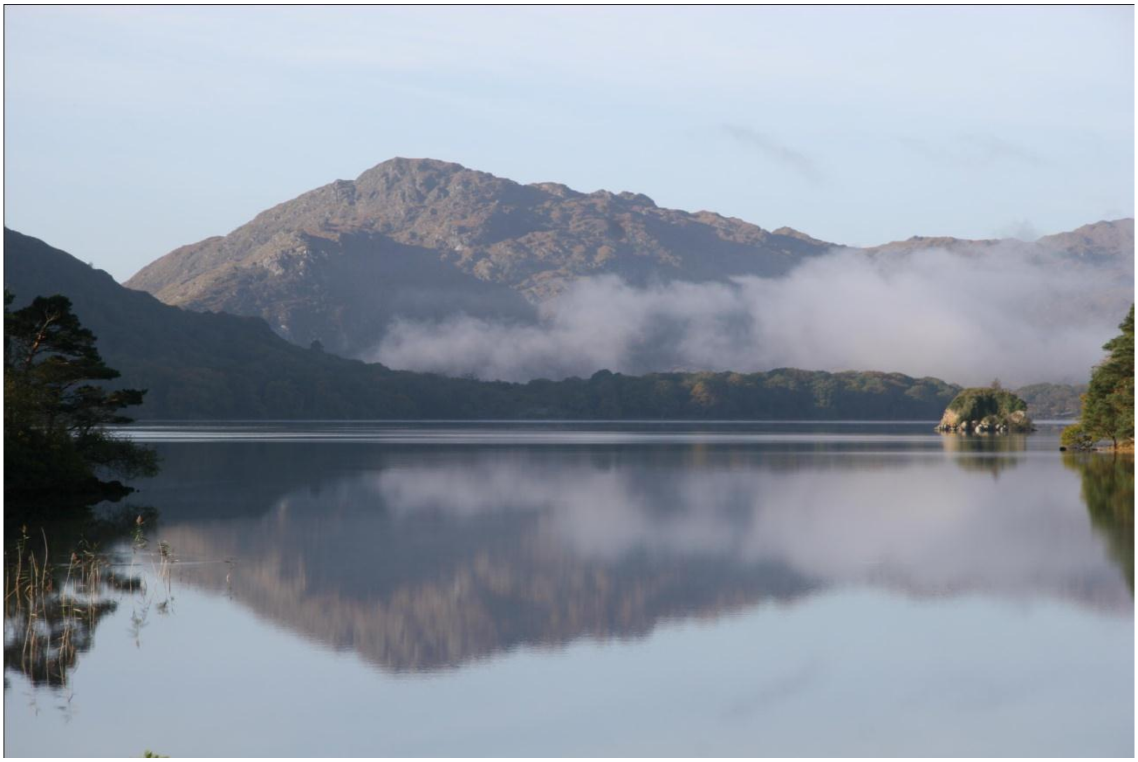
ILLUMINATE

Past, current and future **I**nteractions between pressures, chemica**L** status and bio**L**ogical q**U**ality ele**M**ents for lakes **IN** contr**A**sting catchmen**T**s in Ir**E**land.

EPA/ERTDI PROJECT # 2005-W-MS-40

FINAL REPORT



Muckross, County Kerry, Ireland

Contributing co-authors: Catherine Dalton, Eleanor Jennings, David Taylor, Barry O'Dwyer, Sarah Murnaghan, Kim Bosch, Elvira de Eyto, Karin Sparber

www.palaeolim.ie

Images of fieldwork: (clockwise from lowermost, left) Mask; Feeagh; Leane; launching the boat, Bunaveela; sediment coring, Kerry lakes; sediment core sampling.

Table of contents

Acknowledgements

A successful outcome to ILLUMINATE would not have been possible without the support and help of numerous individuals and institutions. We would like to thank in particular Alice Wemaëre of the EPA and external members of the project steering committee for their guidance and support throughout the project. Thanks are also due to several colleagues for their assistance with field and laboratory work; to several institutions and individuals for permitting use of their data; to Guangjie Chen for the cladoceran analyses; to Aine Gormley, Fergel Nugent and Theresa Hughes for help with geochemical analysis; to Susanne Linnane and colleagues at Dundalk Institute of Technology for allowing levels of sediment-based pigment remains to be determined using their facilities; to the C4i team at Met Éireann and to the Rossby Centre (Swedish Meteorological and Hydrological Institute) for provision of future climate data; to Conservation Services (County Kerry, Ireland) for access to data and reports on the Killarney lakes, including unpublished findings; and to the numerous landowners, estate managers and Marine Institute staff who facilitated access to the study sites.

Disclaimer

June 2010

Project team members

David Taylor (Principal Investigator), Eleanor Jennings*, Sarah Murnaghan, Kim Bosch, Barry O'Dwyer, Norman Allott
School of Natural Sciences
Trinity College
University of Dublin
Dublin 2
Ireland
Tel. +353 (0)1 896 1581
E-mail: taylord@tcd.ie

*Now at:
Department of Applied Sciences
Dundalk Institute of Technology
Dublin Road
Dundalk
Ireland
Tel: + 353 (0) 42 9381804 Ext.: 2804
E-mail: Eleanor.jennings@dkit.ie

Catherine Dalton (Project Manager), Karin Sparber
Department of Geography
Mary Immaculate College
University of Limerick
South Circular Road
Limerick
Ireland
Tel: + 353 (0) 61 204 931
E-mail: catherine.dalton@mic.ul.ie

Elvira de Eyto, Phil McGinnity
Marine Institute
Furnace
Newport
Co. Mayo
Ireland
Tel: + 353 (0) 98 42305
E-mail: elvira.deeyto@marine.ie

Phil Jordan
School of Environmental Sciences,
University of Ulster,
Cromore Road,
Coleraine BT52 1SA
Northern Ireland
Tel. +44 (0)2870 324 401
E-mail: p.jordan@ulster.ac.uk

Helen Bennion,
Environmental Change Research Centre
University College London
Gower Street
London WCIE 6BT
England
Tel. +44 (0)20 7679 0519
E-mail: h.bennion@geog.ucl.ac.uk

David Lenihan
Kerry County Council
Aras An Chontae
Rathass
Tralee
Ireland
Tel. +44 (0)66 718 3500
E-mail: dlenihan@kerrycoco.ie

Paddy Kavanagh
ESBI
Lisaun Industrial Estate
Galway
Ireland
Tel. +44 (0)91 746 804
E-mail: Paddy.Kavanagh@esbi.ie

Acronyms, abbreviations & symbols used in the text

The following provides an explanation for the various acronyms, abbreviations and symbols used in this research report.

Acronym, abbreviation or symbol	Explanation	Acronym, abbreviation or symbol	Explanation
˚C	degrees centigrade	kg	kilogram
µg	Microgram	km	kilometre
µS	Microsecond	KMM	Kirk McClure Morton (Engineering Consultants)
^{117}Cs	radioactive isotope of Caesium	l	litre
^{13}C	one of the stable isotopes of Carbon	LIMPACS	Human impacts on lake ecosystems (IGBP/PAGES Focus 4 project)
^{14}C	radioactive isotope of Carbon	LOI	loss on ignition
^{15}N	Nitrogen isotope	m	Metre
^{210}Pb	radioactive isotope of Lead	M	Molar
^{210}Po	radioactive isotope of Polonium	Max	Maximum
^{241}Am	radioactive isotope of Americium	Mg	Magnesium
AET	Actual Evapotranspiration	mg	Milligram
Al	Aluminium	MI	Marine Institute, Ireland
AMS	Accelerator Mass Spectrometry	Min	Minimum
BP	Before Present (before 1950 AD)	ml	Millilitre
BUFFER	Key nutrient transport mechanisms important for the prediction of nutrient and phytoplankton concentrations in European standing waters (EU FP5 project)	mm	Millimetre
C	Carbon	Mn	Manganese
C_3	three Carbon compound (phosphoglycerate) that is the first product of photosynthesis and used to define a group (C_3) of autotrophic plants	N	Nitrogen
c.	circa (about)	Na	Sodium
C41	Community Climate Consortium for Ireland project	NAO	North Atlantic Oscillation
Ca	Calcium	NaOH	Sodium Hydroxide
CAEDYM	Computational Aquatic Ecosystem Dynamics Model	NH_4	Ammonium
cal.	Calibrated	nm	Nanometre
CANOCO	Canonical Correspondence	no.	Number
Car	Carotenoids	NO_2	Nitrogen Dioxide (nitrite)
cc	cubic centimetre	NO_3	Nitrogen Trioxide (nitrate)
Cd	Cadmium	NS	Nash-Sutcliffe coefficient
CDOM	chromophoric dissolved organic matter	OECD	Organisation for Economic Co-operation and Development
CFB	Central Fisheries Board, Ireland	OM	organic matter
CF-IRMS	Continuous Flow Isotope Ratio Mass Spectrometry	OPW	Office of Public Works, Ireland
chl-a	chlorophyll-a	P	Phosphorus
chl-b	chlorophyll-b	p	Probability
Chls	Chlorophylls	PAST	Palaeontological Statistics software
CIC	Constant Initial Concentration	PCA	Principal Components Analysis
CLIME	Climate and Lake Impacts in Europe (EU FP5 project)	pers comm.	personal communication
cm	Centimetre	pH	Potential of Hydrogen (a measure of acidity)

Co	Cobalt	Phaeo-a	phaeophytin-a
CO_2	Carbon dioxide	PIRLA	Paleoecological Investigation of Recent Lake Acidification project
CO_3	Carbon trioxide (carbonate)	PO_4	Phosphate
coeff	Coefficient	Ppt	Precipitation
CONISS	Constrained Incremental Sums of Squares	PROTECH	Phytoplankton responses to environmental change model
CORINE	Coordination of Information on the Environment	PSIMPOLL	Computer programme for plotting and analysing sedimentary data
Cr	Chromium	Q	a statistical test statistic
CRL	Candidate Reference Lake	QC	Quality control
CRS	constant rate of supply	RBD	River Basin District
CSO	Central Statistics Office, Ireland	RCAO	Rossby Centre Atmosphere-Ocean model
CSPLOT	general purpose computer programme for plotting sedimentary data	RCM	Regional Climate Model
Cu	Copper	REBECCA	Relationships between ecological and chemical status of surface waters (EU FP6 project)
CWR	Centre for Water Research	RESCALE	Catchment and Climate Change (Marine Institute Ireland-funded project)
D.W.	dry weight	RMSEP	root mean square error of prediction
DC	Delta Change	S.I.	Statutory Instrument
DCA	Detrended Correspondence Analysis	SAC	Special Areas of Conservation
DED	District Electoral Division	SAFER	Secure Archive for Environmental Research data (EPA environmental data archive)
DI-pH	Diatom inferred pH (reconstructed epilimnic pH)	SAR	sediment accumulation rate
Dis P	Dissolved Phosphorus	SCP	spheroidal carbonaceous particles
DI-TP	Diatom inferred Total Phosphorus (reconstructed epilimnic Total Phosphorus)	SHETRAN	Système Hydrologique Europeén Transport model
DM	dry matter	Si	Silica
DOC	Dissolved Organic Carbon	Sp PPT	spring precipitation
DOM	Dissolved Organic Matter	sp.	species (biological)
DPM	disintegrations per minute	SRES	Special Report on Emission Scenarios
DW	dry weight	STP	sewage treatment plant
DWT	deep water temperature	Su	Summer
DYRESM	Dynamic Reservoir Simulation Model	Su AT	summer air temperature
EF	Enrichment Factor	SWAT	Soil and Water Assessment Tool
EPA	Environmental Protection Agency, Ireland	SWRB	South Western River Basin
ERTDI	Environmental Research Technological Development and Innovation	SWT	surface water temperature
ESBI	Electricity Supply Board International, Ireland	THMs	Trihalomethanes
Est.	Estimated	TN	Total Nitrogen
et al.	et alia (literally, and others)	TP	Total Phosphorus
EURO-LIMPACS	Integrated Project to Evaluate the Impacts of Global Change on European Freshwater Ecosystems (EU FP6 project)	UK	United Kingdom
FAAS	flame atomic absorption spectrometry	UNESCO	United Nations Educational Scientific and Cultural Organisation
Fe	Iron	USLE	Universal Soil Loss Equation
Fil	Filamentous	UV	ultraviolet radiation
FIPS	Forest Inventory and Planning System	val.	Validation
g	Gram	Vensim	Ventana simulation computer software
GCM	Global Climate Model	W	Watt
GUI	graphical user interface	WFD	Water Framework Directive
GW	Groundwater	WHO	World Health Organisation

GWLF	Generalised Watershed Loading Functions model	Win AT	winter air temperature
ha	Hectare	Winter WT	Winter water temperature
HCl	Hydrogen Chloride	WP	Work Package
HF	Hydrogen Fluoride	WRBD	Western River Basin District
HPLC	High Pressure Liquid Chromatography	Wt	weight
ICES	International Council for the Exploration of the Sea	yr	year
ICP-OES	Inductively Coupled Plasma Optical Emission Spectrometry	zeax	zeaxanthin (pigment)
ILLUMINATE	Past, current and future interactions between pressures, chemical status and biological quality elements for lakes in contrasting catchments in Ireland (EPA project)	Zn	Zinc
IN-SIGHT	Identification of reference status for Irish lake typologies using palaeolimnological methods and techniques (EPA project)	δ	delta (change in)
K	Potassium		

Executive Summary

The Environmental Protection Agency (EPA) Ireland-funded project 'Past, current and future interactions between pressures, chemical status and biological quality elements for lakes in contrasting catchments in Ireland' (ILLUMINATE) demonstrates the benefits of integrating high quality ecological, environmental and palaeolimnological datasets within a dynamic modelling framework. The project also marks the first application of coupled ecological pressure-response models specifically calibrated for catchments in Ireland. Interactions between current and past ecological pressures and responses are quantified through analyses of a combination of contemporary, historical and palaeolimnological datasets. Results are then used to inform runs of coupled dynamic ecological pressure-response models that are used to simulate future scenarios of catchment-lake linkages.

ILLUMINATE focused on three case study catchments in Ireland, each of which was selected on the basis of their being relatively rich in high quality ecological, climatic and hydromorphological data and because they had contrasting catchment characteristics and current and past anthropogenic pressures: the Leane (South West River Basin District (SWRBD)) and the Burrishoole and Mask (Western River Basin District (WRBD)). Within these study sites, most of the research effort targeted the following freshwater lakes and associated relevant datasets: Leane (Leane catchment); Feeagh (Burrishoole catchment); and Mask (Mask catchment). Bunaveela (Burrishoole) and Muckross (Leane) were also included, although analyses at these two lakes did not progress beyond a relatively preliminary level. The case study catchments comprise a range of contrasting levels of population densities and intensities of farming and afforestation and accommodate a variety of pressures, including acidification, nutrient enrichment from both diffuse and point sources, organic loading, and land cover and climate variability and associated soil erosion.

ILLUMINATE had two key aims. First, the project aimed to establish reference conditions and to determine aquatic ecological responses to particular and combined past pressures in the three study catchments. Second, ILLUMINATE aimed to use coupled dynamic ecological pressure-response models in combination with existing and new environmental information to produce

and evaluate simulations of past and future scenarios that can be used to demonstrate key ecological pressures and responses of direct relevance to the implementation of the WFD in Ireland. A third, lesser, aim was to provide informed comment on the at risk characterisation of the lakes studied in detail, where possible.

1) Establish reference conditions and examine aquatic ecological responses to past pressures.

A combination of limnological and palaeolimnological (lake sediment-based) techniques and existing environmental and ecological datasets was employed in order to meet this aim. Sediment cores were collected from a total of five lakes: Leane, Muckross, Bunaveela, Feeagh and Mask. A high degree of inter-site variation in rates of sediment accumulation was evident following dating of the sediment cores. The lowermost sediment samples obtained from Leane, Bunaveela, Feeagh and a basin in the southwest of Mask dated to, respectively, c. 1950, c. 1890, c. 1895 and c. 1870. By contrast, rates of sediment accumulation at Muckross and two sites at Mask (the eastern and western/central basins) appeared very low, and the time period of most interest to the current research – the last 150 years or so - was represented by only the uppermost few cm of sediment.

Leane catchment

Some inwash, possibly as a result of catchment afforestation, is evident in the sedimentary record from Muckross. Overall, however, the palaeolimnological evidence suggests the persistence of oligotrophic conditions throughout the time period covered by the sedimentary record analysed. This is not the case for Leane, however, where nutrient enrichment from the early 1960s forced a transition first to meso-eutrophic and then to eutrophic conditions. Inputs of P in the form of untreated sewage from Killarney are likely to have been a major contributor to eutrophication pressures upto the implementation of improved sewage treatment facilties completed in the 1980s, after which date diffuse (largely agricultural) sources of nutrients are prominent.

Burrishoole catchment

According to the sediment-based information obtained, low nutrient levels prevailed at Bunaveela in the Burrishoole catchment until the 1980s, when increased levels of catchment disturbance and nutrient enrichment, apparently associated with afforestation and overgrazing, became evident. The aquatic effects of catchment disturbance and nutrient enrichment appear earlier in the sedimentary record from Feeagh, and date to the mid 1950s. On the basis of reconstructed epilimnic P concentrations, Feeagh experienced mesotrophic conditions from the late 1960s, while mesotrophic conditions did not develop at Bunaveela until the late 1980s/early 1990s.

Mask catchment

Mask was the most complex, geographically and ecologically, of the catchments and lakes studied in the current research. Major intra-lake differences in sedimentation, and in the degree of preservation of sedimentary information, created problems in data collection and interpretation. Two of the three coring sites in Mask provided relatively long sedimentary records, in terms of the time period covered, while the third permitted relatively high resolution reconstructions of environmental variations over the last c. 140 years. Combined sedimentary evidence from Mask indicates that low nutrient levels prevailed throughout much of the last c. 6000 years. Nutrient enrichment may have commenced at a relatively early date, although more certainty is attached to sedimentary evidence of eutrophication that dates to the last 150 years or so. Early enrichment of the site may have been cultural: rural population levels were much higher than present in western Ireland up to the famines of the mid 19th century. Increased livestock densities, particularly from the late 1950s/early 1960s, appear to have caused catchment erosion and a subsequent phase of nutrient enrichment, and led to the establishment of strongly mesotrophic – possibly even eutrophic – conditions in Mask by the early 1980s.

2) Simulated ecological variations and their drivers

The Generalised Watershed Loading Functions (GWLF) model was used to simulate historical catchment loads, while the in-lake models DYRESM and CAEDYM were used to examine the impacts of these changes on lake ecology at Leane and Mask. The approach enabled impacts of future climate changes and potential changes in land management and population on nutrient loading to be investigated. The chosen models were validated using documentary and instrumental information relating to the sites, in addition to new sedimentary data collected as part of ILLUMINATE.

For all three catchments, modelled variations in hindcast Total Phosphorus (TP) loads were in agreement with measured sediment P. Hindcast simulations for Leane, Feeagh and Mask indicated an increase in TP loading from, respectively, the 1940s, the 1960s and 1972. For all three sites, hindcast simulations of N loads generally followed the same trend as those of TP, but were an order of magnitude higher. Hindcast simulations of variations in lake temperature indicate that warming has occurred at all three sites. Moreover, significant positive associations were evident between simulated lake water temperature profiles and the North Atlantic Oscillation (NAO), reflecting the strong relationship between the NAO and local climatic variability. Hindcast CAEDYM simulations for Leane showed increasing levels of chlorophyll-a for the period prior to available documentary and sedimentary information. Thereafter, the model generally replicated monitored conditions. Cyanobacterial chlorophyll-a was found to be the main contributor to these levels. Hindcast simulations of annual levels of chlorophyll-a for Mask were relatively low for the period 1905-1950, increasing three-fold from 1950 to the 1990s.

Forecast simulations employing future climate projections indicate increased loadings of dissolved P and TP during the late winter and reduced levels in spring and early summer for all three sites. This change in loadings of dissolved P was attributed to variations in stream flow, while those of TP were related to variations in sediment loading. In addition, simulations of in-lake responses for Leane suggested that these increases in TP loading together with projected future increases in water temperatures may result in an overall increase in chlorophyll-a and a switch from mesotrophic to eutrophic conditions. For Feeagh, forecast simulations suggest that predicted changes in water temperature will result in increased levels of dissolved organic carbon (DOC).

3) Examine current at risk characterisation of the study lakes

Computer-based models of links between catchment conditions and aquatic physical and biological responses were used to examine the current at risk characterisation of the study lakes in the context of dynamic ecological pressures. The combination of empirical data and modelled output that characterised ILLUMINATE suggests that the original characterisation of Leane and

Mask as ‘at significant risk’ of not meeting the requirements of WFD (Anon 2005) is correct. However, while the available evidence supports the characterisation of Muckross as ‘probably not at significant risk’, the same cannot be said for Feeagh in the Burrishoole catchment. Rather this site would appear to be at significant risk of not meeting the requirements of the WFD, because of its nutrient enriched state and the continued presence in the catchment of the responsible drivers (afforestation, over-grazing and erosion).

Aside from providing empirical information on aquatic reference conditions in the three study catchments, and a test of current at risk characterisations, ILLUMINATE acts as a demonstration of the utility and potential benefits of combining computer-based modelling of catchment and associated lake ecosystem condition and linkages with other sources of information. In the case of ILLUMINATE, these other sources of information were existing documentary and instrumental evidence, and data from ecological and sedimentological analyses. The information can be used to fine-tune model output, and as a basis for realistic future scenarios. The approach adopted in ILLUMINATE is flexible, readily updatable as new technologies and data become available, and highly portable. As demonstrated in the report that follows, the approach is of direct relevance to the EU Water Framework Directive (WFD) and therefore to River Basin District (RBD) managers and environmental regulators in the Irish Ecoregion and, indeed, farther afield.

Chapter 1. Introduction

1.1 Introduction

The Environmental Protection Agency (EPA) Ireland-funded project ‘Past, current and future interactions between pressures, chemical status and biological quality elements for lakes in contrasting instrumented catchments in Ireland’ (ILLUMINATE) demonstrates the benefits of integrating high quality ecological, environmental and palaeolimnological datasets within a dynamic modelling framework, and marks the first application of coupled ecological pressure-response models specifically calibrated for water catchments in Ireland. Interactions between current and past ecological pressures and responses are quantified through analyses of a combination of contemporary, historical and palaeo datasets. Once quantified, the interactions inform runs of coupled dynamic ecological pressure- response models that are used to simulate future scenarios of catchment-lake linkages. These future scenarios are of direct relevance to the EU Water Framework Directive (WFD) and therefore to River Basin District (RBD) managers and environmental regulators in Ireland.

The ILLUMINATE project had a clear mandate: to make the most effective, environmental policy-relevant use of research infrastructure and ecological and environmental data to model, in a dynamic way, links between a range of individual and combined ecological pressures and responses. Because a substantial amount of relevant information already exists and because they act as receptacles for integrations of catchment-wide processes, the main foci were lakes in three contrasting catchments located in two RBDs: the Leane (South West River Basin District (SWRBD)) and the Burrishoole and Mask (Western River Basin District (WRBD)) catchments. Within these case study catchments most of the research effort targeted the following freshwater lakes and associated, relevant datasets: Leane and Muckross (Leane catchment); Bunaveela and Feeagh (Burrishoole catchment); and Mask (Mask catchment) (Figure 1.1). In particular, ILLUMINATE has concentrated most of its activities and attention on the three lakes of Leane, Feeagh and Mask.

The case study catchments were selected on the basis of their being relatively rich in high quality ecological, climatic and hydromorphological data that are of direct relevance to the WFD and that are often lacking for European catchments (Heiskanen & Solimini 2005). Moreover, the case study catchments and their associated lakes incorporate several at risk categories, on the basis of a report relating to Article 5 of the WFD concerning the characterisation and analysis of RBDs in Ireland (Anon 2005). These at risk categories refer to the chances of individual bodies of surface and groundwater not meeting the exacting environmental quality objectives of the WFD by the end of the current implementation period (2015). Four at risk categories are recognised in the report: at significant risk; probably at significant risk; probably not at significant risk; and not at significant risk. Furthermore, the case study catchments are characterised by different, predominant aquatic ecosystem pressures. Thus the case study catchments comprise examples of lakes probably not at significant risk (Feeagh, Muckross) and at significant risk (Leane, Mask) (Bunaveela is too small in area to meet the >0.5 km^2 threshold for lakes that are not in protected catchments and that are not used for the abstraction of water for consideration in the Article 5 report).

The case study catchments support contrasting levels of population densities and intensities of farming and afforestation and accommodate a variety of pressures, including acidification, nutrient enrichment, organic loading, diffuse source pollution and land cover and climate changes and associated erosion. Of these pressures, diffuse agricultural and urban pollution is thought to be the most significant in the Leane catchment, whereas pressures from land cover changes and morphological alterations to rivers are thought the most significant in the Burrishoole catchment. In the case of the Mask catchment, which comprises contrasting basement geologies, topographies and land uses, the pressures on Mask, a partially marl lake, are varied. All aquatic ecosystem pressures in the study catchments are likely to be subject to variations in the years up to and beyond the 2015 deadline for implementation of the WFD, just as they have been in the past.

ILLUMINATE has been a joint research effort, involving collaboration between the universities of Dublin, Limerick, London and Ulster, the Newport Research Laboratory of the Marine Institute, Kerry County Council/SWRBD, the Environmental consultancy firm ESBI and the

WRBD. The research was set within a methodological framework that integrated existing and new empirical data with dynamic ecological pressure-response models. New ecological data, including enumerations of aquatic diatoms and invertebrates, together with radiometrically-dated, multi-proxy, sediment-based palaeolimnological information, has enabled the extension of currently available ecological and environmental time-series datasets to before the period of significant human pressures and impacts in two of the case study catchments. In the case of the third catchment (Leane), only a relatively short extension of monitoring data to the 1940s was possible using palaeolimnological techniques and the equipment available owing to a high rate of sediment accumulation, in part resulting from the high productivity of the lake. Extending datasets on water quality and related ecological variations back beyond the current monitoring-based records allows recent, current and anticipated aquatic perturbations to be viewed in the context of ecologically meaningful timescales and previous events and recovery phases. These extended datasets have also provided a basis for hindcast and forecast simulations for lakes in the three study catchments, using ecological pressure-response models.

1.2 The at risk characterisation of freshwater lakes in Ireland

Ireland showed commitment to ensuring that all of the nation's water bodies will, as a minimum, meet the criteria for good ecological status by 2015 from a relatively early stage in development and implementation of the WFD. Anon (2005) reports results from a baseline risk assessment of human pressures and impacts on water bodies in Ireland, including lakes. The report identifies those waters that, according to the best information currently available, might not meet all of the criteria for good status, owing to pressures arising from human activities. These waters are said in the report to be 'at significant risk' and comprise 5% of groundwater bodies, 29% of river water bodies, 18% of lake water bodies, 30% of transitional water bodies and 12% of coastal water bodies. In addition, 56% of groundwater bodies, 35% of river water bodies, 20% of lake water bodies, 23% of transitional water bodies and 15% of coastal water bodies are characterised as 'probably at significant risk'. In other words, they may not comply with all the criteria for good status by 2015 unless action is taken during the next decade. Anon (2005) goes on to stress that this assessment of risk is initial, is based on ecological datasets and understanding that are frequently incomplete, and does not consider future changes in pressures or management (at national, regional or local scales). Examples of possible changes in Ireland up to and beyond the WFD implementation deadline of 2015 include the effects of implementing the National Spatial Strategy, agricultural sector reform and climate change.

The characterisation of water bodies in Ireland effectively resulted in a bi-partite classification, owing to differences in the level of confidence. Water bodies where there was high confidence that conditions had been impacted, or were likely to be impacted by 2015, and where there was similarly high levels of confidence that water bodies had not been not impacted, or were unlikely to be impacted by 2015, were characterised as, respectively, 1a, ‘at significant risk’ and 2b, ‘not at significant risk’. Where confidence in the outcome of the risk assessment was lower, however, water bodies were characterised as either 1b ‘probably at significant risk’ or 2a ‘probably not at significant risk’. Although the SWRBD and the WRBD overall contain relatively low numbers of water bodies characterised as at risk from pressures relating to human activities, according to data presented in Anon (2005), intra-RBD variations exist. Furthermore, Anon (2005) did not consider lakes $< 0.5\text{km}^2$ in area, although these account for a considerable portion of the total area of fresh surface water bodies in Ireland.

Reducing uncertainties associated with the current characterisation of water bodies in Ireland is likely to require the collection of additional data, some of which may come from the continuation of existing monitoring programmes. Some is, however, likely to require the development and implementation of new techniques of data acquisition and analysis. Improved understanding of the links between pressures and impacts and how pressures (and impacts) are likely to vary in the future is also required for greater confidence in any future characterisation exercises. Indeed, in their analysis of important knowledge gaps that jeopardise successful implementation of the WFD, as part of the REBECCA project, Heiskanen & Solimini (2005) identified a shortage of studies on broadly based ecological responses to combined pressures (including changes in climate and catchment characteristics) as particularly problematic and deserving of further research. They also mention a shortage of information on ecological responses to pressures, such as nitrogen (N), organic loading (DOC) and other pollutants. Bridging these gaps in understanding and data was beyond the scope of REBECCA, which relied entirely on existing information (Boorman 2005).

ILLUMINATE was oriented towards addressing the WFD-relevant knowledge gaps identified by Heiskanen & Solimini (2005) and outlined above. End products include a greater understanding of the links between individual and combinations of ecological pressures and responses and an enhanced capability for forecasting and visualising impacts, time lags and recovery times in the period to and beyond 2015. Moreover, by facilitating the development of existing catchment-based research and expertise in Ireland, particularly in the fields of ecological sampling, modelling and analysis and palaeolimnology, and collaborative links nationally and internationally, ILLUMINATE has also enhanced the reputation of Ireland as a location for world-class, policy-relevant environmental research.

1.3 Overview of the Research Programme

ILLUMINATE was divided into four integrated work packages (WPs) (Table 1.1). Collectively the WPs: collated existing datasets for the three case study catchments and examined available catchment pressure and ecological response models; utilised palaeolimnological methodologies to establish reference conditions and past variations in ecological pressures and responses for the lakes studied; and integrated existing and new spatial, temporal and palaeolimnological datasets within a common database (Appendix 1.1). Chapter 2 provides brief descriptions of the case study catchments and the lakes that formed the main foci of ILLUMINATE. Subsequent chapters cover the agreed outputs from the ILLUMINATE project.

Table 1.1 Summary of work packages forming the ILLUMINATE project.

Work Package	**Objectives**
Work Package 1 (WP1)	Collation and evaluation of existing literature and data sets for the three case study catchments of relevance to ILLUMINATE, evaluations of available ecological response models, and situation of the project in relation to recent and current research, in particular CLIME, LIMPACS, EURO-LIMPACS and REBECCA.
Work Package 2 (WP2)	Utilisation of limnological and palaeolimnological techniques to acquire new ecological data and to establish reference conditions and to quantify and evaluate the historical ecological responses to particular and combined pressures.
Work Package 3 (WP3)	Integration of datasets via coupled dynamic ecological pressure-response models to produce and evaluate simulations of past and future scenarios that can be used to demonstrate key ecological pressures and responses of direct relevance to the implementation of the WFD in Ireland
Work Package 4 (WP4)	Dissemination of results/demonstration workshop and successful completion of two PhD theses

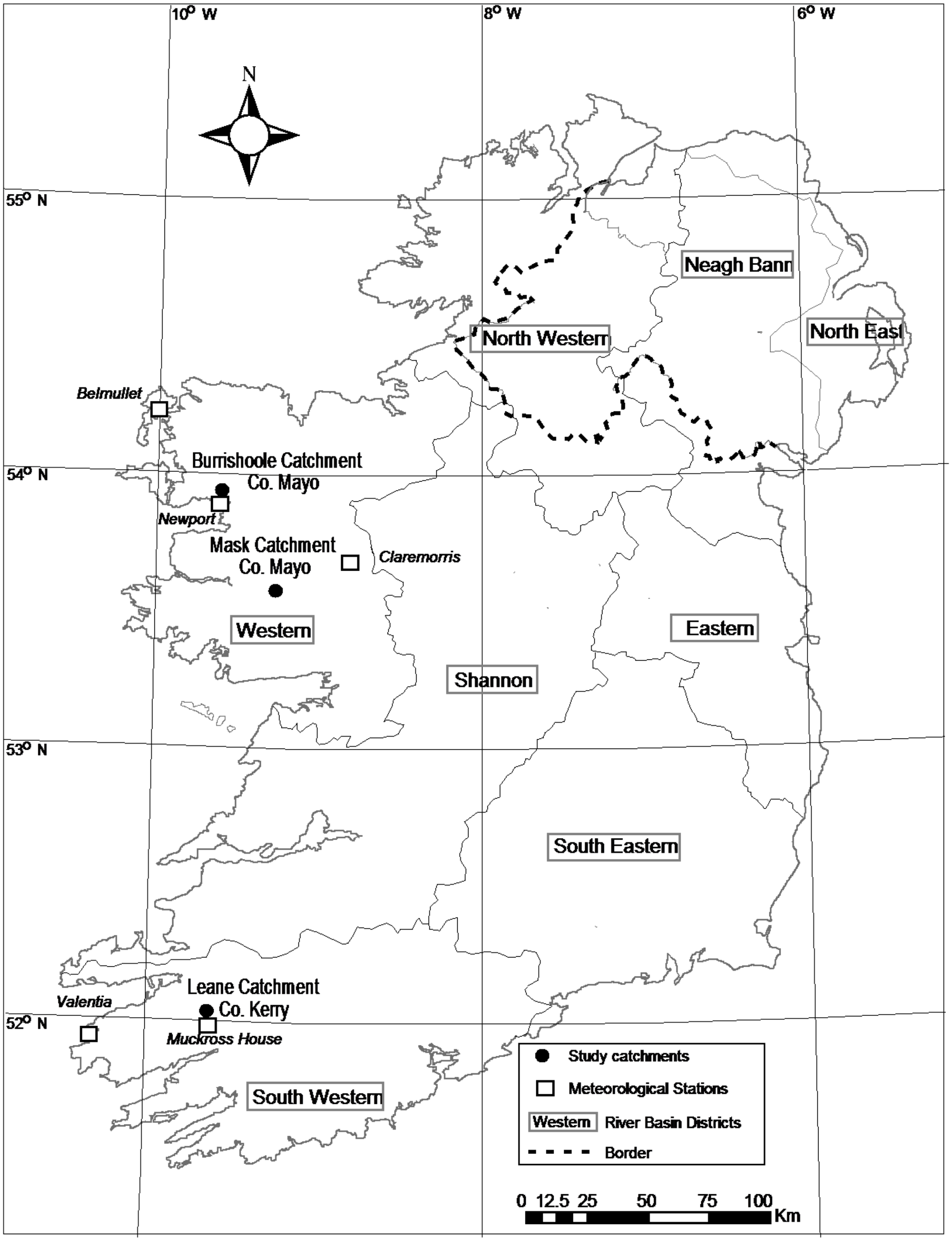


Figure 1.1 The three ILLUMINATE case study catchments and the eight River Basin Districts (RBDs) in the Irish Ecoregion (Ecoregion number 17). The locations of meteorological stations mentioned in the text are also shown.

Chapter 2. Description of Study Catchments and Lakes

This chapter presents descriptions of the study catchments and lakes, including geology, soil type and land use, and a summary of available data on recent lake chemistry, trophic status and ecology. The latter includes information collected during the project to address data gaps for the sites. A summary of the potential drivers of change in these lakes is also presented, based on available meteorological and census data. Trends in meteorological data are described using regression analyses. All data sets were first checked for normality and serial correlation using, respectively, the Ryan-Joiner test and Durbin Watson test and the software package MINITAB 13.1. Population data were available from the Irish Central Statistics Office (CSO) for the district electoral divisions (DEDs) within the catchments for all census years from 1901 to present. Where catchment and DED boundaries intersected, the size of population within the catchment was estimated based on area, while taking account of the locations of any large centres of population.

2.1 Leane catchment (SWRBD)

The Leane catchment (52° 05'N 9° 36'W) covers 553 km^2 (Table 2.1) and consists of two contrasting components: an area of upland mountain peat and forest to the south and west that drains through the two smaller lakes (Upper and Muckross) into Leane, the largest lake in the catchment, and an area to the east that is mainly agricultural grassland (Figure 2.1). There are three main inputs to Leane: the River Flesk, the River Deenagh, and the Long Range (which drains the Upper subcatchment). The River Laune forms the only outflow from the lake. The town of Killarney, with a population of 13,497 (CSO 2006), lies on the eastern shores of Leane. A fourth input, the Folly Stream, drains a small area of 9.5 km^2 surrounding Killarney. The main sewage treatment plant (STP) for the town discharges into this stream. The Flesk is the largest subcatchment of Leane. According to Office of Public Works (OPW) data, the Flesk and the Deenagh subcatchments together accounted for 60% of the hydraulic loading to Leane during the period 1983 to 2005. Of the remaining 40%, 34% entered Leane from the Upper catchment through the Long Range. The three lakes of Killarney are all contained within Killarney National Park, while Leane is also a UNESCO biosphere reserve (Twomey et al. 2000).

Climate and weather

For the most part, the Leane catchment is in receipt of Atlantic air masses and associated precipitation originating from the southwest and experiences a cool temperate and oceanic climate. Weather is strongly influenced by climatic conditions in the Atlantic region, in particular the NAO (Jennings et al. 2000; Blenckner et al. 2007) and, to a lesser extent, by the latitudinal position of the Gulf Stream (Jennings & Allott 2006). High positive NAO index years are associated with milder, wetter and windier conditions in western Europe (Blenckner et al. 2007), while Jennings and Allott (2006) reported that spring and early summer were warmer and sunnier in southwest Ireland when the Gulf Stream was in a more northerly position.

The closest synoptic station to Leane is the Valentia observatory, situated ca. 40 km southwest of Killarney (Figure 1.1). Meteorological data are also available from Muckross House, on the eastern shores of the lake, from 1969. Based on data acquired from Met Éireann, annual average air temperature for the period 1941-2005 ranged from 9.7 ^{o}C in to 11.6 ^{o}C, with eight of the years from 1995 to 2005 having values greater than 11 ^{o}C (Figure 2.2 a). The mean value for the period 1970 to 2005 was 10.7^{o}C. There was no overall increase in air temperature at Valentia over the period 1941 to 2005, which included relatively warm years in the 1940s, although there was a significant increase in the period from 1970 to 2005 ($r^2 = 0.31$, $p < 0.0005$). There was also a significant increase in annual precipitation during the same period ($r^2 = 0. 15$, $p < 0.005$) (Figure 2.2 b). Annual precipitation values ranged from a low of 990 mm in 1970 to a high of 1923 mm in 2003. The average for the period 1970 to 2005 was 1512 mm year^{-1}. The average air temperature at Muckross from 1970 to 2005 was 10.5 °C. Average annual rainfall for the same period was 1691 mm year^{-1}, slightly higher than for Valentia, and was also greater than 2000 mm in five of the years between 1997 and 2005. There was a significant increase in air temperature ($r^2 = 0.37$, $p < 0.0001$) and precipitation ($r^2 = 0.20$, $p < 0.01$) over time. Rainfall also varies considerably across the catchment, from approximately 1000 mm year^{-1} in the northeast to 2700-3200 mm year^{-1} in the southwest (Allott et al. 2008).

Geology, soils and land use

Two distinct and contrasting rock types outcrop in the catchment: Devonian Old Red Sandstone forms the upland mountain topography to the southwest, enclosing most of Muckross, while Lower Carboniferous Limestone underlies the lowlands to the northeast and northwest. Leane spans the geological divide, being underlain by sandstone in the south and limestone in the north. Copper was mined during the 18th and 19th centuries on the Muckross peninsula and was associated with woodland exploitation and fires (Mitchell 1988; 1990), while a period of intense estate management and woodland restoration followed the cessation of mining activities (Mitchell & Cooney 2004).

The Killarney valley contains the largest area (ca. 1200 ha) of semi-natural woodland in Ireland (Mitchell 1990). *Alnus* is a common component of woodland on low-lying calcareous soils, while vegetation on the extensive areas of base-poor peatland is characterised by *Calluna vulgaris* and members of the Poaceae (Quirke 2001). The predominant land use in the lowland area is grassland-based livestock farming, while in upland areas to the south and the west of Leane sheep are grazed and there are some forestry plantations (Bracken 1998). The main CORINE land cover classes in the catchment in 2000 were pasture (25%), forestry (11%) and upland peat (28%) (CLC 2000; Appendix 2.1); coniferous plantations accounted for about 65% of forest cover, with the remainder deciduous woodland.

Data from the CSO indicated increases in cattle numbers in the catchment from the 1970s onwards and large increases in sheep numbers in the 1990s (Figure 2.3 a and b). Cattle numbers were relatively stable in the period from the 1940s to the late 1960s, but increased between the 1960 and 2000 censuses (from 15,739, or 33 head km^{-2}, to 22,994, or 48 head km^{-2}), after which numbers declined slightly. Cattle numbers in the Upper subcatchment were consistently low (<5 per km^{-2}), reflecting a lack of pasture. As in most parts of Ireland, sheep numbers rose dramatically during the 1980s and 1990s (Figures 2.3 b). The human population in the three Leane subcatchments declined from the 1940s to the 1960s (Figure 2.3 c), a period of large-scale movements of people from rural areas to towns and cities and emigration overseas (CSO 1997). The population overall has since recovered somewhat, although the level of increase has been patchy. For example, the relative increase in population for 1961 to 2002 was greater in the Deenagh and Upper subcatchments (80% and 59% respectively) than in the larger Flesk subcatchment (20%). Moreover, the population of Killarney has almost doubled during the same period (rising from c. 7,000 to over 13,400). In addition, there has also been a rise in tourist numbers since the 1960s, with most tourist visits occurring during the summer months (Quirke 2001). There was little change in the percentage pasture in the catchment over time (Figure 2.3 d), although the level of intensification in livestock farming in these areas would have increased in line with national trends. The main period of afforestation, which was almost exclusively on upland peat soils, took place during the 1970s.

Surface waters

Leane, a type 8 (deep, large and moderately alkaline) lake under the EPA's lake typology (Table 2.1), has been the focus of attention for many years owing to its importance to tourism and angling. Concerns were first raised about its water quality in 1967 (Fehily & Shipman 1967), and the lake has been the subject of ongoing monitoring since the 1970s (see Twomey et al. 2000 for summary). The lake has undergone several changes in trophic status in recent decades (KMM 2000, 2003; Twomey et al. 2000; Jennings et al. 2008). Leane was classed as mesotrophic for most of the period to the early 1980s. Chlorophyll-a concentrations then increased and the lake was classified as moderately eutrophic in 1983 and 1984. The change in the trophic state of the lake was at that time linked to increased P concentrations, primarily from municipal wastes. Following the completion of a new STP for Killarney in the mid 1980s, the trophic status improved and the lake was classed as oligotrophic in 1990 and 1991 and as mesotrophic for most of the 1990s. However, in 1997 hypertrophic conditions were recorded, with chlorophyll-a levels greater than 65 mg m^3 at all three sites used for assessment (Twomey et al. 2000). Strongly eutrophic conditions were again recorded in 1998, with concentrations of 38 and 70 μg l^{-1} at two of the three sites (KMM 2000). This decline in water quality was again linked to increased P inputs, with diffuse sources thought to contribute the bulk of the increased loading.

In the late 1990s, Kerry County Council initiated a catchment monitoring and management programme for Leane (KMM 2000, 2003). This programme included management measures focused on reducing P inputs, particularly from diffuse sources. Monitoring is on-going, focusing on a range of parameters, including levels of dissolved and total nutrients. In 1999, the trophic status of the lake improved from strongly eutrophic to moderately eutrophic, while results for

2000 indicated a return to mesotrophic conditions. Chlorophyll-a concentrations in 2001 again indicated mesotrophic conditions in the lake. However, maximum chlorophyll-a levels have increased to the upper end of the mesotrophic class in recent years.

Based on an analysis of monitoring data for Upper and Muckross lakes from 1984 to 1992, Twomey et al. (2000) concluded that the three lakes did not form a trophic series with water acquiring nutrients as it passed down through the catchment and instead reported that Muckross consistently had lower P concentrations and phytoplankton production than Upper. According to palaeolimnological data from the EPA-funded IN-SIGHT project (Leira et al. 2006), however, Upper has not experienced significant distortion in phytoplankton populations and diatom-inferred, epilimnic pH and TP (respectively, DI-pH and DI-TP) levels over the last c. 150 years and currently appears to be in reference state. Upper is characterised as ‘not at significant risk’ (2b), whereas Muckross - a type 4 (deep, large lake and low alkaline) lake according to the EPA typology - and Leane are characterised as, respectively, ‘probably not at significant risk’ (2a) and ‘at significant risk’ (1a) (Table 2.1).

Ecology

<u>*Leane*</u>

Phytoplankton

Only a small number of qualitative phytoplankton studies have been conducted on Leane since the early 1900s (West & West 1906; Flanagan & Toner 1975; Horkan 1976). Since the early 1970s the biological quality of Leane has been monitored and researched by several bodies, including the National Parks and Wildlife Service, Kerry County Council, Conservation Services, Trinity College Dublin and University College Dublin. Monitoring has focused on the annual collection of records of aquatic macrophytes and profundal invertebrates; no detailed monitoring of phytoplankton was carried out until 1999/2000 (Twomey et al. 2001). Twomey et al. (2001) highlighted *Anabaena flos-aquae* as the most important contributor to algal blooms and algal biomass generally in Leane, with other taxa including *Aphanizomenon flos-aquae* and *Oscillatoria aghardii*. Kerry County Council currently monitor algal populations via the collection of three shoreline and two open water trawls on a weekly basis from April to September and monthly for the rest of the year. Phytoplankton is examined qualitatively for key genera (*Anabaena, Asterionella, Ceratium, Coelosphaerium*, *Microcystis, Oscillatoria* and *Tabelleria*) and groups (e.g. green algae). Relatively few quantitative phytoplankton data existed prior to the commencement of the ILLUMINATE project, mainly dating to 1999 and 2000.

