pb_{excess}$ meant that equilibrium with supported ^{210}Pb was reached at *c.* 24 cm; two well-resolved ^{137}Cs peaks were evident at 14.5 and 6.5 cm (Figure 4.4b), suggesting little post-depositional mixing of sediments. The estimated sediment accumulation rate suggests that core bottom samples date to at least the mid 19th century. Only small variations in organic matter were found (Figure 4.5c), while DMAR declined from the base of the core to *c.* 1880, after which date it stabilised at about 0.025 g cm^{-2} yr^{-1} (Figure 4.6c). Concentrations and, to a lesser extent, accumulation rates of Cd, Fe, K, Na and U were much higher before *c.* 1880 than after, while the reverse was true for sedimentary Ca, Mn and TP.

A planktonic flora (e.g., *Aulacoseira ambigua*, *A. subarctica*, *Asterionella formosa* commonly associated with meso-eutrophic conditions and a variety of small *Stephanodiscus* spp. typical of highly eutrophic conditions) characterised the analysed samples (Figure 4.7c). Non-planktonic taxa were, however, also relatively abundant (~ 25%) in the basal sample and the DI-TP data record a transition from a mesotrophic to a hypertrophic state by the late 19th century. Reduced DI-TP levels, although still hypertrophic, were evident from the mid-20th century with further increases post-c. 1980. The onset of hypertrophic conditions also coincided with major peaks in diatom concentration and accumulation rate data. Lower abundances of planktonic cladocerans, including *Chydorus sphaericus,* and greater abundance of the mesotrophic *Alonella nana* were found in the bottom sample (Figure 4.8c), possibly reflecting nutrient enrichment. A predominance of planktonic taxa (*Daphnia* and *Bosmina*) in the core top sample may indicate a decreased extent of suitable littoral habitat. Poor pollen and spore preservation necessitated analysis of a sample from 10-11 cm (c. 1960). Differences in pollen and spores indicate a decline in deciduous woodland taxa (*Betula* [birch], *Corylus* and *Fagus*) that is partially masked by increased pollen from *Alnus, Fraxinus* [ash], *Quercus* and *Salix* (Table 4.8). Levels of Poaceae and *Pinus*-type pollen increased substantially.

Egish

Unsupported ^{210}Pb concentrations exhibit a hiatus between 6.5 and 8.5 cm depth (Figure 4.4c), possibly due to sediment slumping. Applying the CRS model to the unsupported ^{210}Pb profile yielded a chronology that is in agreement with the observed ^{137}Cs profile, which locates the onset of weapons fallout at a depth of *c.* 14 cm in the core. The LOI profile (Figure 4.5d) shows three distinct peaks in organic matter, the uppermost one preceding the hiatus in the ^{210}Pb profile. DMAR shows little variation before a major increase from the *c.* 1980s (Figure 4.6d), and this pattern is matched closely by sedimentary accumulation rates for all elements analysed. Fe, Mn and TP concentrations showed a similar pattern of variation, rising *c.* 1950. Concentrations of Ca, Na and K were much more variable, with several pre-1950s peaks evident.

Periphytic taxa (mainly small *Achnanthes* and *Fragilaria*, and a few planktonic diatom species, e.g., *Aulacoseira subarctica*) were common in the core bottom sample (Figure 4.7d). The abundances of planktonic diatoms, generally low in the core bottom, increased markedly from *c.* 1980 and, particularly, post *c.* 1990, but diatom diversity was low in the core top sample. Two taxa were largely responsible for the increased abundances of planktonic forms: *Cyclostephanos dubius* and, post *c.* 1990, *Stephanodiscus parvus*. *S. parvus* is characteristic of highly eutrophic conditions. DI-TP data record a transition during the 1980s from a mesotrophic to eutrophic state with marked spikes in diatom concentration and accumulation rates. High diatom productivity also appears to have coincided with the initial major increase in rate of sediment accumulation: the ^{210}Pb profile suggests a rapid increase in sediment accumulation rate from the late 1980s, before declining in the most recent period. Cladoceran assemblages changed from being characterised by chydorids in the core bottom sample to characterised by planktonic *Daphnia* and *Bosmina* in the core top sample (Figure 4.8d). Species shifts included a major decline in *Alona rustica* and increases in *A. quadrangularis* and *Chydorus sphaericus*, changes that are indicative of nutrient enrichment. *Alona rustica* is commonly associated with dystrophic waterbodies and absent from enriched environments (Duigan 1992). Comparison of the pollen and spore content in the core bottom with the sample from 5-6 cm (*c.* 1992) indicated the replacement of hazel woodland by more closed-canopy forms of deciduous woodland (containing *Quercus* and *Ulmus*), conifers and grassland (Table 4.8).

Inchiquin

Unsupported ^{210}Pb concentrations showed an exponential decline with depth (Figure 4.4d), while application of the CRS and ^{137}Cs models indicated a relatively high rate of sediment accumulation overall (Table 4.7). There was little change in the proportion of organic matter to *c.* 1970 (Figure 4.5e); DMAR and sediment accumulation rate data, with the exception of TP, were also largely constant to *c.* 1970, at which point they increased before declining from *c.* 1990 (Figure 4.6e). The profile of sedimentary TP accumulation rate was similar to DMAR to *c.* 1990, then increased before declining again from *c.* 2000. No clear link between DMAR and sediment chemistry concentration data is evident, however, with the latter either showing an overall increase (Fe, Mn, TP) or relatively little variation (Ca, K, Na) to *c.* 2000, followed by a decline.

Diatom assemblages show a transition, *c.* 1980, from an assemblage dominated by benthic (e.g., *Amphora pediculus*) to planktonic (e.g., small *Cyclotella* and *Stephanodiscus*) taxa (Figure 4.7e). DI-TP, indicative of mesotrophy throughout the core, approached the OECD (1982) lower threshold for the eutrophic category during the 1990s, with peak DI-TP values correlating with spikes in diatom concentration and accumulation rate data. Planktonic cladocera were far more abundant in the core top sample compared with the core bottom sample (Figure 4.8e), although most taxa encountered were recorded in both core top and bottom samples, albeit in different abundances, and both core bottom and top cladoceran assemblages appear to represent meso-eutrophic conditions. The pollen and spore data (Table 4.8) also indicate relatively minor changes in vegetation in the catchment since the early 20^{th} century, with woodland composition and extent remaining largely unchanged and a small increase in grassland cover evident.

Mullagh

A broad peak in the ^{137}Cs data precluded the construction of a ^{137}Cs-based chronology (Figure 4.4e). However, application of the CRS model to the unsupported ^{210}Pb profile indicates an overall rate of sediment accumulation of 0.04 g cm yr^{-1} (Table 4.7), which compares well with 0.03 g cm yr^{-1} estimated for a core collected previously (Nowlan *et al*. 2000). The proportion of organic matter varied little to *c.* 1975, rising to a peak in the core top (Figure 4.5f). DMAR showed little variation to the 1960s, declined during the later part of that decade, before showing a major peak in the 1970s and a smaller increase from *c.* 2000 (Figure 4.6f). Down-core variations in sediment chemistry accumulation rates are similar to those for DMAR, although the peak during the 1970s is less evident in Mn and TP. Sedimentary Mn and TP concentrations initially declined before increasing from the 1970s and particularly from *c.* 2000. Ca concentrations increased to *c.* 1990 and then declined, while K and Na concentration data showed a similar pattern of fluctuations before reaching a peak in the late 1970s and early 1980s. Only the Fe accumulation rate and concentration profiles concur, although the 1970s peak was much more subdued in the latter.

Diatom assemblages show a marked change from the late 1960s and particularly from post *c.* 1990 (Figure 4.7f). Benthic and epiphytic taxa, particularly *Fragilaria pseudoconstruens*, *Staurosira elliptica* and *Staurosirella pinnata*, associated with oligo-mesotrophic conditions, were replaced primarily by planktonic taxa, such as *Asterionella formosa, Aulacoseira ambigua*, *A. granulata* var. *angustissima* and the small centrics *Cyclotella* and *Stephanodiscus*. DI-TP increased exponentially, passing from oligo-mesotrophic levels at the base of the core into the eutrophic range during the 1980s and approaching hypertrophic conditions post-2000. Highest diatom concentrations were recorded from samples predating *c.* 1970. Diatoms were also relatively abundant, although diversity was low, following the development of highly eutrophic conditions. Comparisons of cladoceran remains indicate that *Chydorus piger*, indicative of oligo-mesotrophic conditions, was more common and planktonic taxa far less abundant in the core bottom than in the core top sample (Figure 4.8f), while pollen and spore assemblages indicate a decline in deciduous woodland taxa and marked increases in Poaceae and the aquatic *Myriophyllum* (Table 4.8).

Sillan

Unsupported ^{210}Pb concentrations remain constant with depth to *c.* 12 cm before declining exponentially, while the ^{137}Cs profile shows a broad peak (Figure 4.4f). Application of the CRS model (compatible with the ^{137}Cs profile) yielded an estimated average sediment accumulation of 0.053 g cm^{-2} yr^{-1}, implying that basal sediments in the cores used for sediment chemistry and microfossil analyses date to the beginning of the 20th century (Table 4.7). Basal sediments were relatively inorganic (Figure 4.5g); DMAR fluctuated throughout the core, but was highest from the start of the record to the late 1950s and from the late 1970s/early 1980s (Figure 4.6g). Sedimentary TP (both accumulation rates and concentrations) exhibited a sharp increase from the 1940s to the 1960s, and again from the 1980s. Ca and Mn both showed an overall increase from the base to the core top, with Mn showing a distinct peak in the late 1980s, while Fe remained more or less constant throughout the core (although the accumulation rate data show a distinct overall increase from *c.* 1980). K and Na concentrations showed a steady decline from the base of the core. A similar trend is apparent from the accumulation rate data for these two elements to the late 1970s, after which date the trend was reversed.

Only slight down-core differences in diatom assemblages are evident (Figure 4.7g). Planktonic *Aulacoseira* was prominent throughout the core and benthic and epiphytic taxa were most abundant in the core bottom sample. DI-TP levels indicate enrichment from the beginning of the sedimentary record (c. 1900) and the establishment of eutrophic conditions by *c.* 1930. A peak in diatom concentration occurred *c.* 1950 followed by a decline in the 1980s before rising again in the 1990s. The chydorid *Alona quadrangularis* showed a marked increase between core bottom and top samples (figure 4.8g), while oligo-mesotrophic taxa declined, and there was also an increase in the planktonic/littoral ratio. Comparisons between the pollen and spore contents of the core bottom sample and a sample from 15-16 cm (c. 1970) indicate a decline in woodland taxa and conifers concomitant with a rise in grasses (Table 4.8).

Ordination

The examination of down-core variations in diatom assemblages was facilitated through DCA (Figure 4.9). Comparisons between top and bottom samples for cores from all seven lakes indicate similar trajectories – although different magnitudes – of difference and suggest common ecological pressure or pressures. *Pseudostaurosira brevistriata* and members of the genus *Staurosira* characterised core bottom samples, while planktonic *Aulacoseira* and *Stephanodiscus* species were characteristic of core top samples.

4.4 Discussion

Reference conditions

The hindcasting of biological reference conditions for lake types that have no extant examples of reference conditions was a key deliverable in WP3. Based on the results presented above, all of the lakes studied in WP3 were oligo-mesotrophic or mesotrophic at the onset of the sedimentary records retrieved. Sediment core bottom samples ranged in age from late 18^{th} to the early 20^{th} century and were characterised by a relatively diverse diatom flora, in which benthic and epiphytic types were prominent with DI-TP ranging from 12 to 21 $\mu g\ l^{-1}$, and diverse littoral cladoceran assemblages generally indicative of abundant aquatic macrophyte cover. Pollen and spores preserved in core bottom samples appear to reflect a mosaic of deciduous woodland and grassland in the catchments and therefore post major human-induced changes in vegetation.

In the case of Atedaun the core bottom diatom assemblage (estimated to be post-1950, although chronological control was weak owing to a poorly resolved ^{210}Pb dating profile) was characterised by non-planktonic taxa, with *Amphora pediculus* and *Achnanthidium minutissimum* predominant. Overall the assemblage was very diverse and indicative of oligo-mesotrophic to mesotrophic conditions, while abundant *Achnanthidium minutissimum* and *Amphora pediculus* suggest shallow waters. The occurrence of taxa associated with epiphytic habitats suggests the presence of macrophytes. Remains of cladocera also indicate low to medium nutrient concentrations and an abundance of macrophytes. The core bottom diatom assemblage for Ballybeg dates to the late 19^{th} century and is relatively diverse, with non-planktonic taxa, such as *Pseudostaurosira brevistriata* and *Staurosira construens*, predominant, and is typical of alkaline, shallow lakes of intermediate nutrient status. Cladocera remains recovered from the core bottom sample are also indicative of mesotrophic conditions, although the abundance of *Alona guttata/rectangular* and *Chydorus sphaericus* may indicate declining ecological state (De Etyo *et al.*, 2003).

Planktonic taxa, particularly *Aulacoseira subarctica*, characterised the core bottom diatom assemblage for Crans, dating to the early to mid 19th century, and indicative of alkaline, mesotrophic waters. Planktonic taxa were also abundant among the cladocera (planktonic/littoral ratio = 4:1, Table 4.9), with *Daphnia* particularly abundant. Among the chydorids *Alona guttata/rectangular*, *A. affinis* and *Alonella nana*, all taxa with low to moderate TP optima, were predominant. The core bottom diatom assemblage from Egish, which may have been as old as the late 18th century in age, was dominated by non-planktonic taxa (*c.* 83% of the whole assemblage) and was indicative of shallow, oligo-mesotrophic conditions. Abundant epiphytic taxa suggest that macrophytes were extensive. *Pseudostaurosira brevistriata* and the small, benthic *Staurosira elliptica* were the most abundant non-planktonic diatom taxa; planktonic taxa, such as *Aulacoseira subarctica*, were also present. Chydorids were abundant among the cladocera remains, indicating littoral conditions, with *Alona rustica* particularly abundant.

The core bottom sample from Inchiquin dates to the *c.* 1930s. If this sample is assumed to equate to reference conditions, then non-planktonic taxa, notably *Achnanthidium minutissimum* and *Amphora pediculus*, characterised the reference diatom assemblage and indicated mesotrophic conditions. Planktonic forms, such as *Stephanodiscus parvus*, which is indicative of nutrient enrichment, were also present, although in low abundances. Mesotrophic conditions were also indicated by the cladocera remains, with planktonic forms only slightly outnumbered by benthic chydorids. However, the core bottom sample from Inchiquin contained high proportions of *Alona rectangular* and *Chydorus sphaericus*, both of which are associated with declining ecological state (De Etyo *et al.* 2003). The age of the core bottom diatom assemblage from Mullagh could not be determined to an acceptable level of certainty. However, it was similar in composition to the reference sample from Egish, which potentially dated to the late 18th century, being characterised by the non-planktonic taxa *Fragilaria pseudoconstruens, Pseudostaurosira brevistriata*, *Staurosira elliptica* and *Staurosirella pinnata* indicative of oligo-mesotrophic conditions. The large numbers of benthic taxa indicate shallow waters, while the high percentage of epiphytic diatoms suggests that macrophytes were abundant. A predominance of benthic forms is repeated among the cladocera. High levels of *Alona quadrangularis* and *Chydorus sphaericus* suggest a moderate nutrient status.

The core bottom sample from Sillan dates to the early 20th century. Planktonic taxa were predominant in this sample, the most abundant being *Aulacoseira ambigua*, *A. granulata* var.*angustissima*, *A. subarctica* and *Puncticulata radiosa*. The benthic taxon *Achnanthidium minutissimum* was also common. The assemblage indicates relatively deep, mesotrophic waters. The abundance of epiphytic taxa in the core bottom sample suggests that macrophytes were more common than today. The remains of cladocera also indicate mesotrophic conditions; planktonic forms were abundant, and diversity levels were the highest for any of the WP3 lakes (Table 4.9).

Long-term variations in trophic status

Five of the seven lakes studied as part of WP3 (Ballybeg, Crans, Egish, Mullagh and Sillan) show clear evidence of substantial nutrient enrichment (>50 $\mu g\ l^{-1}$ TP), and two of these (Crans and Egish) show a >ten-fold increase in DI-TP over the time covered by the sedimentary records analysed (Figure 4.10). Of the two lakes that do not show substantial nutrient enrichment, DI-TP levels for one (Atedaun) show a change in trophic status (from mesotrophic to eutrophic). Similarities exist between sites in changes in diatom and cladocera assemblages, as is evident for diatoms in the DCA results (Figure 4.9): generally, the abundances of planktonic taxa increase up-core, replacing benthic and epiphytic taxa. All the lakes have experienced periods of catchment disturbance and nutrient enrichment, with steep increases in DI-TP associated with unsustained increases in diatom productivity and sharp falls in diversity. The microfossil and DI-TP reconstructions indicate that Crans and Sillan have been nutrient-enriched since, respectively, the late 19th and early 20th centuries, while the trophic status of Inchiquin remained comparatively stable. Relatively low population densities and the high proportion of unimproved or low intensity land use in the Inchiquin catchment (Irvine *et al.* 2000; Wemeare 2005) were no doubt important, and P-buffering due to high alkalinity of the lake may have facilitated the maintenance of a relatively stable nutrient status (Hobbs *et al.* 2005). Large periodic flushing may, however, also be important for removal of phytoplankton from both the lake and sedimentary record. Allott (1990) found a much reduced summer mean chlorophyll *a*: winter TP ratio in Inchiquin compared with other lakes in the region.

Five of the sediment profiles indicate accelerated enrichment post *c.* 1980: the profile for Inchiquin remains relatively stable and in the mesotrophic range, while weak chronological control for the sediments from Atedaun precludes precise dating (although levels of DI-TP and diatom concentrations for this site indicate a rapid increase in productivity towards the top of the core). Accelerated enrichment post *c.* 1980 has also been reported for several lakes in Northern Ireland (Anderson 1997; Zhou *et al.* 2000; Jordan *et al.* 2001; Foy *et al.* 2003), despite reduced exports of P from point sources during the same period (Foy *et al.* 1995; EHS 2000; Jennings *et al.* 2003). Enrichment is also evident in levels of sedimentary TP for WP3 lakes, although the co-variance of sedimentary TP with DMAR, Fe and Mn suggests that enhanced catchment erosion was an important contributing factor to increased sedimentary TP (Boyle 2001). Increased inputs of P from soils that have become saturated with P as a result of agricultural practices (Tunney *et al.* 1997; Foy *et al*. 2003) provide one explanation. Recently increased internal P as a result of the release of P from sediments (Søndergaard *et al.* 1999; Jordan and Rippey 2003; Phillips *et al.* 2005) provide another, or complementary, explanation. The Mn reconstructions for Ballybeg, Crans, Egish, Mullagh and Sillan provide evidence of this. Increased Mn dating from c 1980 at Inchiquin could be associated with local sewage discharges dating from that period. Therefore, while Ballybeg, Egish and Mullagh show a unidirectional trend of increasing TP beginning in the 1960s-1980s, often in association with sedimentary evidence of catchment disturbance and urban and industrial developments (e.g., expansion of the creamery at Egish in the 1970s), Crans, Inchiquin and Sillan have more complex histories

Catchment disturbance and nutrient enrichment at Crans, dating from the late 19th century, with the lake becoming hypertrophic by the turn of the 20th century, tie-in with evidence from other lakes in Northern Ireland. Eutrophication commenced in the late 19th century at Heron (Anderson 1997) and Neagh (Battarbee 1978; Foy *et al.* 2003) and at the beginning of the 20th century at Upper Lough Erne (Battarbee 1986). Early cultural eutrophication was also reported for meres in central England (Anderson 1995). Nutrient concentrations were reduced at Crans around the 1950s, but increased again from the 1980s, presumably as a response to increased supply or reduced flushing of P. Decreases in amounts of P incorporated within sediments have also been noted elsewhere in small lakes in Northern Ireland (Rippey and Anderson 1996; Rippey *et al.* 1997) and attributed to internal P loading and losses through the lake outflow. A similar trend of relatively early initial eutrophication followed by recovery and a second phase of nutrient enrichment was evident at Sillan, with eutrophication commencing early in the 20th century, followed by reduced nutrient status in the 1970s and 1980s and a second period of nutrient enrichment post *c.* 1990, which could have been linked to relatively recent developments in the catchment, such as the caravan site mentioned previously.

Although the onset of large-scale deforestation predates the oldest sediments analysed here, there are similarities in the direction of changes in catchment vegetation evident in the pollen and spore data (amounting in most cases to reduced deciduous tree cover, although an expansion of hazel woodland and a concomitant reduction in the extent of grassland is indicated at Atedaun). At Crans and Egish changes in pollen appear to represent succession in woodland remnants involving the shading-out of taxa associated with more open forms of woodland. Pollen from Ballybeg, Crans and Egish also indicate an expansion of conifer plantations during the period covered by the sedimentary records. Because *Pinus*-type pollen can be transported long distances, this expansion may not have been local. However, an expansion of conifer plantations at Ballybeg could explain the increase in area of the CORINE forest/woodland category between 1990 and 2000 (Table 4.3).

The preceding provides an indication of the variability between sites in terms of the onset of disturbance and enrichment and of the potentially complex nature of trophic history at a particular lake. Together the results suggest that a reference date of 1850 as recommended by some scientists 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 the management of trophic status under the WFD, activities directed at achieving a 20-40 year old reference status for a particular lake type might seem more appropriate (and achievable) than a 150 year old baseline. In sites that experienced an early onset of eutrophication (e.g. Crans and Sillan) the *c.* 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 in place until relatively recently.

To conclude, results generated by the use of multi-proxy palaeolimnological techniques aimed at hindcasting reference conditions at a selection of impacted lakes and at quantifying the extent and rate of deviation in conditions provide evidence that:

- Complex and locally specific trophic histories are characteristic, thus highlighting the difficulties of setting *a priori* a *terminus ad quem* for type specific reference conditions for lakes. The data generated in WP3 indicate, however, that all of the impacted lakes were originally oligo-mesotrophic or mesotrophic in nature, even though the date to which these conditions prevailed varied.
- Sediment core bottom (reference) samples were characterised by a relatively diverse diatom flora, in which benthic and epiphytic types were prominent, with DI-TP ranging from 12 to 21 $\mu g\ l^{-1}$ (oligo-mesotrophic to mesotrophic) and diverse littoral cladoceran assemblages indicative of abundant aquatic macrophyte cover.
- Substantial nutrient enrichment (>50 $\mu g\ l^{-1}$ TP) was a feature at Ballybeg, Crans, Egish, Mullagh and Sillan (from typology classes 5, 6, 7, 8 and 9), with two (Crans

and Egish, from, respectively, typology classes 7 and 6) showing a >ten-fold increase in DI-TP, over the time covered by the sedimentary records analysed. In the other two lakes studied in WP3, chronological control was too weak for Atedaun to allow detailed temporal analyses, although a change in trophic status is indicated by the core top sample, while conditions at the Inchiquin varied but stayed within the mesotrophic range.

- Accelerated enrichment has occurred post *c.* 1980 at five sites.

Figure 4.1 Location of impacted lakes cored as part of WP3 during August and September 2004.

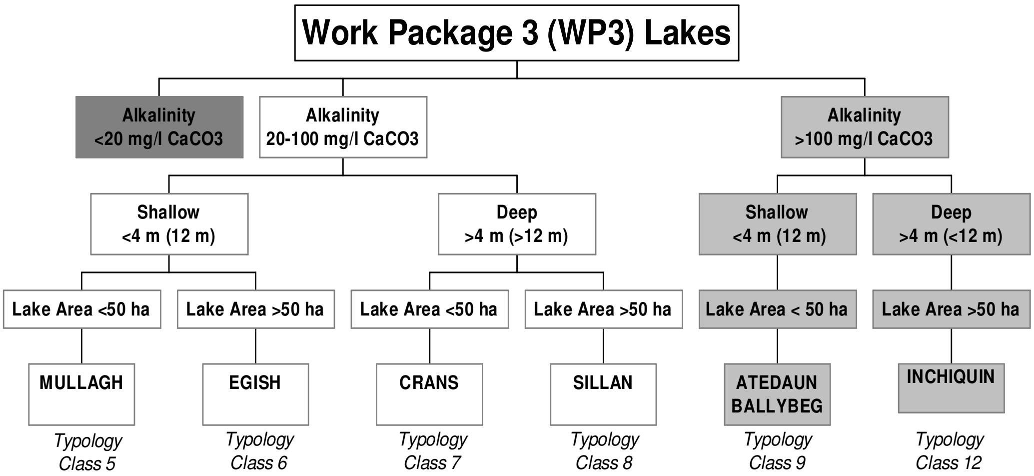


Figure 4.2 Lake typology classification of WP3 study sites

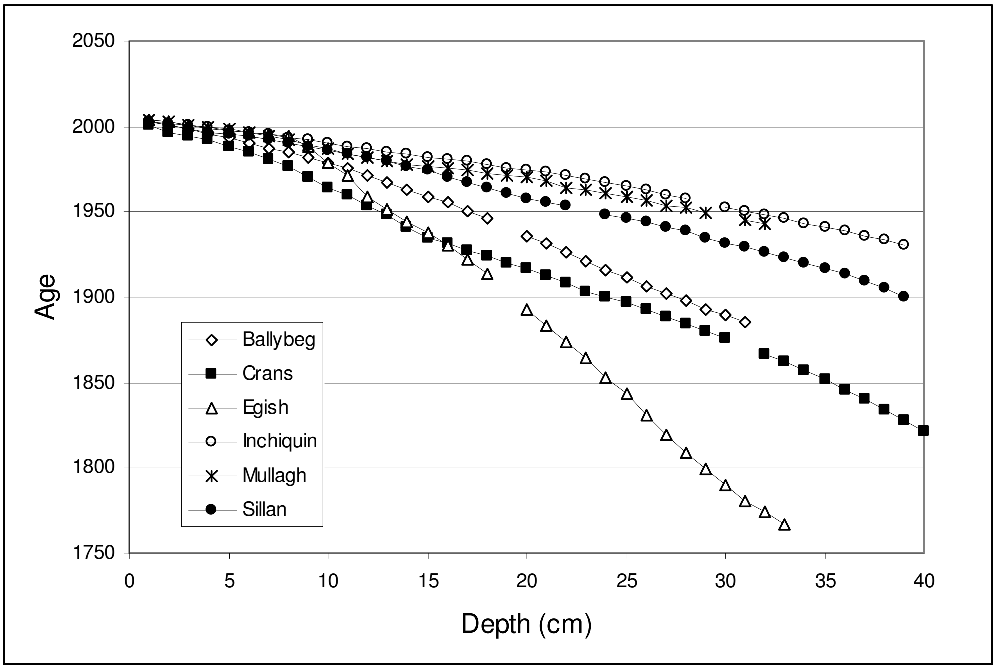


Figure 4.3 Age-depth profiles for six WP3 sediment cores. Gaps in the profiles represent the point where extrapolation was employed for proximate longer cores. Data for Atedaun not shown.

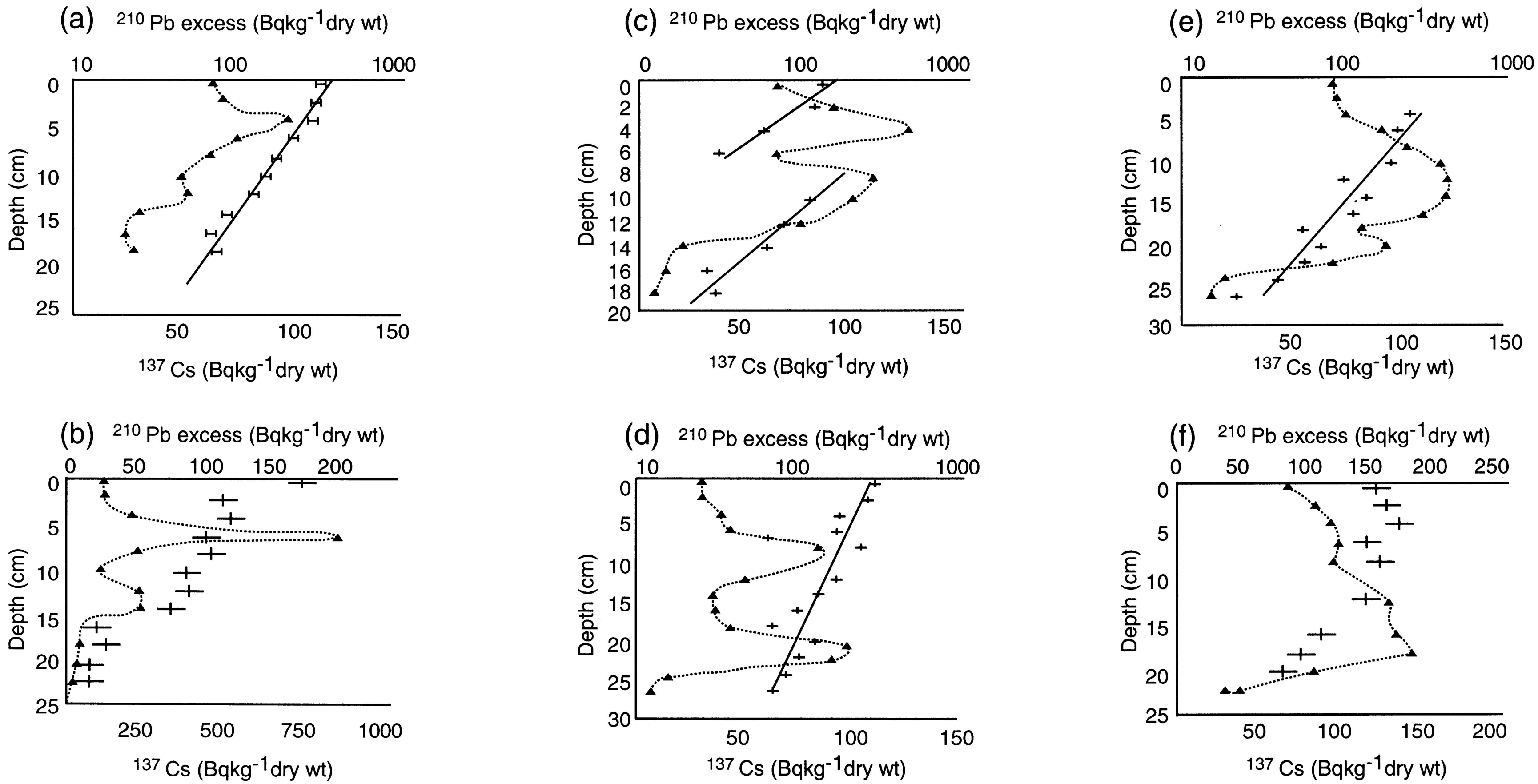
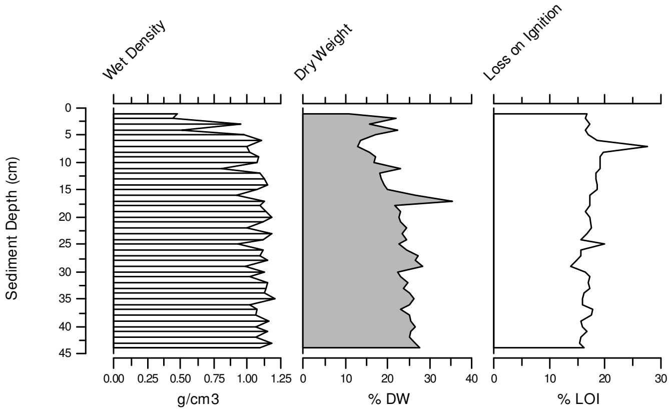
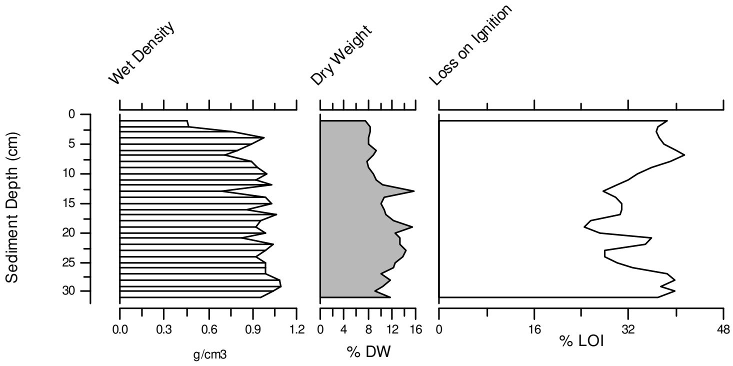


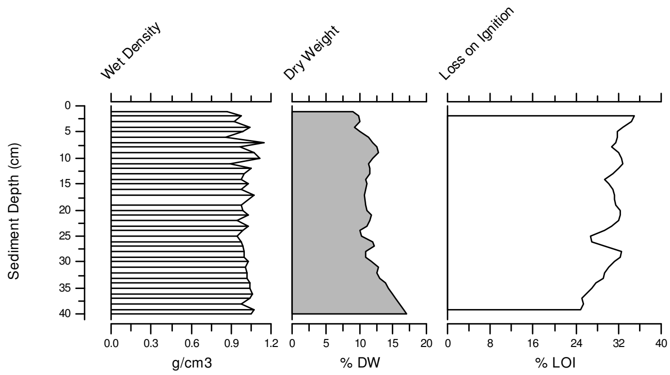
Figure 4.4 Down-core variations in ^{137}Cs (dotted line) and $^{210}Pb_{excess}$ (with 1SD error bars) (a) Ballybeg; (b) Crans; (c) Egish; (d) Inchiquin (e) Mullagh; (f) Sillan. Data for Atedaun not shown.


Wet Density
Dry Weight
Loss on Ignition
Sediment Depth (cm)
0 5 10 15 20 25 30 35 40 45
0.00 0.25 0.50 0.75 1.00 1.25
g/cm3
0 10 20 30 40
% DW
0 10 20 30
% LOI

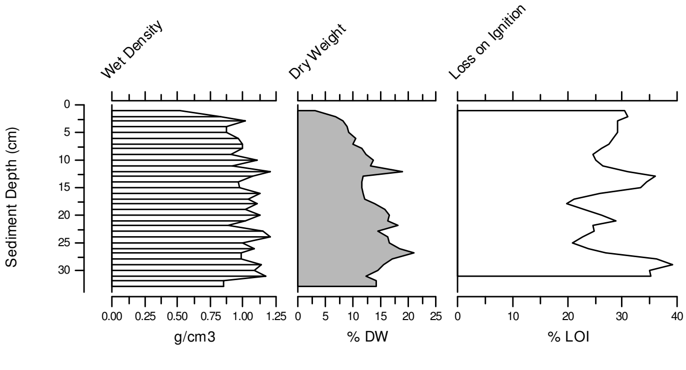
(a)


Wet Density
Dry Weight
Loss on Ignition
Sediment Depth (cm)
0 5 10 15 20 25 30
0.0 0.3 0.6 0.9 1.2
g/cm3
0 4 8 12 16
% DW
0 16 32 48
% LOI

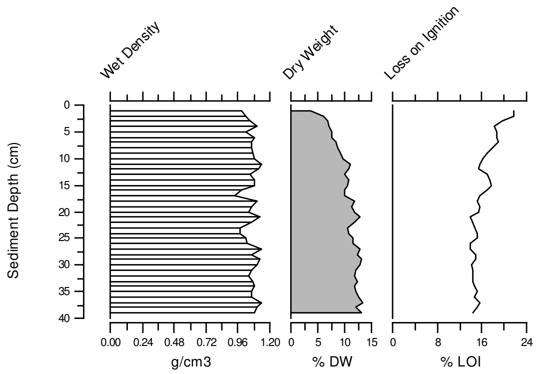
(b)


Wet Density
Dry Weight
Loss on Ignition
Sediment Depth (cm)
0 5 10 15 20 25 30 35 40
0.0 0.3 0.6 0.9 1.2
g/cm3
0 5 10 15 20
% DW
0 8 16 24 32 40
% LOI

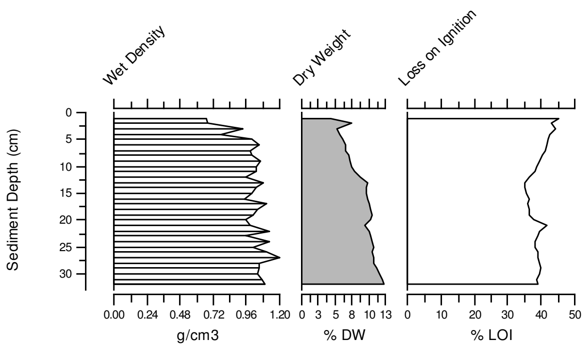
(c)


Wet Density
Dry Weight
Loss on Ignition
Sediment Depth (cm)
0 5 10 15 20 25 30
0.00 0.25 0.50 0.75 1.00 1.25
g/cm3
0 5 10 15 20 25
% DW
0 10 20 30 40
% LOI

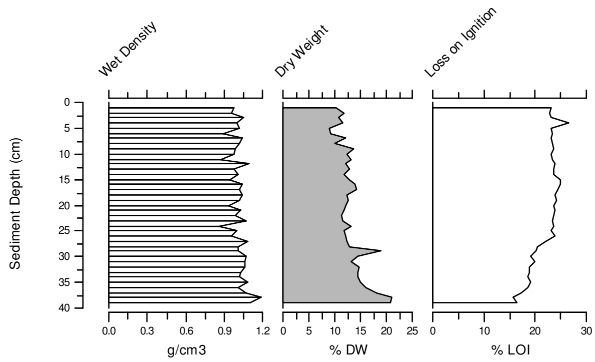
(d)



(e)

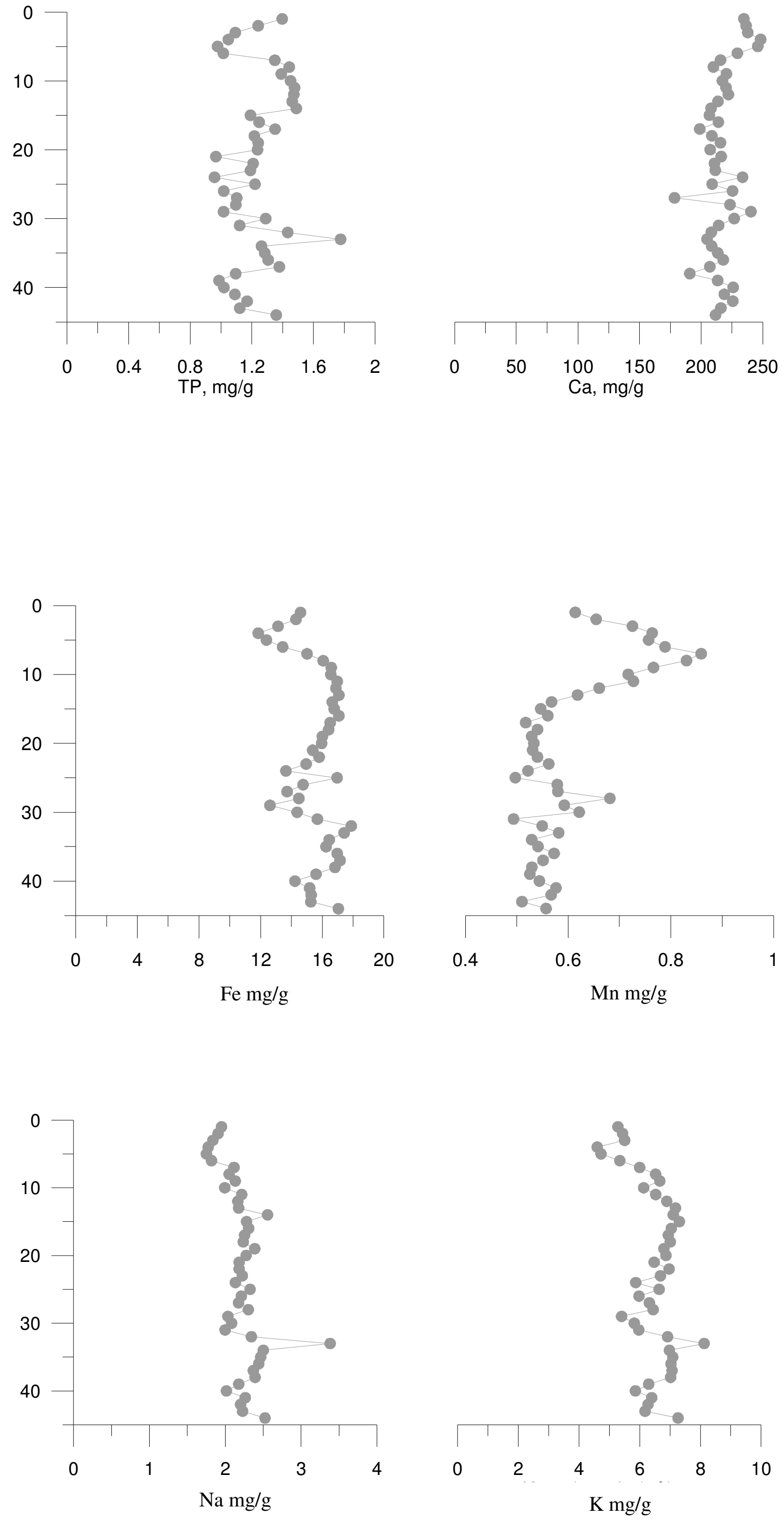


(f)

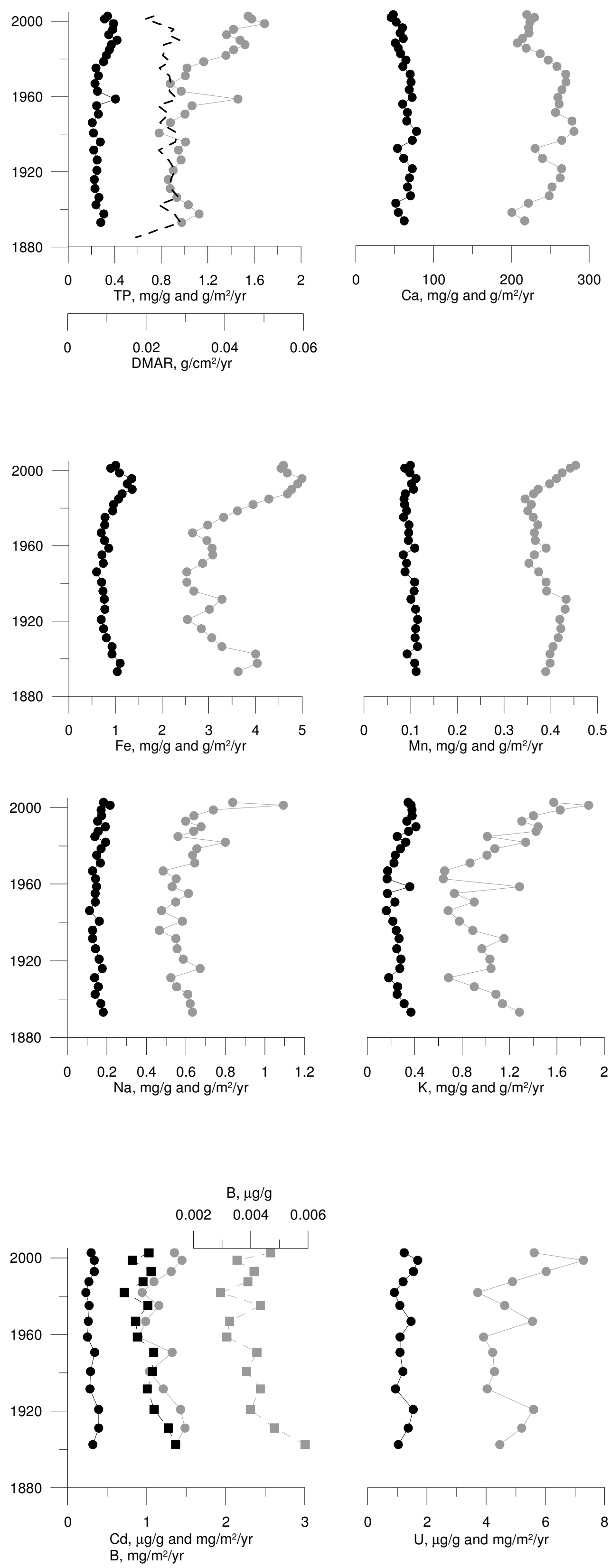


(g)

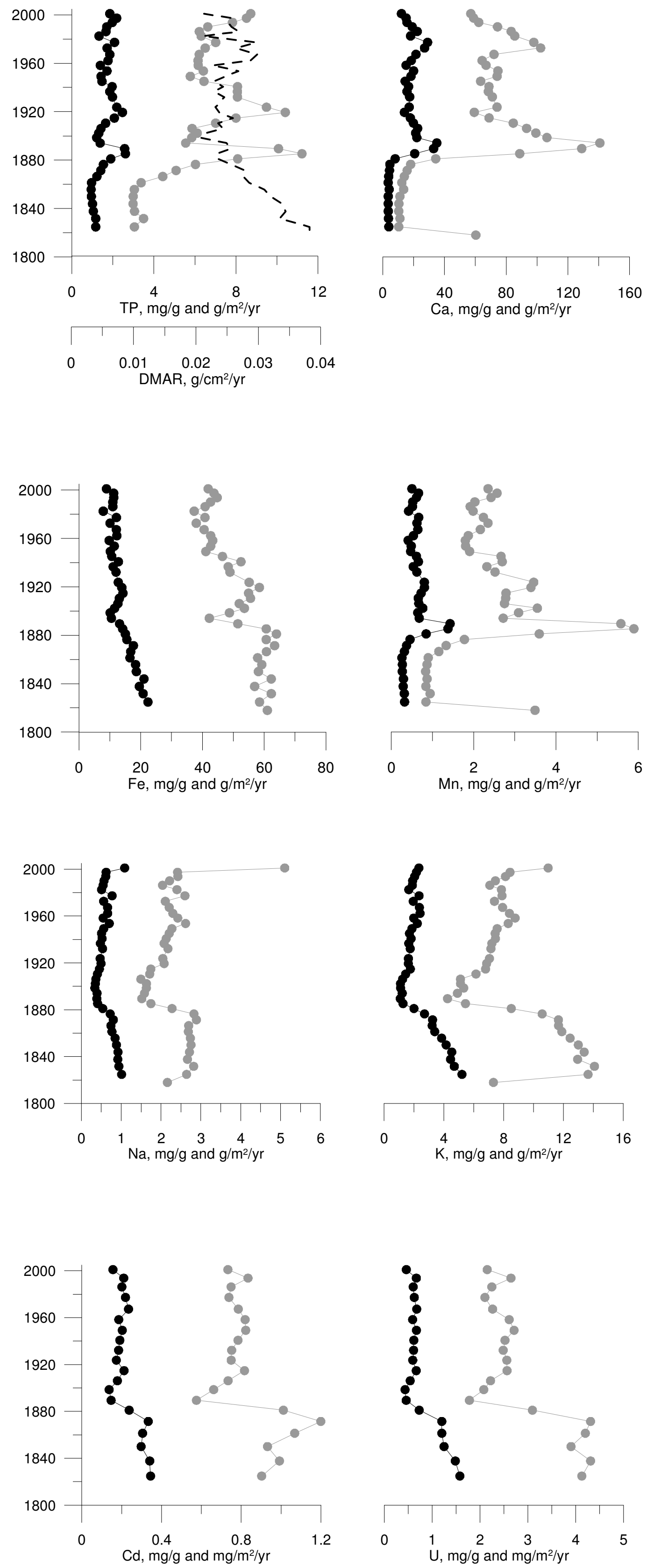
Figure 4.5 Down-core variations in density of wet sediment (g cm^{-3}), water content (as % DW) and organic content as loss on ignition (%LOI). (a) Atedaun; (b) Ballybeg; (c) Crans; (d) Egish; (e) Inchiquin (f) Mullagh; (g) Sillan.