Both open water and littoral algal samples were collected as part of ILLUMINATE. Ecological methods are outlined in Appendix 2.2. Open water phytoplankton data are reported here. Forty-four algal taxa were identified in five samples collected between March and October 2007 (the June sample was poorly preserved and no counts were possible). A full list of taxa, together with density, biovolume and biomass estimates, collected in 2007, is provided in Appendix 2.3. Of the taxa enumerated, 22 belonged to the Chlorophyta, 10 to the Bacillariophyta and seven to the Cyanophyta. Taxonomic richness ranged from a minimum of 17 taxa in March to a maximum of 32 in July. Algal density was estimated at 2,129 cells ml^{-1} in March and reached a high of 5,657 cells ml^{-1} in May (Table 2.2; Figure 2.4). A minimum density of 1,938 cells ml^{-1} was observed in July. The August peak (28,838 cells ml^{-1}) was due largely to a bloom of cyanobacteria, composed mainly of *Aphanocapsa* sp. and *Oscillatoria limnetica*.

Total algal biomass ranged from a minimum of 633 mm^3 m^{-3} in March to a maximum of 1,694 mm^3 m^{-3} in May. Bacillariophyta had the greatest biomass, while Chlorophyta and Chrysophyta had comparatively low biomasses. The May biomass peak was composed largely of the colonial Bacillariophyta *Aulacoseira*, with a biomass of 1,150 mm^3 m^{-3}, while the August peak comprised mainly cyanobacteria, with a biomass of 833 mm^3 m^{-3}. In May, two Cryptophyta species of *Chroomonas* together with Chlorophyta were also common. Algal biomass decreased in July, when the Dinoflagellata *Ceratium hirudinella* reached its maximum abundance. From August, cyanobacteria increased in abundance, while the biomass of the remainder of the algal groups decreased or remained stable. Cyanobacteria biomass had declined by October.

Zooplankton

Variations in abundances of profundal macroinvertebrates and littoral invertebrates were measured for Leane between early 1980 and 2000 (Twomey et al. 2001). In addition, monitoring of zooplankton abundances in 1999/2000 revealed spring and autumn peaks in cladocerans (mainly *Daphnia* spp.) (Twomey et al. 2001), suggesting that this group was grazing mainly on diatoms. Copepod numbers were also observed to increase from April to August 1999, and then fall over winter before increasing again in late March 2000. Samples collected from Leane during ILLUMINATE were assessed for Cladocera (planktonic and littoral). Only zooplankton data are presented as part of this report. No water volume data were available for Leane and thus zooplankton abundances are reported in % terms. Five species of Cladocera (*Bosmina coregoni*, *Bythotrephes longimanus*, *Chydorus sphaericus*, *Daphnia hyalina-longispina* and *Diaphanosoma brachyurum*) together with copepods and nauplii were enumerated in water samples collected from Leane during the period March to October 2007 (Table 2.3).

<u>Muckross</u>

Phytoplankton

A qualitative assessment of the phytoplankton population was carried out by Horkan (1976) between 1971 and 1974, and a more detailed quantitative assessment was made by Twomey et al. (2001) in 1999/2000. In the latter, low algal biomass (according to measurements of both chlorophyll-a and phytoplankton biovolume) suggested very low nutrient status and high water quality. Kerry County Council currently samples algae in Muckross qualitatively on a weekly basis (via a shoreline haul in Dundag Bay) in the summer months. Littoral and open water algal samples were collected from Muckross as part of the ILLUMINATE project; however, no phytoplankton data are presented as part of this report.

Zooplankton

Profundal macro invertebrate monitoring data were collected for Muckross between early 1980 and 2000 while zooplankton data were collected for 1999/2000 (Twomey et al. 2001). The latter reported that the relative abundance of the larger cladocerans was quite different from that in Leane. *Daphnia* only occurred in significant numbers in the first half of 1999 and hardly at all in 2000. In contrast to Leane, *D. brachyurum* was most abundant in both years, while the small cladoceran *Bosmina* was also common. Calanoid postnaupliar copepods were at all times more numerous than postnaupliar cyclopoids. For the ILLUMINATE project, samples were analysed for cladocerans (planktonic and littoral) from Muckross. Only zooplankton data are presented as part of this report. No water volume data were available, and thus zooplankton data are reported in % terms. Five species of Cladocera (*Bosmina coregoni*, *Chydorus sphaericus*, *Daphnia* *hyalina-longispina*, *Diaphanosoma brachyurum* and *Polyphemus pediculus*), copepods and nauplii were observed in samples collected between March and October 2007 (Table 2.4). Copepods and nauplii were most abundant generally, while *Diaphanosoma brachyurum* was also common. *Daphnia hyalina-longispina* was also abundant in the sample collected in June.

2.2 Burrishoole Catchment (WRBD)

The Burrishoole catchment (53º 55' N 9º 55' W; c. 100 km^2) in the WRBD comprises seven lakes of various sizes and about 45 kilometres of interconnecting rivers and streams (Whelan et al. 1998) (Figure 2.5). The catchment has national and international importance as an index site for salmonid monitoring. Data collected from the Burrishoole fish trapping facilities are used extensively by the International Council for the Exploration of the Seas to gauge the overall status of salmon, sea trout and eel stocks in Ireland and in the north Atlantic more generally. This is enabled by trap installations between loughs Furnace and Feeagh that monitor all movements of fish between the open sea and the catchment. These traps enable full censuses to be carried out on wild salmon, sea trout and eels. The census data record a decline in stocks of these taxa in the last few decades (ICES 2009a & b; Poole et al. 2007).

Blanket peats are extensive in the catchment, while afforestation schemes, commencing in 1951, account for 23% of land cover (Coillte pers. comm.). In addition to forestry, sheep farming is important (Weir 1996). Several studies have highlighted degradation of the Burrishoole catchment associated with afforestation and overgrazing (e.g. Allott et al. 2005; May et al. 2005) in the past five decades, but the impact of this degradation on fish stocks is unknown. Links between climate variability and freshwater survival of Atlantic salmon in the catchment have recently been identified (McGinnity et al. 2009). The western and headwater parts of the catchment have Special Areas Conservation (SAC) status (Site Code 000534).

Climate and weather

The Burrishoole catchment is located close to the Atlantic coast and therefore experiences a temperate, oceanic climate with mild winters and relatively cool summers. The area is also influenced by the NAO (Jennings et al. 2000; Blenckner et al. 2007). A meteorological station

(Newport) has been in operation in the Burrishoole catchment on the shores of Furnace since 1960. Average annual air temperature at Newport for 1970 to 2005 was 10.2 ^{o}C (Figure 2.6 a). The closest synoptic meteorological stations to the Burrishoole catchment are Claremorris, in the Robe subcatchment (Mask) and 43 km to the southeast, and Belmullet, c. 40 km to the north-west. Annual air temperature from the Newport station show a significant upward trend (r^2 = 0.26; p<0.0005). No upward trend in precipitation is evident, however. Annual precipitation at Newport ranged from 1175 mm in 1971 to 1929 mm in 1999. The average for the period 1970 to 2005 was 1570 mm year^{-1}.

Spatially, rainfall levels vary from about 1800 mm year^{-1} in the northwest of the catchment to less than 1300 mm year^{-1} to the east of Feeagh (MI pers. comm.). Maximum summer temperatures in the Burrishoole catchment rarely exceed 20°C, while minimum winter temperatures are usually between 2°C and 4°C (Marine Institute pers. comm.). The maximum air temperature recorded at Newport was 33.9°C in July 2006, while the minimum temperature recorded was -8.2°C in February 1969 (MI unpublished data). Mean annual air temperature and precipitation at the synoptic station at Claremorris for the period 1970 to 2005 were 9.2 °C and 1511 mm, respectively. There was no overall trend in annual air temperatures from 1950, but there was a significant upward trend from 1970 to 2005 (r^2 = 0.22; $p \leq 0.005$). As with the Newport station, there was no overall trend in precipitation over this period.

Geology, soils and land use

Late Precambrian metamorphic rocks and smaller areas of sandstone and limestone characterise the geology of the catchment (Parker 1977; Long et al. 1992; Irvine et al. 2001). Western parts of the catchment (Glenamong, Altahoney and Maumaratta subcatchments) predominantly comprise quartzite/schist, acidic in nature and with poor buffering capacity, whereas the geology is much more complex in the east (Rough, Lodge, Goulaun and Cottage subcatchments), and also includes veins of volcanic rock, dolomite, wacke and pure schist. The additional minerals available ensure greater buffering capacity and aquatic production. In the lower parts of the catchment, towards Clew Bay, the metamorphic rocks dip below Devonian Old Red Sandstone and Carboniferous Limestone. A terminal moraine, marking the boundary between metamorphic and sedimentary rock-types, separates Feeagh from the tidal Furnace. Deglaciation left the area blanketed with a sandstone-bearing till (the Newport till) (Kiely et al. 1974). The overlying soils are mainly poorly-drained gleys and peaty podsols, with blanket peatlands covering the mountain slopes to the north.

Land cover in the catchment comprises 64% peatbog, 23% forestry, with the remaining 13% being made up of smaller pockets of transitional woodland and scrub, natural grasslands and agricultural land (CLC 2000; Appendix 2.1). Much of the peatbog area is commonage, and is used for sheep grazing. Vegetation cover on the blanket peats is characterised by *Molinia caerulea*, *Schoenus nigricans* and *Scirpus caespitosus* (O'Sullivan 1993).

Cattle numbers in the Feeagh catchment (Figure 2.7 a) have been consistently low since the early 1900s (< 5 per km^{-2}) owing to a shortage of pasture. By comparison, sheep numbers increased rapidly from the mid-1970s, and especially during the 1980s, as a result of the availability of EU subsidies (Figure 2.7 b) (Weir 1996; O'Connor 2000). The CSO recorded approximately 509 sheep in the Burrishoole catchment (Srahmore DED) in the 1970s, 3712 in the 1980s, 8968 in the 1990s and 9402 by the beginning of the current century (ca. 88 km^{-2}) (CSO 1970, 1980, 1991, 2000). Compulsory destocking under programmes such as the Commonage Framework Plans, in combination with the introduction of the Single Farm Payment scheme, has led to a substantial decrease in the number of sheep in the west of Ireland by 2002, and recent CSO figures indicate a destocking of up to 30% for the Galway/Mayo/Roscommon area (CSO 2008), which includes the Burrishoole catchment. Following consultation with landowners, the MI estimated that destocking in the Burrishoole catchment was nearer 50%. Heavy grazing, mainly by large numbers of sheep, has led to erosion of water-saturated substrates in the catchment, particularly in winter (Allot et al. 2005). Human population levels have been consistently low, decreasing from a little over 300 in the early 1900s to 113 in the 2002 census (Figure 2.7 c), again in-line with regional trends (CSO 1997). Afforestation has been the most significant change in land use over time (Figure 2.7 d). In total, commercial forestry accounts for about 23% of the total catchment area (FIPS database, Forest Service). Afforestation commenced in 1951 and expanded between 1960 and 1969; the main taxa are Sitka spruce (*Picea sitchensis*) (26%) and Lodgepole pine (*Pinus contorta*) (70%) (Coillte unpublished data). Clear-felling of planted trees commenced in the early 1990s: approximately 672 hectares (or c. 30% of the total plantation area) have been removed to date (MI unpublished data).

Surface waters

As a result of geological and edaphic differences, the western and eastern subcatchments of the Burrishoole catchment are distinct. Rivers and streams on the western side are generally more acidic, with low buffering capacity (alkalinities in the order of -2.7 to 7.5 mg l^{-1} $CaCO_3$) and low aquatic production (Marine Institute unpublished data). Those on the eastern side are nearer circumneutral with alkalinities in the order of 15-20 mg l^{-1} $CaCO_3$. Bunaveela and Feeagh are the two largest freshwater bodies in the catchment and are part of a cascade of lakes that spans a gradient from oligotrophic headwaters to tidal transitional waters. Feeagh is an EPA typology class 4 lake (deep, >50 ha and low alkalinity) and is oligotrophic, distinctly coloured, with a pH of 6.7 (Table 2.1). Bunaveela is an oligotrophic, acid-neutral, headwater lake, and being deep, of low alkalinity but <50 ha is categorised in EPA typology class 3. According to Anon (2005), Feeagh is regarded as ‘probably not at significant risk’ (category 2a), while in 2003 the lake was classed by the EPA Ireland as a Candidate Reference Lake (CRL). Neither assessment concurs with work carried out in the Burrishoole catchment over the past two decades. For example, Leira et al. (2006) provide palaeolimnological data, collected as part of the EPA/ERTDI-funded IN-SIGHT project, to suggest that nutrient enrichment and slight – although not statistically significant – acidification have impacted Feeagh over the last c. 80 years. Bunaveela is too small for inclusion in the characterisation report, but the impacts of overgrazing and forestry are likely to have been significantly less than at Feeagh (where adverse impacts are evident in subcatchments draining into the lake).

Ecology

Feeagh

Phytoplankton

A total of 40 algal taxa were identified in six samples, collected between April and October 2007 as part of ILLUMINATE. Of those that were most common, 17 taxa belonged to the Chlorophyta, and 11 to the Bacillariophyta. Algal density (number of cells ml^{-1}), biovolume and biomass estimations for water samples from open water sites are given in Table 2.5 and

Appendix 2.3. Species richness, in terms of number of taxa identified, ranged from a minimum of 22 in April to a maximum of 32 in July. Algal abundance was high in April (2,833 cells ml^{-1}), with successive peaks in July (2,897 cells ml^{-1}) and September (2,969 cells ml^{-1}). Members of the Cryptophyta were present over the entire sampling period, decreasing from 1,644 cells ml^{-1} in July to a minimum of 318 cells ml^{-1} in October. Bacillariophyta exhibited two peaks in April and September. Chlorophyta abundance was highest in July and September. Cyanophyta were present during the warmer months from June to September. The decrease in algal abundance in October is concurrent with lower levels of chlorophyll-a recorded for Feeagh (MI pers. comm.).

Total algal biomass ranged from a maximum of 722 mm^3 m^{-3} in July to a minimum of 154 mm^3 m^{-3} in October (Figure 2.8). Cryptophyta had the highest biomass, while Cyanophyta and Chrysophyta had the lowest. In the April and May samples Cryptophyta (small planktonic species (*Chroomonas acuta* and *Chroomonas minuta*) and large celled *Cryptomonas* sp.) and diatoms (*Asterionella formosa*, *Aulacoseira* (two species), *Cyclotella kuetzingiana* and *Tabellaria flocculosa* var. *asterionelloides*) were most abundant. Cryptophyta biomass reached a peak in June, when the abundance of *Cryptomonas* was highest. The biomass of members of the Chlorophyta, Cyanophyta and Dinoflagellata reached a maximum in July, decreased in August and increased again in September. Low productivity and minimum algal biomass were evident in October, when diatoms were the most important algal group.

The data presented contribute significantly to the knowledge about primary productivity in Feeagh. The only other temporal study of phytoplankton in the lake is from 1996 (Irvine et al. 2001) when Cryptophyta were again numerically the most important group. There may be some taxonomic discrepancies between the two studies, as the main Cryptophyte recorded in 1996 was *Rhodomonas minuta*, while in 2007 a mix of *Chroomonas acuta* and *Chroomonas minuta* was noted. The taxonomy of this group has been updated recently, and following consultation with the authors of the 1996 study, both studies appear to have counted the same taxon – i.e. *C. minuta*. The dominance of cryptophytes in Feeagh is most likely linked to the colour of the water, and the lower levels of light penetration, as many cryptophytes are capable of photosynthesising in low light conditions (Gervais 1997; Hammer et al. 2002).

Zooplankton

Lake invertebrates, zooplankton and littoral cladocera were collected as part of The Ecological Assessment of Irish Lakes (1996-1999) (Irvine et al. 2001) A monthly zooplankton monitoring programme conducted by the MI commenced in 2003 and is ongoing, and the samples collected and enumerated as part of the ILLUMINATE project are being assimilated into this long term study. Zooplankton and littoral chydorid samples were collected as part of ILLUMINATE. However, only zooplankton data are presented as part of this report. Zooplankton taxa enumerated in water samples from Feeagh comprised three species of Cladocera (*Bosmina longirostris*, *Daphnia hyalina-longispina*, and *Diaphanosoma brachyurum*), copepods and nauplii; abundances are shown in Table 2.6. *Bosmina longirostris* and *Daphnia hyalina-longispina* were present in the February to June samples and were subsequently displaced by *Diaphanosoma brachyurum*. *Diaphanosoma brachyurum* had a maximum abundance in the August sample (20 organisms l^{-1}), but was less abundant in samples collected subsequently. The abundance of copepods increased from February to July, but was lower in the samples collected in August, September and October. Nauplii were present from February to June with a mean proportional abundance of 27%, declined in July and increased to 38% in September and October. The abundance of *Diaphanosoma* in the summer is similar to the pattern found in Bunaveela, and is presumably related to the ability of *D. brachyurum* to avoid high predation by fish in coloured lakes (Confer et al. 1978.). Seasonal variations are consistent with data collect in 1996-1997 (Irvine et al. 2001) and 2003-2009 (MI pers. comm.), with winter and spring peaks of *Daphnia* and *Bosmina*, followed by summer peaks in *D. brachyurum* and calanoid copepods. The occurrence of *Bosmina longirostris* is interesting as Irvine et al. (2001) found that *B. coregoni* tended to be the more prevalent *Bosmina* species in low productivity and low alkalinity lakes in Ireland.

Bunaveela

Phytoplankton

No phytoplankton data are available for Bunaveela.

Zooplankton

Sampling for zooplankton and littoral chydorids commenced with the ILLUMINATE project: no zooplankton data were previously available for Bunaveela. Zooplankton taxa recorded comprised members of the Cladocera (*Bosmina longirostris, Chydorus piger, Daphnia hyalina-longispina*, *Diaphanosoma brachyurum* and *Polyphemus pediculus*), copepods and nauplii (Table 2.7). *Daphnia hyalina-longispina* was the only cladoceran species present in February and March. The abundance of *Diaphanosoma brachyurum* increased between May and August (from 2 to 33%) before declining during the following months. Copepod numbers increased from February to May and maintained high abundances (60%), apart from a decline in August. Nauplii were abundant in February and March (60%), but their relative abundance decreased in the subsequent months. Zooplankton taxa recorded at Bunaveela are typical for coloured, low productivity lakes. The presence of *Diaphanosoma brachyurum* in large numbers in the summer is consistent with the preference of this species for coloured, low pH lakes (Irvine et al. 2001), under which conditions a transparent carapace may provide some protection from fish predation (Confer et al. 1978).

2.3 Mask Catchment (WRBD)

Mask (53° 36’ N, 9° 22’ W) is a large lake (8,200 ha) with a catchment comprising limestone lowlands in the east, with two large inflows (the River Robe and the Keel canal) draining mostly agricultural grasslands, and siliceous mountains in the west, with several small, fast-flowing streams draining mainly upland peats (Figure 2.9). Geographical complexity of the catchment is also reflected in bathymetry, with the lake occupying several sub-basins. The eastern part of the lake has a maximum depth of c. 14 m and is moderately alkaline with good transparency (McGarrigle & Champ 1999), while in the west the lake has a maximum depth of c. 64 m and is relatively acidic and high in dissolved organic matter (DOM) (McGarrigle & Champ 1999). Precipitated marl (calcite) is restricted to the eastern part of the lake basin where it forms a conspicuous component of sediments. Less than 3% of the total catchment area for Mask is forested (CLC 2000; Appendix 2.1). Mask is recognised as one of the most important natural wild brown trout fisheries in Europe, and supports relatively large populations of Arctic char and charophytes (McGarrigle & Champ 1999).

Climate and weather

Climate conditions at Mask, located approximately 30 km from the Atlantic coast, are cool-temperate, with a strong oceanic influence. Meteorological data, available from Claremorris in the Robe subcatchment (c. 17.5 km from the lake) (Figure 2.9), are described above.

Geology, soils and land use

The eastern and western parts of the Mask catchment contrast markedly, in terms of geology, landscape and land use. Carboniferous Limestone forms the low-lying eastern part, whereas the Partry uplands characterising the western uplands are sculptured from relatively resistant siliceous Ordovician sandstones and mixed volcanics (Holland 2009). Base-poor upland peat soils predominate in the western part of the catchment, while lowland calcareous soils underlay agricultural grasslands to the east.

Agricultural grasslands in the eastern part of the catchment are grazed mainly by cattle. The western part of the catchment is mostly rough grazing on upland blanket peats by sheep, with a limited extent of agricultural grassland on lower slopes. Afforestation in this part of the catchment dates to the last 20 years but remains relatively limited in extent (<3% catchment area over the period 1990 to 2000) (CLC 2000). Cattle numbers in the Mask subcatchments increased in the early 1900s to 99,578 in 1911 (c. 115 head km^{-2}), after which they decreased until the mid-1920s (Figure 2.10 a). From 1960 cattle numbers increased again, peaking in 1991 at 145,352 (c. 169 head km^{-2}), twice the population estimated for the 1940s. The sheep population in the Mask catchment was relatively high in the early part of the 20th century (Figure 2.10 b); estimates suggest that there were 278,580 sheep in 1911 (c. 325 head km^{-2}), after which stocking levels declined until 1960 and then rose again until 1965 (275, 539, or c. 321 head km^{-2}). From 1980, sheep numbers increased rapidly, reaching peak numbers in 2000 (302,296, or c. 350 head km^{-2}). Human population levels were at their highest at the beginning of the 20th century and then declined from 34,990 in 1900 to 18,220 in 1970 (Figure 2.10 d). Levels continued to fall through the 1970s and 1980s, reaching a low of 15,203 in the 1996 census, but have recovered slightly since (16,250 according to the 2000 census). The eastern part of the catchment, where human population densities are highest, has two urban centres (Ballinrobe and Claremorris). Both are located on the river Robe, and each have populations of about 2,500 (CSO 2006). An increase in numbers of cattle and sheep through the 20th century was not associated with a commensurate increase in area of land classified as pasture (Figure 2.10 d). Instead the increased numbers raised stocking densities on the existing acreage of grazed land.

Surface waters

According to the EPA typology, Mask is a type 12 lake (deep and large with high alkalinity) (Table 2.1). The river Robe in the east is the largest inflow to Mask followed by the Keel canal, the only outflow from Lough Carra, a smaller marl lake in the north of the catchment (Figure 2.9). Several tributaries drain the siliceous uplands of the Partry mountains in the west, namely, Finny, Srah, Glensaul and Srahnalong (McGarrigle & Champ 1999). Mask discharges primarily via underground seepage into Lough Corrib, Co. Galway.

Mask is complex, biologically, chemically and physically (McCarthy et al. 2001). Water in most parts of the lake is moderately hard with a relatively low colour and good transparency (Flanagan & Toner 1975; McGarrigle & Champ 1999), although western parts of the lake receive relatively base-poor run-off from the Partry mountains and therefore are of lower pH**.** Monitoring data for Mask indicate a deterioration in water quality over the last ca. 20 years, during which time the trophic status of the lake changed from oligotrophic to mesotrophic (Toner et al. 2005), leading to its current ‘at significant risk’ (1a) characterisation (Anon 2005). Diffuse P loadings arising from agricultural practices in the Robe, which are believed to contribute up to about 85% of the total P load to Mask (McGarrigle & Champ 1999), and Carra subcatchments have increased in recent years, and particularly during the winter months (McGarrigle & Champ 1999; Irvine et al. 2003). Agriculture in the catchment is therefore regarded as the most likely source of increased eutrophication pressures. In the west, the Owenbrin subcatchment has been impacted by overgrazing by sheep (McGarrigle & Champ 1999).

There are two main STPs in the catchment, both located in the Robe subcatchment (at Ballinrobe and Claremorris). Primary treatment of waste commenced at both in the late 1940s, while secondary treatment (with P removal) was installed in Ballinrobe in 1996 (McGarrigle & Champ 1999), and in 2000 in Claremorris (K. Shally pers.comm). A large increase in the number of houses in rural areas has occurred in the catchment over the last ca. 15 years, and effluent from domestic septic systems may now be making an important contribution to nutrient loading in the lake.

Ecology

No primary ecological data were collected from Mask through ILLUMINATE because of budget constraints. However, secondary ecological data, in the form of unpublished algal counts, were made available by the Central Fisheries Board (CFB, T. Champ & J. King pers. comm.). These data comprise monthly single-point samples collected during 1975, 1983, 1984 and 1986. Monthly phytoplankton analyses were also undertaken during the period March 1996 to July 1997 as part of the EPA-funded project: Eutrophication Processes in the Littoral Zones of Western Irish Lakes (McCarthy et al. 2001).

Phytoplankton

Phytoplankton data were collected between 1975 and 1986 (J. King pers. comm.). In 1975 cyanobacteria, and *Oscillatoria agardhii* in particular, were common in algal cell counts from April through December. Subsequent sampling in 1983-1986 recorded a shift, with diatoms outnumbering Chlorophyta and cyanobacteria in cell counts in most months. *Asterionella*, *Melosira* and *Tabellaria* were the most abundant components of the spring diatoms blooms, while *Fragilaria crotonensis* was prevalent in the warmer summer months. An increase in *Stephanodiscus/Cyclotella* species was evident in the algal assemblages from 1985. McCarthy et al. (2001) indicate that phytoplankton patterns in Mask over 1996 and 1997 were typical of mesotrophic conditions, exhibiting two algal peaks, one (the highest) in spring and a second smaller and more prolonged peak in summer/autumn. Diatoms were particularly abundant in the spring but subsequently declined owing to a depletion of silica (Si). *Oscillatoria agardhii* was persistent in phytoplankton populations throughout the sampling period and exhibited an autumn peak. Mask was classified as being on the oligotrophic/mesotrophic boundary (McGarrigle & Champ 1999), based on chlorophyll-a and TP levels over the period 1976 to 1995.

Zooplankton

No historical zooplankton data are available for Mask.

Table 2.1 Physical and chemical characteristics of the study lakes. Measurements compiled from various sources or measured in ILLUMINATE. * EPA typology class refers to a system adopted by EPA Ireland for classifying lakes into different types, according to lake surface area, depth and alkalinity.

	Leane	**Muckross**	**Bunaveela**	**Feeagh**	**Mask**
Coordinates (Irish Grid)	V 931 891	V 952 855	F 987 093	F 965 000	M 102 636
Latitude, Longitude	52° 02’ 09 N 09° 33’ 08 W	52° 00’ 32 N 09° 31’ 32 W	53° 56’ 50 N 09° 34’ 50 W	53° 56’ 50 N 09° 34’ 50 W	53.36°45 N 9 ° 22°60 W
*EPA typology class	8	4	3	4	12
Lake area (ha)	1987	275	47	392	8200
Max length (km)	8.46	3.05	1.15	3.94	16.5
Max width (km)	4.83	1.38	0.8	1.11	13.0
Shore length (km)	29.6	10.0	4.7	12.2	101.4
Catchment (ha)	55,300	12,640	447	7873	85,900
Ratio area lake /catchment	0.036	0.022	0.1	0.048	0.10
Mean depth (m)	13.4	31.3	n/a	14.5	19.5
Max. depth (m)	65	80	23	45	64
Volume (m^3)	2.67 x 10^8	8.58 x 10^7	n/a	5.89 x 10^7	2.70 x 10^9
Altitude (m.a.m.s.l.)	20	20	120	20	21
Max. catchment alt. (m)	1050	1050	388	716	673
Annual retention time (y)	0.57	0.82	n/a	0.47	0.89
Risk characterisation	1a	2a	n/a	2a	1a
Alkalinity (mg l^{-1} $CaCO_3$)	16-28	5-22	n/a	5.8	15.9-112.6
Mean annual TP (µg l^{-1})	14-21	10-14	12	8	6-35
Colour (mg l^{-1} PtCo)	40-60	15-30	68	80	0-94
pH	6.0-7.9	6.0-7.0	6.7	6.7	6.6-8.6
Conductivity (µS cm^{-1})	95	75	86	86	246.1
Max Chl-a (mg m^{-3})	10.4-24.7	3.2-6.3	3.0	1.1	0.6-10.8
Annual max Secchi (m)	2.6-3.7	4.6-6.1	n/a	1.7	2.6-7.1
Trophic state	Mesotrophic	Oligotrophic	Oligotrophic	Oligotrophic	Mesotrophic

Table 2.2 Leane: algal density (cells ml^{-1}) March to October 2007.

	March	May	July	Aug.	Oct.
Bacillariophyta	393	877	252	231	219
Chlorophyta	64	1400	270	287	632
Chrysophyta	0	0	3	0	0
Cryptophyta	1638	1739	19	8	361
Cyanophyta	34	1641	1386	28311	13612
Dinoflagellata	0	0	8	2	0
Total Algal Density	2129	5657	1938	28838	14824

Table 2.3 Leane: % abundance (based on individuals ml^{-1}) of cladocerans, copepods and nauplii (March to October 2007).

Month	*Daphnia hyaline -longispina*	*Bosmina longirostris*	*Diaphanosoma brachyurum*	*Chydorus sphaericus*	*Bythotrephes longimanus*	Copepod	Nauplii
March	0.7	4.7	0.5	0.0	0.0	70.0	24.1
May	0.8	12.5	0.0	0.0	0.0	74.9	11.8
June	8.6	42.0	4.2	0.0	0.0	42.5	2.8
July	0.8	1.0	10.8	0.0	0.0	71.8	15.7
August	1.1	1.3	3.1	0.7	0.2	59.9	33.7
Octobter	9.0	9.0	4.7	0.0	0.0	56.6	20.6

Table 2.4 Muckross: % abundance (based on individuals ml^{-1}) of cladocerans, copepods and nauplii (March to October 2007).

Month	*Daphnia hyalina-longispina*	*Bosmina longirostris*	*Diaphanosoma brachyurum*	*Polyphemus pediculus*	*Chydorus sphaericus*	Copepod	Nauplii
March	1	0	3	0	0	44	52
May	1	0	20	0	0	56	22
June	44	2	12	0	0	24	19
July	0	1	11	0	0	48	38
August	0	0	45	0	0	47	9
October	0	0	4	0	0	74	22

Table 2.5 Feeagh: algal density (cells ml^{-1}) April to October 2007.

	April	May	June	July	August	September	October
Bacillariophyta	560	363	128	259	313	626	366
Chlorophyta	200	142	325	504	250	957	184
Chrysophyta	26	13	19	86	25	11	1
Cryptophyta	2046	1796	1534	1644	646	1302	318
Cyanophyta	0	0	21	401	47	73	21
Dinoflagellata	0	1	1	3	1	0	0
Total algal density	2833	2315	2027	2897	1281	2969	890

Table 2.6 Feeagh: numbers l^{-1} of *Bosmina longirostris*, *Daphnia hyalina-longispina* and *Diaphanosoma brachyurum*, copepods and nauplii (February and October 2007).

Month	*Daphnia hyalina-longispina*	*Bosmina longirostris*	*Diaphanosoma brachyurum*	Copepod	Nauplii
February	1.47	6.87	0.00	0.93	3.80
May	2.89	4.94	0.08	3.22	3.48
June	1.04	2.22	0.13	5.94	4.04
July	0.22	0.60	3.85	9.28	2.90
August	0.13	0.14	19.98	7.55	4.43
September	0.02	0.00	7.73	10.77	9.68
October	0.01	0.08	9.75	15.88	17.65

Table 2.7 Bunaveela: numbers l^{-1} of cladocerans, copepods and nauplii February to October 2007.

Month	*Daphnia hyalina-longispina*	*Bosmina longirostris*	*Diaphanosoma brachyurum*	*Chydorus piger*	*Polyphemus pediculus*	Copepod	Nauplii
February	0.11	0.00	0.00	0.00	0.00	0.55	0.96
March	0.77	0.00	0.00	0.00	0.00	5.47	9.73
May	1.10	0.01	0.47	0.02	0.00	6.67	2.27
July	0.61	0.00	5.74	0.00	0.00	20.67	6.30
August	0.87	0.00	5.77	0.00	0.00	5.67	5.19
September	0.25	0.00	0.24	0.00	0.01	9.27	5.50
October	1.71	0.00	0.52	0.00	0.00	13.06	7.25

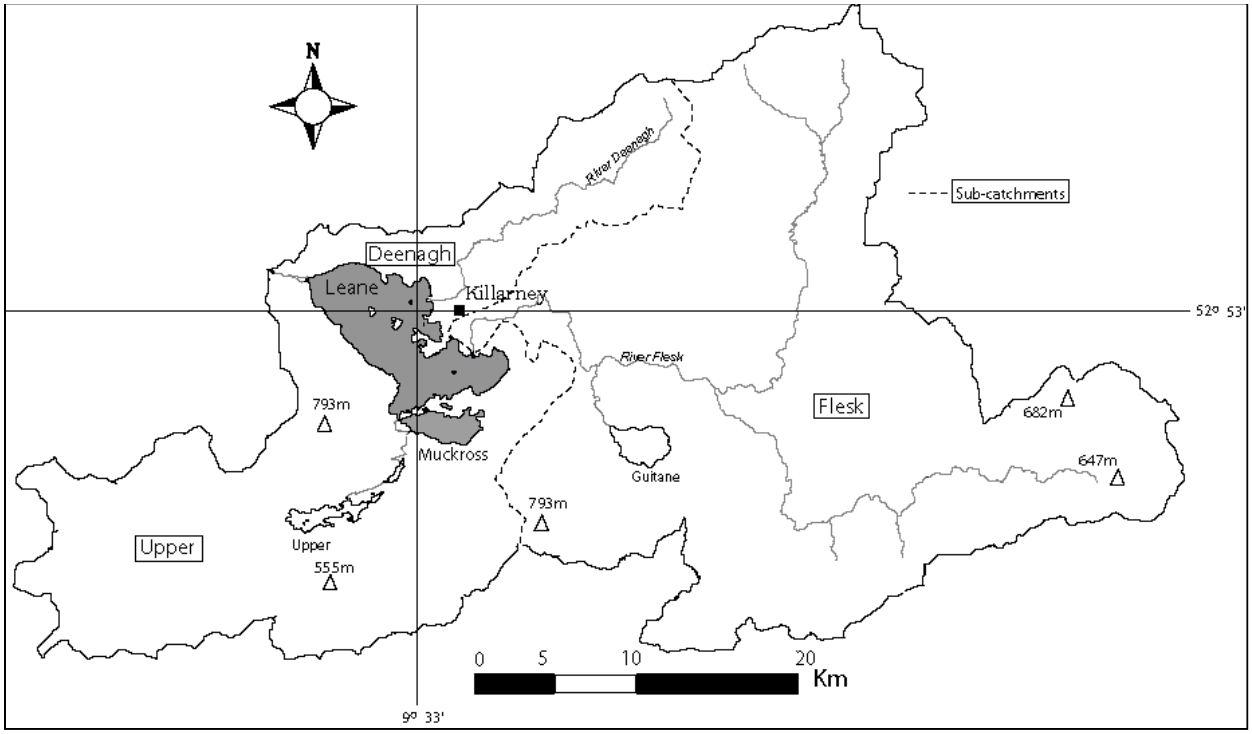


Figure 2.1 The Leane catchment, showing the location of Leane and Muckross and main subcatchments (Upper, Deenagh and Flesk).

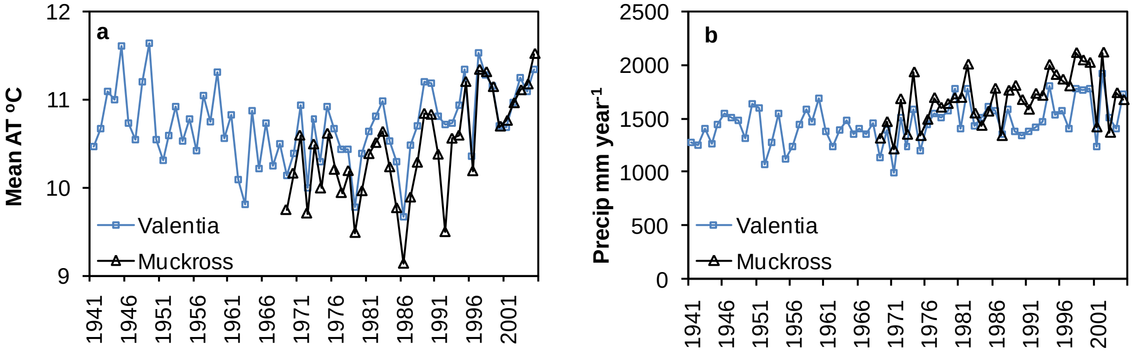


Figure 2.2 Mean annual air temperature (^{o}C) (a), annual precipitation (mm) (b), Valentia (1941-2005) and Muckross (1969-2005).

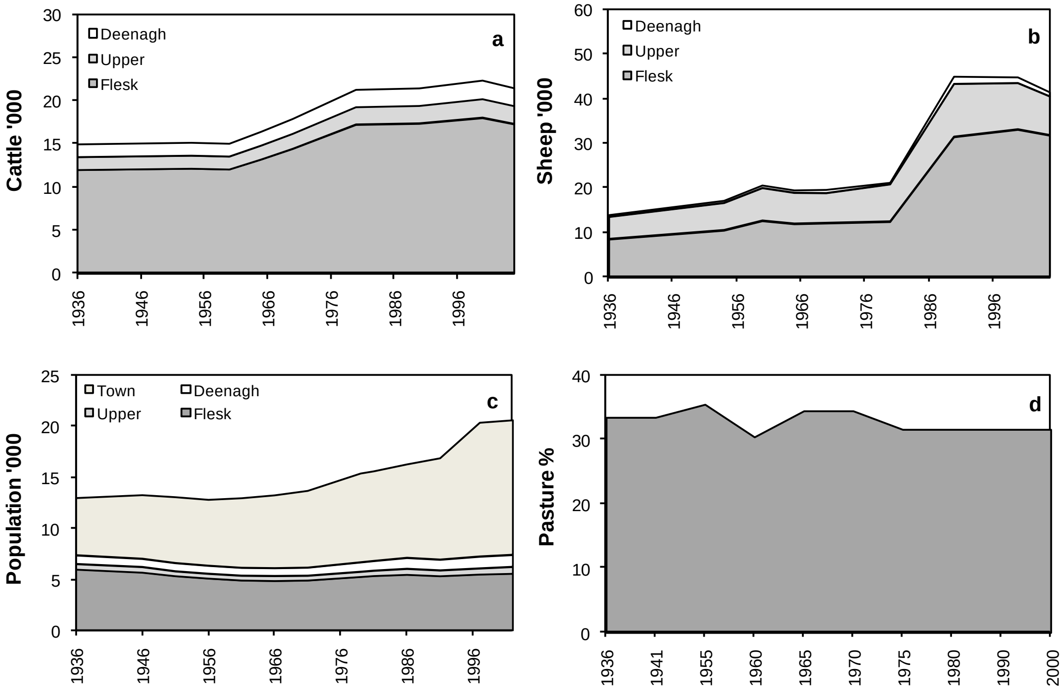


Figure 2.3 Leane: annual values for change in catchment cattle numbers (a), sheep numbers (b), population (c) and % pasture (d) (1936 to 2005).

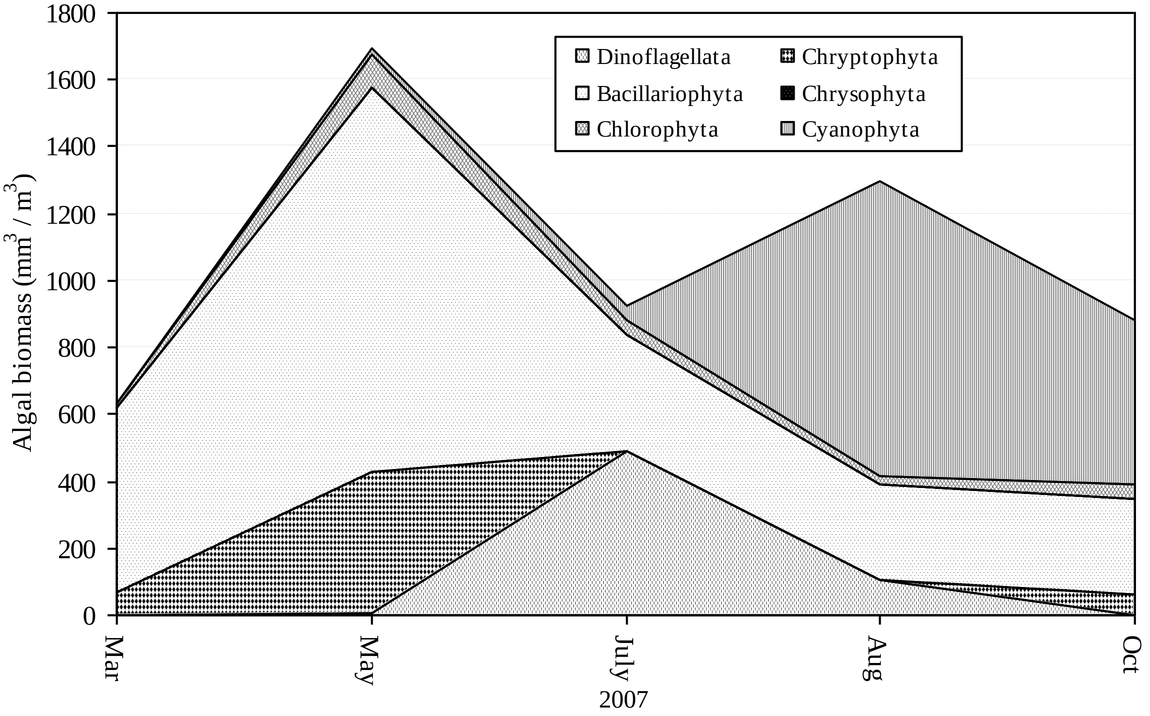


Figure 2.4 Leane: algal biomass estimates March to October 2007

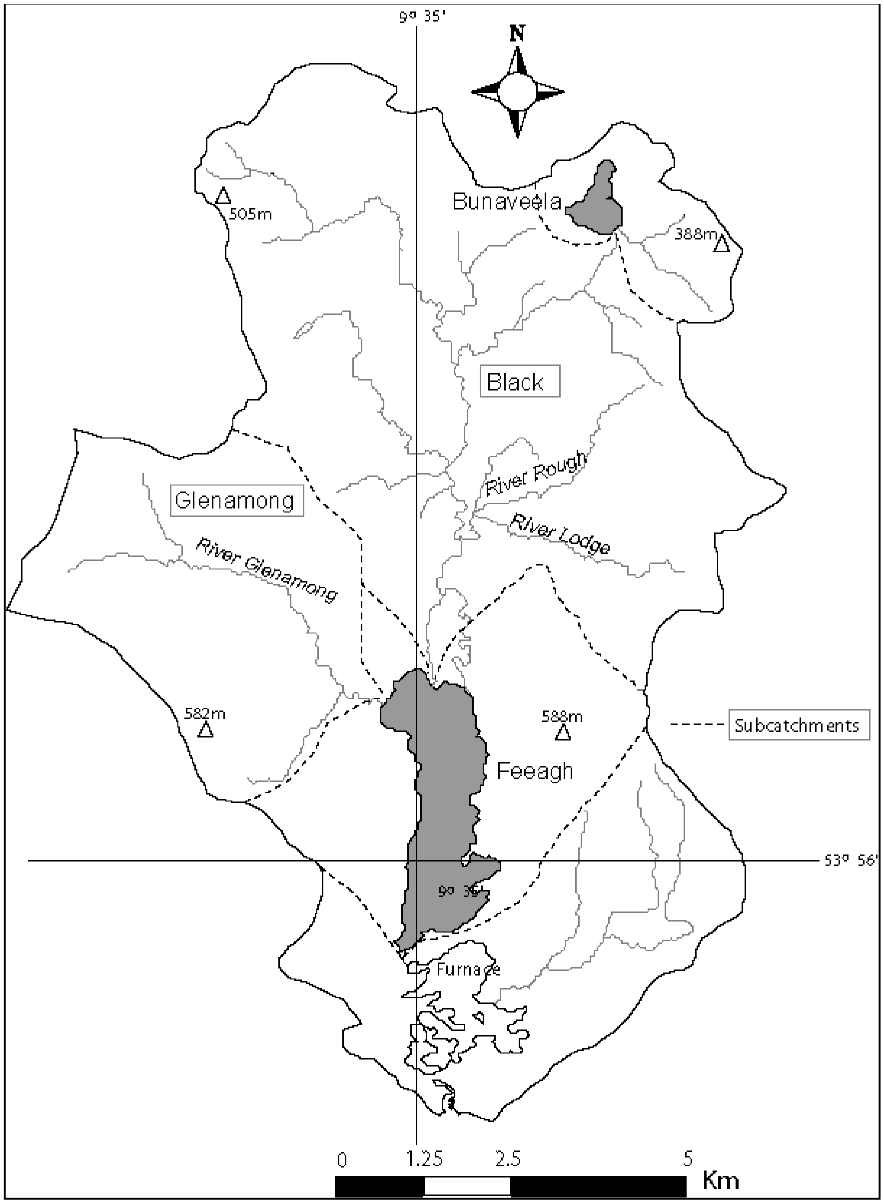


Figure 2.5 The Burrishoole catchment showing the locations of Bunaveela and Feeagh and the main subcatchments (Glenamong and Black).

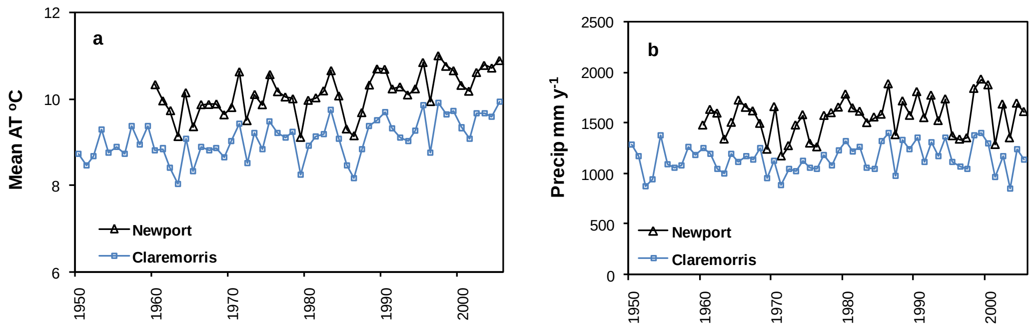


Figure 2.6 Mean annual air temperature (^oC) (a), annual precipitation (mm) (b), Claremorris (1950-2005) and Newport (1960-2005).

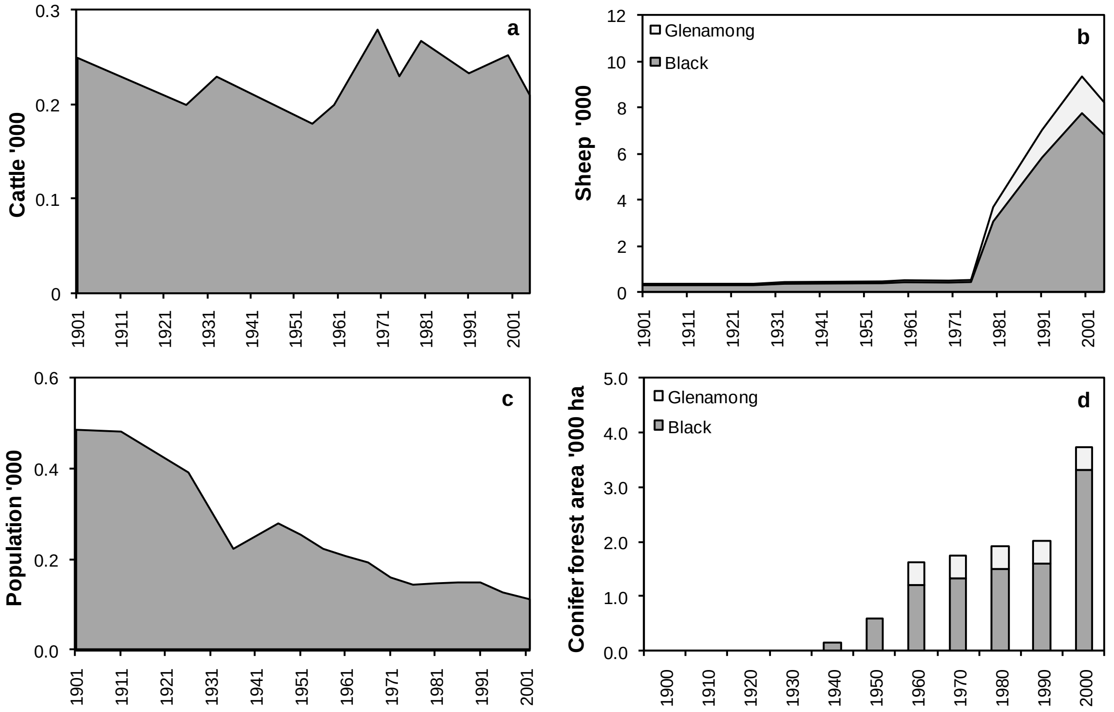


Figure 2.7 Feeagh: annual values for change in catchment cattle numbers (a), sheep numbers (b), population (c) and coniferous afforestation (ha) (d) (1901 to 2005).

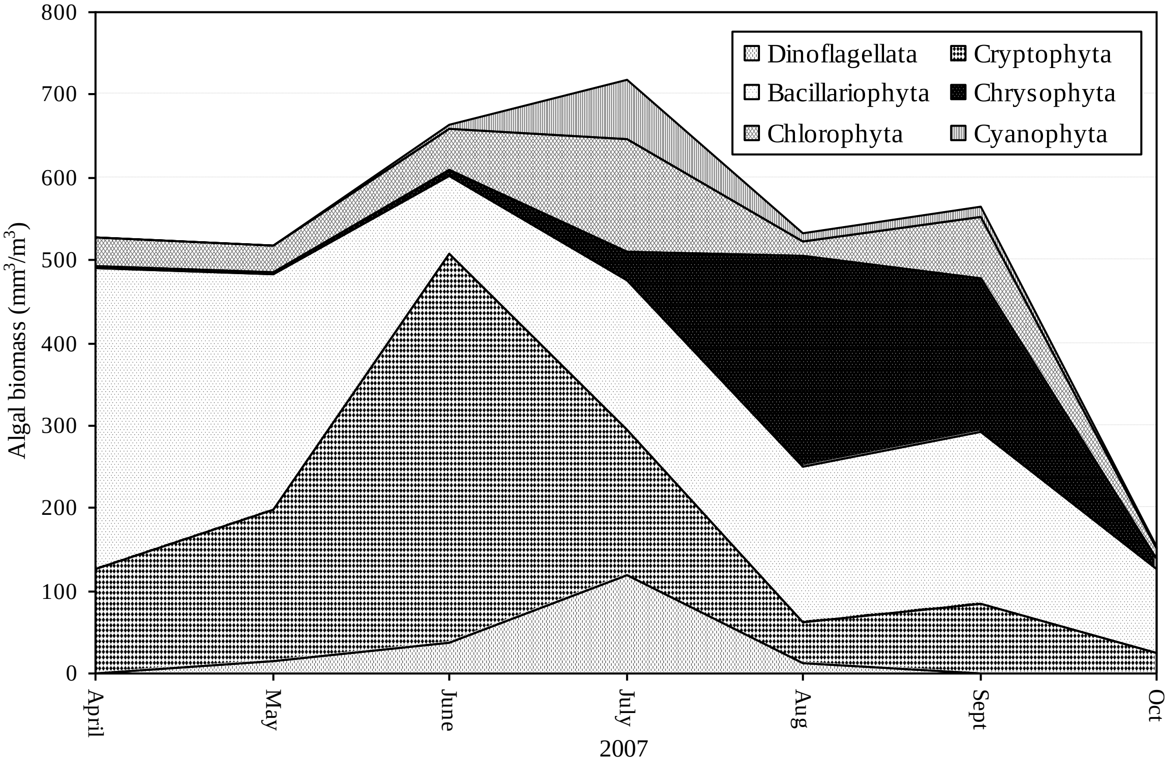


Figure 2.8 Feeagh: estimates of algal biomass (April to October 2007).

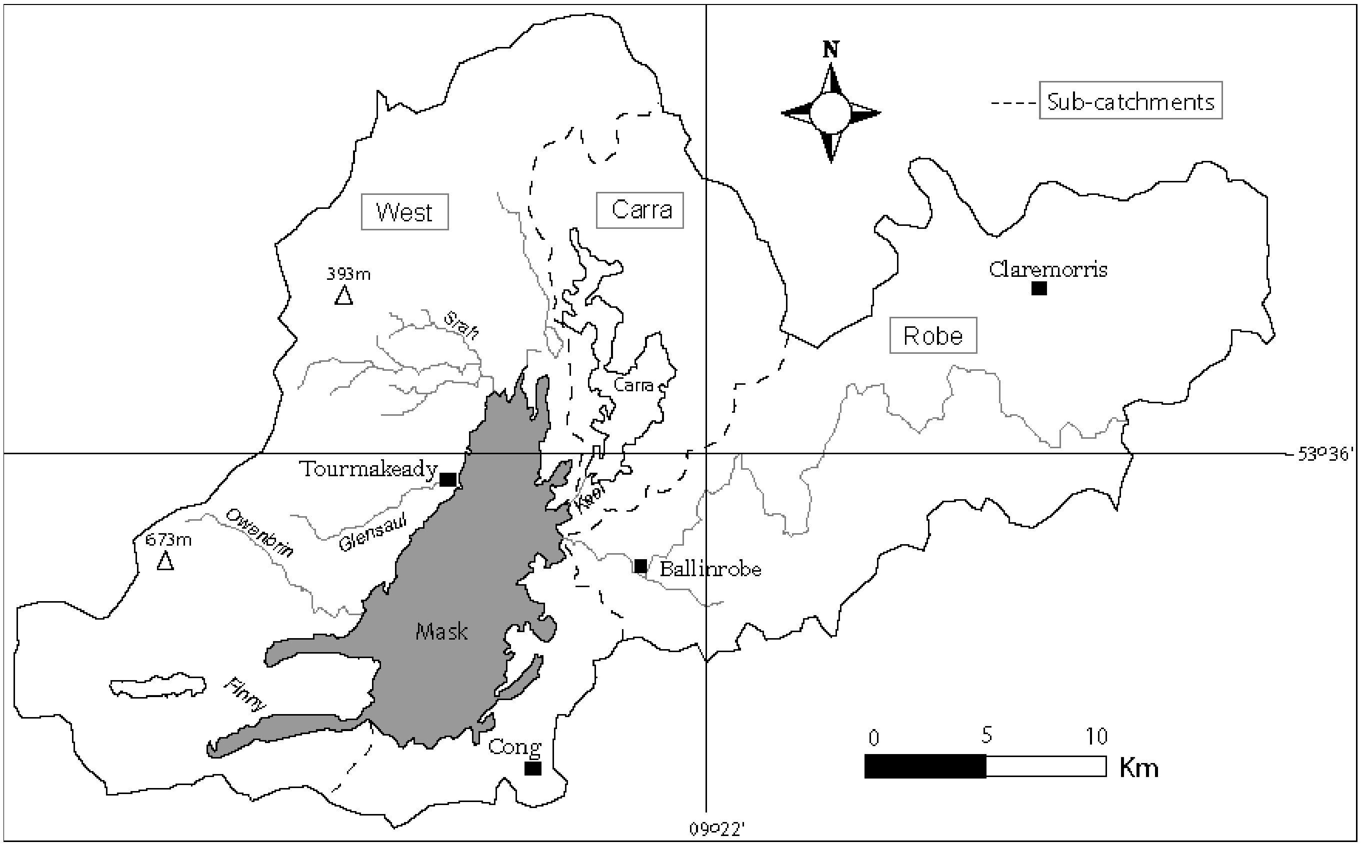


Figure 2.9 The Mask catchment, showing the locations of Mask, principal urban areas in the catchment, key inflow rivers and subcatchments. The Keel canal links loughs Carra and Mask.

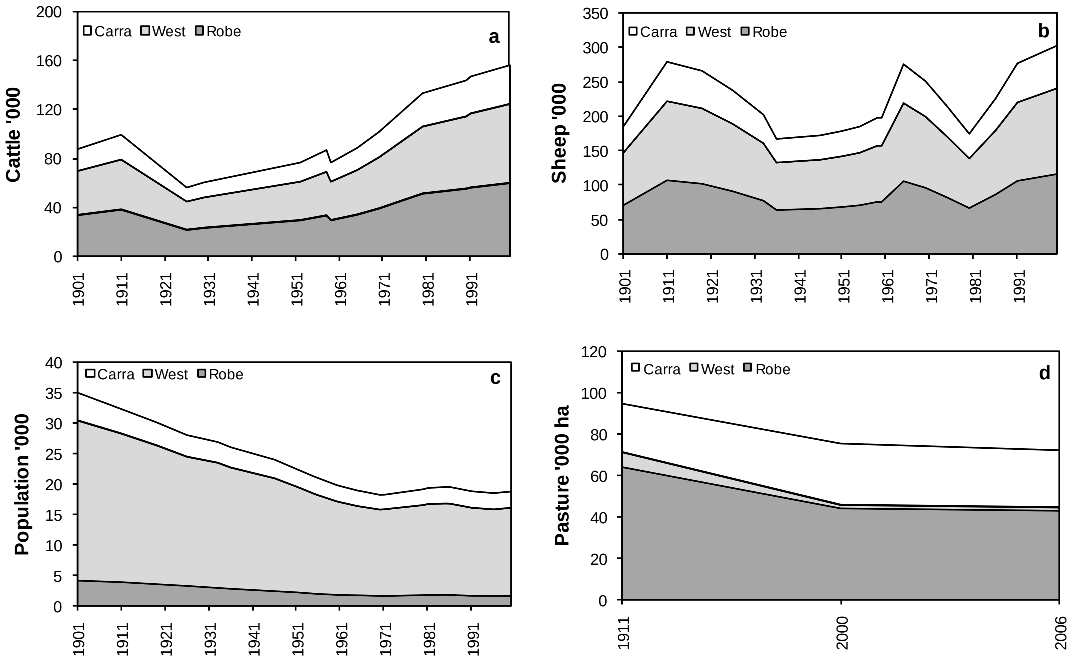


Figure 2.10 Mask: changes in cattle (a), sheep and (b), human population levels; (c) variations in extent of pasture (ha) (d) in the catchment (1901 to 2005)**.**

Chapter 3. Palaeolimnology

3.1 Introduction

This chapter describes and interprets the results of WP 2 of ILLUMINATE, which aimed to reconstruct reference conditions and past and current variations in ecological pressures and responses over the last 100-200 years for lakes in the three study catchments. WP2 therefore involved:

(1) Input to current ecological sampling programmes, thereby bridging gaps in existing datasets, with the more complete datasets used to calibrate and/or validate palaeolimnological reconstructions and computer modelling simulations.

(2) Collection of multiple cores of sediment.

(3) Laboratory-based analyses of sedimentary components. This part of the research involved reconstructions of up-core (through time) variations in open water and littoral cladoceran subfossils, macrophyte remains, and abundances of diatoms, pollen, chlorophyll-a and possible UV-specific algal pigments, ^{210}Pb and important chemical element contents. The objectives of this part of the WP were two-fold: first, to establish chronological frameworks and estimates of sediment accumulation rates (SAR) for the sediment cores collected; and second, to quantify temporal variations in individual and combined ecological pressures and responses.

(4) For lakes with adequate chronological control, establishment of reference conditions and reconstructions of up-core variations in ecological conditions (based on data assembled in (1) and generated through (2 and 3) above).

(5) Reconstruction of major climate trends and events (e.g. NAO-linked variations in rainfall and temperature) in the SWRBD and WRBD using meteorological data, in order to identify and quantify potential climatic drivers of aquatic ecosystem changes.

(6) Statistical analyses of multivariate, palaeolimnological and environmental data following well-established procedures in order to estimate the level of variance in aquatic biota, preserved in lake sediments, which can be explained by categories of measured variables (e.g. rainfall, anthropogenic inputs, and land cover) and therefore the possible significance of individual and combined ecological pressures in the past.

The key WP2 targets and deliverables were:

(i) establishment of chronologies for sediment cores from up to five lakes in the Leane, Burrishoole and Mask catchments, based on radiometric (gamma-spectrometric) techniques (measurement of levels of sediment-based ^{137}Cs, ^{241}Am and ^{210}Pb).

(ii) **c**haracterisation of pre-anthropogenic baseline reference conditions using multi-proxy palaeolimnological techniques (analyses of subfossils, organic isotopes and chemical element concentrations and accumulation rates) for each of the study lakes with adequate chronological control.

(iii) reconstructions of current and past ecological pressures (i.e. quantification of changes in acidity, TP and N levels, transparency (DOC and suspended sediments), land cover change, sediment input and climate) and responses, and determination of rates of ecosystem recovery (if evident) over the last c. 200 years in the study lakes.

(iv) Evaluation of the roles of different pressures and combinations of pressures using statistical techniques.

(v) A basis for simulations of future ecological pressures and responses to and beyond the WFD implementation deadline of 2015.

The contribution made by ILLUMINATE to ongoing ecological sampling in the three study catchments has been covered in the preceding chapter; the methods used in obtaining modern ecological (cladoceran and phytoplankton) data are outlined in Appendix 2.2. The remainder of this chapter focuses on describing the techniques used to obtain sediment-based palaeolimnological data from the study sites, and the interpretation of this evidence.

3.2 Field Methods

3.2.1 Sediment coring

Sediment cores were collected from the study lakes between August 2006 and August 2009. Sediment cores were generally extracted from the deepest point in a lake basin. However, Mask was found to have a particularly complex bathymetry, and in this case sediment cores were taken from three different locations in the lake (section 3.5.5). Sediment cores were also taken from the littoral zones of some lakes. Sediment cores were collected in all cases using a Renberg gravity corer (Renberg & Hansson 2008). The cores were sub-sampled at 1 cm intervals and transported in sealed and labelled sampling bags to Dublin, Dundalk and Limerick for geochemical, lithological and macro and microfossil analyses. Sediment samples for pigment analysis were frozen at -80 °C within one hour of collection, and transported to Dundalk Institute of Technology on dry ice, stored in a freezer (at -70 °C) and analysed within one month of collection in the field

3.3 Laboratory Methods

3.3.1 Sediment chronologies

The length of a lake sediment record is a function of the time period over which sediments have accumulated, the rate of accumulation and the number and duration of any hiatuses (Dalton et al. 2009). The rate at which lake sediments accumulate varies within and between lakes and over time, owing to differences in lake productivity, sediment movement and focusing and the degree of catchment disturbance. Establishing the time period represented by a sequence of sediments – or chronological control – is a crucial part of palaeolimnologial investigations, as good chronological control permits establishment of not only the age of particular conditions represented in the sediment-based proxies, but also rates of past environmental changes. In ILLUMINATE chronological control for cores of deepwater sediment was largely based upon the measurements of activity of radioactive isotopes (^{14}C, ^{210}Pb and ^{137}Cs). No chronologies were established for shallow water cores collected for macrofossil analysis, because of cost, and results for cores from littoral sites are therefore reported according to depth only. For Mask, estimated ages based on measured activities of radioactive isotopes were verified through counts of spheroidal carbonaceous particles (SCPs). SCPs are released to the atmosphere as a result of the incomplete combustion of fossil fuels in power stations. Leira et al. (2006) describe the use of SCPs to date cores of lake sediment from Ireland, which utilises very distinctive profiles of deposition that SCPs have in lake sediments in northwest Europe (Rose et al. 1995). Distinctive features in these profiles relate to the commencement, expansion and increased regulation of power station emissions.

AMS ^{14}C dating

The organic carbon component of lake sediments deposited over the last c. 40,000 years can be dated using radiocarbon (^{14}C) dating techniques (Björck & Wohlfarth 2001). In order to obtain a maximum age for the sediment sequences obtained, samples of macrofossils extracted from basal core samples (and mid-core in Mask) were dated by Beta Analytic, USA, using the Accelerator Mass Spectrometry (AMS) ^{14}C technique. Approximately 5-10 g of plant macrofossils were extracted with fine forceps and separated from the associated sediment matrix. Samples were then wrapped in aluminium foil for despatch to Beta Analytic. Because the rate of sedimentation in Leane, a very productive lake, was clearly very high (see below) and because ^{14}C dating cannot be applied to organic material that is younger than c. 200 years, no AMS ^{14}C analysis was on sediment samples from Leane.

^{210}Pb & ^{137}Cs

Lake sediments also contain radioactive isotopes that are shorter-lived than ^{14}C (e.g. lead (^{210}Pb) and caesium (^{137}Cs)) and that can be used to date material that has accumulated during the last c. 100-200 years (Appleby 2001; Björck & Wohlfarth 2001). ^{210}Pb has a half-life of 22.3 years: thus down-profile declines in ^{210}Pb activity can be used as a basis for dating recently deposited sediments, while ^{137}Cs, with a half life of 30.2 years, is anthropogenic in origin and associated with the development of nuclear-based weapons and power generating technologies. Although ^{137}Cs is globally dispersed in the atmosphere, current levels are lower than they were in the recent past. In fact there have been two peaks in atmospheric concentrations of ^{137}Cs that are also represented in sediments: one around 1963 associated with the atmospheric detonation of nuclear bombs, and just before the implementation of the Test Ban Treaty, and a second in 1986 linked to the Chernobyl nuclear power station accident.

Preparation of samples for analyses of ^{210}Pb and ^{137}Cs activities involved drying c. 2 g of wet sediment at 60 ºC for 2 days and grinding the dried samples (c. 0.5 g) using a mortar and pestle. Determination of ^{210}Pb was made indirectly through the determination of ^{210}Po, a grand-daughter isotope of ^{210}Pb, as outlined by Eakins & Morrison (1978); analysis was conducted at the laboratories of Flett Research Ltd, Canada, using Ortec 'Ortet' alpha spectrometery, a duplicate sample was analysed every tenth sample. Sedimentation accumulation rate (SAR) was determined using both the Constant Initial Concentration (CIC) - which can provide good results at sites with uniform sediment (and therefore ^{210}Pb) accumulation rates (Appleby & Oldfield 1978) - and the Constant Rate of Supply (CRS) - which can accommodate variations in accumulation of ^{210}Pb (Appleby 2001) - models. The CIC model assumes that the rate of unsupported ^{210}Pb is constant and that the initial activity of unsupported ^{210}Pb laid down on the lake bed remains unaffected by post-depositional processes and decays exponentially with time. In contrast, the CRS model assumes that the absolute flux of ^{210}Pb remains constant regardless of sediment accumulation rate. Thus changes in sediment accumulation rate through time will result in changes in the initial concentration of excess unsupported ^{210}Pb. In these circumstances, the dates of older sediments are calculated not from their present concentration but from the distribution of ^{210}Pb throughout the sediment core (Appleby 2001).

Spheroidal Carbonaceous Particles (SCPs)

Concentrations of SCPs were measured in samples of core sediments from Mask using the method of Rose (1994) (detection limit of 100 SCPs gDM^{-1}). The results of the analyses were used in support of a radiometrically-based chronology (Rose et al. 1995; Rose 2001).

For each deepest-point coring site a single, well-dated core acted as the master chronology; sedimentation rates and ages from this core were extrapolated to the other sediment cores from the same site.

Reporting of age of sediment-based evidence

The ages of sedimentary evidence established from variations in ^{210}Po and ^{137}Cs activity are reported throughout this report in terms of the approximate year (and are therefore prefixed with c.) determined from the estimated SAR (as in, for example, c. 1987). For material older than c. 200 years, e.g. some of the evidence from Mask, ages were estimated using simple linear regression, interpolation and extrapolation (Mullins 2003), based on an assumed relationship between ^{14}C-established age (the independent variable) and sample depth (the dependent variable), and are reported as BP (years before present, where the present is 1950 AD).

3.3.2 Variations in organic matter content (loss-on-ignition (% LOI))

Percentage loss-on-ignition (% LOI) is a widely applied method that provides a measure of relative proportions of organic and inorganic matter in the sediment (Heiri et al. 2001). In addition, sediment cores collected from proximate locations at the same coring site can be compared and cross-matched through a sample depth v sample depth comparison of % LOI. A trial version of the computer programme CSPLOT was also used in cross-correlation of cores from Feeagh and Leane (sub-section 3.4 below).

Wet sediment core samples were weighed, dried in an oven for 12 hours at a temperature of 100 ºC and weighed again after cooling (% DW). Samples were then placed in a furnace for 5 hours at a temperature of 550ºC. After cooling in a desiccator the samples were weighed again. The percentage organic matter (% LOI) was calculated using the following formula:

$$LOI_{550} = ((DW_{100}-DW_{550})/DW_{100})*100$$

Where LOI_{550} is LOI at 550 ºC as a percentage, DW_{100} is the dry weight after drying at 100 ºC and DW_{550} is the dry weight of the sample after ignition in the furnace at 550ºC (Heiri et al. 2001).

3.3.3 Geochemistry

Elemental chemistry

Up-core variations in levels of chemical elements were determined at the University of Ulster, Coleraine (Leane, Muckross) and in the Centre for the Environment, Trinity College Dublin (Bunaveela, Feeagh, Mask). Elemental extraction was achieved using sequential acid digestion (Boyle 2001). For Mask, Bunaveela and Feeagh, sediment concentrations of Al, Ca, Fe, K, Mn, Na, P and N were determined using inductively couple plasma optical emission spectroscopy (ICP-OES) (Stefánsson et al. 2007), while for Leane and Muckross concentrations of Cd, Cr, Co, Cu, Zn, Pb, P, Fe, Na, Mg and Ca were determined using flame atomic absorption spectrometry (FAAS) (Jordan et al. 2001). For samples analysed at both laboratories, quality control was assured through repeat digests and the use of validated and certified reference material. Major elements (Al, Ca, K, Mg and Na) were analysed to assist in the reconstruction of phases of catchment inwash, while the redox-sensitive elements (Fe and Mn) were included to detect redox-mediated changes in the ability of sediments to bind elements. Trace elements (Cd, Cr, Co, Cu, Zn, Pb) were analysed as proxies of inputs of untreated sewage, inorganic fertilizer and atmospheric deposition, while total concentrations of P and N (the latter in Burrishoole only) were analysed to detect phases of nutrient enrichment and to support microfossil data. In addition to geochemical concentration data, chemical accumulation rates were also calculated based on the product of chemical concentration (mg g^{-1}) and sediment accumulation rate (g cm^{-2} yr^{-1}) data.

Stable isotopes

Measurements of stable C and N isotopes can be used to determine the source(s) of organic matter in lake sediments. According to Cerling (1999), $\delta^{13}C$ values for organic C derived from C_3 plants generally range from –35 ‰ to –20 ‰, whereas C from C_4 plants generally ranges from –14 ‰ to –10 ‰ (-16 ‰ to –9 ‰, according to de Freitas et al. (2002)). Aquatic algae, by comparison, have values ranging from -23 ‰ to -12 ‰ (Smith & Epstein 1971). Analyses of $\delta^{15}N$ in lake sediments have been used to determine variations in inputs of reactive N from anthropogenic sources (Wolfe et al. 2001), which can be an important – and often under-valued – year-round pressure in oligotrophic lakes and seasonally in those enriched with P (Carvalho & Defew 2005:18). C/N ratios of sedimentary organic matter content were also calculated and can be used to distinguish allochthonous from authochthonous material. Ratio values of 4-10 and >20 are thought to be representative of organic matter originating from, respectively, phytoplankton and vascular terrestrial-plants, while ratio values of 13-14 are thought to represent contributions from a mixture of terrestrial- and aquatic sources (Meyers 2003). C/N ratios for sewage derived organic matter are generally low (c. 4-6) (Brennan et al. 1994).

Ten samples of sediment per core were prepared for analysis of $\delta\ ^{13}C$, $\delta\ ^{15}N$, % C and % N. Sample preparation was based on Lohse et al. (2000), Talbot (2001) and Wolfe (2001). Smear slides were made for every sample to determine the nature of organic matter in the sediment prior to analysis. Samples were digested with 1M HCl for 2 hours in a water bath at 60 ºC to remove carbonate carbon. The digested samples were then washed with deionised water and oven-dried at 60 ºC for 48 hours. Up-core analyses of stable C and N isotopes were carried out using the University of Dublin’s Thermo Delta^{plus} Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS).

3.3.4 Biological remains

Pollen and plant macrofossils

The analysis of pollen preserved in lake sediments is the principal technique for reconstructing past variations in vegetation cover in a catchment as a result of changes in climate and level and form of human activity. Standard protocols for preparing and analysing pollen (Bennett & Willis 2001) were followed. *Lycopodium* spores (1 tablet) were added to approximately 4 ml of wet sediment in a test tube to enable calculation of pollen density. The samples were digested with HCl to remove carbonates and inorganic material. Samples were then concentrated by sieving and treated with NaOH to dissolve humic materials and HF to degrade Si when necessary. Glacial acetic acid was added to remove water from the samples prior to adding a mixture of acetic anhydride and sulphuric acid to remove cellulose. Samples were stained with saffranine and permanently mounted on microscope slides in silicon oil. Pollen grains were identified through reference to type material and to the identification key provided in Moore et al. (1991). A minimum of 300 pollen grains were counted in each sample. Two pollen sums were used. In order to identify changes in catchment land cover and vegetation, one pollen sum included all identifiable pollen grains and spores, excluding those from aquatic plants. In addition, and in order to assess any major changes in chemical and hydromorphological conditions, abundances of pollen and spores from aquatic plants were calculated on the basis of a second pollen sum comprising the total number of pollen and spores encountered, including aquatics.

Macrofossil analysis followed Birks (2001). Sample comprising 20 cm^3 of wet sediment were disaggregated by soaking in a 10% sodium pyrophosphate solution overnight, before being separated into different size fractions using sieves with 125 and 250 µm mesh sizes. Macrofossils were separated using a binocular microscope at x12 magnification and examined and identified at x40 magnification through comparison with photographs, illustrations and identification keys (Birks 2007; Mauquoy & van Geel 2007), and following consultation with Prof. Hilary Birks, University of Bergen, Norway.

Phytoplankton

Algal Pigments

Up-core variations in algal pigment concentrations (chlorophyll-a, chlorophyll-b, diatoxanthin, fucoxanthin, lutein, phaeophytin-a and zeaxanthin) (Table 3.1) were determined in the laboratories of Dundalk Institute of Technology using High Pressure Liquid Chromatography (HPLC) and following the technique of Airs et al. (2001). Sediment core samples were analysed at 1 cm intervals. The sediment samples were defrosted in the dark and 0.5 g of sediment was placed in centrifuge tubes. The tubes were filled with 6 ml of 100 % acetone for extraction of the pigments. Samples were sonificated for 35 seconds and then centrifuged (0°C) for 10 minutes. The supernatant was collected and refrigerated in an aluminium covered vial. The process was repeated with the sediment sample until the supernatant was clear. The final pigment extract was concentrated through drying with the gas N_2. The dried sample was then dissolved in 3 ml of 100% acetone. Of this solution, 1.5 ml was mixed with 0.64 ml of purified water in a syringe and filtered through a 0.2 µm syringe filter into a dark glassed HPLC sample vial. The HPLC used was a Dionex UVD 170-U with a P680 HPLC pump, a Dionex TCC-100 column compartment with thermostat and an Ultimate 3000 autosampler. Two Dionex ODS2 3 µm columns (150 mm x 4.6 mm I.D.) were used in-line and preceded by a guard column (C18 ODS Octadecyl, 4 mm x 3 mm I.D.). For every sample, 100 µl was injected into the column. Elution was carried out using a mobile phase gradient, comprising acetonitrile, methanol, 0.01 M ammonium acetate and ethyl acetate at a flow rate of 0.7 ml min^{-1}. Pigments were detected at 412-440-454-460 nm over a period of 90 minutes per sample. The concentration was calculated by the area under each pigment peak and compared with known standards, with the detection limit initially set at three times the standard deviation of background levels. Before running the samples, the method was tested with pure pigment standards supplied by DHI Denmark. Sediment pigment concentrations (mg g^{-1} OM) were expressed as a proportion of sediment organic content, estimated by % LOI (see above).

Diatoms

Diatoms are widely used as biological indicators of water quality. The remains of diatoms in sediments can be used to derive estimates of DI-pH and DI-TP, based on robust relationships with pH (Battarbee 1984; Jones et al. 1986; Anderson & Korsman 1990; Patrick & Stevenson

1990) and P (Hall & Smol 1992; Bennion et al. 1996) and the transfer function approach (Chen et al. 2008).

Diatoms were prepared using the methodology outlined by Battarbee et al. (2001). A Meiji ML2000 light microscope and x100 oil immersion objective (giving a total magnification overall of x1000) were used for diatom enumerations. A Nikon Coolpix 4500 digital camera attached to the microscope was used to verify taxonomic features and to record sample specimens. Over 300 valves were counted in each sample. Taxonomic identification mainly followed Krammer & Lange-Bertalot (1986, 1988, 1991a, 1991b, 2000), Foged (1977) and Lange-Bertalot & Metzeltin (1996) and taxon authorities are listed in Appendix 3.1. The relative abundances of individual diatom species were calculated (%), as were diatom concentrations (cells g^{-1}) and accumulation rates (cells cm^{-2} yr^{-1}). DI-TP and DI-pH were calculated using a 70-lake diatom TP model (r^2_{jack} = 0.74; RMSEP = 0.21) and pH model (r^2_{jack} = 0.89; RMSEP = 0.32) for the Irish Ecoregion described in Chen et al. (2008).

Zooplankton

Cladocera remains

Sediment core samples from Leane and Feeagh were prepared and analysed for Cladocera using a modified version of the standard method described by Frey (1986). Cladoceran remains were identified and enumerated with a compound microscope and phase contrast attachment at x250 to x400 magnifications. Taxonomy of the remains followed Frey (1959, 1960, 1962a, 1962b, 1964), Goulden & Frey (1963) and Alonso (1996). Species names with authorities are listed in Appendix 3.2. Counts of remains were adjusted to represent individuals, as one individual Cladocera has two shells, one headshield and one postabdomen. As well as counting the often more abundant pelagic specimens, at least 70-100 benthic (chydorid) individuals were counted for each sample, thus enabling calculation of benthic/planktonic ratios.

3.4 Statistical Analysis

Sediment core correlation

Up-core variations in % LOI can be used to adjust for relatively minor differences in sedimentation between adjacent cores from the same coring site, and therefore as a basis for extending a chronology established for one core to other, closely-distanced cores (Carol et al. 1998; Brancelj et al. 2002). To assist in cross-correlation between adjacent cores, the unpublished computer programme CSPLOT (Malcolm Clarke pers. comm.) was applied to sediment cores collected from Leane and Feeagh (an example of this application, for Feeagh, is described in Appendix 3.3), and involved determining the level of similarity between a dated core (master sequence) of sediments and proximately located, undated sediment cores.

Zonation of stratigraphic data

The main groupings (or zones) of diatom, pollen, geochemical and algal pigment data were identified by stratigraphically constrained, incremental sum of squares cluster analysis (CONISS) (Grimm 1987), a form of agglomerative analysis using the computer software programme PSIMPOLL (Bennet 1996). CONISS creates a dendrogram based on similarities between adjacent samples. Closely matched, stratigraphically-contiguous samples are then grouped progressively in an agglomerative hierarchical fashion. Geochemical and algal pigment data were square root transformed prior to analysis. The ‘broken-stick’ model was used to determine the optimum number of zones in a sequence (Bennett 1996).

Zones were labelled according to an alphanumeric code comprising sets of two letters and a number, each separated by a hyphen. In this the first set of letters refers to the proxy (e.g. P = pollen, D = diatoms), while the second refers to the site (e.g. L = Leane). The number that follows is the actual number of the zone. Zones are numbered from the bottom of the sequence upwards (e.g. P-L-1, P-L-2 etc.).

Evaluation of geochemical sources

Correlation analysis, principal components analysis (PCA) and the enrichment factor (EF) approach were employed to distinguish between the different sources of input for geochemical elements deposited at each site. Correlation analysis assessed the degree of association between different elements, organic matter and rates of sediment accumulation. PCA distinguished between sources of input (natural and anthropogenic) of geochemical elements (e.g. Ruiz

Fernandez et al. 2007; Wu et al. 2007) and assessed the degree of geochemical element enrichment (i.e. above those levels considered as background). Concentration baselines for individual elements were determined according to the procedure of the Paleoecological Investigation of Recent Lake Acidification (PIRLA) project (Binford 1990). Accordingly, the mean (x) and standard deviation (σ) of the apparently constant values for measured concentrations of elements in the lowermost sediment samples of each core were estimated; if the next higher concentration was $< x + \sigma$, then this concentration was included in the set of constant values and the standard deviation was re-calculated. This procedure continued until the concentration in the next higher level was greater than $x + \sigma$. The asymptotic values were assumed to be the geochemical baselines for the different elements. In addition, Al was used as a passive tracer element for EFs calculated for samples collected from Bunaveela, Feeagh and Mask using the function:

$$EF = (M / Al)_{sample} / (M / Al)_{baseline}$$

where M is the metal studied (Binford 1990).

Ordination

In order to detect and summarise the main patterns of variation in the palaeolimnological datasets, multivariate ordination techniques were employed using the computer software programs CANOCO (version 4.5) (ter Braak & Šmilauer 2002) and PAST (Hammer et al. 2001). Ordination enables a reduction in the dimensionality of multivariate palaeolimnological data sets and allows description by a small number of new axes that make the greatest contribution to variance. The information is then expressed as a reduced number of ordination axes that are, by definition, orthogonal and uncorrelated (Birks & Birks 2006). Moreover, these new axes can be treated individually and can be plotted in combination with sediment core data against depth/estimated year. Palaeolimnological datasets (geochemistry, pollen, macrofossil, algal pigments and diatoms) were ordinated on an individual basis for each site. Detrended correspondence analyses (DCA) indicated gradients less than 2.5 standard deviation units for all datasets. Consequently linear methods were applied (ter Braak & Prentice 1988). PCA, conducted on a correlation matrix, was used to determine variation in the palaeolimnological datasets and the underlying gradients. For diatom and pollen datasets, only those taxa with, respectively, >2% abundance in at least two samples or >3% abundance in at least one sample were included in the analyses in order to minimise the influence of rare species. In addition, species abundance and pigment concentration data were square-root transformed to compensate for high variability and skewed distributions.

3.5 Results

3.5.1 SWRBD: Leane

The following refers to data obtained from Leane through the sedimentary sampling techniques described previously. Analyses of these data are also covered in this section. Six cores were collected from Leane over the course of the ILLUMINATE project during 2006 and 2007 (Table 3.2; Figure 3.1).

Sediment chronologies

Chronological control for Leane was based on up-core variations in activity of the two relatively short-lived radioactive isotopes ^{210}Pb and ^{137}Cs. No material from Leane was dated using either the AMS ^{14}C or the SCP techniques, owing to a very high rate of sediment accumulation.

^{210}Pb & ^{137}Cs

Excess activity of ^{210}Po (a proxy for ^{210}Pb) declines with depth, from a maximum activity of 25.41 DPM g^{-1} in the uppermost sediment sample analysed to a minimum towards the base of the core of 5.37 DPM g^{-1} (Table 3.3). However some variability in ^{210}Po activity is evident and, as a result, the CRS model was applied. Based on an application of the CRS model, average sediment accumulation rate was estimated at 0.281-0.378 g cm^{2} yr^{-1}. Accordingly, the lowermost sample analysed in the core was dated at c. 1955. Levels of ^{137}Cs activity confirm these estimates, with peaks in activity evident at 32-33 cm and 20-21 cm likely representing, respectively, maximum fallout from nuclear weapons testing (c. 1963) and from Chernobyl (1986) (Figure 3.2).

According to the chronology established through ILLUMINATE, Leane has the highest rate of sediment accumulation of all of the lakes studied in the project and one of the highest reported for Ireland (Nowlan et al. 2000; Taylor et al. 2006b).

Variations in organic matter content (loss-on-ignition (% LOI))

Levels of organic matter content generally fluctuate around 20% in all cores, with a slight increase evident from the late-1970s. Co-variance in the proportions of organic matter in sediment samples from equivalent depths in cores collected from the deepest point in Leane was confirmed using correlation analysis and CSPLOT (Figure 3.3; Appendix 3.3).

Geochemistry

Elemental chemistry

Up-core variations in levels of chemical elements for Leane are similar, on a depth-for-depth basis, in both concentration and accumulation rate form (Figure 3.4a). Four zones were identified: G-L-1 (pre-c. 1958); G-L-2 (c. 1958 to c. 1968); G-L-3 (c. 1968 to c. 1987) and G-L-4 (post-c. 1987). Overall, G-L-1 (pre-c. 1958) is characterised by decreasing accumulations of major, trace and redox-sensitive elements. A peak in levels of trace elements is evident at c. 1962. From c. 1962, levels of trace and nutrient elements increase, with the former reaching a second peak in c. 1968, while those of the major elements remain relatively constant. Increased levels of the major, redox-sensitive, trace and nutrient elements are evident from the mid-1970s (G-L-3 and G-L-4). Increasing levels of major elements, particularly Ca, are also apparent in G-L-4 Estimated EFs for trace elements, particularly Cd and Zn, in G-L-3 were >1, thus indicating inputs from anthropogenic sources (Figure 3.4b). By comparison, anthropogenic enrichment by P is evident in all zones, and particularly in G-L-3 between c. 1970 and c. 1990, while enrichment by Ca is clearly evident post-c. 1990 in G-L-4.

Stable Isotopes

Levels of δ^{15}N are consistently above the threshold value for terrestrial plants (3.7‰) but below that for aquatic plants (4.9‰) (Meyers 1994) (Figure 3.3). Measured levels of δ^{15}N increase slightly from 4.2‰ in the basal sample to 4.9‰, indicating a proportion of the organic matter is from aquatic plants (a conclusion also supported by C/N ratios). Low levels of δ^{13}C indicate that detritus from terrestrial C_3 plants is the predominant source of organic material in the sediments, however. In addition, the C:N ratios indicate little input of particulate sewage (Brennan et al. 1994).

Biological remains

Pollen & plant macrofossils

A total of 23 pollen and spore types were identified. Up-core variations in pollen data are illustrated in Figure 3.5 and were divided into two zones: P-L-1 and P-L-2, with the zone boundary between the two dating to c. 1978. Pollen from deciduous woodland taxa, notably *Alnus*, *Betula*, conifer-type and coryloid-type, are generally common throughout the sequence, contributing between 50-60% to the pollen sum. An increase in abundance of conifer-type pollen from c. 1978 characterises the P-L-1/ P-L-2 boundary, with peak levels dated c. 1987.

Macrofossil remains were recovered from eight sediment core samples from a littoral area adjacent to Tomies wood, close to the southwest shore of the lake (Figure 3.1). Fragments of the bryophytes *Aulacomnium*, *Drepanocladus*, *Palludella* and *Sphagnum*, all in their living state associated with peatlands, were the most common macrofossils encountered (Table 3.4). Remains of these taxa generally decline in abundance towards the top (above 29 cm) of the sediment core, while the remains of filamentous algae increase.

Phytoplankton

Algal Pigments

Sediment-based pigment data were grouped into five zones: AP-L-1 (c. 1950- c. 1953), AP-L-2 (c. 1953-c. 1961), AP-L-3 (c. 1961-c. 1968), AP-L-4 (c. 1968-c. 1995) and AP-L-5 (post-c. 1995) (Figure 3.6). The lowermost zones, AP-L-1 and AP-L-2, are characterised by low levels of all algal pigments. Concentrations of fucoxanthin and diatoxanthin pigment remains increase in AP-L-3 from the 1960s. Further increases are evident in all algal pigments from the 1970s onwards (AP-L-4). The carotenoid zeaxanthin, commonly associated with cyanobacteria, shows distinctive peaks in the early 1970s, the mid-1980s and c. 1994. However, the pigment is also produced by green algae and higher plants under photosynthetic stress (i.e. zeaxanthin is considered a photoprotective pigment) (Young 1991). Further increases in concentrations of the pigments chlorophyll-a, chlorophyll-b, fucoxanthin and phaeophytin-a, are evident in AP-L-5 from c. 1995.

Diatoms

The remains of diatoms were examined in 38 levels: 234 taxa in total were enumerated. Diatom counts are summarised in Figure 3.7, while diatom abundance data are provided in Appendix 3.4. Up-core variations in diatom abundances were grouped into three zones: D-L-1 (c. 1945 to c. 1953); D-L-2 (c. 1953 to c. 1963) and D-L-3 (post-c. 1963). Relatively high abundances of *Achnanthidium minutissimum* characterise the lowermost zone. In contrast, in D-L-2, abundances of *A. minutissimum* decrease while those of *Aulacoseira ambigua* increase. Oligotrophic species (e.g. *Cyclotella comensis* and *C. radiosa*) are conspicuous components of D-L-1 and D-L-2. *Aulacoseira subarctica* and *Stephanodiscus neoastraea* increase at c. 1963 (the D-L-2/D-L-3 zone boundary), while *Cyclotella comensis* and *C. radiosa* decline, representing a shift from mesotrophic to more nutrient-rich conditions. This is reflected in rising DI-TP values to c. 30 µg l^{-1} TP in D-L-3. *Aulacoseira subarctica* has a TP optimum of c. 29 µg l^{-1} (Chen et al. 2008) and is a key driver of the DI-TP increase. However, the diatom transfer function appears to overestimate in-lake levels of TP: for example, the surface sediment sample had a DI-TP estimate of 30 µg l^{-1} TP compared with measured mean annual TP of 14-21 µg l^{-1} TP (Table 2.1). DI-pH values fluctuate around pH 7.6 (slightly alkaline) and generally increase up-core along with DI-TP.

Zooplankton

Five sediment core samples were examined for cladocera remains (Table 3.5). Benthic chydorid species (*Alona* spp. and *Alonella excisa*) are present in low levels (c. 5%) in the basal core sample and decline up-core. Littoral chydorids were replaced by planktonic Bosminidae and Daphniidae species by c. 1962, with *Daphnia* predominating from c. 1972. The benthic/planktonic ratio is less than one for the entire core, indicating an impoverished benthic fauna.

Ordination and synthesis of Leane palaeoenvironmental data

The dominant signals evident in the palaeoenvironmental data for Leane are illustrated in the primary ordination axes and key driving variables in Figure 3.8. Estimated average SAR, at 0.33 g cm^{-2} yr, is high, with a high rate (0.39 g cm^{-2} yr) already evident as early as c. 1953. In contrast, levels of organic matter content remain relatively low and show little variation up-core.