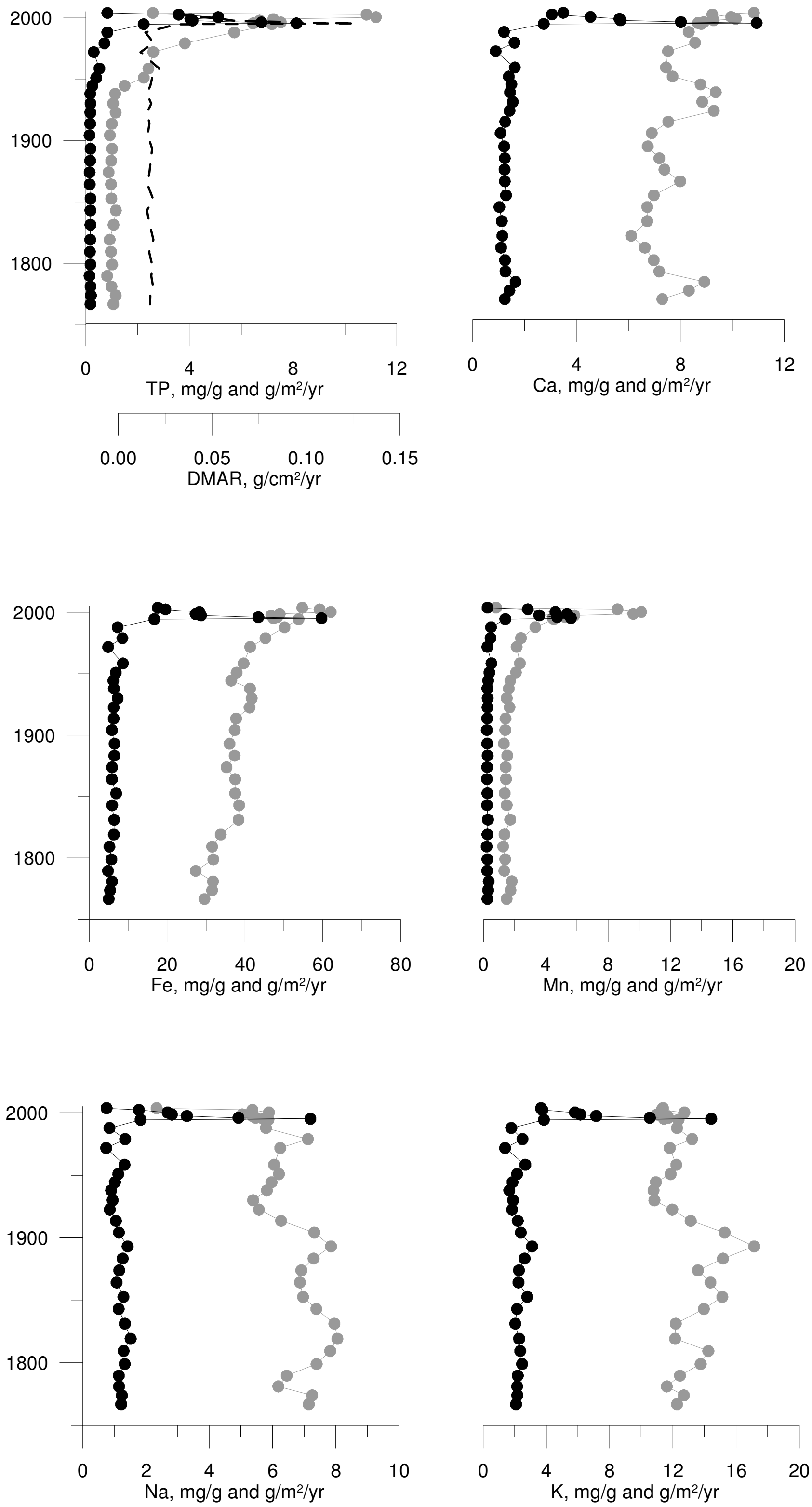
(a)


2000
1960
1920
1880
0 0.4 0.8 1.2 1.6 2
TP, mg/g and g/m²/yr
0 0.02 0.04 0.06
DMAR, g/cm²/yr
0 100 200 300
Ca, mg/g and g/m²/yr
0 1 2 3 4 5
Fe, mg/g and g/m²/yr
0 0.1 0.2 0.3 0.4 0.5
Mn, mg/g and g/m²/yr
0 0.2 0.4 0.6 0.8 1 1.2
Na, mg/g and g/m²/yr
0 0.4 0.8 1.2 1.6 2
K, mg/g and g/m²/yr
B, µg/g
0.002 0.004 0.006
0 1 2 3
Cd, µg/g and mg/m²/yr
B, mg/m²/yr
0 2 4 6 8
U, µg/g and mg/m²/yr

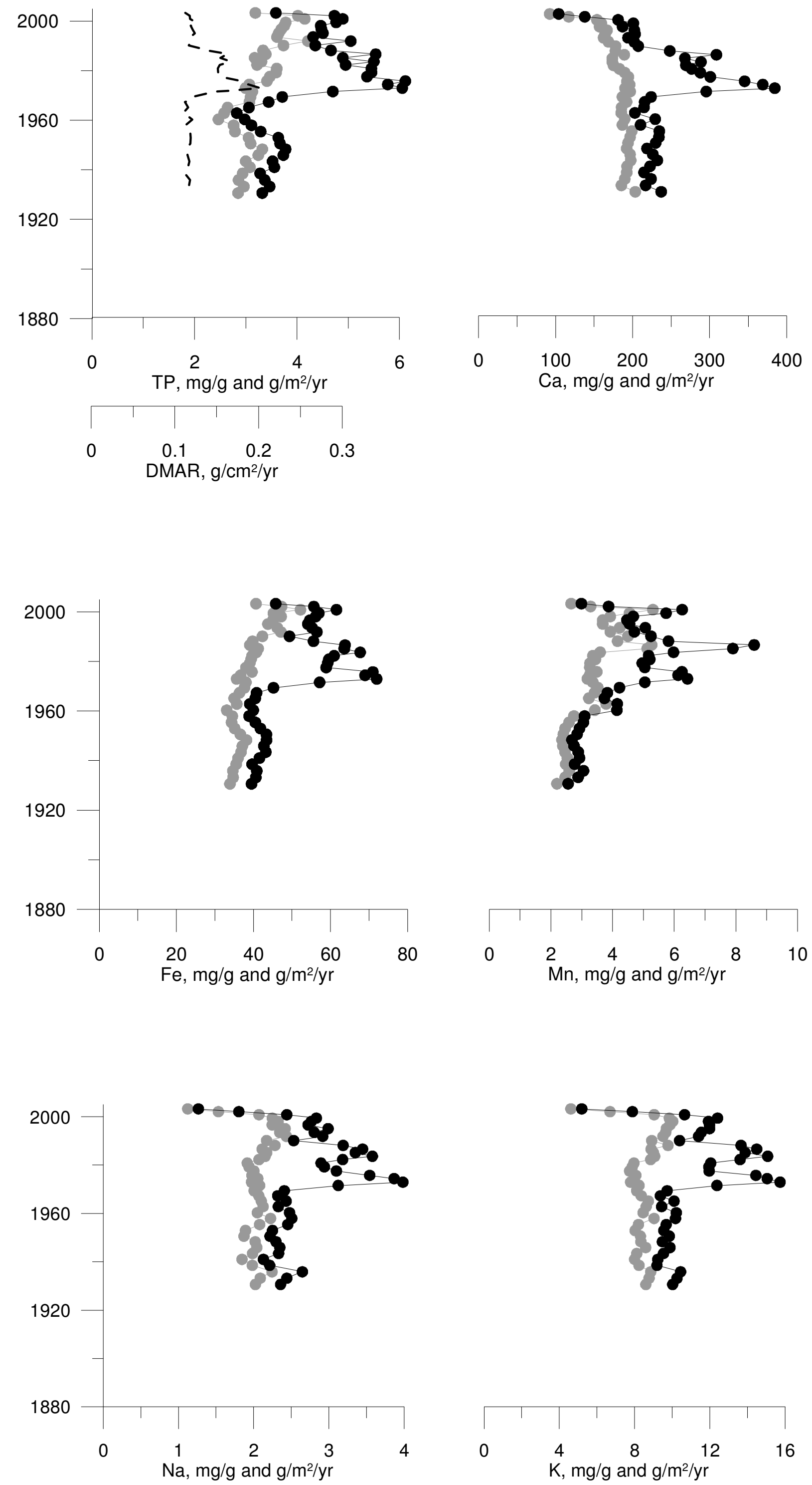
(b)


TP, mg/g and g/m²/yr
DMAR, g/cm²/yr
Ca, mg/g and g/m²/yr
Fe, mg/g and g/m²/yr
Mn, mg/g and g/m²/yr
Na, mg/g and g/m²/yr
K, mg/g and g/m²/yr
Cd, mg/g and mg/m²/yr
U, mg/g and mg/m²/yr

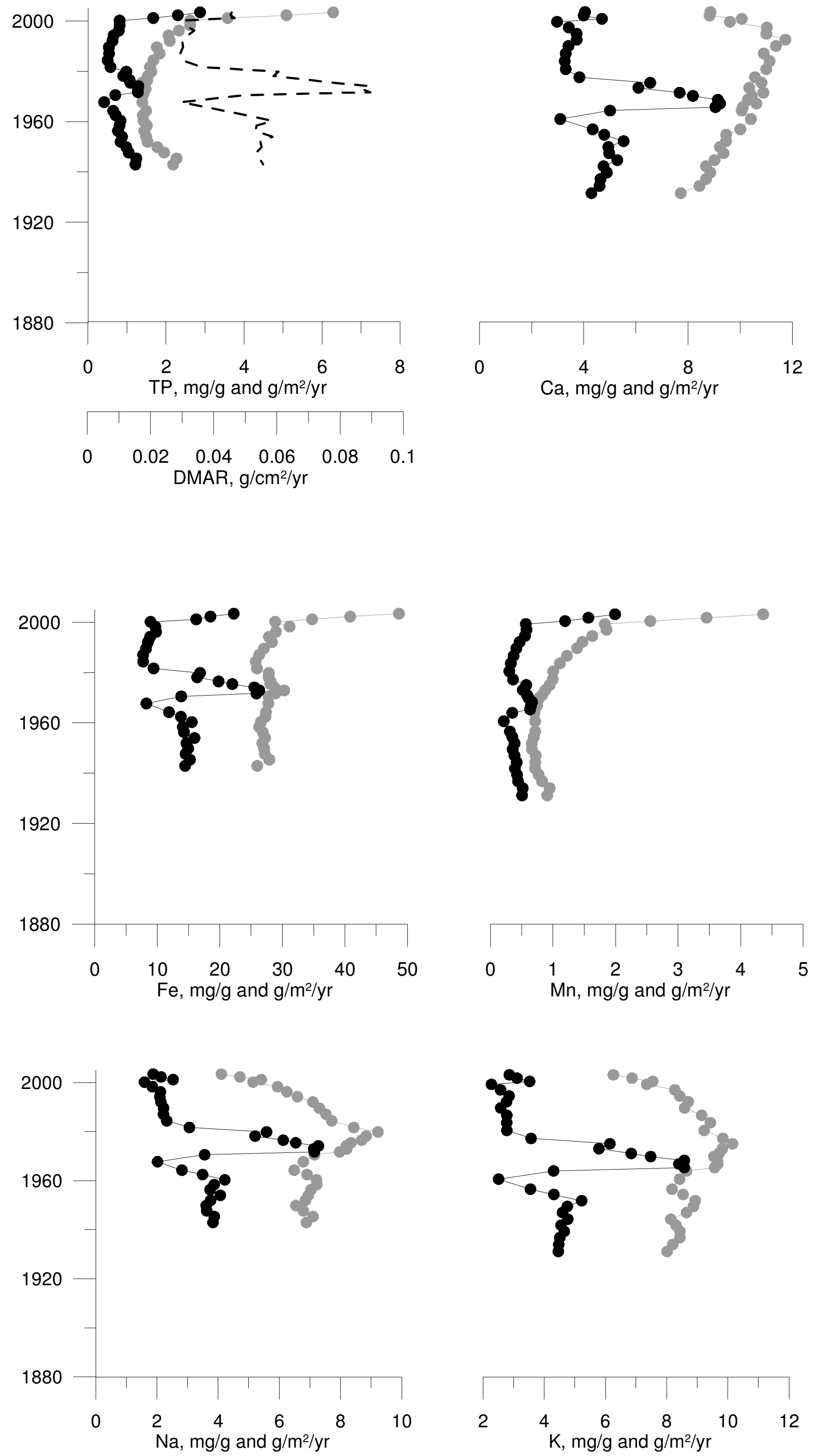
(c)


2000
1900
1800
0
4
8
12
TP, mg/g and g/m²/yr
0.00
0.05
0.10
0.15
DMAR, g/cm²/yr
Ca, mg/g and g/m²/yr
0
20
40
60
80
Fe, mg/g and g/m²/yr
16
20
Mn, mg/g and g/m²/yr
2
6
10
Na, mg/g and g/m²/yr
K, mg/g and g/m²/yr

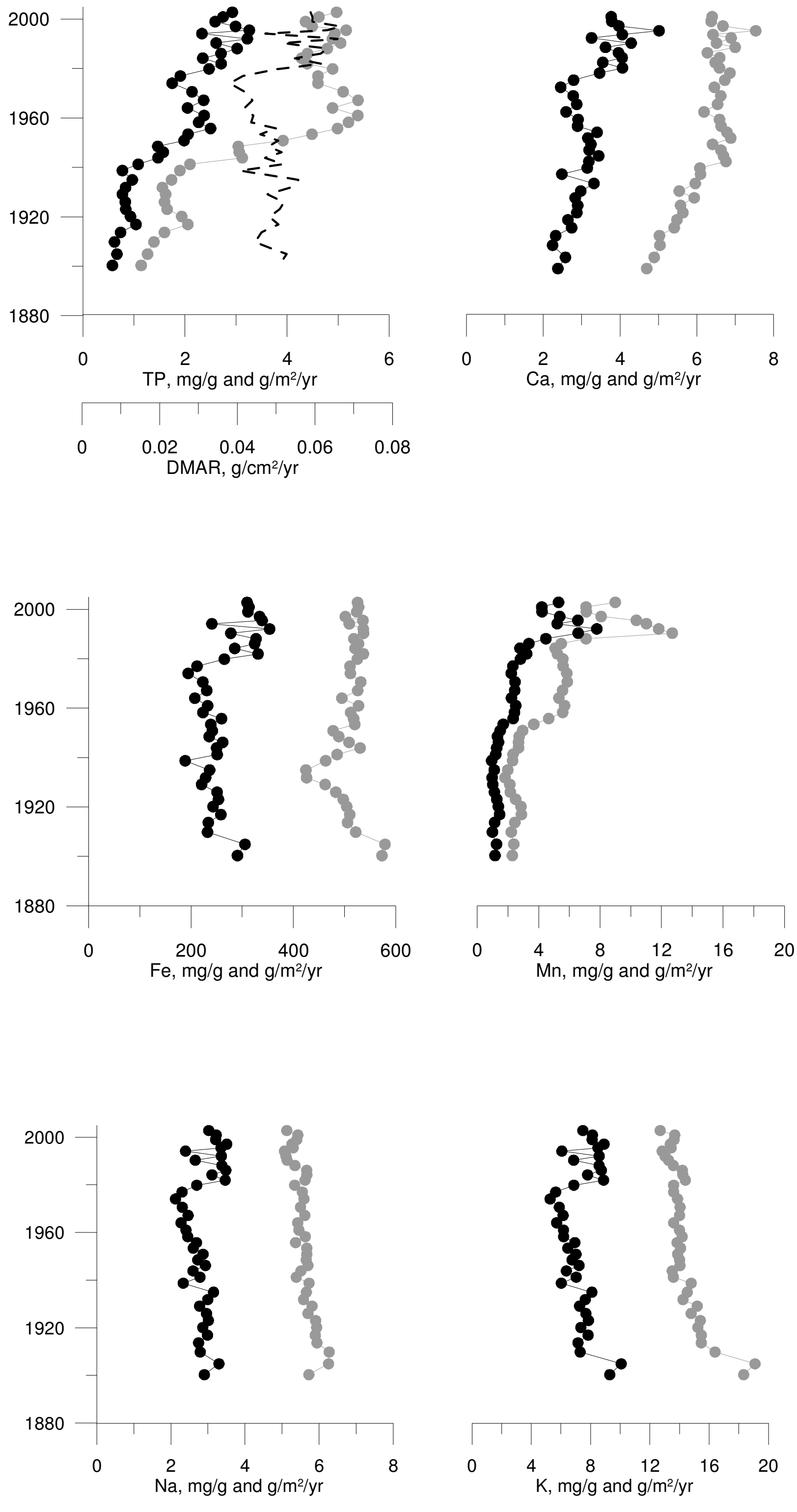
(d)


2000
1960
1920
1880
0 2 4 6
TP, mg/g and g/m²/yr
0 0.1 0.2 0.3
DMAR, g/cm²/yr
0 100 200 300 400
Ca, mg/g and g/m²/yr
0 20 40 60 80
Fe, mg/g and g/m²/yr
0 2 4 6 8 10
Mn, mg/g and g/m²/yr
0 1 2 3 4
Na, mg/g and g/m²/yr
0 4 8 12 16
K, mg/g and g/m²/yr

(e)

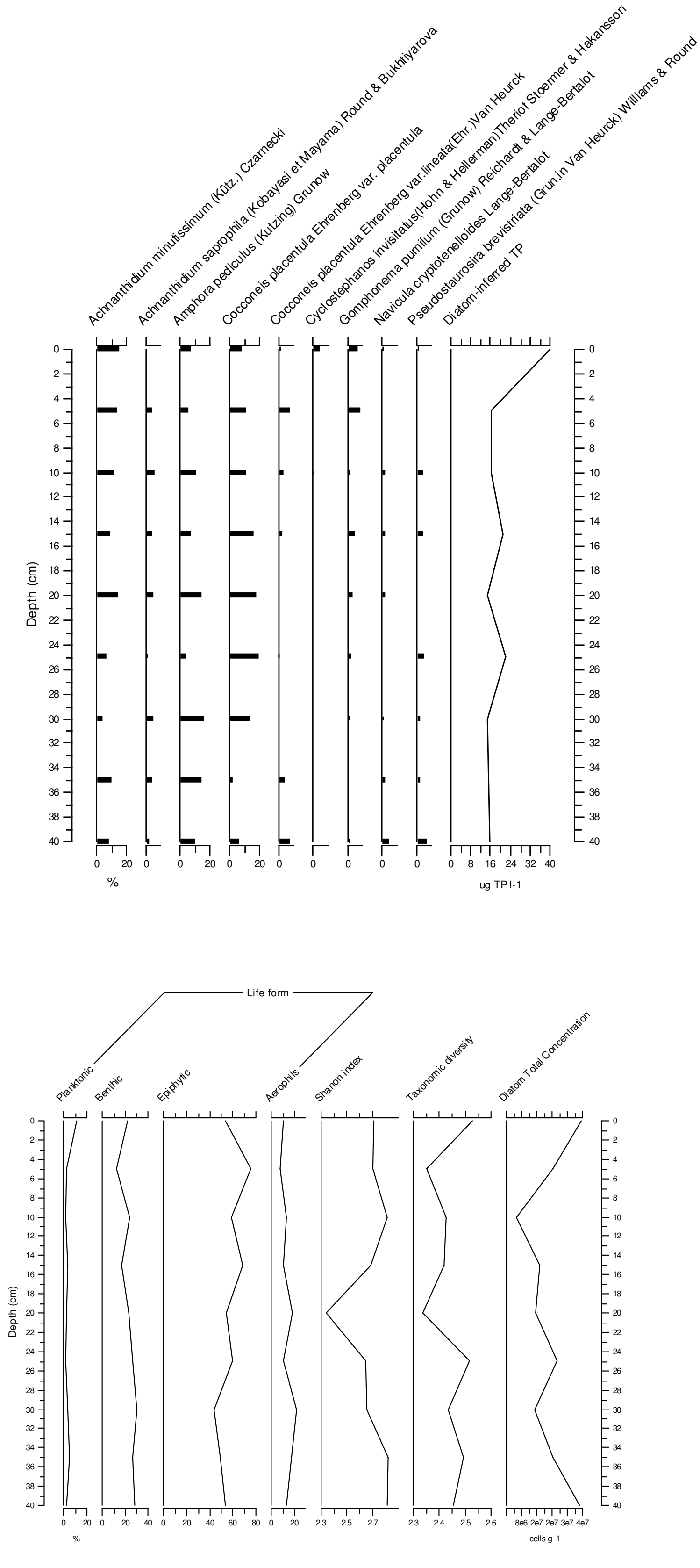

2000
1960
1920
1880
0
2
4
6
8
TP, mg/g and g/m²/yr
0
0.02
0.04
0.06
0.08
0.1
DMAR, g/cm²/yr
0
4
8
12
Ca, mg/g and g/m²/yr
0
10
20
30
40
50
Fe, mg/g and g/m²/yr
0
1
2
3
4
5
Mn, mg/g and g/m²/yr
0
2
4
6
8
10
Na, mg/g and g/m²/yr
2
4
6
8
10
12
K, mg/g and g/m²/yr

(f)



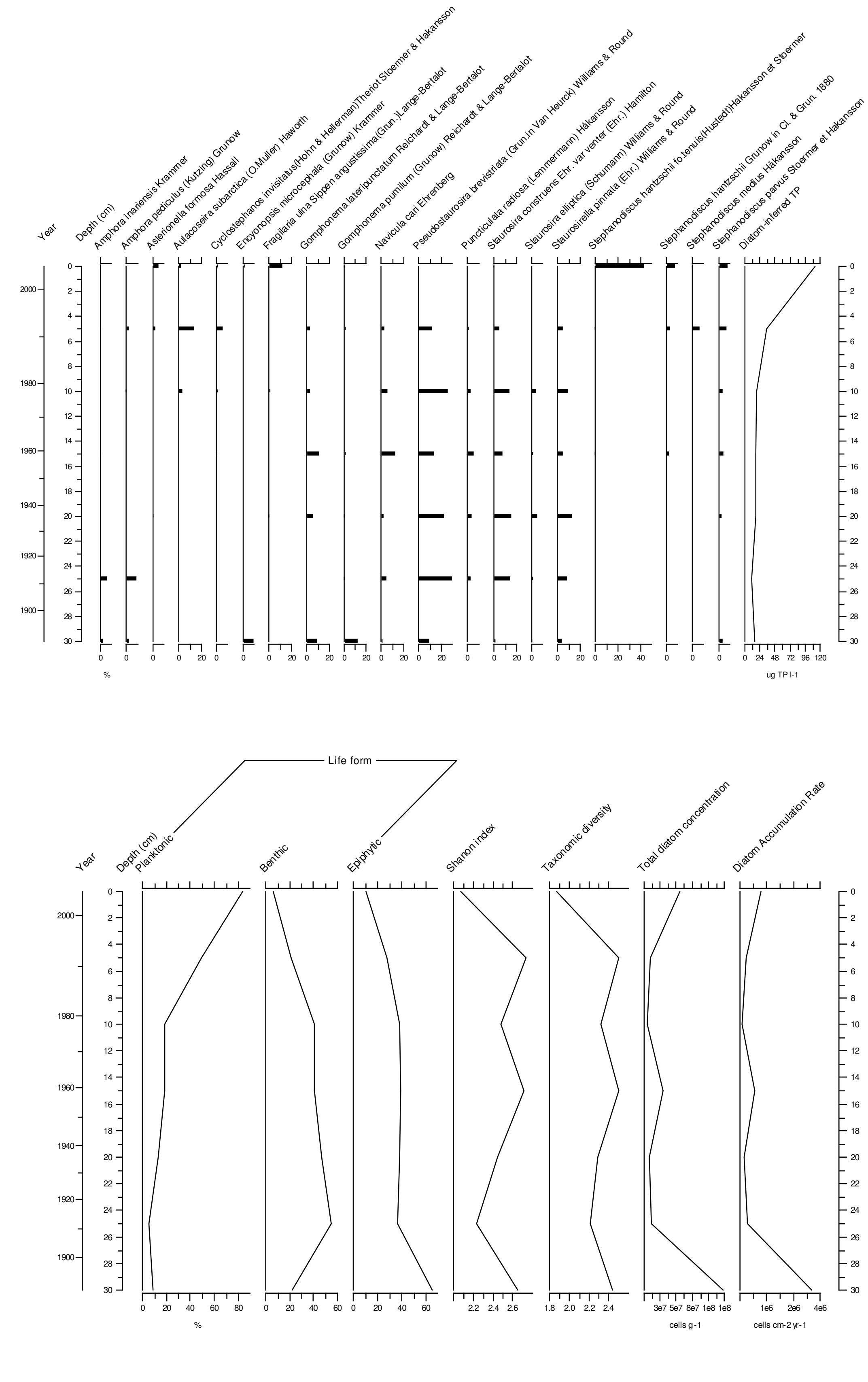
(g)

Figure 4.6 Down-core variations in DMAR and sediment chemistry (sedimentary P, Ca, Fe, Mn, Na and K). Grey circles are chemical concentrations; black circles are chemical accumulation rates. DMAR is shown in the top left panels as a dashed line. Data are plotted on an age scale. (a) Atedaun; (b) Ballybeg; (c) Crans; (d) Egish; (e) Inchiquin (f) Mullagh; (g) Sillan. Note that for Atedaun (a) data are plotted in concentration form only.

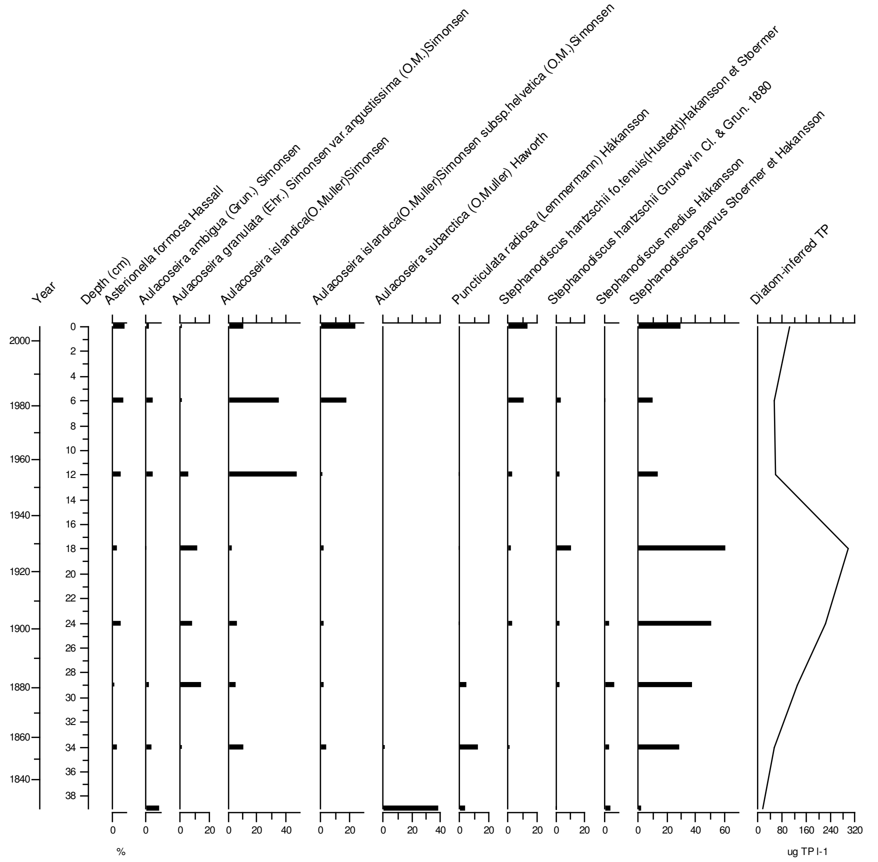


Achnanthidium minutissimum (Kütz.) Czarnecki
Achnanthidium saprophila (Kobayasi et Mayama) Round & Bukhtiyarova
Amphora pediculus (Kutzing) Grunow
Cocconeis placentula Ehrenberg var. placentula
Cocconeis placentula Ehrenberg var.lineata(Ehr.)Van Heurck
Cyclostephanos invisitatus(Hohn & Hellerman)Theriot Stoermer & Hakansson
Gomphonema pumilum (Grunow) Reichardt & Lange-Bertalot
Navicula cryptotenelloides Lange-Bertalot
Pseudostaurosira brevistriata (Grun.in Van Heurck) Williams & Round
Diatom-inferred TP
Depth (cm)
%
ug TP l-1
Life form
Planktonic
Benthic
Epiphytic
Aerophils
Shanon index
Taxonomic diversity
Diatom Total Concentration
Depth (cm)
%
cells g-1

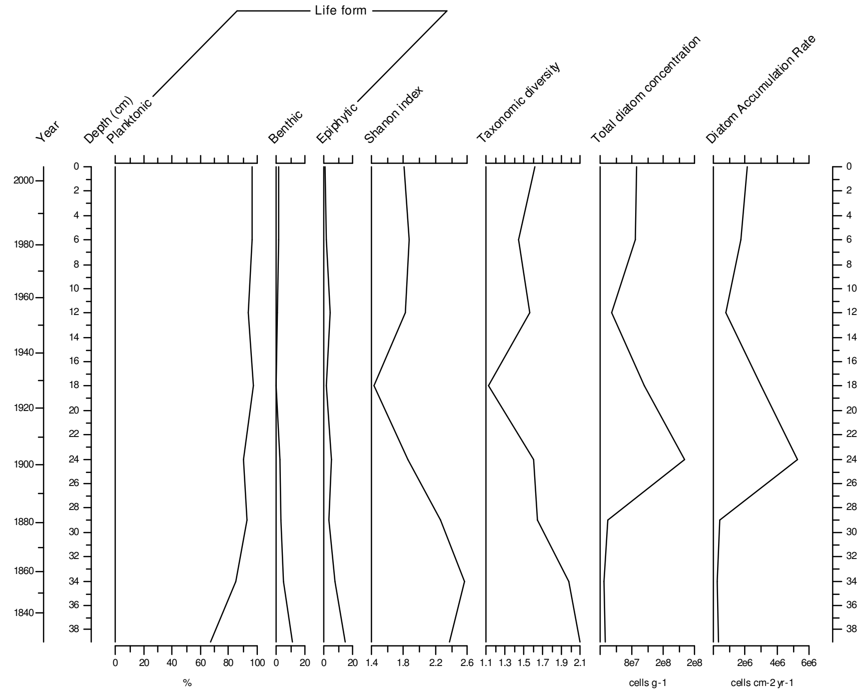
(a)


Year
Depth (cm)
Amphora inariensis Krammer
Amphora pediculus (Kutzing) Grunow
Asterionella formosa Hassall
Aulacoseira subarctica (O.Muller) Haworth
Cyclostephanos invisitatus(Hohn & Hellerman)Theriot Stoermer & Hakansson
Encyonopsis microcephala (Grunow) Krammer
Fragilaria ulna Sippen angustissima(Grun.)Lange-Bertalot
Gomphonema lateripunctatum Reichardt & Lange-Bertalot
Gomphonema pumilum (Grunow) Reichardt & Lange-Bertalot
Navicula cari Ehrenberg
Pseudostaurosira brevistriata (Grun.in Van Heurck) Williams & Round
Puncticulata radiosa (Lemmermann) Håkansson
Staurosira construens Ehr. var venter (Ehr.) Hamilton
Staurosira elliptica (Schumann) Williams & Round
Staurosirella pinnata (Ehr.) Williams & Round
Stephanodiscus hantzschii fo.tenuis(Hustedt)Hakansson et Stoermer
Stephanodiscus hantzschii Grunow in Cl. & Grun. 1880
Stephanodiscus medius Håkansson
Stephanodiscus parvus Stoermer et Hakansson
Diatom-inferred TP
%
ug TP l-1
Life form
Planktonic
Benthic
Epiphytic
Shanon index
Taxonomic diversity
Total diatom concentration
Diatom Accumulation Rate
cells g-1
cells cm-2 yr-1

(b)

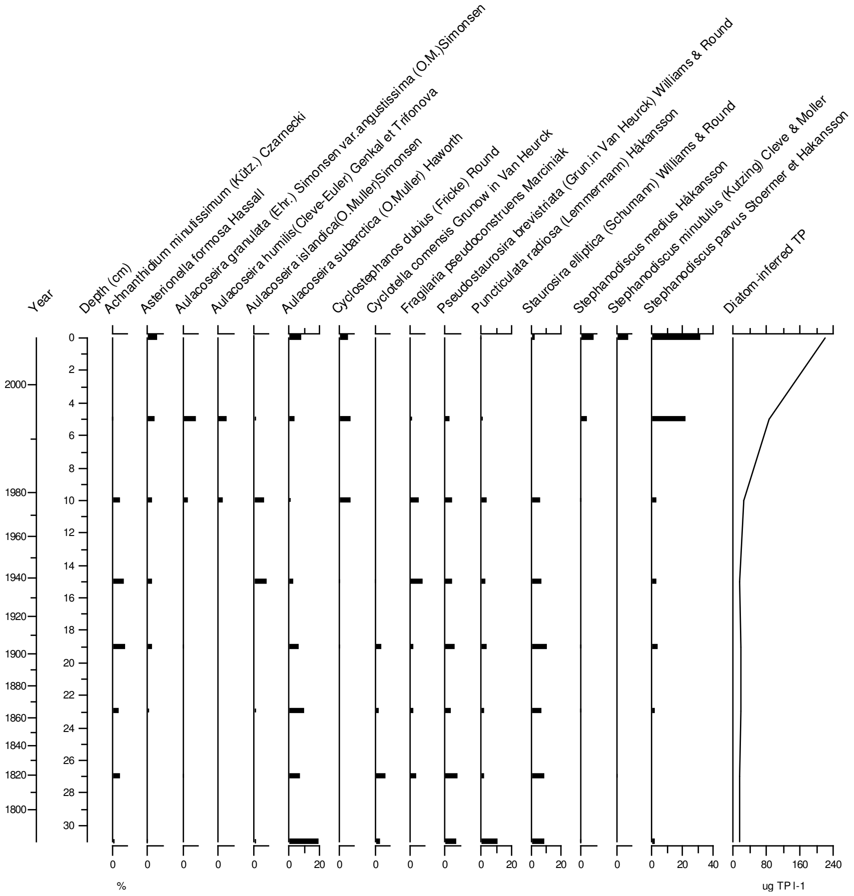


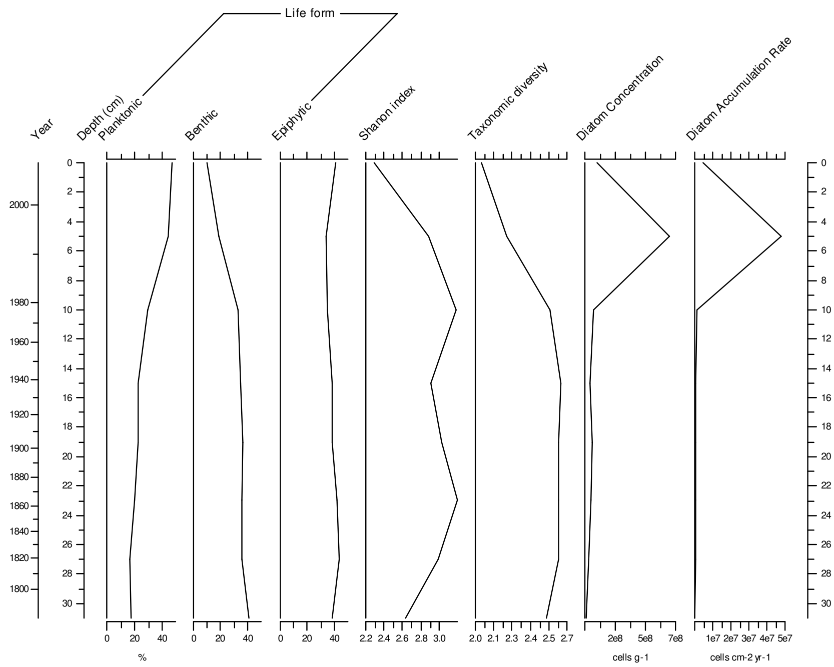
Year
Depth (cm)
Asterionella formosa Hassall
Aulacoseira ambigua (Grun.) Simonsen
Aulacoseira granulata (Ehr.) Simonsen var.angustissima (O.M.)Simonsen
Aulacoseira islandica(O.Muller)Simonsen
Aulacoseira islandica(O.Muller)Simonsen subsp.helvetica (O.M.)Simonsen
Aulacoseira subarctica (O.Muller) Haworth
Puncticulata radiosa (Lemmermann) Håkansson
Stephanodiscus hantzschii fo.tenuis(Hustedt)Hakansson et Stoermer
Stephanodiscus hantzschii Grunow in Cl. & Grun. 1880
Stephanodiscus medius Håkansson
Stephanodiscus parvus Stoermer et Hakansson
Diatom-inferred TP
%
ug TP l-1



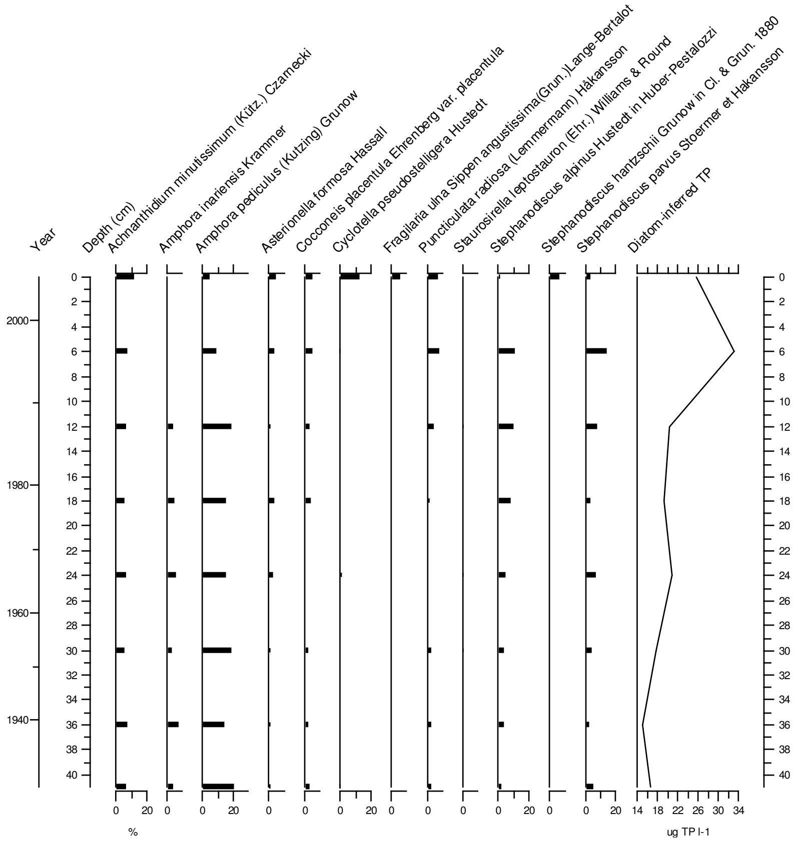
Life form
Year
Depth (cm)
Planktonic
Benthic
Epiphytic
Shanon index
Taxonomic diversity
Total diatom concentration
Diatom Accumulation Rate
%
cells g-1
cells cm-2 yr-1

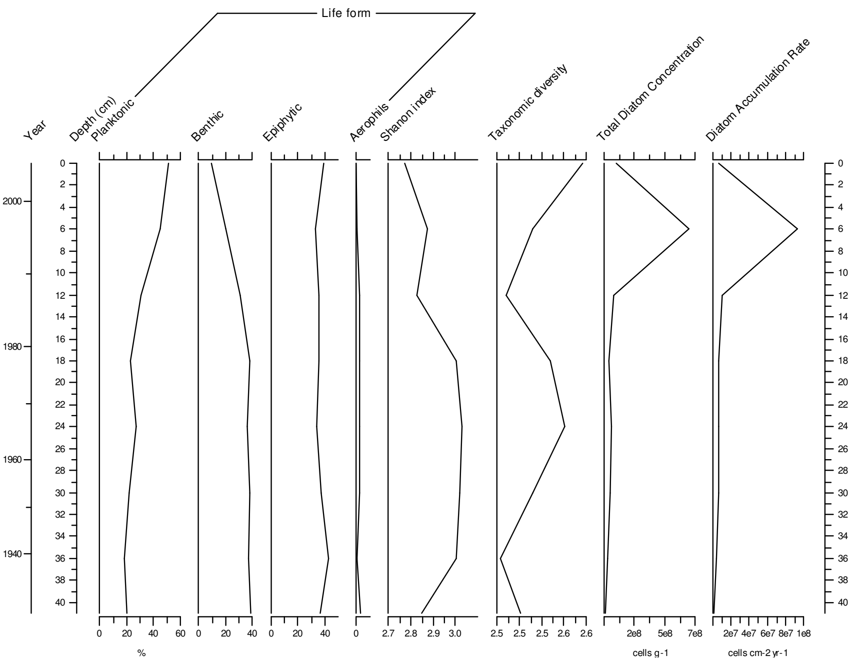
(c)


Year
Depth (cm)
Achnanthidium minutissimum (Kütz.) Czarnecki
Asterionella formosa Hassall
Aulacoseira granulata (Ehr.) Simonsen var.angustissima (O.M.)Simonsen
Aulacoseira humilis(Cleve-Euler) Genkal et Trifonova
Aulacoseira islandica(O.Muller)Simonsen
Aulacoseira subarctica (O.Muller) Haworth
Cyclostephanos dubius (Fricke) Round
Cyclotella comensis Grunow in Van Heurck
Fragilaria pseudoconstruens Marciniak
Pseudostaurosira brevistriata (Grun.in Van Heurck) Williams & Round
Puncticulata radiosa (Lemmermann) Håkansson
Staurosira elliptica (Schumann) Williams & Round
Stephanodiscus medius Håkansson
Stephanodiscus minutulus (Kutzing) Cleve & Moller
Stephanodiscus parvus Stoermer et Håkansson
Diatom-inferred TP
%
ug TP l-1

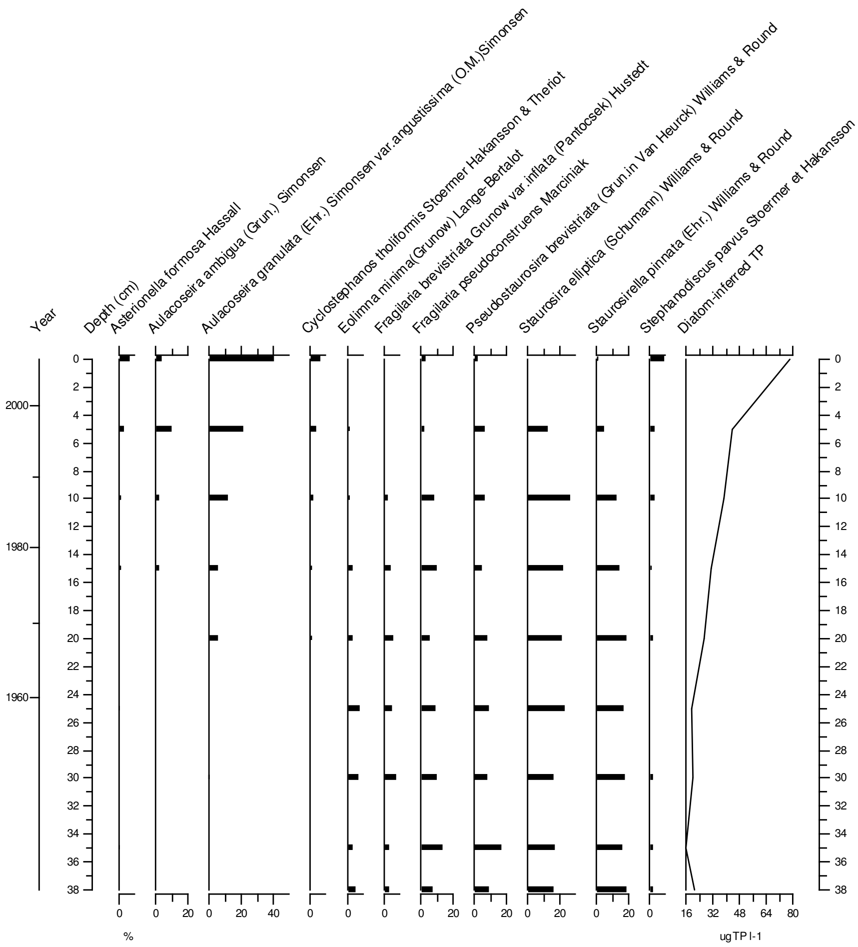

Life form
Year
Depth (cm)
Planktonic
Benthic
Epiphytic
Shanon index
Taxonomic diversity
Diatom Concentration
Diatom Accumulation Rate
%
cells g-1
cells cm-2 yr-1

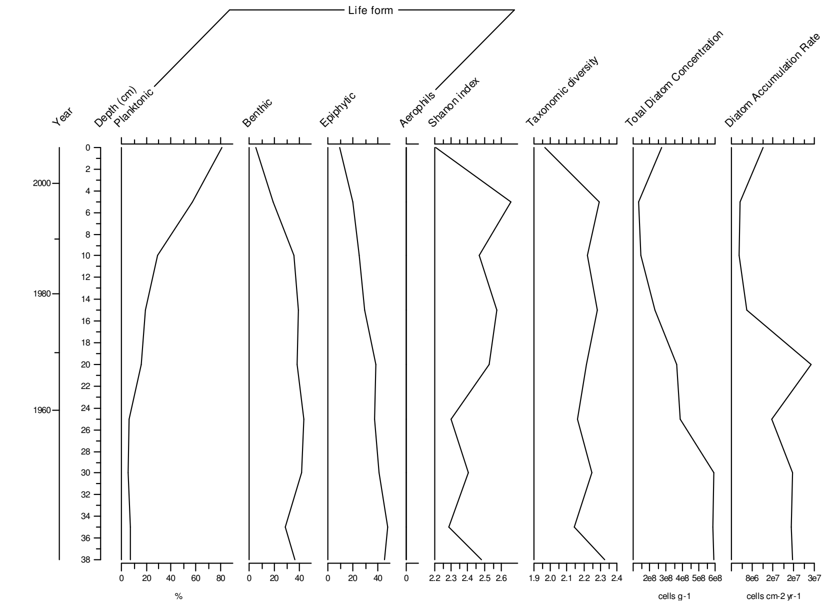
(d)



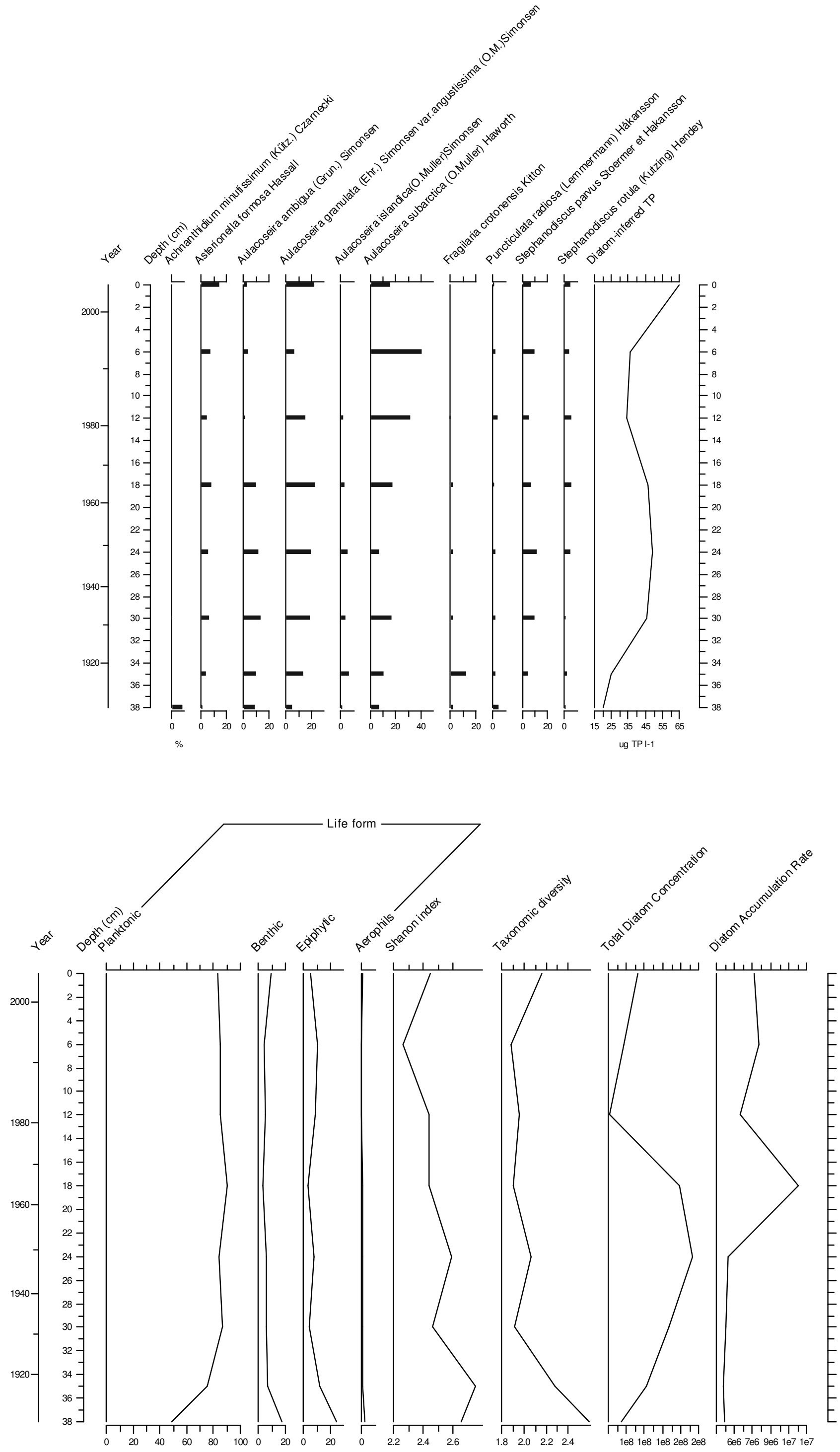


(e)


Year
Depth (cm)
Asterionella formosa Hassall
Aulacoseira ambigua (Grun.) Simonsen
Aulacoseira granulata (Ehr.) Simonsen var.angustissima (O.M.)Simonsen
Cyclostephanos tholiformis Stoermer Hakansson & Theriot
Eolimna minima(Grunow) Lange-Bertalot
Fragilaria brevistriata Grunow var.inflata (Pantocsek) Hustedt
Fragilaria pseudoconstruens Marciniak
Pseudostaurosira brevistriata (Grun.in Van Heurck) Williams & Round
Staurosira elliptica (Schumann) Williams & Round
Staurosirella pinnata (Ehr.) Williams & Round
Stephanodiscus parvus Stoermer et Hakansson
Diatom-inferred TP
2000
1980
1960
%
ugTP l-1

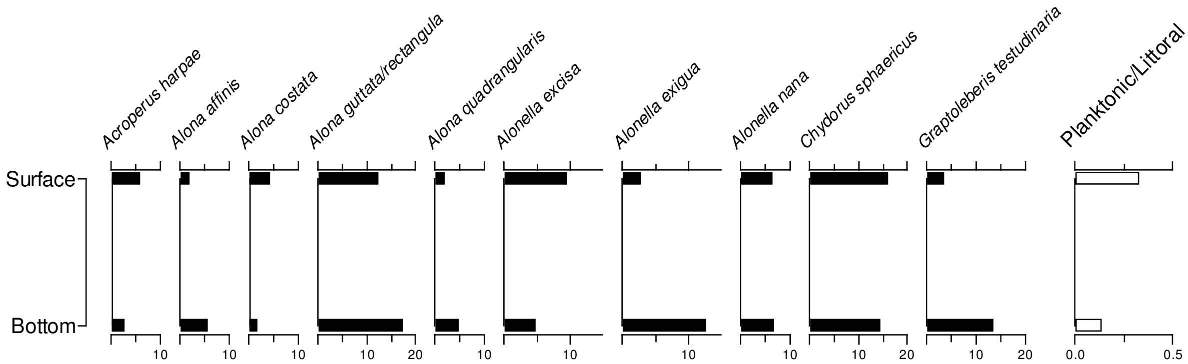

Life form
Year
Depth (cm)
Planktonic
Benthic
Epiphytic
Aerophils
Shanon index
Taxonomic diversity
Total Diatom Concentration
Diatom Accumulation Rate
2000
1980
1960
%
cells g-1
cells cm-2 yr-1

(f)

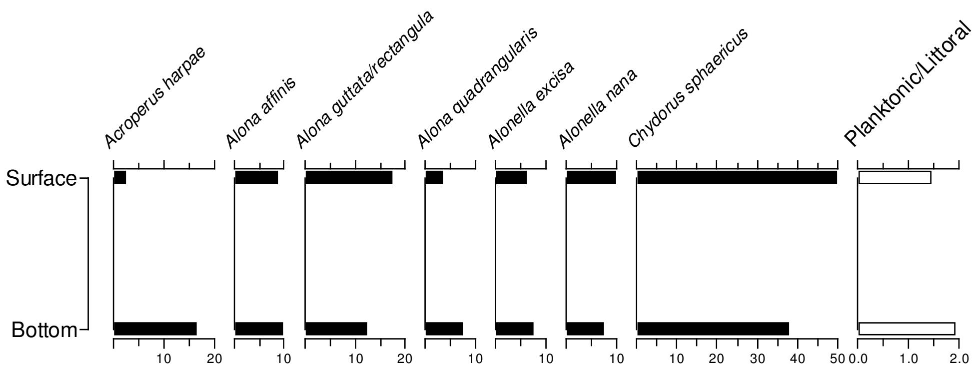


(g)