Axis 1 in the geochemistry data accounts for 77% of the variation and is primarily associated with Cd (0.9), which is representative of anthropogenic inputs, and to a lesser extent P (0.2) and Ca (-0.1). Levels of sediment P increase from c. 1950, presumably due to nutrient enrichment from anthropogenic sources (EF >1; Binford 1990) (Figure 3.4b). A slight reduction in levels of sediment P is evident in the late 1980s, most likely linked to the installation of biological treatment facilities in the STP in 1984. Increased levels of P are again evident from c. 1990 associated with increases of Ca and redox-sensitive Fe. Increased sedimentary Ca may be a eutrophication effect, and due to increased biological consumption of CO_2 and precipitation of $CaCO_3$ (Meyers 2006). Eutrophication may itself be a consequence of an increased supply of nutrients from diffuse agricultural sources (Jennings et al. 2008), particularly as sediment Pollen and spore data also appear to reflect agricultural intensification and afforestation in the catchment. Oxygen depletion of hypolimnial waters in the lake are known to have occurred during this period (Twomey et al. 2000) and this may have resulted in the release of sediment P, further adding to eutrophication pressures.

Algal responses to increased nutrient levels are evident in increases in concentrations of sediment-based pigments, a switch to more nutrient tolerant diatom assemblages and increases in DI-TP. Most of the variation (85%) in the pigment data is associated with changes in the levels of chlorophyll-a and zeaxanthin. Low levels of algal pigments are present until c. 1960. Subsequent peaks appear to coincide with algal blooms that occurred in the early-1970s, mid-1980s and late-1990s (Twomey et al. 2000). Ordination of the diatom assemblages confirms the early predominance of oligotrophic taxa in the sedimentary record, followed from c. 1960 by eutrophic species. This switch is evident in the onset of a more nutrient enriched state and higher pHs (according to DI-TP and DI-pH data). Diatom assemblages in basal core samples suggest that Leane experienced relatively low nutrient levels between c. 1945 and the late-1950s, with DI-TP estimates of c. 15 $\mu g\ l^{-1}$ TP suggesting mesotrophic conditions. The level of DI-TP increases by 100% (probably an over-estimate and an artefact of the transfer function used) from the early 1960s, suggesting meso-eutrophic conditions. Moreover, the benthic/planktonic cladocerans ratio for Leane is highest in the basal sample (c. 1945), indicating the richest benthic fauna for the period of time covered by the sedimentary record from Leane analysed in the current research. A change up-core in the abundances of littoral and planktonic forms may be a response to lower water transparency, a decline in available macrophyte habitat or some combination of the two, and is indicative of reduced ecological status (de Eyto et al. 2003).

Table 3.1 Pigments measured in this study and commonly recovered from lake sediments. Relative degree of chemical stability is ranked from 1 (most) to 3 (least) stable and their taxonomic affinities are outlined (after Leavitt & Hodgson 2001).

Pigment	**Stability**	**Affinity**
Phaeophytin-a	1	Chlorophyll-a derivative
β, *β* -carotene	1	*Plantae, Algae*, some phototrophic bacteria
Lutein	1	*Chlorophyta, Euglenophyta, Plantae*
Zeaxanthin	1	Cyanobacteria
Echinenone	1	Cyanobacteria
Chlorophyll-b	2	*Plantae, Chlorophyta, Euglenophyta*
Diatoxanthin	2	*Bacilariophyta, Dinophyta, Chrysophyta*
Fucoxanthin	2	*Dinophyta, Bacilariophyta, Chrysophyta*
Myxoxanthophyll	2	Colonial cyanobacteria
Chlorophyll-a	3	*Plantae, Algae*

Table 3.2 Leane: sediment cores.

Core code	**Date collected**	**Location**	**Latitude, Longitude**	**Depth of water (m)**	**Length of core (cm)**	**Analyses**
L-1	31/10/2006	Deepest point	09º33' W, 52º01' N	64.1	57	LOI, diatoms, cladocera
L-2	31/10/2006	Deepest point	09º33' W, 52º01' N	64.1	45	Pollen, radiometric dating, LOI,
L-3	31/10/2006	Deepest point	09º33' W, 52º01' N	64.1	40	LOI
L-4	31/10/2006	Deepest point	09º33' W, 52º01' N	64.1	57	DW, geochemistry
L-5	04/04/2008	Deepest point	09º33' W, 52º01' N	64.9	52	LOI, pigments, isotopes
L-6	13/05/2007	Tomies Wood	09º34' W, 52º01' N	20	38	Macrofossils

Table 3.3 Leane: chronology-related data. ^{210}Po (total and unsupported) and ^{137}Cs activity; and estimated sediment accumulation rates (SAR) based on CRS and linear regression models.

Sample ID (depth cm)	Dry wt./ wet cc. gcm^{-3}	Cumul-ative mass gcm^{-2}	^{210}Po total activity DPM g^{-1}	^{210}Po unsup-ported activity DPM g^{-1}	^{137}Cs DPM g^{-1}	CRS estimated age (years)	CRS SAR gcm^{-2} yr^{-1}	Linear regression estimated age
LeaneC2 (4-5)	0.383	2.489	28.0	25.41	8.38	6.8	0.366	7.7
LeaneC2 (8-9)	0.398	4.082	25.1	22.54	8.40	11.4	0.345	12.7
LeaneC2 (12-13)	0.420	5.762	22.1	19.52	8.50	16.3	0.344	17.9
LeaneC2 (16-17)	0.392	7.330	20.2	17.63	15.80	21.1	0.328	22.8
LeaneC2 (20-21)	0.348	8.720	18.2	15.70	19.96	25.4	0.319	27.1
LeaneC2 (24-25)	0.401	10.322	17.2	14.63	14.21	30.9	0.294	32.1
LeaneC2 (28-29)	0.356	11.746	15.4	12.88	20.18	35.9	0.284	36.5
LeaneC2 (32-33)	0.344	13.121	13.2	10.70	24.71	40.6	0.294	40.8
LeaneC2 (36-37)	0.371	14.606	10.5	7.92	15.32	44.9	0.346	45.4
LeaneC2 (40-41)	0.406	16.229	10.7	8.17	7.04	50.5	0.287	50.5
LeaneC2 (44-45)	0.396	17.218	7.9	5.37	1.64	53.1	0.385	53.6

Table 3.4 Leane: macrofossil remains.

	Allochthonous											Autochthonous		
	Arboreal				Non-arboreal									
Depth (cm)	*Betula*	*Picea*	*Pinus*	*Quercus*	*Aulacomnium*	*Carex*	*Drepanocladus*	Ferns	*Juncus*	*Palludella*	*Sphagnum*	*Chara*	Fil. algae	Total no. /sample
1	24	2	4	2	0	0	120	2	0	0	70	2	58	284
3	6	2	2	2	26	8	60	2	8	100	100	2	72	390
5	6	0	0	1	7	0	100	0	3	10	146	0	22	295
9	2	0	1	0	88	0	97	4	8	170	91	0	2	463
13	9	1	0	2	110	0	170	6	19	290	179	0	0	786
21	10	2	2	1	124	0	163	9	10	189	40	2	0	552
29	12	0	10	2	102	0	326	18	26	418	76	0	0	990
37	4	0	0	0	48	0	10	1	8	41	213	0	0	325

Table 3.5 Leane: Relative (%) abundances of cladocerans and benthic planktonic ratios from selected sediment core samples.

Depth (cm) **CRS estimated age (years)**	**57** **c. 1948**	**44** **c. 1962**	**30** **c. 1972**	**16** **c. 1987**	**2** **c. 2006**
Benthic Species					
Acroperus harpae	1.6	0.8	0.0	1.2	0.0
Alona affinis	4.8	0.8	0.0	2.3	1.3
Alona guttata/rectangula	4.0	1.6	2.5	4.7	2.6
Alona intermedia	0.0	0.0	0.0	1.2	0.0
Alona quadrangularis	4.0	0.0	3.7	1.2	0.0
Alona rustica	4.8	0.0	1.2	2.3	1.3
Alonella excisa	5.6	3.1	0.0	3.5	1.3
Alonella exigua	0.8	1.6	0.0	0.0	0.0
Alonella nana	1.6	2.3	2.5	1.2	1.3
Alonopsis elongata	0.8	0.0	0.0	0.0	0.0
Camptocercus rectirostris	4.0	2.3	0.0	1.2	0.0
Chydorus piger	3.2	0.0	0.0	1.2	1.3
Chydorus sphaericus	2.4	1.6	2.5	2.3	1.3
Eurycercus lamellatus	1.6	3.1	1.2	1.2	1.3
Graptoleberis testudinaria	1.6	0.8	2.5	0.0	0.0
Leydigia leydigii	0.0	0.0	0.0	1.2	0.0
Monospilus dispar	0.8	0.8	0.0	1.2	1.3
Pleuroxus trigonellus	1.6	0.0	2.5	0.0	5.3
Pleuroxus truncatus	4.8	0.8	0.0	0.0	1.3
Pleuroxus uncinatus	0.0	0.0	0.0	0.0	1.3
Planktonic Species					
Bosmina longirostris	1.6	6.3	0.0	5.8	0.0
Bosmina longispina	28.8	5.5	4.9	10.5	13.2
Bosmina sp.	15.2	59.4	27.2	30.2	26.3
Daphnia longispina group	6.4	9.4	49.4	27.9	39.5
Benthic:planktonic ratio	**0.9**	**0.2**	**0.2**	**0.3**	**0.3**

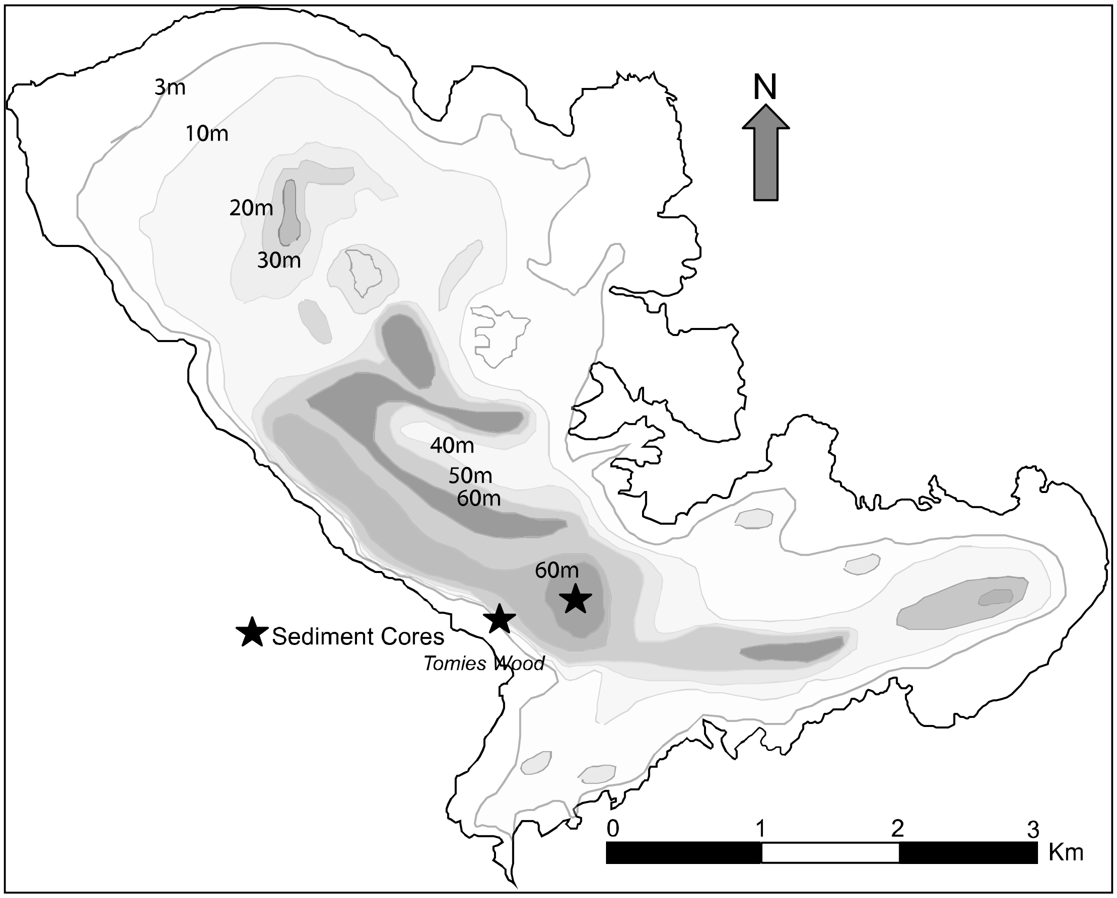


Figure 3.1 Leane: bathymetry and locations of sediment coring sites.

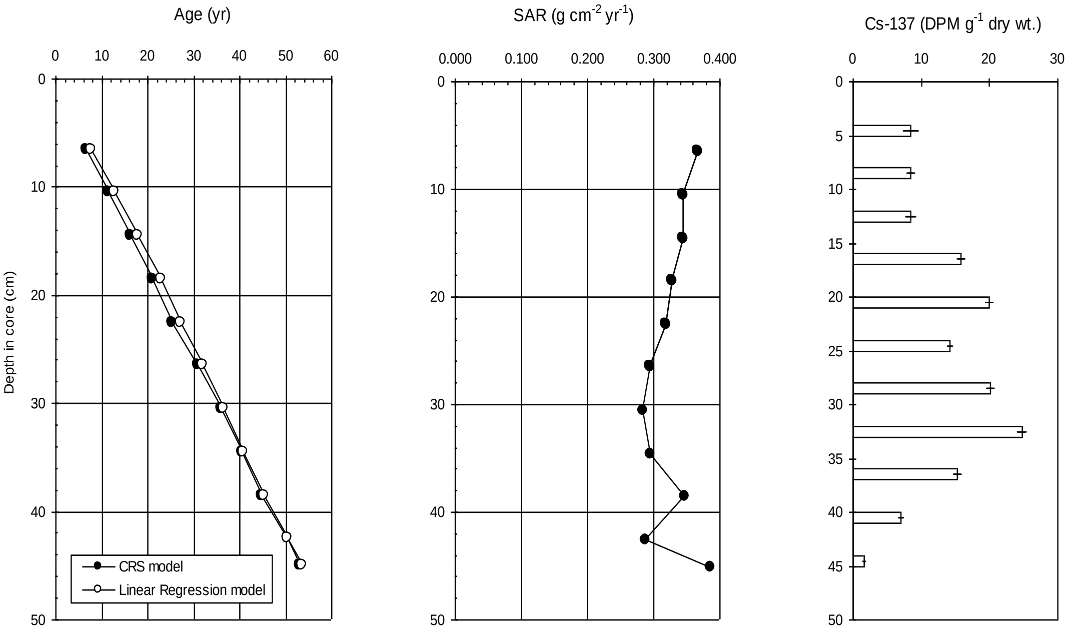


Figure 3.2 Leane: age (yr) vs. depth (cm) (CRS and Linear Regression models); up-core variations in sediment accumulation rates (SAR), and ^{137}Cs activity.

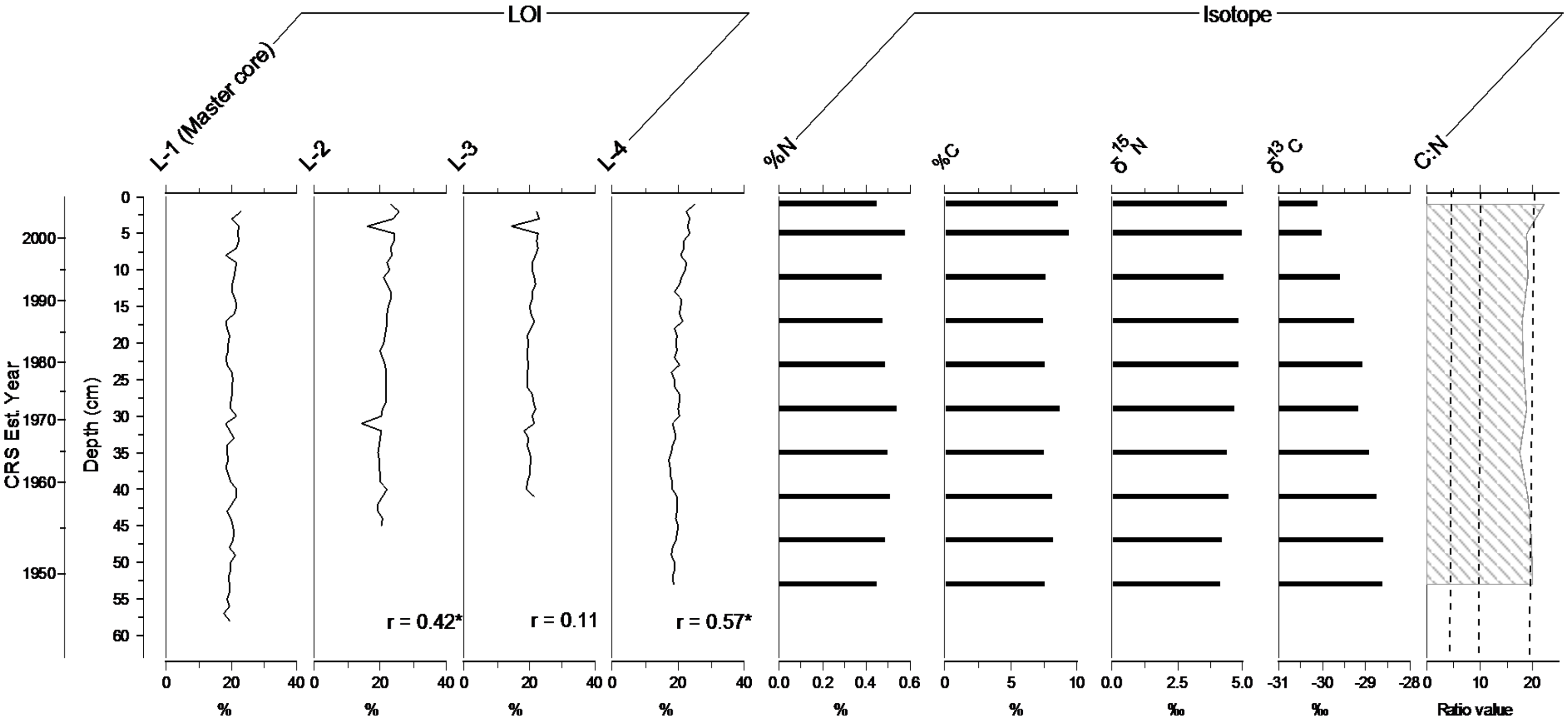


Figure 3.3 Leane: up-core variations in % LOI (*= significant), δ^{15}N and δ^{13}C and ratios of C/N. Threshold C/N ratio values (4, 10 and 20) indicating the predominant source of organic material are represented with dashed lines (see Meyers 2003 and text for details).

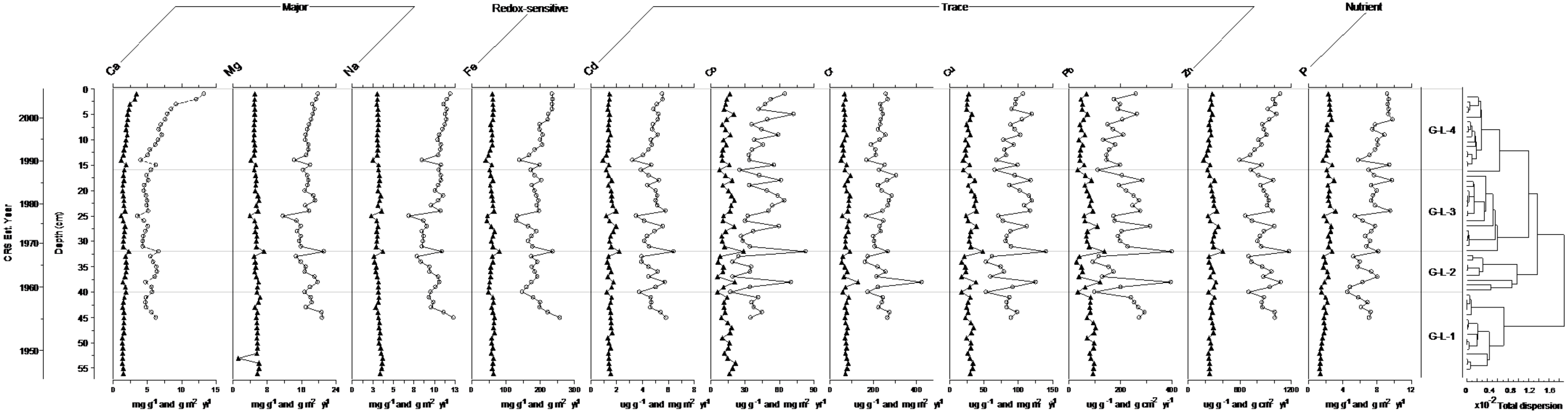


Figure 3.4a Leane: up-core variations in concentration (▲) and accumulation rate (○) data for chemical elements.

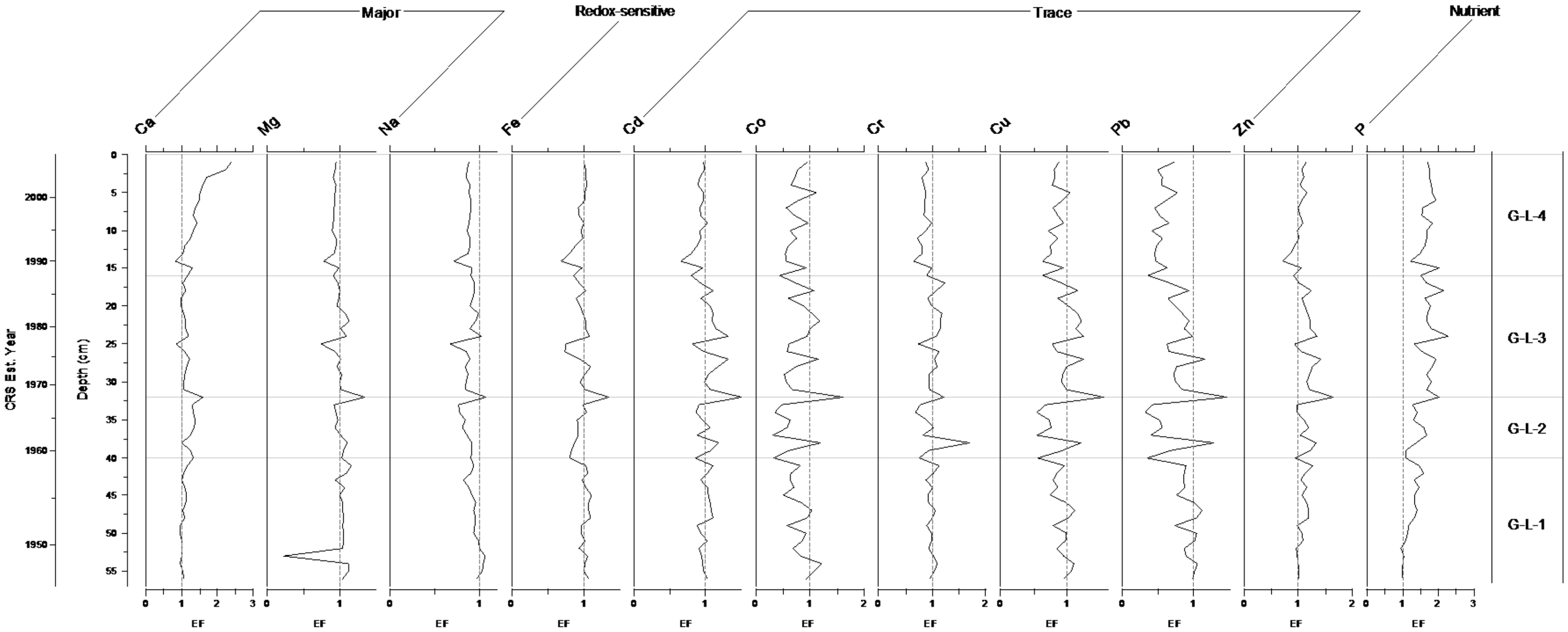


Figure 3.4b Leane: up-core variations in Enrichment Factors (EFs). EF = 1 is highlighted.

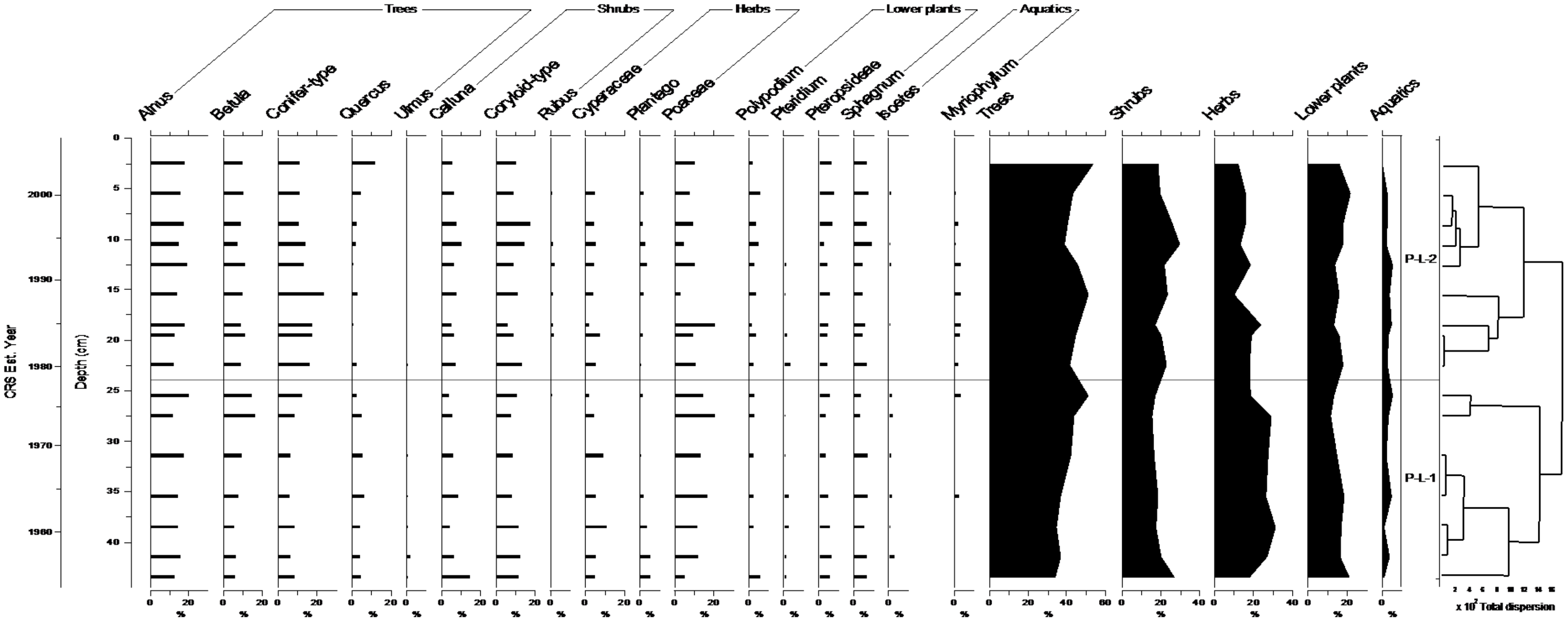


Figure 3.5 Leane: up-core variations in pollen data. For information on pollen sums used, see text**.**

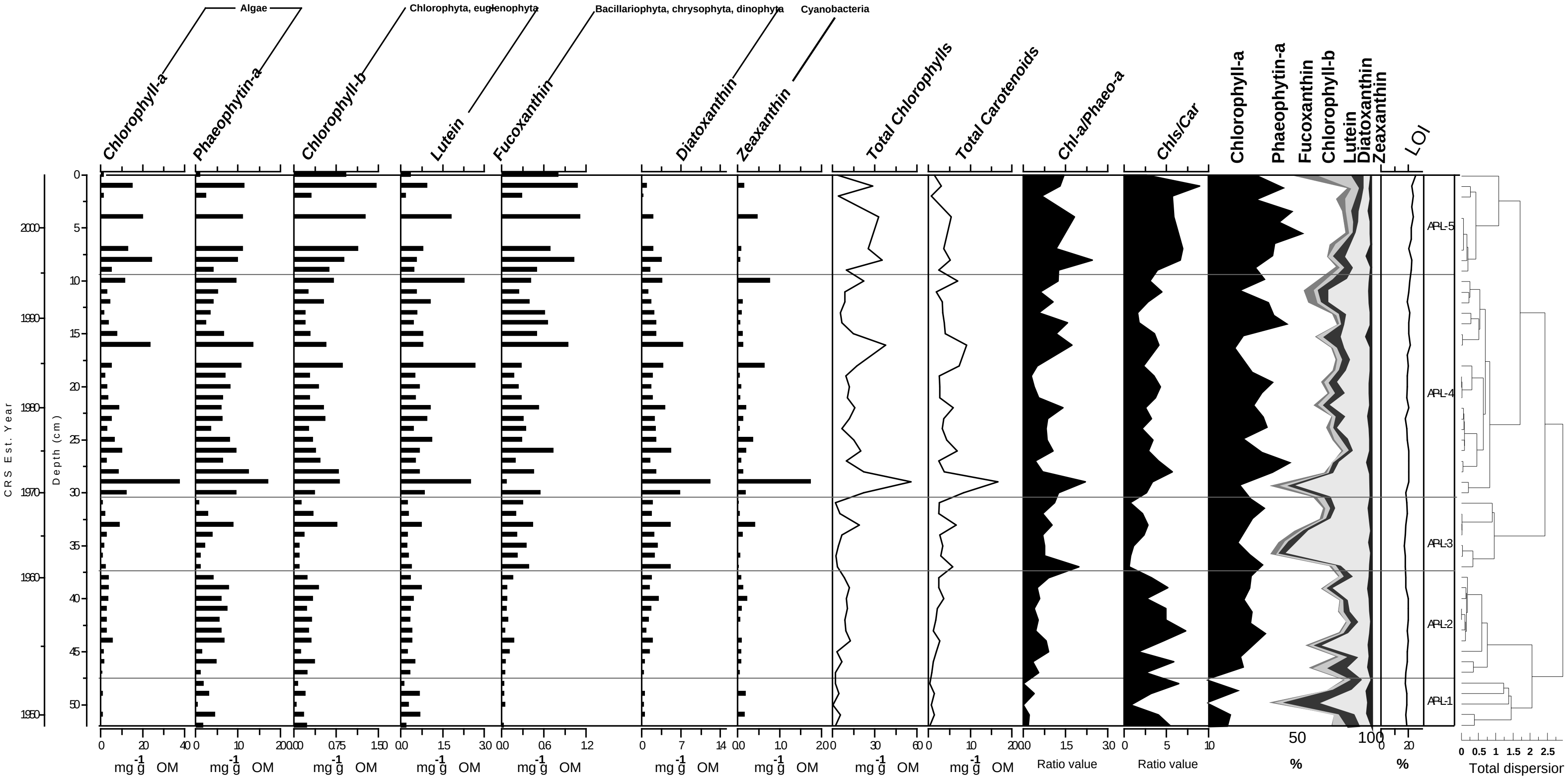


Figure 3.6 Leane: up-core variations in algal pigment concentrations. Total chlorophylls = chl-a, chl-b and phaeophytin-a, total carotenoids = lutein, diatoxanthin, fucoxanthin and zeaxanthin.

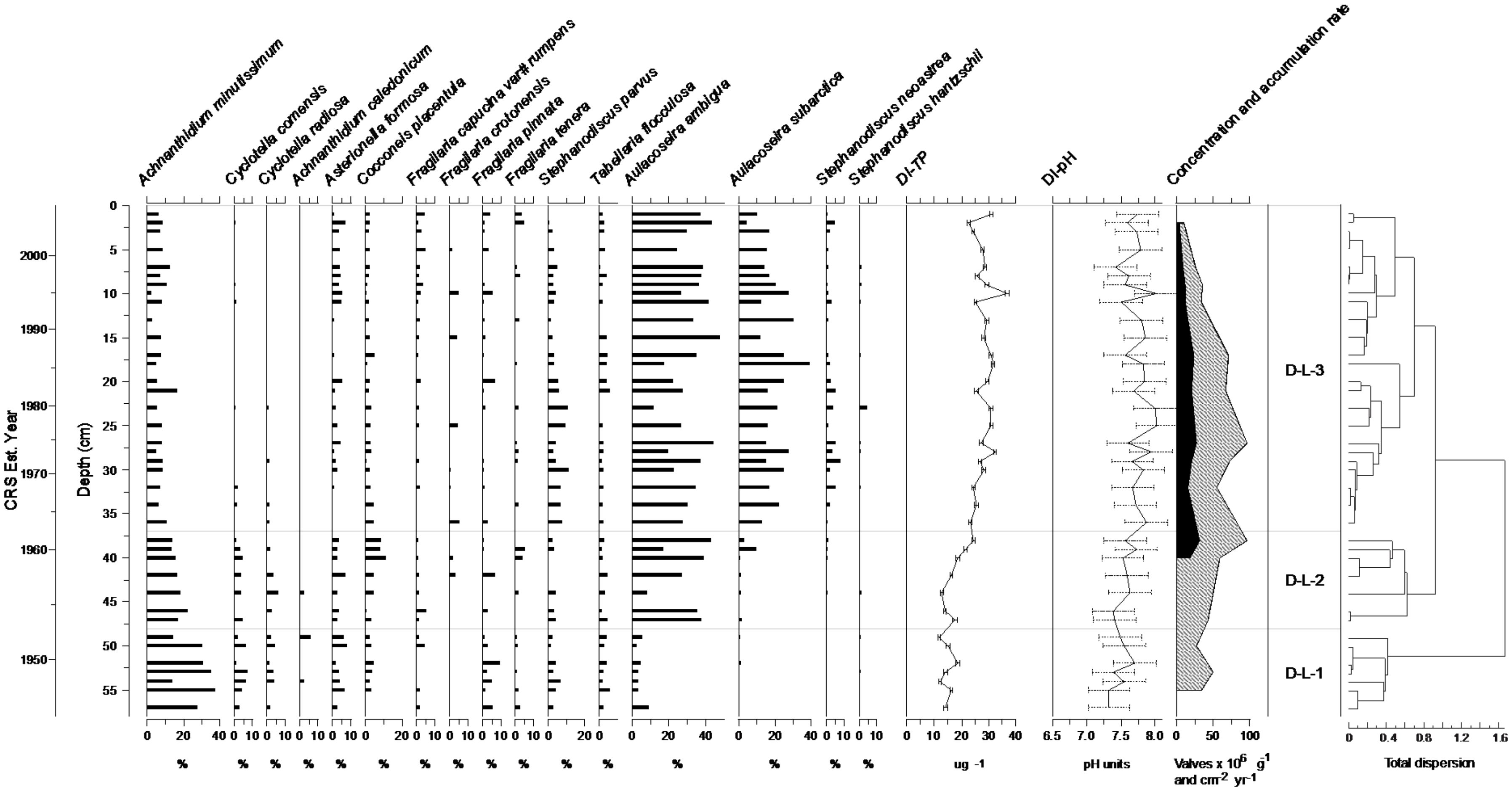


Figure 3.7 Leane: up-core variations in abundances of remains of diatoms and DI-TP and DI-pH, concentrations (black silhouette) and flux (grey silhouette).

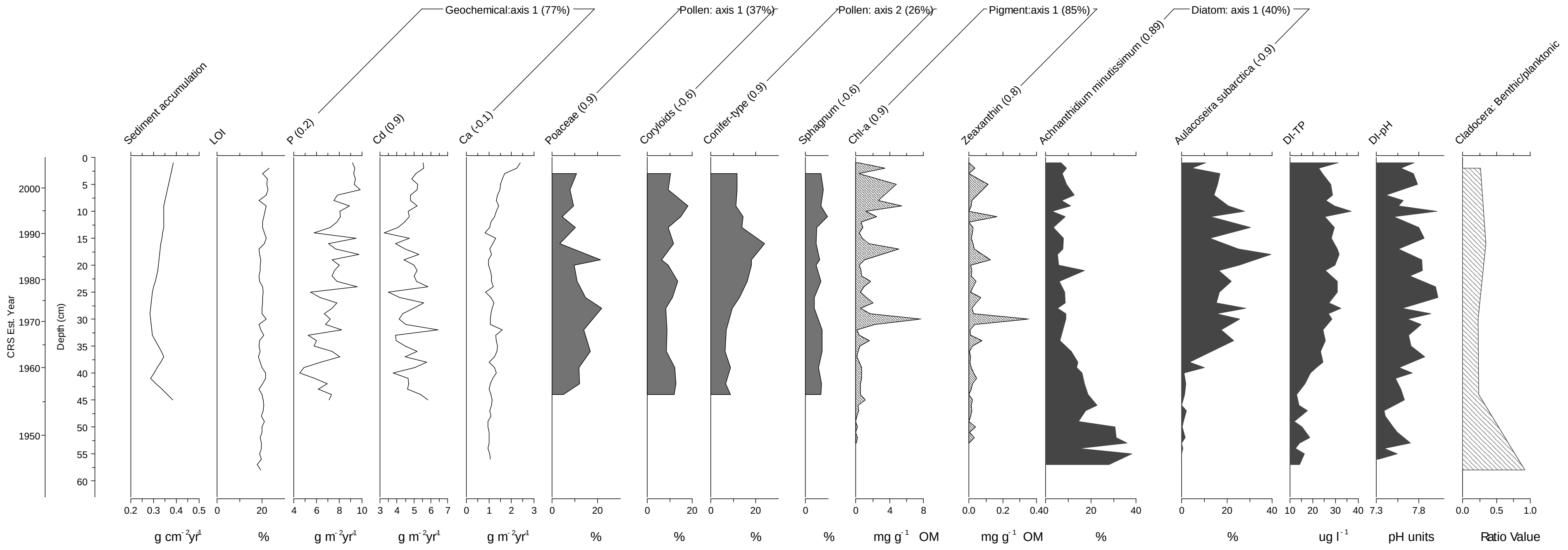


Figure 3.8 Leane: synthesis of multi-proxy palaeolimnological data.

3.5.2 SWRBD: Muckross

The following refers to data obtained from Muckross through the sedimentary sampling techniques described previously. Analyses of these data are also covered in this section. Note that because the chronology established indicated an extremely low rate of sediment accumulation, and therefore the time period of most interest was represented by a very shallow accumulation of deposits, ecological sampling and analyses of sediments from the lake were truncated compared with Leane. Six sediment cores were collected from the deep waters in Muckross as part of the ILLUMINATE, however (Table 3.6; Figure 3.9).

Sediment chronologies

Chronological control for Muckross was based on up-core variations in activity of the two relatively short-lived isotopes ^{210}Pb and ^{137}Cs: no material from Muckross was dated using either the AMS ^{14}C or the SCP techniques.

^{210}Pb & ^{137}Cs

Excess ^{210}Po activity declined rapidly and exponentially with depth, with levels above those considered background in only the uppermost two samples in the core analysed. Maximum levels of activity (45.9 DPM g^{-1}) in the sample from 3-4 cm drop to 4.4 DPM g^{-1} for the sample at 7-8 cm. Furthermore, maximum activity of ^{137}Cs (17.1 DPM g^{-1}), in the surface sample, declines to 2.7 DPM g^{-1} at 7-8 cm depth and remains more or less constant thereafter (Table 3.7; Figure 3.10). Consequently, establishing chronological control for the site was problematic: the regression model suggests an average sediment accumulation rate of 0.0284 g cm^{-2} yr^{-1} ($r^2 = 0.93$), while the CRS model estimates the average rate of sediment accumulation at 0.0251 g cm^{-2} yr^{-1}. Moreover, the estimates of average sediment accumulation rate have substantial uncertainties associated with them because so few points are available for modelling. Both the CRS and linear regression models indicate that about 80 to 90 years of sediment accumulation is represented in the uppermost 5 cm of the profile. Age predictions older than these, in the deeper sections of the core, are not considered reliable. Radiocarbon dates are required to confirm the slow rates of sedimentation indicated by measured activities of ^{137}Cs and ^{210}Pb.

Variations in organic matter content (loss-on-ignition (% LOI))

Generally up-core variations in % LOI are greater than for Leane, with highest values in the bottom, middle and top parts of the core (Figure 3.11). Levels of organic matter do not co-vary (r=0.2), suggesting a high level of intra-coring site variation in sedimentation. Consequently CSPLOT was not applied to the Muckross cores.

Geochemistry

Elemental chemistry

Up-core variations in elemental chemistry data are expressed in concentration form only, because of difficulties in establishing reliable sediment accumulation rates (Figure 3.12a), and were grouped into five zones (G-M-1, G-M-2, G-M-3, G-M-4 and G-M-5). The boundaries for the lowermost three zones are in the period where chronological control is weak; thus only the boundary between the uppermost two zones (G-M-4 and G-M5) has been dated with any confidence (at c. 1935). G-M-1 is characterised by decreasing levels of many of the trace elements analysed. Rising levels of Ca, Pb and P are conspicuous in G-M-2, while peaks in Fe and P characterise G-M-3. G-M-5 (from c. 1935) is distinguished from G-M-4 by higher levels of Ca, Cd and Zn. Calculated EFs generally equate to background level (EF<1) (Figure 3.12b), suggesting that natural inputs of elements account for the highest level of variation.

Stable isotopes

Up-core variations in $\delta^{13}C$ and $\delta^{15}N$ are relatively minor (Figure 3.11). Values for $\delta^{13}C$ are between -28‰ and -29‰, whereas levels of $\delta^{15}N$ are between 2.5‰ and 3.65‰. Both $\delta^{13}C$ and $\delta^{15}N$ values indicate a mainly terrestrial, C_3 source for much of the organic C, as is also implied by the C/N ratios.

Biological remains

Because of the problems of establishing a reliable chronology for Muckross sediments, only very attenuated analyses of biological proxies – relative to other sites studied as part of ILLUMINATE – were carried out. The following is an account of the results of those analyses.

Pollen and plant macrofossils

Pollen analysis was conducted on six sediment samples (Figure 3.13). Conifer-type pollen is the most abundant arboreal pollen type, and is particularly abundant in the uppermost two samples analysed. Despite the small number of samples analysed, two pollen zones are evident (P-M-1 and P-M-2), with the boundary between the two dated at c. 1945. Abundant conifer-type pollen characterises the uppermost of these two zones.

Up-core variations in macrofossils from eight samples from a sediment core collected from a littoral location in the northern part of the lake (Figure 3.9) are illustrated in Table 3.8. Remains of *Betula* fruits, scales and catkins were frequent in most samples. Macrofossils of *Alnus* are only evident above 15 cm, while remains of the moss *Polytrichum* are found throughout the core.

Phytoplankton

Algal pigments

No algal pigments were analysed in the Muckross sediments.

Diatoms

Abundances of diatom remains were enumerated in nine samples and 103 species were identified**.** Up-core variations in diatom abundances are illustrated in Figure 3.14 and listed in Appendix 3.4. Because of uncertainties over chronological control, diatom abundances could not be expressed in accumulation rate form. Up-core variations in diatom abundance data were grouped into three zones: D-M-1, D-M-2 and D-M-3. High diatom concentrations and occurrences of *Achnanthidium minutissimum*, *Brachysira vitrea*, *Cyclotella comensis*, *Cyclotella distinguenda* var. *unipuncta*, *Cyclotella radiosa* and *Cyclotella rossii* characterise D-M-1. Declines of *Cyclotella* spp. are evident in D-M-2. Low diatom concentrations are evident in D-M-3. DI-TP estimates are generally low (8-12 $\mu g\ l^{-1}$ DI-TP), suggesting that oligotrophic conditions have prevailed for the entire sedimentation period, while only small changes are evident in DI-pH.

Zooplankton

No zooplankton remains were analysed in the Muckross sediments.

Ordination and synthesis of Muckross palaeoenvironmental data

Estimated SAR, based on just three data points, is very low for the last c. 100 years (i.e. in the uppermost 10 cm of the sediment core) at 0.02 g $cm^{-2}\ yr^{-1}$, and radiocarbon dates are required to determine the age of the older sediments below c. 10 cm depth.

Palaeolimnological data, summarised in Figure 3.25, indicate changes in sediment source over the period of time represented by the sediment core, with substantial mid-core increases in organic matter and further increases in the last c. 100 years. Ordination of chemical element data shows high levels of Cu and Cd at the core base, followed by mid-core declines coincident with high organic matter, and high levels of Ca and Cd in the last c. 100 years. The peaks in Fe are most likely buried redox-related enrichment layers, the first synchronous with P, and may be indicative of post-depositional re-mobilisation of P (Boyle 2001). A decline in the abundance of conifer-type pollen between 45 and 25 cm may be linked to extensive woodland exploitation associated with copper mining activity near Muckross in the 18th and 19th century (Mitchell & Cooney 2004). A subsequent increase in abundances of conifer-type pollen could reflect afforestation in the catchment, which could also explain concomitant increases in Ca and Cd. Ca is generally associated with organic matter input (Mackereth 1966), and increased sedimentary Ca may reflect increased input arising from soil disturbance associated with the preparation of land for afforestation, while increased levels of Cd could represent run-off of fertilizers used to promote tree growth (De Meeus et al. 2002). The diatom data suggest that TP and pH at the site have remained relatively stable, with oligotrophic conditions persisting throughout the period of time represented by the sedimentary record.

Table 3.6 Muckross: sediment cores.