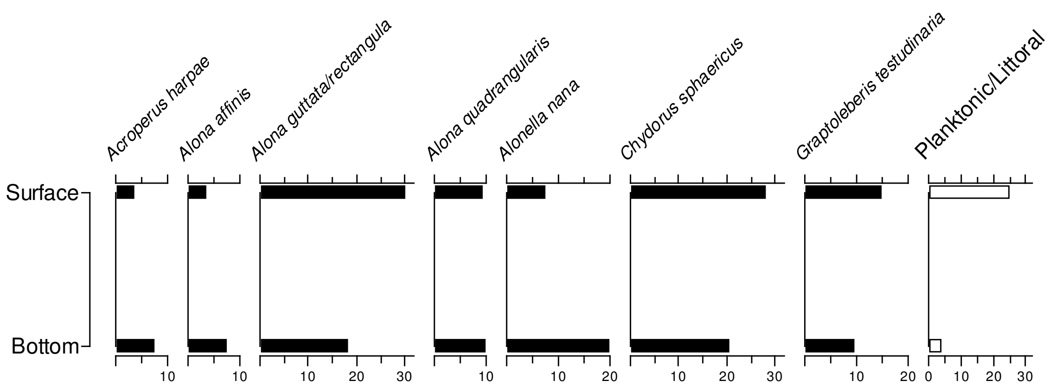
Figure 4.7 Down-core variations in common diatom taxa and other diatom-related parameters, including DI-TP. (a) Atedaun; (b) Ballybeg; (c) Crans; (d) Egish; (e) Inchiquin (f) Mullagh; (g) Sillan. All data are portrayed against both depth (cm) and estimated age, except for Atedaun (data portrayed only against depth (cm)). Diatom concentration and accumulation rate data are in, respectively, number of frustules g^{-1} and number of frustules cm^{-2} yr^{-1} (both x 10^{e})


Acroperus harpae
Alona affinis
Alona costata
Alona guttata/rectangula
Alona quadrangularis
Alonella excisa
Alonella exigua
Alonella nana
Chydorus sphaericus
Graptoleberis testudinaria
Planktonic/Littoral
Surface
Bottom
10
10
10
10 20
10
10
10
10
10 20
10 20
0.0 0.5

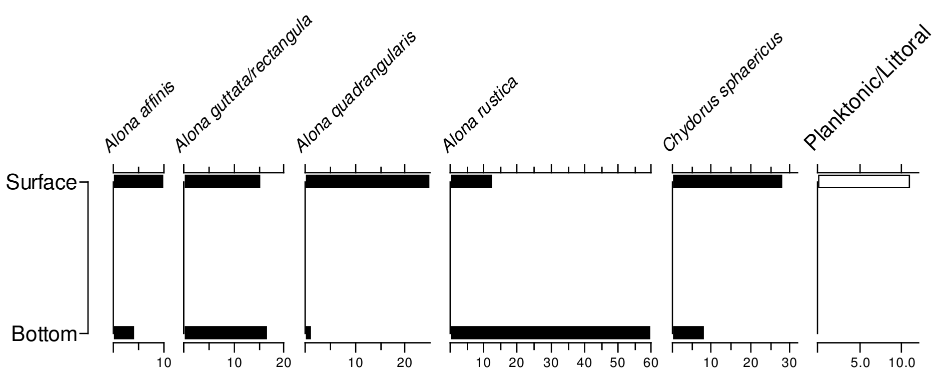
(a)


Acroperus harpae
Alona affinis
Alona guttata/rectangula
Alona quadrangularis
Alonella excisa
Alonella nana
Chydorus sphaericus
Planktonic/Littoral
Surface
Bottom
10 20
10
10 20
10
10
10
10 20 30 40 50
0.0 1.0 2.0

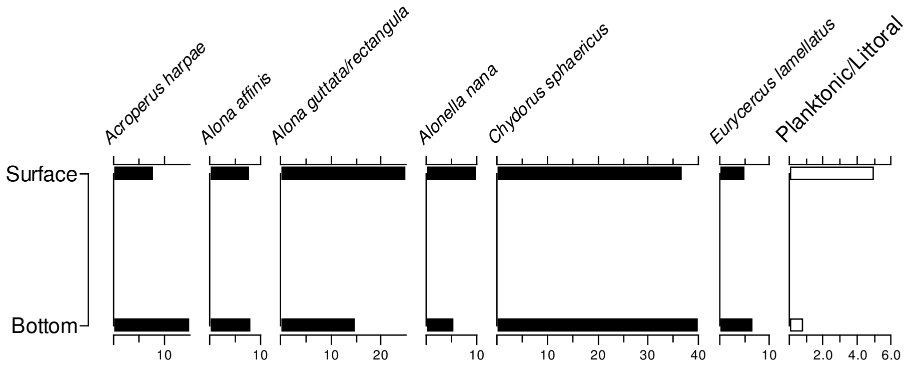
(b)


Acroperus harpae
Alona affinis
Alona guttata/rectangula
Alona quadrangularis
Alonella nana
Chydorus sphaericus
Graptoleberis testudinaria
Planktonic/Littoral
Surface
Bottom
10
10
10 20 30
10
10 20
10 20 30
10 20
0 10 20 30

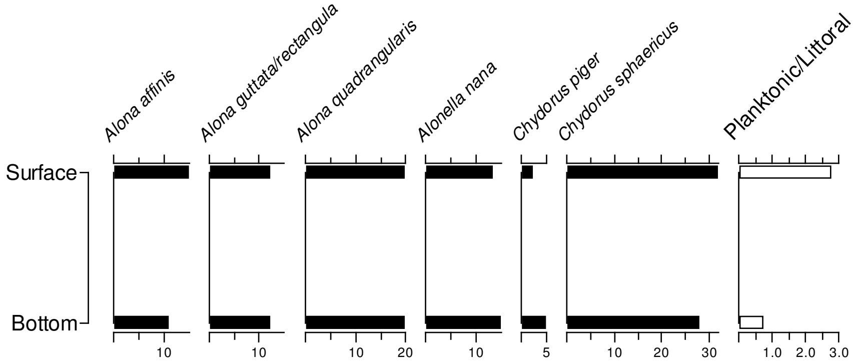
(c)


Alona affinis
Alona guttata/rectangula
Alona quadrangularis
Alona rustica
Chydorus sphaericus
Planktonic/Littoral
Surface
Bottom
10
10 20
10 20
10 20 30 40 50 60
10 20 30
5.0 10.0

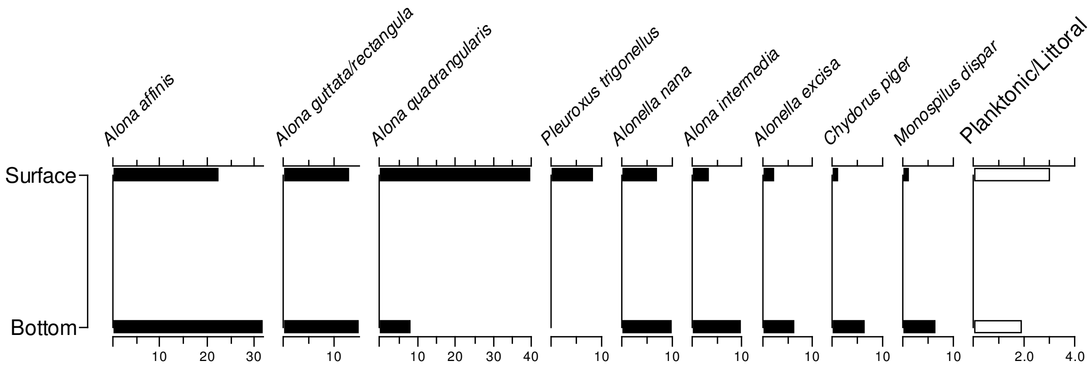
(d)



(e)



(f)



(g)

Figure 4.8 Abundances (%) of selected chydorid species in sediment core bottom and top (surface) samples (and see Table 4.9). a) Atedaun; (b) Ballybeg; (c) Crans; (d) Egish; (e) Inchiquin (f) Mullagh; (g) Sillan. Note that the planktonic/littoral ratio for the core bottom sample for (d) Egish is too low to plot on this figure.

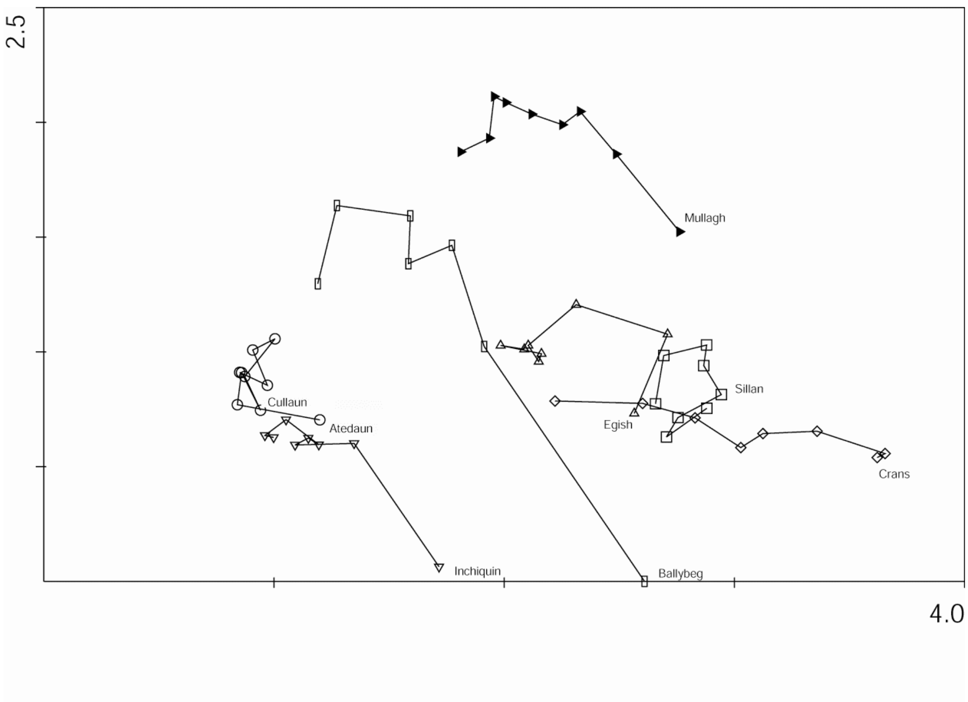


Figure 4.9 DCA biplot combining all sediment samples from seven WP3 lakes. Lake names are given next to the core top sample from that lake; contiguous samples from the same core are linked with a connecting line. Units = SD.

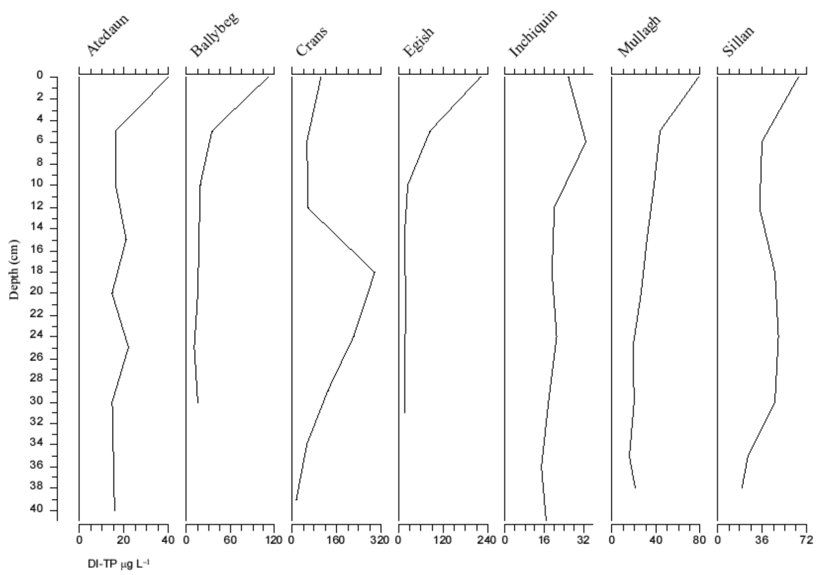


Figure 4.10 Summary of down-core variations in DI-TP (µg l^{-1}) for the seven WP3 lakes (data plotted against depth (cm))

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	na	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	na	8

Table 4.1 Summary of locational information and physical characteristics for WP3 lakes. Information provided by the EPA.

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		128.0	84.3			Wemaere 2001
Crans	1989/1990	8.82	316	2.45*	89.0	48.0		Northern Ireland Lake Survey Database (unpubl)
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	 354	161.8 140	19.3 21	 4.5	 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 4.2 Summary of chemical characteristics for WP3 lakes..

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

Table 4.3: Summary information of percentage of land cover in catchment for lakes cored as part of WP3. Land cover information is from the CORINE (1990 & 2000) databases and was provided by the EPA.

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	0
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 4.4: *Bathymetry Data*

Reference	TP range µg l^{-1}	Lakes *n*	Apparent r^2	RMSE log µg TP l^{-1}	RMSEP log µg TP l^{-1}	Model
Anderson *et al.* (1993)	25-800	43	0.75/0.77	0.17/0.16		WA
Anderson and Rippey (1994)	15-800	49	0.80	0.19	0.24	WA
Anderson and Odgaard (1994)	25-1000	27	0.80	0.15		WA
Bennion (1994)	25-646	30	0.79	0.16	0.28	WA
Wunsan and Schmidt (1995)	2-266	86	0.61/0.65	0.12/0.22	0.35/0.36	WA
Bennion *et al.* (1995)	2-263	44	0.60	0.32	0.37	WA
Bennion *et al.* (1996)	5-1190	152	0.91	0.15	0.21	WA
Lotter *et al.* (1998)	6-520	72	0.93	0.11	0.19	WA-PLS
Bradshaw and Anderson (2001)	1-369	45	0.75/0.79	0.17/0.15	0.24/0.27	WA
IN-SIGHT WP3	0-675	73	0.89	0.15	0.31	WA-PLS

Table 4.5 Performance of different diatom-inferred TP datasets based on WA or WA-PLS models, including the model developed specifically for WP3 lakes. The RMSEP values are based on either leave-one-out jacknifing or bootstrapping. n = number of lakes, WA = weighted averaging, WA-PLS = weighted averaging partial least squares.

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

Table 4.6 WP3 lake sediment core details

Lake	Length of core (cm)	210Pbexcess (Bq m-2 y-1)	137Cs (Bq m-2)	Estimated average sediment accumulation rate (g cm-2 yr-1)	Estimated age of particular sample depths	
					Core dated directly (CRS chronology) (± 1 SD)	Core used for microfossil analyses (estimated age) (± 1 SD)
Atedaun	23	>83	>5200	na	na	na
Ballybeg	29	90	784	0.026 ± 0.002	1944 ± 5 at 18-19cm	c. 1889 ± 11 at 29-30cm*
Crans	31	51	3500	0.028 ± 0.007	1916 ± 15 at 22-23cm	c. 1825 ± 37 at 38-39cm*
Egish	31	66	1400	0.017 ± 0.004	1913 ± 24 at 18-19cm	c. 1781 ± 50 at 30-31cm*
Inchiquin	27	320	2960	0.12 ± 0.02	1956 ± 4 at 25-26cm	c. 1931 ± 8 at 38-39cm*
Mullagh	27	90	1600	0.04 ± 0.01	1950 ± 4 at 26-27cm	Pre-1950 at 37-38
Sillan	23	120	2600	0.053 ± 0.012	1954 ± 4 at 22-23cm	1905 ± 13 at 37-38cm*

Table 4.7 $^{210}Pb_{excess}$ supply rates, ^{137}Cs inventories, estimated sediment accumulation rates, and extrapolated and estimated ages of selected core samples. NB Confidence intervals for extrapolated ages (*) were derived from estimated accumulation rates for the lowermost part of the core where there was evidence for varying sediment accumulation rates. An abrupt change in accumulation rate towards the base of the core from Mullagh made precise estimation of basal age impossible.

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

Table 4.8 % pollen data. Data underlined are for core bottom samples. See text for information on pollen sums used. AT = Atedaun, BA = Ballybeg, CR = Crans, EG = Egish, IN =Inchiquin, MU = Mullagh, SI = Sillan

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

Table 4.9 Summary of planktonic and littoral cladocera data and Shannon Diversity Index (H) of chydorid species for the seven WP3 lakes.

Chapter 5
Analogue matching approach for identifying appropriate reference sites for impacted lakes

5.1 Introduction

The potential of the Modern Analogue Technique (MAT) (Juggins 1994) to identify examples of extant reference conditions for impacted lakes in the Irish Ecoregion was examined in WP3. MAT was devised as a means of examining floristic similarities between modern diatom assemblages (e.g. Flower *et al*. 1997). The technique can also be used to compare the composition of assemblages from different periods in the past, and to compare present-day assemblages with fossil assemblages. A key assumption in the latter is that if close analogues are found to exist between modern and core bottom assemblages then the similarities should extend to other, taxonomically unrelated groups (e.g., fish, benthic macroinvertebrates).

Thus MAT provides a mathematical means of matching fossil with present-day assemblages, and therefore of identifying extant examples of reference conditions for impacted lakes that have preserved in their sediments a record of past, pre-human impact environments. To date MAT has been used in the UK to identify restoration targets for lakes based on diatoms (Flower *et al*. 1997) and, more recently, based on both diatoms and cladocera (Simpson 2003).

5.2 Methods

The MAT training dataset

The MAT training dataset comprised diatom data from surface sediment samples from 13 medium and high alkalinity CRLs (from typology classes 6, 8, 10 and 12 – see Table 5.1) sampled as part of WP2. Medium and high alkalinity CRLs were selected in order to provide as close a match as possible for levels of alkalinity (a major factor influencing the composition of aquatic biota) recorded for WP3 study lakes. Thus the CRLs selected were assumed to have as similar community composition to the impacted lakes prior to their disturbance as possible, given the constraints of the relatively small amount of reliable, relevant data available. The training dataset consisted of a matrix of 13 samples and abundance data for 367 diatom taxa, 62 of which had abundances of >2% in at least two samples. MAT was then used to determine whether any of the diatom assemblages in core bottom samples from WP3 lakes had close analogues, and therefore whether reference conditions for impacted lakes are currently exhibited by one or more CRLs included in the training set.

MAT

The degree of similarity (or dissimilarity) between diatom assemblages in surface sediment samples in the MAT training set and diatom assemblages in core bottom (reference) samples from the seven lakes studied as part of WP3 was established using SCD (see Chapter 3). As with WP2, a SCD score of 0.4 was viewed as the critical threshold in determining the level of similarity between two assemblages. Thus a SCD score > 0.4 meant no modern analogue existed among the selection of CRLs for reference conditions in currently impacted lakes.

5.3 Results

MAT

There is no good modern analogue for the sediment core bottom sample from Atedaun in the analogue training set, i.e. no modern analogue sample has an SCD score of ≤ 0.40 (Figure 5.1). Bunny provides the closest match, with a SCD score of 0.76 (Table 5.2). Both Atedaun and Bunny are high alkalinity lakes, and the non-planktonic *Amphora pediculus* was predominant in the surface sediment sample from Bunny and in the core bottom sample from Atedaun. However, differences exist in the abundances of less prominent taxa, such as *Achnantidium minutissimum* and *Cocconeis* spp.

The sediment core bottom sample from Ballybeg and the surface sample from Bane are relatively closely matched (SCD = 0.37), with *Amphora pediculus, Pseudostaurosira brevistriata*, *Staurosira construens* var. *venter* and *Staurosirella pinnata* abundant. Both Ballybeg and Bane are highly alkaline. Bane has a greater mean depth, however, which might explain some of the differences between the assemblages.

No close analogues are apparent from the SCD scores for the core bottom sample from Crans and the analogue training dataset (Figure 5.1). Ballynakill, with an SCD score of 0.68, was least dissimilar: the planktonic *Aulacoseira subarctica,* a species indicative of low-medium nutrient conditions, and *Puncticulata radiosa* were common in both core bottom and surface sediment assemblages, although their relative abundances differed. Both Crans and Ballynakill are medium alkalinity lakes. Crans, however, has a greater average depth than Ballynakill.

The core top sample from Ballynakill performed better as a modern analogue for the core bottom sample from Egish (SCD = 0.4), with the non-planktonic *Achnanthidium* *minutissimum* and *Staurosira elliptica*, and the planktonic *Aulacoseira subarctica* and *Cyclotella comensis* present in both. Ballynakill and Egish are both moderately alkaline and are shallow water lakes, while Ballynakill is currently mesotrophic.

SCD scores between the Inchiquin core bottom sample and the modern analogue training set showed no close analogues, the least dissimilar surface sediment samples being from Bunny (0.63) and Annaghmore (0.70). All three lakes have high alkalinity levels. However, Inchiquin is a large deepwater lake while the latter two are small and shallow. SCD scores for Mullagh indicate an absence of modern analogues in the training dataset, the least dissimilar being Bane (1.02), Ballynakill (1.38) and Muckanagh (1.40). Both Mullagh and Ballynakill are moderately alkaline, while Bane and Muckanagh are highly alkaline. The relatively low abundances of *Pseudostaurosira brevistriata, Staurosirella pinnata* and *Staurosirella elliptica* in the core top samples from Bane, Ballynakill and Muckanagh, compared with the greater abundances found in the core bottom sample from Mullagh, are the most likely explanation for the high SCD scores.

The diatom assemblage in the sediment surface sample from Ballynakill provided a poor analogue match for Sillan (SCD = 0.62), despite both being moderately alkaline lakes. The diatoms *Achnanthidium minutissimum*, *Aulacoseira ambigua*, *Aulacoseira subarctica* and *Puncticulata radiosa* characterised both the core bottom sample from Sillan and the surface sample from Ballynakill. The planktonic taxa *Aulacoseira granulata* was more abundant in the core bottom sample from Sillan than in the surface sample from Ballynakill.

In summary, good modern analogues were 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 MAT training set. Top-bottom intra-core comparisons carried out as part of WP2, however, indicate that both of the potential analogues for Ballybeg and Egish are not at present in reference condition.

5.4 Discussion

According to the results discussed above, good modern analogues exist in the relatively small training dataset for two of the seven impacted lakes studied as part of WP3 (Table 5.2). The two CRLs in the training dataset that appear to provide good modern analogues (Ballynakill and Bane) should be investigated further as they appear to have the potential to serve as physical, chemical and biological target conditions for some types of impacted lakes.

However, according to intra-core analyses in WP2, both Ballynakill and Bane currently exhibit biologically important deviations from reference conditions (SCD scores from intra-core comparisons of, respectively, 0.51 and 0.56 – and see Table 5.1), thus weakening their potential to serve as restoration benchmarks.

The low number of good modern analogues for the core bottom samples from impacted lakes suggests that: a) conditions that are reflected in the core bottom samples are unique and do not exist at present; or b) the range of conditions included in the training set is too small. The low number of sites included in the training set would tend to suggest the latter: diatom assemblages in core bottom samples generally contain higher abundances of benthic diatom assemblages than the surface samples comprising the MAT training set, thus constraining the number of good analogue matches for pre-disturbance reference conditions.

Other applications of MAT to define reference conditions have benefited from a far larger training dataset. For example, the training datasets in Flower (1997) and Simpson *et al.* (2005) comprised, respectively, 194 and 83 lakes. By comparison, Bennion *et al*. (2004a) utilised a training dataset comprising 30 lakes to identify modern analogues for three lakes impacted by eutrophication. Despite this relatively large dataset when compared to the small number of test sites (impacted lakes), no close modern analogues were found when only diatom assemblages were relied upon. However, applying the same procedure using a combined diatom and cladocera training dataset enabled the identification of close modern analogues.

To conclude, the results suggest that:

- MAT potentially can provide a means of identifying extant examples of appropriate restoration targets for eutrophic lakes and therefore could prove an important tool during the implementation phase of the WFD.
- In order to maximise the potential of MAT, a larger training dataset than the one used here is required. An enlarged training dataset should comprise more lakes and more biological indicators than the one developed for WP3, and possibly include data from adjacent ecoregions.

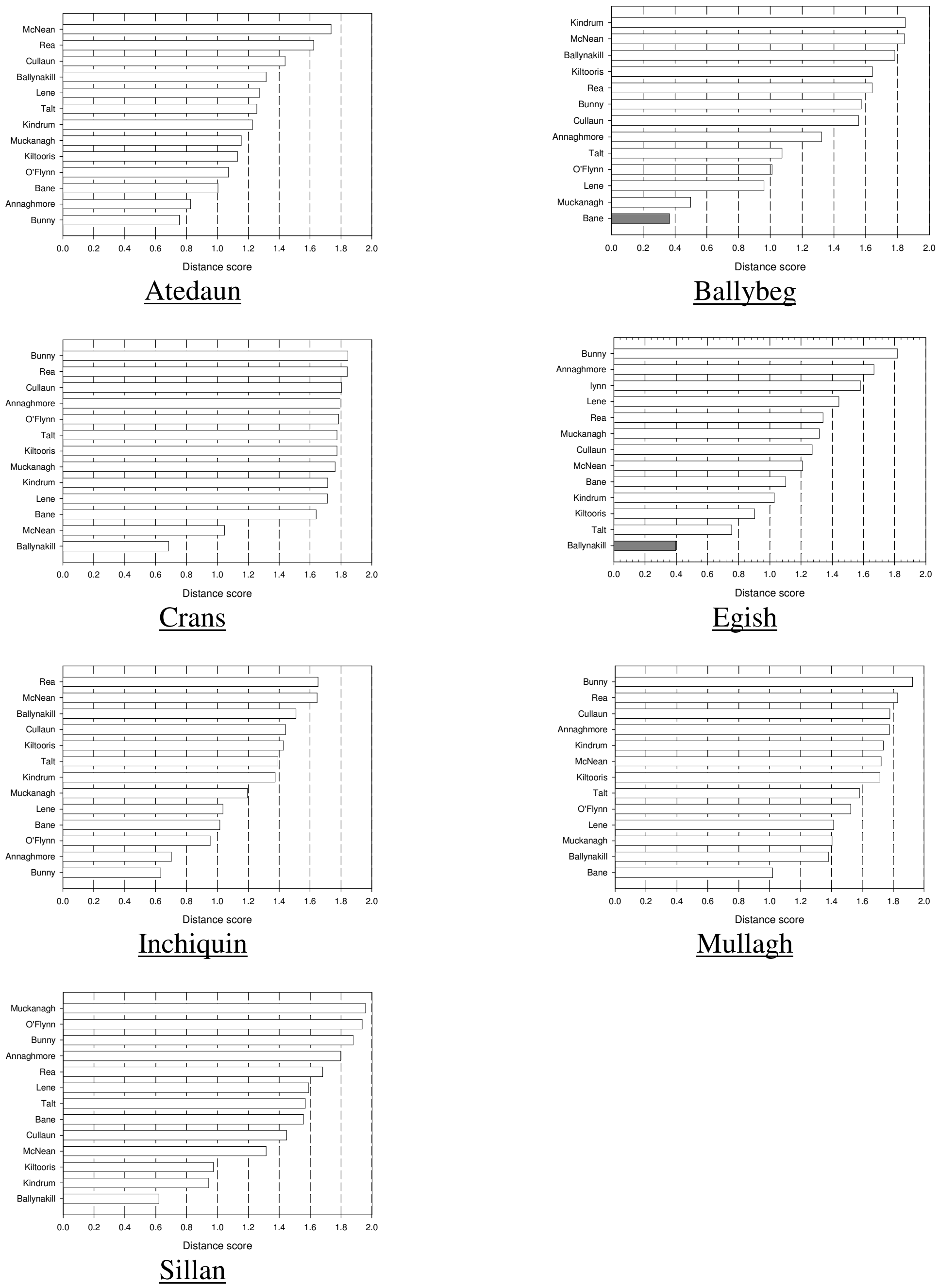


Figure 5.1 Histograms of the SCD scores for diatom assemblages in sediment core bottom samples from the seven impacted WP3 lakes and core top samples from the 13 CRLs comprising the MAT training dataset samples. SCD scores ≤ 0.4 are highlighted.

Lake name	Grid Ref.	Altitude (m)	Lake area (ha)	Max. depth (m)	pH	Cond ($\mu S\ cm^{-1}$)	Alkalinity ($mg\ l^{-1}$ $CaCO_3$)	Chl *a* $\mu g\ l^{-1}$	TP $\mu g\ l^{-1}$	SCD score*
Annaghmore	M 900 837	46	53.1	5.7	8.5	351	159.4	0.4	6	0.84
Ballynakill	L 856 225	13	23.9	16.4	7.1	244	20.0	3.7	5	0.51
Bane	N 550 712	112	75.4	16.9	8.4	297	132.5	1.4	5	0.56
Bunny	R 375 967	17	102.9	11.6	8.5	361	156.2	1.4	5	0.35
Cullaun	R 315 905	16	49.7	20.1	8.4	393	172.0	0.8	6	1.30
Kiltooris	G 676 972	7	43.5	13.5	7.2	205	27.4	1.4	14	0.29
Kindrum	C 185 430	8	60.8	11.0	8.3	318	69.5	5.5	11	0.42
Lene	N 510 685	93	416.2	19.7	8.5	250	104.9	3.4	6	0.48
McNean	H 040 400	50	977.8	16.9	7.6	116	23.6	6.9	17	0.15
Muckanagh	R 370 925	17	96.1	17.8	8.5	462	208.6	0.8	5	0.46
O'Flynn	M 585 795	77	137.5	3.4	8.5	333	138.9	0.8	10	0.33
Rea	M 615 155	81	301.1	20.9	8.5	308	128.5	2.4	6	0.47
Talt	G 398 150	130	97.3	23.0	8.0	190	85.1	1.9	8	0.96

Table 5.1 CRLs used as sources of data for the MAT training dataset. * = based on intra-core (core top-bottom) comparisons carried out in WP2 (see Chapter 3)

Impacted lake	**Closest modern analogue**			**Minimum SCD (3 DP)**
	SCD <0.40	**SCD ≥0.40 to <0.71**	**SCD ≥ 0.71**	
Atedaun			Bunny	0.755
Ballybeg	Bane			**0.365**
Crans		Ballynakill		0.684
Egish	Ballynakill			**0.397**
Inchiquin		Bunny		0.663
Mullagh			Bane	1.021
Sillan		Ballynakill		0.623

Table 5.2 Summary of MAT results (SCD scores for core bottom samples from impacted lake and closest modern analogue among CRL training dataset of 13 core top (surface sediment) samples) (only diatom taxa with abundances >2 % included in analysis). SCD scores falling below the threshold (i.e. ≤ 0.4) are in bold in far right column

Conclusions

- Diatom assemblages in sediment core top samples from 11 (32 %) of 34 CRLs showed relatively little deviation from those in sediment core bottom samples from the same lakes. The core bottom samples from ten of these sites appeared to pre-date *c.* 1950, or the onset of agricultural intensification and major aforestation in the catchments, with the basal sample from the eleventh site (O'Flynn) being imprecisely dated at younger than *c.* 1850. Assuming that the diatom assemblages reflect more general biological conditions, the 11 CRLs to have their reference status confirmed comprise: Barfinnihy (typology class 3); Bunny (typology class 10); Doo (typology class 3); Dunglow (typology class 2); Keel (typology class 1); Kiltooris (typology class 6); McNean (typology class 8); Nahasleam (typology class 1); O'Flynn (typology class 10); Upper (typology class 4); and Veagh (typology class 4).
- Large, deep, low alkalinity lakes (typology class 4) appear particularly prone to biological deviations from reference conditions over the periods of time represented by the sediment cores analysed (82 % of this type of CRL studied showed biologically important deviations from reference conditions).
- Acidification and nutrient enrichment were important drivers of biological changes at those CRLs that did not have their reference condition confirmed, while other factors, such as climate change, were probably also important, and may have contributed to biologically important deviations at some low alkaline lakes in particular.
- Reconstructions based on down-core variations in several proxies of lake and catchment conditions from seven impacted lakes, drawn from EPA typology classes 5, 6, 7, 8, 9 and 12, indicate complex and locally-specific trophic histories.
- The results of analyses of sediment core bottom (reference) samples from the seven impacted lakes suggest that reference conditions at these sites equate to oligo-mesotrophic or mesotrophic conditions. Diverse diatom flora in which benthic and epiphytic types were prominent are indicated, while reconstructed levels of DI-TP levels ranged from 12 to 21 $\mu g\ l^{-1}$. The analyses also revealed diverse littoral cladoceran assemblages indicative of abundant aquatic macrophytes and catchment vegetation cover characterised by a mosaic of deciduous woodland and grassland.
- Substantial nutrient enrichment (>50 $\mu g\ l^{-1}$ TP) and accelerated enrichment post *c.* 1980s characterised results from five of the impacted lakes (Ballybeg, Crans, Egish, Mullagh and Sillan), with two (Crans and Egish) showing a more than ten-fold increase in DI-TP over the time covered by the sedimentary records analysed.

Although chronological control was weak for Atedaun, the results also indicated that this lake had experienced nutrient enrichment, and that enrichment had been particularly intense during the most recent period.

- MAT has the potential to be a useful tool in the identification of appropriate restoration targets for impacted lakes. However, in order to allow the true potential of the technique to be realised a larger dataset that the one available to IN-SIGHT researchers is needed.
- Application of the palaeolimnological approach in IN-SIGHT has revealed significant shortfalls in the amount of relevant information currently available and the severe difficulties in setting *a priori* a *terminus ad quem* for type specific reference conditions in the Irish Ecoregion.
- Palaeolimnology, although relatively under-developed as a science in Ireland, has great potential as a tool in the implementation phase of the WFD, and is therefore deserving of further investment. Future palaeolimnological research in Ireland aimed at facilitating implementation of the WFD would benefit from high resolution, multi-proxy based studies of radiometrically-dated sediment cores and from close links with palaeolimnological research taking place in neighbouring ecoregions. This research ought to focus on the establishment of reference conditions for those types of lakes without extant examples of high quality status, on the development of new sediment-based proxies of water quality and catchment conditions, and on understanding the links between ecological pressures and responses in aquatic ecosystems.

References cited in main text

Allott, N. A. (1990) *Limnology of six western Irish Lakes.* University of Dublin, Dublin

Alonso, M. (1996). *Crustacea, Branchiopoda*. In: *Fauna Ibérica*, vol. 7. Ramos, M.A. *et al.* (Eds). Museo Nacional de Ciencias Naturales. CSIC. Madrid. 486 pp.

Andersen, J.H., Conley, D.J. and Hedal, S. (2004). Palaeoecology, reference conditions and classification of ecological status: the EU Water Framework Directive in practice. *Marine Pollution Bulletin*, 49, 283-290.

Anderson, N. J., (1995) Naturally eutrophic lakes: reality, myth or myopia? *Trends in Ecology and Evolution*, 10: 137-138.

Anderson, N.J. (1997) Historical changes in epilimnetic phosphorus concentrations in six rural lakes in NorthernIreland. *Freshwater Biology*, 38: 427 -440.

Anderson, N.J. (1989) A whole-basin diatom accumulation rate for a small eutrophic lake in Northern Ireland and its palaeoecological implications. *Journal of Ecology,* 77: 926-946.

Anderson, N.J. and Battarbee, R.W. (1994). Aquatic community persistence and variability; A palaeolimnological perspective. In: P.S. Giller, A.G. Hildrew and D. Raffaelli (eds) *Aquatic Ecology; Scale, Pattern and Processes*. Blackwell Scientific Publications, London, pp 233-259.

Anderson, N.J. and Odgaard, B.V. (1994) Recent palaeolimnology of three shallow Danish lakes. *Hydrobiologia*, 275/276: 411-422.

Anderson, N.J. and Rippey, B. (1994) Monitoring lake recovery from point-source eutrophication: the use of diatom-inferred epilimnetic total phosphorus and sediment chemistry. *Freshwater Biology*, 32: 625-639.

Anderson, N.J., Rippey, B. and Gibson, C.E. (1993) A comparison of sedimentary and diatom-inferred phosphorous profiles: implications for defining pre-disturbance nutrient conditions. *Hydrobiologia*, 253: 357-366.

Anon (1997) *Blackwater Catchment Rural Development Strategy*. Unpublished report. Brady Shipman Martin, Kirk McClure Morton, Minnock Barron, Belfast

Anon (2000) Directive 2000/60/EC of the European Parliament and of the council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Communities,* 1-327.

Battarbee, R.W. (1978) Observations on the recent history of Lough Neagh and its drainage basin. *Philosophical Transactions of the Royal Society of London*, Series B, 281: 303-345.

Battarbee, R.W. (1984) Spatial variations in the water quality of Lough Erne, Northern Ireland, on the basis of surface sediment diatom analysis. *Freshwater Biology,* 14: 539-545.

Battarbee, R.W. (1986) The eutrophication of Lough Erne inferred from changes in the diatom assemblages of ^{210}Pb and ^{137}Cs-dated sediment cores. *Proceedings of the Royal Irish Academy*, 86B: 141-168.

Battarbee, R. W. (1999). The importance of palaeolimnology to lake restoration. *Hydrobiologia*, 395/396: 149-159.

Battarbee, R.W., Charles, D.F., Dixit, S.S. and Renberg, I. (1999) Diatoms as indicators of surface water acidity. *The Diatoms: Applications for the Environmental and Earth Sciences* (eds E.F. Stoermer & J.P. Smol), pp. 85-127. Cambridge University Press, Cambridge.

Battarbee, R. W., V. J. Jones, Flower, R.J., Cameron, N.G., Bennion, H., Carvalho, L. and Juggins, S. (2001) Diatoms. In J. P. Smol, H. J. B. Birks and W. M. Last (eds) *Tracking Environmental Change Using Lake Sediments. 3: Terrestrial, Algal and Siliceous Indicators*. Kluwer Academic Publishers, Dordrecht, pp. 155-202.

Bennett, K.D. and K. J. Willis (2001). Pollen. In: Smol, J. P., H. J. B. Birks and W. M. Last (eds), *Tracking Environmental Change Using Lake Sediments Vol. 3: Terrestrial, Algal, and Siliceous Indicators*. Kluwer Academic Publishers, Dordrecht: 5-32

Bennion, H. (1994) A diatom-phosphorous transfer function for shallow, eutrophic ponds in southeast England. *Hydrobiologia*, 275/276: 391-410.

Bennion, H., Davidson, T., Simpson, G., Solovieva, N., Rose, N., Theophile, S., Yang, H., Anderson, N.J., Brooks S. and Peglar, S. (2004a) *Identification of reference lakes and evaluation of palaeoecological approaches to define reference conditions for UK (England, Wales, Scotland and Northern Ireland) ecotypes*. Final report (Project WFD08) to Scotland and Northern Ireland Forum for Environmental Research (SNIFFER).

Bennion, H., Fluin, J. and Simpson, G.L. (2004b) Assessing eutrophication and reference conditions for Scottish freshwater lochs using subfossil diatoms. *Journal of Applied Ecology*, 41: 124-138.

Bennion, H., Juggins, S. and Anderson, N.J. (1996) Predicting epilimnetic phosphorous concentrations using and improved diatom-based transfer function and its application to lake eutrophication management. *Environmental Science and Technology*, 30: 2004-2007.

Bennion, H. and Smith, M.A. (2000) Variability in the water chemistry of ponds in south-east England, with special reference to the seasonality of nutrients and implications for modelling trophic status. *Hydrobiologia*, 436: 145-158.

Bennion, H., Wunsam, S. and Schmidt, R. (1995) The validation of diatom-phosphorus transfer functions: an example from Mondsee, Austria. *Freshwater Biology*, 34: 271-283.

Birks, H. J. B. (1995). Quantitative palaeoenvironmental reconstructions. In D. Maddy and J. S. Brew (eds) *Statistical Modelling of Quaternary Science Data*. QRA, Cambridge: 161-254.

Birks, H.J.B. (1998) Numerical tools in palaeolimnology - progress, potentialities, and problems. *Journal of Paleolimnology,* 20: 307-332.

Birks, H.J.B., Juggins, S. and Line, J.M. (1990a) Lake surface-water chemistry reconstructions from palaeolimnological data. *The Surface Waters Acidification Programme* (ed B.J. Mason), pp. 301-313. Cambridge University Press, Cambridge.

Birks, H.J.B., Line, J.M., Juggins, S., Stevenson, A.C. and ter Braak, C.J.F. (1990b) Diatoms and pH reconstruction. *Philosophical Transactions of the Royal Society of London Series B-Biological Sciences*, 327: 263-278.

Boyle, J.F. (2001) Inorganic geochemical methods in palaeolimnology. In: W.M. Last and J.P. Smol (eds) *Tracking Environmental Change Using Lake Sediments Volume 2 Physical and Geochemical Methods*, Kluwer Academic Publishers, Amsterdam, pp 83-141.

Bradshaw, E.G. (2001). *Linking land and lake. The response of lake nutrient regimes and diatoms to long-term land-use change in Denmark*. Ph.D., University of Copenhagen.

Bradshaw, E.G. and Anderson, N.J. (2001) Validation of a diatom-phosphorus calibration set for Sweden. Freshwater Biology, 46: 1035-1048.

Bradshaw, E. G., Anderson, N.J., Jensen, J.P. and Jeppesen, E. (2002) Phosphorus dynamics in Danish lakes and the implications for diatom ecology and palaeoecology. *Freshwater Biology*, 47: 1963-1975

Cameron, N. G., Birks, H. J. B., Jones, V. J., Berge, F., Catalan, J., Flower, R.J., Garcia, J., Kawecka, B., Koinig, K.A., Marchetto, A., Sánchez-Castillo, P., Schmidt, R., Šiško, M., Solovieva, N., Štefkovál1, E. & Toro, M. 1999 Surface-sediment and epilithic diatom pH calibration sets for remote European mountain lakes (AL:PE Project) and their comparison with the Surface Waters Acidification Programme (SWAP) calibration set. *Journal of Paleolimnology*, 22, 291-317.

Champ, W.S.T. (1977) Trophic status of fishery lakes. In W.K. Downey and G.N. Uid (eds), *Lake pollution prevention by eutrophication control*, 65–77. Dublin and Killarney. Stationery Office.

Clarke, K.R. and Warwick, R.M. (1998) A taxonomic distinctness index and its statistical properties. *Journal of Applied Ecology*, 35: 523-531.

Connolly, L. (1997) *A Palaeolimnological study of L. Conn, Co. Mayo*. Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin.

Cox, B. (1989) *A paleolimnological study of the acidification of the Upper Lake; Glendalough, Co. WickJow*, Unpublished Ph.D. Thesis. University College Dublin.

Cox, B.C. and Murray, D.A. (1991) A palaeolimnological study of the Upper Lake, Glendalough, Co. Wicklow and Lough Veagh, Co. Donegal. In *Acid Sensitive Surface Waters in Ireland* (ed. J. Bowman). Environment Research Unit Dublin, pp. 273-319.

Cumming, B.F., Smol, J.P., Kingston, J.C., Charles, D.F., Birks, H.J.B., Camburn, K.E., Dixit, S.S., Uutala, A.J. and Selle, A.R. (1992) How much acidification has occurred in Adirondack region lakes (New York, USA) since preindustrial times? *Canadian Journal of Fisheries and Aquatic Sciences,* 49: 128-141.

Dalton, *c.* (1999) *A palaeolimnological investigation of acidity in humic lakewaters in Connemara, W. Ireland*. Unpublished Ph.D. University College London

Davison, W. (1993) Iron and manganese in lakes. *Earth-Science Reviews*, 34: 119 -163.

De Eyto, E., Irvine, K. and Free, G. (2002) The use of members of the family Chydoridae (Anomopoda, Branchiopoda) as an indicator of lake ecological quality in Ireland. *Biology and Environment: Proceedings of the Royal Irish Academy,* 102B (2): 81-91

De Eyto, E., Irvine, K. García -Criado, F., Gyllstrom, M., Jeppensen, E., Kornijow, R., Miracle, M.R., Nykannen, M., Bareiss, C., Cerbin, S., Salujoe, J., Franken, R., Stephens, D. and Moss, M. (2003) The distribution of chydorids (Branchiopoda, Anomopoda) in European shallow lakes and its application to ecological quality monitoring. *Archiv Fur Hydrobiologie,*156: 181-202.

Dixit, S.S., Smol, J.P., Charles, D.F., Hughes, R.M., Paulsen, S.G. and Collins, S.G. (1999) Assessing water quality changes in the lakes of the northeast United States using sediment diatoms. *Canadian Journal of Fisheries and Aquatic Sciences*, 56(:131-152.

Donnelly, J.S. (2001) *The Great Irish Potato Famine*. Boston Publishing, Stroud.

Douglas, D.J. and Murray, D.A. (1987) The Palaeolimnology of Irish Lakes: Lough Leane, Killarney, Co. Kerry. *Irish Journal of Environmental* Science, IV (2): 33-41.

Duigan, *c.* (1992) The ecology and distribution of the littoral freshwater Chydoridae Branchiopoda, Anomopoda of Ireland, with taxonomic comments on some species. *Hydrobiologia,* 241: 1-70

Duigan C.A. (1993) The Cladocera of Lough Maam, Co. Donegal, Ireland. Unpublished report to *AL:PE II, Acidification of Mountain Lakes: Palaeolimnology and Ecology*.

ECDGE (2004a). *WFD Newsletter* 2nd Edition (February), p. 2

ECDGE (2004b). *WFD Newsletter* 3rd Edition (October), p. 2.

Edwards, K. J. and Whittington, G. (2001) Lake sediments, erosion and landscape change during the Holocene in Britain and Ireland. *Catena,* 42: 143-173.

EHS (Environment and Heritage Service) (2000) *Managing the water environment in Northern Ireland 2000*. EHS, Belfast.

Engstorm D.R. and Wright H.E. (1984) Chemical stratigraphy of lake sediments as a record of environmental change. In: Hawarth E.Y. and Lund J.G.W. editors. *Lake sediments and environmental history*, Leicester: Leicester University Press, 11 -67.

Farrell, C. (1996) A Palaeolimnological study of Glendalough Lake, Lower, Co. Wicklow. Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin.

Flanagan, P.J. and Toner, P.F. (1975) *A preliminary survey of Irish lakes*. An Foras Forbatha, 164.

Flower, R.J., Juggins, S. and Battarbee, R.W. (1997) Matching diatom assemblages in lake sediment samples: the implications for lake conservation and restoration with special reference to acidified systems. *Hydrobiologia,* 344: 127-40.

Flower, R.J., Rippey, B., Rose, N.L., Appleby, P.G. and Battarbee, R.W. (1994) Palaeolimnological evidence for the acidification and contamination of lakes by atmospheric pollution in western Ireland. *Journal of Ecology*, 82: 581-596.

Foy, R.H., Lennox S.D. and Gibson C.E. (2003) Changing perspectives on the importance of urban phosphorus inputs as the cause of nutrient enrichment in Lough Neagh. *The Science of the Total Environment*, 310: 87-99.

Foy, R.H., Smith, R.V., Jordon *c.* and Lennox S.D. (1995) Upward trend in soluble phosphorus loadings to Lough Neagh despite phosphorus reduction at sewage treatment works. *Water Research,* 29: 1051-1063.

Fozzard, I., Doughty, R., Ferrier, R.C., Leatherland, T. and Owen, R. (1999) A quality classification for management of Scottish standing waters. *Hydrobilogia,* 395/396, 443-453

Frey, D.G. (1959) The taxonomic and phyolgenetic significance of the headr pores of the genus Chydoridae (Cladocera). *Internationale Revue der Gesamten Hydrobiologie,* 44: 27-50

Frey, D.G. (1960) The ecological significance of cladoceran remains in lake sediments. *Ecology,* 41: 684-699

Frey, D.G. (1962a) Cladocera from the Eemian interglacial of Denmark. *Journal of Paleontology,* 36: 1133-1154.

Frey, D.G. (1962b). Supplement to: The taxonomic and phylogenetic significance of the head pores of the Chydoridae (Cladocera). *Internationale Revue der Gesamten Hydrobiologie,* 47: 603-609

Frey, D.G. (1964) Differentiation of *Alona costata* SARS from two related species (Cladocera, Chydoridae). *Crustaceana,* 8: 159-173.

Frey, D.G. (1986) Cladocera analysis. In *Handbook of Holocene Paleoecology and Paleohydrology* (Berglund., B.E., ed.). John Wiley and Sons, 667-692

Gibson, C.E. (1991) Contributions to the regional limnology of Northern Ireland: (4) the lakes of Co. Tyrone. *The Irish Naturalists' Journal*, (23)11: 430-436.

Gibson, C.E., Anderson, N.J., Zhou, Q., Allen, M. and Appleby, P.G. (2003) Changes in sediment and diatom deposition in lower Lough Erne *c.* 1920-90. *Biology and Environment*, 103B: 31-39.

Goulden, C.E., Frey, D.G., (1963) The Occurrence and Significance of Lateral Head Pores in the Genus *Bosmina* (Cladocera). *Internationale Revue der Gesamten Hydrobiologie,* 48: 513-522

Hall, R. I., Leavitt, P. R., Smol, J. P. and Zirnhelt, N. (1997) Comparison of diatoms, fossil pigments and historical records as measures of lake eutrophication. *Freshwater Biology*, 38: 401-417.

Hall, R.I. and Smol, J.P. (1999) Diatoms as indicators of lake eutrophication. *The Diatoms: Applications for the Environmental and Earth Sciences* (eds E.F. Stoermer & J.P. Smol), pp. 128-168. Cambridge University Press, Cambridge.

Hill, M.O. and Gauch, H.G. (1980) Detrended Correspondence Analysis, an improved ordination technique. *Vegetatio*, 42: 47-58.

Hilton, J., Lishman, J.P. and Millington, A. (1986) A comparison of some rapid techniques for the measurement of density in soft sediments. *Sedimentology*, 33: 777-781.

Hobbs, W., Irvine K. and Donohue I. (2005) Using sediments to assess the resistance of a calcareous lake to diffuse nutrient loading. *Archiv Fur Hydrobiologie,* 164: 109-125.

Huang, C.C.1994. Multi-disciplinary studies of lake sediments towards the reconstruction of late-glacial and holocene environments in western Ireland. Ph.D., NUI, Galway.

Hudson, J.J., Dillon, P.J. and Somers, K.M. (2003) Long-term patterns in dissolved organic carbon in boreal lakes: the role of incident radiation, precipitation, air temperature, southern oscillation and acid deposition. *Hydrology and Earth System Sciences*, 7: 390-398.

Iribas, A.R. (1996) *Recent trends in productivity of Lough Ennell as observed in sediment Cores*. Unpublished M.Appl.Sc. thesis, University College Dublin.

Irvine, K., Allott, N., De Eyto, E., Free, G., White, J., Caroni, R., Kennelly, C., Keaney, J., Lennon, C., Kemp, A., Barry, E., Day, S., Mills, P., O' Riain, G., Quirke, B., Twomey, H., Sweeney, P. (2001). *The Ecological Assessment of Irish Lakes: the development of a new methodology suited to the needs of the EU Directive for surface waters*. Environmental Protection Agency, Wexford.

Irvine, K., Allott, N., Mills, P. and Free, G. (2000) The use of empirical relationships and nutrient export coefficients for predicting phosphorus concentrations in Irish lakes. *Verhandlungen Internationale Vereinigung fur Limnologie,* 27**:** 1127-1131

Jager, P. and Rohrs, J. (1990) Coprecipitation of phosphorus with calcite in the eutrophic Wallersee (alpine foreland of Salzburg, Austria). *Internationale Revue der Gesamten Hydrobiologie*, 75, 153-173**.**

Jennings, E., P. Mills, P. Jordan, J-P. Jensen, M. Søndergaard, A. Barr, G. Glasgow and K. Irvine (2003) *Eutrophication from agricultural sources Seasonal patterns and effects of phosphorous. Final Research Report (2000-LS-2.1.7-M2).* EPA, Wexford.

Jeppesen, E., Leavitt, P., De Meester, L. and Jensen, J.P. (2001). Functional ecology and palaeolimnology: using cladoceran remains to reconstruct anthropogenic impact. *Trends in Ecology and Evolution,* 16(4): 191-198

Jones, D.S., Stevenson, A.C., and Battarbee, R.W. (1989) Acidification of lakes in Galloway, South West Scotland: a diatom and pollen study of the post-glacial history of the Round Louch of Glenhead. *Journal of Ecology*, 77: 1-23.

Jordan, P., Menary, W., Daly, K., Kiely, G., Morgan, G., Byrne, P. and Moles, R. (2005) Patterns and processes of phosphorus transfer from Irish grassland soils to rivers - integration of laboratory and catchment studies. *Journal of Hydrology*, 304: 20-34.

Jordan, P. and Rippey, B. (2003) Lake sedimentary evidence of phosphorus, iron and manganese mobilisation from intensively fertilised soils. *Water Research*, 37: 1426-1432.

Jordan P., Rippey B. and Anderson N.J. (2001). Modelling diffuse phosphorus loads from land to freshwater using the sedimentary record. *Environmental Science and Technology,* 35: 815–815.

Jordan P., Rippey B. and Anderson N.J. (2002). The 20th Century wholebasin trophic history of an inter-drumlin lake in an agricultural catchment. *Science of the Total Environment,* 297: 161-173.

Juggins, S. (1994) *MAT Modern Analog Technique* Version 1.0. Unpublished Computer Programme

Juggins, S. (2003) *C2 Software for ecological and palaeoecological data analysis and visualisation.* User guide Version 1.3, pp. 69. Newcastle University, Newcastle upon Tyne.

Karst-Riddoch, T.L., Pisaric, M.F.J. and Smol, J.P. (2005) Diatom responses to 20th century climate-related environmental changes in high-elevation mountain lakes of the northern Canadian Cordillera. *Journal of Paleolimnology*, 33: 265-282.

Kauppila, T., Moisio, T. & Salonen, V.P. (2002) A diatom-based inference model for autumn epilimnetic total phosphorus concentration and its application to a presently eutrophic boreal lake. *Journal of Paleolimnology*, 27: 261-273.

Kingston, J.C., Birks, H.J.B., Uutala, A.J., Cumming, B.F. & Smol, J.P. (1992) Assessing trends in fishery resources and lake water aluminium from palaeolimnological analyses of siliceous algae. *Canadian Journal of Fisheries and Aquatic Sciences,* 49: 116-127.

Korsman, T. and Birks, H.J.B. (1996) Diatom-based water chemistry reconstructions from northern Sweden: A comparison of reconstruction techniques. *Journal of Paleolimnology*, 15: 65-77.

Koster, D., Racca, J.M.J. and Pienitz, R. (2004) Diatom-based inference models and reconstructions revisited: methods and transformations. *Journal of Paleolimnology*, 32: 233–246.

Krammer, K. and Lange-Bertalot, H. (1986) Bacillariophyceae. 1. Teil: Naviculaceae. In H. Ettl, J. Gerloff, H. Heynig and D. Mollenhauer (eds) *Süßwasserflora von Mitteleuropa*, Vol. 2/1, pp. 876. Fischer-Verlag, Stuttgart.

Krammer, K. and Lange-Bertalot, H. (1988) Bacillariophyceae. 2. Teil: Bacillariaceae, Epithemiaceae, Surirellaceae. In H. Ettl, J. Gerloff, H. Heynig and D. Mollenhauer (eds) *Süßwasserflora von Mitteleuropa*, Vol. 2/2, pp. 596. Fischer-Verlag, Stuttgart.

Krammer, K. and Lange-Bertalot, H. (1991a) Bacillariophyceae. 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. In H. Ettl, J. Gerloff, H. Heynig and D. Mollenhauer (eds) *Süßwasserflora von Mitteleuropa*, Vol. 2/3, pp. 576. Fischer-Verlag, Stuttgart.

Krammer, K. and Lange-Bertalot, H. (1991b) Bacillariophyceae. 4. Teil: Achnanthaceae. Kritische Ergänzungen zu Navicula (Lineolatae) und Gomphonema. In H. Ettl, J. Gerloff, H. Heynig and D. Mollenhauer (eds) *Süßwasserflora von Mitteleuropa*, Vol. 2/4, pp. 437. Fischer-Verlag, Stuttgart.

Leira, M., Cole, E. and Mitchell, F.J.G. (2003) Climate Impacts on Upland Irish Lakes: Irish Palaeoecological analysis and synthesis. *3rd International Limnogeology Congress, Tucson, Arizona*. Abstract Volume pp 155

Leira, M., Jordan, P., Taylor, D., Dalton, C., Bennion, H. and Irvine, K. (2006) Assessing the ecological status of candidate reference lakes in Ireland using palaeolimnology. *Journal of Applied Ecology,* 43: 816-827.

Liehu, A., Sandman, O. and Simola, H. (1986) Effects of peatbog ditching in lakes: problems in palaeolimnological interpretation. *Hydrobiologia*, 143: 417-424.

Linnane, S. (1997) *A Palaeolimnological investigation of Lough Bray Lower, Co. Wicklow* Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin.

Linnane, S.M. and Murray, D.A. (2001) A palaeolimnological investigation of an upland mountain lake on the east coast of Ireland. *Verhandlungen Internationale Vereinigung fur Limnologie,* 27: 1204-1208.

Linnane, S. M. and Murray, D. A. (2002) Hindcasting recent trends in trophic status of lakes on the Rvier Shannon, Ireland – results from short sediment cores analyses. *Verhandlungen Internationale Vereinigung fur Limnologie,* 28: 1050-1055.

Lotter, A.F., Appleby, B.G., Bindler, R., Dearing, J.A., Grytnes, J.A., Hofmann, W., Kamenik, C., Lami, A., Livingstone, D. M., Ohlendorf, C., Rose, N. and Sturm, M. (2002) The sediment record of the past 200 years in a Swiss high-alpine lake: Hagelseewli (2339 m.a.s.l). *Journal of Palaeolimnology*, 28: 111-127.

Lotter, A.F., Birks, H.J.B., Hofmann, W. and Marchetto, A. (1998) Modern diatom, cladocera, chironomid and chrysophyte cyst assemblages as quantitative indicators for the reconstruction of past environmental conditions in the Alps. II. Nutrients. *Journal of Palaeolimnology*, 19: 443-463.

Mackereth, F.J.H. (1966) Some chemical observations on post-glacial lake sediments. *Philosophical Transactions of the Royal Society B*, 250: 165 -213.

Martin, E. (1994) *A Palaeolimnological study of Lough Ree*. Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin.

Michelutti, N., Douglas, M.S.V. and Smol, J.P.. (2003) Diatom response to recent climate change in a high arctic lake (Char Lake, Cornwallis Island, Nunavut). *Global and Planetary Change*, 38: 257-271.

Murray, D.A. (1998) *Studies on sediment cores from L. Gill, Co. Sligo.* Report to EU LIFE L. Gill Management Project, Sligo County Council

Murray, D.A and Douglas, D.J. (1976) Some sedimentary pigment determinations in a 1.0m core from L. Ennell, a eutrophic lake in the Irish midlands. In *Palaeolimnology of Lake Biwa and the Japanese Pleistocene* 4 (ed. S. Horie), pp. 703-714.

Neal, C., House, A.W., Jarvie, H.P., Neal, M., Hill, L. and Wickham, H. (2005) Phosphorus fractions in the River Dun, the Kennet and Avon Canal and the River Kennet, southern England. *Science of the Total Environment*, 344: 107-128.

Nolan, K (1993) *A Palaeolimnological study of L. Derg*. Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin.

Nolan, Y. (1997) Aspects of the Palaeolimnology of Lough Dan, Co. Wicklow. Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin

Nowlan, N.V., Mitchell, P.I., Murray, D.A., Leon-Vintro, L. and Seymore, E. (2000) Measurement and interpretation of lead-210 and caseium-137 profiles in relation to recent sedimentation in some Irish lakes. *Verhandlungen Internationale Vereinigung fiir Theoretische und Angewandte limnologie,* 27: 2303-2306.

O'Brien, N. (1995) *A Palaeolimnological study of Lough Mullagh, Co. Cavan*. Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin.

O'Connell M, Walsh R, O'Connor B and McCarthy TK (2001) *Lake Sediments.* In (ed. McCarthy TK) *Investigation of eutrophication processes in the littoral zones of western Irish lake*s. EPA R&D series No. 13 Final Report, pp. 247-312.

O'Connor , J.P. and Bracken, J.J. (1978) *A comparative limnological study of two Irish lakes (Lough Sillan, Co. Cavan and Lough Dan, Co. Wicklow).* Irish Fisheries Investigations Series A No. 17.

O'Connor, B. (1998) *A report on sediment profile imagery surveys of Loughs Conn, Cullin and Mask*. Aqual-Fact International Services LtD Galway.

Oldfield, F., Appleby, P.G. and Battarbee, R.W. (1978). Alternative ^{210}Pb dating: results from the New Guinea Highlands and Lough Erne. *Nature*, 271: 339-342.

Orloci, L. (1967) An agglomerative method for classification of plant comminities. *Journal of Ecology*, 55: 193-206.

Overpeck, J.T., Webb, T. and Prentice, I.C. (1985) Quantitative Interpretation of Fossil Pollen Spectra - Dissimilarity Coefficients and the Method of Modern Analogs. *Quaternary Research*, 23: 87-108.

Parise, G. & A. Riva, 1982. Cladocera remains in recent sediments as indices of cultural eutrophication of Lake Como. Schweiz Z. Hydrol, 44: 277-278

Patrick, S.T. (1986) *The influence of sanitary and other social changes on the eutrophication of Lough Erne, Ireland, since c. 1850*. Unpublished Ph.D., London, University College.

Phillips, G., Kelly, A., Pit, J-A., Sanderson, R. and Taylor E. (2005) The recovery of a very shallow eutrophic lake, 20 years after the control of effluent derived phosphorus. *Freshwater Biology*, 50: 1628-1638.

Pielou, E.C. (1975) *Ecological Diversity*. Wiley Interscience, New York.

Ramstack, J.M., Fritz, S.C., Engstrom, D.R. and KHeiskary, S.A. (2003) The application of a diatom-based transfer function to evaluate regional water-quality trends in Minnesota since 1970. *Journal of Paleolimnology,* 29: 79-94.

Reavie, E.D., Smol, J.P. and Dillon, P.J. (2002) Inferring long-term nutrient changes in southeastern Ontario lakes: comparing paleolimnological and mass-balance models. *Hydrobiologia*, 481:61-74.

REFCOND (2003) Principles and methods for establishing reference conditions and ecological status class boundaries for inland surface waters. *Policy Summary to the REFCOND Guidance Document, version 2003-03-21*. CIS Working Group 2.3, CIS-WFD, 15pp.

Reid, M. (2005) Diatom-based models for reconstructing past water quality and productivity in New Zealand lakes. *Journal of Paleolimnology,* 33: 13-38.

Renberg, I. (1991) The HON-Kajak sediment corer. *Journal of Paleolimnology*, 6: 167-170.

Rippey, B. and Anderson, N.J. (1996) Reconstruction of lake phosphorous loading and dynamics using the sedimentary record. *Environmental Science and Technology*, 30: 1786-1788.

Rippey, B., Anderson N.J. and Foy R.H. (1997) Accuracy of diatom-inferred total phosphorus concentrations and the accelerated eutrophication of a lake due to reduced flushing and increased internal loading. *Canadian Journal of Fisheries and Aquatic Sciences*, 54: 2637-2646.

Rippey, B., Murphy, R.I. and Kyle, S.W. (1982) Anthropogenically derived changes in sedimentary flux of Mg, Cr, Ni, Cu, Zn, Hg, Pb, and P in Lough Neagh sediments, Northern Ireland. *Environmental Science and Technology,* 16, 23-30.

Robbins, J. A., Edgington, D. N. and Kemp, A. L. W. (1978). Comparative ^{210}Pb, ^{137}Cs, and pollen geochronologies of sediments from Lakes Ontario and Erie. *Quaternary Research*, 10: 256-278.

Rose, N.L. (2001) Fly-ash particles. In: W.M. Last and J.P. Smol (eds) *Tracking Environmental Change Using Lake Sediments Volume 2 Physical and Geochemical Methods*, Kluwer Academic Publishers, Amsterdam, pp 319-349

Rose, N.L., Alliksaar, T., Bowman, J.J., Fott, J., Harlock, S., Punning, J.-M., St.Clair-Gribble, K., Vikic, J. and Watt, J. (1998) The FLAME project: general discussion and conclusions. *Water, Air and Soil Pollution,* 106, 329-351.

Rose, N. L., Harlock, S., Appleby, P.G. and Battarbee, R.W. (1995) Dating of recent lake sediments in the United Kingdom and Ireland using spheroidal carbonaceous particle (SCP) concentration. *The Holocene*, 5, 328-335.

Rose, N. and Theophile, S. (2004). *An assessment of sediment chronologies for 35 lakes in Ireland based on skeleton spheroidal carbonaceous particle profiles. A report for IN-SIGHT (EPA/ERTDI Project #2002-W-LS/7).* ECRC Research Report # 97, ECRC, UCL.

Rühland, K., Priesnitz, A. and Smol, J.P. (2003) Palaeolimnological evidence from diatoms for recent environmental changes in 50 lakes across Canadian arctic treeline. *Arctic, Antarctic and Alpine Research*, 35, 110-123.

Simpson, G.L. (2003) *Defining restoration targets for acidified upland lakes using diatom and cladoceran sub-fossil remains and the modern analogue approach*. PhD Thesis. University of London, London. UK.

Simpson G.L., Shilland, E.M., Winterbottom, J.M. and Keay, J. (2005). Defining reference conditions for acidified waters using a modern analogue approach. Environmental Pollution 137: 119-133.

Smol, J. P. (2002) *Pollution of Lakes and Rivers: A Paleoenvironmental Perspective*. Arnold Publishers, London; Co-published by Oxford University Press, New York.

Smol, J.P. and Cumming, B.F. (2000) Tracking long-term changes in climate using algal indicators in lake sediments. *Journal of Phycology*, 36: 986-1011.

Smol, J.P., Wolfe, A.P., Birks, H.J.B., Douglas, M.S.V., Jones, V.J., Korhola, A., Pienitz, R., Rühland, K., Sorvari, S., Antoniades, D., Brooks, S.J., Fallu, M-A., Hughes, M., Keatley, B., Laing, T., Michelutti, N., Nazarova, L., Nyman, M., Paterson, A.M., Perren, B., Quinlan, R., Rautio, M., Saulnier-Talbot, E., Siitonen, S., Solovieva, N. and Weckström, J. (2005) Climate-Driven Regime Shifts in Arctic Lake Ecosystems. *Proceedings of the National Academy of Sciences*, 102, 4397-4402.

Sorvari, S. Korhola, A. and Thompson, R. (2002) Lake diatom response to recent Arctic warming in Finnish Lapland. *Global Change Biology*, 8: 153-163.

Søndergaard, M., J.P. Peder and E. Jeppesen (1999) Internal phosphorus loading in shallow Danish lakes. *Hydrobiologia*, 408/409: 145-152

Stoermer E.F & Smol J.P. (eds) (1999) *The Diatoms: Applications for the Environmental and Earth Sciences*. Cambridge University Press, Cambridge 469 pp.

ter Braak, *c.* J. F. and van Dam, H. (1989) Inferring pH from diatoms: a comparison of old and new calibration methods. *Hydrobiologia*, 178: 209-223.

ter Braak, C.J.F. and Juggins, S. (1993) Weighted averaging partial least squares regression (WA-PLS): An improved method for reconstructing environmental variables from species assemblages. *Hydrobiologia*, 269/270: 485-502.

ter Braak, C.J.F. and Šmilauer, P. (2002) *CANOCO Version 4.5* Biometrics, Wagenigen.

Tunney, H., Breeuwsma, A., Withers, P. J. A. and Ehlert, P. A. I. (1997) Phosphorus fertilizer strategies: past, present and future. In H. Tunney, O.T. Carton, P.C. Brookes and A.E. Johnson, A. E. *Phosphorus Losses from Soil to Water.* CAB International, New York: 358-361

van Dam, H., Mertens, A. and Sinkeldam, J. (1994) A coded checklist and ecological indicator values of freshwater diatoms from the Netherlands. *Netherlands Journal of Aquatic Ecology,* 28: 117-133.

Wahl, E.R. (2004) A general framework for determining cutoff values to select pollen analogs with dissimilarity metrics in the modern analog technique. *Review of Palaeobotany and Palynology* 128: 263-280.

Wemaere, A. (2001) *Lakes of County Clare – Monitoring Report 2000-20001* EPA, Ireland.

Wemaere, A. (2005) *Ecological assessment of the lakes of County Clare - Relationships between catchment landuses and water ecological quality*. Unpublished PhD thesis. Trinity College Dublin.

Williams, N.K. (2000) *Hindcasting the cladoceran (Crustacea)*. Unpublished PhD thesis. University College, Dublin.

Wolin, J.A. and Stoermer, E.F. (2005) Response of a Lake Michigan coastal lake to anthropogenic catchment disturbance. *Journal of Paleolimnology*, 33: 73-94.

Wood, R.B. Taylor, J.A., Andrew T.E and Carter, *c.* (1996) Environmental Change in Lough Garadice since the seventeenth century based on cladoceran remains in the sediments. *Biology and Environment. Proceedings of the Royal Irish Academy,* 96B: 33-44.

Wunsam, S. and Schmidt, R. (1995) A diatom-phosphorus transfer function for alpine and pre-alpine lakes. *Memoria Istituto Italiano Idrobiologia*, 53, 85-99.

Zhou, Q., C.E. Gibson and R.H. Foy (2000) Long-term changes of nitrogen and phosphorus loadings to a large lake in north-west Ireland. *Water Research*, 34: 922-926.

Zielinski, R.A., Asher-Bolinde,r S., Meier, A.L., Johnson, C.A. and Szabo, B.J. (1997) Natural or fertiliser derived uranium in irrigation drainage: a case study in southeastern Colorado, USA. *Applied Geochemistry*, 12: 9-21.

Appendices

Appendix 1 List of 76 CRLs identified by the EPA

Lake name	Grid Ref.	Altitude (m)	Lake area (ha)	Catchment area : lake area	Estimated mean depth (m)	pH	Alkalinity (mg l^{-1} $CaCO_3$)	Chla µg l^{-1}	TP µg l^{-1}
Acrow	R 193 687	195	6.4	4.62	>3	5.14	-0.4	6.2	18
Allen	G 960 200	50	3597		>3				
Altan	B 940 230	37	132		>3				
Annaghmore	M 900 837	46	53.1	7.45	<3	8.46	159.4	0.4	6
Anure	B 820 165	36	158.6	23.50	>3	6.57	12.50	3.71	6
Arderry	L 995 457	37	81.1	17.79	>3	6.33	6.14	1.77	6
Ballynakill	L 856 225	13	23.9	5.90	>3	7.1	20.02	3.71	5
Bane	N 550 712	112	75.4	6.23	>3	8.43	132.5	1.4	5
Barfinnihy	V 850 768	249	13.6	5.82	>3	6.84	4.2	3.2	4
Barra	B 935 120	90	62.6	31.45	>3	6.31	3.80	0.85	5
Beltra	M 070 980	15	410.1	23.54	>3	7.39	19.43	2.10	
Bunny	R 375 967	17	102.9	9.05	<3	8.47	156.2	1.4	5
Caragh	V 725 905	15	490.7	33.12	>3	6.66	3.3	2.4	5
Cloon	V 702 777	90	76.8	22.38		6.74	2.2	3.6	5
Cloonaghlin	V 610 709	109	127.7	8.01	>3	6.82	2.0	3.6	5

Cloongat	L 689 472	14	8.1	74.63	>3	6.36	2.52	0.12	2
Coomsharan	V 629 843	161	80		>3				
Corrib	M 150 450	6	17290.9	17.09	>3				
Corrib Up.					>3	8.14	103.30	5.80	12
Coumalocha	S 287 100	498	2.6		>3				
Coumduala	S 293 143	468	1.7	9.22	>3	6.33	-0.8	82.6	13
Coumfea	S 278 099	520	1.8		>3				
Craghy	B 795 115	14	49.8	50.66	>3	5.78	75.76	1.41	9
Crottys	S 326 125	419	3.5	2.18	>3	6.38	1.9	0.8	6
Cullaun	R 315 905	16	49.7	26.58	>3	8.40	172.0	0.8	6
Currane	V 530 660	6	1034.8	10.05	>3	7.00	5.1	3.8	5
Dan	O 150 40	200	102.9	61.41	>3	5.11	-0.1	0.8	6
Doo	C 359 394	283	9.0	47.44	>3	5.88	2.05	2.30	12
Doo	L 835 685	30	154.5	178.07	>3	6.69	2.26	1.05	7
Dunglow	B 782 117	13	61.2	61.53	<3	5.73	59.63	1.81	6
Easky	G 442 225	180	119.2	9.06	>3	6.53	4.04	2.94	7
Fad Inishowen East	C 539 439	233	12.3	4.95	>3	6.35	5.02	1.41	7
Fad Inishowen West	C 397 427	125	40.4	7.94	>3	6.4	6.43	2.18	3
Fee	L 790 613	47	173.7	9.07	>3	6.55	3.06	0.93	9

Feeagh	F 965 000	11	394.8	21.45	>3	7.39	9.60	1.33	8
Fin	L 841 657	28	13.7	226.78	>3	6.74	0.52	0.85	9
Glenawough	L 992 677	218	73.1		>3				
Gartan	C 050 156	67	204.9	37.79	<3	7.06	11.95	2.42	5
Glencar	G 750 435	28	114.6	35.97	>3	8.44	94.3	4.4	5
Glencullin	L 819 696	38	34.2	17.76	>3	6.37	2.5	2.14	4
Golagh	G 965 662	101	60.4	7.60	>3	7.20	6.1	3.6	19
Guitane	W 025 845	77	246.3	7.72	>3	6.96	4.4	2.0	5
Hibbert	L 881 231	15	25.4	12.00	>3	6.69	5.09	3.63	9
Inchiquin	V 835 628	42	77.5	23.15	>3	6.51	2.2	2.8	7
Keel (Rosses)	B 847 162	136	11.4	34.69	<3	5.3	2.4	2.10	8
Kiltooris	G 676 972	7	43.5	12.76	>3	7.18	27.43	1.41	14
Kindrum	C 185 430	8	60.8	6.03	>3	8.27	69.47	5.52	11
Kylemore	L 770 552	35	132.2	15.82	>3	6.59	6.99	0.56	6
Lene	N 510 685	93	416.2	3.11	>3	8.46	104.9	3.4	6
Mask	M 100 600	20	8342.9	11.25	>3	8.19	107.11	3.51	12
Maumeen	L 615 412	5	56.4	4.05	<3	6.81	12.03	5.04	15
Maumwee	L 977 484	46	27.6	14.35	<3	6.07	6.30	1.25	5
McNean	H 040 400	50	977.8	12.31	>3	7.60	23.6	6.9	17
Melvin	G 900 540	25	2206.4	8.30	>3	8.15	54.1	4.4	15
Mourne	H 068 896	168	66.6	13.32	>3	6.77	0.7	2.2	6

Muckanagh	R 370 925	17	96.1	23.05	>3	8.53	208.6	0.8	5
Muckross	V 950 852	17	266.9	51.41	>3	6.82	5.3	0.8	3
Nafooey	L 970 595	25	248.3	13.56	>3	6.79	5.49	0.52	4
Nahasleam	L 971 244	33	28.1	81.10	<3	6.5	9.59	1.33	7
Nakirka	V 735 892	173	5.7	9.24	>3	6.12	0.4	3.2	4
Nalughraman	G 657 886	180	56.3	3.95	>3	6.26	5.96	0.97	3
Namanfin	G 797 839	128	23.2	7.97	n/a	6.55	8.58	1.93	7
Nambrackkeagh	L 821 603	65	6.7	8.28	>3	5.98	2.26	0.48	10
Naminn	C 396 419	150	15.0	7.33	>3	6.55	7.0	0.64	10
Naminna	R 176 710	169	20.2	4.50	<3	6.02	0.7	3.8	8
O'Flynn	M 585 795	77	137.5	13.35	>3	8.51	138.9	0.8	10
Oorid	L 930 460	45	60.5	12.22	>3	6.40	8.06	1.41	7
Owel	N 400 580	97	1021.8	3.15	>3	8.49	109.5	2.4	9
Rea	M 615 155	81	301.1	3.55	>3	8.54	128.5	2.4	6
Salt	C 124 262	246	28.9	3.48	>3	7.18	26.43	0.60	1
Shindilla	L 960 460	38	70.2	13.75	>3	6.45	6.17	1.49	4
Talt	G 398 150	130	97.3	5.85	>3	8.01	85.09	1.89	8
Tay	O 160 750	250	50.0	40.06	>3	5.12	-0.3	0.6	8
Upper	V 900 817	18	169.9	66.56	>3	6.41	2.8	1.8	5
Veagh	C 022 215	40	260.9	14.14	>3	6.30	2.16	1.69	0
Waskel	B 738 161	3	30.9	10.15	>3	5.70	78.15	1.25	5

Appendix 2: References for studies where individual CRLs are the focus (up to 2003)

Lake	Parameter	Reference
Allen	Plankton	Bowman, J. (1998) River Shannon Lake Water Quality Monitoring 1995 to 1997. EPA Ireland.
		Champ, W.S.T. (1988) Lough **Allen** water quality assessment. Central Fisheries Board, Dublin
		Environmental Impact Statement for retention of existing salmon smolt farm on Lough **Allen**, Co. Leitrim. Hibernor Atlantic Salmon Ltd
Bunny		Ragneborn-Tough, L., Pybus, M.J. and Pybus, C. (1999) A hydrographic study of Lough **Bunny**, Co. Clare. Biology and Environment 99B(3): 191-196.
Caragh		Heuff, H. and Horkan, K. (1984) **Caragh**. In Whitton BA Ecology of European rivers. Blackwell Scientific 363-384
Corrib		Annomymous (1986) Corrib Catchment. Water Quality Management Plan
	Fish	Annomymous (1996) A fish stock report for Loughs **Corrib**, Mask and Carra and future management options. Central Fisheries Board, Dublin.
	Diatoms	Barbiero, R.P. (2000). A multi-lake comparison of epilithic diatom communities on natural and artificial substrates. Hydrobiologia 438:157-170.
	Fish	Brown, J. (1989) Salmon research in the **Corrib** catchment , western Ireland. In Proceedings of the Institute of Fisheries Management 20th Annual Study Course (Eds T. Cross and B. Ottway) Regional Technical College Galway 12-14th September pp. 166-178.
	Fish	Conneely, J.J. and McCarthy, T.K. (1984) The metazoan parasites of freshwater fishes in the **Corrib** catchment areaIreland. J. Fish Biology 24: 363-375.
	Macroinvert	Connolly, B. and McCarthy, T.K. (1993) Mayflies (Ephemeropterna) of the **Corrib** catchment, Ireland. In Costello, MJ and Kelly KS (eds) Biogeography of Ireland past present and future. Occasional Publication of the Irish Biogeographical Society No 2 57-71

	Crustacea	Creighton, R.H. (1893) Crustacea from Upper Lough Erne and Lough **Corrib**. Ir. Nat. 2: 24.
	Cladocera	Fitzmaurice, P. (1965) Studies of the Planktonic Cladocera in Lough **Corrib** and in the Carna district with particular reference to qualitative and quantitative seasonal frequency of the cladoceran fauna in Lough Corrib. Unpublished M.Sc. thesis, National University of Ireland
	Fish	Igoe, F., Byrne, C., O'Grady, M.F., Gargan, P., O'Neill, J., Roche, W. and Molloy, S. (1998) The current status of arctic char (Slavelinus alpinus L.) in the Lough Corrib catchment. Verhandlungen Internationale Vereinigung fiir Theoretische und Angewandte limnologie Abstract Volume p. 267
	Macrophyte	King, J.J. and Champ, W.S.T. (1977). Macrophytes of L. **Corrib** and L. Carra. An interim report. Dublin. Central Fisheries Board.
	Macrophyte	Krause, W. and King, J.J. (1994). The ecological status of Lough **Corrib**, Ireland, as indicated by physiographic factors, water chemistry and macrophyte flora. Vegetatio 110: 149-161.
	Plankton	Mooney, E.P. and O'Connell, M. (1990). The phytosociology and ecology of the aquatic and wetland communities of the lower **Corrib** basin, County Galway. Proc. R. Ir. Acad. Vol 90B(5): 58-97
	Plankton	Mooney, E.P. (1989) A study of Lough **Corrib,** western Ireland and its phytoplankton. Hydrobiologia 175: 195-219.
	Macrophyte	Scully, C.A. (1989) Ecological studies of the aquatic species, Eriocaulon aquaticum (Hill) druce and Lobelia dortmanna L. M.Sc., National University of Ireland, Galway, 42-8943
	Fish	Went, A.E.J. (1979) 'Ferox' trout Salmo trutta L. of Loughs Mask and **Corrib.** Journal of Fish Biology 15: 255-262
Currane		Whelan, K.F. and Roche, W. (1986) Preliminary survey of the Lough **Currane** catchement and recommendations for the overall development of the fishery. Internal Management Report. Central Fisheries Board, 90 pp.
Dan		Igoe, F. and Kelly-Quinn, M. (2002) Arctic char Salvelinus alpinus L. of Lough **Dan**: extinct? Ir. Nat. J. Vol. 27 (1) 2—9.

	Chironomid	Nolan, Y. (1997) Aspects of the Palaeolimnology of Lough **Dan**, Co. Wicklow. Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin.
		O'Connor, J.P. and Bracken, J.B. (1980) A comparative limnological study of two Irish lakes (Lough Sillan, Co.Cavan and Lough **Dan**, Co. Wicklow). Irish Fisheries Investigations Series A No, 17 24pp.
		O'Connor, J.P. (1975) Freshwater Studies; Part I – A limnological survey of Lough **Dan** and Sillan; Part II – An investigation of the Trichopterous Fauna and its distribution in various habitats in Ireland. University College Dublin 343 pp.
Doo (Ky)	Chironomid	Redmond, T. (1974) The post glacial developmental history of **Doo** Lough, Muckross Peninsula, Killarney, Co. Kerry. Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin.
Doo (Mo)		O'Connell, M., Mitchell, F., Readman, P., Doherty, T. and Murray, D.A. (1987) Palaeoecological investigations towards the reconstruction of the post-glacial environment at Lough **Doo**, County Mayo, Ireland. Journal of Quarternary Science, 2, 149-164.
Feeagh	Fish	Byrne, C.J. (2000) The parasite community structure of stocked and wild brown trout (Salmo trutta L.). Ph.D., Trinity College Dublin (Univ. of Dublin)
		Matthews, M.A., Poole, W.R., Dillane, M.G. and Whelan, K.F. (1997). Juvenile recruitment and smolt output of brown trout (Salmo trutta L.) and Atlantic salmon (Salmo salar L.) from a lacustarine system in western Ireland. Fisheries Research 31: 19-37.
	Fish	Molloy, S., Holland, C. and Poole, R. (1995) Metazoan parasite community structure in brown trout from two lakes in western Ireland. Journal of Helminthology 69: 237-242.
		Partridge, J.K. and Foy, R.M. (1972) Report on the hydrography of Lough **Feeagh**, and its benthic, planktonic and littoral organisms. Rep. Salm. Res. Trust Ireland No. XVI. Appendix 1.

		Poole, W.R., Whelan, K.F., Dillane, M.G., Cooke, D.J. and Matthews, M.A. (1996) The performance of sea trout , Salmo trutta L., stocks from the Burrishole system, western Ireland 1970-1994. Fish Magmt. Ecol., 3: 3 73-92.
		Stewart, M. (1972) A preliminary survey of the plankton of Lough **Feeagh**. In annual report of Salmon Research Trust, Ireland: 39-42.
Guitane		Avison, M. (1982) The geology of the Lough **Guitane** volcanic complex and associated sediments, County Kerry, Ireland. Ph.D. thesis, Keele Germany
Lene	Fish	Tierney, P. (1995). The cycling of Polymorphus minutus (Goeze 1782), through it's intermediate and definitive hosts in Ireland, with notes on some other parasite species. Ph.D., Trinity College Dublin (Univ. of Dublin)
Mask	Fish	Annomymous (1996) A fish stock report for Loughs Corrib, **Mask** and Carra and future management options. Central Fisheries Board, Dublin.
		Bowyer, P.A. (1998) Preliminary study of the circulation in Lough Mask. Verhandlungen Internationale Vereinigung fiir Theoretische und Angewandte limnologie Abstract Volume p. 293.
		Coyle, J. (1991). Report on water quality of Lough Carra and Lough **Mask**. Carra-Mask Angling Federation.
	Fish	Doherty, D. (1999). Studies on the parasite assemblages and general biology of some rare and endangered Irish fishes. Ph.D., University College, Galway.
		Donnelly, K. (2001). The response of Lough Conn and Lough **Mask**, two Irish western lakes, to total phosphorus loading, 1995-1999. Ph.D., University College, Dublin.
	Macrophyte	King, J.J. (1996) Macrophytes of L. **Mask**, L.Conn and L. Cullin. July-August 1995). An interim report. EPA commissioned report, Central Fisheries Board, Dublin 14 pp.
		Magrane, B. (1998). The biology (age, growth, diet and fecundity) of pike (Esox lucius, L.) in Lough **Mask**, an Irish limestone lake. M.Sc., University College, Dublin, 48-6399

		McGarrigle, M.L., Hallissey, R., Donnelly, K. and Kilmartin, L. (1998) Phosphorous loadings to Lough Conn and Lough **Mask**, Co. Mayo, Ireland. Verhandlungen Internationale Vereinigung fiir Theoretische und Angewandte limnologie Abstract Volume p. 110.
		McGarrigle, M.L. and Champ, W.S.T. (1999). Keeping pristine lakes clean: Loughs Conn and **Mask**. Hydrobiologia 395/396: 455-69
	Plankton	Monaghan, F. (1993) Phytoplankton in Lough **Mask**. Carra-Mask Angling Federation.
	Sediment	O'Connor, B. (1998). A report on sediment profile imagery surveys of Loughs Conn, Cullin and **Mask.** Aqual-Fact International Services LtD Galway.
		Santillo, D. and Pocock, I. (1994). Water quality status of the Carra-**Mask** system, Co. Mayo Ireland. Greenpeace Ireland, Technical note 02/94.
	Fish	Went, A.E.J. (1979) 'Ferox' trout Salmo trutta L. of Loughs **Mask** and Corrib. Journal of Fish Biology 15: 255-262
Maumwee		Bowman, J.J. (1991) A limnological study of Lough **Maumwee** and Glendalough Lake. Ph.D., University College, Dublin.
	Plankton	Coyle, S.M. (1991) A study of the zooplankton of four Irish lakes of varying acidity: Glendalough Lake Upper, Lough **Maumwee**, Lough Naminna and Doo Lough. M.Sc., University College, Dublin.
	Plankton	Coyle, S. and Murray, D.A. (1991) A study of the zooplankton of four Irish lakes, Glendalough (upper), L.Naminna, L. **Maumwee** and Doo Lough in the period 1987-1989. In Acid Sensitive Surface Waters in Ireland (ed. J. Bowman). Environment Research Unit Dublin, pp. 273-319.
	Cladocera	De Eyto, E. (2000). The ecology of the family Chydoridae (Branchiopoda, Anomopoda) and its application to lake monitoring. Ph.D., Trinity College Dublin (Univ. of Dublin)
	Diatoms, Geochem., Lithology, Dating	Flower, R.J., Rippey, B., Rose, N.L., Appleby, P.G. and Battarbee, R.W. (1994). Palaeolimnological evidence for the acidification and contamination of lakes by atmospheric pollution in western Ireland. Journal of Ecology 82: 581-596.

	SCP	Rose, N.L., Harlock, S., Appleby, P.G. and Battarbee, R.W. (1995). Dating of recent lake sediments in the United Kingdom and Ireland using spheroidal carbonaceous particle (SCP) concentration profiles. The Holocene, 5.3: 328-335.
Melvin		Anderson, N. J., Patrick, S.T. and Appleby, P.G. (1996). Palaeolimnological surveys of Lough Erne and Lough **Melvin.** Final Report to the Department of Environment (NI) with Funding by the INTEREG Programme.
	Fish	Cawdery, S.A.H. (1989) Morphological and biochemical population differentiation in salmonid fishes Ph.D., Queen's University Belfast.
	Fish	Ferguson, A. and Mason, F.M. (1981) Allozyme evidence for reproductively isolated sympatric populations of brown trout Salmo trutta L. in Lough **Melvin**, Ireland. Jorunal of Fish Biology 118: 629-642.
	Fish	Ferguson, A. and Taggart, J.B. (1991) Genetic differentiation among the sympatric brown trout (Salmo trutta) poputations of Lough **Melvin**, Irelnad. Biological Journal of the Linnean Society 43: 221-237.
	Fish	Ferguson, A. (1986) Lough **Melvin** – a unique fish community. Occasional Papers in Irish Science and Technology, Royal Dublin Society No. 1 17 pp.
	Fish	McVeigh, H.P. (1989) Mitochondrial DNA and salmonid population structure Ph.D., Queen's University Belfast, 39-6769
	Fish	McVeigh, H.P., Hynes, R.A. and Ferguson, A. (1995) Mitochondrial DNA differentiation of sympatric populations of brown trout Salmo trutta L. in Lough **Melvin**, Ireland. Canadian Journal of Fisheries and Aquatic Sciences 52 1617-1622.
Maumeen		Huang, C.C. (1994). Multi-disciplinary studies of lake sediments towards the reconstruction of late-glacial and late-glacial and holocene environments in western Ireland. Ph.D., University College, Galway.
Naminna	Plankton	Coyle, S.M. (1991) A study of the zooplankton of four Irish lakes of varying acidity: Glendalough Lake Upper, Lough Maumwee, Lough **Naminna** and Doo Lough. M.Sc., University College, Dublin.
	Plankton	Coyle, S. and Murray, D.A. (1991) A study of the zooplankton of four Irish lakes, Glendalough (upper), L.**Naminna,** L. Maumwee and Doo Lough in the period 1987-1989. In Acid Sensitive Surface Waters in Ireland (ed. J.

		Bowman). Environment Research Unit Dublin, pp. 273-319..
Owel		Forde, G.P. (1985). A comparative study of Loughs Ennell and **Owel**, Co. Westmeath with special reference to macroinvertebrate populations. Ph.D. Theses, University College Dublin,
		French, R. J. (1991) A study of heavy metal concentrations in sediments, fish and selected fauna from Loughs Sheelin and **Owel** in relation to intensive pig-farming in the Lough Sheelin catchment. M.Sc. thesis, University College Dublin.
	Chironomid	McGarrigle, M.L. (1975) The post glacial development of Loughs Ennell and **Owel** as inferred from chironomid sub-fossil remains. Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin
		Murray, D.A. and Douglas, D.J. (1997). Eutrophication; past, present and future?. In Lake pollution eutrophication control (eds. WK Downey and G. Ni Uid). National Science Council Proceedings, pp 86-95
	Fish	Quigley, D.T.G. and Flannery, K. (1997) Arctic char Salvelinus alpinus L.: First record from L. Anascaul, Co. Kerry; further records from Loughs Buanveela, Kindrum and Coomasaharn; and notice of an introduction to Lough **Owel.,** Co. Westmeath. Ir. Nat. Journal 26 (11/12): 435-439.
	Cladocera	Redmond, T.K. (1977) A palaeolimnological study of cladoceran microfossils in sedimentary cores from two Irish lakes, Lough Ennell and Lough **Owel**, Co. Westmeath. Unpublished M.Sc. thesis, University College Dublin.
		Smyth, T. (1996). An investigation of freshwater Bryozoa (Class Phylactolaemata) in the canal outlet of Lough **Owel**, Co. Westmeath, Ireland. M.Sc., Trinity College Dublin (Univ. of Dublin), 46-10462
Tay		Cox, B. (1984) A Palaeolimnological study of Lough **Tay**, Co. Wicklow. Unpublished B.Sc. Honours thesis, Department of Zoology, University College, Dublin
Upper	Chironomid	Douglas, D.J. (1975) The Chironomid fauna of the Killarney Valley, Co. Kerry, its distribution, ecology and post-glacial developmental history. Unpublished Ph.D. Thesis, University College Dublin.

	Chironomid	Douglas, D.J. and Murray, D.A. (1980) A checklist of Chironomidae of the Killarney Valley catchment area Ireland. In Murrray DA (ed) Chironomidae – ecology, systematics, cytology and physiology. Pergamon press Oxford pp 123-129.
	Macro-inverts	Wise, E.J. and O'Connor, J.P. (1997) Observation on the distribution and relative abundance of the Ephemeroptera and Plecoptera in the Killarney valley, Co. Kerry Ireland. In Ephemeroptera and Plecoptera : Biology-Ecology-Systematics (eds P Landolt and M Sartoid pp. 75-79. Fritbourg-1997.
Veagh	Diatoms, Geochem., Dating	Cox, B.C. and Murray, D.A. (1991). A palaeolimnological study of the Upper Lake, Glendalough, Co. Wicklow and Lough **Veagh,** Co. Donegal. In Acid Sensitive Surface Waters in Ireland (ed. J. Bowman). Environment Research Unit Dublin, pp. 273-319.
	Cladocera	Coyle, S. and Murray, D.A. (1989) Studies on the cladoceran fauna and recent history of Lough **Veagh**, Co, Donegal. Report to the National Parks Section, Office of Public Works.
	Diatoms	Flower, R.J., Rippey, B., Rose, N.L., Appleby, P.G. and Battarbee, R.W. (1994). Palaeolimnological evidence for the acidification and contamination of lakes by atmospheric pollution in western Ireland. Journal of Ecology 82: 581-596.
	Chironomid	Heneghan, L (1986) The Chironomidae of Glen**veagh** National Park Co. Donegal: an annotated inventory. Unpublished M.Sc.theses, University College, Dublin.
	Crustacea	Lynch, J.M. (1994) Two new lotic locations for Crangonys pseudogracilis Bousfield, 1958 (Crustacea: Amphipoda). Irish Naturalist Journal 24: 462-463.
	Macroinvert	Lynch, J.M., Byrne, C.F. and Bowman, J.J. (1995) Ameletus inopinatus Eaton and other Ephemeroptern from Glen**veagh** National Park, Co. Donegal, Ireland. Bulletin of the Irish Biogeographical Society 18: 30-36.
	Cladocera	Murray, D.A. and Coyle, S. Studies on the Cladocera of Lough **Veagh**, Glenveagh National Park, Co. Donegal. Department of Zoology, University College Dublin. Unpublished Report

	SCP	Rose, N.L., Harlock, S., Appleby, P.G. and Battarbee, R.W. (1995). Dating of recent lake sediements in the United Kingdom and Ireland using spheroidal carbonaceous particle (SCP) concentration profiles. The Holocene, 5.3: 328-335.

Appendix 3 Multiple lake studies that include references to CRLs (to 2003)

Reference	Detail	CRL Lakes Examined
Brook, A.J. (1958). Desmids from the plankton of some Irish Loughs. Proc. RIA Vol 59 (B) 71-91	Plankton	Melvin, Corrib, Beltra, Kylemore, Oorid
Caffrey, J.M., O'Boyle, E. and O'Mongain, E. (1999) Contributions to the limnology of Ireland: selected lakes in Cos Donegal, Sligo, Mayo, Galway, Kerry and Wicklow. Ir. Nat. J. Vol. 26 (5/6): 149-164.	Chemistry	Arderry, Barfinnihy, Caragh, Cloonaglin, Coomsaharan, Cloon, Dan, Fee, Fin, Kylemore, Glencar, Golagh, Guitane, Maumwee, Maumween, Melvin, Muckross, Nakirka, Oorid, Shindilla, Tay, Upper
Caroni, R. (2000). Freshwater zooplankton and pH; A study of natural patterns and experimental response. Ph.D., Trinity College Dublin (Univ. of Dublin).	Zooplankton	Bunny, Cullaun, Dan, Easky, Feeagh, Lene, Maumwee, Talt
Champ, W.S.T. (1997). Trophic Status of Fishery Lakes. In Lake pollution eutrophication control (eds. WK Downey and G. Ni Uid). National Science Council Proceedings, pp. 65-78.		Allen, Arderry, Corrib, Mask, O'Flynn, Owel
Charlesworth, J.K. (1963) The bathymetry of the larger lakes of Ireland. Proc. R.I.A. 63B: 61-71		Corrib, Mask
Creed, K. (1999) Studies on the metazoan parasites of *Salmon trutta* (L.), *Anguilla anguilla* (L.) and Platichthys flesus (L.) in the west of Ireland with reference to Clare Ireland. Ph.D., University College, Galway		Mask, Corrib
De Eyto, E. (2000). The ecology of the family Chydoridae (Branchiopoda, Anomopoda) and	Cladocera	Bunny, Cullaun, Dan, Easky, Feeagh, Lene, Maumwee, Talt

its application to lake monitoring. Ph.D., Trinity College Dublin (Univ. of Dublin)		
Flanagan, P.J. and Toner, P.F. (1975). A preliminary survey of Irish Lakes. An Foras Forbartha, Dublin. 164 pp.	Topography, Chemistry, Plankton	Allen, Altan, Beltra, Caragh, Corrib, Easky, Feeagh, Gartan, Lene, Mask, O'Flynn, Owel, Rea, Salt, Veagh
Foged, N. (1977). Freshwater diatoms in Ireland. Biblio. Phycol. 34: 1-222.	Diatoms	Anure, Bunny, Caragh, Muckross
Free, G. (2002) The relationship between catchment characteristics and lake chemistry in the Republic of Ireland.	Chemistry	Bunny, Cullaun, Dan, Easky, Feeagh, Lene, Maumwee, Talt
Irvine, K. Clare Co. Council Internal Reports (unpublished)	Chemistry	Acrow, Bunny, Cullaun, Muckanagh, Naminna
Irvine, K., et. al. (2001). The Ecological Assessment of Irish Lakes: the development of a new methodology suited to the needs of the EU Directive for surface waters. Environmental Protection Agency, Wexford.	Ecology	Bunny, Caragh, Cullaun, Dan, Easky, Feeagh, Lene, Maumwee, Muckross, Owel, Rea, Talt
Keaney, J. (1997). Cladocera-Crustacea-pseudofossils as indicators of trophic status in some Irish lakes. Unpublished M.Sc thesis, Trinity College, University of Dublin.	Cladocera	Bunny, Cullaun, Dan, Feeagh, Lene, Maumwee, Owel, Rea, Talt
Kennelly, C. (1997) A regional limnology of Ireland. Unpublished M.Sc. thesis, Trinity College, Dublin.		Arderry Barfinnihy Barra Beltra Cloon Dunglow Dan Fin Guitane Gartan Inchquinn, Lene, Namanfin, Nambrackkeagh, Muckross, Oorid Owel,Tay, Upper, Veagh Waskel
Lucey, J., Bowman, J.J., Clabby, K.J., Cunnigham, P., Lehane, M., MacCarthaigh, M., McGarrigle, M.L. and Toner, P..F. (1999). Water Quality in Ireland 1995-1997. Environmental Protection Agency, Wexford.		Allen, Caragh, Corrib, Guitane, Lene, Mask, Maumwee, Melvin, Muckross, Owel

Macan, T.T. and Lund, J.W.G (1954) Records from some Irish Lakes. Proc. RIA Vol 56 (B) 135-157. [Part 1 Mollusca, Gammarus, Ascellus, Ephemeroptera and Heteroptera]	Macroinvert.	Allen, Dunglow, Gartan, Glencar, Melvin, Mourne, Talt, Veagh,
McCarthy, T.K. et al (2001) Investigation of eutrophication processes in the littoral zones of western Irish lakes. R and D Report No. 13 Environmental Protection Agency, Wexford.	Plankton, Fish Macrophyte, Macroinvert., Chironomid,	Corrib, Mask
McGarrigle, M.L. (1988). Calibration of a water quality remote sensing spectrometer. M.Sc., University College, Dublin, 40-3233		Arderry, Boliska, Doo, Fee, Glencullin, Kylemore, Maumeen, Oorid, Shindilla
McGarrigle, M.L. (1990). National Survey of Lakes by Remote Sensing. Environmental Research Unit, pp. 48.		Arderry, Boliska, Doo, Fee, Glencullin, Kylemore, Maumeen, Oorid, Shindilla
Moriarty, C. (1973) Distribution of freshwater macroinvertebrates in Ireland 1967-1972. Ir. Nat. J. 17:409-412.	Macroinvert.	Corrib, Mask
Murray, D.A. and O'Byrne-Ring, N. (1981) Lake sediments as indices of productivity: studies on Irish and Italian lakes. Irish Journal of Environmental Science, 1, (2), 35-40.	Chlorophyll pigments	Allen, Beltra, Caragh Corrib, O'Flynn, Easky, Feeagh
O'Riordan, C.E. (1971) The freshwater copepod work of GP Farran together with some other notes. Proc RIA 71 B 85-96.	Copepod	Caragh, Currane, Dan, Doo, Easky, Melvin, Rea, Shindilla,Talt
Pearsall, W.H. and Lind, E.A. (1942) The distribution of phytoplankton in some north-west Irish loughs. Proc. R. Ir. Acad. Vol 48B: 1-24.	Plankton	Cloonagat, Doo?, Fee, Kindrum, Kylemore,
Quigley, D.T.G. and Flannery, K. (1997) Arctic char *Salvelinus alpinus* L.: First record from L. Anascaul, Co. Kerry; further records from		Coomasaharn, Kindrum, Owel

Loughs Buanveela, Kindrum and Coomasaharn; and notice of an introduction to Lough Owel., Co. Westmeath. Ir. Nat. Journal 26 (11/12): 435-439.		
Round, F.E. and Brook A.J. (1959) The phytoplankton of some Irish loughs and an assessment of their trophic status. Proc. R. Ir. Acad. Vol 60 B(4): 167-191.	Plankton	Arderry, Beltra, Bunny, Corrib, Glencar, Kylemore, Melvin, Oorid, Rea, Talt,
Round, F.E. (1959) A comparative survey of the epipelic diatom flora of some Irish loughs. Proc. R. Ir. Acad. Vol 60 B(4): 193-215.	Diatoms	Cloonagat, Doo, Fee, Kylemore,
Went, A.J. (1945) The distribution of Irish char (*Salvelinus* spp) Proc. R. Ir. Acad. 50B: 167-189.	Fish	Currane, Coomasaharn, Corrib,Dan, Fad, Gartan, Glenawough, Keel, Kindrum, Kylemore, Mask; Melvin, Owel,Tay, Veagh
West, W. (1904) Freshwater algae of West Ireland. 127pp.		Arderry Upper Caragh Guitane Kylemore Shindilla Muckross Oorid
West, W. and West G.S. (1906) A comparative study of the plankton of some Irish lakes. Trans. R. Ir. Acad. 33B: 77-116(6 plates).	Plankton	Caragh, Corrib, Guitane, Keel, Maumeen,
White, J. (2000). Littoral macro-invertebrates in lakes: patterns of distribution and potential use in ecological assessment. Ph.D., Trinity College Dublin (Univ. of Dublin).	Macroinverts .	Bunny, Cullaun, Dan, Easky, Feeagh, Lene, Maumwee, Talt

Appendix 4 Bathymetric survey details for CRLs studied in WP2

Bathymetric surveys were conducted as part of the IN-SIGHT project for 26 lakes (table and figures below). Depth measurements are needed to locate the deepest waters in each lake for sediment core extraction. Additionally, mean lake depth measurements were necessary to confirm typology classification and provide more accurate estimations of lake volume. Bathymetric maps were available for the other 10 project lakes as follows:- Bathymetric maps were produced for loughs Easky, Kiltooris , Kindrum, Talt and Rea as part of a survey carried out by De Eyto (2000). Bathymetric data were available for Lough Bunny in Ragneborn-Tough *et al.* (1999), Lough Feeagh in Partridge and Foy (1972), Lough Naminna in Waemaere (2001) and Lough Veagh in Flower *et al.* (1994). It was not possible to collect detailed bathymetry data for Lough Dan at the time of coring, because of dangerously strong winds.