Core code	Date Collected	Location	Latitude, Longitude	Depth of water (m)	Length of core (cm)	Analysis
M-1	01/11/2006	Deep water	09º31' W, 52º00' N	53.3	40	LOI
M-2	01/11/2006	Deep water	09º31' W, 52º00' N	53.3	44	Pollen, radiometric dating, LOI,
M-3	01/11/2006	Deep water	09º31' W, 52º00' N	53.3	48	LOI, diatoms
M-4	01/11/2006	Deep water	09º31' W, 52º00' N	53.3	42	DW, geochemistry
M-5	04/04/2008	Deep water	09º31' W, 52º00' N	67.5	46	LOI, pigments, isotopes
M-6	01/11/2006	NE shallow area	09º30' W, 52º00' N	10	36	Macrofossils

Table 3.7 Muckross: ^{210}Po (total and unsupported) and ^{137}Cs activity, and estimated sediment accumulation rates (SAR) based on CRS and Linear Regression models.

Sample ID (depth cm)	Dry wt./ wet cc. gcm^{-3}	Cumul-ative mass gcm^{-2}	^{210}Po total activity DPM g^{-1}	^{210}Po unsup-ported activity DPM g^{-1}	^{137}Cs DPM g^{-1}	CRS estimated age (years)	CRS SAR gcm^{-2}yr^{-1}	Linear regression estimated age
MuckC2 (3-4)	0.406	2.23	45.9	43.0	17.1	88.9	0.025	78.5
MuckC2 (7-8)	0.527	4.34	4.4	2.3	2.7	133.4	0.047	152.6
MuckC2 (11-12)	0.652	6.95	2.8	0.6	0.6	283.7	0.017	244.3
MuckC2 (15-16)	0.828	10.26	2.2	0.0	0.7			
MuckC2 (19-20)	0.402	11.87	1.7		0.2			
MuckC2 (23-24)	0.409	13.51	2.3		0.4			
MuckC2 (27-28)	0.545	15.69	1.9		0.4			
MuckC2 (31-32)	0.687	18.43	1.5		0.2			
MuckC2 (35-36)	0.460	20.27	1.8		0.4			
MuckC2 (39-40)	0.452	22.08	1.5		0.6			
MuckC2 (43-44)	0.422	23.14	1.3		0.4			

Table 3.8 Muckross: macrofossil remains.

	Allochthonous							Autochthonous	
	Arboreal		Non-arboreal						
Depth (cm)	*Alnus*	*Betula*	*Drepanocladus*	*Ericaceae*	*Eriophorum sp.*	Ferns	*Polytrichum*	*Chara*	Total no. /sample
0	0	3	0	0	0	0	0	0	3
5	5	25	20	0	0	1	3	0	54
10	5	35	10	0	20	0	0	1	71
15	5	43	1	2	1	0	3	0	55
20	0	20	0	0	0	0	2	0	22
25	0	55	0	0	0	0	3	1	59
30	0	50	3	2	0	0	0	0	55
35	0	35	10	0	0	0	3	0	48

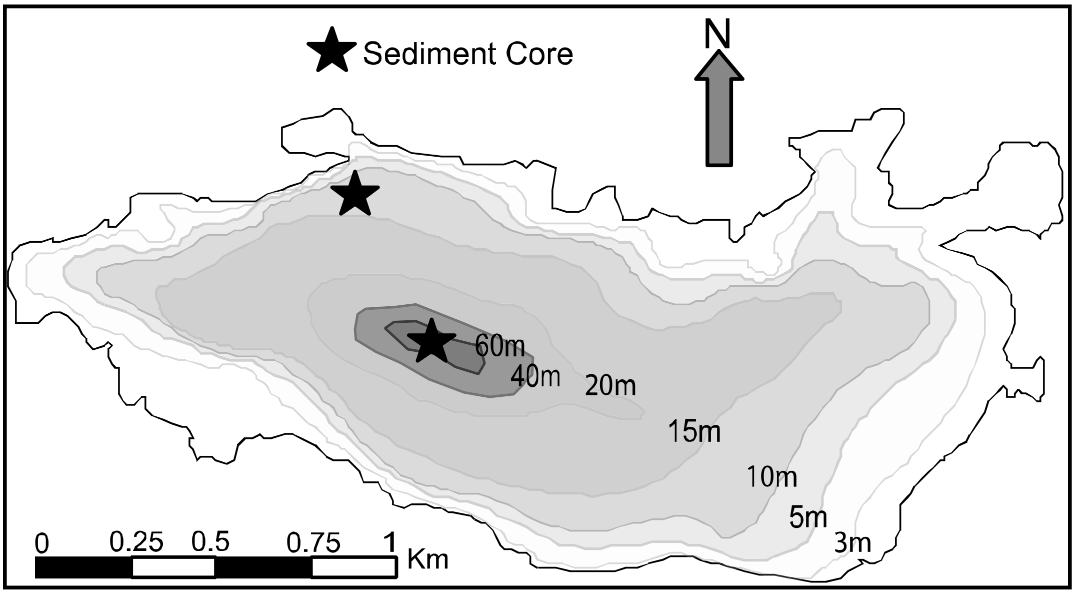


Figure 3.9 Muckross: bathymetry and locations of sediment coring sites.

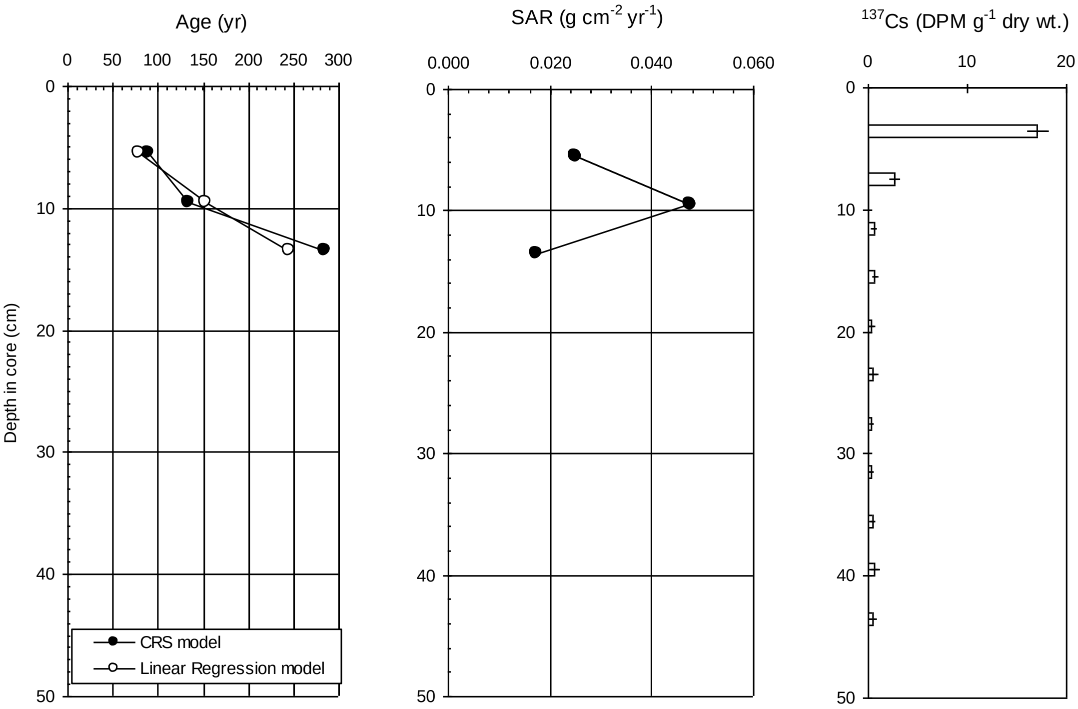


Figure 3.10 Muckross: age (yr) vs. depth (cm) (CRS and Linear Regression models); up-core variations in sediment accumulation rates (SAR), and ^{137}Cs activity..

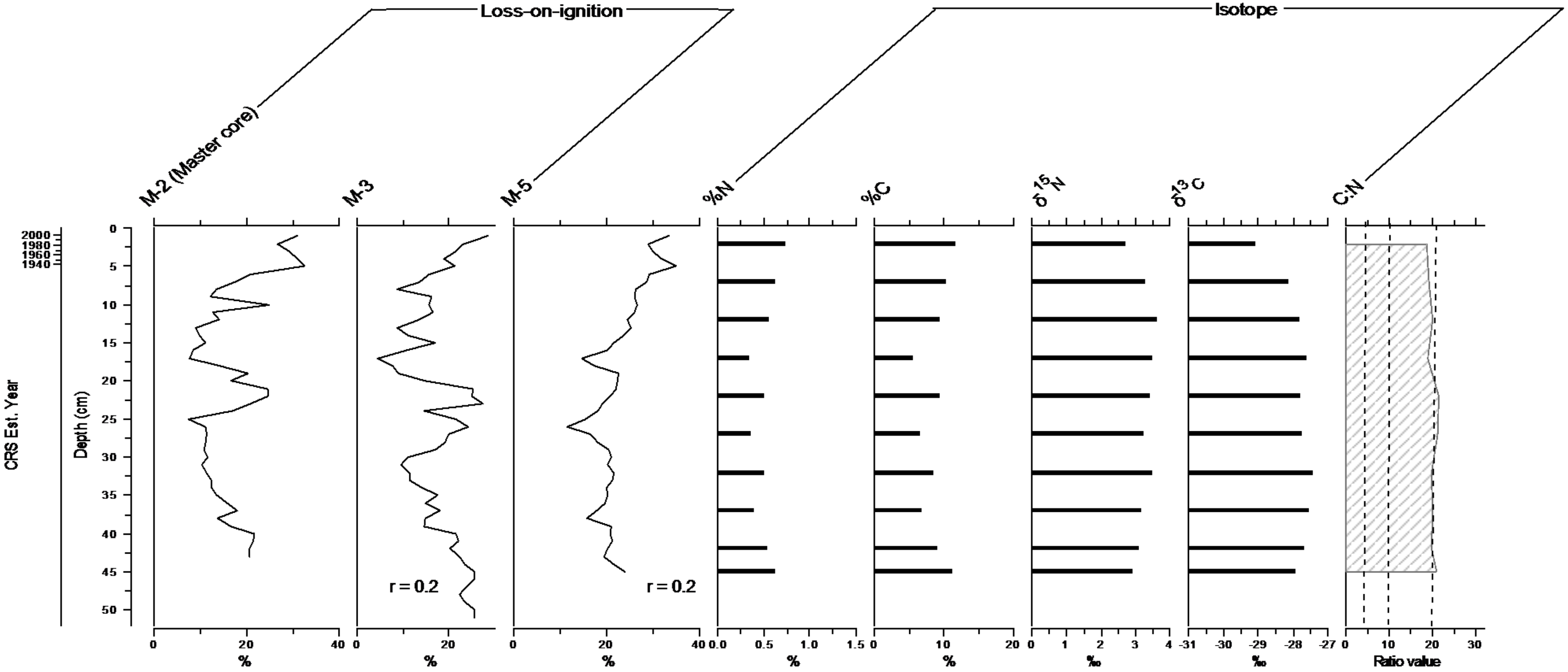


Figure 3.11 Muckross: up-core variations in % LOI, δ^{15}N and δ^{13}C and ratios of C/N. Threshold C/N ratio values (4, 10 and 20) indicating the predominant source of organic material are represented with dashed lines (see Meyers 2003 and text for details).

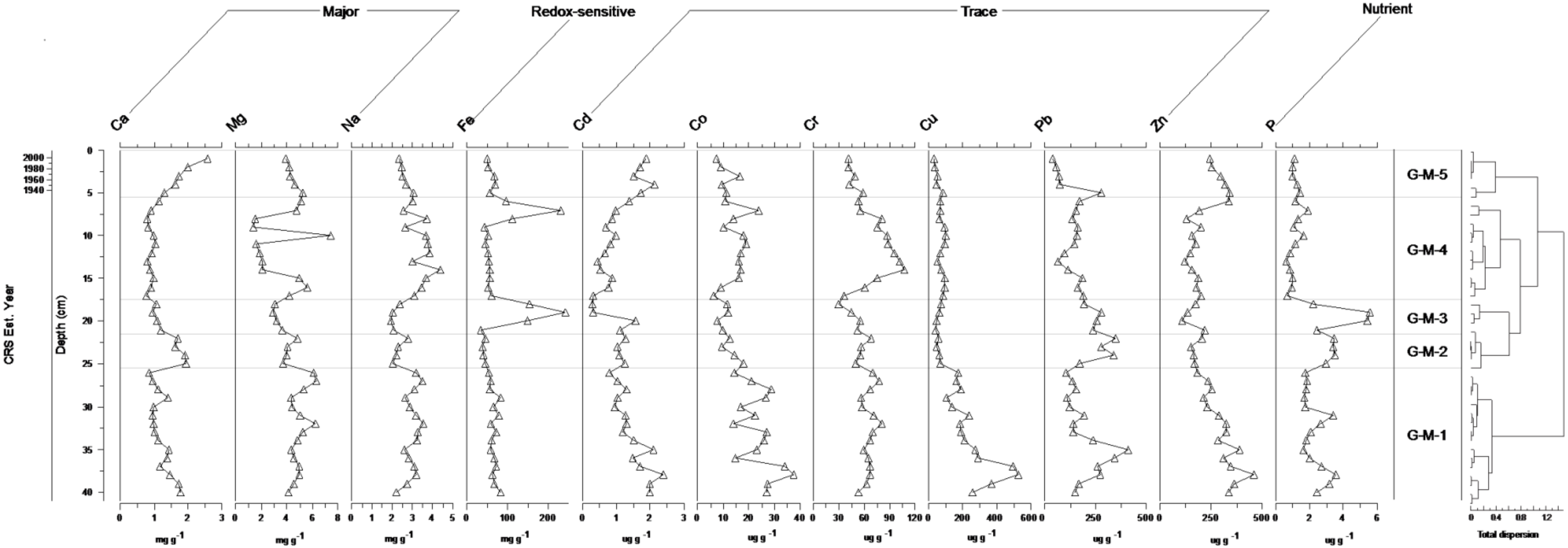


Figure 3.12a Muckross: up-core variations in concentrations of major, trace elements and Fe and P

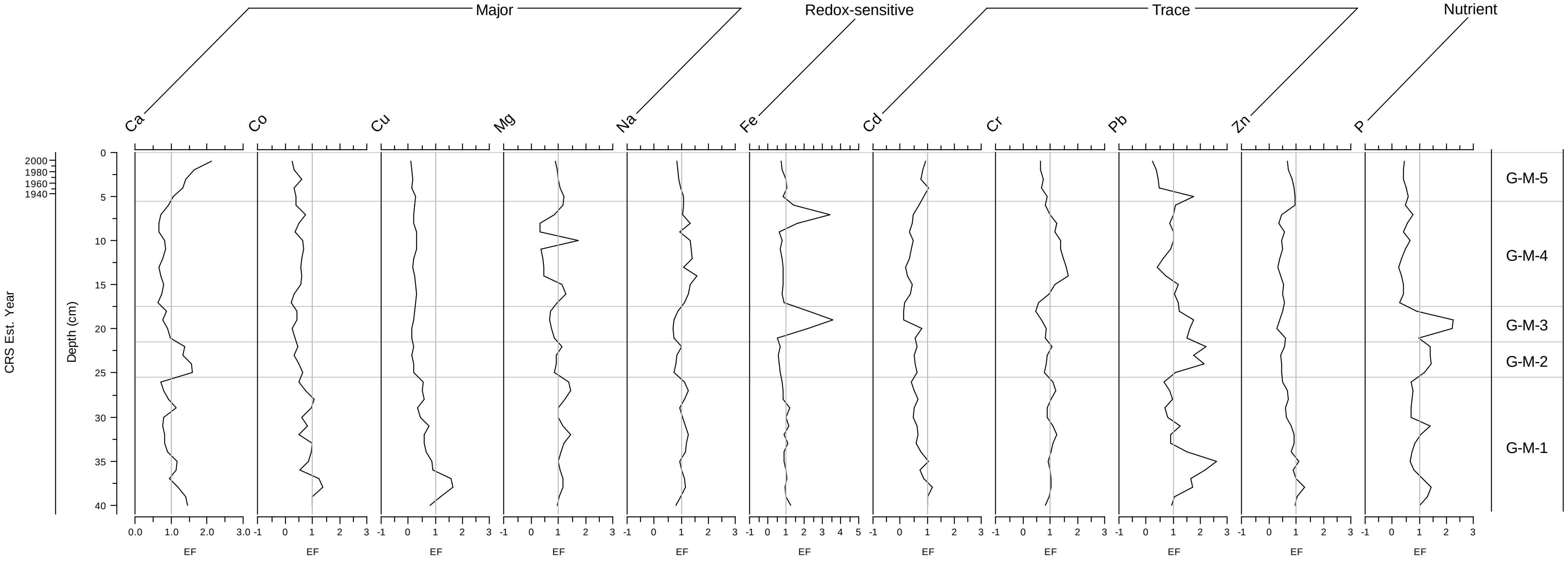


Figure 3.12b Muckross: up-core variations in Enrichment Factors (EFs). EF = 1 is highlighted.

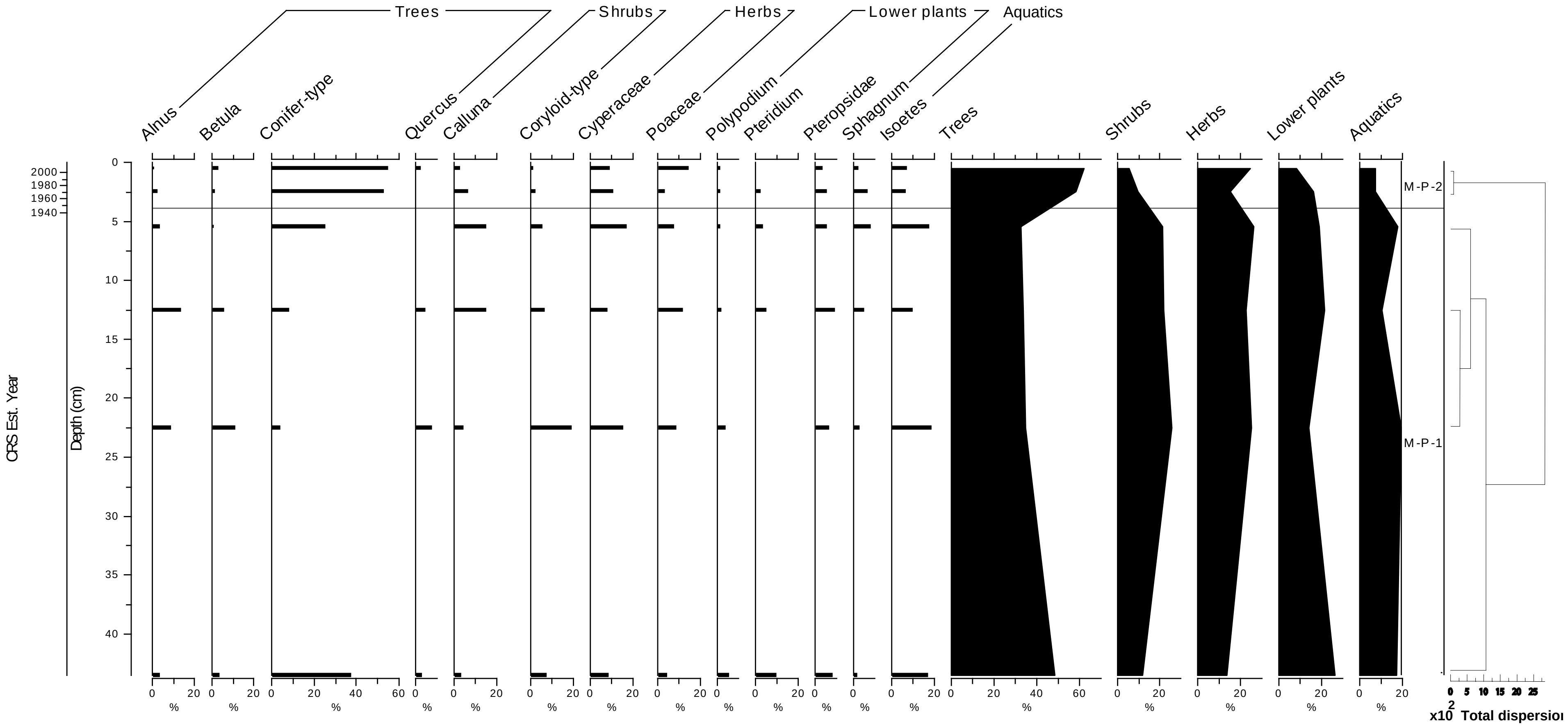


Figure 3.13 Muckross: up-core variations in pollen data. For basis of pollen sum, see text.

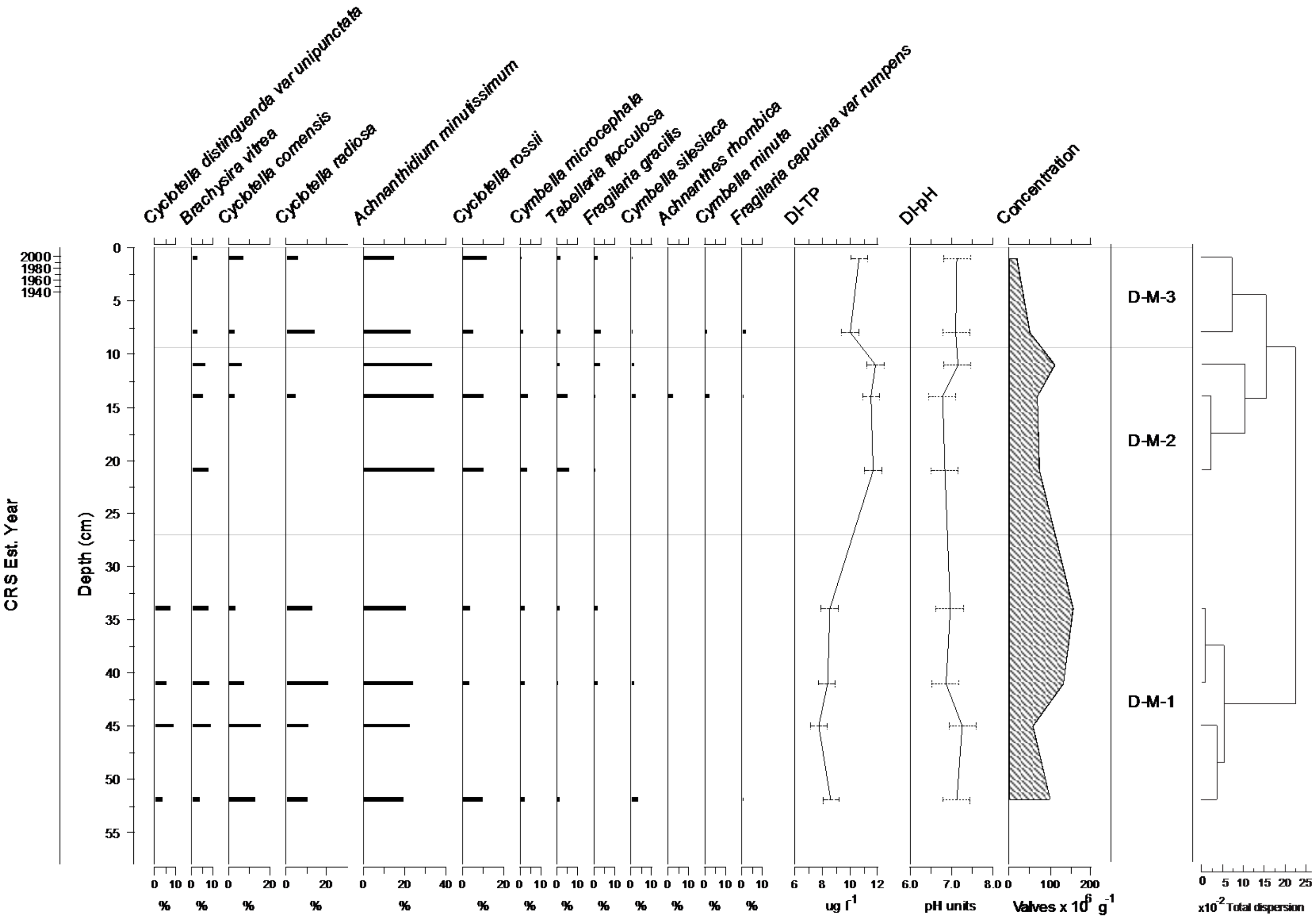


Figure 3.14 Muckross: up-core variations in remains of diatoms, DI-TP and DI-pH and diatom concentrations.

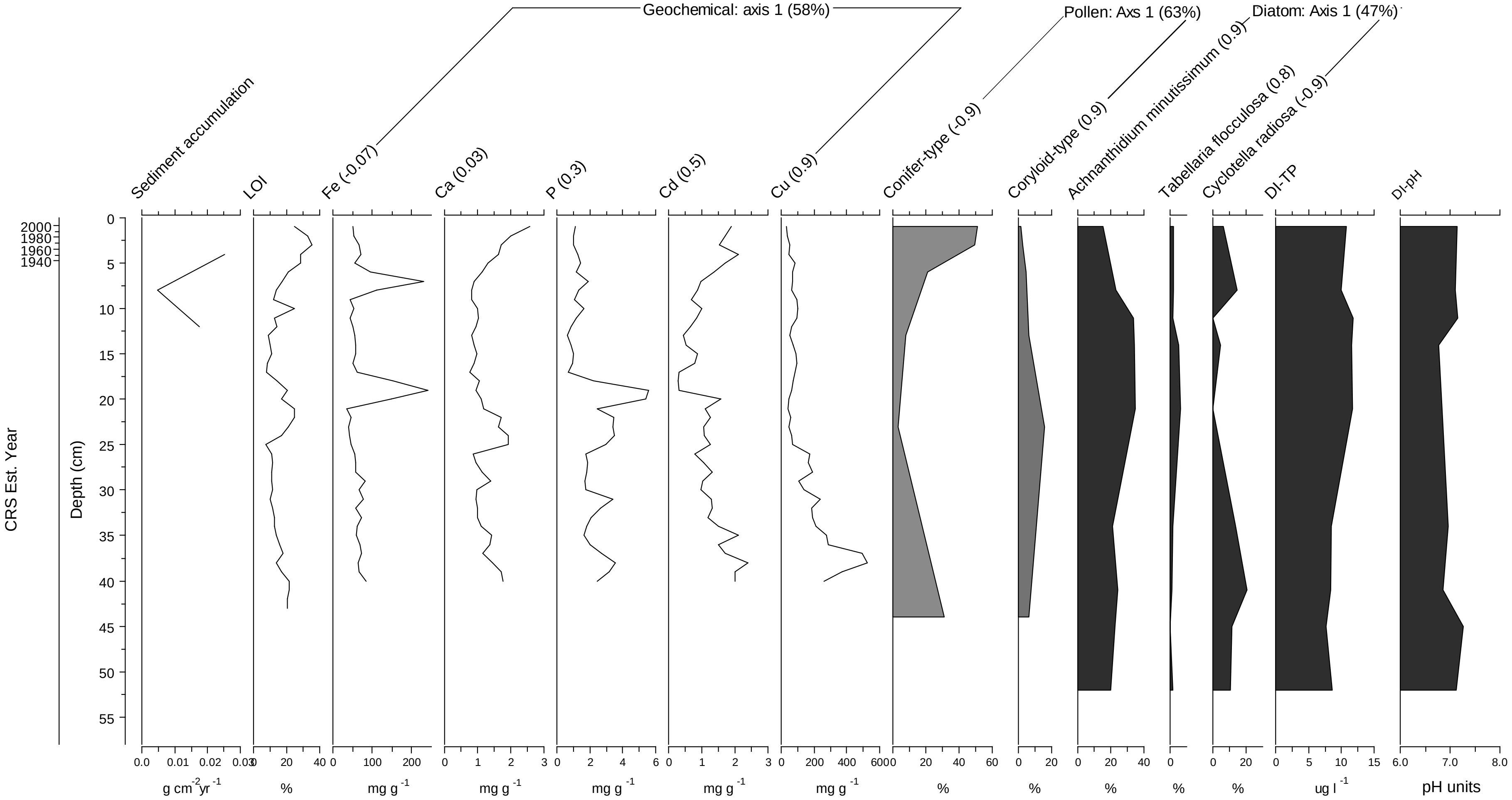


Figure 3.15 Muckross: synthesis of multi-proxy palaeolimnological data.

3.5.3 WRBD: Bunaveela

The following refers to data obtained from Bunaveela through the sedimentary sampling techniques described previously. Analyses of these data are also covered in this section. Five sediment cores were collect from Bunaveela in the ILLUMINATE project (Table 3.9; Figure 3.15).

Sediment chronologies

Chronological control for sediments from Bunaveela was established on the basis of AMS ^{14}C, ^{210}Pb and ^{137}Cs analyses.

AMS ^{14}C dating

A plant macrofossil from the base (49-50 cm) of one of the cores of sediment was dated using the AMS ^{14}C technique at 2810 +/- 40 BP measured radiocarbon age ($\delta\ ^{13}C$ = 28.3 ‰) (Appendix 3.5). This gives a calibrated age range of 2862-2957 cal. BP (Stuiver & Reimer 1993).

^{210}Pb & ^{137}Cs

Levels of excess ^{210}Po decrease with depth; highest and lowest levels were measured in the surface and lowermost sediment samples, respectively (Table 3.10; Figure 3.16). However, variation in activity is apparent, particularly between 9.5 cm and 17.5 cm, and therefore the CRS model was applied to the determination of SAR. Accordingly, SAR decreased gradually with depth (0.360-0.133 g cm^{-2} yr^{-1}), except for an abrupt increase at 13.5 cm (0.360 g cm^{-2} yr^{-1}), with the estimated age of the lowermost core sample c. 1890. These estimates receive some support from measured activities of ^{137}Cs that are high (~20 DPM g^{-1}) in the uppermost sediments, peaking at 21-22 cm and 13-14 cm, presumably reflecting increased atmospheric levels due to, respectively, nuclear weapons testing and the Chernobyl accident (Figure 3.16). The close agreement between the ^{210}Po and ^{137}Cs chronologies suggests that the AMS dated macrofossil is of secondary origin, possibly a result of peat erosion and inwash from the catchment, and thus chronological control provided by the shorter-lived isotopes has been adopted in the current research.

Variations in organic matter content (loss-on-ignition (% LOI))

Up-core variations in organic matter show little inter-core differences and all cores are significantly correlated (Figure 3.17). Thus it was possible to extend chronological control, once established, to other cores from the same coring location, and for cross-comparisons to be made between cores.

Geochemistry

Elemental chemistry

Up-core variation in levels of chemical elements for Bunaveela are expressed in concentration, accumulation rate (Figure 3.18a) and EF (Figure 3.18b) forms. The data were grouped into five zones: G-B-1 (pre-c. 1890-c. 1906); G-B-2 (c. 1906-c. 1933); G-B-3 (c. 1933-c. 1984); G-B-4 (c. 1984-c. 1992); G-B-5 (c. 1992-c. 1999) and G-B-1 (post c. 1999). Measured levels of the major, redox-sensitive and nutrient elements remain relatively constant in G-B-1 and G-B-2. In contrast, accumulation rates of all elements increase in G-B-3 from c. 1950, reaching a peak at c. 1980 before declining in G-B-4. Zones G-B-5 and G-B-6 are characterised by fluctuating amounts of the major elements and a sharp increase in levels of both the redox-sensitive and nutrient elements. EFs are greater than background levels from the late 1980s, indicating increased anthropogenic inputs in the relatively recent past for all elements apart from K. EFs for K show little up-core variation.

Stable isotopes

Little up-core variation in $\delta^{13}C$ and $\delta^{15}N$ is evident (Figure 3.17). Measured levels of $\delta^{15}N$ are all about 2 ‰, while those of $\delta^{13}C$ decline, slightly, up-core. Ratios of C/N remain relatively constant with values just above 20 indicative of a predominantly terrestrial source for organic matter. An increase in C/N ratio values is evident around 16 cm (c. 1980), suggesting a period of enhanced inputs of organic matter. Moreover, when taken together, C:N ratios and $\delta^{13}C$ values indicate that organic material comprises a mixture of terrestrial C_3 and aquatic plant remains.

Biological remains

Pollen and plant macrofossils

Pollen was enumerated in 20 samples; up-core variations in pollen data were grouped into three zones: P-B-1 (pre-c. 1890 to c. 1971), P-B-2 (c. 1971 to c. 1992) and P-B-3 (post-c. 1992) (Figure 3.19). The aquatic species *Isoetes* has a noticeable presence in P-B-1. An increased abundance of conifer-type pollen is evident from c. 1971 and particularly post c. 1992. This increase is concomitant with declines in pollen from shrub taxa (*Calluna* and coryloid-type).

Plant macrofossil remains were examined in three samples from a short core (12 cm) collected in the littoral zone in the eastern part of the lake (Table 3.11). Remains of the bryophytes *Paludella* and *Sphagnum* are frequent, as are those of the rush *Juncus*.

Phytoplankton

Algal Pigments

Up-core variations in concentrations of sediment-based algal pigments are presented in Figure 3.20 and have been grouped into three zones: AP-B-1 (pre c. 1935 to c. 1955), AP-B-2 (c. 1955 to c. 2001), and AP-B-3 (post c. 2001). There is little to distinguish AP-B-1 and AP-B-2, aside from a much greater variability in zeaxanthin concentrations in the latter. Both zones are characterised by very low (< 0.1 mg g^{-1} OM) chlorophyll-a concentrations. By comparison, AP-B-3 is characterised by higher concentrations of chlorophyll-a, diatoxanthin, zeaxanthin, and declines in phaeophytin-a. Chlorophyll-a values (up to 2.21 mg g^{-1} OM) in AP-B-3 are more than three times the highest value (0.66 mg g^{-1} OM) in the rest of the sequence.

Diatoms

One hundred and forty-five diatom taxa were enumerated in the eight sediment samples analysed. A summary of up-core variations in these is provided in Figure 3.21, while diatom abundances are listed in Appendix 3.4. Up-core variations in diatom abundances were grouped into two zones (Figure 3.21). Diatom concentrations increase from c. 1970 and are coincident with a rise in abundances of *Asterionella formosa, Achnanthidium minutissimum* and *Aulacoseira granulata*. Increased abundances of *Aulacoseira subarctica* distinguish D-B-2 (the surface sample) from D-B-1. DI-TP indicates that Bunaveela has been oligotrophic for most of the last 100 years. An increase in DI-TP is evident from the late 1980s. *Aulacoseira subarctica,* which is particularly abundant in D-B-2, has a TP optimum of c. 29 µg l^{-1} (Chen et al. 2008). For most of the record from Bunaveela, DI-pH is slightly below 7, but shows an increase from the mid 1980s.

Zooplankton

Zooplankton remains were not examined in the Bunaveela sediment core.

Ordination and synthesis of Bunaveela palaeoenvironmental data

The primary ordination axes and key driving variables evident in palaeolimnological data preserved in the Bunaveela sediments are highlighted in Figure 3.22. Overall, SAR increases up-core, peaking in the early 1980s. In contrast, organic matter content remains relatively constant, only increasing in the late 1990s. Ordination indicates that the majority of variation in the geochemical element data is associated with Al, redox-sensitive Fe and Mn, and the nutrients TP and N. The concurrence between geochemical profiles and SAR suggests catchment weathering and erosion drove many of the changes in geochemistry until c. 1980, after which there were increased loadings of organic rich sediments and redox-sensitive and nutrient elements, presumably as a result of inwash.

Ordination of pollen and spore data from this site indicates that the main source of variation is an increased presence of conifers beginning in the early 1980s. Low algal pigment concentrations were found in the Bunaveeela sediments, with increases in chlorophyll-a and diatoxanthin evident post-1980. Up-core variations in algal pigment data are largely associated with varying levels of chlorophyll-a, according to PCA. Similarly, a large amount of the total variation in the diatom data is driven by up-core changes in abundances of the nutrient tolerant species *Aulacoseira subarctica* (0.9) and of the nutrient intolerant taxa *Cyclotella comensis* (0.95) and *Cyclotella comta* (0.7). These changes are reflected in post-1980 increases in DI-TP and DI-pH.

The main changes evident in the sediment data from Bunaveela are linked to nutrient enrichment and sediment inwash, and possibly increased pH, associated with catchment disturbance. The latter is more-or-less contemporaneous with afforestation in the catchment.

Table 3.9 Bunaveela: sediment cores

Core code	Date Collected	Location	Latitude, Longitude	Depth of water (m)	Length of core (cm)	Analysis
B-1	16/08/2006	Deepest point	09º32' W, 53º50' N	21.7	50	Pollen, radiometric dating, LOI, geochemistry
B-2	16/08/2006	Deepest point	09º32' W, 53º50' N	21.7	49	LOI, diatoms
B-3	12/11/2007	Deepest point	09º32' W, 53º50' N	21	45	LOI, isotopes, pigments
B-4	01/10/2008	Near-shore (east)	09º32' W, 54º01' N	8.3	12	LOI, macrofossils
B-5	27/08/2009	Deepest point	09º32' W, 53º50' N	21	35	Pollen, radiometric dating, LOI, geochemistry

Table 3.10 Bunaveela: ^{210}Po (total and unsupported) and ^{137}Cs activity, and estimated sediment accumulation rates (SAR) based on CRS and Linear Regression models.

Sample ID (depth cm)	Dry wt./ wet cc. gcm^{-3}	Cumul-ative mass gcm^{-2}	^{210}Po total activity DPM g^{-1}	^{210}Po unsup-ported activity DPM g^{-1}	^{137}Cs DPM g^{-1}	CRS estimated age (years)	CRS SAR gcm^{-2} yr^{-1}	Linear regression estimated age
BunaC1 (5-6)	0.42	3.15	47.6	44.6	20.0	13.0	0.242	20.4
BunaC1 (9-10)	0.36	4.60	38.8	35.8	22.6	19.6	0.221	29.8
BunaC1 (13-14)	0.37	6.09	21.5	18.6	30.9	23.7	0.360	39.4
BunaC1 (17-18)	0.38	7.62	29.8	26.8	27.0	31.1	0.209	49.3
BunaC1 (21-22)	0.38	9.14	28.3	25.3	38.1	39.9	0.173	59.1
BunaC1 (25-26)	0.40	10.74	23.4	20.5	32.7	49.9	0.160	69.5
BunaC1 (29-30)	0.45	12.55	20.1	17.1	8.0	63.5	0.133	81.2
BunaC1 (33-34)	0.46	14.41	12.5	9.5	4.3	75.1	0.161	
BunaC1 (37-38)	0.36	15.86	10.6	7.7	3.5	85.3	0.142	
BunaC1 (41-42)	0.43	17.58	8.3	5.3	3.3	97.2		
BunaC1 (45-46)	0.49	19.55	6.6	3.6	1.6	110.8		
BunaC1 (49-50)	0.40	20.56	4.9	1.9	1.1	115.8		

Table 3.11 Bunaveela: macrofossil remains.

	Allochthonous												Autochthonous		
	Arboreal		Non-arboreal												
Depth (cm)	*Picea*	*Pinus*	*Aulocomnium*	*Calluna vulgaris*	*Drepanocladus*	*Empetrum nigrum*	Ferns	*Isolepis setacea*	*Juncus*	*Paludella*	*Polytrichum*	*Sphagnum*	*Carex rostrata*	*Isoetes lacustris*	Total no. /sample
1	5	1	140	1	45	25	1	1	131	234	5	43	3	0	635
6	7	1	30	0	100	35	6	0	156	234	22	322	2	0	915
10	3	0	10	1	40	104	10	0	221	110	24	310	0	1	834

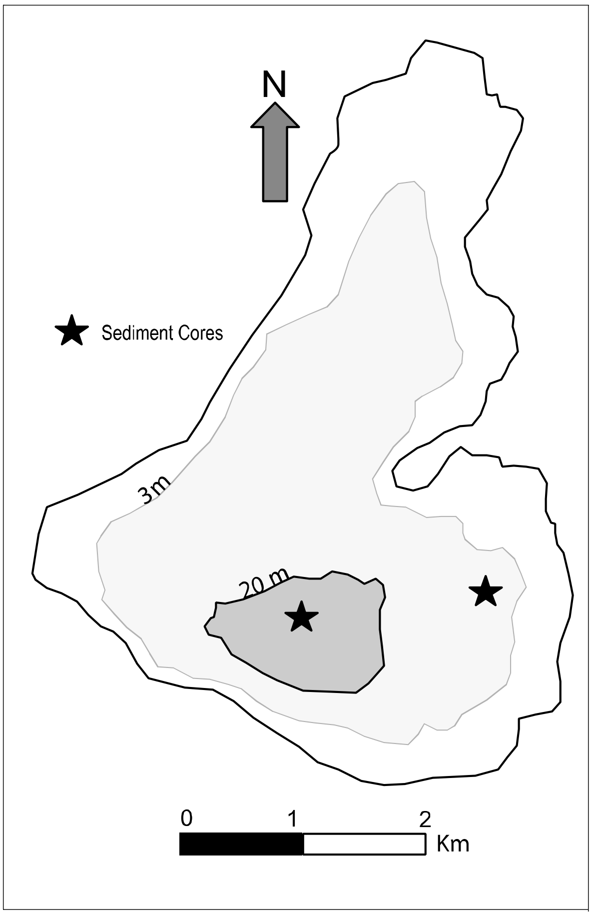


Figure 3.15 Bunaveela: bathymetry and locations of sediment core sites.

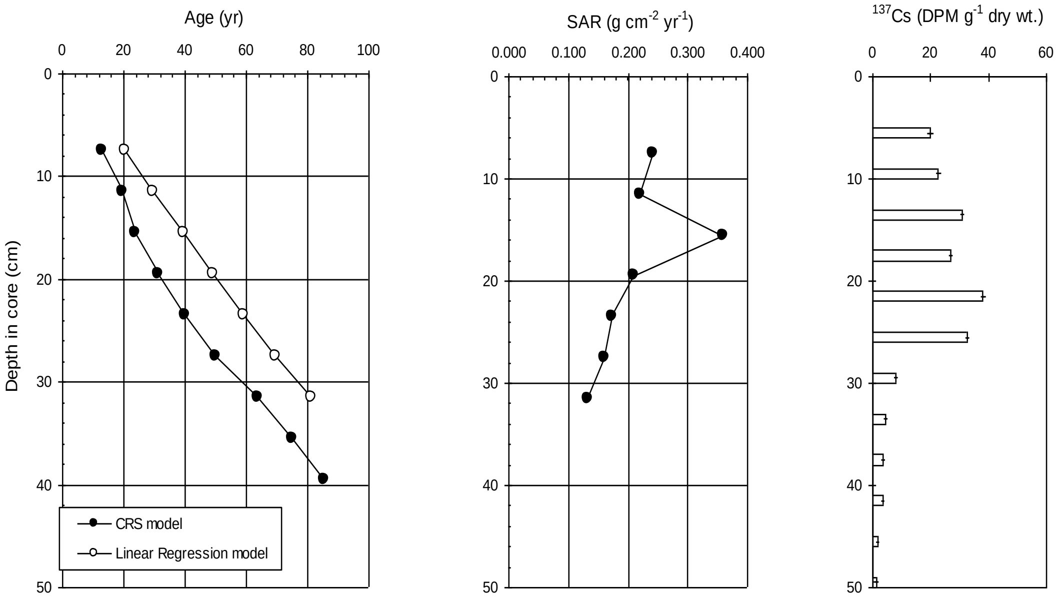


Figure 3.16 Bunaveela: age (yr) vs. depth (cm) (CRS and Linear Regression models); up-core variations in sediment accumulation rates (SAR), and ^{137}Cs activity.

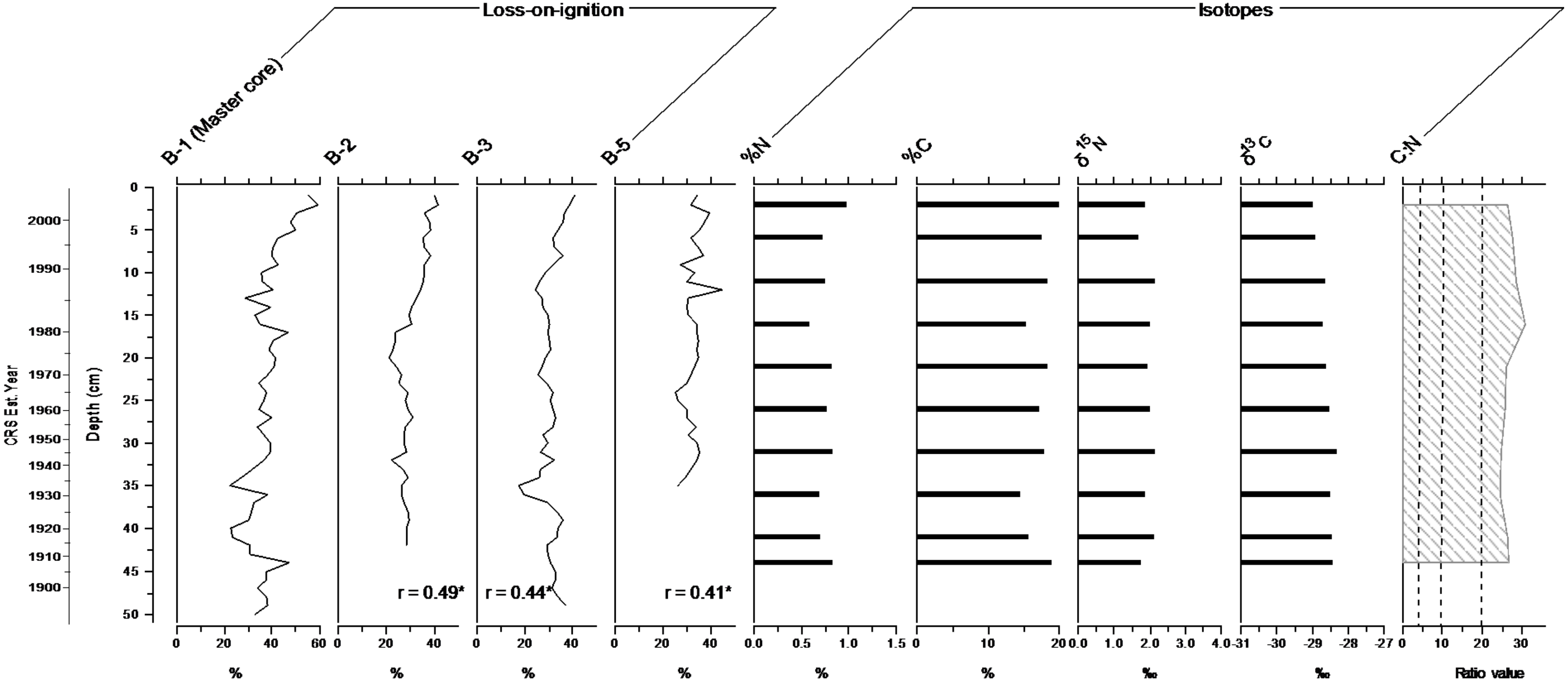


Figure 3.17 Bunaveela: up-core variations in % LOI (*= significant), $\delta^{15}N$ and $\delta^{13}C$ and ratios of C/N. Threshold C/N ratio values (4, 10 and 20) indicating the predominant source of organic material are represented with dashed lines (see Meyers 2003 and text for details).