Methods

Field bathymetric surveys were carried out on 26 lakes between June-October 2003. Lakes depths were recorded from an inflatable boat using a portable depth sounder. The position of each sampling site was recorded using a portable GPS. The GPS had a positional accuracy of between 5 and 10m. An average of five depth measurements per lake hectare was achieved in the IN-SIGHT survey. In some instances full geographic coverage was not possible and this has resulted in incomplete bathymetry maps (Annaghmore, Dunglow, Kindrum, Upper McNean and Nahasaleam). Sufficient coverage was achieved however to highlight the deepest waters from which sediment cores were extracted from these lakes.

All GPS and depth data were inputted as point (x, y) data into ArcMap. Lake boundaries were extracted from the 1:50,000 O.S. Discovery Map series and digitised. Lake bathymetries were produced by carrying out a surface interpolation (Spline), within the Spatial Analyst extension of ArcMap, producing a raster coverage of the lake depth. The interpolations were then reclassified by grouping the cells into new classes of depth intervals, resulting in a graduated classification of the depth surface. The number of depth class interval varies between 4 and 8 and the strongest colour class represents the deepest waters.

References

De Eyto, E. (2000) *The ecology of the family Chydoridae (Branchiopoda, Anomopoda) and its application to lake monitoring*. Ph.D., Trinity College Dublin (Univ. of Dublin)

Flower, R.J., Rippey, B., Rose, N.L., Appleby, P.G., and Battarbee, R.W. (1994) Palaeolimnological evidence for the acidification and contamination of lakes by atmospheric pollution in western Ireland. *Journal of Ecology*, 82, 581-596.

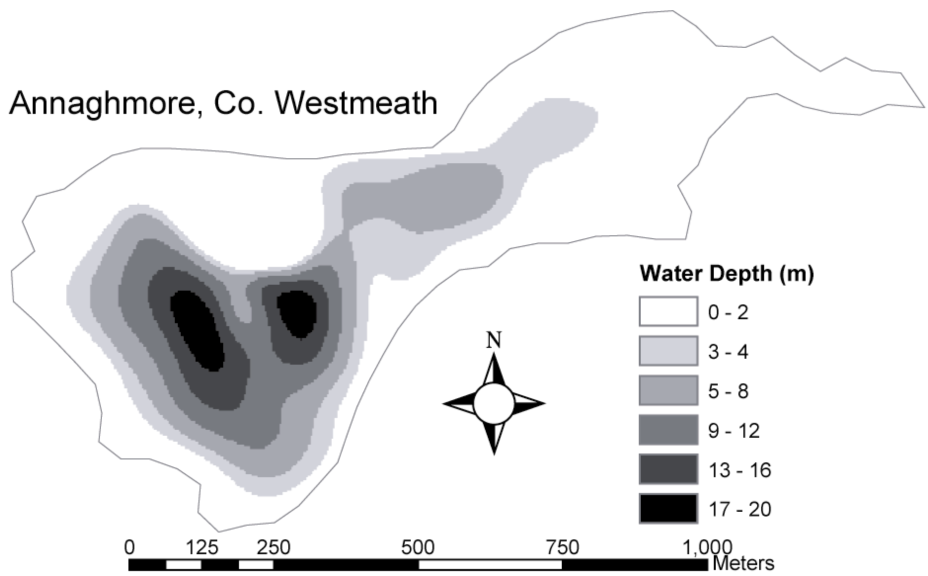
Partridge, J.K. and Foy, R.M. (1972) *Report on the hydrography of Lough Feeagh, and its benthic, planktonic and littoral organisms*. Rep. Salm. Res. Trust Ireland No. XVI.

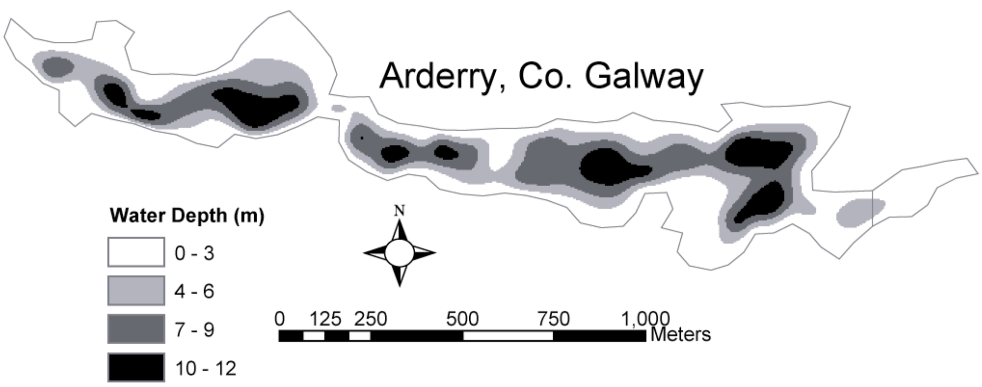
Ragneborn-Tough, L., Pybus, M.J. and Pybus, *c.* (1999) A hydrographic study of Lough Bunny, Co. Clare. *Biology and Environment*, 99B (3): 191-196.

Wemaere, A. (2001) *Lakes of County Clare – Monitoring Report 2000-20001* EPA, Ireland

IN-SIGHT bathymetry data for 26 lakes.

EPA Lake Code	Lake name	Number of *IN-SIGHT* bathymmetry spot measurements	*IN-SIGHT* Mean depth (m)	*IN-SIGHT* Max. depth (m)	EPA Max. depth (m)	EPA est. Mean depth (m)	Area (ha)	Approx. lake volume (m^3)
26-0155a-1060-000	Annaghmore	33	5.8	16.0	5.7	<4	53	308
38-00022-0060-000	Arderry	65	5.7	11.7	11.6	>4	81	462
31-000r4-1120-000	Ballynakill	43	6.7	19.0	16.4	>3*	24	160
31-000r4-2040-000	Bane	27	10.9	16.5	16.9	>4	75	822
07-00159-0930-000	Barfinnihy	28	9.8	18.0	16.7	>4	14	134
21-00216-0020-000	Barra	25	4.4	12.0	6.0	>4	63	275
38-00048-0490-000	Bunny			13.0	11.6	<4	103	
27-00158-1760-000	Cloonaghlin	58	12.0	27.0	29.4	>4	128	1533
21-00213-0090-000	Cullaun	38	13.4	25.0	20.1	>4	50	666
27-00158-1190-000	Dan			32.0	33.5	>4	103	
39-00008-0010-000	Doo	23	5.3	16.5	6.8	>4	9	48
38-00016-0070-000	Dunglow	29	5.5	8.0	6.1	<4	61	337
35-00114-0150-000	Easky			10.5	11.0	>4	119	
40-0000c-0020-000	Fad (East)	43	5.6	13.5	13.6	>4	12	69
32-00132-0020-000	Fee	90	15.5	32.0	31.5	>4	174	2692
32-00130-0010-000	Feeagh			41.0	43.0	>4	395	
39-00031-0270-000	Keel (Rosses)	23	5.2	10.0	10.5	>4	11	59
32-00130-0050-000	Kiltooris			14.5	13.5	<4	43	
38-00022-0080-000	Kindrum		6.6	12.5	11.0	>4	61	401
38-u6_38-0110-000	Kylemore	73	11.7	30.0	25.1	>4	132	1546
32-00133-0050-000	Lene			18.5	19.7	>4	416	
07-00159-1150-000	McNean (upper)	49	6.7	14.5	16.9	>3*	978	6551
30-00143-1580-000	Muckanagh	44	7.0	19.0	17.8	>4	96	673
31-t4_31-0010-000	Nahasleam	31	2.1	5.6	1.4	<4	28	59
30-00143-1460-000	Nambrackkeagh	38	4.1	8.5	8.8	>3*	7	28
36-00123-1070-000	Naminn	35	3.9	11.0	7.8	>3*	15	59
31-000r4-0720-000	Naminna			14.0	8.4	<4	20	
28-00152-0060-000	O'Flynn	46	2.8	14.5	3.4	>3*	137	385
29-00145-0180-000	Oorid	62	5.5	14.0	12.0	>4	61	333
38-00027-0110-000	Rea	27	14.5	23.0	20.9	>4	301	4366
31-000r4-0950-000	Shindilla	60	8.1	22.0	23.0	>4	70	569
34-00110-0630-000	Talt			40.0	23.0	>4	97	
10-00171-0090-000	Tay	34	17.1	35.0	32.8	>4	50	855
22-00207-0260-000	Upper	112	14.5	36.0	36.1	>4	170	2463
38-00027-0210-000	Veagh			49.0	28.0	>4	261	


Annaghmore, Co. Westmeath
Water Depth (m)
0 - 2
3 - 4
5 - 8
9 - 12
13 - 16
17 - 20
N
0
125
250
500
750
1,000
Meters


Arderry, Co. Galway
Water Depth (m)
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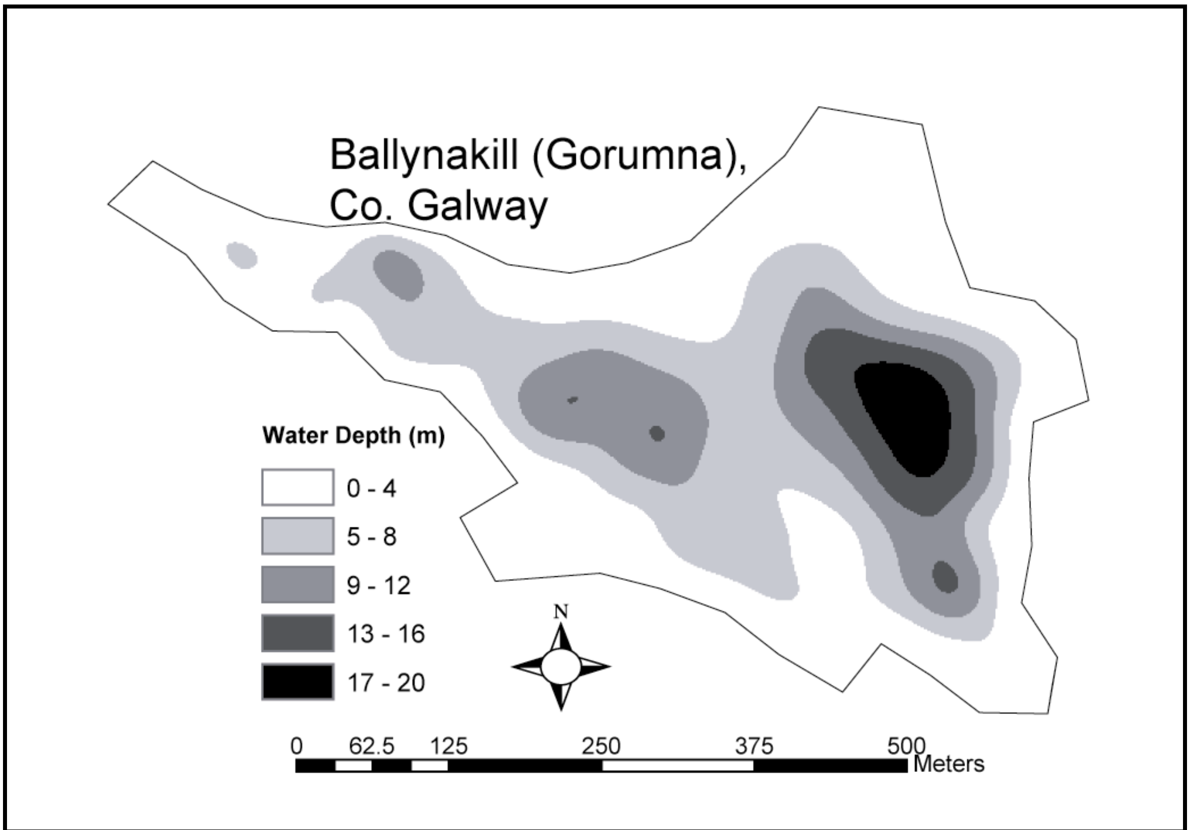
4 - 6
7 - 9
10 - 12
N
0
125
250
500
750
1,000
Meters


Ballynakill (Gorumna), Co. Galway
Water Depth (m)
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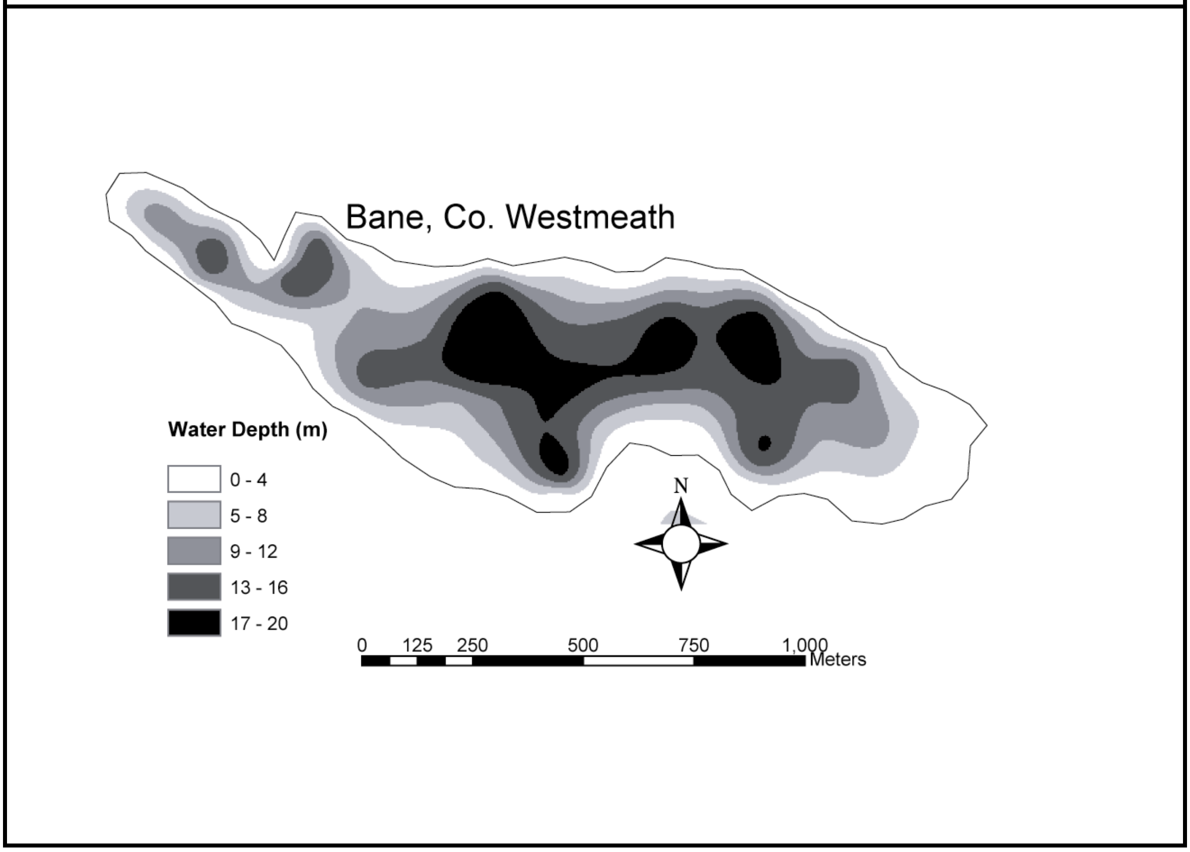
5 - 8
9 - 12
13 - 16
17 - 20
N
0
62.5
125
250
375
500
Meters


Bane, Co. Westmeath
Water Depth (m)
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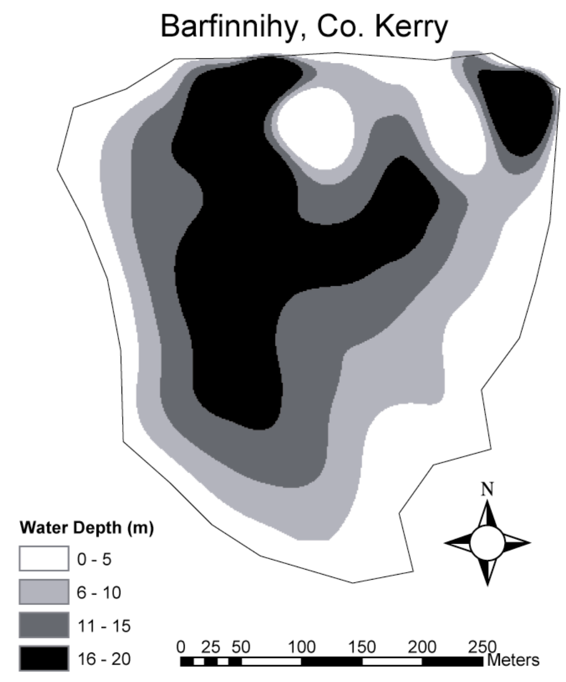
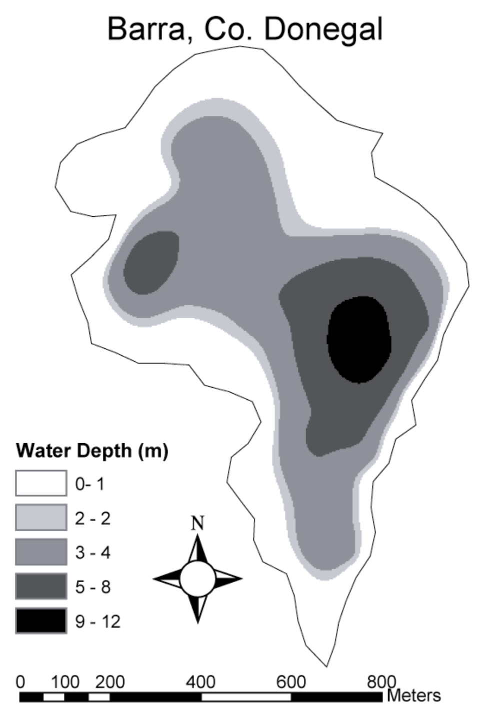
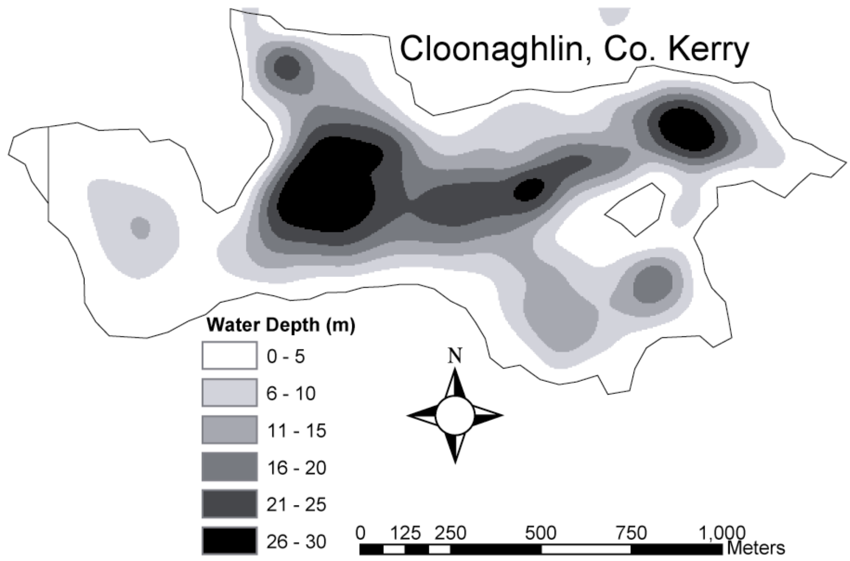
5 - 8
9 - 12
13 - 16
17 - 20
N
0
125
250
500
750
1,000
Meters

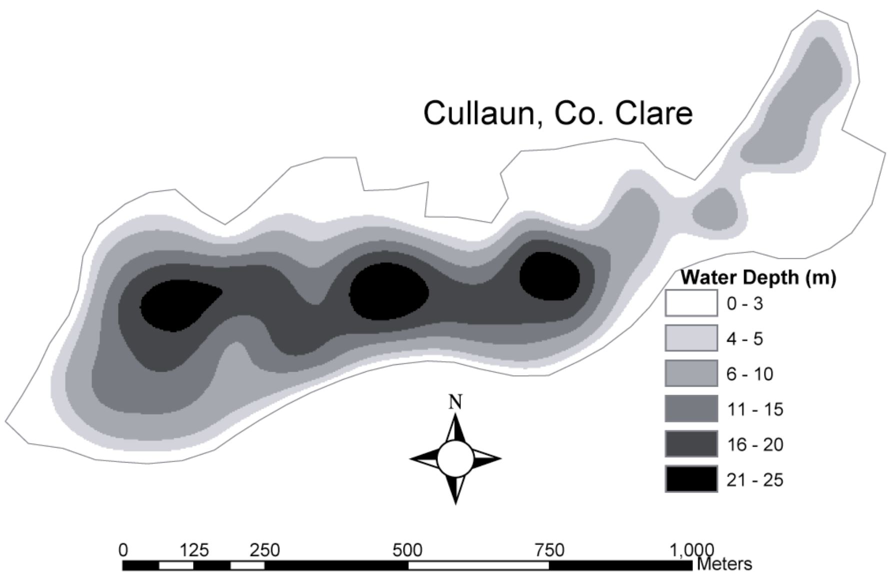


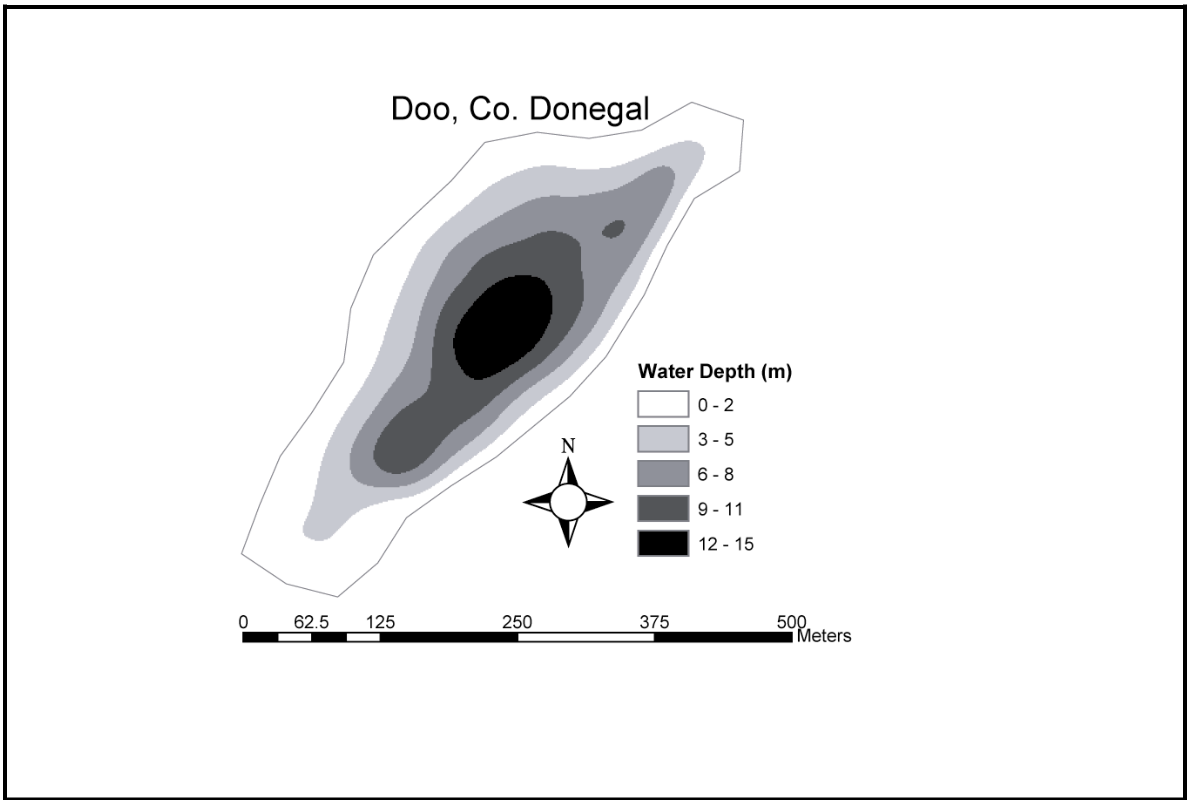
Barfinnihy, Co. Kerry
Water Depth (m)
0 - 5
6 - 10
11 - 15
16 - 20
N
0 25 50 100 150 200 250
Meters

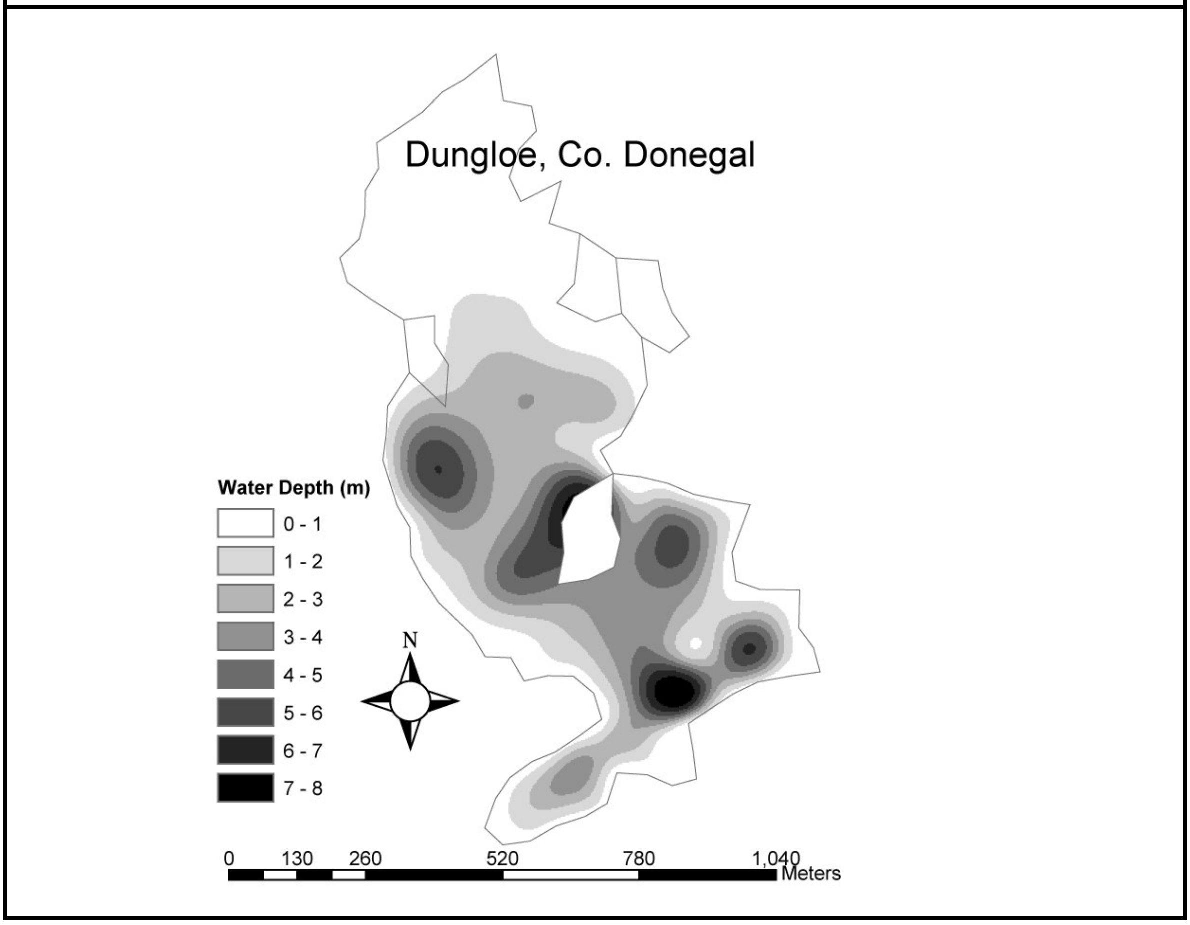


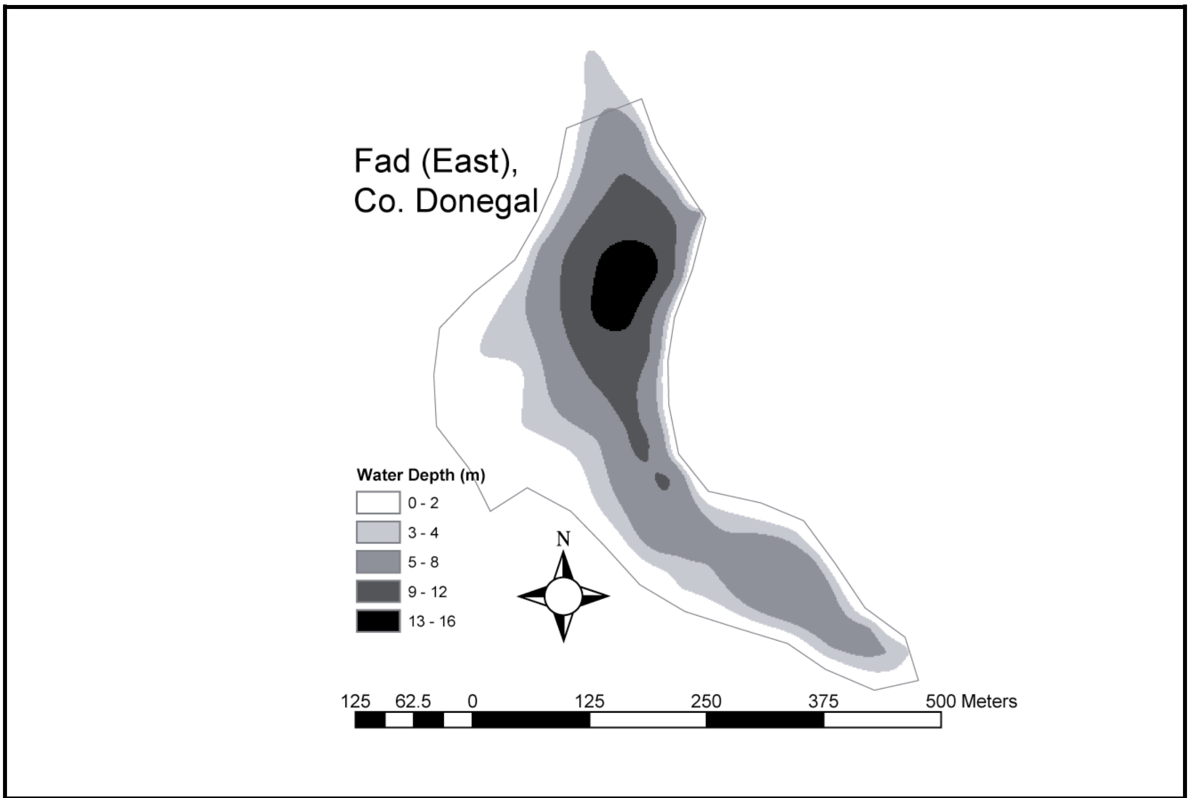
Barra, Co. Donegal
Water Depth (m)
0- 1
2 - 2
3 - 4
5 - 8
9 - 12
N
0 100 200 400 600 800
Meters

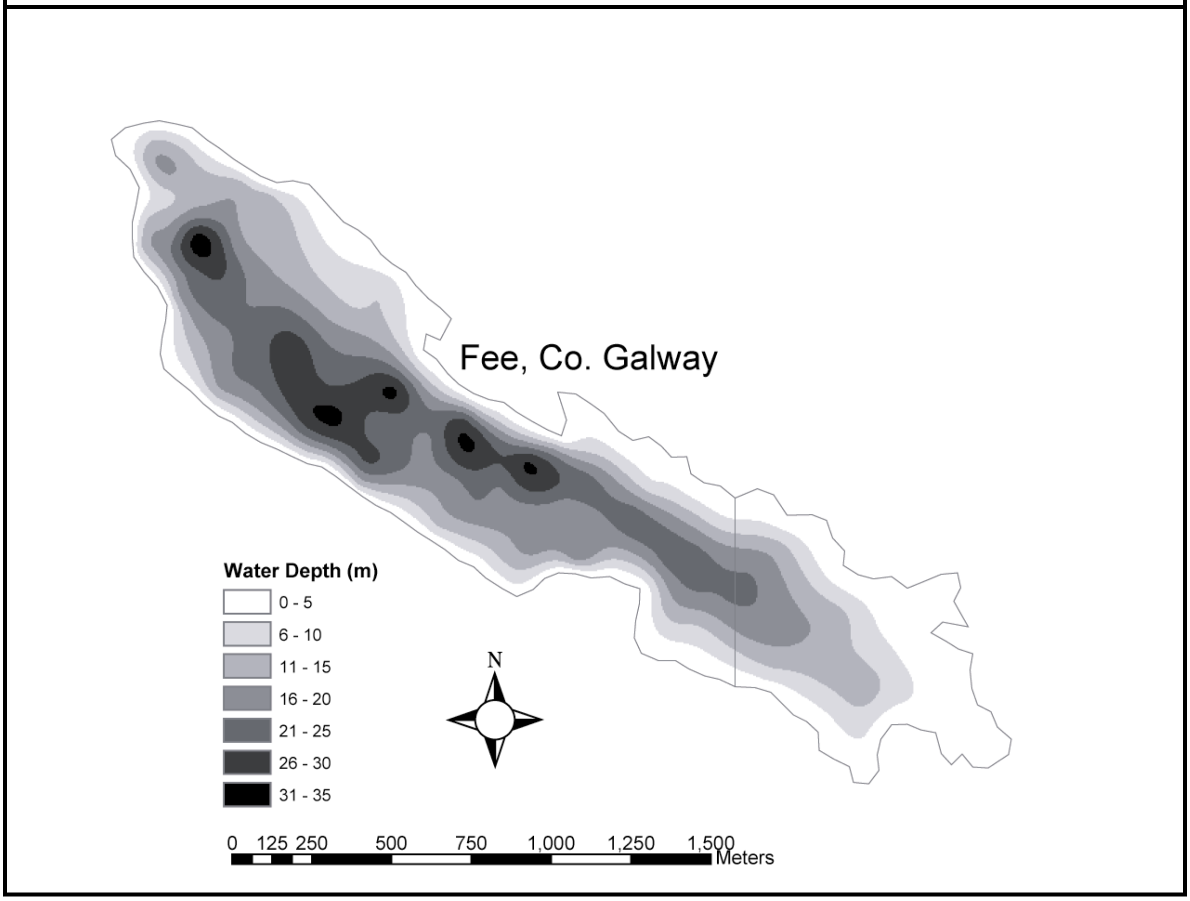

Cloonaghlin, Co. Kerry
Water Depth (m)
0 - 5
6 - 10
11 - 15
16 - 20
21 - 25
26 - 30
N
0 125 250 500 750 1,000
Meters

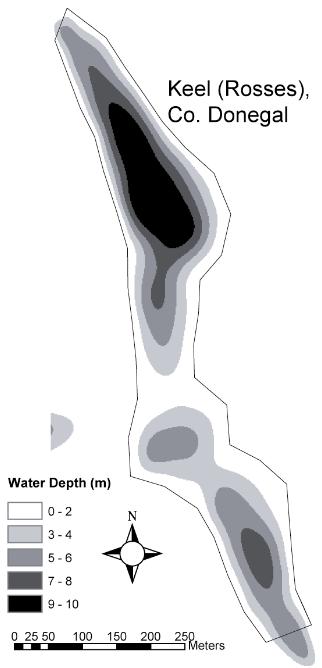

Cullaun, Co. Clare
Water Depth (m)
0 - 3
4 - 5
6 - 10
11 - 15
16 - 20
21 - 25
N
0 125 250 500 750 1,000
Meters

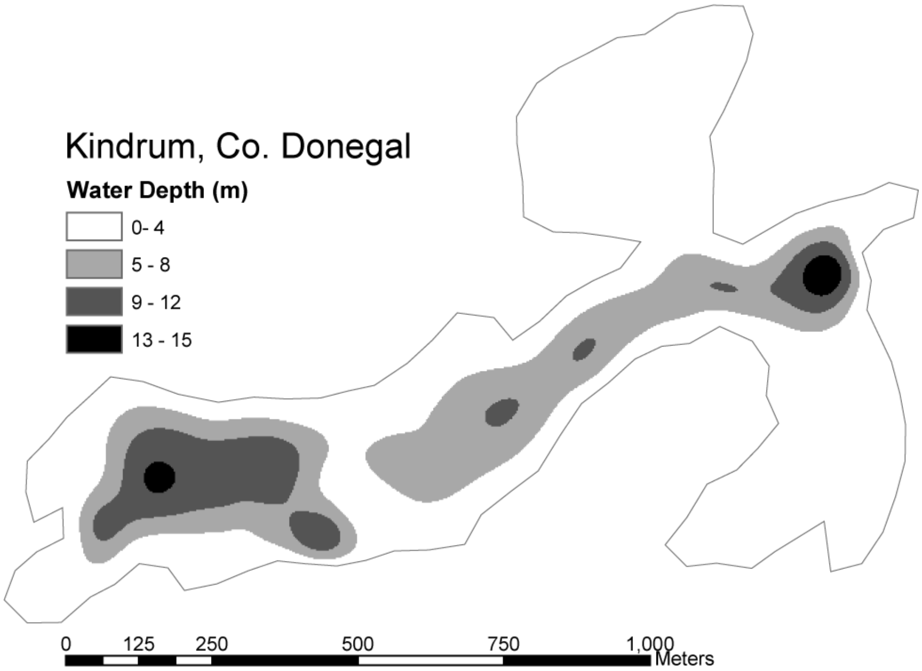

Doo, Co. Donegal
Water Depth (m)
0 - 2
3 - 5
6 - 8
9 - 11
12 - 15
N
0
62.5
125
250
375
500
Meters

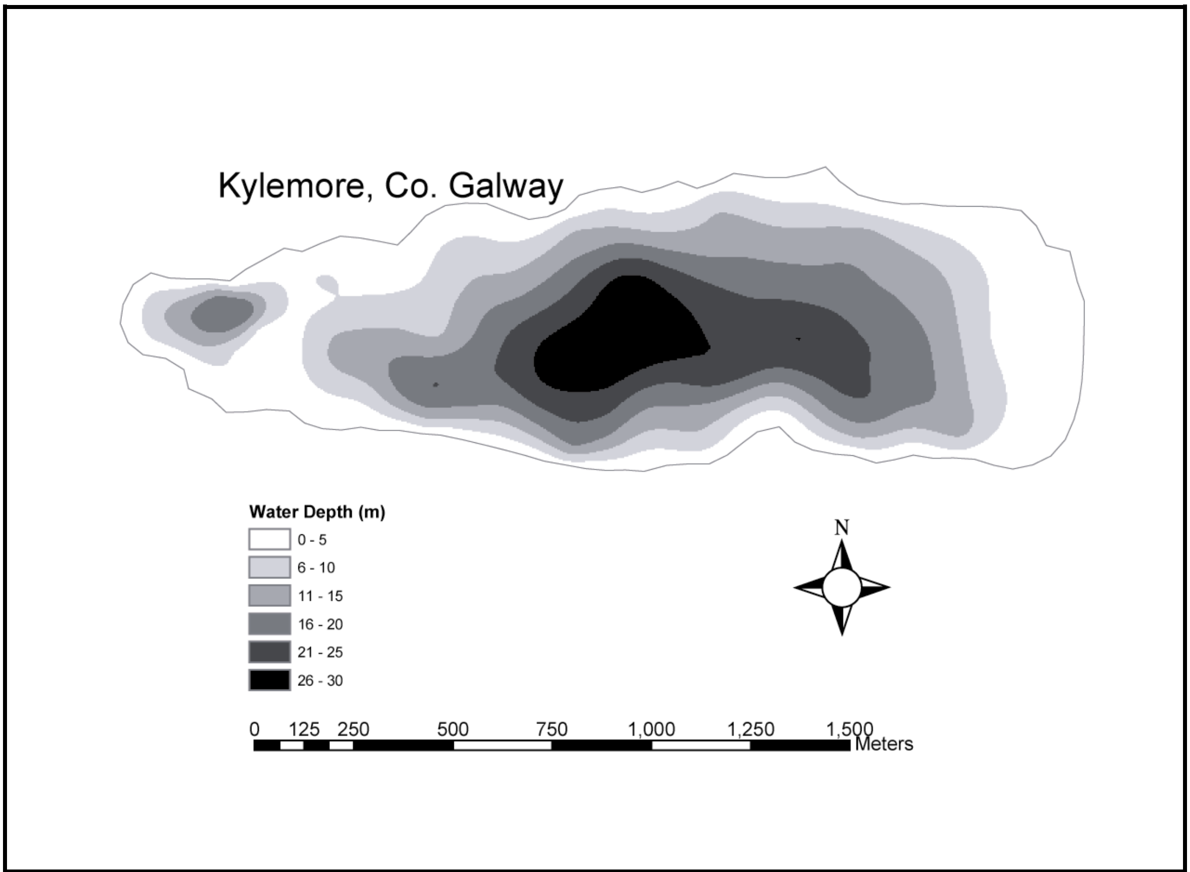

Dungloe, Co. Donegal
Water Depth (m)
0 - 1
1 - 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
N
0
130
260
520
780
1,040
Meters

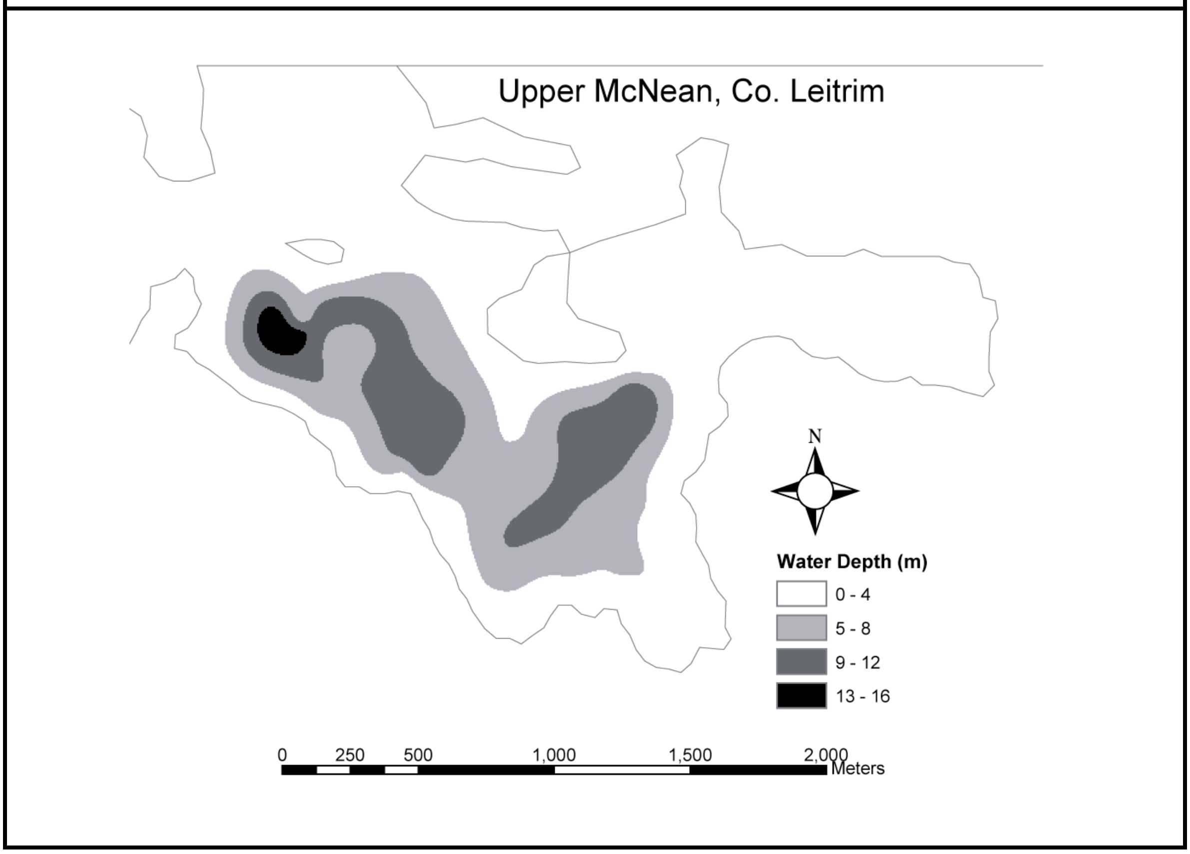

Fad (East),
Co. Donegal
Water Depth (m)
0 - 2
3 - 4
5 - 8
9 - 12
13 - 16
N
125
62.5
0
125
250
375
500 Meters

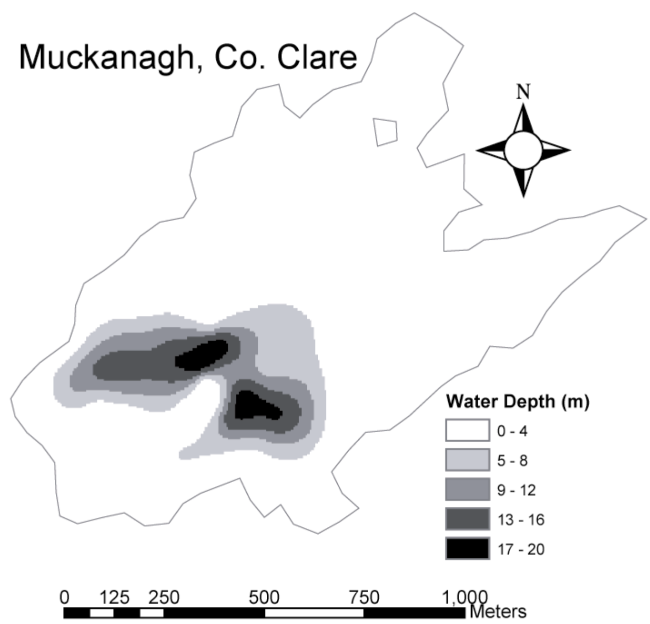

Fee, Co. Galway
Water Depth (m)
0 - 5
6 - 10
11 - 15
16 - 20
21 - 25
26 - 30
31 - 35
N
0
125
250
500
750
1,000
1,250
1,500
Meters

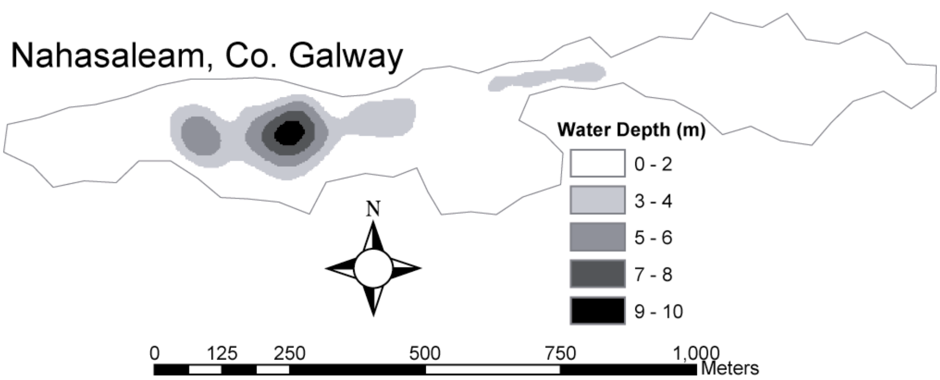

Keel (Rosses),
Co. Donegal
Water Depth (m)
0 - 2
3 - 4
5 - 6
7 - 8
9 - 10
N
0 25 50 100 150 200 250
Meters

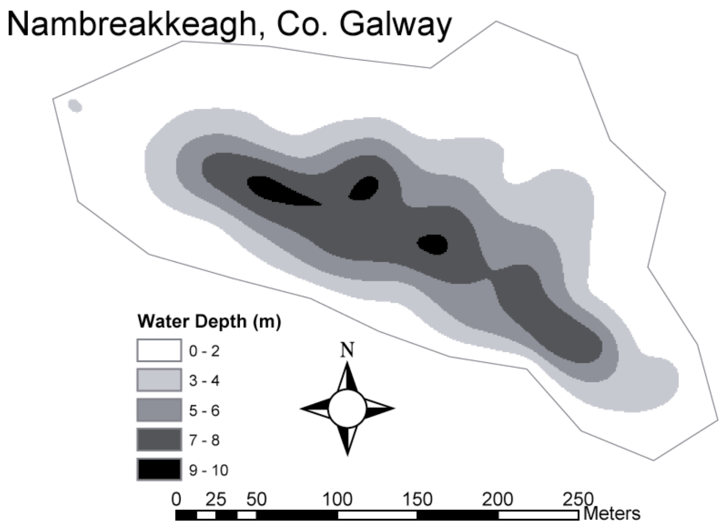

Kindrum, Co. Donegal
Water Depth (m)
0- 4
5 - 8
9 - 12
13 - 15
0 125 250 500 750 1,000
Meters


Kylemore, Co. Galway
Water Depth (m)
0 - 5
6 - 10
11 - 15
16 - 20
21 - 25
26 - 30
N
0
125
250
500
750
1,000
1,250
1,500
Meters

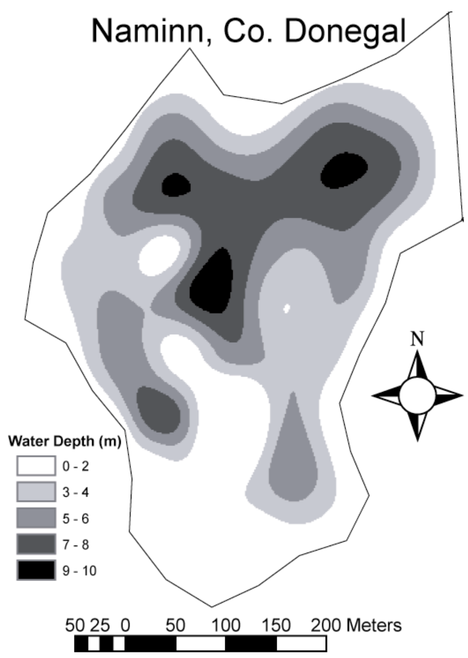

Upper McNean, Co. Leitrim
N
Water Depth (m)
0 - 4
5 - 8
9 - 12
13 - 16
0
250
500
1,000
1,500
2,000
Meters


Muckanagh, Co. Clare
N
Water Depth (m)
0 - 4
5 - 8
9 - 12
13 - 16
17 - 20
0 125 250 500 750 1,000
Meters

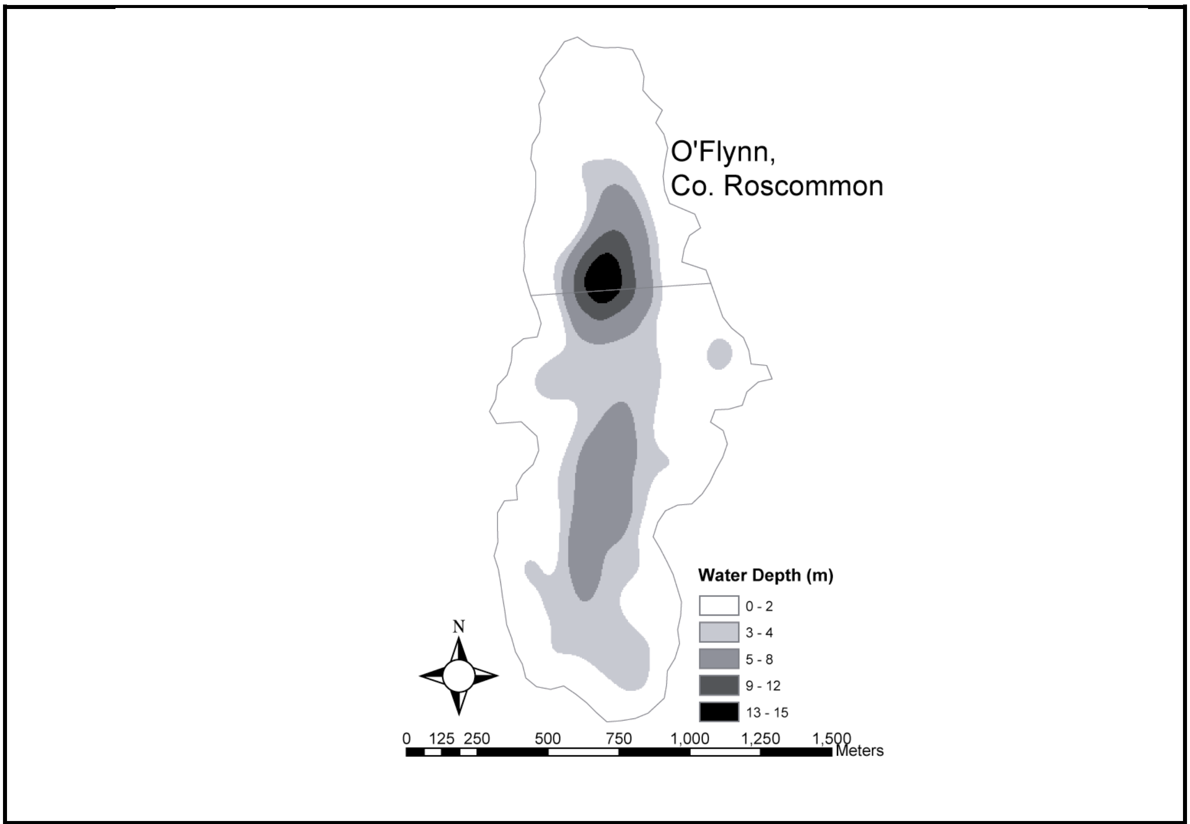

Nahasaleam, Co. Galway
Water Depth (m)
0 - 2
3 - 4
5 - 6
7 - 8
9 - 10
N
0 125 250 500 750 1,000
Meters

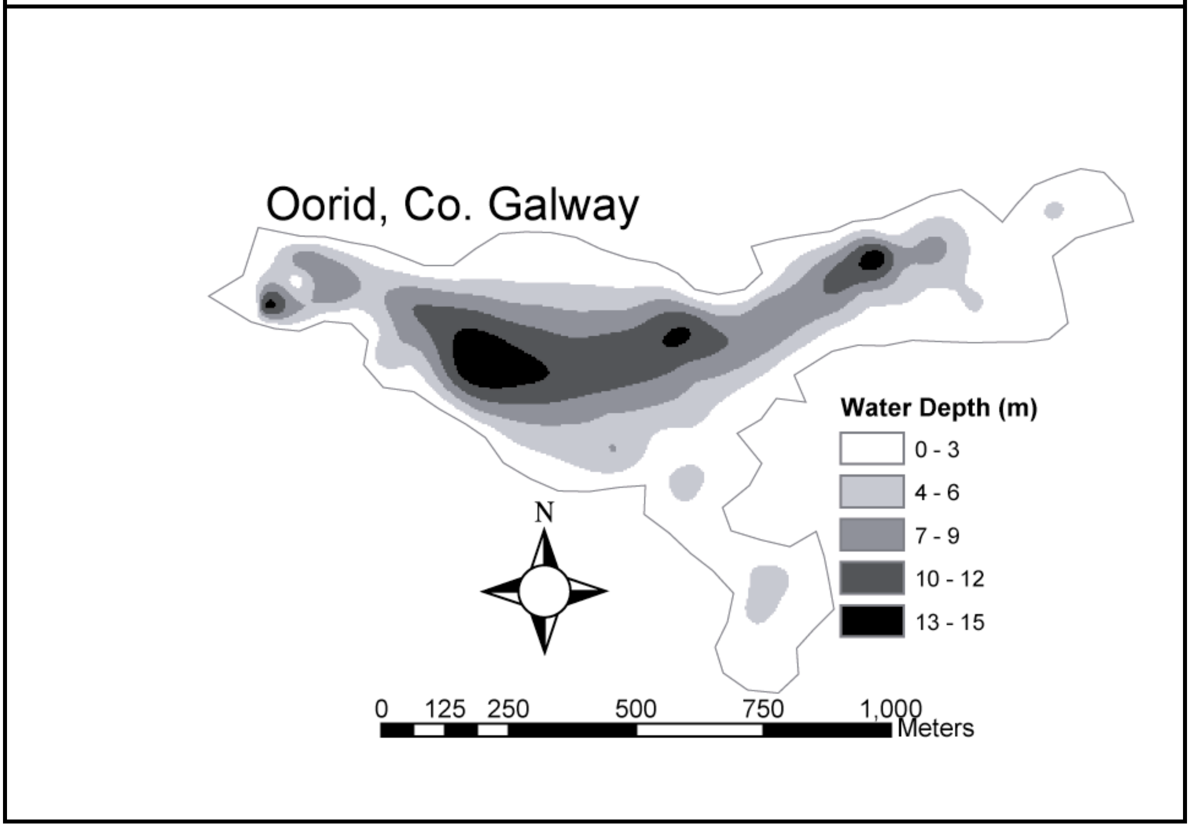


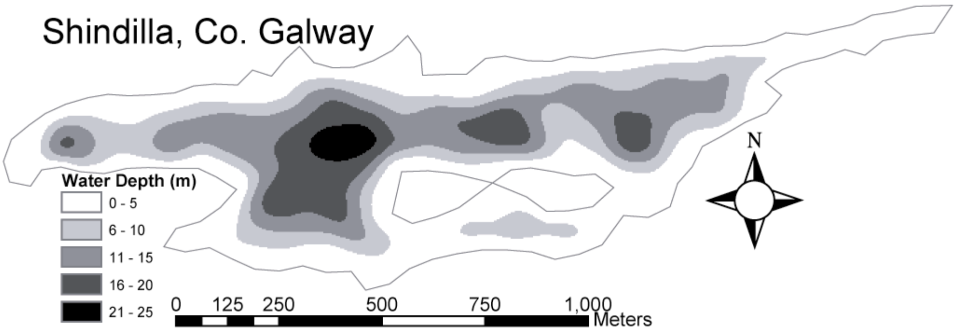
Nambreakkeagh, Co. Galway
Water Depth (m)
0 - 2
3 - 4
5 - 6
7 - 8
9 - 10
N
0 25 50 100 150 200 250
Meters

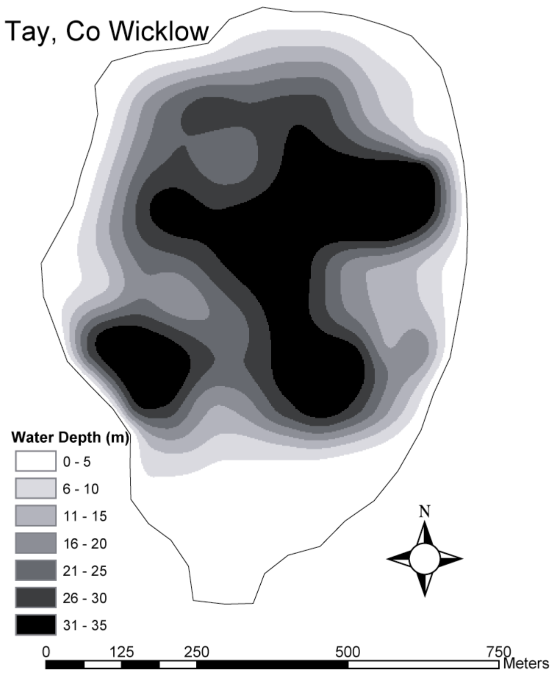


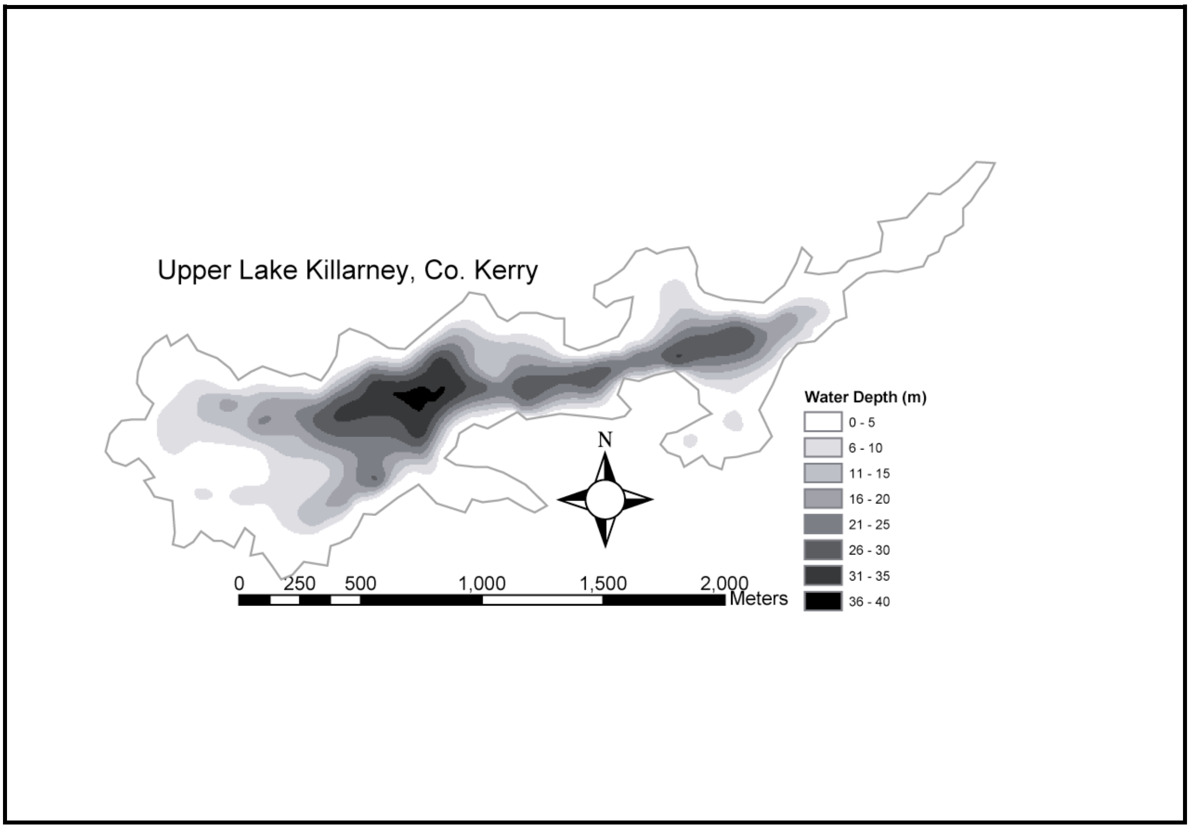
Naminn, Co. Donegal
Water Depth (m)
0 - 2
3 - 4
5 - 6
7 - 8
9 - 10
N
50 25 0 50 100 150 200 Meters


O'Flynn,
Co. Roscommon
Water Depth (m)
0 - 2
3 - 4
5 - 8
9 - 12
13 - 15
N
0 125 250 500 750 1,000 1,250 1,500
Meters


Oorid, Co. Galway
Water Depth (m)
0 - 3
4 - 6
7 - 9
10 - 12
13 - 15
N
0 125 250 500 750 1,000
Meters


Shindilla, Co. Galway
Water Depth (m)
0 - 5
6 - 10
11 - 15
16 - 20
21 - 25
0 125 250 500 750 1,000
Meters
N

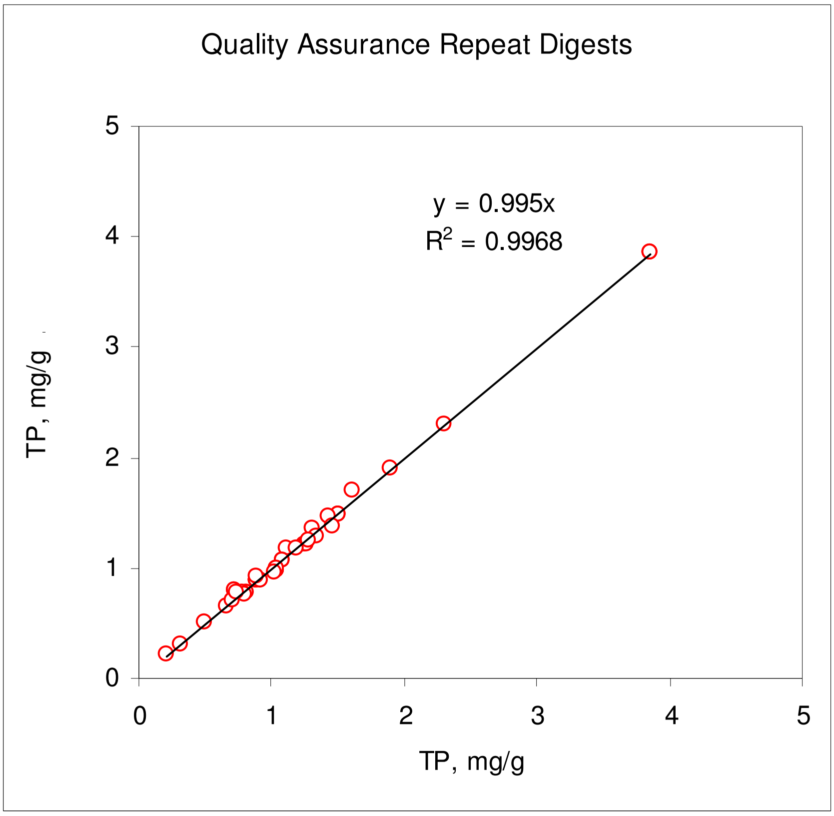

Tay, Co Wicklow
Water Depth (m)
0 - 5
6 - 10
11 - 15
16 - 20
21 - 25
26 - 30
31 - 35
0 125 250 500 750
Meters
N


Upper Lake Killarney, Co. Kerry
N
0
250
500
1,000
1,500
2,000
Meters
Water Depth (m)
0 - 5
6 - 10
11 - 15
16 - 20
21 - 25
26 - 30
31 - 35
36 - 40

Appendix 5 Quality Assurance for sediment chemistry

Repeat Digests

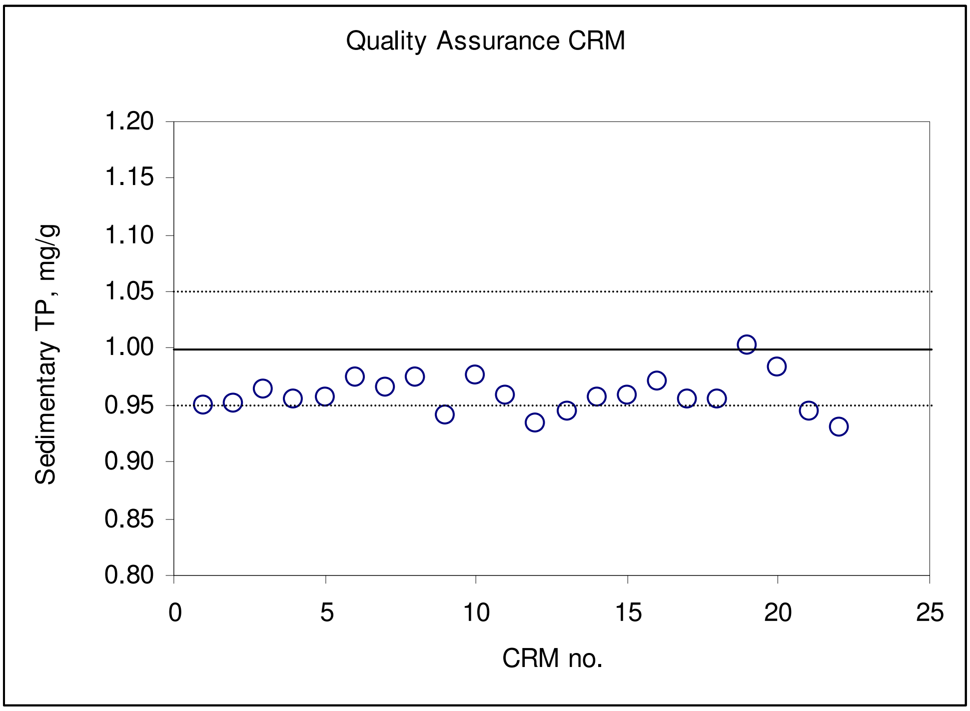
Quality assurance using blank and repeat digests indicates that errors associated with the digestion process were minimal. The average solution TP concentration of blank digests (*n* = 17) was 0.002mg/L (range 0.000 – 0.005mg/L) and considered below the analytical limits of detection. Repeat digest comparisons for TP are shown in the figure immediately below as being close to unity with a coefficient of determination close to 100%.



Repeat digest (TP, *n* = 39) quality assurance on digest process.

Certified Reference Material (CRM)

The CRM concentration for TP was 1.00mg/g (± 0.05mg/g) and the results of measured TP concentration on this material are shown in the figure immediately below. Of 22 samples, 5 had concentrations less than the limit of 0.95mg/g. The differences between the measured and expected CRM TP concentrations were treated as uncertainty and chemical concentrations in these digest batches were adjusted accordingly to take this slight error into account.



Measured CRM TP concentrations (n = 22) and within limits expected concentrations.

Environmental Change Research Centre

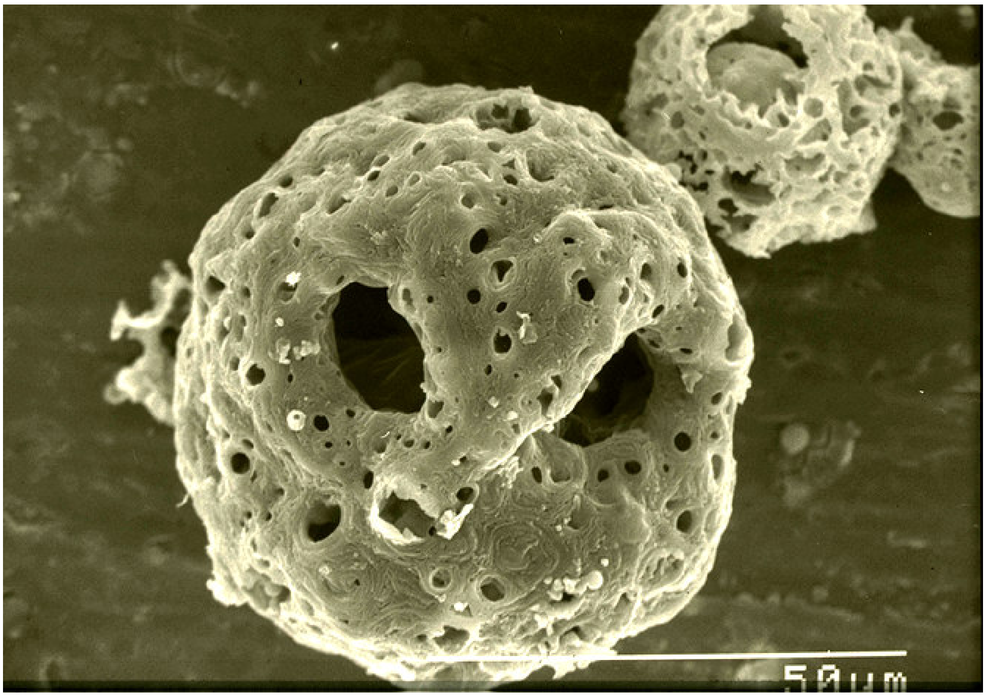
Research Report No. 97

An assessment of sediment chronologies for 35 lakes in Ireland based on skeleton spheroidal carbonaceous particle profiles

A report for IN-SIGHT (EPA/ERTDI Project #2002-W-LS/7)

Neil L. Rose and Sophie Theophile

May 2004



ISSN: 1366-7300 Environmental Change Research Centre, UCL

Contents

Executive summary

- Five samples from each of 35 sediment cores were received for SCP analysis in order to determine an estimate for 1850 and if possible a rough sediment chronology for each core.

- Dates were ascribed using three SCP profile features for which dates had been attributed from previous studies: The start of the SCP record (1850 ± 25); the rapid increase in SCP concentration (1950 ± 10) and the SCP concentration peak (1980 ± 3).

- SCP profiles were seen to fall into three categories:

1. Incomplete, where SCPs were present in all samples. In these cases a depth for 1850 was extrapolated below the base of the core.
2. Complete, where the start of the SCP record, and hence 1850, lies within the length of the core. In these cases, depths for 1950 and 1980 were extrapolated assuming a reasonably constant sediment accumulation rate and assessed against available data.
3. Short or curtailed SCP profiles, where SCPs were only present in the upper one or two samples. These were assumed to be due to slow sediment accumulation rates and were found to be clustered in the mid-west and south-west.

   Approximately one third of cores were found in each category.

- Given the very small number and the coarse interval between samples any estimated chronology contains a lot of uncertainty. Further, to produce any chronology at all requires a number of assumptions. The main one of these is that sediment accumulation rate has not varied greatly over the last 150 years. Without this assumption, no chronologies can be attributed to the profiles, however, the lack of samples also means that it is not possible to determine whether this is a reasonable assumption or not. A number of external driving factors can influence sediment accumulation rate and it is therefore probable that this assumption is not valid in many cases.

- Further, it is possible that all SCP concentration profiles could be the result of sediment accumulation rate alterations. However, in general the main SCP features remain identifiable unless major sediment accumulation rate changes occur at key points in the profile. Such changes can usually be identified in a more detailed profile, but is not possible here.

- At one site, Nambrackkeagh, where radiometric data were available, estimated SCP chronologies appear to give good agreement with the preliminary ^{210}Pb dates.

- Estimated depths for 1850 and rough chronologies were produced for almost all sites. However, given the coarse nature of the samples it was not possible to say anything further about regional variability of the profiles. Independent dating of more detailed SCP profiles are required from across Ireland in order to calibrate the SCP chronology. This work would make the SCP dating technique more useful and reliable in future Irish studies.

- Spatial distributions of SCP surface sediment concentrations and inventories were found to agree well with data from the EU funded project 'FLAME' (1994 – 1996). Areas of low contamination were identified in central areas and the mid- and south-west. Areas of high contamination were identified in the north (possibly influenced by the power station at Coolkeragh, north of Derry), the east (from industry around Dublin) and around the Shannon Estuary (Moneypoint and Tarbert power stations).

Introduction

IN-SIGHT

The priority area Palaeolimnological Investigation for candidate reference lakes (2002-W-LS/7), established under Phase 3 of the ERTDI Programme 2000-2006, recognises the importance of palaeolimnological research to the effective implementation of the EU Water Framework Directive (WFD). Palaeolimnological techniques can help to establish baseline reference conditions in lakes, including those that have been heavily impacted by humans, and indicate the timing, rate and direction of changes to the ecological quality of aquatic ecosystems. The IN-SIGHT project (**I**dentification of refere**N**ce-**S**tatus for **I**rish lake typolo**G**ies using palaeolimnological met**H**ods and **T**echniques) builds upon recent and current monitoring programmes in Irish lakes, results from palaeolimnology techniques developed and applied in previous research, the varied experiences of the project personnel and ideas derived in co-operation with current work in Ireland, UK and further afield.

The project is comprised of three work packages that aim to a) identify candidate reference lakes; b) establish reference status across the spectrum of Irish lake typologies, including those for which no reference sites exist at present; c) contribute to the development of effective strategies for monitoring environmental changes in Irish lakes; and d) provide an indication of targets for restoration of water quality in anthropogenically-impacted lakes.

SPHEROIDAL CARBONACEOUS PARTICLES

In order to identify reference conditions for lakes selected for IN-SIGHT an estimate of sediment chronology is required so that analyses can be undertaken at appropriate sediment depths, equivalent to a date at which reference conditions were thought to prevail. There are a number of techniques available to provide such chronologies, and spheroidal carbonaceous particle (SCP) analysis was selected as the sediment concentration profiles of these contaminants can provide a rapid and reliable means of sediment dating (see below).

SCPs are produced only from the high temperature combustion of fossil-fuels and have no natural sources. Therefore, in lake sediments they provide an unambiguous record of industrially-derived, atmospherically deposited pollution. Apart from physical mixing, by bioturbation for example, little post-depositional alteration of the SCP record occurs and, once calibrated to an independent chronology, the resulting robust and replicable SCP concentration profile can be used to date sediment cores from across broad regions.

Sediment material from 35 selected lakes from the Republic of Ireland was received for SCP analysis. Five samples from within a single sediment core, taken at roughly equidistant levels from the sediment surface to the core base, were analysed with the aim of providing a broad estimate of sediment chronology for each core. The selected lakes were located mainly in the west of Ireland with a few sites in central and eastern areas. The names and locations of these sites are shown in Figure 1.

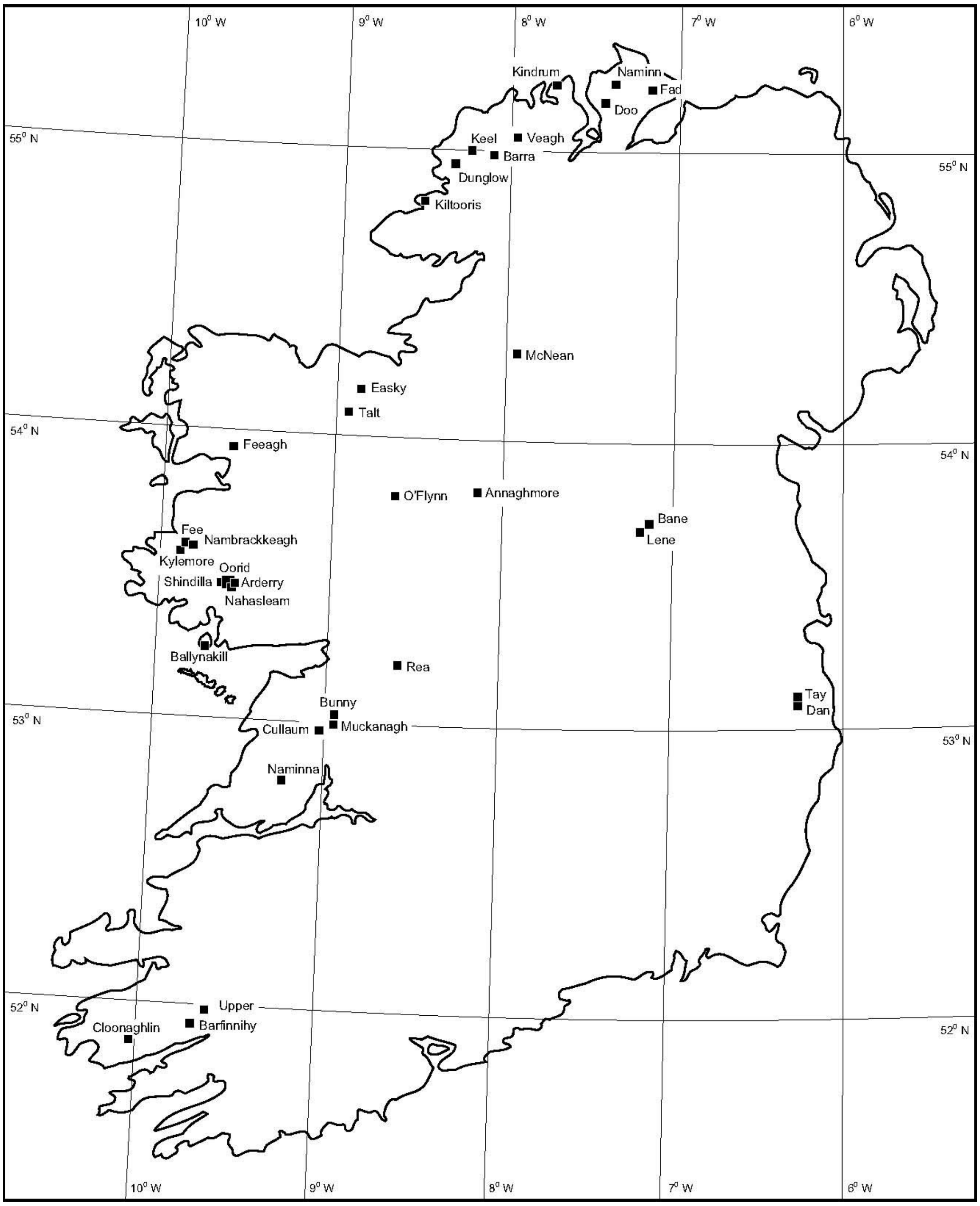


Figure 1. INSIGHT site location map.

Methods

SPHEROIDAL CARBONACEOUS PARTICLE ANALYSIS

SCPs are composed mainly of elemental carbon and therefore although physically fragile are chemically robust. Unwanted fractions of the sediment can therefore be removed by the use of strong mineral acids without affecting the particles. The procedure for extraction and enumeration of SCPs from the sediment samples followed Rose (1994). Sequential attack using HNO_3, HF and HCl removed organic, siliceous and carbonate fractions respectively resulting in a suspension of mainly carbonaceous material in water. A known fraction of this suspension was then evaporated onto a coverslip and the number of SCPs counted at 400 times magnification under a light microscope. Where no SCPs were found in a sample, slides were re-made and re-counted in order to confirm this result. Sediment concentrations are calculated in units of 'number of SCP per gram dry mass of sediment' or gDM^{-1}. Cumulative SCP inventories were also calculated for each core.

For each set of sediment digestions, a SCP reference sediment was also included. This SCP standard is currently under development (Rose, unpublished data) but allows an indication as to the comparability of the data resulting from each sediment digestion. Reference SCP concentrations for the INSIGHT sample digestions had a mean of 6395 gDM^{-1} compared to the SCP reference mean (currently N = 24; this work is still in progress, so this value will eventually change) of 6152 gDM^{-1} suggesting that the SCP concentration data from the INSIGHT sediment digestions are reliable.

SEDIMENT DATING

The identification of SCP dating horizons for Irish sediment cores, used in this study, is mainly based on Rose et al (1995). In this paper, good agreement was found for the main SCP dating features at all Irish sites for which ^{210}Pb-dated SCP profiles existed. These were as follows: the start of the SCP record: 1880s; the start of the rapid increase in SCP concentration: 1960s and the peak in SCP concentration, 1981 ± 2. However, these Irish cores were few and were limited to sites in Donegal. It is therefore uncertain how these dates relate to sediment cores further south.

More recently, further work has been undertaken in the north of Ireland (including Northern Ireland) where the dated SCP features were found to relate closely to a broad geographic area covering much of northern UK (Rose & Appleby, in prep). Here, the start of the SCP record was found to be 1850 ± 25, whilst the SCP concentration peak was found to be 1980 ± 3. Hence, whilst there are differences between the two datasets, given the errors involved in the calibration chronologies, they do give broad, reasonable agreement. However, there is currently a lack of independently dated SCP profiles in southern Ireland with which to calibrate a SCP dating chronology.

SCP records for many sites across Europe (Rose et al., 1999) show the start of the record to be *c.* 1850, whilst the rapid increase is found to be c.1950 resulting from the post-Second World War boom in the electricity generation industry and the first widespread availability of cheap oil. Therefore, it may be that the later dates for the start of the SCP record in the Donegal sites (Rose et al., 1995) is due to the detection limit of the technique (these early studies employed an early variation on the SCP digestion; Rose, 1990) and given the transboundary pollutant transfer between the UK and Ireland (Bowman & Harlock, 1998; Rose & Harlock, 1998) it is likely that the start of the SCP record in Ireland is similar to that of the UK and much of Europe i.e 1850 ± 25.

The peak in SCP concentration, whilst being the most reliable and easily definable feature in a SCP profile, is also the most locally variable (Rose & Appleby, in prep) and this results from regional differences in industrial emissions, introduction of particle arrestor technology and flue-gas desulphurisation, and changes in fuel-types and industry. This feature has been seen to vary considerably across the UK (Rose & Appleby, in prep) from 1970 in southern England to 1990 in the north-east and it is therefore currently unknown uncertain how this varies across the Republic of Ireland. However, as the Donegal sites gave a date of 1981 ± 2 and the north of Ireland (including Northern Ireland) gives a date of 1980 ± 3, a date of 1980 is probably not unreasonable, especially given the coarseness of the sampling interval within this project.

The rapid increase in concentration is likely to be reasonably consistent as it relates to a Europe-wide phenomenon. Rose & Appleby (in prep) suggest that regionality of the SCP record within the UK converges at this point and it is likely, given the European dimension to this feature and its cause, that this is similar across Ireland.

Finally, Rose & Appleby (in prep) have found that the use of a cumulative SCP percentage profile allows more dates to be allocated to each core. However, such an approach is not applicable here due to the low numbers of samples from each core and the lack of calibration in most of the country. A future project to properly calibrate the SCP record across the whole of Ireland would therefore be a very useful exercise.

In summary, the following dates are employed in this report to allocate chronologies to the INSIGHT sediment cores:

The start of the SCP record:	1850 ± 25
The rapid increase in SCP concentration	1950 ± 10
The peak in SCP concentration	1980 ± 3

Results

Sediment chronologies based on coarse sampling intervals will have high levels of uncertainty. The main aim of this work was to provide an estimate for the date 1850 AD identifiable as the start of the SCP record. Therefore, identification of the presence or absence of SCPs in the lower samples was crucial and additional counts were made on samples where SCP concentrations were found to be 0 gDM^{-1}.

Given this primary aim, three main profile types were identified amongst the 35 sediment cores.

1. Those in which SCPs were found in all samples, including the basal sample. This suggests that the full core represents a post-1850 period, and any estimate of this date will be an extrapolation beyond the base of the core.
2. Profiles in which at least the bottom sample has 0 gDM^{-1}. This allows an estimate of 1850 to be made within the current core, with the obvious caveats relating to the sampling interval for that core.
3. Profiles for which SCPs only appear in the surface sample or in the two uppermost samples where the lower sample has low SCP concentration. Profiles of this sort imply one of three things. First, this is a very slow accumulation rate core and the entire profile is contained within the interval of the upper one or two samples. Second, the sediment record, or core, has been disturbed (e.g. by dredging) thereby removing some of the profile. Third, this is a clean area into which a recent, new source has been commissioned thereby taking the SCP record from below to above detection limit in recent times. If the second hypothesis is true then it is not possible to interpret the SCP profile. It is also difficult to do this in the third case, unless there is knowledge of the new source. However, the analytical detection limits within this project are good (where available sample weight allows) and therefore it is unlikely that recent sediments would be below detection limit anywhere in Ireland unless accumulation rate was very high. Therefore,

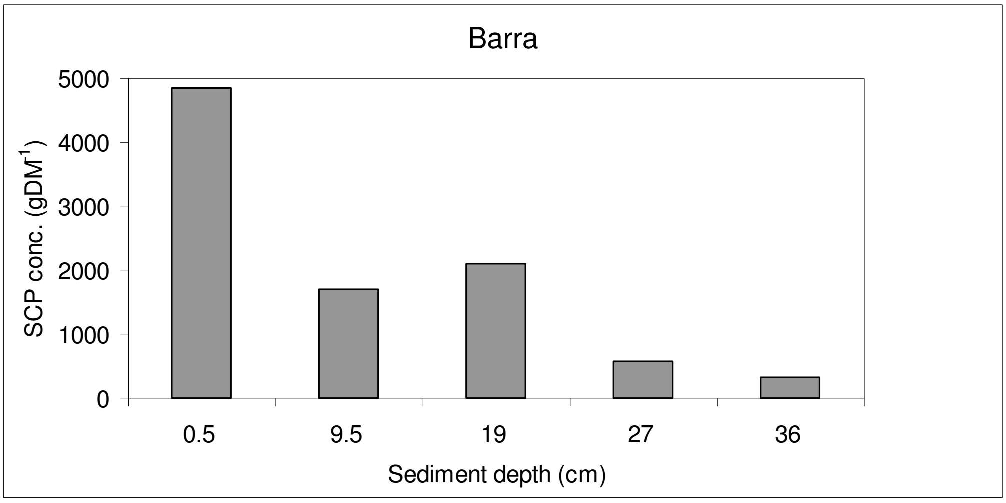
here it has been assumed that the record is intact and that these profiles are due to slow accumulation rates.

For a few samples, only a very small sediment weight was received. This increases the limit of detection, makes error margins large and in one instance suggests a concentration of 0 gDM^{-1}in the surface sample of a core where SCP concentrations are elevated below it. Such small sample weights therefore make interpretation more difficult. These instances are discussed in more detail with the relevant sites.

The results for each site are given below sub-divided into the three profile categories. Summary figures are presented for each site whilst full data are provided in an Appendix. At a few sites (Veagh, Naminna) previous data are available and these are used to provide additional interpretation. At two other sites (Tay, Nambrackkeagh) preliminary dates from INSIGHT itself were available and these are also used. It may be that more recent dating is now available for these or other sites but if so, these have not been made available at the time of writing this report.

Section 1: Incomplete SCP profiles.

Barra: (B 935 120)

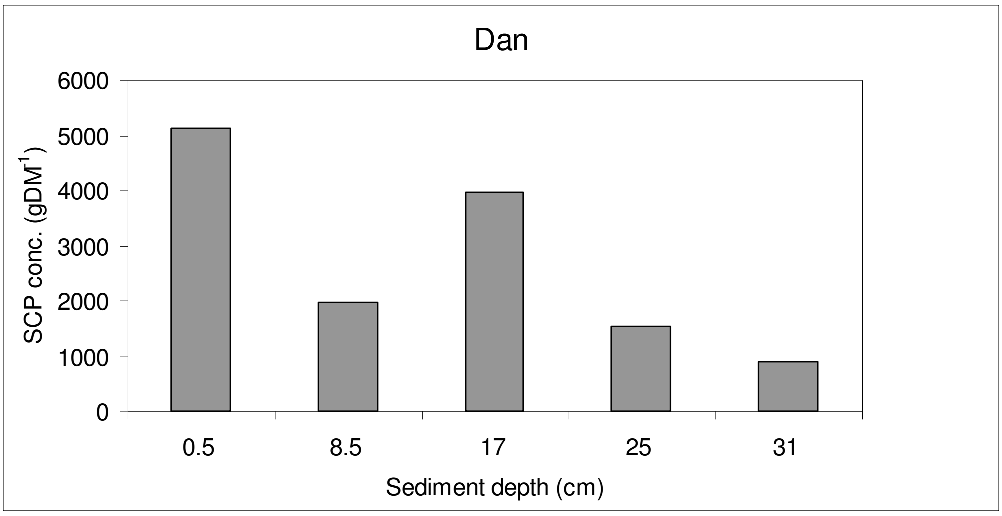


SCPs are present in all samples from Barra suggesting that the entire core represents a post-1850 period. The maximum observed SCP concentration of almost 5000 gDM^{-1} is in the surface sample and the peak concentration therefore probably lies somewhere between 0.25 and 9.5 cm. However, unless there has been a great change in sediment accumulation rate over the course of the period covered by the core it is unlikely that the SCP concentration peak is in this surface sample.

Assuming a reasonably constant accumulation rate then if the peak concentration falls between 5.5 cm and 9.5cm then this would be sufficient for the start of the SCP record (and hence 1850) to fall below the base of the core. Given the concentration at 36cm is still easily detectable, it is likely that the peak lies somewhere near the mid-point of this range. This being the case, then 1950 would lie between 17 and 22 cm and 1850 would fall between 50 and 63 cm.

Therefore, best estimate chronology:	1980:	7.5 – 9.5 cm
	1950:	17 – 22 cm
	1850:	50 – 63 cm

Dan: O 150 040

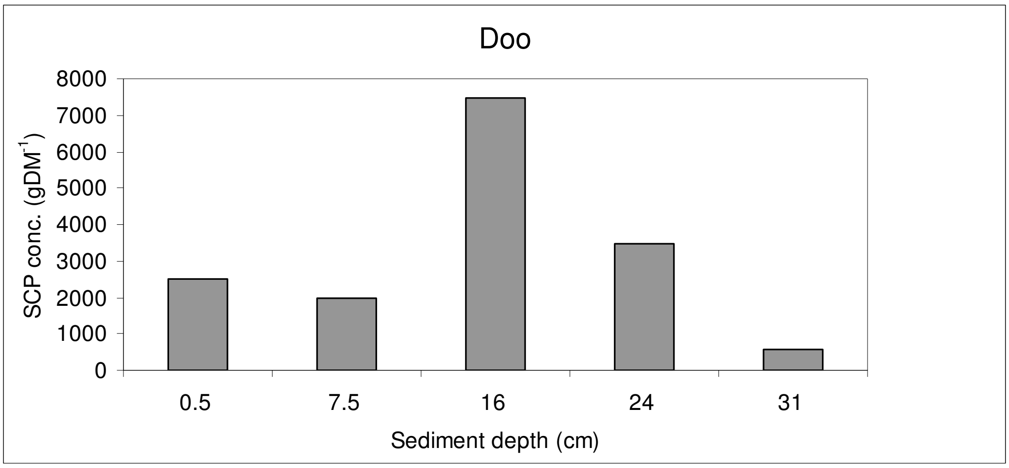


SCPs are present in all samples from Dan suggesting that the entire core represents a post-1850 period. The profile is also similar to that of Barra. The maximum observed SCP concentration of just over 5000 gDM^{-1} is in the surface sample and the peak concentration therefore probably lies somewhere between 0.25 and 8.5 cm. However, unless there has been a great change in sediment accumulation rate over the course of the period covered by the core it is unlikely that the SCP concentration peak is in this surface sample.

Assuming a reasonably constant accumulation rate then if the peak concentration falls between 5 cm and 8.5cm then this would be sufficient for the start of the SCP record (and hence 1850) to fall below the base of the core. Given the concentration at 31cm is still easily detectable, it is likely that the peak lies somewhere near the mid-point of this range. This being the case, then 1950 would lie between 17 and 22 cm and 1850 would fall between 50 and 63 cm.

Therefore, best estimate chronology:	1980:	6.5 – 8.5 cm
	1950:	15 – 20 cm
	1850:	43 – 57 cm

Doo: C 359 394



SCPs are present in all samples from Doo suggesting that the entire core represents a post-1850 period. The maximum observed SCP concentration of almost 7500 gDM^{-1} is in the 15 – 16cm sample and the peak concentration therefore probably lies somewhere between 8 and 23 cm. If the peak were to lie towards the bottom of this range this would imply a sediment accumulation rate of almost 1 cm yr^{-1} and this seems high given the SCP concentrations present throughout the core.

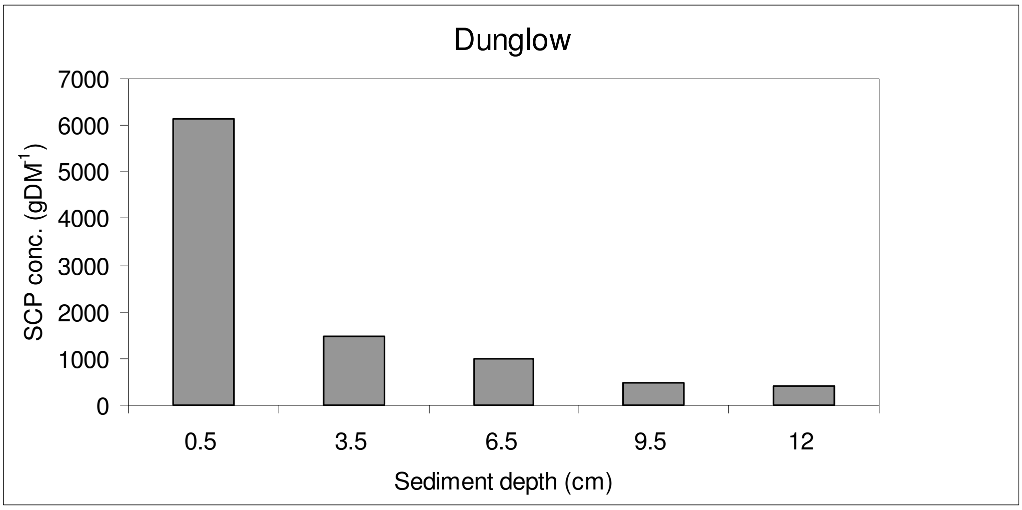
If the trend observed in the lower samples is real then it maybe the rapid increase in concentration lies between 25 and 30 cm suggesting an accumulation rate of *c.* 0.5 cm yr^{-1}. Assuming a reasonably constant accumulation rate this would place the SCP concentration peak between 10.5 cm and 13 cm and the start of the SCP record (and hence 1850) somewhere between 72 and 86cm. This certainly fits the observed data, but remains rather speculative.

Therefore, best estimate chronology:	1980:	10.5 – 13cm
	1950:	25 – 30 cm
	1850:	72 – 86 cm

Further note:

This site is located reasonably close to Barra but the (incomplete) SCP inventory is almost three times higher and, despite being incomplete, is one of the highest inventories in the INSIGHT dataset. It is difficult to explain these data unless Doo lies downwind of a local source and Barra, upwind.

Dunglow: B 782 117



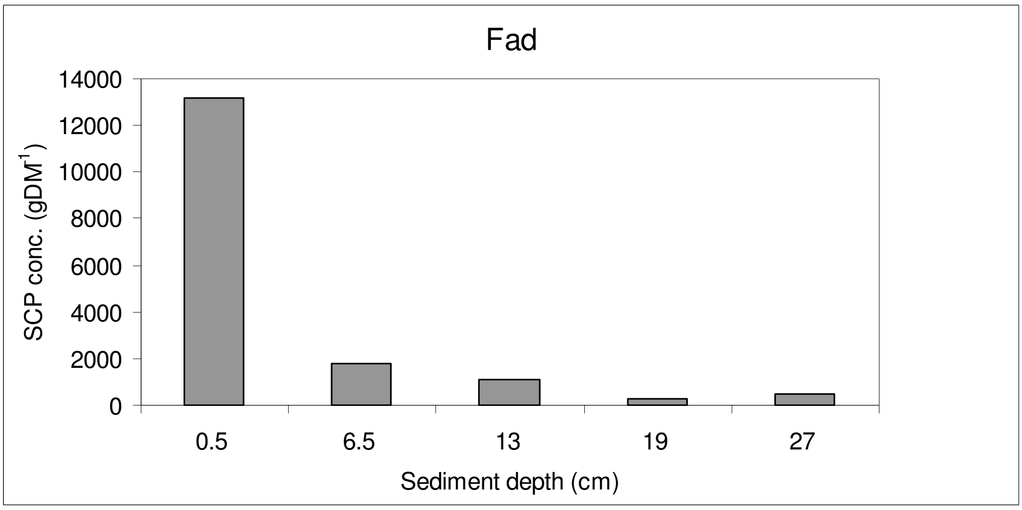
SCPs are present in all samples from Dunglow suggesting that the entire core represents a post-1850 period. However, this is a short core and so perhaps this is not surprising. The maximum observed SCP concentration of just over 6000 gDM^{-1} is in the surface sample and the peak concentration therefore probably lies somewhere between 0 and 3 cm. However, unless there has been a great change in sediment accumulation rate over the period covered by the core it is unlikely that the SCP concentration peak is in this surface sample.

Assuming a reasonably constant sediment accumulation rate then the dating must be reasonably constrained in order to fit the observed data. If the SCP peak is above 1.5cm then the start of the record should be observed. If the peak is below 2.5 cm then the start of the rapid increase (1950) would be between 6.5 and 9.5cm which would seem unlikely. If the peak is at 2cm, then the rapid increase would start at *c.* 4.5 cm and the SCP record would start at *c.* 13 - 14 cm, just below the base of the core, which from the data seems reasonable. It should be stressed that all this speculation is reliant on a constant sediment accumulation rate. The data could also be explained by a period of elevated accumulation rate at some earlier point in the lake's history, in which case 1850 could be lower than 13 – 14cm. If recent accumulation rate had increased then this would shift the SCP concentration peak to a lower depth, but it cannot move too far in this direction as the 3 – 3.5cm concentration is considerably lower than the surface concentration.

Therefore, best estimate chronology:

1980: 1.5 – 2.5 cm
1950: 4 – 6 cm
1850: c. 13 – 15 cm

Fad Inishowen East: C 439 439



SCPs are present in all samples from Fad suggesting that the entire core represents a post-1850 period. The maximum observed SCP concentration of over 13000 gDM^{-1} is in the surface sample and the peak concentration therefore lies somewhere between 0.25 and 6 cm. If there has been a reasonably constant sediment accumulation rate then the concentration peak needs to be below 4 cm in order that 1850 lie below 27cm. However, the shape of the profile would suggest that the rapid increase should also fall above the 6 – 7cm sample. If this is the case then for SCPs still to be present at 27cm then there must have been a period of elevated sediment accumulation rate at some earlier point in the lake's history.