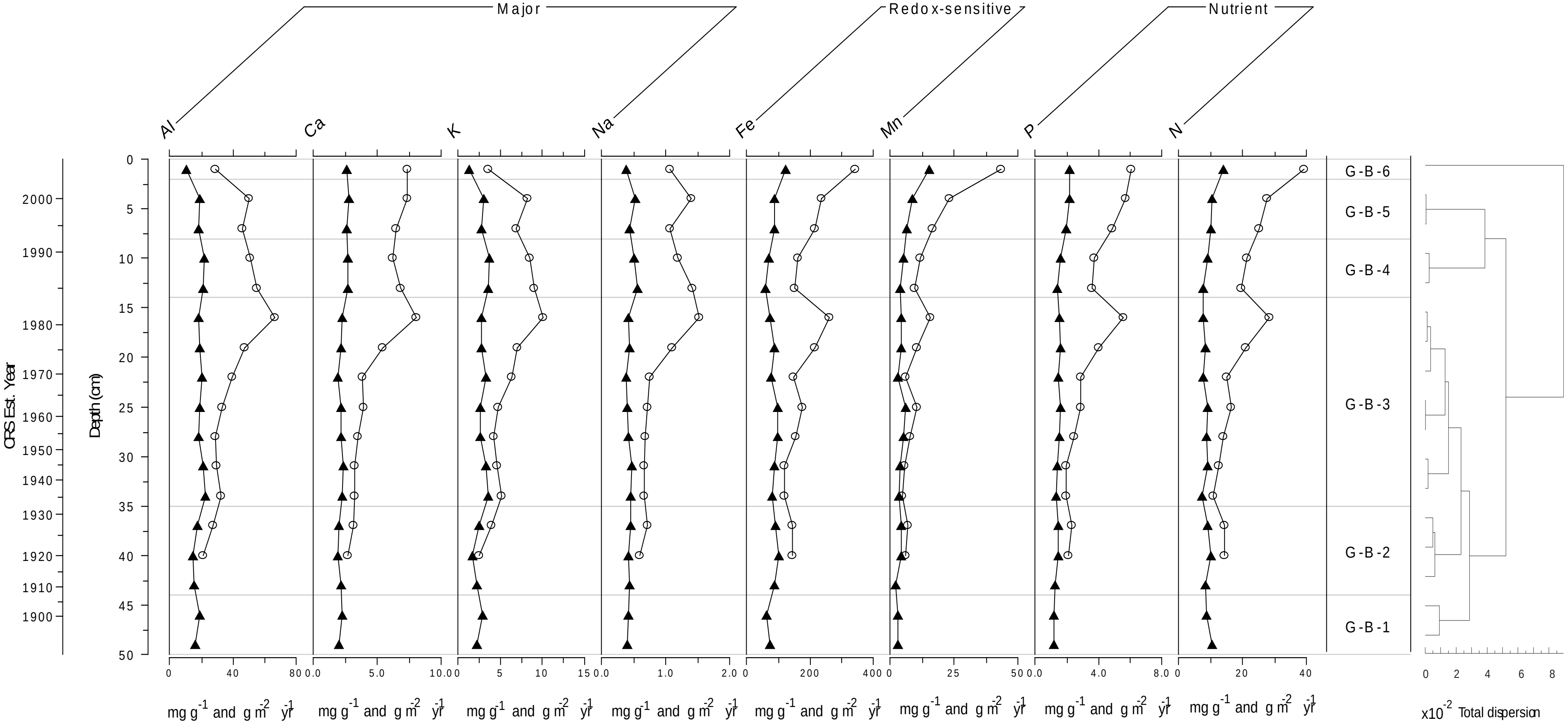


Figure 3.18a Bunaveela: up-core variations in concentration (▲) and accumulation rate (○) for chemical elements

l

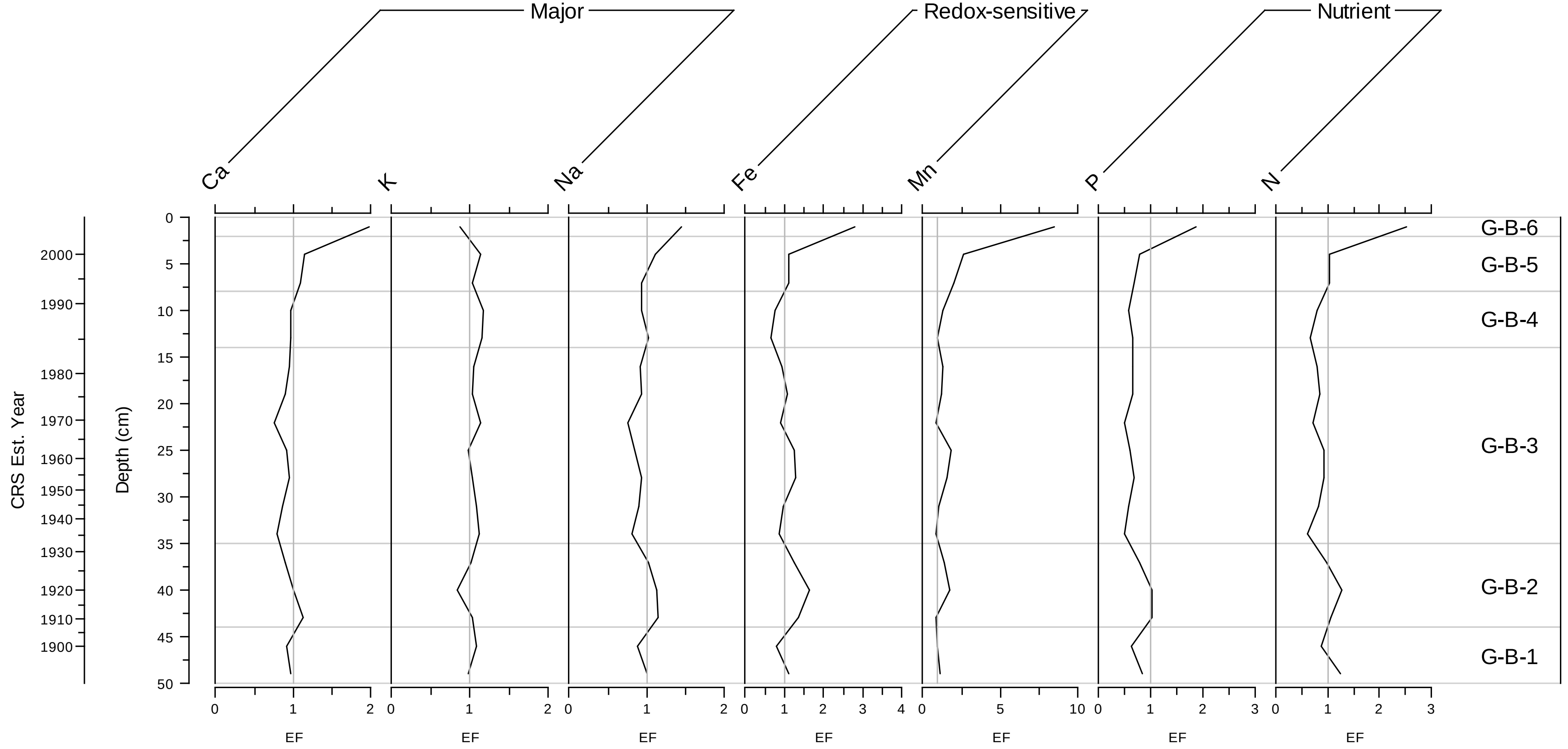


Figure 3.18b Bunaveela: up-core variations in EFs. EF = 1 is highlighted.

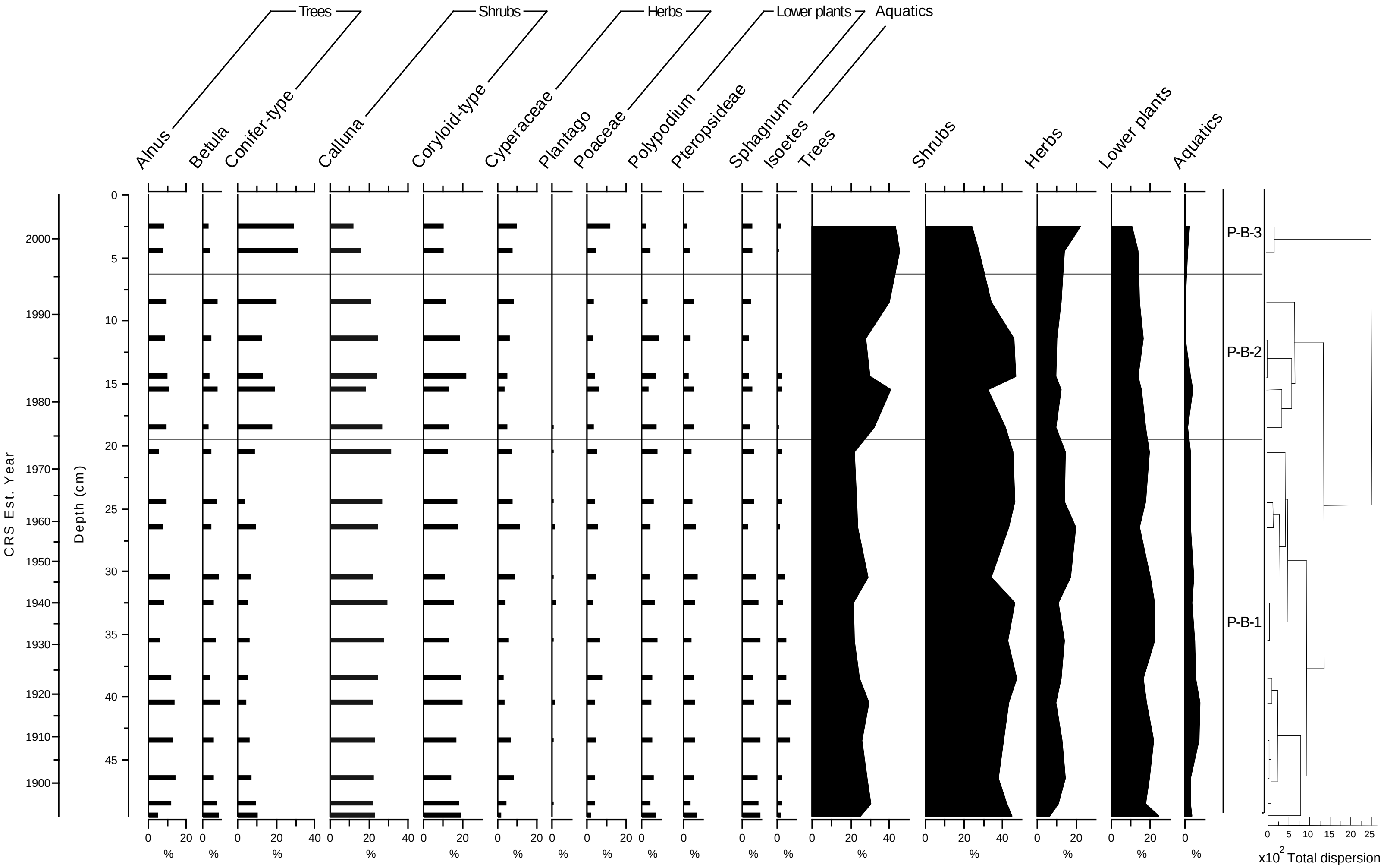


Figure 3.19 Bunaveela: up-core variations in pollen data. For information on pollen sum used, see text.

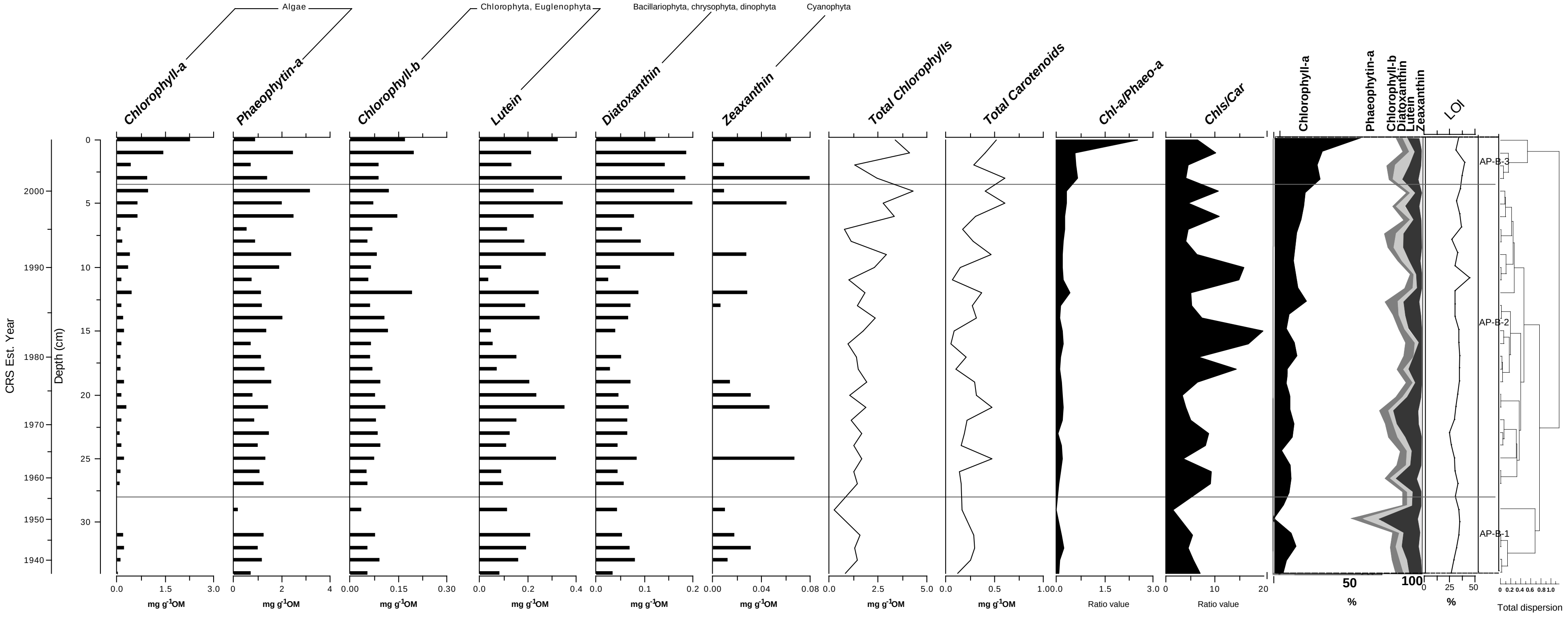


Figure 3.20 Bunaveela: up-core variations in algal pigment concentrations. Total chlorophylls = chl-a, chl-b and phaeophytin-a, total carotenoids = lutein, diatoxanthin, fucoxanthin and zeaxanthin.

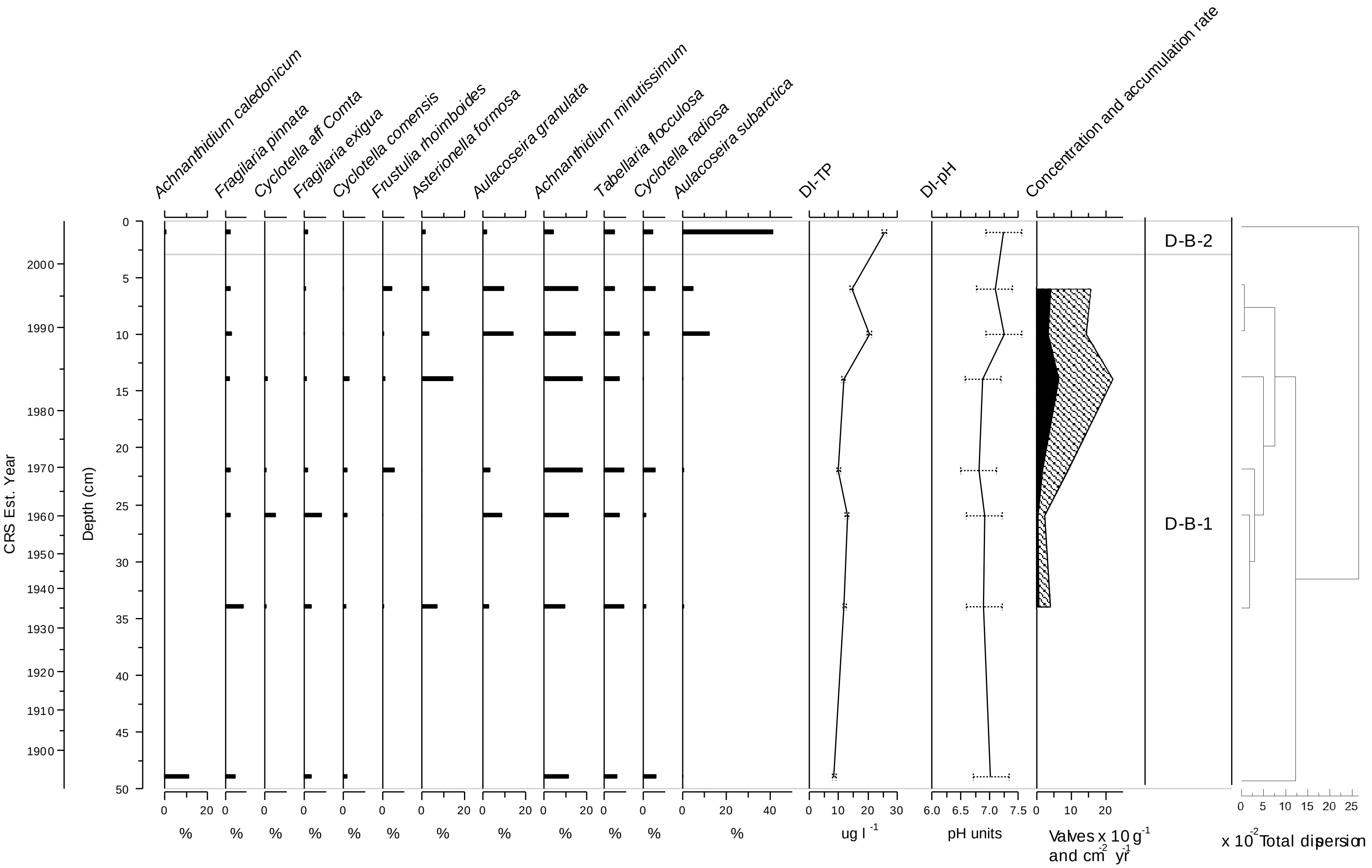


Figure 3.21 Bunaveela: up-core variations in abundances of diatom remains, DI-TP and DI-pH, concentrations (black silhouette) and flux (grey silhouette).

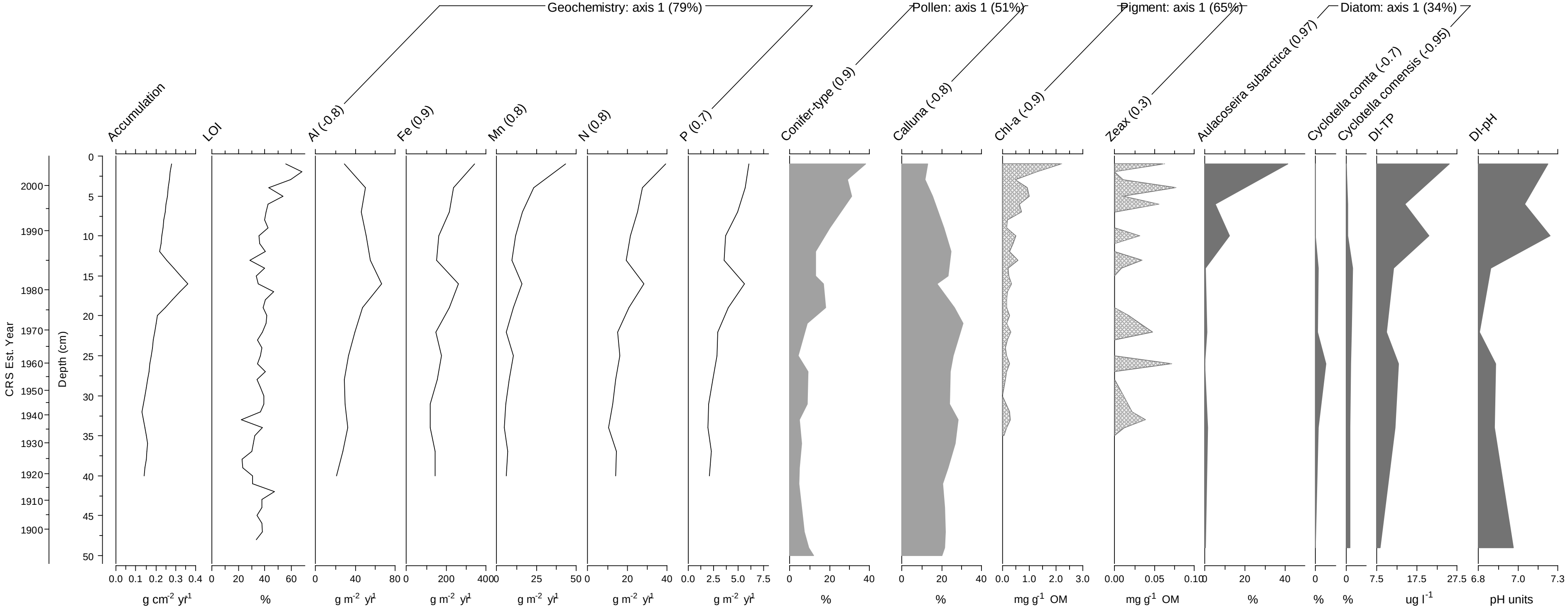


Figure 3.22 Bunaveela: synthesis of multi-proxy palaeolimnological data.

3.5.4 WRBD: Feeagh

The following refers to data obtained from Feeagh through sedimentary sampling techniques described previously. Analyses of these data are also covered in this section. Six sediment cores were extracted from Feeagh during ILLUMINATE (Table 3.12; Figure 3.23).

Sediment chronologies

Chronological control for sediments from Feeagh was established on the basis of AMS ^{14}C, ^{210}Pb and ^{137}Cs analyses.

AMS ^{14}C dating

A plant macrofossil from the base (62-63 cm) of one of the cores of sediment from the deepest point was dated using the AMS ^{14}C technique at 3960 +/- 50 BP measured radiocarbon age ($\delta\ ^{13}$C = 26.8 ‰) (4299 to 4518 cal. BP (Stuiver & Reimer 1993)) (Appendix 3.5).

^{210}Pb & ^{137}Cs

^{210}Po activity declines, exponentially, with depth (Table 3.13), and the CRS model could therefore be applied. Estimated SAR ranged from 0.171-0.288 g cm^{-2} yr^{-1} (Figure 3.24): the lowermost sample in the dated core was dated to c. 1895. These estimates were confirmed by up-core variations in ^{137}Cs activity. Due to the agreement between the ^{210}Po and ^{137}Cs chronologies, the AMS ^{14}C-dated macrofossil probably represents erosion of peat in the catchment and the secondary deposition at the coring site of anomalously old carbon.

Variations in organic matter content (loss-on-ignition (% LOI))

The organic matter content of sediment core samples is relatively low below c. 30 cm (c. 1950) in all cores (Figure 3.25). Above this depth the amount of organic matter increases, reaching c. 40 % at the surface. Sediment cores were cross-correlated using correlation analysis and CSPLOT (Appendix 3.3), ensuring a high level of confidence in the extension of chronological control to other cores from the same coring location.

Geochemistry

Elemental chemistry

Up-core variations in concentration and accumulation rate data for chemical elements were grouped into five zones (Figure 3.26a): G-F-1 (c. 1880 to c. 1900), G-F-2 (c. 1900 to c. 1940), G-F-3 (c. 1940 to c. 1984), G-F-4 (c. 1984 to c. 2000) and G-F-5 (post c. 2000). Levels of all elements display only a minor degree of variation in G-F-1. In G-F-2, levels of both the major and redox-sensitive elements peak at c. 1925. G-F-3 is characterised by increasing accumulation rates of all elements post c. 1960. G-F-4 sees continued increases, while G-F-5 is characterised by declines in major (Al, Ca and K) and redox-sensitive elements. EFs for nutrient elements P and N co-vary up-core, and are above background levels through G-F-3 and G-F-4, indicating that anthropogenic inputs became the main source of variation from c. 1950. EFs for Fe, K and Mn are also generally above 1.0, while EFs for all elements, with the exception of K, show abrupt increases across the G-F-4/G-F-5 boundary.

Stable isotopes

Levels of $\delta^{13}C$ indicate a predominantly terrestrial, C_3 plant source for organic carbon in the samples analysed (Figure 3.25). Measured levels of $\delta^{15}N$ increase up-core and are within the range characteristic of terrestrial plants, which is also supported by the C/N ratios.

Biological remains

Pollen and plant macrofossils

Pollen was enumerated in 16 samples from Feeagh (Figure 3.27). Up-core variations were grouped into two zones (P-F-1 and P-F-2), with the boundary between the two dating to c. 1982. The main changes across the P-F-1/P-F-2 boundary are increases in conifer-type and *Calluna* pollen.

Plant macrofossil remains were examined in nine samples from a short sediment core (17 cm) collected from a littoral area in the eastern part of Feeagh (Figure 3.23). The predominant macrofossil remains include *Drepanocladus* and ferns (Table 3.14). Increasing amounts of *Juncus, Carex, Polytrichum* and *Isoetes lacustris* are visible above 8 cm, while remains of *Pinus* and *Drepanocladus* decrease in abundance. The appearance of the remains of *Larynx* and *Picea* above 6 cm in the core would appear to reflect afforestation in the catchment.

<u>*Phytoplankton*</u>

Algal pigments

Up-core variations in concentrations of sediment-based pigments were grouped into two zones: AP-F-1 and AP-F-2, with the boundary between the two dated to c. 2001 (Figure 3.28). Phaeophytin-a, a product of chlorophyll-a degradation, was the most abundant pigment in the samples analysed and is known to persist longer than other pigments in the sediment record (Scheer 1991; Villanueva et al. 1994). Low pigment concentrations, within the range of oligotrophic lakes (Lami et al. 2000), are as expected, given that actual measurements of lake water chlorophyll-a are also low (max. 1.1 mg m^{-3}; Table 2.1). From c. 1970 there is a small increase in diatoxanthin, and concentrations of chlorophyll-a and diatoxanthin increase from c. 1997. AP-F-2 (post-c. 2001) is characterised by increased pigment concentrations: concentrations of many pigments are initially lower in AP-F-2 when compared with AP-F-1, but increase from c. 2003.

Diatoms

A total of 245 diatom taxa was enumerated in 30 samples (Figure 3.29 and Appendix 3.4). Up-core variations in abundances were grouped into three zones: D-F-1 (c. 1880 to c. 1967), D-F-2 (c. 1967 to c. 1987) and D-F-3 (post c. 1987) (Figure 3.29). D-F-1 is characterised by relatively abundant *Achnanthidium minutissimum*, *Cyclotella comensis* and *C. kuetzingiana*, whereas D-F-2 is characterised by lower levels of *Achnanthidium minutissimum* and increased abundances of *Asterionella formosa* and *Aulacoseira granulata*, and declines in *Cyclotella* species. This floristic change represents a shift to diatom taxa tolerant of nutrient rich conditions. Up-core variations in levels of DI-TP increase markedly from c. 1962: before this date, oligotrophic conditions (8-10 μg l^{-1} TP) are evident; whereas mesotropic conditions (15-18 μg l^{-1} TP) are established from c. 1967. A sharp fall in abundances of *Asterionella formosa* and increases in numbers of *Achnanthes oblongella*, *Aulacoseira granulata* and *Aulacoseira subarctica* characterise D-F-3, as does peak DI-TP. DI-pH shows little variation up-core.

<u>*Zooplankton*</u>

Remains of cladocerans were enumerated in four sediment core samples: two from the upper part (post-c. 1997) and two (dated c. 1965 and c. 1972) from the lower part of a sediment core (Table 3.15). Chydorid taxa, which prefer the littoral areas of lakes, were relatively abundant in the samples from the lower part of the core, with *Alona rustica* accounting for more than 40% of remains in the lowermost sample examined. *A. rustica* is normally common in dystrophic waterbodies and is generally absent in nutrient enriched environments (Duigan 1992). The upper most samples in contrast were characterised by the planktonic taxa *Daphnia* and *Bosmina*, and lower levels of *Alona rustica*. The benthic/planktonic ratio changes from five in the lower samples to < 1 in the upper samples.

Ordination and synthesis of Feeagh palaeoenvironmental data

The primary ordination axes and key driving variables evident in the Feeagh palaeoenvironmental data are highlighted in Figure 3.30. Up-core increases in SAR and % LOI data are evident from the mid- to late-1950s and are likely products of catchment disturbance. Ordination of geochemical element data, in particular levels of Mn and Fe, suggests a change in redox state to less oxygenated conditions from c. 1995. Increased levels of Mn and Fe in surface sediments, possibly due to diffusive migration or cycling within the water column, are not unusual and are generally thought to be temporary (Boyle 2001). A second major cause of variation within the data, according to the results of ordination, appears to be nutrient enrichment, with increased TP and N from c. 1960 coincident with enhanced EFs (>1), SAR and levels of $\delta^{15}N$; increased catchment erosion from the mid-20th century could have contributed to heightened inputs of nutrients to the site.

Sediment-based remains of plants (in the form of pollen, spores and macrofossils) confirm a shift in catchment vegetation, and in particular an increase in conifers, from c. 1955. Additionally isotope data suggest that organic matter originated largely from terrestrial sources (C_3 plants), based on the ranges suggested by de Freitas et al. (2001). Low concentrations of algal pigments and very low chlorophyll-a : phaeophytin-a ratios, indicating poor preservation of pigments, characterise the sediments recovered from Feeagh. Indeed, a large part of the variation in pigment data, according to the results of PCA, is associated with chlorophyll-a and the chlorophyll decay product phaeophytin-a. Poor preservation conditions for pigments could have been caused by a combination of high levels of DOC, enhanced by peat erosion in the catchment, and organic matter from allochthonous sources in general (Lami et al. 2000), with the effects locally exacerbated by low aquatic productivity.

Ordination of the diatom dataset for Feeagh produced a first axis of variation that accounted for 42% of the total variance and was positively associated with *Aulacoseira subarctica* and negatively associated with *Cyclotella comensis* (TP optima of, respectively, c. 29 μg^{-1} TP and c. 8 μg^{-1} TP, according to Chen et al. (2008)). This assemblage shift to nutrient tolerant species c. 1980 represents a second phase of enrichment: a first phase from c. 1955 is exemplified by increasing DI-TP (together with increased abundances of *Asterionella formosa* and a decline in levels of *Achnanthidium minutissium*). DI-pH shows a relatively minor increase (within the error range) over the sedimentary record analysed. From c. 1965 the cladoceran assemblages also change, from largely benthic species to assemblages increasingly characterised by planktonic taxa by c. 1972. This shift may be the result of increased levels of turbidity associated with inwash of material from the catchment, and, as a result, a decrease in available macrophyte habitat (Duigan & Birks 2000; Jeppesen et al. 2001).

Table 3.12 Feeagh: sediment cores

Core code	Date Collected	Location	Latitude, Longitude	Depth of water (m)	Length of core (cm)	Analysis
F-1	15/08/2006	Deepest point	09º34' W, 53º56' N	46	42	LOI, cladocera
F-2	15/08/2006	Deepest point	09º34' W, 53º56' N	45.5	64	LOI, pollen, radiometric dating geochemistry,
F-3	15/08/2006	Deepest point	09º34' W, 53º56' N	47	42	LOI, diatoms
F-4	12/11/2007	Deepest point	09º34' W, 53º56' N	47.2	56	LOI, isotopes
F-5	01/10/2008	Near-shore (east)	09º34' W, 53º56' N	5	17	LOI, macrofossils
F-6	27/08/2009	Deepest point	09º34' W, 53º56' N	46	55	LOI, pigments

Table 3.13 Feeagh: ^{210}Po (total and unsupported) and ^{137}Cs activity, and estimated sediment accumulation rates (SAR) based on CRS and Linear Regression models.

Sample ID (depth cm)	Dry wt./ wet cc. gcm^{-3}	Cumulative mass gcm^{-2}	^{210}Po total activity DPM g^{-1}	^{210}Po unsupported activity DPM g^{-1}	^{137}Cs DPM g^{-1}	CRS estimated age (years)	CRS SAR gcm^{-2}yr^{-1}	Linear regression estimated age
FeeC2 (2-3)	0.34	1.72	53.8	49.6	14.4	6.8	0.252	7.5
FeeC2 (7-8)	0.34	3.42	39.8	35.6	17.2	12.7	0.288	15.0
FeeC2 (12-13)	0.23	4.59	39.0	34.8	24.6	17.4	0.250	20.1
FeeC2 (17-18)	0.35	6.32	32.0	27.9	39.9	24.0	0.262	27.7
FeeC2 (22-23)	0.37	8.19	31.2	27.0	25.4	32.7	0.213	35.8
FeeC2 (27-28)	0.40	10.18	28.7	24.6	35.1	44.4	0.171	44.6
FeeC2 (32-33)	0.53	12.83	18.1	13.9	8.0	57.2	0.207	56.2
FeeC2 (37-38)	0.44	15.04	13.0	8.8	4.1	66.8	0.231	65.9
FeeC2 (42-43)	0.49	17.49	10.2	6.0	2.4	76.6	0.250	76.6
FeeC2 (47-48)	0.45	19.73	9.4	6.6	2.1	90.8	0.158	86.4
FeeC2 (52-53)	0.41	21.80	7.4	4.6	2.2			
FeeC2 (57-58)	0.46	24.10	4.6	1.8	0.3			
FeeC2 (62-63)	0.46	25.50	3.6	0.7	0.4			

Table 3.14 Feeagh: macrofossil remains.

	Allochthonous																	Autochthonous		
	Arboreal						Non-arboreal													
Depth (cm)	*Alnus*	*Betula*	*Juniperus*	*Larix*	*Pinus*	*Picea*	*Aulocomnium*	*Empetrum nigrum*	*Calluna*	*Carex*	*Drepanocladus*	*Isolepis setacea*	*Juncus*	Fern	*Paludella*	*Polytrichum*	*Rubus*	*Sphagnum*	*Isoetes lacustris*	*Montia fontana*	Total no. /sample
0	1	14	3	2	1	4	0	1	3	16	0	3	65	35	76	11	4	5	20	1	265
2	0	28	0	0	1	0	180	25	0	8	60	2	103	319	100	17	24	52	30	0	949
4	0	27	0	0	1	0	0	4	2	7	30	0	89	283	245	13	7	41	4	1	754
6	0	22	0	2	2	0	90	35	2	1	110	1	148	319	220	7	3	13	2	2	979
8	0	8	0	0	2	0	520	4	8	6	160	0	161	173	302	3	1	61	0	0	1409
10	0	10	0	0	2	1	60	34	0	1	80	0	91	193	132	2	5	46	1	1	659
12	0	32	0	0	8	0	312	21	5	4	90	0	60	412	20	2	7	76	2	0	1051
14	1	23	0	0	6	1	60	69	0	3	160	2	49	236	110	0	3	36	1	0	760
16	0	15	0	0	0	0	60	1	16	2	10	10	62	183	120	10	3	103	1	0	596

Table 3.15 Feeagh: Cladocera species/groups and benthic planktonic ratios from selected sediment core samples.

Depth (cm)	**41**	**34**	**10**	**2**
CRS estimated age (years)	**c. 1965**	**c. 1972**	**c. 1997**	**c. 2004**
Benthic species				
Acroperus harpae	3.6	0.0	0.0	1.1
Alona affinis	3.6	1.7	0.9	1.1
Alona guttata var. *tuberculata*	3.6	0.0	0.0	0.0
Alona guttata/rectangular	0.0	10.0	7.0	13.8
Alona quadrangularis	5.4	5.0	2.6	5.3
Alona rustica	44.6	28.3	13.9	4.3
Alonella excise	1.8	1.7	0.0	0.0
Alonella nana	1.8	3.3	2.6	1.1
Alonopsis elongate	1.8	3.3	0.0	0.0
Camptocercus rectirostris	1.8	1.7	0.0	1.1
Chydorus piger	7.1	5.0	1.7	1.1
Chydorus sphaericus	3.6	3.3	0.0	1.1
Eurycercus lamellatus	1.8	0.0	1.7	0.0
Graptoleberis testudinaria	0.0	0.0	0.0	1.1
Monospilus dispar	0.0	1.7	0.9	2.1
Pleuroxus aduncus	0.0	0.0	0.0	1.1
Pleuroxus sp.	1.8	0.0	0.0	1.1
Rhynchotalona falcate	0.0	0.0	0.9	0.0
Planktonic Species				
Bosmina longirostris	0.0	5.0	20.0	41.5
Bosmina longispina	3.6	5.0	0.0	0.0
Bosmina sp.	10.7	8.3	28.7	10.6
Daphnia longispina group	3.6	16.7	19.1	12.8
Benthic:planktonic ratio	**4.6**	**1.9**	**0.5**	**0.5**

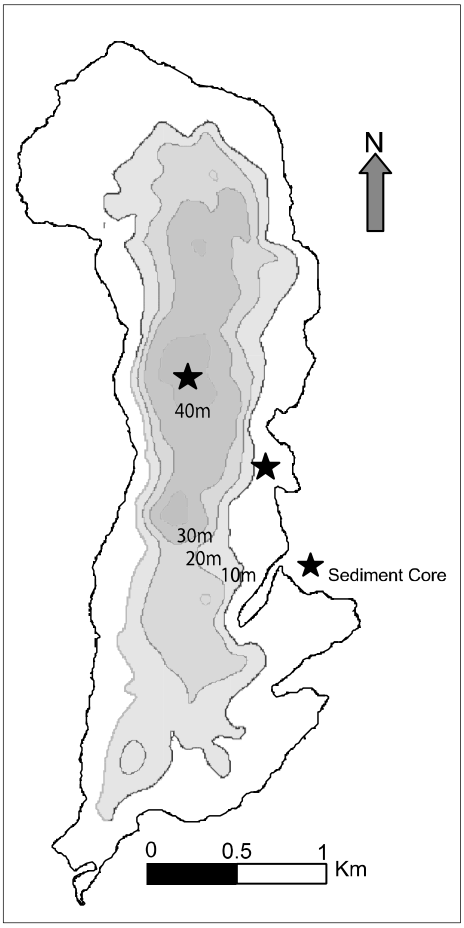


Figure 3.23 Feeagh: bathymetry and locations of sediment core sites.

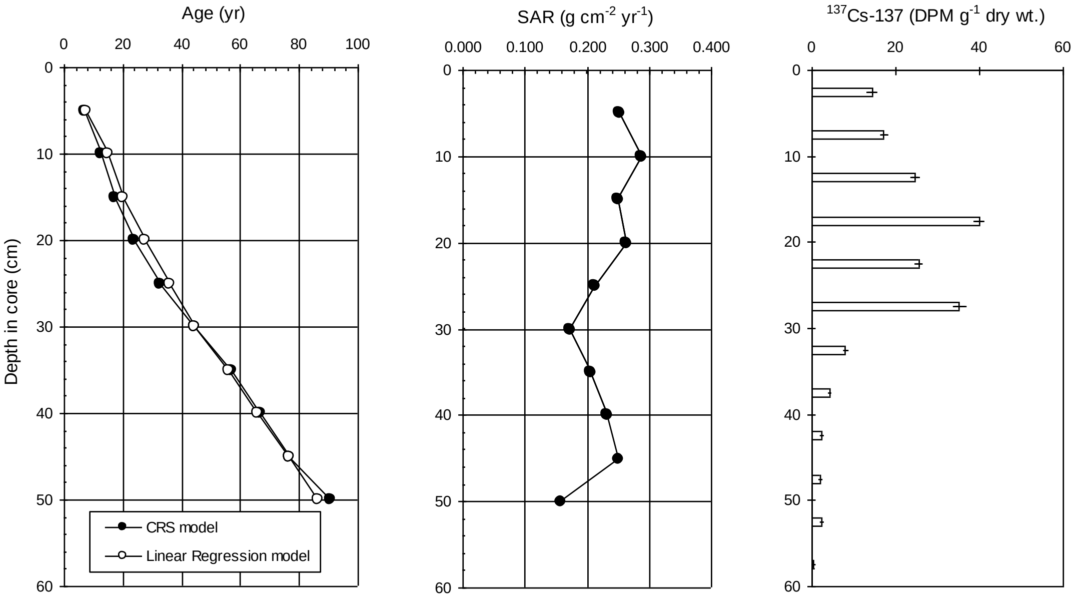


Figure 3.24 Feeagh: age (yr) vs. depth (cm) (CRS and Linear Regression models); up-core variations in sediment accumulation rates (SAR), and ^{137}Cs activity.

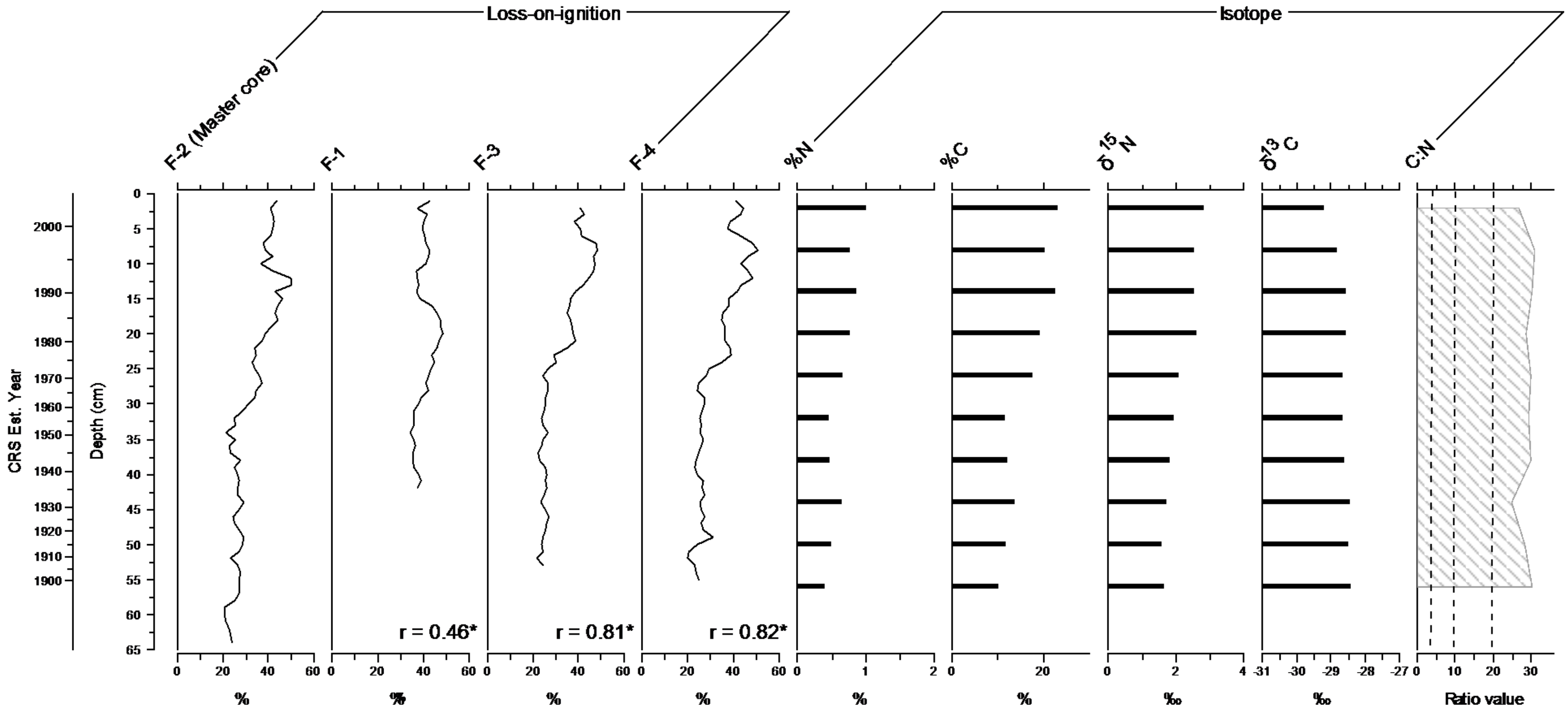


Figure 3.25 Feeagh: up-core variations in % LOI (*= significant), δ^{15}N and δ^{13}C and ratios of C/N. Threshold C/N ratio values (4, 10 and 20) indicating the predominant source of organic material are represented by dashed lines (see Meyers 2003 and text for details).

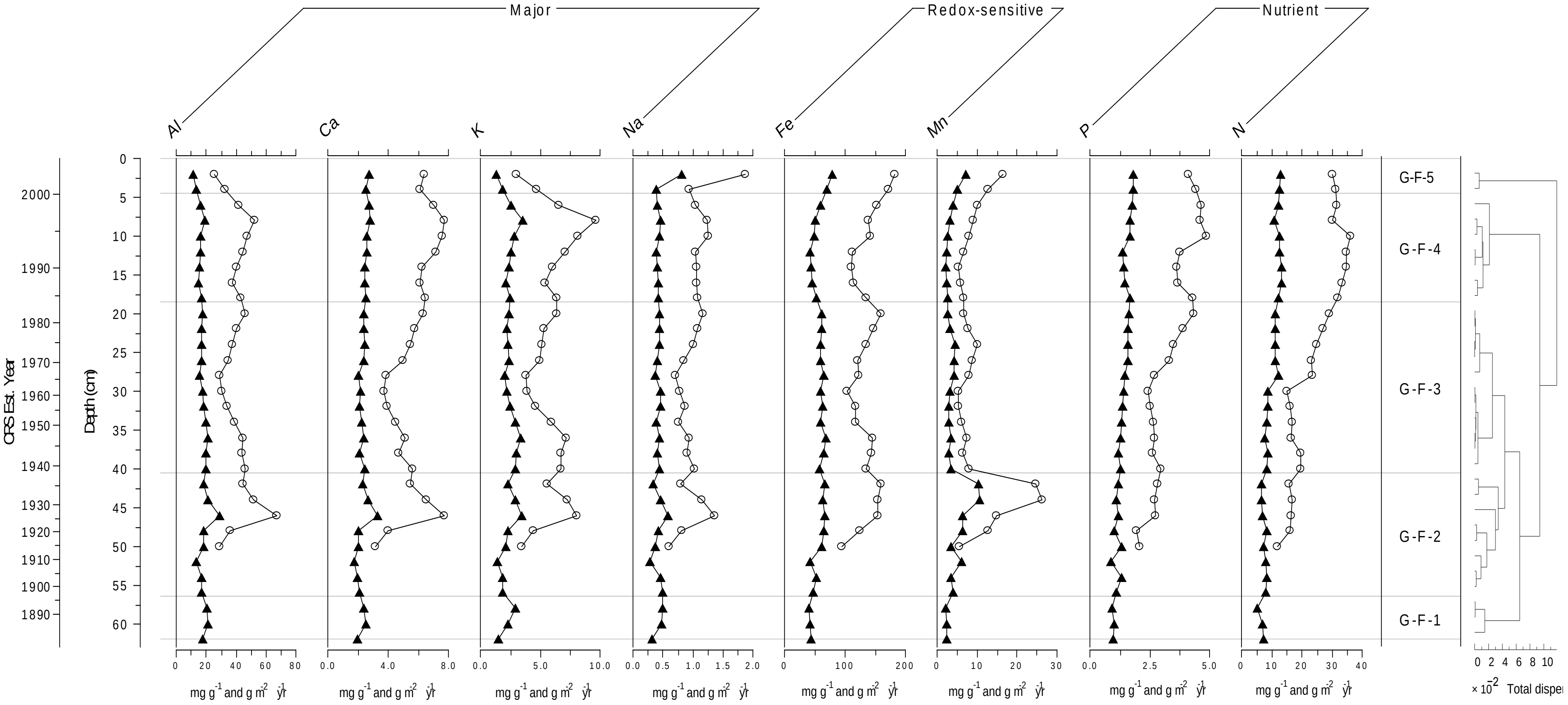


Figure 3.26a Feeagh: up-core variations in concentration (▲) and accumulation rate (○) data for chemical elements.

I

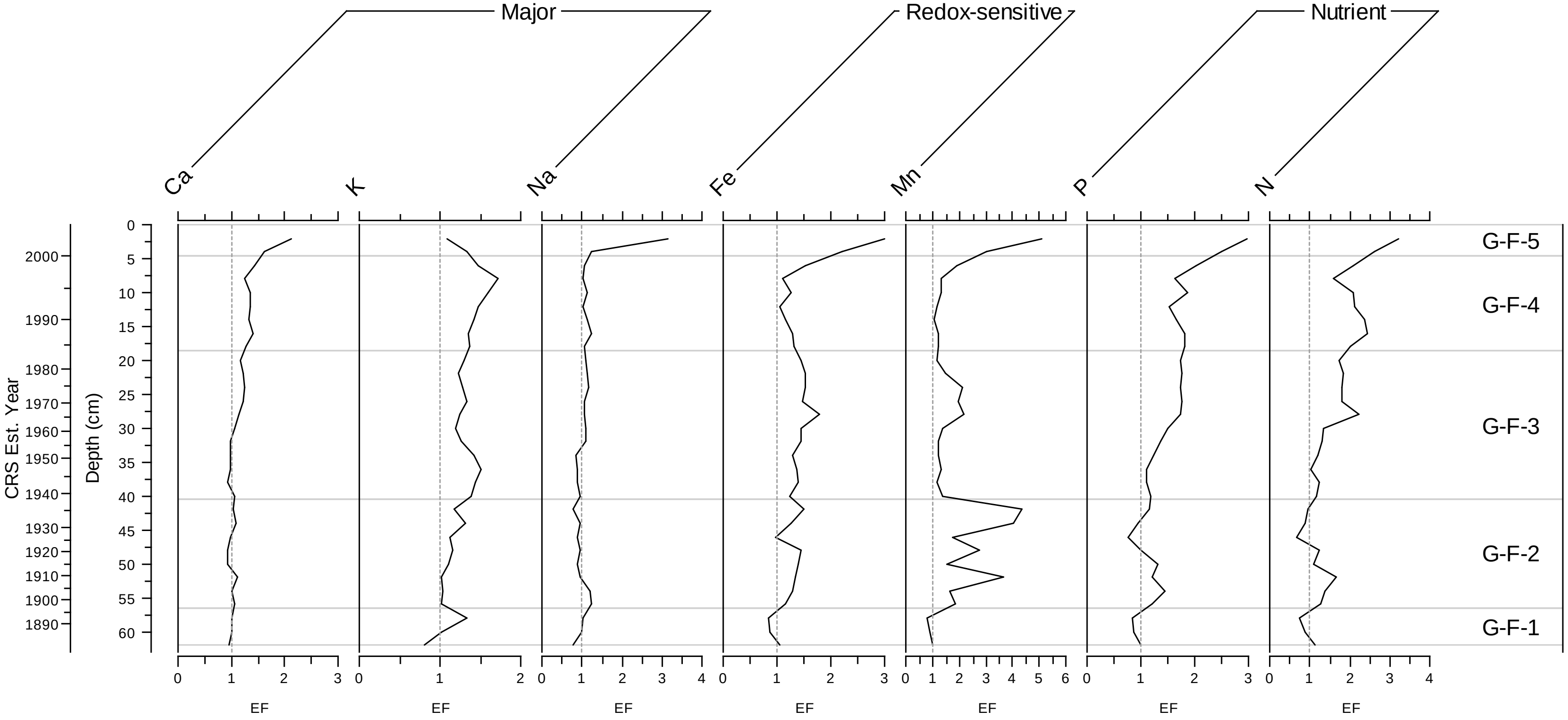


Figure 3.26b Feeagh: up-core variations in EFs. EF = 1 is highlighted.

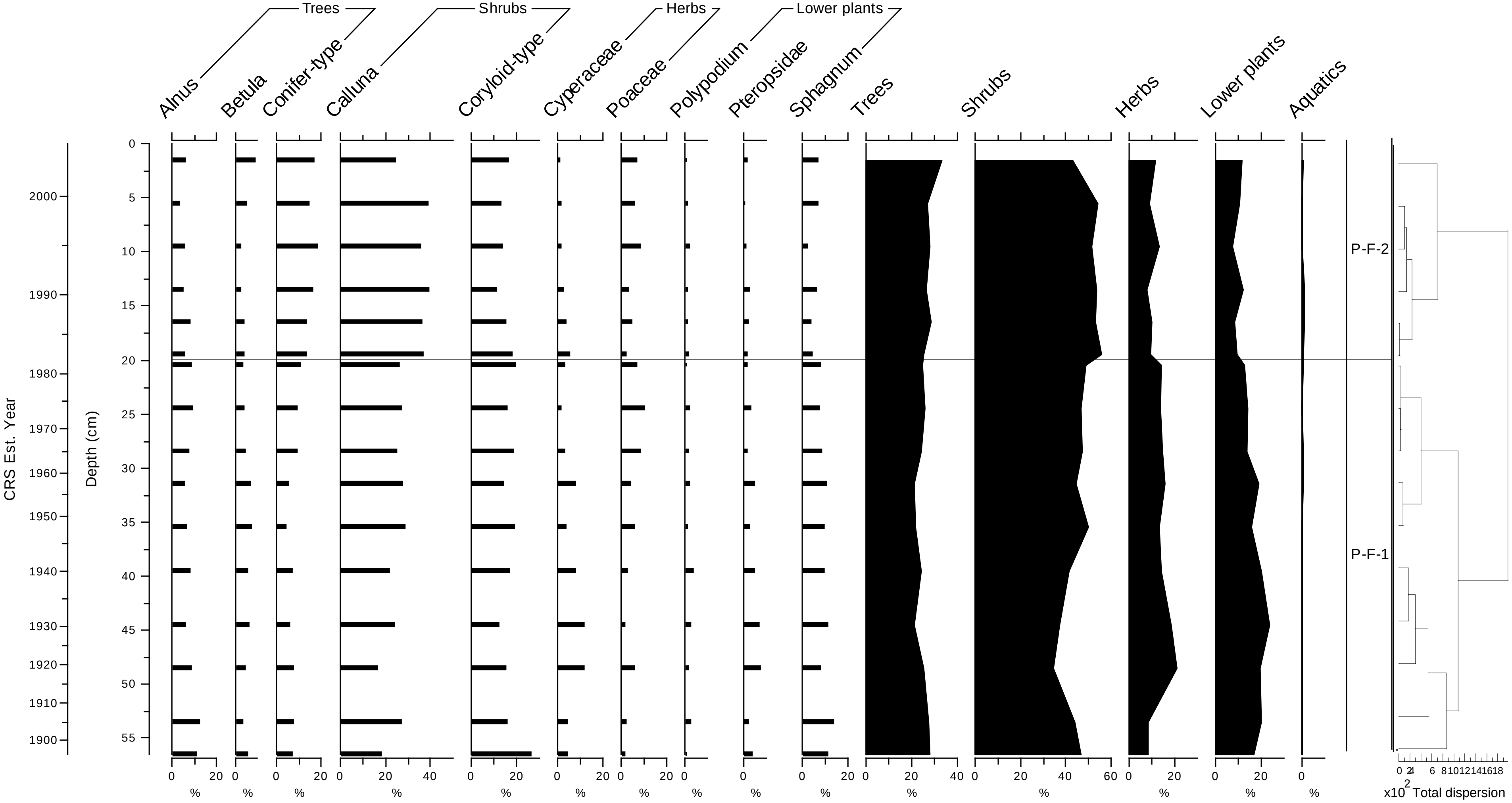


Figure 3.27 Feeagh: up-core variations in pollen abundances (%). For details on pollen sum, see text.

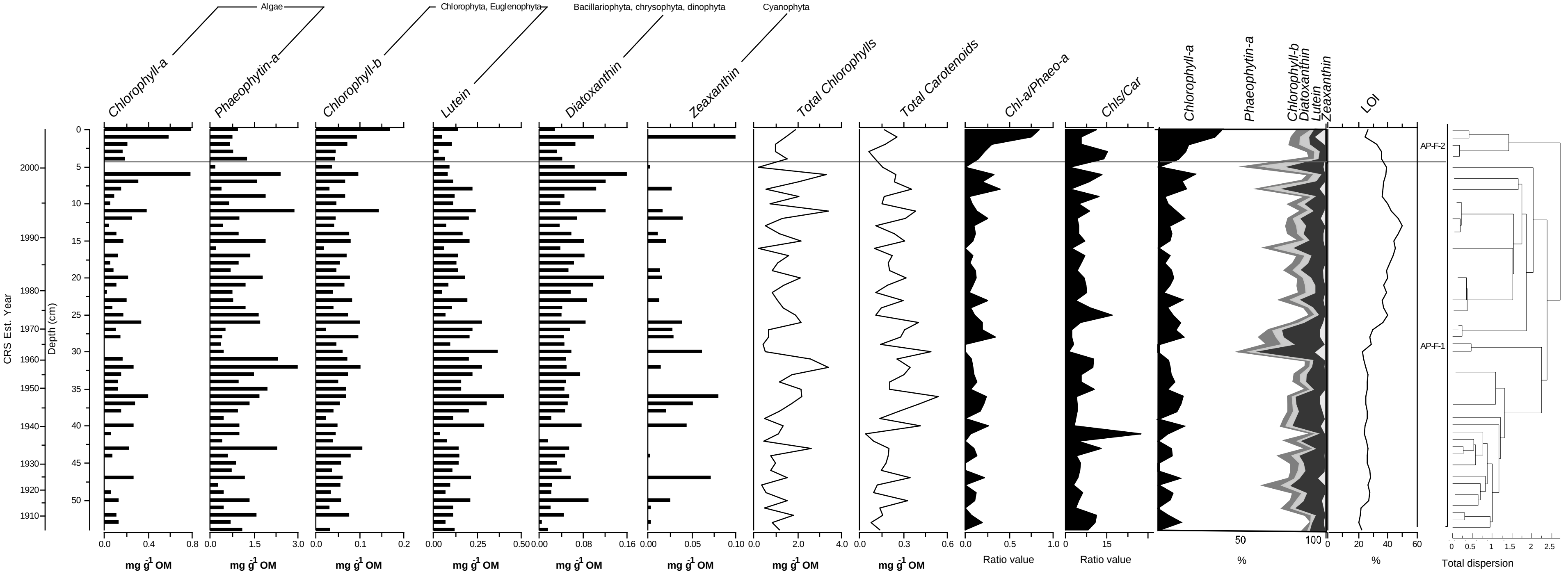


Figure 3.28 Feeagh: up-core variations in algal pigment concentrations. Total chlorophylls = chl-a, chl-b and phaeophytin-a, total carotenoids = lutein, diatoxanthin, fucoxanthin and zeaxanthin.

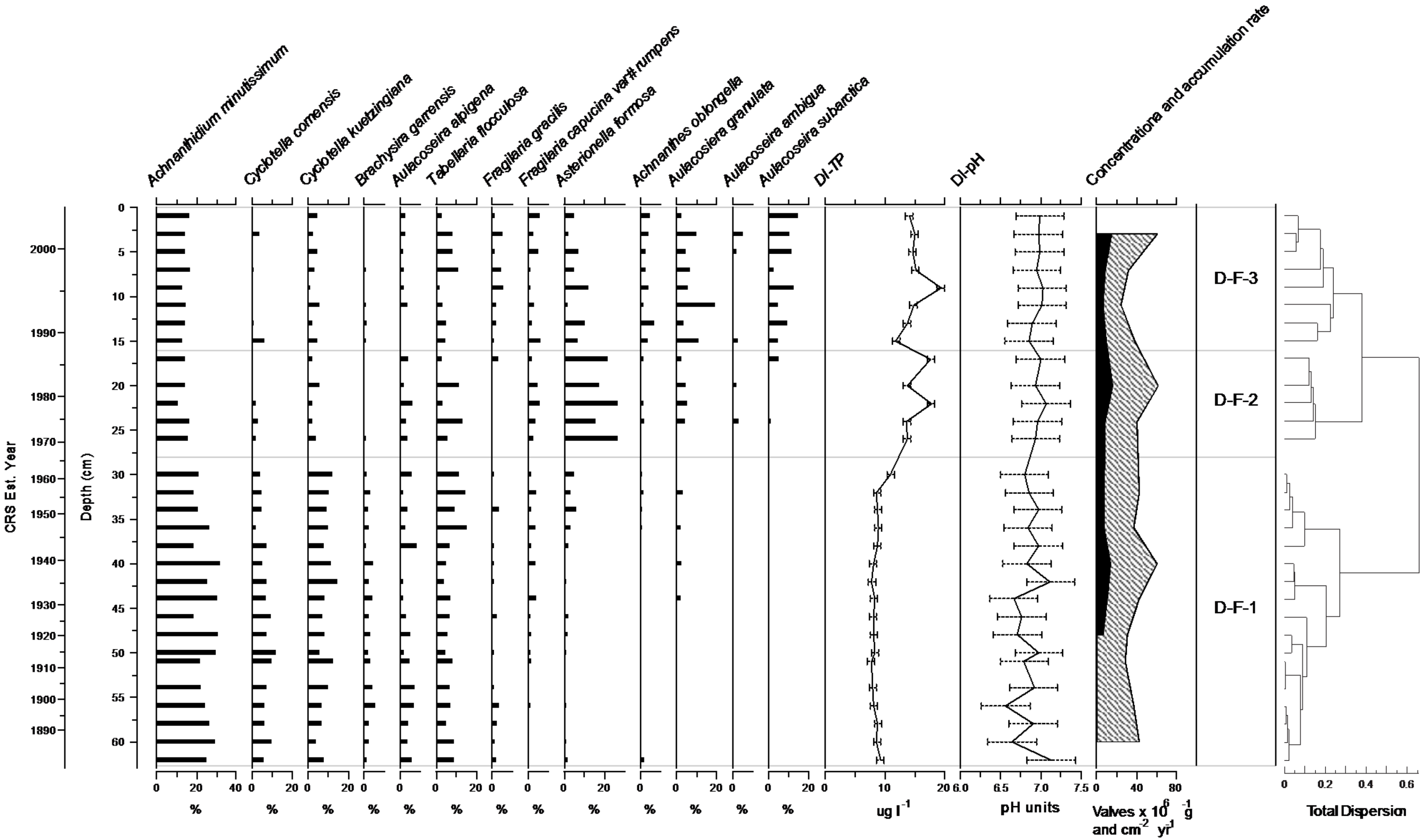


Figure 3.29 Feeagh: up-core variations in diatom abundances, DI-TP and DI-pH, concentrations (black silhouette) and flux (grey silhouette).

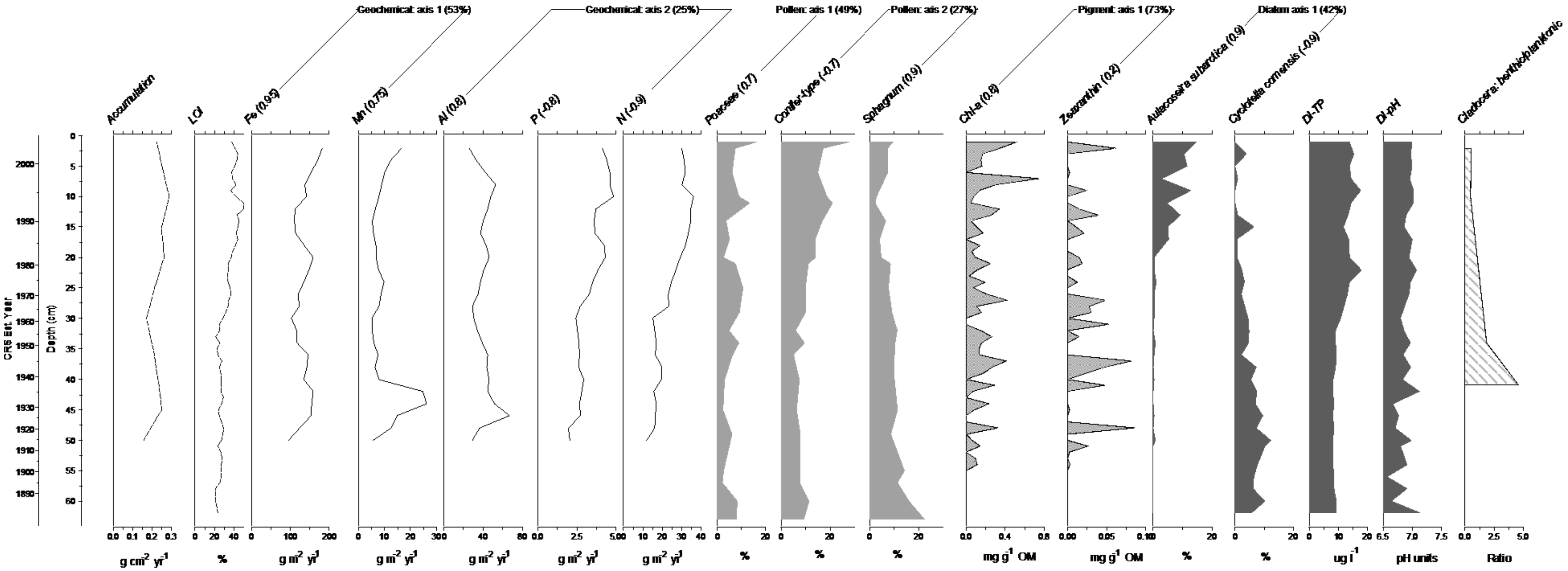


Figure 3.30 Feeagh: synthesis of multi-proxy palaeolimnolgical data.

3.5.5 WRBD: Mask

Data obtained from Mask through the ecological and sedimentary sampling techniques described previously are outlined in the following sub-sections. Analyses of these data are also covered. Because of the great variability in sedimentation evident from test coring, eight sediment cores were collected from three different coring sites at Mask (Figure 3.31; Table 3.16): site 1 western (deepest) part of the lake; site 2 eastern Robe (closest to the part of the catchment supporting intensive forms of agriculture) and site 3 southwest (adjacent to upland, acidic parts of the catchment).

Sediment chronologies

Chronological control for sediments from Mask was established on the basis of AMS ^{14}C, ^{210}Pb and ^{137}Cs analyses. Chronologies for two of the three coring sites were verified using up-core variations in SCPs.

AMS ^{14}C dating

Samples of plant macrofossils from cores from the deepest part of the lake (site 1) and the Robe sub-basin (site 2) were dated using the AMS ^{14}C technique. Site 1 samples, from 40-41 cm and 20-21 cm, were dated at, respectively, 5370 +/- 60 BP ($\delta\ ^{13}C = -27.5$ ‰) (6125 to 6290 cal BP) and 3830 +/- 40 BP ($\delta^{13}C = -26.6$ ‰) (4184 to 4406 cal. BP). Plant macrofossils from a basal sample (22-23 cm) from a core from site 2 were dated to 2550 +/- 40 BP ($\delta\ ^{13}C = -26.2$‰) (2618 to 2757 cal. BP). Conventional AMS 14C dates were calibrated using Calib 5.01 and the Intcal04.14c dataset (Stuiver & Reimer 1993; Reimer et al. 2004).

^{210}Pb & ^{137}Cs

Up-core variations in ^{210}Po and ^{137}Cs activity indicate very different SARs for the three coring sites (tables 3.17-3.19 and figures 3.32-3.34). At site 1, the deepest part of the lake overall, levels of ^{210}Po and ^{137}Cs activity were only above background in the uppermost 1.5 cm of the core, and sedimentation rates from this site are therefore assumed to be relatively low (Figure 3.32). Consequently, basal samples from sediment cores from this site are likely comparatively old, as is borne out by the AMS ^{14}C dates. Higher rates of sediment accumulation are evident in up-core variations in ^{210}Po and ^{137}Cs in cores of sediment from coring sites 2 and 3 (figures 3.33 and 3.34). The absence of two peaks in ^{137}Cs activity in the core from site 2 (eastern Robe), the shallowest site cored at Mask and close to the entry point for the Keel canal, is perhaps due to sediment mixing in the upper part of the core or to sedimentation being interrupted by periods of no accumulation or to dissolution of Si. The estimnated age of the basal sample in the sediment core obtained from site 3 is c. 1870.

As a result of variable sedimentation rates in Mask sediment cores, from both site 1 (deepest point) and site 2 (eastern sub-basin), SAR profiles were estimated using a combination of variations in ^{210}Po and ^{137}Cs activity for recent (the last c. 100 to 200 years) depositions of sediments, and AMS ^{14}C calibrated ages for sediment older than c. 200 years.

Following on from the above, the estimated basal ages of dated cores from coring sites 1, 2 and 3 at Mask are, respectively, c. 6200 BP, c. 2700 BP and c. 1870. However, the dated core from site 2 was relatively short (22 cm) when compred with another core from the same coring site subjected to sedimentary analysis (32.5 cm, Table 3.16). As a result the diatom data from this site, which are from the longer core, are likely to represent variations in water quality in the lake for a period of time that is longer than the last c. 2700 years. Similarly diatoms, geochemistry and macrofossil data for site 3 are all from cores that were longer than the one dated radiometrically.

SCPs

Concentrations of SCPs in four and five sediment core samples from, respectively, site 1 (deepest point) and site 2 (eastern Robe) were used to verify sediment accumulation rates and ages based on the radiometric dating techniques (Table 3.20). In both cases, up-core variations in concentrations of SCPs were in agreement with the chronologies established through AMS ^{14}C, ^{210}Pb and ^{137}Cs analyses.

Variations in organic matter content (loss-on-ignition (% LOI))

Results of % LOI analyses are illustrated in figures 3.35-3.37. The three coring sites show very different profiles. The profiles of three cores from site 1 are highly correlated (r = 0.9). Relatively stable organic matter content (c. 20% LOI) is evident to 7 cm (c. 1200 BP), followed by a general decline to the top of the core. Two sediment cores from site 2 in the eastern Robe sub-basin have similar profiles, in which very low organic matter content precede markedly increased levels between c. 3000 BP and c.

1750 BP, and are significantly correlated (r = 0.9). Three sediment cores from site 3 in the southwest of the lake have the highest organic matter content, at c. 30-35%.

Geochemistry

Elemental chemistry

Analysis of sediment geochemistry was conducted on cores from all three sites. No accumulation rates were calculated for cores from sites 1 and 2 owing to uncertainties over chronological control.

Site 1 deepest point: The base of the sequence analysed for chemical elemental content dates to c. 5820 BP. Up-core variations in concentrations of chemical elements are illustrated in Figure 3.38a. These data were grouped into three zones: G-MK1-1 (c. 5820 BP to c. 5520 BP); G-MK1-2 (c. 5520 BP to c. 1180 BP) and G-MK1-3 (post-c. 1180 BP). G-MK1-1 is characterized by low levels of K, Mn and P. G-MK1-2 has rising levels of major, trace and nutrient elements with peaks in TP and K concentrations at, respectively, c. 4300 BP and c. 2850 BP. Declines in all major, trace and nutrient elements are evident prior to G-MK1-3 and further decreases are evident after c. 1180 BP. EFs are generally low for the majority of the sequence with the exception of K (Figure 3.38b). EFs for Na, Fe, Mn and P show evidence of enrichment c. 1320 BP, while Fe and P continue to increase throughout G-MK1-3.

Site 2 eastern Robe: Up-core variations in concentrations of chemical elements from a sediment core from the eastern Robe coring site are illustrated in Figure 3.39a. The data were grouped into three zones: G-MK2-1 (pre c. 2700 BP to 435 BP) has declining levels of trace and major elements with the exception of Ca and P. Sediment P concentrations increase from c. 2000 BP and continue to rise with Ca in G-MK2-2 (c. 435 BP to c. 1980) and G-MK2-3 (post-c. 1980). Variations in EFs are illustrated in Figure 3.39b and suggest enrichment of Ca and P levels commenced at a relatively early date, possibly from as early as c. 2500 BP but with more certainty attached to increases post-c. 1830.

Site 3 southwest: Up-core variations in chemical concentration and accumulation rate data (Figure 3.40a) in the core from site 3 (basal sediments date to c. 1870) were grouped into three zones: G-MK3-1 (c. 1870 to c. 1948); G-MK3-2 (c. 1948 to c. 1986) and G-MK3-3 (post-c.1978). Low concentrations of chemical elements are evident for most of G-MK3-1. A sharp increase in levels of Al, K and Fe occurs at c. 1940 and concentrations remain high throughout G-MK3-2. This zone is also characterised by increases in concentrations of P and Mn, while further increases are also evident in G-MK3-3 (post-c. 1986). EFs are initially high in G-MK3-1 (c. 1870-1880) and then decline to below threshold levels (<1) (Figure 3.40b). Anthropogenic enrichment is evident in all elements from the 1960s onwards in G-MK3- 2 and G-MK3-3.

<u>*Stable isotopes*</u>

$\delta^{15}N$ levels are relatively stable at 3‰ in the core from the deepest water (site 1) until c. 1500 BP, after which date they rise to 6‰ (Figures 3.35). A similar level of increase is evident (2.5-6‰ $\delta^{15}N$) over the period of time represented by the core from the eastern Robe (Figure 3.36), while levels > 2.5‰ $\delta^{15}N$ are evident in the shorter core collected from the southwest of the lake (Figure 3.37). $\delta^{13}C$ values generally in the range -27 to -29‰ indicate a mainly terrestrial source for organic material. C:N ratios fluctuate between 15 and 20 in the core from site 1 and decline to 13 in the surface sediments. However, a peak in C:N ratios, evident at site 2 pre-c. 2700 BP, suggests substantial inwash of terrestrial material to the lake. Ratio values in the range 13-15 characterise the remainder of the core. C:N ratios in the core from site 3 are relatively high (>25), suggesting inwash of material from the catchment over the last c. 150 years.

Biological remains

<u>*Macrofossils*</u>

No pollen data were analysed in the Mask sediment cores. However, detailed macrofossil analysis was conducted on sediment cores from the three sites.

Site 1 deepest point: Up-core variations in macrofossil assemblage data were grouped into five zones (Figure 3.41). M-MK1-1 (c. 5700 BP to c. 1650 BP) is characterised by aquatic plant remains (charophytes) with some terrestrial plant remains and relatively few non-plant remains. Charophyte remains are absent and amounts of terrestrial plant material are low for most of M-MK1-2 (c. 1650 BP to c. 1100 BP). Charophytes reappear near the top of the zone, and there is a marked increase in *Nitella* remains. M-MK1-3 (c. 1100 BP to c. 600 BP) is characterised by an increase in terrestrial and non-plant remains. Charophyte remains are rate in M-MK1-4 (c. 600 BP to c. 1920), while terrestrial and non-plant remains increase. In M-MK1-5 (c. 1920 to c. 2007) *Chara* branchlets and *Nitella* oospores disappear, while terrestrial plant remains decrease and non-plant material increases.

Site 2 eastern Robe: Macrofossil data from the eastern Robe site were grouped into five zones (Figure 3.42). M-MK2-1 (c. 2500 BP to c. 2280 BP) is characterised by very low concentrations of macrofossils and consists primarily of zooplankton remains. No macrofossils were present in M-MK2-2 (c. 2280 BP to c. 1940 BP). M-MK2-3 (c. 1940 BP to c. 390 BP) encompasses a period alternating between samples containing no macrofossils to samples with relatively high concentrations. Bivalves increase in abundance in this zone, as do oospores of *Chara* and *Nitella* and the remains of Trichoptera. Increased abundances of non-plant remains up-core in M-MK2-4 (c. 390 BP to c. 1975) are similar to those in the preceding zone (M-MK2-3). Abundances of macrofossils vary abruptly in M-MK2-5 (post-c. 1975), however, with levels of terrestrial remains declining while those of charophytes increase, particularly in the uppermost part of the zone.

Site 3 southwest: Three zones were identified in the macrofossil data for a core from site 3 (Figure 3.42). Terrestrial plant remains are abundant in M-MK3-1 (c. 1870 to c. 1934), with few aquatic plant remains and little non-plant material recovered. M-MK3-2 (c. 1934 to c. 1982) is characterised by a reduction in some terrestrial plant taxa remains and an increase in both aquatic plants (charophytes) and non-plant remains from c. 1943. M-MK3-3 (c. 1982 to 2007) shows a reduction in some terrestrial plant taxa and an increase in aquatic plants (charophytes) in the uppermost sediment samples.

Phytoplankton

Algal pigments

No algal pigments were examined in the Mask sediment cores.

Diatoms

Site 1 deepest point: Of the 42 levels examined only 21 had good diatom frustule preservation (Figure 3.44; Appendix 3.4). In these, a total of 35 diatom taxa was enumerated. Up-core variations in diatom assemblage data were grouped into five zones (Figure 3.44). D-MK1-1 (c.5800 BP to c. 4800 BP) is characterised by benthic/epiphytic diatom species (*Achanthidium*, *Brachysira* and *Cymbella*), while planktonic species are rare. These species indicate oligotrophic conditions and circumneutral to high pH. D-MK1-2 (c. 4800 BP to c. 4300 BP) is characterised by declines in the abundances of benthic/epiphytic species (e.g. *Brachysira, Cymbella* and *Eunotia*). *A. granulata* can be an indicator of mesotrophic to eutrophic lake conditions. D-MK1-3 (c. 4350 to c. 1650 BP) initially has poor diatom preservation until post-c. 3600 BP. Toward the top of the zone abundances of *Achanthidium* and *Brachysira* are reduced, while *Epithemia*, *Fragilaria* and species associated with high nutrient concentrations (*Cyclotella oscellata* and *Mastagloia smithii*) increase. The planktonic taxa *Fragilaria crotonensis* and *Tabellaria flocculosa* increase in D-MK1-4 (c. 1650 BP to c. 500 BP). Abundances of *Cyclotella oscellata* decrease, however. *Stephanodiscus hantzii*, which can indicate high nutrient concentrations and/or increasing lake water depth (Brugam et al. 1998), is also present with low abundances. Benthic species disappear in D-MK1-5 (post-c. 500 BP) and the abundances of planktonic forms are greatly increased.

Reconstructed DI-TP suggests that oligotrophic conditions (i.e. <10 μg l^{-1} TP (OECD 1982)) prevailed throughout most of the c. 5800 BP period covered by sediments from site 1. A switch into mesotrophic conditions occurred in the upper part of the sedimentary record, while DI-TP approached the lower threshold of eutrophic conditions during the most recent period. The low sample resolution (just two samples over a 500 year period) in the upper part of the core limits further interpretation. DI-pH suggests alkaline conditions persisted throughout the time period covered by the core.

Site 2 eastern Robe: The diatom content of thirty seven samples in a core from site 2 were analysed, but preservation was also poor (Figure 3.45; Appendix 3.4). This core extended for almost 10 cm beyond the base of the radiometrically-dated core from the same coring site. A total of 18 diatom taxa was identified in 14 levels, and up-core variations in these were grouped into three zones. The benthic species *Fragilaria pinata* and *Mastoglolia smithii* are common in D-MK2-1 (pre c. 2700 BP to c. 1450 BP), which also includes a peak in abundance of the planktonic taxon *Cyclotella oscellata* at c. 2300 BP. The latter coincides with a major increase in organic matter (Figure 3.36). D-MK2-2 (c. 1450 BP to c. 1972) is characterised by the disappearance of *Cyclotella oscellata*, *Fragilaria pinata* and *Mastoglolia smithii*. Abundances of the planktonic taxa *Asterionella formosa*, *Fragilaria crotonensis* and *Tabellaria flocculosa* increase in D-MK2-3 (post-c. 1972), making a substantial contribution to diatom concentrations.

Reconstructed DI-TP reveals that oligotrophic conditions were present at site 2 until the relatively recent past. A switch to mesotrophic conditions in the upper part of the sedimentary record is evident, with DI-TP increasing from c. 8 μg l^{-1} prior to c. 600 BP to c. 26 μg l^{-1} by c. 300 BP. A fall in DI-TP follows but increasing DI-TP is again evident from c. 1950. By comparison, DI-pH has remained relatively stable throughout the period represented by the sedimentary record from this site.

Site 3 southwest: Low diatom diversity characterised sediments from site 3, with just nine diatom taxa enumerated (Figure 3.46; Appendix 3.4). Poor preservation conditions resulted in the recovery of diatoms in just 29 of 43 levels analysed. Up-core variations in the relatively depauperate diatom assemblages were grouped into three zones. *Tabellaria flocculosa*, indicative of relatively acidic waters (Chen et al. 2008), and *Achnanthidium minutissimum* were present throughout the core, while benthic species were rare. The planktonic species *Tabellaria flocculosa* and, post-c. 1910, *Asterionella formosa* and *Fragilaria capucina* were common components of D-MK3-1 (c. 1870 to c. 1940). *Aulacoseira granulata* and *Fragilaria crotonensis* increase in abundance in D-MK3-2 (c. 1940 to c. 1990), coincident with an initial decline in *Asterionella formosa* and *Fragilaria capucina*, suggesting the establishment of moderate to high nutrient levels. *Asterionella formosa* abundances recover later in the zone and continue to increase (to c. 60%) in D-MK3-3, subsequently declining along with other planktonic species from c. 1996.

According to reconstructed DI-TP, the southwest part of Mask has remained within the mesotrophic range since at least c. 1870. DI-TP ranges from c. 20 μg l^{-1} near the bottom of the core (c. 1870) and rises to a peak of 38 μg l^{-1} (c. 1923). DI-TP falls to 20 μg l^{-1} between c. 1945 and c. 1960, then increases post-1960, peaking at 34 μg l^{-1} in the mid-1990s. A decline in planktonic taxa evident in the diatom assemblages appears to be coincident with reduced DI-TP post the mid-1980s productivity peak. DI-pH fluctuates between 6.8 and 7.7 for the period of time represented by the core, with variations in pH apparently in step with those of TP.

Zooplankton

No zooplankton remains were analysed in the Mask sediments.

Ordination and synthesis of Mask palaeoenvironmental data

Synthesis plots of the Mask palaeoenvironmental data are illustrated in figures 3.47-3.49.

Site 1 deepest point: Increases in SAR, decreases in % LOI and variations in geochemical data appear to represent a change in sources in the catchment for allochthonous lake sediment over the duration of the sedimentary record. Levels of Al and K, presumably originating from erosion and weathering of alumino-silicate bedrock and soils in the catchment, decrease from c. 2500 BP. Moreover, levels of Fe decrease initially before increasing between c. 5200 BP and c. 1200 BP. These increases are followed by sharp falls. P follows a similar trend, peaking at c. 3900 BP. Macrofossil data appear to indicate a change over time from primarily autochthonous to allochthonous sources. Ordination of the macrofossil data produced a first axis of variation accounting for c. 80% of the total variation and characterised by a large increase in the abundance of *Carex* seeds and by a substantial reduction in *Chara* remains from c. 1650 BP. A second axis accounted for just less than 20% of the total variation and was characterised by a rapid increase in fern spores from c. 1650 BP.

Fluctuating levels of *Achnanthidium minutissimum* and *Mastogloia smithii* are the main contributors to the first axis of variation from ordination of diatom data. These fluctuations may reflect variations in diatom preservation, possibly driven by climate change (Roberts 1998). Oscillations in climate conditions, between relatively wet and dry periods, can affect lake water levels and water chemistry (Simms 2005), and hence taphonomic conditions, and this may have been the case at site 1. The DI-pH profile also varies, and this variation could represent an effect of climate change. Abundances of *Achnanthidium minutissimum*, a primary coloniser that responds well to disturbance and change (Barbiero 2000), vary widely, but generally increase post-c. 1800 BP. The abundances of *Mastogloia smithii*, a large benthic diatom species, also vary and the diatom actually disappears at c. 600 BP along with *Chara* remains. The DI-TP profile is relatively stable (<10 µg l^{-1} TP) until c. 700 BP, at which point DI-TP increases into the high end of the mesotrophic range.

Site 2 eastern Robe: SAR, % LOI and the first ordination axis for geochemical data for this site appear to reflect a change in catchment sediment source or changes in catchment conditions (for example, soil development) over time. Percentage LOI data support a change in sediment source from c. 1500 BP, with a 3-fold rise in organic matter. SAR is relatively low throughout most of the profile and begins to increase after c. 1880 and again after c. 1975. Axis 1, accounting for the vast majority of variation in geochemical data, is characterised mainly by decreasing levels of Al, Fe and Mn, and increasing levels of P. An up-core increase in sediment P coincides with a marked decrease in Fe:P ratios, highlighting the potential for internal (i.e. sediment-derived) P loading in this part of the lake. A very similar pattern is evident from the sediments of Lough Carra (Irvine et al. 2003). Variations in macrofossil data, summarised by ordination axis 1 for these data, are characterised by calcareous bivalves, *Chara* and Trichoptera cases. Recurring climate changes resulting in oscillations in lake water chemistry, depth and clarity may account for this variability (Roberts 1998; Chambers & Blackford 2001; Simms 2005), as may also have been the case at site 1 in the past. *Chara* branchlets are more common between c. 1800 BP and c. 1880, suggesting high water transparency and low nutrient levels. Between c. 1880 and c. 1984, abundances of *Chara* branchlets, *Chara* oospores and Trichoptera are all low, reflecting increased nutrient levels and reduced water clarity in the lake. A response in aquatic taxa is also evident in the diatom data, with a shift from a predominantly benthic to planktonic assemblage and increases in DI-TP reflecting nutrient enrichment. Ordination revealed the substantial contribution made to overall diatom variation by the taxa *Cyclotella oscellata* and *Mastogloia smithii*, both of which have TP optima < 10 µg l^{-1} (Chen et al. 2008). The planktonic species *Asterionella formosa* and *Tabellaria flocculosa*, with TP optima of c. 13 and c. 36 µg l^{-1}, respectively (Chen et al. 2008), also make important contributions to variability: *Tabellaria flocculosa* increased from c. 350 BP, while *Asterionella formosa* increased from c. 1910 BP. There is evidence of a recovery in water quality over the last c. 20 years, with macrofossil remains making a substantial contribution to variability, while the contribution of *Asterionella formosa* declines.

Site 3 southwest: While there is little variation evident in SAR and % LOI, ordination of geochemical element data indicate relatively recent changes in nutrient conditions at site 3. Axis 1 of the ordinated geochemical data is characterised mainly by Fe and, to a lesser extent, Mn, Ca and P, levels of which increase very gradually up-core. Increases in levels of Mn and P are more pronounced after c. 1978. Furthermore, the Fe:P ratio also declines substantially over the last 100 years, to a point where internal P loading is possible. The second axis of variation in geochemical data is represented mainly by Al and K, with sharp increases in levels of these evident at c. 1888 and c. 1940. The primary ordination axes in the macrofossil data are characterised by remains of *Sphagnum* and by *Chara* branchlets on axis 1, and by terrestrial plant macrofossils and bivalves on axis 2. *Sphagnum* remains are common from c. 1870 to c. 1925, while those of *Chara* are low in abundance or absent during this same period. A decline in the amount of *Sphagnum* remains thereafter indicates a reduction in allochthonous inputs from the peat-dominated western side of the catchment. *Chara* branchlets and oospores are present from c. 1878, although the abundance of oospores remains very low until c. 1995.

Small increases in levels of Ca at c. 1925 and c. 1990 and an increase in calcareous bivalves post-c. 1970 may reflect a greater influence of relatively nutrient rich, alkaline water from the eastern part of the catchment. Diatom and macrofossil remains oscillate in abundance and appear to track variations in water chemistry and productivity over the last century. *Tabellaria flocculosa*, which has relatively low TP (c. 13 µg l^{-1}) and pH (6.7 pH units) optima (Chen et al. 2008), is abundant until c. 1905, when DI-TP is relatively low (c. 20 µg l^{-1}). *Asterionella formosa* and *Fragilaria capucina* are both planktonic species with high (c. 36 µg l^{-1}) and moderate (c. 21 µg l^{-1}) TP optima, respectively (Chen et al. 2008). Furthermore, they are both considered to have circumneutral pH optima (Chen et al. 2008). Both diatoms increase in abundance from the 1920s, and presumably make a substantial contribution to increased levels of DI-TP. By c. 1935, *Tabellaria flocculosa* is once again abundant, DI-TP has declined, DI-pH has increased and levels of *Chara* have risen. *Asterionella formosa* and *Fragilaria capucina* become abundant, while levels of *Chara* remains decline from c. 1925 and in the early 1960s.

Sediment-based proxies of past environmental conditions from Mask provide evidence of nutrient enrichment of the lake possibly commencing long before generally assumed reference baselines for aquatic ecosystems in Ireland. This nutrient enrichment may have been human-induced, or possibly climatically-driven (or some combination of the two). Alternatively sediment-based evidence of nutrient enrichment at Mask may be more apparent than real, and an artefact of differential preservation of biological remains, owing to fluctuations in water chemistry. Preservation of biological proxies was a problem at all three coring sites, with the remains of diatoms and/or macrofossils being completely absent from some sections of sediment cores.

Table 3.16 Mask: sediment cores.