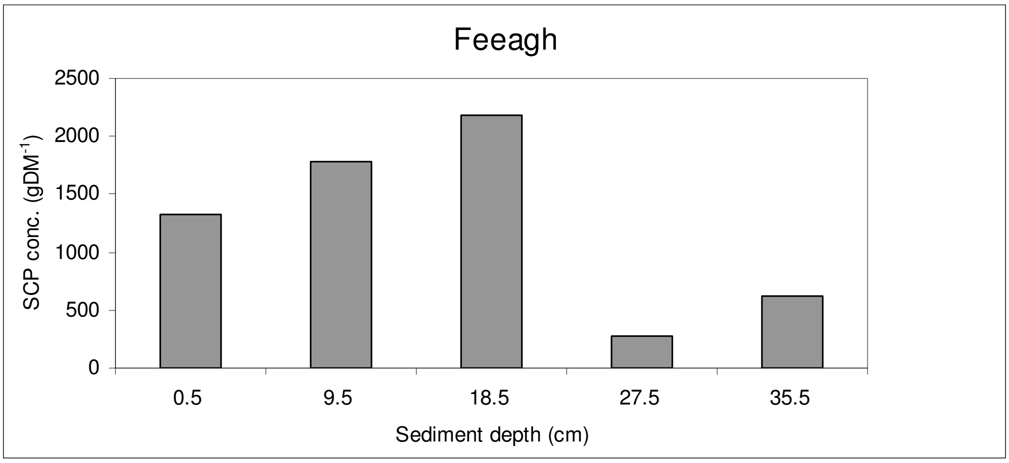
It would seem that the lowest sediment depth at which the start of the rapid increase (1950) could lie would be 6 – 7cm. If this is the case then the SCP peak would be at 2.5 – 3cm but 1850 would be at *c.* 19cm unless a period of elevated accumulation rate had occurred prior to 1950. Assuming sediment accumulation rate variations at this site does not preclude the identification of any of the key SCP dating features, then the best estimate chronology is:

1980: 2 – 4 cm
1950: 6 – 7 cm
1850: > 27 cm

Further note:

This site is located reasonably close to Doo, has a high surface concentration and a reasonably high (incomplete) SCP inventory. It would therefore seem likely that the site is impacted by the same source as Doo.

Feeagh: F 965 000



SCPs are present in all samples from Feeagh suggesting that the entire core represents a post-1850 period. The maximum observed SCP concentration of almost 3000 gDM^{-1} is in the 18 – 19 cm sample and the peak concentration therefore probably lies somewhere between 10 and 27 cm.

Assuming a reasonably constant accumulation rate then any depth below 4.5 cm for the SCP concentration peak is sufficient for the start of the record to fall below 37 cm. If the trend observed in the lower samples is real then it maybe that the rapid increase in SCP concentration lies between 19 and 27 cm. If this is the case, then for the SCP concentration peak to fall below 10 cm then the rapid increase should lie below 23 cm. Further, an accumulation rate sufficient to put the rapid increase at the bottom of its possible depth range would place the SCP concentration peak at around 12 cm. A peak between 10 and 12 cm and a rapid increase between 23 and 17cm would 1850 and hence the start of the record in the range 66 – 76cm. This certainly fits the observed data, but remains rather speculative.

Therefore, best estimate chronology: 1980: 10 – 12cm
1950: 23 – 27 cm
1850: 66 – 76 cm

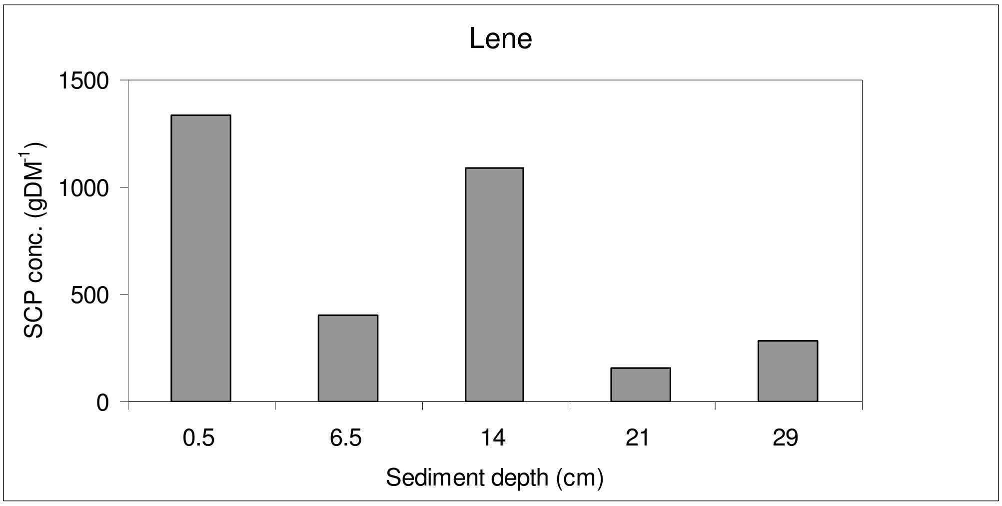
Kiltooris: G 676 972

SCPs are present in all samples from Kiltooris suggesting that the entire core represents a post-1850 period. The maximum observed SCP concentration of over 4000 gDM^{-1} is in the 18 – 19 cm sample and the peak concentration therefore probably lies somewhere between 10 and 26 cm. Assuming a reasonably constant accumulation rate then any depth below 4.5 cm for the SCP concentration peak is sufficient for the start of the record to fall below 35 cm. Unlike Feeagh, the data does not allow an estimate of possible 1950 dates. However, assuming a reasonably constant rate of sediment accumulation, the depth range for the SCP concentration peak provides ranges for the rapid increase (1950) of 23 – 53cm and for the start of the record (1850) of 66 – 150cm.

Given the shape of the profile from the available data and assuming that sediment accumulation rate variations at this site are not obscuring the identification of any of the key SCP dating features then it would seem more probable that these features fall in the upper half of these ranges.

Therefore, best estimate chronology:	1980:	10 – 19 cm (possibly 10 – 26cm)
	1950:	23 – 40 cm (possibly 23 – 53cm)
	1850:	66 – 110 cm (possibly 66 – 150cm)

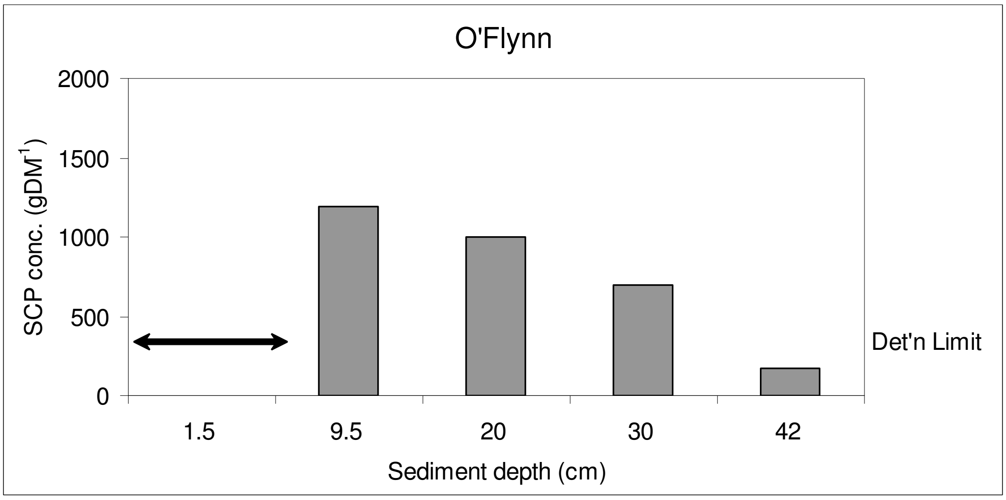
Lene: N 510 685



SCPs are present in all samples from Lene suggesting that the entire core represents a post-1850 period. The maximum observed SCP concentration of just less than 1500 gDM^{-1} is in the surface sample, but the 13 – 14cm sample shows similar concentrations and given the low resolution of sampling interval it is not possible to determine where the true SCP concentration peak might lie. Indeed, assuming a reasonably constant sediment accumulation rate then for SCPs to be present below 29cm then the SCP concentration peak should lie below 4.5 cm. Given the concentration at 6.5 cm it would seem more likely that the peak would therefore lie between 7 and 20cm.

If the rapid increase lies between 14 and 21 cm as seems possible, then this accumulation rate would place the peak at 6 – 9.5 cm and the start of the record at 40 – 62cm. Again, given the concentration at 6.5 cm it would seem more likely that these features lie in the bottom half of these ranges. These dates certainly fit the observed data, but remain very speculative. The observed data would also be explained by a rapid, variable accumulation rate or a disturbed sediment record. In fact, the only definite conclusion is that 1850 lies below 29cm.

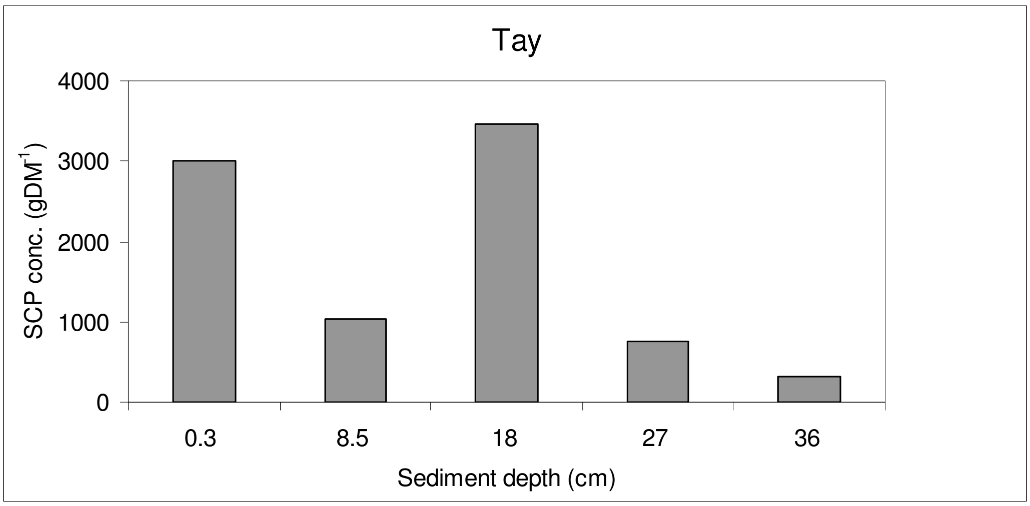
O'Flynn: M 585 795



No surface sample was received for this core and the 1 – 1.5cm sample was very small (< 0.03g). No SCPs were detected in this sample and the low sample weight raised the detection limit considerably. However, this detection limit is still much lower than the concentration in the 9 – 10cm sample suggesting that the SCP concentration peak lies between 1.5 and 19 cm.

Assuming a reasonably constant sediment accumulation rate then for SCPs to be present at 42 cm then the peak must be below 6 cm. Similarly, if the rapid increase lies between 30 and 41 cm as seems possible, then the peak would lie in the range 13 – 17 cm and the start of the record would lie between 85 and 120 cm. However, as with Kiltooris, the only definite conclusion is that 1850 lies below 42 cm.

Tay: O 160 750

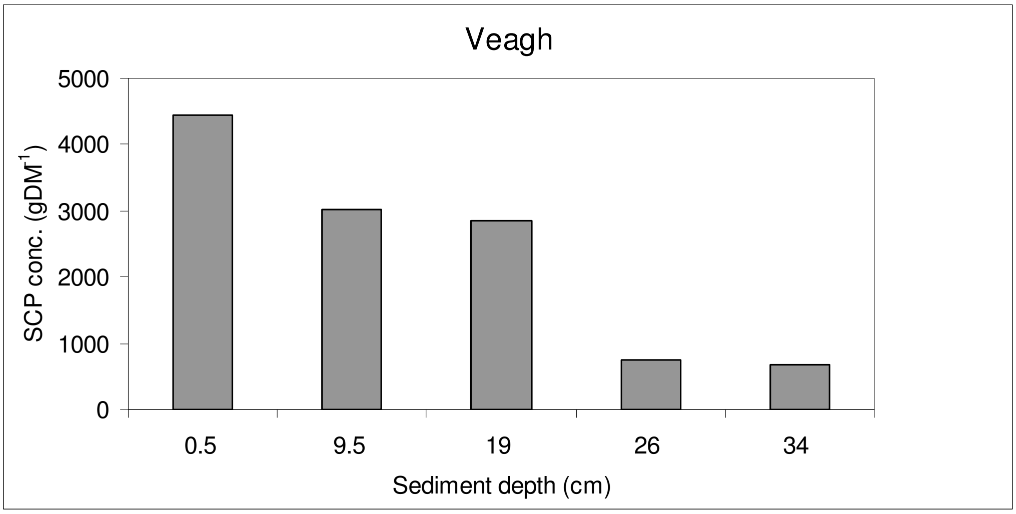


SCPs are present in all samples from Tay suggesting that the entire core represents a post-1850 period. The maximum observed SCP concentration of almost 3500 gDM^{-1} is in the 17 –

18 cm sample and the peak concentration therefore probably lies somewhere between 9 and 26 cm. Although, the surface concentration is similar, assuming a reasonably constant accumulation rate then a depth of below 5.5 cm for the SCP concentration peak is required for the start of the record to fall below 36 cm. If the rapid increase lies between 18 and 26 cm as seems possible, then the peak would lie in the range 8 – 12 cm and the start of the record would lie between 50 and 75 cm. Given the SCP concentration at 8 – 9 cm it seems likely that these features lie in the lower half of these ranges.

However, data from radiometric dating (David Taylor's e-mail of 4 Dec 2003) suggests that the upper 15cm is disturbed possibly as a result of in-washes from the catchment or disturbance during coring. If this is the case then the SCP profile is impossible to interpret except that 1850 lies somewhere below 36cm.

Veagh: C 022 215



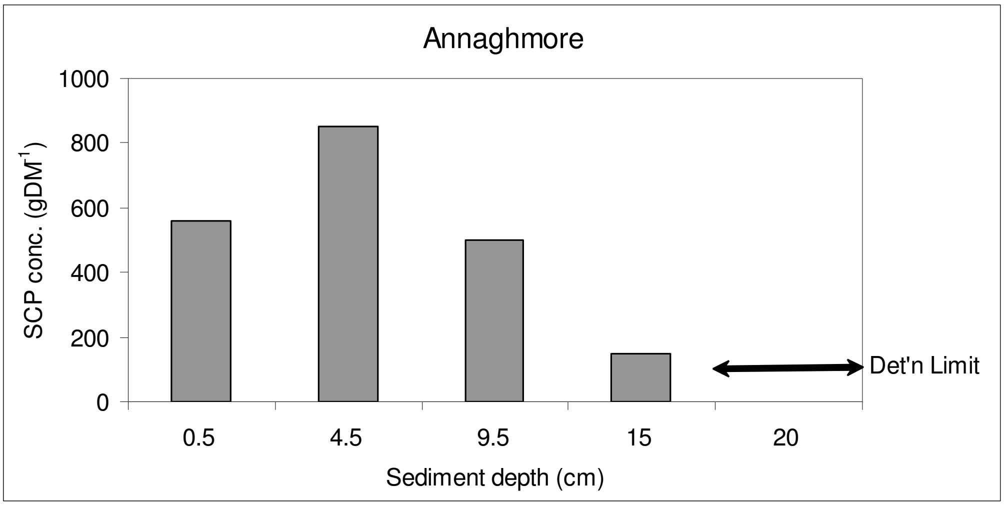
SCPs are present in all samples from Veagh suggesting that the entire core represents a post-1850 period. The maximum observed SCP concentration of almost 4500 gDM^{-1} is in the surface sample and the peak concentration therefore probably lies somewhere between 0.5 and 9 cm. However, unless there has been a great change in sediment accumulation rate over the course of the period covered by the core it is unlikely that the SCP concentration peak is in this surface sample. Indeed, assuming a reasonably constant accumulation rate then a depth of below 5.5 cm for the SCP concentration peak is required for the start of the record to fall below 34 cm. A core taken from Veagh in 1988 and ^{210}Pb-dated (Rose et al., 1995) showed a constant sediment accumulation rate of 0.145 cm yr^{-1} throughout, but the accumulation rate of the current core is considerably faster than this as 1850 would otherwise be at 22-23 cm.

If sediment accumulation rate in the current core is also constant, although faster, then if the SCP peak is between 5.5 and 9 cm, then the rapid increase would lie at 12.5 – 20cm and the start of the record at 37 – 60cm. The shape of the current profile would suggest that the rapid increase lies below 19cm and therefore the lower ends of these ranges seems more likely. This suggests an accumulation rate 2.5 – 3 times faster than the 1988 core, as long as a constant rate is assumed, whilst for SCPs to be present at 34 cm the rate must be at least twice as fast. Interestingly, the peak concentration in the 1988 core is 2.6 times higher than that observed here.

Therefore, best estimate chronology:	1980:	*c*. 9cm
	1950:	*c*. 20cm
	1850:	*c*. 60cm

SECTION 2: COMPLETE SCP PROFILES.

Annaghmore: M 900 837



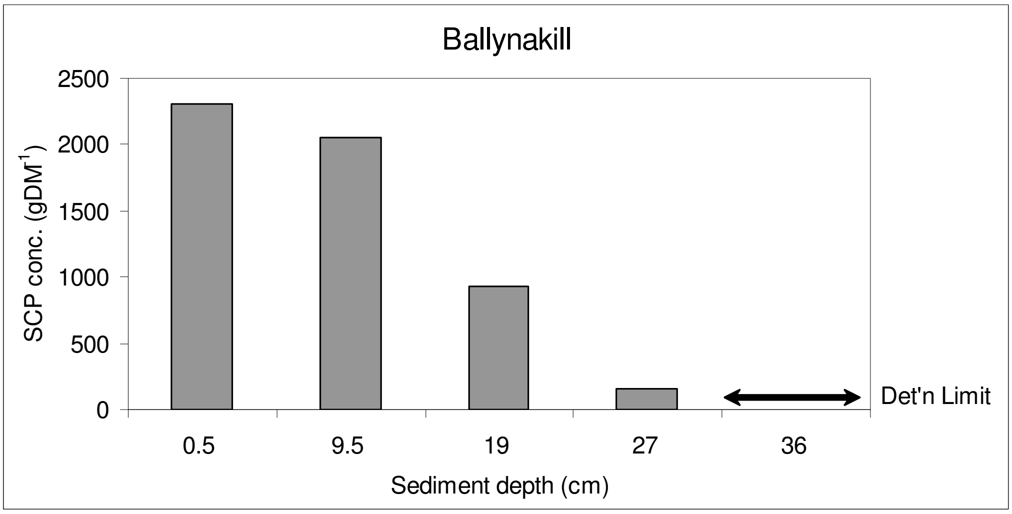
No SCPs are recorded in the 19 – 20 cm sample of Annaghmore suggesting that 1850 lies between 15 and 19 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 2 – 3cm for 1980 (the SCP concentration peak), and 5 – 7cm for 1950 (the start of the rapid increase in SCP concentration). The available data do not contradict these possibilities.

Therefore best estimate chronology: 1980: 2 – 3cm

1950:	5 – 7cm
1850;	17 – 19cm

Ballynakill: L 856 225

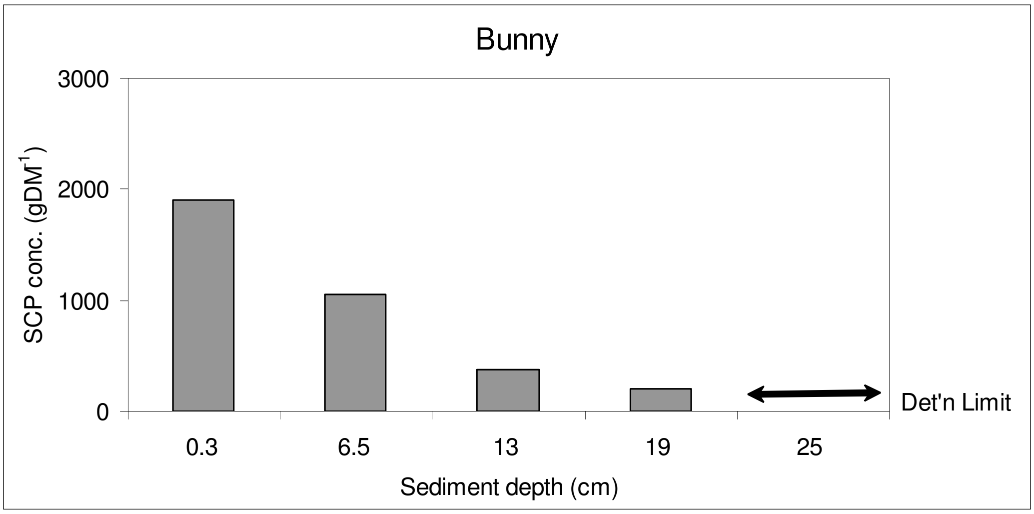


No SCPs are recorded in the 35 – 36 cm sample of Ballynakill suggesting that 1850 lies between 27 and 35 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 4 – 5.5 cm for 1980 (the SCP concentration peak), and 9 – 13 cm for 1950 (the start of the rapid increase in SCP concentration). However, the available data would suggest that the rapid increase is likely to be below 10 cm.

Therefore best estimate chronology:	1980:	4 – 5.5 cm
	1950:	10 – 13 cm
	1850;	29 – 35 cm

Bunny: R 375 967

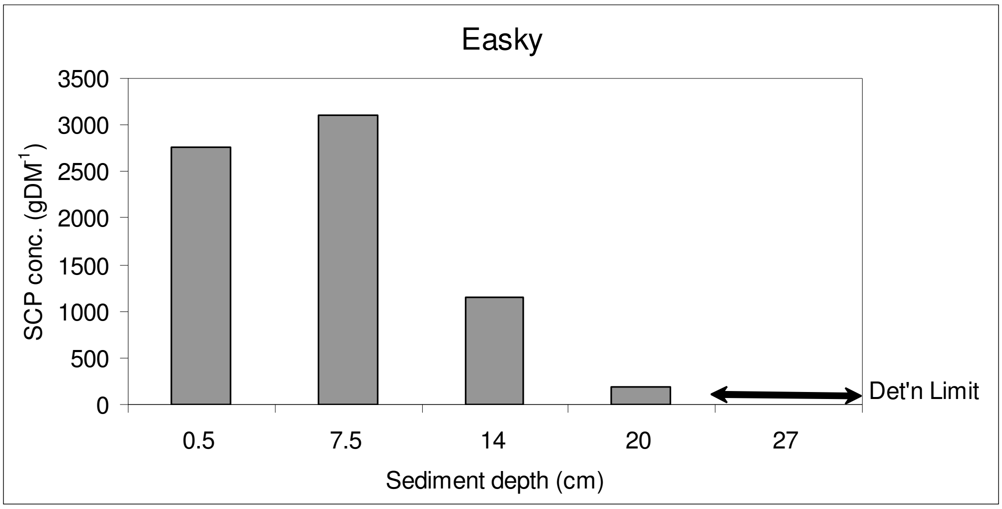


No SCPs are recorded in the 24 – 25 cm sample at Bunny suggesting that 1850 lies between 19 and 24 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 2.5 – 4 cm for 1980 (the SCP concentration peak), and 6 – 8.5 cm for 1950 (the start of the rapid increase in SCP concentration). However, the available data would suggest that the rapid increase is likely to be below 7 cm and hence the other ranges shifting down slightly.

Therefore best estimate chronology:	1980:	3 – 4 cm
	1950:	7 – 8.5 cm
	1850:	21 – 24 cm

Easky: G 442 225

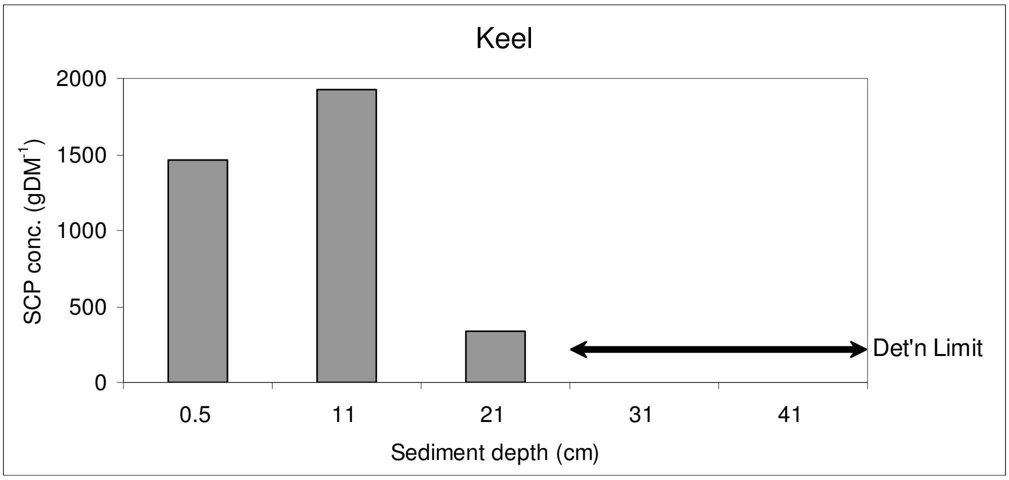


No SCPs are recorded in the 26 – 27 cm sample at Easky suggesting that 1850 lies between 20 and 26 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 3 – 4 cm for 1980 (the SCP concentration peak), and 7 – 9 cm for 1950 (the start of the rapid increase in SCP concentration). However, the available data would suggest that the rapid increase is likely to be below 8 cm and hence the other ranges shift down slightly.

Therefore best estimate chronology:	1980:	3 – 4 cm
	1950:	8 – 9 cm
	1850:	23 – 27 cm

Keel: B 847 162



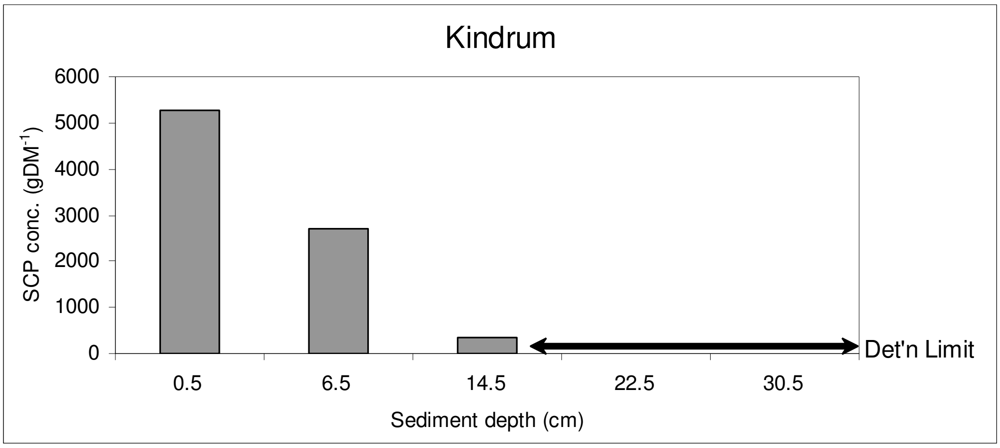
No SCPs are recorded in the 30 – 31 cm or 40 – 41 cm samples at Keel suggesting that 1850 lies between 22 and 30 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 3 – 4.5 cm for 1980 (the SCP concentration peak), and 7 – 11 cm for 1950 (the start of the rapid increase in SCP concentration). However, the available data would suggest that the rapid increase is likely to be below 11 cm and in which case there may have been changes in sediment accumulation rate in this core.

Therefore, without any further available information, the best estimate chronology is as follows:

1980: 3 – 4.5 cm
1950: 11– 15 cm
1850: 28 – 30 cm

Kindrum: C 185 430

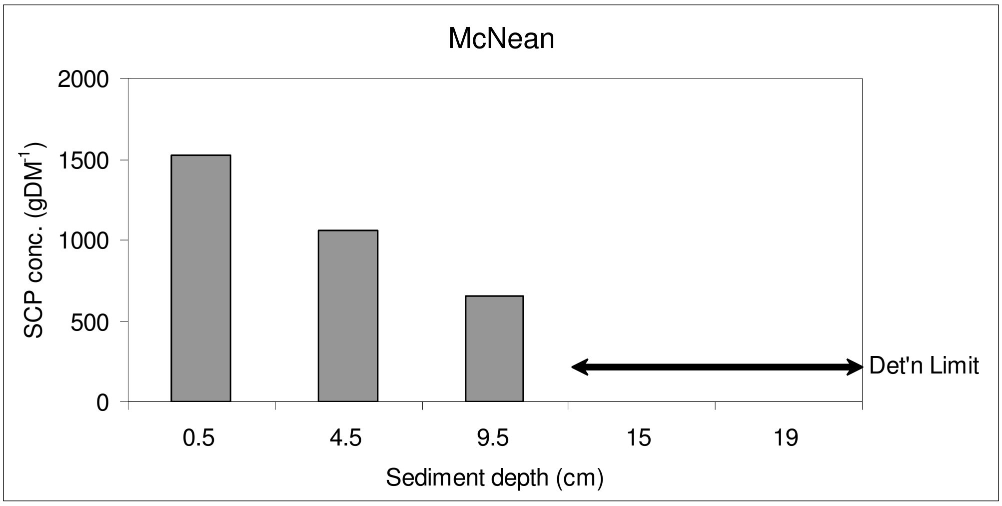


No SCPs are recorded in the 22 – 23 cm or 30 – 31 cm samples at Kindrum suggesting that 1850 lies between 15 and 22 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 2 – 3.5 cm for 1980 (the SCP concentration peak), and 5 – 8 cm for 1950 (the start of the rapid increase in SCP concentration). However, the available data would suggest that the rapid increase is likely to be below 7 cm and hence the other ranges shift down.

Therefore best estimate chronology:	1980:	3 – 4 cm
	1950:	7 – 8 cm
	1850:	20 – 22 cm

McNean: H 040 400

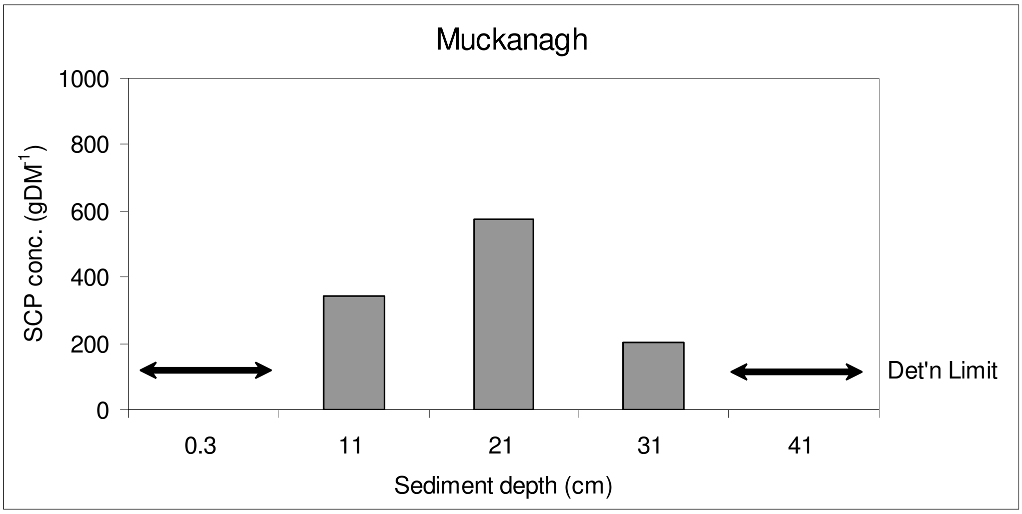


No SCPs are recorded in the 22 – 23 cm sample at McNean suggesting that 1850 lies between 10 and 14 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 1.5 – 2.5 cm for 1980 (the SCP concentration peak), and 3.5 – 5 cm for 1950 (the start of the rapid increase in SCP concentration) and the available data do not contradict these possibilities.

Therefore best estimate chronology:	1980:	1.5 – 2.5 cm
	1950:	3.5 – 5 cm
	1850:	12 – 14 cm

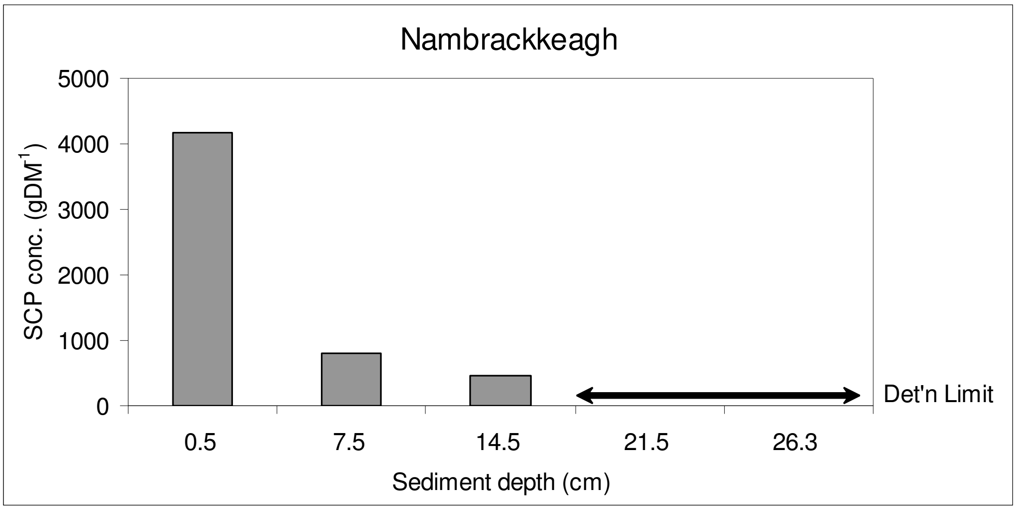
Muckanagh: R 370 925



No SCPs were recorded in the uppermost sample resulting in a concentration below the limit of detection of 150 gDM^{-1}. Further, no SCPs were recorded in the 40 – 41 cm sample at Muckanagh suggesting that 1850 lies between 31 and 40 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 4.5 – 6 cm for 1980 (the SCP concentration peak), and 10.5 – 14 cm for 1950 (the start of the rapid increase in SCP concentration). However, all SCP concentrations are very low and the concentration peak could lie anywhere between 0.5 and 30 cm. However, the low concentrations suggest a rapid sediment accumulation rate and therefore, despite a good detection limit, the start of the record may lie below 40 cm. With, effectively, only three data-points to work from and all with very low SCP concentrations, it is not possible to interpret this profile further.

Nambrackkeagh: L 821 603



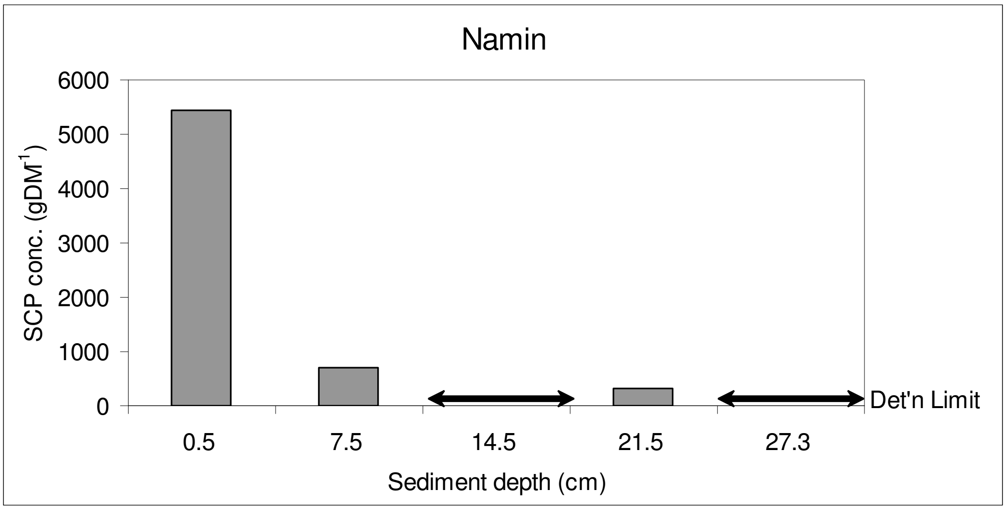
No SCPs are recorded in the 21 – 22 cm sample at Nambrackkeagh suggesting that 1850 lies between 15 and 21 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 2 – 3.5 cm for 1980 (the SCP concentration peak), and 5 – 7.5 cm for 1950 (the start of the rapid increase in SCP concentration). The available data would suggest that the rapid increase is likely to be above 7 cm and hence the other ranges shift up slightly.

Therefore best estimate SCP chronology:	1980:	2.5 – 3.5 cm
	1950:	6 – 7 cm
	1850:	17 – 21 cm

This is in reasonable agreement with preliminary data from radiometric dating (David Taylor's e-mail of 4 Dec 2003) which suggests an accumulation rate of 0.11 cm yr^{-1}. This rate would give 1850 at *c.* 17cm; 1950 at *c.* 6cm and 1980 at 2.5 cm.

Namin: C 396 419



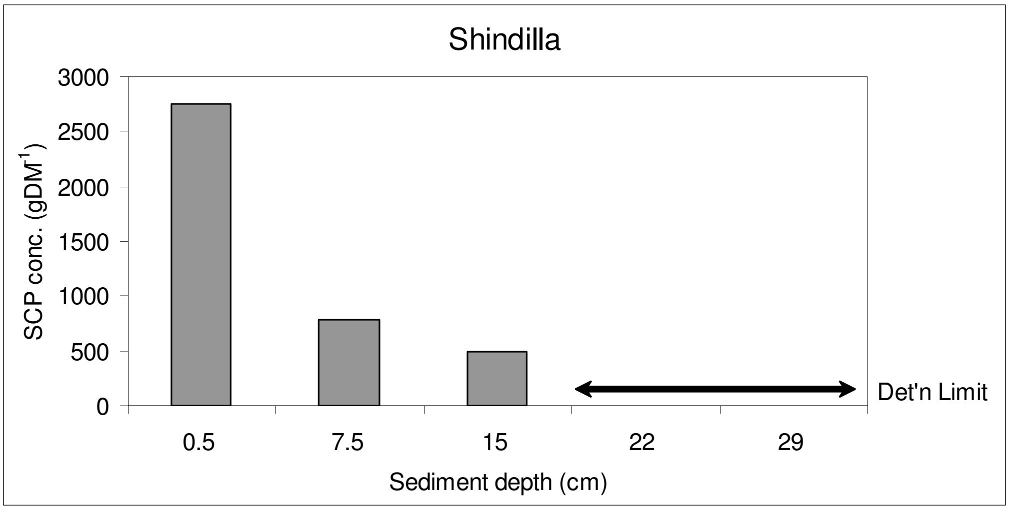
No SCPs are recorded in either the 14 – 15 cm sample or the 27 – 27.5 cm sample at Namin. Assuming no core smearing has occurred, the SCP concentration in the 14 – 15 cm sample is very low (< 138 gDM^{-1}) and the SCP record probably starts between 22 and 27 cm. If core smearing has occurred then the SCP record probably begins between 8 and 14 cm.

However, although the profile shape in the upper levels suggests a slow sediment accumulation rate, Namin is located close to other sites (e.g. Doo, Fad) that show relatively high levels of contamination and high SCP concentrations. Therefore, here it is assumed that the concentrations are real and the profile is correct, i.e. that no smearing has occurred.

This being the case, 1850 lies between 22 and 27 cm. Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 3 – 4.5 cm for 1980 (the SCP concentration peak), and 7.5 – 10 cm for 1950 (the start of the rapid increase in SCP concentration). The available data would suggest that the rapid increase is not likely to be below 7 cm and hence the other ranges must shift upwards, or otherwise there must have been changes in sediment accumulation rate.

Therefore best estimate SCP chronology:	1980:	2.5 – 3.5 cm
	1950:	6 – 7 cm
	1850:	22 – 24 cm

Shindilla: L 960 460

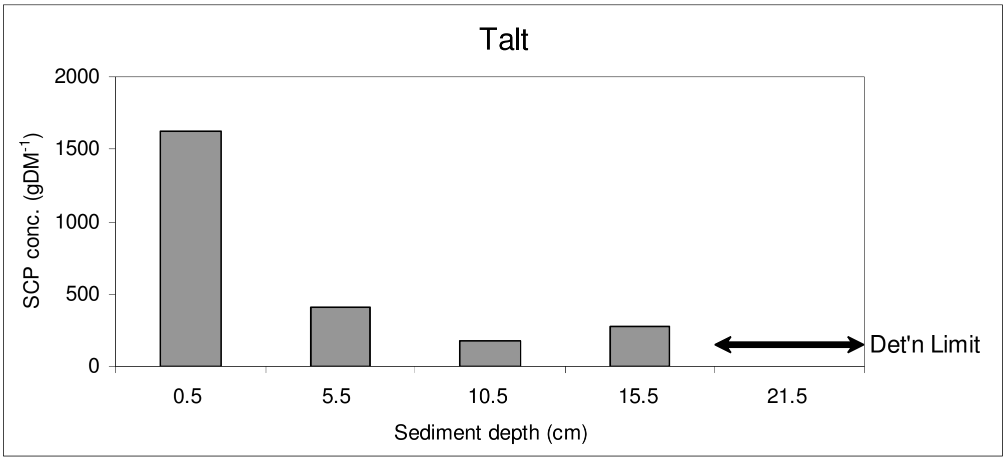


No SCPs are recorded in the 21 – 22 cm sample at Shindilla suggesting that 1850 lies between 15 and 21 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 2 – 3.5 cm for 1980 (the SCP concentration peak), and 5 – 7.5 cm for 1950 (the start of the rapid increase in SCP concentration). The available data would suggest that the rapid increase is likely to be above 7 cm and hence the other ranges shift up slightly.

Therefore best estimate SCP chronology:	1980:	2.5 – 3.5 cm
	1950:	6 – 7 cm
	1850:	18 – 21 cm

Talt: G 398 150

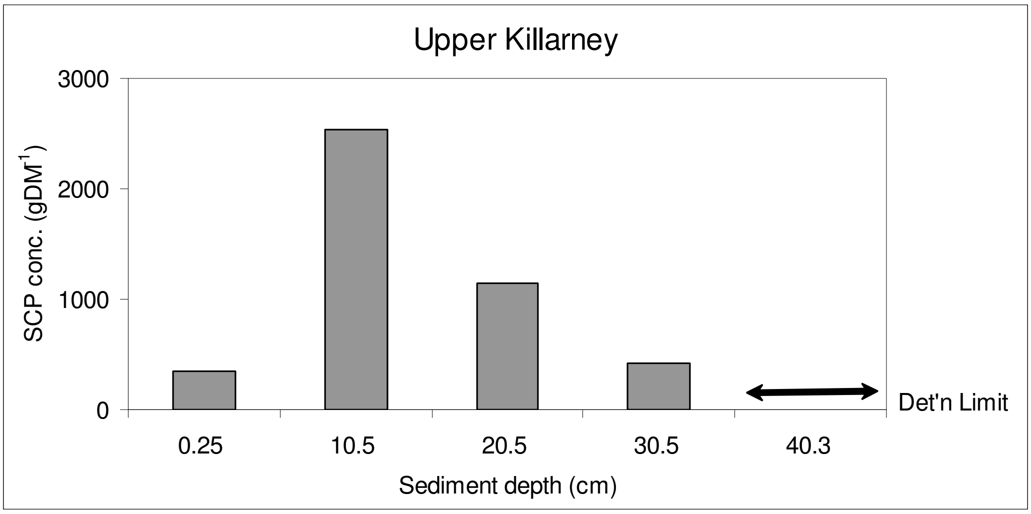


No SCPs are recorded in the 21 – 22 cm sample at Talt suggesting that 1850 lies between 16 and 21 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 2 – 3.5 cm for 1980 (the SCP concentration peak), and 5.5 – 7.5 cm for 1950 (the start of the rapid increase in SCP concentration). The available data would suggest that the rapid increase is unlikely to be below 6 - 7 cm and hence the other ranges shift up slightly.

Therefore best estimate SCP chronology:	1980:	2 – 3.5 cm
	1950:	5.5 – 7 cm
	1850:	18 – 21 cm

Upper Killarney: V 900 817



The received surface sediment sample was very small and whilst SCPs were identified in the sample, the errors are large and confidence in this concentration low.

No SCPs are recorded in the 40 – 40.5 cm sample at Upper Killarney suggesting that 1850 lies between 31 and 40 cm. The shape of the profile suggests that it is probably towards the lower end of this range.

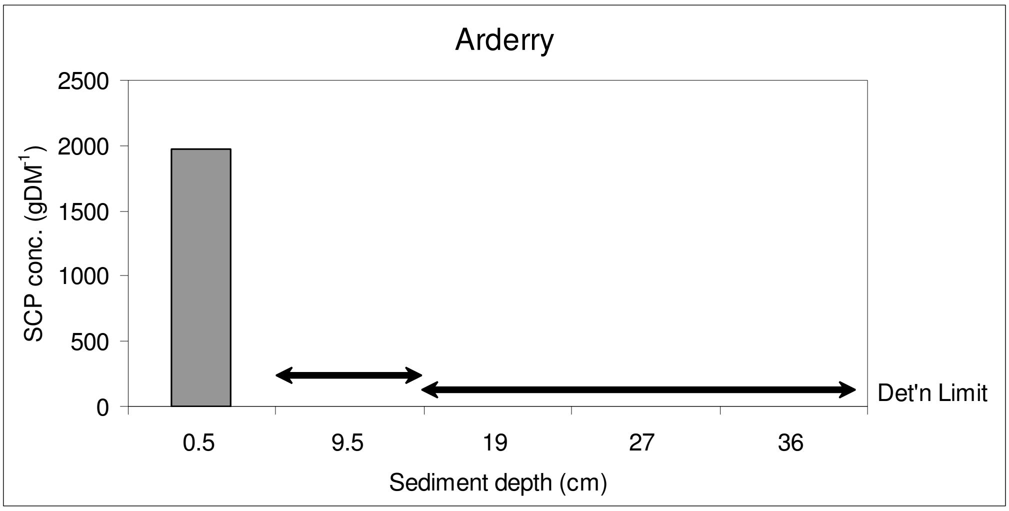
Assuming a reasonably constant rate of accumulation, this depth range for 1850 would suggest a depth of between 4.5 – 6 cm for 1980 (the SCP concentration peak), and 10.5 – 14 cm for 1950 (the start of the rapid increase in SCP concentration). The available data would suggest that the rapid increase is likely to be below 11 cm and hence the other ranges may shift up slightly.

Therefore best estimate SCP chronology:	1980:	4.5 – 6 cm
	1950:	11 – 14 cm
	1850:	35 – 40 cm

SECTION 3: SHORT OR CURTAILED SCP PROFILES.

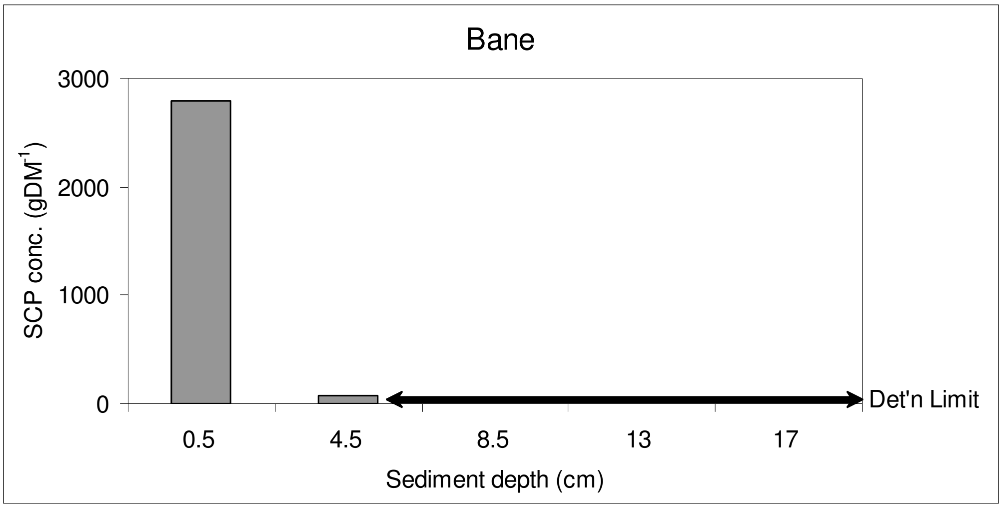
Possible explanations for SCP profiles of this type are described in the methods section. Here, it is assumed that the cores are intact and that the short profiles are due to slow sediment accumulation rate. Some support for this is derived from the location of these lakes. With the exception of Bane, all sites with short SCP profiles are clustered in two areas, the far south-west but mainly the mid-west area from Fee south to Naminna (see Figure 1).

Arderry: L 965 457



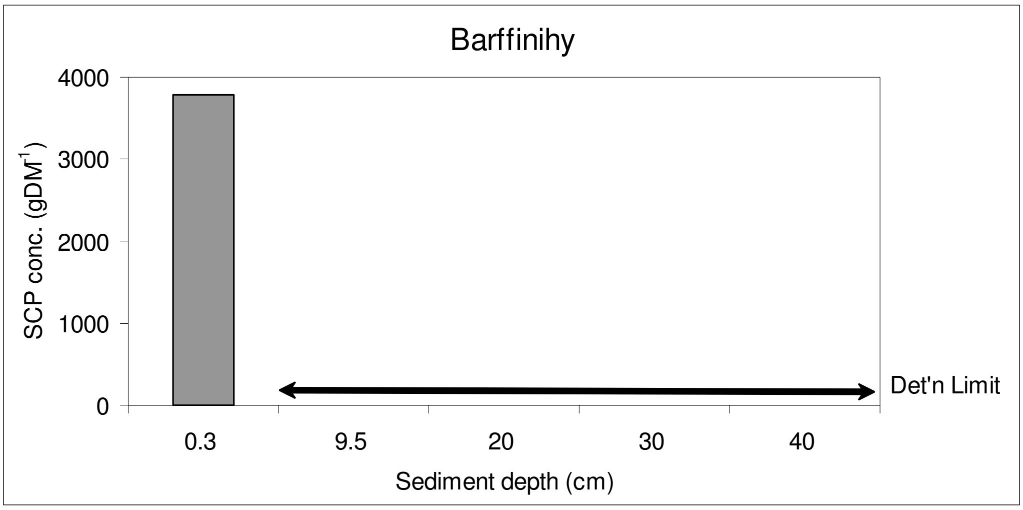
SCPs were only found in the surface sample of the Arderry core. Therefore, assuming this short SCP profile is due to a slow sediment accumulation rate, the whole post-1850 sediment record must lie above 9 cm. No further chronological information is can be determined.

Bane: N 550 712



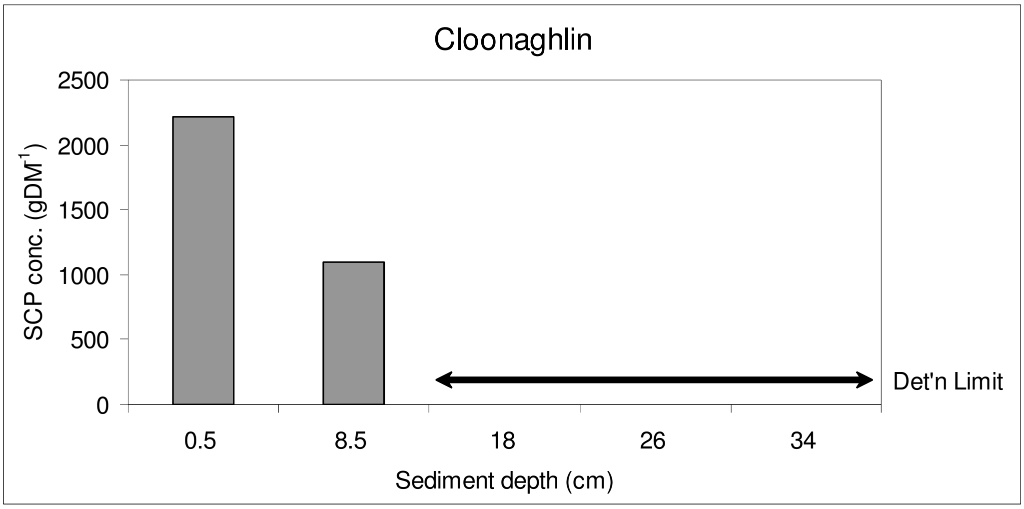
SCPs were only found in the two upper samples of the Bane core. The lower of these contained a very low concentration. Assuming the SCP concentration in this lower sample is not due to core smearing from the higher concentrations in the upper levels then 1850 must lie between 4.5 and 8 cm. If this is the case then, assuming a reasonably constant sediment accumulation rate, 1950 (and the rapid increase in SCP concentration) should be in the range 1.5 – 3 cm and 1980 (the SCP concentration peak) should be between 0.5 – 1.5 cm. It is not possible, from the available data, to confirm this further.

Barfinihy: V 850 768



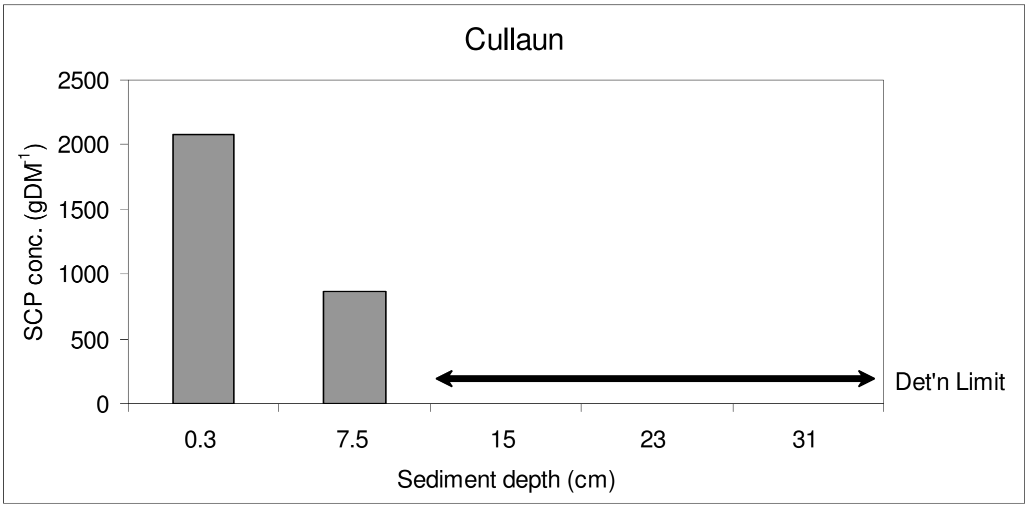
SCPs were only found in the surface sample of the Barfinihy core. Therefore, assuming this short SCP profile is due to a slow sediment accumulation rate, the whole post-1850 sediment record must lie above 9 cm. No further chronological information can be determined.

Cloonaghlin: V 610 709



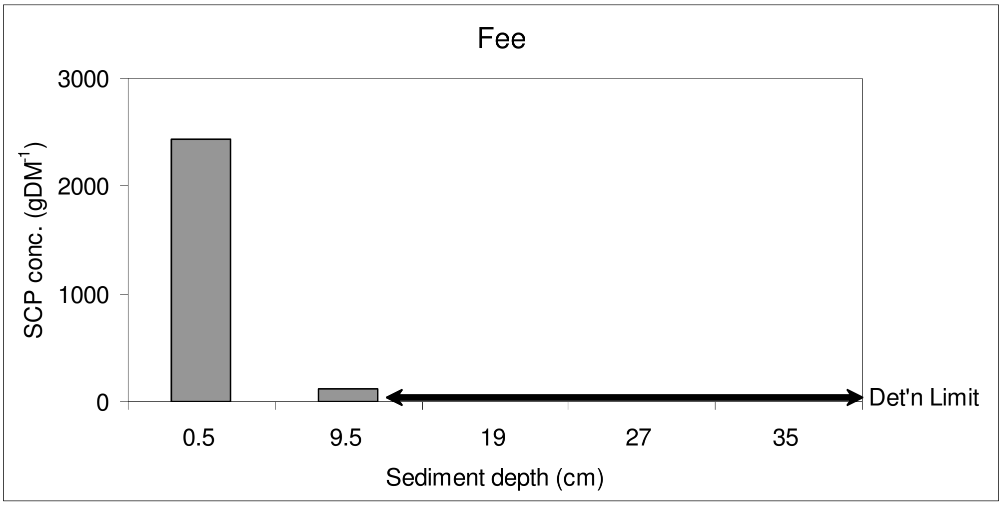
SCPs were only found in the two upper samples of the Cloonaghlin core. Therefore, assuming this short SCP profile is due to a slow sediment accumulation rate, then 1850 must lie between 9 and 17 cm. If this is the case then, assuming a reasonably constant sediment accumulation rate, 1950 (and the rapid increase in SCP concentration) should be in the range 3 – 6 cm and 1980 (the SCP concentration peak) should be between 1 – 2.5 cm. It is not possible, from the available data, to confirm this further.

Cullaun: R 315 905



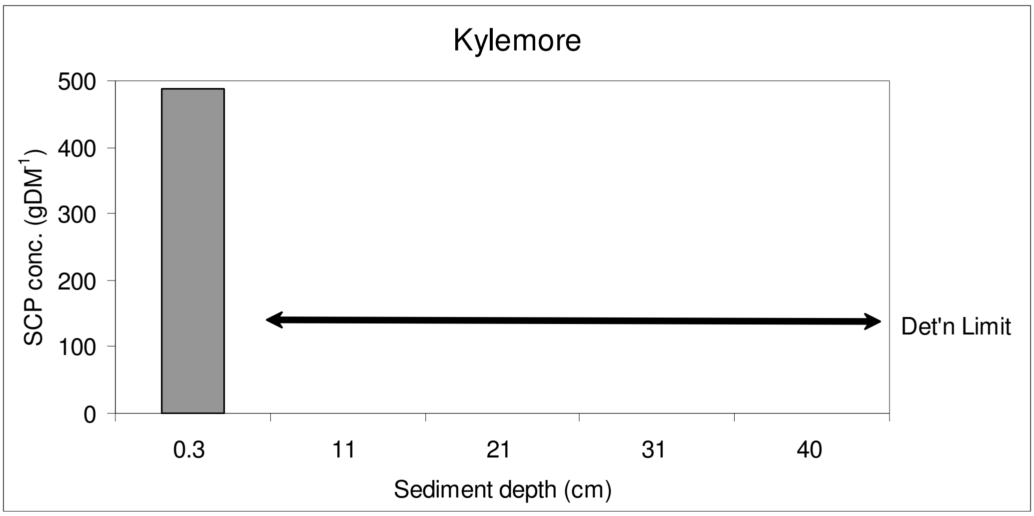
SCPs were only found in the two upper samples of the Cullaun core. Therefore, assuming this short SCP profile is due to a slow sediment accumulation rate, 1850 must lie between 8 and 14 cm. If this is the case then, assuming a reasonably constant sediment accumulation rate, 1950 (and the rapid increase in SCP concentration) should be in the range 2.5 – 5 cm and 1980 (the SCP concentration peak) should be between 1 – 2.5 cm. It is not possible, from the available data, to confirm this further.

Fee: L 790 613



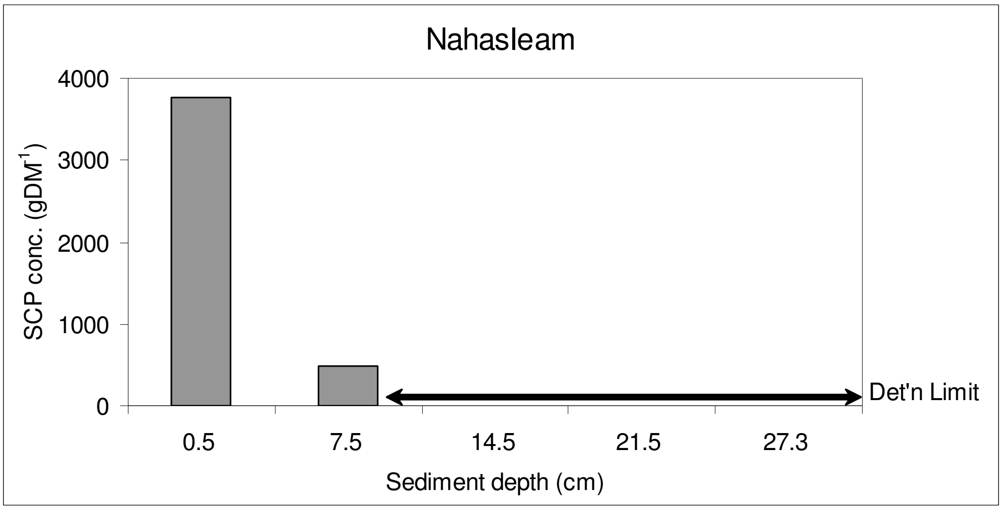
SCPs were only found in the two upper samples of the Fee core. The lower of these contained a very low concentration. Assuming the SCP concentration in this lower sample is not due to core smearing from the higher concentrations in the upper levels then 1850 must lie between 10 and 18 cm. If this is the case then, assuming a reasonably constant sediment accumulation rate, 1950 (and the rapid increase in SCP concentration) should be in the range 3.5 – 6.5 cm and 1980 (the SCP concentration peak) should be between 1.5 – 3 cm. It is not possible, from the available data, to confirm this further.

Kylemore: L 770 552



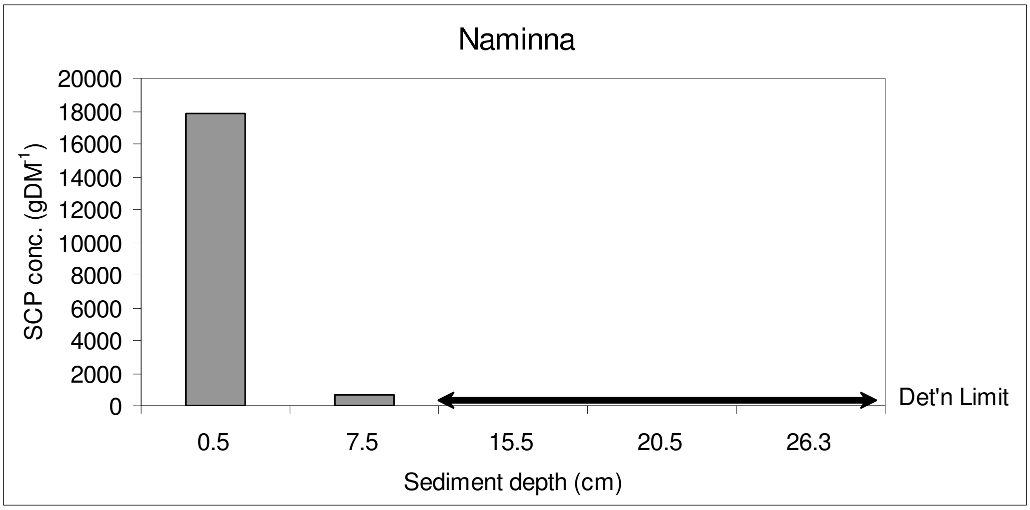
SCPs were only found in the surface sample of the Kylemore core. Therefore, assuming this short SCP profile is due to a slow sediment accumulation rate, the whole post-1850 sediment record must lie above 10 cm. No further chronological information can be determined.

Nahasleam: L 971 244



SCPs were only found in the two upper samples of the Nahasleam core. The lower of these contained a low concentration. Assuming the SCP concentration in this lower sample is not due to core smearing from the higher concentrations in the upper levels then 1850 must lie between 8 and 14 cm. If this is the case then, assuming a reasonably constant sediment accumulation rate, 1950 (and the rapid increase in SCP concentration) should be in the range 2.5 – 5 cm and 1980 (the SCP concentration peak) should be between 1 – 2.5 cm. It is not possible, from the available data, to confirm this further.

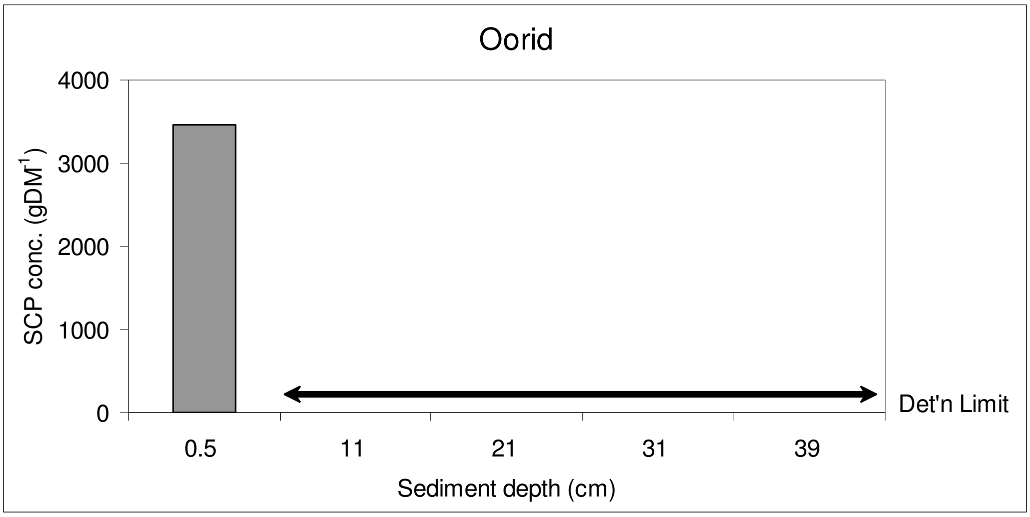
Naminna: R 176 710



SCPs were only found in the two upper samples of the Naminna core. The 7 – 8 cm sample contained a very low concentration. Assuming the SCP concentration in this lower sample is not due to core smearing from the higher concentrations in the upper levels then 1850 must lie between 8 and 15 cm. If this is the case then, assuming a reasonably constant sediment accumulation rate, 1950 (and the rapid increase in SCP concentration) should be in the range 2.5 – 5.5 cm and 1980 (the SCP concentration peak) should be between 1 – 2.5 cm. It is not possible, from the available data, to confirm this further.

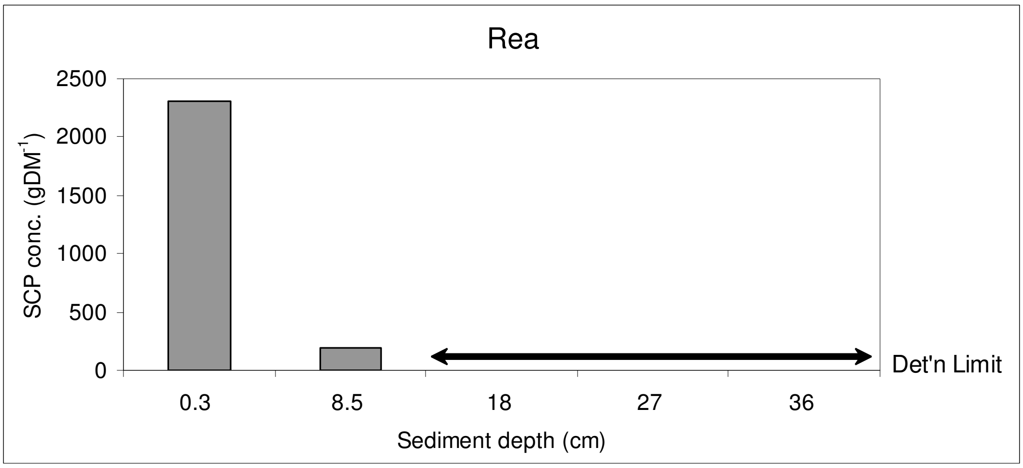
The surface sample from Naminna contains the highest SCP concentration found in the INSIGHT dataset and this may be due to the proximity of the Moneypoint coal-fired power station and the Tarbert oil-fired power station on the River Shannon to the south of this site. This concentration is three times as high as the peak concentration in an undated core taken in 1988. In this earlier core, the SCP profile was incomplete, but extended below a depth of 10 cm.

Oorid: L 930 460



SCPs were only found in the surface sample of the Oorid core. Therefore, assuming this short SCP profile is due to a slow sediment accumulation rate, the whole post-1850 sediment record must lie above 10 cm. No further chronological information can be determined.

Rea: M 615 155



SCPs were only found in the two upper samples of the Rea core. The lower of these contained a low concentration. Assuming the SCP concentration in this lower sample is not due to core smearing from the higher concentrations in the upper levels then 1850 must lie between 9 and 17 cm. If this is the case then, assuming a reasonably constant sediment accumulation rate, 1950 (and the rapid increase in SCP concentration) should be in the range 3 – 6 cm and 1980 (the SCP concentration peak) should be between 1 – 2.5 cm. It is not possible, from the available data, to confirm this further.

SECTION 4: SOME NOTES ON SPATIAL DISTRIBUTION.

Whilst the sites selected for inclusion within IN-SIGHT do not cover the whole of Ireland, some interesting spatial distributions are apparent in both surface sediment concentrations and in full core inventories and it is perhaps worth comparing these with the surface sediment concentration data generated for Ireland within the EU's FLAME project (Bowman & Harlock, 1998).

Surface sediment concentrations are influenced by sediment accumulation rate and therefore, it is difficult to compare these data between sites. However, two sites within the INSIGHT dataset show exceptional surface sediment SCP concentrations, Fad (13200 gDM^{-1}) and Naminna (17900 gDM^{-1}) and it is possible that these reflect atmospherically deposited contamination from local power station sources, Coolkeragh (north of Derry) and Tarbert and Moneypoint (north and south of the River Shannon east of Kilrush) respectively. These areas were also shown to be contaminated areas in the FLAME project.

However, a better inter-site comparison and a better indication of the full historical atmospherically deposited contamination receieved by a site is available from the use of SCP inventory data. A full comparison is not possible at all INSIGHT sites where the SCP record extended below the base of the core, but the spatial distribution can still highlight areas of contamination. In general, SCP inventories fall in the range 100 – 550 x 10^5 m^{-2}. Sites with lower inventories than this (Kylemore, Fee, Arderry, Talt and Bane) are all 'complete' profiles and lie in a band across central Ireland to the west. This was also identified as a low contamination area in Bowman and Harlock (1998).

Six sites in four areas show SCP inventories >700 x 10^5 m^{-2} and interestingly only one of these (Naminna) has a 'complete' profile i.e. the remainder should all have still higher SCP inventories than determined here, thus emphasising the distinction between contaminated and less-contaminated areas. Of these four areas, two were the ones highlighted by surface sediment concentrations, the north (Doo – 1800; Fad - 1040) and around the Shannon estuary (Naminna - 970) whilst the others can also be related to power station sources and were also identified by FLAME. They are: Kiltooris (760) in the north-west possibly influenced by the power station at Bellacorrick, and Tay (1030) and Dan (1130) near the east coast possibly influenced by emissions from electricity generation and industry around Dublin (e.g. North Wall generating station).

In summary, SCP spatial distributions confirm the contaminated areas identified in FLAME and high deposition areas can be attributed to electricity generation sources.

Conclusions

SCP profiles were seen to fall into three categories:

1. Incomplete, where SCPs were present in all samples. In these cases a depth for 1850 was extrapolated below the base of the core.
2. Complete, where the start of the SCP record, and hence 1850, lies within the length of the core. In these cases, depths for 1950 and 1980 were extrapolated assuming a reasonably constant sediment accumulation rate and assessed against available data.
3. Short or curtailed SCP profiles where SCPs were only present in the upper one or two samples. These were assumed to be due to slow sediment accumulation rates and were found to be clusterd in the mid-west and south-west.

Given the very small number and the coarse interval between samples any estimated chronology contains a lot of uncertainty. Further, to produce any chronology at all requires a number of assumptions. The main one of these is that sediment accumulation rate has not varied greatly over the last 150 years. Without this assumption, no chronologies can be attributed to the profiles, however, the lack of samples also means that it is not possible to determine whether this is a reasonable assumption or not. A number of external driving factors can influence sediment accumulation rate and it is therefore probable that this assumption is not valid in many cases.

At one site, Nambrackkeagh, where radiometric data were available, estimated SCP chronologies appear to give good agreement with the preliminary ^{210}Pb dates.

It is not possible to draw any conclusions regarding the regional variability of SCP profiles acoss Ireland and hence the validity of the dates used here. Independent dating of more detailed SCP profiles are required from across Ireland in order to calibrate the SCP chronology. This work would make the SCP dating technique more reliable in future studies.

Spatial distributions of SCP surface sediment concentrations and inventories were found to agree well with data from the EU funded project 'FLAME' (1994 – 1996). Areas of low contamination were identified in central areas and the mid- and south-west. Areas of high contamination were identified in the north (possibly influenced by the power station at Coolkeragh, north of Derry), the east (from industry around Dublin) and around the Shannon Estuary (Moneypoint and Tarbert power stations).

References

Bowman, J.J. & Harlock, S. (1998). The spatial distribution of characterised fly-ash particles and trace metals in lake sediments and catchment mosses: Ireland. *Water, Air and Soil Pollution* 106: 263-286.

Rose, N.L. (1994). A note on further refinements to a procedure for the extraction of carbonaceous fly-ash particles from sediments. *J. Paleolim.* 11: 201-204.

Rose, N.L. & Appleby, P.G. (in prep). Regional applications of lake sediment dating by spheroidal carbonaceous particles: The United Kingdom.

Rose, N.L. & Harlock, S. (1998) The spatial distribution of characterised fly-ash particles and trace metals in lake sediments and catchment mosses in the United Kingdom. *Water, Air and Soil Pollution* 106: 287-308.

Rose, N.L., Harlock, S., Appleby, P.G. & Battarbee, R.W. (1995). The dating of recent lake sediments in the United Kingdom and Ireland using spheroidal carbonaceous particle concentration profiles. *Holocene.* 5: 328-335.

Rose, N.L., Harlock, S. & Appleby, P.G. (1999). The spatial and temporal distributions of spheroidal carbonaceous fly-ash particles (SCP) in the sediment records of European mountain lakes. *Water, Air and Soil Pollution* 113: 1-32.

INSIGHT SCP data.

Site	Top depth (cm)	Bottom depth (cm)	Mean depth (cm)	SCP concentration (gDM^{-1})	90% confidence limits (gDM^{-1})	
KINDRUM	0	0.5	0.25	5259	6474	4044
KINDRUM	6	7	6.5	2706	3369	2043
KINDRUM	14	15	14.5	337	528	146
KINDRUM	22	23	22.5	0	0	0
KINDRUM	30	31	30.5	0	0	0
TALT	0	0.5	0.25	1624	2155	1094
TALT	5	6	5.5	405	685	124
TALT	10	11	10.5	173	343	3
TALT	15	16	15.5	274	465	84
TALT	21	22	21.5	0	0	0
FEEAGH	0	0.5	0.25	1326	2076	576
FEEAGH	9	10	9.5	1775	2780	771
FEEAGH	18	19	18.5	2183	2896	1470
FEEAGH	27	28	27.5	281	557	6
FEEAGH	35	36	35.5	618	1046	190
KEEL	0	0.5	0.25	1463	2291	635
KEEL	10	11	10.5	1931	2777	1085
KEEL	20	21	20.5	340	674	7
KEEL	30	31	30.5	0	0	0
KEEL	40	41	40.5	0	0	0
O'FLYNN	1	2	1.5	0	0	0
O'FLYNN	9	10	9.5	1190	1602	778
O'FLYNN	19	20	19.5	998	1344	652
O'FLYNN	29	30	29.5	694	1087	301
O'FLYNN	41	42	41.5	176	348	4
McNEAN	0	0.5	0.25	1523	2269	777
McNEAN	4	5	4.5	1057	1790	325
McNEAN	9	10	9.5	651	1102	200
McNEAN	14	15	14.5	0	0	0
McNEAN	18	19	18.5	0	0	0
LENE	0	0.5	0.25	1333	1866	799
LENE	6	7	6.5	406	636	176
LENE	13	14	13.5	1093	1416	770
LENE	20	21	20.5	158	313	3
LENE	28	29	28.5	287	486	88
ANNAGHMORE	0	0.5	0.25	559	876	243
ANNAGHMORE	4	5	4.5	852	1167	536
ANNAGHMORE	9	10	9.5	501	784	217
ANNAGHMORE	14	15	14.5	147	291	3
ANNAGHMORE	19	20	19.5	0	0	0
EASKY	0	0.5	0.25	2760	3511	2010
EASKY	7	8	7.5	3112	4076	2148
EASKY	13	14	13.5	1152	1716	587
EASKY	19	20	19.5	181	357	4
EASKY	26	27	26.5	0	0	0

NAHASLEAM	0	0.5	0.25	3757	5404	2110
NAHASLEAM	7	8	7.5	481	953	10
NAHASLEAM	14	15	14.5	0	0	0
NAHASLEAM	21	22	21.5	0	0	0
NAHASLEAM	27	27.5	27.25	0	0	0
BANE	0	0.5	0.25	2796	3831	1760
BANE	4	5	4.5	74	147	1
BANE	8	9	8.5	0	0	0
BANE	12	13	12.5	0	0	0
BANE	16	17	16.5	0	0	0
FEE	0	0.5	0.25	2429	3493	1364
FEE	9	10	9.5	0	0	0
FEE	18	19	18.5	0	0	0
FEE	26	27	26.5	0	0	0
FEE	34	35	34.5	0	0	0
DAN	0	0.5	0.25	5125	6639	3610
DAN	8	9	8.5	1963	2748	1178
DAN	16	17	16.5	3980	5359	2601
DAN	24	25	24.5	1538	2408	668
DAN	30	31	30.5	904	1530	277
DOO	0	0.5	0.25	2485	3575	1396
DOO	7	8	7.5	1957	2740	1174
DOO	15	16	15.5	7468	9298	5639
DOO	23	24	23.5	3493	4575	2410
DOO	30	31	30.5	587	994	180
BARRA	0	0.5	0.25	4843	6275	3412
BARRA	9	10	9.5	1697	2440	953
BARRA	18	19	18.5	2111	2956	1266
BARRA	26	27	26.5	581	1151	12
BARRA	35	36	35.5	318	538	98
NAMINN	0	0.5	0.25	5441	6980	3902
NAMINN	7	8	7.5	713	1411	14
NAMINN	14	15	14.5	0	0	0
NAMINN	21	22	21.5	315	624	6
NAMINN	27	27.5	27.25	0	0	0
KILTOORIS	0	0.5	0.25	668	1131	205
KILTOORIS	9	10	9.5	1960	2819	1101
KILTOORIS	18	19	18.5	4360	5785	2936
KILTOORIS	26	27	26.5	2197	2879	1516
KILTOORIS	34	35	34.5	2012	2893	1130
ARDERRY	0	0.5	0.25	1977	2946	1008
ARDERRY	9	10	9.5	0	0	0
ARDERRY	18	19	18.5	0	0	0
ARDERRY	26	27	26.5	0	0	0
ARDERRY	35	36	35.5	0	0	0
SHINDILLA	0	0.5	0.25	2751	4307	1194
SHINDILLA	7	8	7.5	786	1330	241
SHINDILLA	14	15	14.5	493	976	10
SHINDILLA	21	22	21.5	0	0	0
SHINDILLA	28	29	28.5	0	0	0

BALLYNAKILL	0	0.5	0.25	2305	3315	1295
BALLYNAKILL	9	10	9.5	2056	3063	1048
BALLYNAKILL	18	19	18.5	926	1567	284
BALLYNAKILL	26	27	26.5	155	306	3
BALLYNAKILL	35	36	35.5	0	0	0
VEAGH	0	0.5	0.25	4434	5639	3229
VEAGH	9	10	9.5	3020	4066	1973
VEAGH	18	19	18.5	2847	3986	1708
VEAGH	25	26	25.5	738	1249	227
VEAGH	33	34	33.5	686	1074	298
NAMBRACKKEAGH	0	0.5	0.25	4173	5619	2727
NAMBRACKKEAGH	7	8	7.5	808	1368	248
NAMBRACKKEAGH	14	15	14.5	462	914	9
NAMBRACKKEAGH	21	22	21.5	0	0	0
NAMBRACKKEAGH	26	26.5	26.25	0	0	0
DUNGLOW	0	0.5	0.25	6127	8026	4228
DUNGLOW	3	4	3.5	1463	2292	635
DUNGLOW	6	7	6.5	1007	1705	309
DUNGLOW	9	10	9.5	497	984	10
DUNGLOW	11	12	11.5	428	848	9
FAD	0	0.5	0.25	13199	15010	11387
FAD	6	7	6.5	1775	2553	997
FAD	12	13	12.5	1097	1718	476
FAD	18	19	18.5	290	575	6
FAD	26	27	26.5	491	831	151
MUCKANAGH	0	0.5	0.25	<158	0	0
MUCKANAGH	10	11	10.5	345	539	150
MUCKANAGH	20	21	20.5	577	860	294
MUCKANAGH	30	31	30.5	204	345	63
MUCKANAGH	40	41	40.5	<145	0	0
BARFFINIHY	0	0.5	0.25	3792	4623	2961
BARFFINIHY	9	10	9.5	<183	0	0
BARFFINIHY	19	20	19.5	<121	0	0
BARFFINIHY	29	30	29.5	<169	0	0
BARFFINIHY	39	40	39.5	<169	0	0
REA	0	0.5	0.25	2312	3068	1557
REA	8	9	8.5	193	383	4
REA	17	18	17.5	<135	0	0
REA	26	27	26.5	0	0	0
REA	35	36	35.5	0	0	0
CLOONAGHLIN	0	0.5	0.25	2219	2944	1494
CLOONAGHLIN	8	9	8.5	1100	1581	618
CLOONAGHLIN	17	18	17.5	<156	0	0
CLOONAGHLIN	25	26	25.5	<237	0	0
CLOONAGHLIN	33	34	33.5	<209	0	0
CULLAUN	0	0.5	0.25	2073	2598	1549
CULLAUN	7	8	7.5	867	1247	487
CULLAUN	14	15	14.5	<162	0	0
CULLAUN	22	23	22.5	<195	0	0
CULLAUN	30	31	30.5	<225	0	0
TAY	0	0.5	0.25	3015	3949	2081

TAY	8	9	8.5	1035	1489	581
TAY	17	18	17.5	3465	4489	2441
TAY	26	27	26.5	754	1277	232
TAY	35	36	35.5	310	615	6
NAMINNA	0	0.5	0.25	17896	20141	15650
NAMINNA	7	8	7.5	668	1047	290
NAMINNA	15	16	15.5	<277	0	0
NAMINNA	20	21	20.5	<205	0	0
NAMINNA	26	26.5	26.25	<233	0	0
OORID	0	0.5	0.25	3467	4375	2559
OORID	10	11	10.5	<162	0	0
OORID	20	21	20.5	<242	0	0
OORID	30	31	30.5	<177	0	0
OORID	38	39	38.5	<209	0	0
UPPER	0	0.5	0.25	347	687	7
UPPER	10	11	10.5	2540	3205	1875
UPPER	20	21	20.5	1145	1705	584
UPPER	30	31	30.5	420	711	129
UPPER	40	40.5	40.25	<213	0	0
KYLEMORE	0	0.5	0.25	488	764	212
KYLEMORE	10	11	10.5	0	0	0
KYLEMORE	20	21	20.5	0	0	0
KYLEMORE	30	31	30.5	0	0	0
KYLEMORE	39	40	39.5	0	0	0
BUNNY	0	0.5	0.25	1906	2612	1200
BUNNY	6	7	6.5	1053	1568	537
BUNNY	12	13	12.5	371	736	7
BUNNY	18	19	18.5	200	395	4
BUNNY	24	25	24.5	<259	0	0

Appendix 7 Full names (including authorities) for diatoms with abundances > 2% in sediment samples analysed as part of IN-SIGHT WP2 & WP3

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
Aulacoseira islandica (O.Muller) Simonsen subsp. *helvetica* (O.M.)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. *lineata* (Ehr.)Van Heurck
Cocconeis placentula Ehrenberg var. *placentula*
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 pseudoswaz*i (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

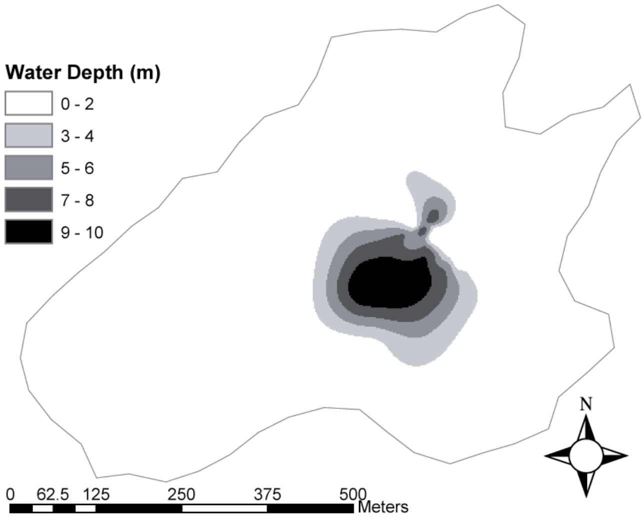
Appendix 8 Descriptions of main differences in diatom assemblages between sediment core top and bottom samples

CRL	Diatom assemblages	
	Core top sample	**Core bottom sample**
Annaghmore	Benthic alkaliphilous diatoms dominate the surface sedimente assemblage: *Amphora pediculus, Mastogloia lacustris, Mastogloia elliptica*	*Fragilaria brevistriata, Eunotia arcus, Mastogloia lacustris*
Arderry	Planktonic diatoms dominate the assemblage. Oligo-mesotrophic *Aulacoseira ambigua* and *Cyclotella kuetzingiana* are the most abundant taxa. Benthic circumneutral *Achnanthes minutissima* is also present	The reference assemblage is dominated by the planktonic *Cyclotella kuetzingiana*, along with the benthic *Achnathes minutissima*
Ballynakill	*Aulacoseira subarctica, Fragilaria capucina, Achnanthes minutissima, Cyclotella ocellata*	*Cyclotella ocellata, Cyclotella comensis, Achnanthes minutissima*
Bane	*Fragilaria brevistriata* and *Cyclotella praetermissa*	Assemblage dominated by small benthic taxa: *Fragilaria brevistriata, Fragilaria construens*
Barfinnihy	Circumneutral diatoms dominate the surface sediment assemblage. Benthic *Achnanthes minutissima* is the most abundant diatom, followed by the planktonic *Cyclotella kuetzingiana* and *Cyclotella stelligera*	A similar assemblage dominates the reference sediment sample made up by *Achnanthes minutissima, Cyclotella kuetzingiana* and *Cyclotella stelligera*
Barra	Small benthic *Fragilaria exigua* and the acidophilous *Eunotia incisa* are the more abundant diatoms	Benthic diatoms such as *Cymbella perminuta* and *Tabellaria flocculosa* dominate the assemblage
Bunny	Assemblage dominated by benthic *Amphora pediculus* and *Mastogloia lacustris* and centric *Cyclotella distinguenda*	*Amphora pediculus, Mastogloia lacustris*
Cloonaghlin	Plankton assemblage dominated by *Cyclotella stelligera* along with benthic *Achnanthes minutissima*	Planktonic *Cyclotella kuetzingiana* is the dominant diatom. Benthic *Fragilaria exigua* is also present
Cullaun	Planktonic dominated assemblage: *Cyclotella comensis*	Benthic dominated assemblage with alkaline and eutrophic taxa. *Amphora pediculus* is the dominant taxon
Dan	Circumneutral *Fragilaria virescens* is the most abundant diatom. Acidophilous taxa such as *Tabellaria flocculosa, Eunotia incisa* and *Pinnularia subcapitata*	Acidophilous *Tabellaria flocculosa* and *Eunotia pectinalis*
Doo	Circumneutral to acidobiontic taxa characterise the surface sediment assemblage. Most abundant taxa are *Achnanthes minutissima, Tabellaria quadriseptata* and *Tabellaria flocculosa*. Planktonic eutrophic *Asterionella formosa* is also present	Benthic *Achnanthes minutissima* and *Tabellaria flocculosa* dominate
Dunglow	Small benthic *Fragilaria exigua* dominates the surface sediment assemblage	*Fragilaria exigua* comprises nearly 50% of the reference sediment assemblage
Easky	A non-planktonic assemblage dominated by *Fragilaria exigua* and *Achnanthes minutissima*	Plankton dominated assemblage, with circumneutral *Cyclotella kuetzingiana* and *Cyclotella polymorpha. Fragilaria exigua* is also abundant
Fad	Circumneutral diatoms dominate the	None preserved

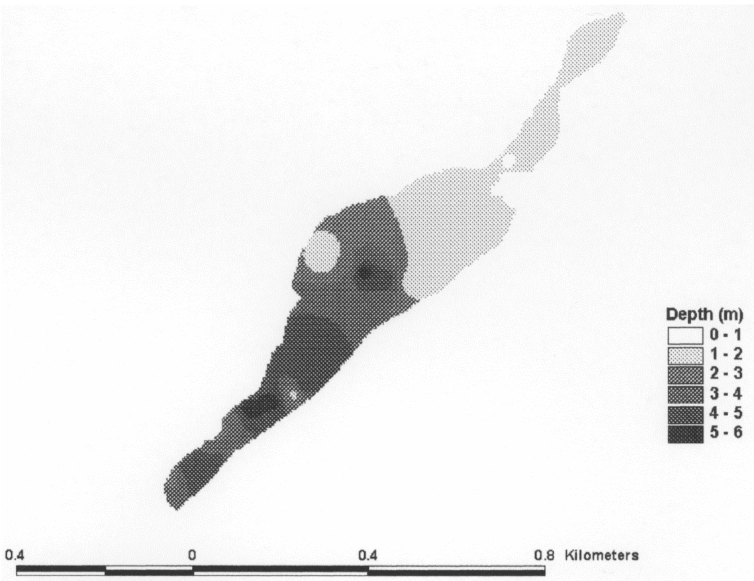
	surface sediment assemblage. Planktonic diatom *Cyclotella comensis* is the most abundant diatom. Benthic *Fragilaria exigua, Achnanthes minutissima* also dominate the assemblage	
Fee	Planktonic dominated community comprising eutrophic *Aulacoseira ambigua, Cyclotella kuetzingiana, Asterionella formosa* and benthic *Achnanthes minutissima*	Planktonic *Cyclotella kuetzingiana* is the dominant diatom
Feeagh	Planktonic *Aulacoseira subarctica* dominates the surface sediment diatom assemblage *(40%)*	*Achnanthes minutissima, Cyclotella comensis* and *Cyclotella kuetzingiana* are the most abundant taxa in the reference sample
Keel	*Asterionella ralfsii* is the dominant diatom in the surface sediment samples reaching an abundance of 66% of the total diatom frustule count. *A.ralfsii* is considered an indicator of nutrient enrichment	Bottom sample assemblage is composed of *Asterionella ralfsii (21%)* and the acidophilous and mesotrophic*Tabellaria floculosa*
Kiltooris	Surface sediment sample is dominated by *Achnanthes minutissima* and *Cyclotella comensis*	*Achnanthes minutissima* and *Cymbella microcephala* dominate the bottom diatom assemblage.
Kindrum	*Achnanthes minutissima* and *Cyclotella comensis* are the dominant taxa	*Cyclolla comensis* is also the most abundant diatom. *Achnanthes minutissima* and *Cymbella microcephala* are the second most abundant diatoms at the bottom sample assemblage.
Kylemore	Meso-eutrophic *Asterionella ralfsii* is the most abundant diatom. Benthic *Achnanthes minutissima* is also abundant	Reference sample is characterised by a mixture of benthic and planktonic circumneutral taxa: *Achnanthes minutissima, Cyclotella striata, Cyclotella comensis*
Lene	Alkaline dominated assemblage with planktonic and epiphytic taxa. Abundant taxa are *Stephanodiscus parvus, Fragilaria brevistriata* and *Cyclotella radiosa*	Eutrophic and alkaline assemblage with benthic and planktonic diatoms: *Mastogloia lacustris, Cyclotella radiosa, Amphora pediculus* and *Fragilaria brevistriata*
McNean	Plankton dominated assemblage characterised by eutrophic *Cyclostephanos dubius* and oligo-mesotrophic *Aulacoseira subarctica* and *Cyclotella comensis*	*Aulacoseira subarctica, Cyclostephanos dubius, Cyclotella comensis* also characterise the down-core assemblages
Muckanagh	Non-planktonic assemblage with alkaline and eutrophic to indifferent taxa: *Fragilaria brevistriata, Amphora pediculus, Mastogloia lacustris*	Alkaline dominated assemblage with benthic taxa: *Mastogloia lacustris, Fragilaria brevistriata*
Nahasleam	The circumneutral *Fragilaria exigua* dominates the assemblage; acidic diatoms as *Frustulia saxonica* are also abundant	The reference assemblage is dominated by benthich circumneutral diatoms such as *Achnanthes minutissima, Fragilaria exigua, Cymbella gracilis*
Nambrackkeagh	Surface sediment sample shows low abundance of *Cyclotella kuetzingiana* and is dominated by *Achnanthes minutissima* and *Fragilaria exigua*	Planktonic diatom *Cyclotella kuetzingiana* is the most abundant diatom species in the bottom sample. *Eunotia incisa* is also present
Naminn	The surface sediment assemblage is composed by circumneutral diatoms such as *Achnanthes minutissima, Cyclotella comensis* and *Fragilaria exigua*	Benthic *Fragilaria exigua* and *Achnanthes minutissima* are the most abundant diatoms
Naminna	Benthic circumneutral *Fragilaria*	Non planktonic assemblage characterizes the

	exigua and acidophilous *Cymbella gracilis* dominate the surface sediment assemblage	reference sediment sample with *Cymbella gracilis, Achnanthes minutissima* and *Eunotia incisa*
O'Flynn	Benthic assemblage dominated by *Achnanthes lanceolata, Cocconeis neothumensis* and *Amphora pediculus*	*Achnanthes lanceolata, Amphora pediculus*
Oorid	Planktonic taxa dominate the surface sediment sample (*Cyclotella comensis, Cyclotella kuetzingiana*). Benthic *Achanthes minutissima* is also present	Planktonic *Cyclotella kuetzingiana* and *Cyclotella comensis* are the dominant taxa
Rea	Assemblage dominated by planktonic *Cyclotella comensis.* Benthic alkaline taxa are also common: *Mastogloia lacustris, Gomphonema lateripunctatum*	*Mastogloia lacustris, Fragilaria brevistriata*
Shindilla	*Cyclotella kuetzingiana, Cyclotella comensis* and Achnanthes *minutissima*	Planktonic *Cyclotella kuetzingiana* and *Cyclotella comensis* are the dominant taxa
Talt	*Cyclotella comensis, Fragilaria brevistriata, Achnanthes minutissima*	*Fragilaria brevistriata, Fragilaria construens, Amphora pediculus*
Tay	Non-planktonic assemblage comprising *Achnanthes helvetica, Achnanthidium* spp. and *Eunotia incisa*	Planktonic *Aulacoseira* species dominate the reference samples (*Aulacoseira subarctica, Aulacoseira alpigena*)
Upper	Circumneutral *Achnanthes minutissima* and acidophilous *Tabellaria flocculosa*	Benthic *Achnanthes minutissima* and *Anomoeoneis garrensis*
Veagh	Plankton dominated assemblage characterised by *Cyclotella kuetzingiana,* and acidophilous *Tabellaria flocculosa*	Planktonic *Cyclotella kuetzingiana* and *Cyclotella schumannii* dominate the reference sample

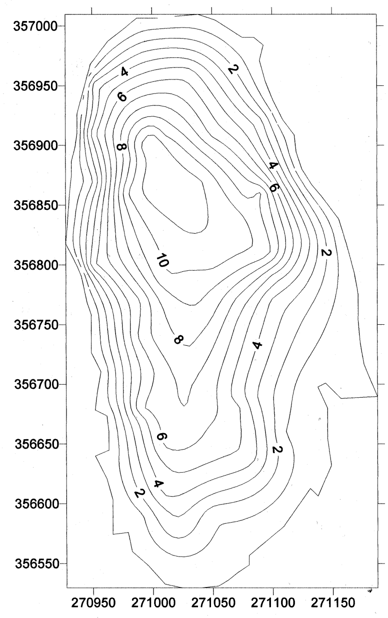
Appendix 9 Bathymetric maps for the seven impacted lakes studied as part of WP3



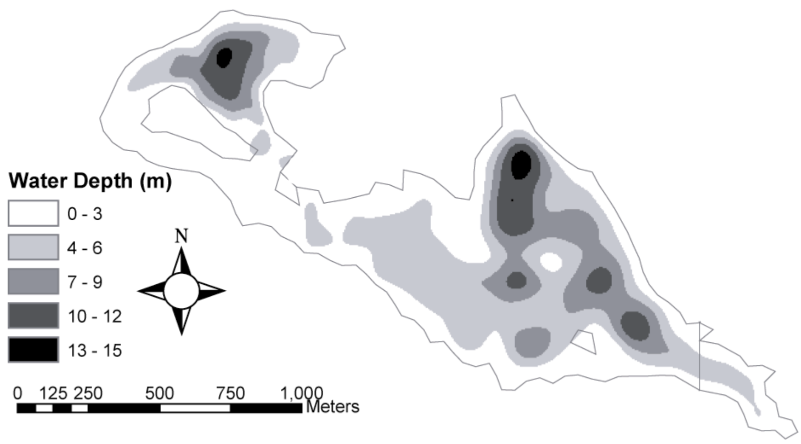
Atedaun



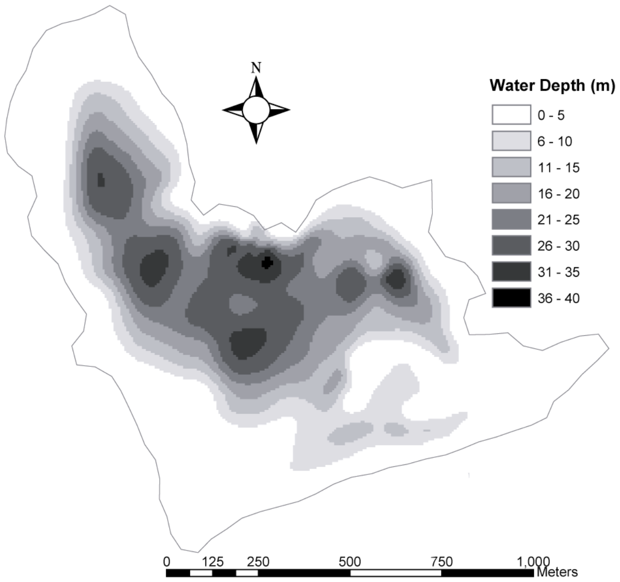
Ballybeg (source Wemaere, 2001)


357000
356950
356900
356850
356800
356750
356700
356650
356600
356550
270950
271000
271050
271100
271150

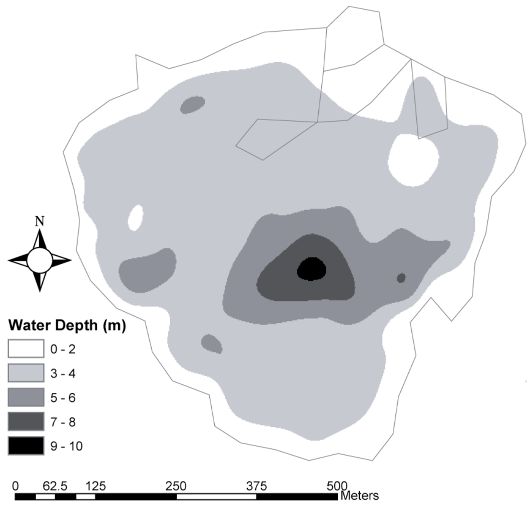
Crans


Water Depth (m)
0 - 3
4 - 6
7 - 9
10 - 12
13 - 15
N
0 125 250 500 750 1,000
Meters

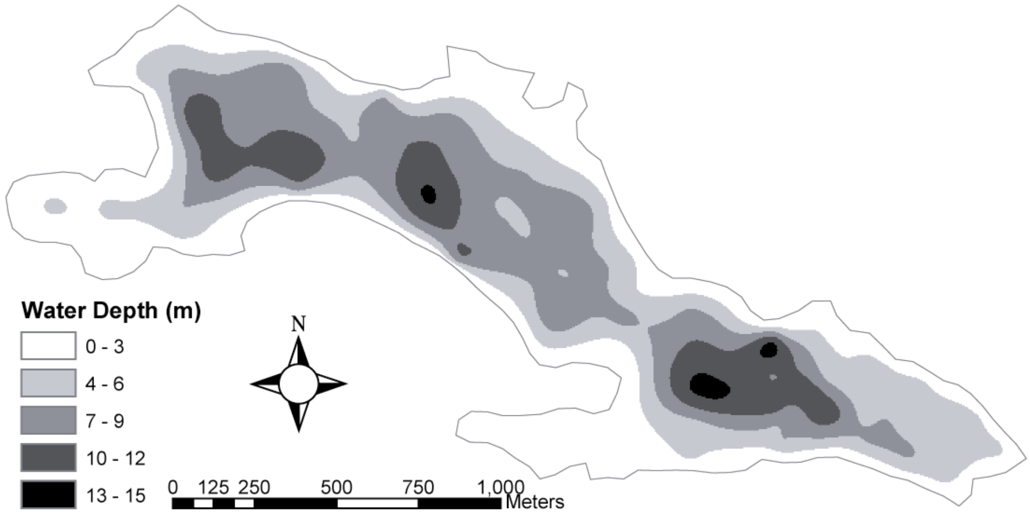
Egish



Inchiquin



Mullagh



Sillan

Appendix 10 Summary of Cladocera counts (raw data) for core top and bottom sediment samples from WP3 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	40-4	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**

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