Core code	**Date Collected**	**Location**	**Latitude, Longitude**	**Depth of water (m)**	**Length of core (cm)**	**Analyses**
		Site 1				
MK-8	14/03/07	deepest point	09º22' W, 53º36' N	62	41	Dating
MK-9	14/03/07	deepest point	09º22' W, 53º36' N	62	37	LOI, diatoms, geochemistry
MK-10	14/03/07	deepest point	09º22' W, 53º36' N	62	34.5	Macrofossils
		Site 2				
MK-4	14/03/07	eastern Robe	09º18' W, 53º38' N	15	32.5	LOI, diatoms, geochemistry
MK-5	14/03/07	eastern Robe	09º18' W, 53º38' N	15	23	Macrofossils, dating
		Site 3				
MK-11	15/03/07	southwest	09º26' W, 53º35' N	20	38	Radiometric dating
MK-12	15/03/07	southwest	09º26' W, 53º35' N	20	38	LOI, diatoms, geochemistry
MK-13	15/03/07	southwest	09º26' W, 53º35' N	20	35	Macrofossils

Table 3.17 Mask (site 1 deepest point): ^{210}Po (total and unsupported) and ^{137}Cs activity, and estimated sediment accumulation rates (SAR) based on CRS model

Sample ID (depth cm)	Dry wt./ wet cc. gcm^{-3}	Cumul-ative mass gcm^{-2}	^{210}Po total activity DPM g^{-1}	^{210}Po unsup-ported activity DPM g^{-1}	^{137}Cs DPM g^{-1}	CRS estimated age (years)	CRS SAR gcm^{-2}yr^{-1}	Linear regression estimated age
MK-C8 (0-0.5)	0.64	0.32	5.56	3.06	7.41	42.92	0.0075	n/a
MK-C8 (0.5-1)	0.64	0.64	3.59	1.09	3.56	85.85	0.0075	
MK-C8 (1-1.5)	0.51	0.90	2.50	0.00	2.44	128.77		
MK-C8 (1.5-2)	0.41	1.10	2.85	0.35	1.44			
MK-C8 (2-2.5)	0.20	1.20	1.97	-0.53	1.46			
MK-C8 (2.5-3)	0.24	1.32	2.82	0.32	1.38			
MK-C8 (3-3.5)	0.23	1.44	2.84	0.34	0.80			
MK-C8 (3.5-4)	0.23	1.55	2.66	0.17	1.19			
MK-C8 (4-4.5)	0.17	1.64	2.71	0.21	0.67			
MK-C8 (4.5-5)	0.18	2.00	2.67	0.17	1.17			
MK-C8 (8-9)	0.18	2.72	2.10	-0.40	0.19			
MK-C8 (12-13)	0.20	3.51	3.15	0.65	0.45			
MK-C8 (16-17)	0.16	4.16	3.85	1.35	0.59			
MK-C8 (20-21)	0.19	4.93	3.37	0.87	0.53			
MK-C8 (24-25)	0.16	5.58	2.58	0.08	0.73			
MK-C8 (28-29)	0.15	6.20	2.73	0.23	0.36			
MK-C8 (32-33)	0.18	6.93	2.81	0.31	0.21			
MK-C8 (36-37)	0.34	8.30	2.32	-0.18	0.34			
MK-C8 (40-41)	0.22	8.86	2.58	0.08	0.27			

Table 3.18 Mask (site 2 eastern Robe): ^{210}Po (total and unsupported) and ^{137}Cs activity, and estimated sediment accumulation rates (SAR cm yr^{-1}) based on CRS and Linear Regression models.

Sample ID (depth cm)	Dry wt./ wet cc. gcm^{-3}	Cumul-ative mass gcm^{-2}	^{210}Po total activity DPM g^{-1}	^{210}Po unsup-ported activity DPM g^{-1}	^{137}Cs DPM g^{-1}	CRS estimated age (years)	CRS SAR gcm^{-2}yr^{-1}	Linear regression estimated age
MK-C5 (0.5-1)	0.31	0.31	14.28	12.77	13.92	8.67	0.0360	9.34
MK-C5 (1-1.5)	0.34	0.65	12.80	11.29	14.00	16.73	0.0314	16.90
MK-C5 (2-2.5)	0.37	1.02	8.14	6.63	27.37	25.68	0.0411	27.91
MK-C5 (3-3.5)	0.40	1.42	7.34	5.83	41.59	37.44	0.0339	39.84
MK-C5 (4-4.5)	0.53	1.95	5.20	3.69	27.23	63.86	0.0303	63.79
MK-C5 (6-7)	0.74	2.68	3.37	1.86	31.46		0.0303	113.39
MK-C5 (8-9)	0.74	3.42	1.80	0.29	30.06			157.42
MK-C5 (10-11)	0.74	4.16	1.95	0.44	12.45			234.45
MK-C5 (15-16)	0.70	4.86	2.17	0.66	6.27			
MK-C5 (20-21)	1.27	6.13	2.90	1.39	3.83			
MK-C5 (24-25)	1.49	7.61	2.33	0.82	1.62			

Table 3.19 Mask (site 3 southwest): ^{210}Po (total and unsupported) and ^{137}Cs activity, and estimated sediment accumulation rates (SAR) based on CRS and Linear Regression models.

Sample ID (depth cm)	Dry wt./ wet cc. gcm^{-3}	Cumul-ative mass gcm^{-2}	^{210}Po total activity DPM g^{-1}	^{210}Po unsup-ported activity DPM g^{-1}	^{137}Cs DPM g^{-1}	CRS estimated age (years)	CRS SAR gcm^{-2}yr^{-1}	Linear regression estimated age
MK-C11 (1-1.5)	0.18	0.18	35.54	n/a	13.92	n/a	n/a	4.76
MK -C11 (1.5-2)	0.27	0.45	34.74		14.00			18.98
MK -C11 (7-8)	0.16	0.61	34.93		27.37			31.44
MK-C11 (10-11)	0.20	0.82	27.41		41.59			42.10
MK-C11 (13-14)	0.17	0.99	27.40		27.23			50.98
MK-C11 (16-17)	0.21	1.20	22.01		31.46			62.13
MK-C11 (19-20)	0.15	1.35	16.54		30.06			69.93
MK-C11 (22-23)	0.18	1.53	12.29		12.45			79.33
MK-C11 (25-26)	0.21	1.74	9.59		6.27			90.49
MK-C11 (28-29)	0.20	1.94	8.35		3.83			101.01
MK-C11 (31-32)	0.21	2.15	6.27		1.62			111.97
MK-C11 (34-35)	0.23	2.38	4.80		0.62			124.11
MK-C11 (37-38)	0.35	2.73	3.24		0.49			136.26

Table 3.20 Mask: SCP concentrations for sediment core samples from site 1 (deepest point) and site 2 (eastern Robe) coring sites

Site	Core	Core Depth (cm)	SCP concentration (no. g^{-1})
1 (deepest point)	MK C8	0 - 0.5	3056
		2 - 2.5	0
		3 - 3.5	0
		6 - 7.0	0
		20 – 21	0
2 (eastern Robe)	MK C5	0 - 0.5	2047
		2.0 - 2.5	2784
		11 – 12	0
		20 – 21	0

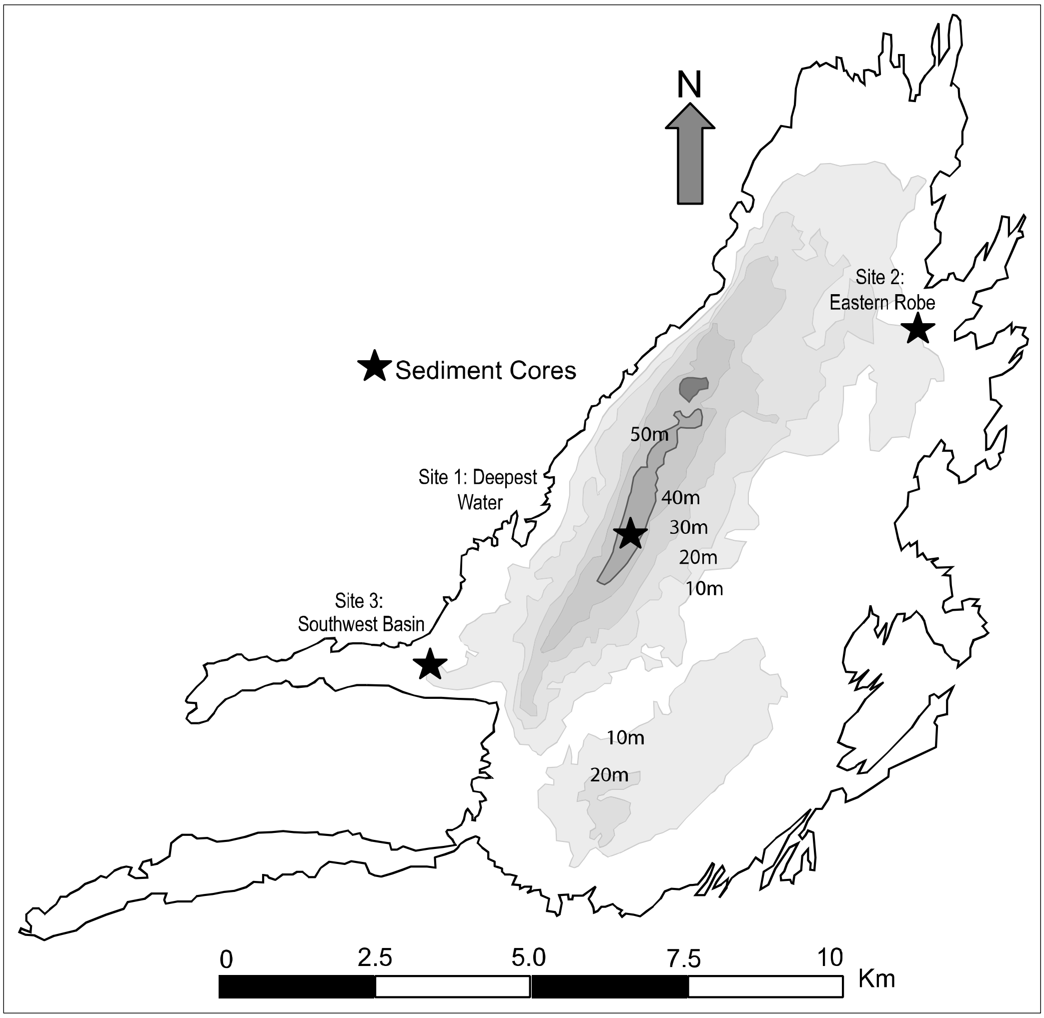


Figure 3.31 Mask: bathymetry and location of sediment cores

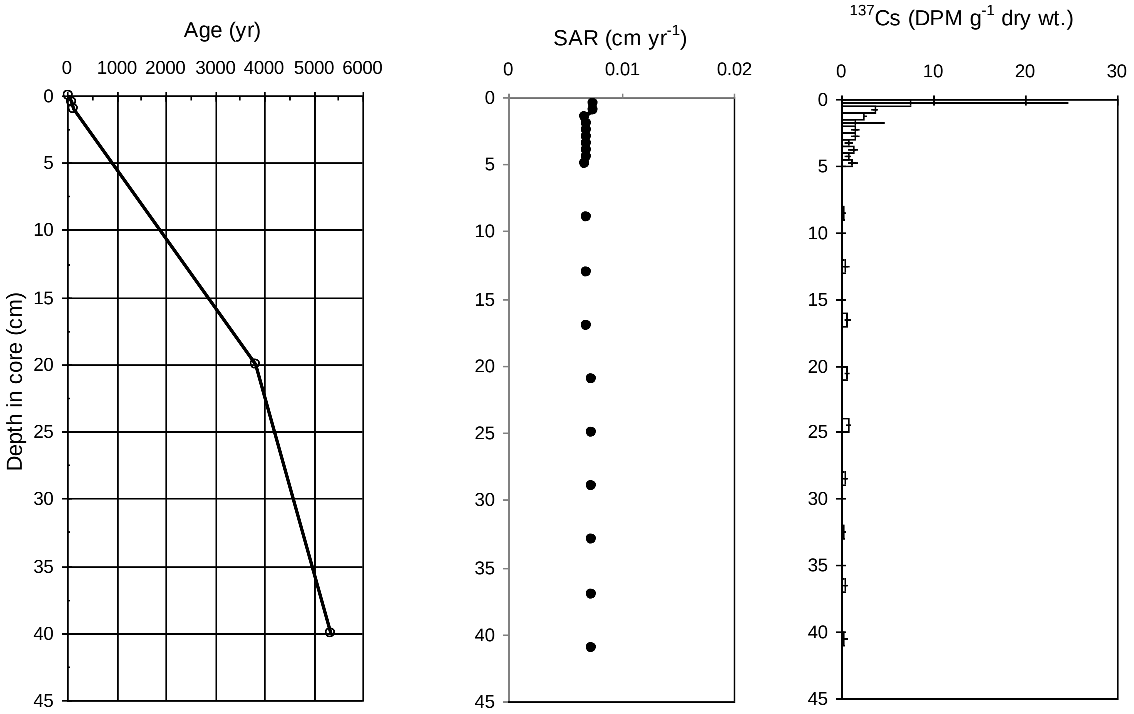


Figure 3.32 Mask coring site 1 (deepest point): age (yr) vs. depth (cm); up-core variations in sediment accumulation rates (SAR cm yr^{-1}), and ^{137}Cs activity. Note age depth profile and SAR (cm yr^{-1}) estimated using a combination of radiometric ages and AMS ^{14}C calibrated ages (BP).

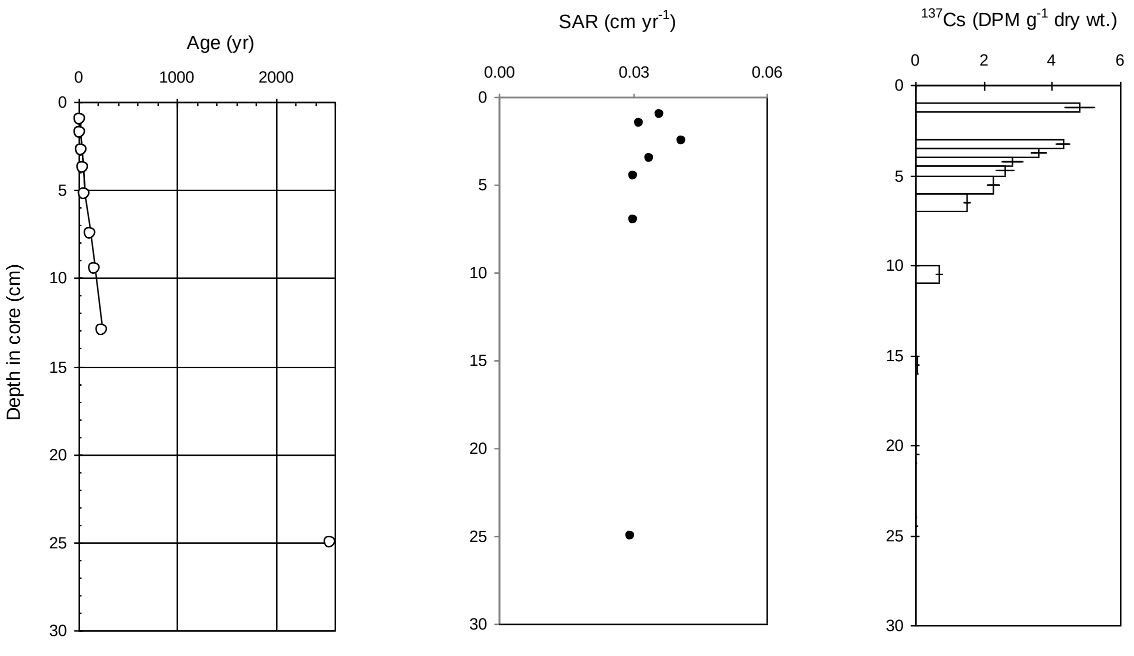


Figure 3.33 Mask coring site 2 (eastern Robe): age (yr) vs. depth (cm); up-core variations in sediment accumulation rates (SAR cm yr^{-1}), and ^{137}Cs activity. Note age depth profile and SAR estimated using a combination of radiometric ages and AMS ^{14}C calibrated ages (BP).

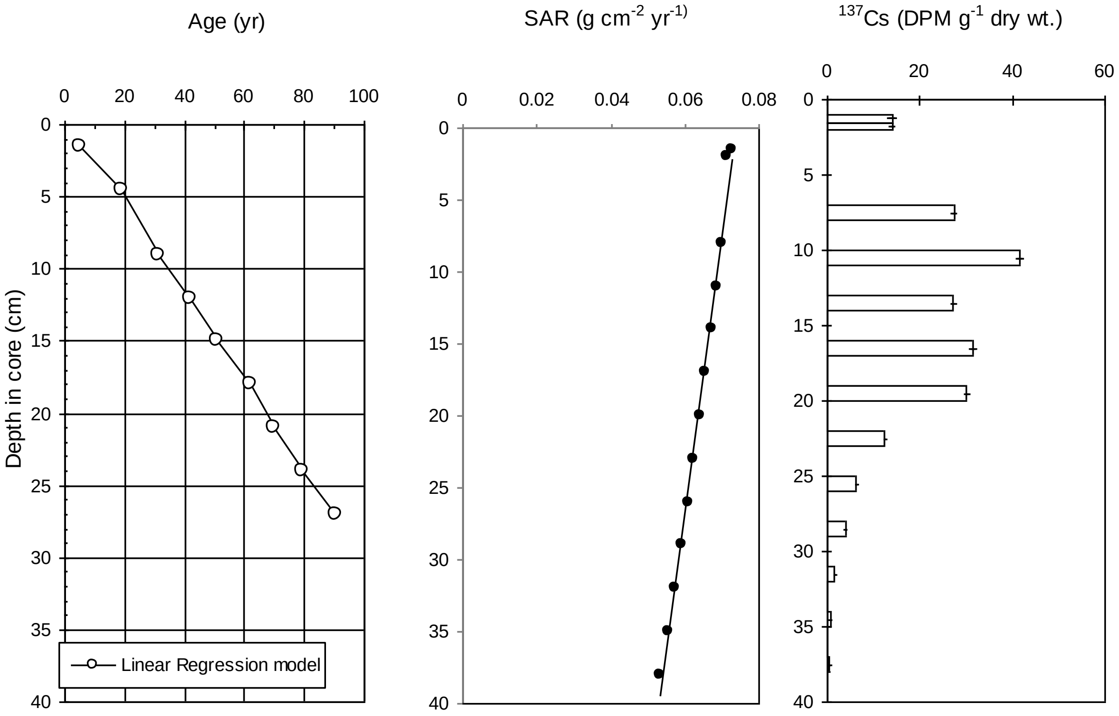


Figure 3.34 Mask coring site 3 (southwest): age (yr) vs. depth (cm) (Linear Regression model); up-core variations in sediment accumulation rates (SAR g cm^{-2} yr^{-1}), and ^{137}Cs activity.

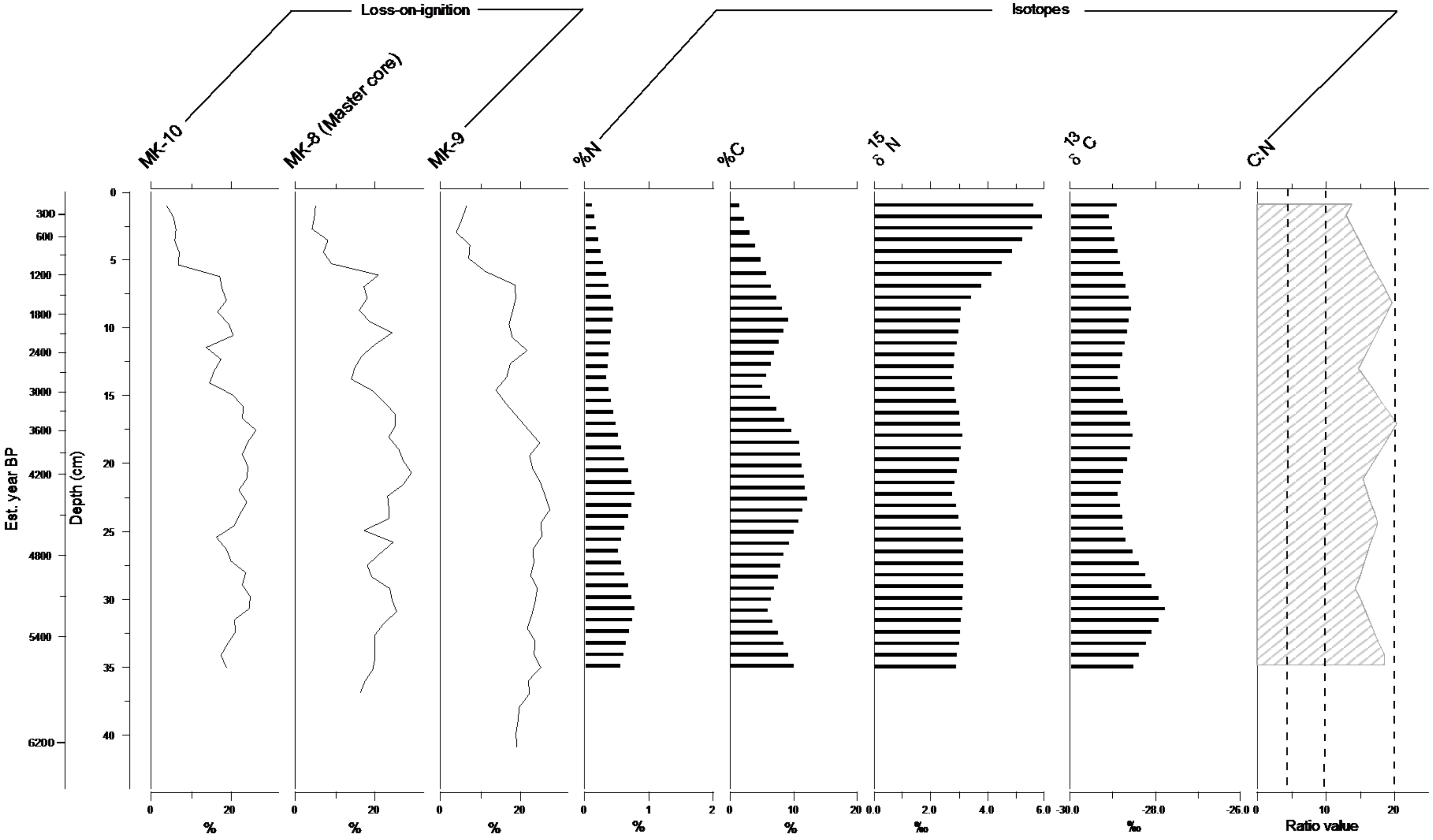


Figure 3.35 Mask coring site 1 (deepest point): up-core variations in % LOI (*=significant), δ^{15}N and δ^{13}C and ratios of C/N. Threshold C/N ratio values (4, 10 and 20) indicating the predominant source of organic material are represented with dashed lines (see Meyers 2003 and text for details).

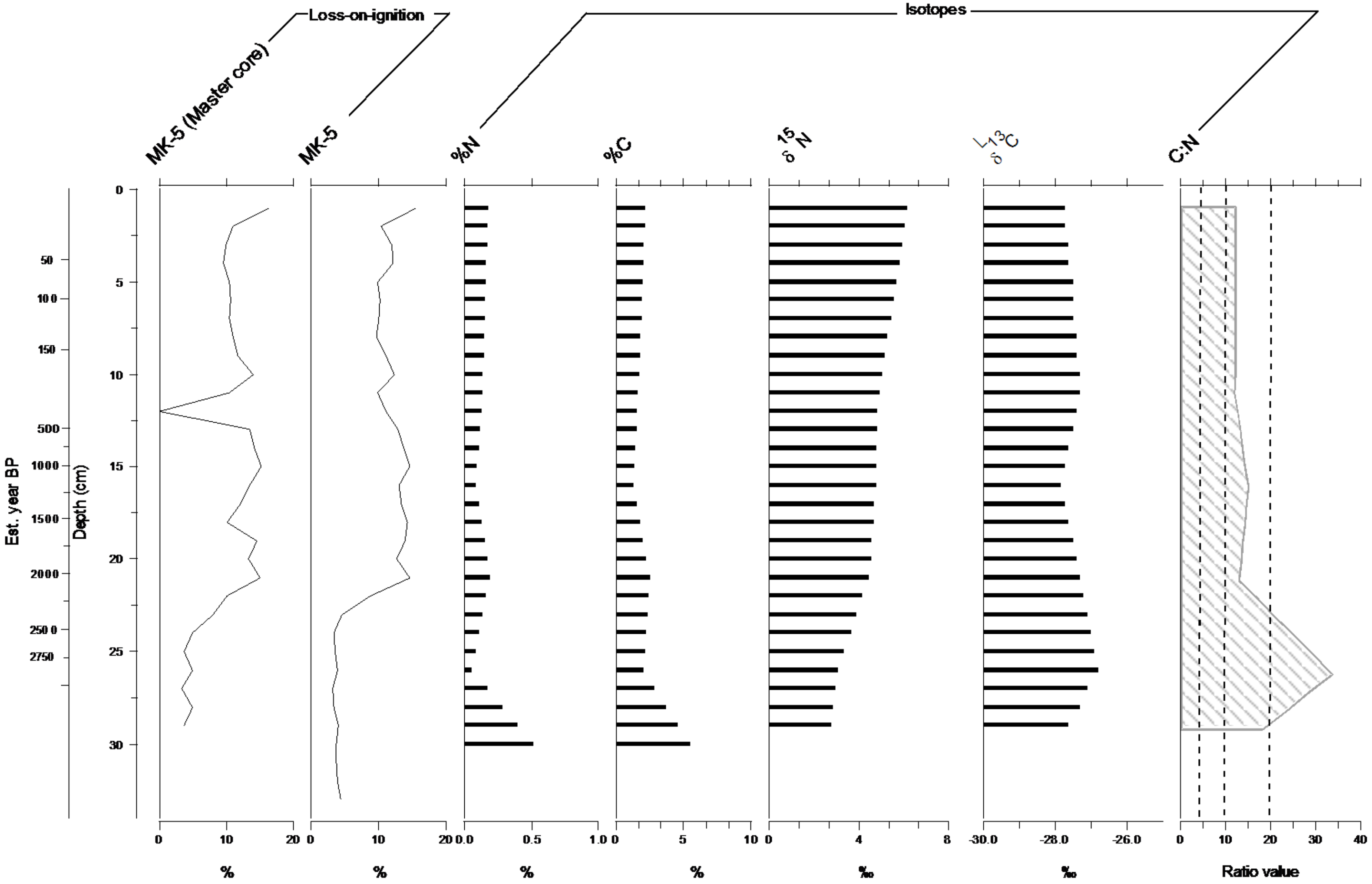


Figure 3.36 Mask coring site 2 (eastern Robe): up-core variations in % LOI (*=significant), δ^{15}N and δ^{13}C and ratios of C/N. Threshold C/N ratio values (4, 10 and 20) indicating the predominant source of organic material are represented with dashed lines (see Meyers 2003 and text for details).

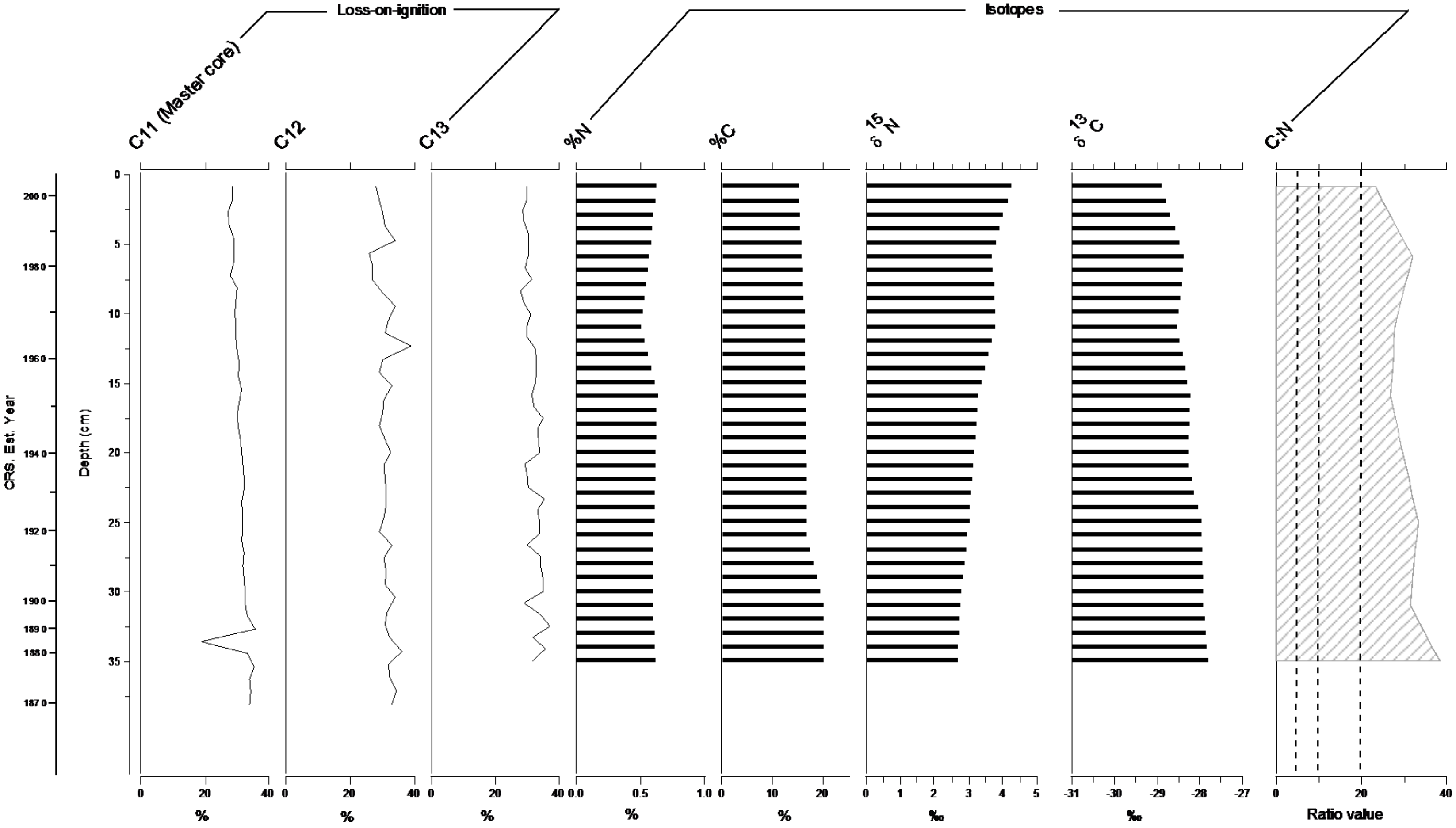


Figure 3.37 Mask coring site 3 (southwest): up-core variations in % LOI (*=significant), δ^{15}N and δ^{13}C and ratios of C/N. Threshold C/N ratio values (4, 10 and 20) indicating the predominant source of organic material are represented with dashed lines (see Meyers 2003 and text for details).

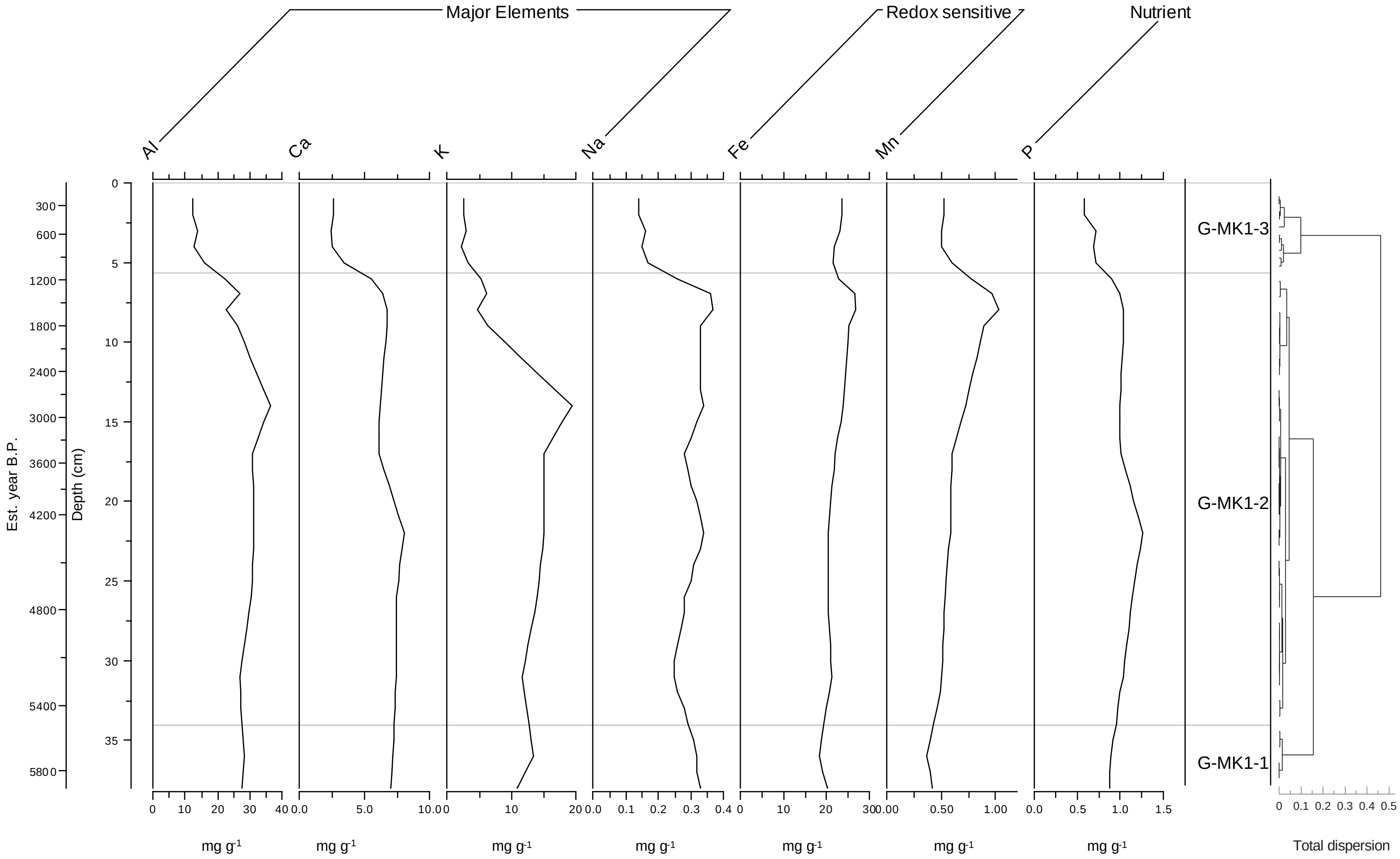


Figure 3.38a Mask site 1 (deepest point): up-core variations in concentration of chemical elements. No accumulation rate data are presented due to problems with dating.

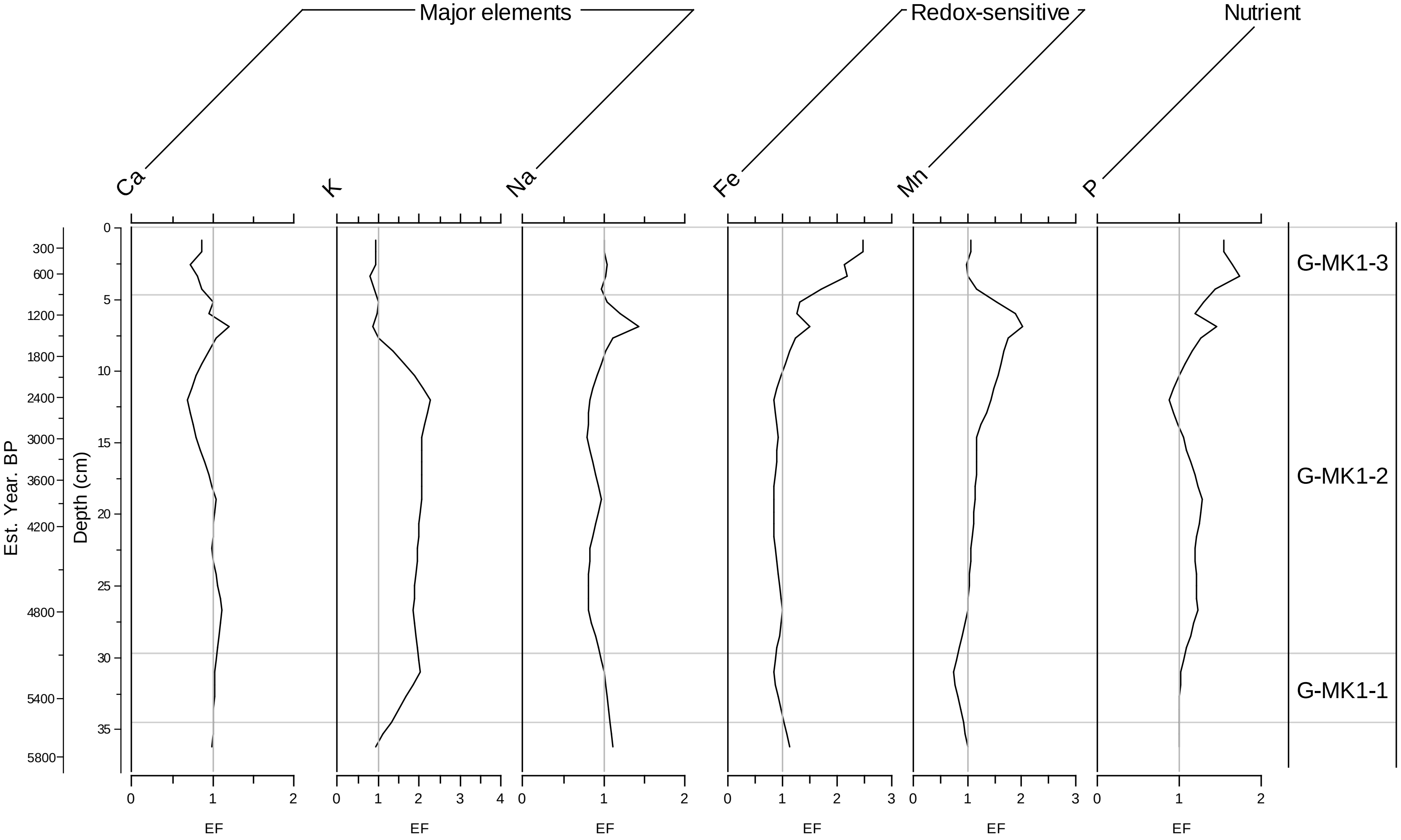


Figure 3.38b Mask site 1 (deepest point): up-core variations in EFs. EF = 1 is highlighted

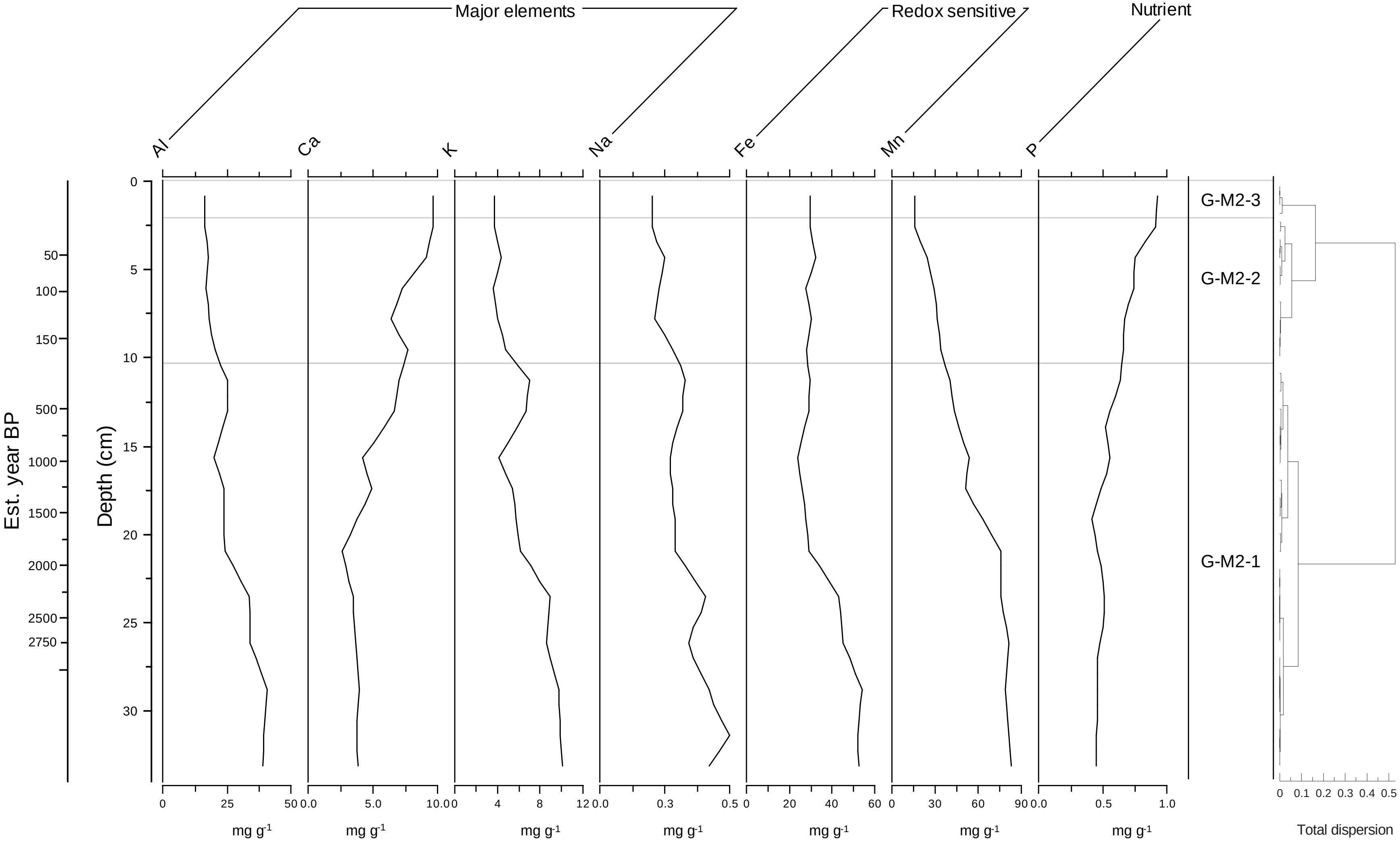


Figure 3.39a Mask coring site 2 (eastern Robe): up-core variations in concentration of chemical elements. No accumulation rate data are presented due to problems with dating. Note that dating of this core was part based on a basal ^{14}C date from a shorter core (23 cm-long)

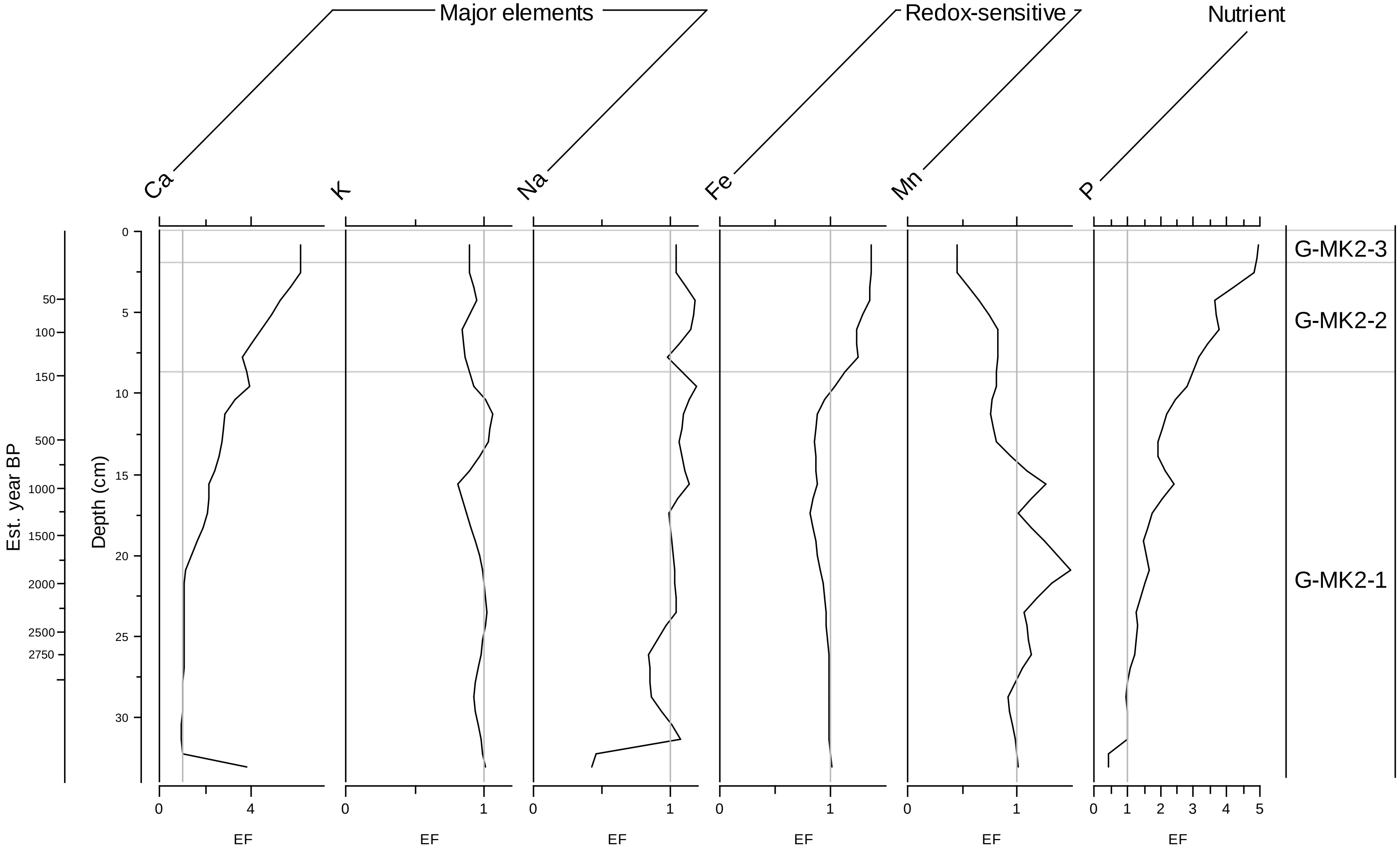


Figure 3.39b Mask (site 2, eastern Robe): up-core variations in EFs. EF = 1 is highlighted

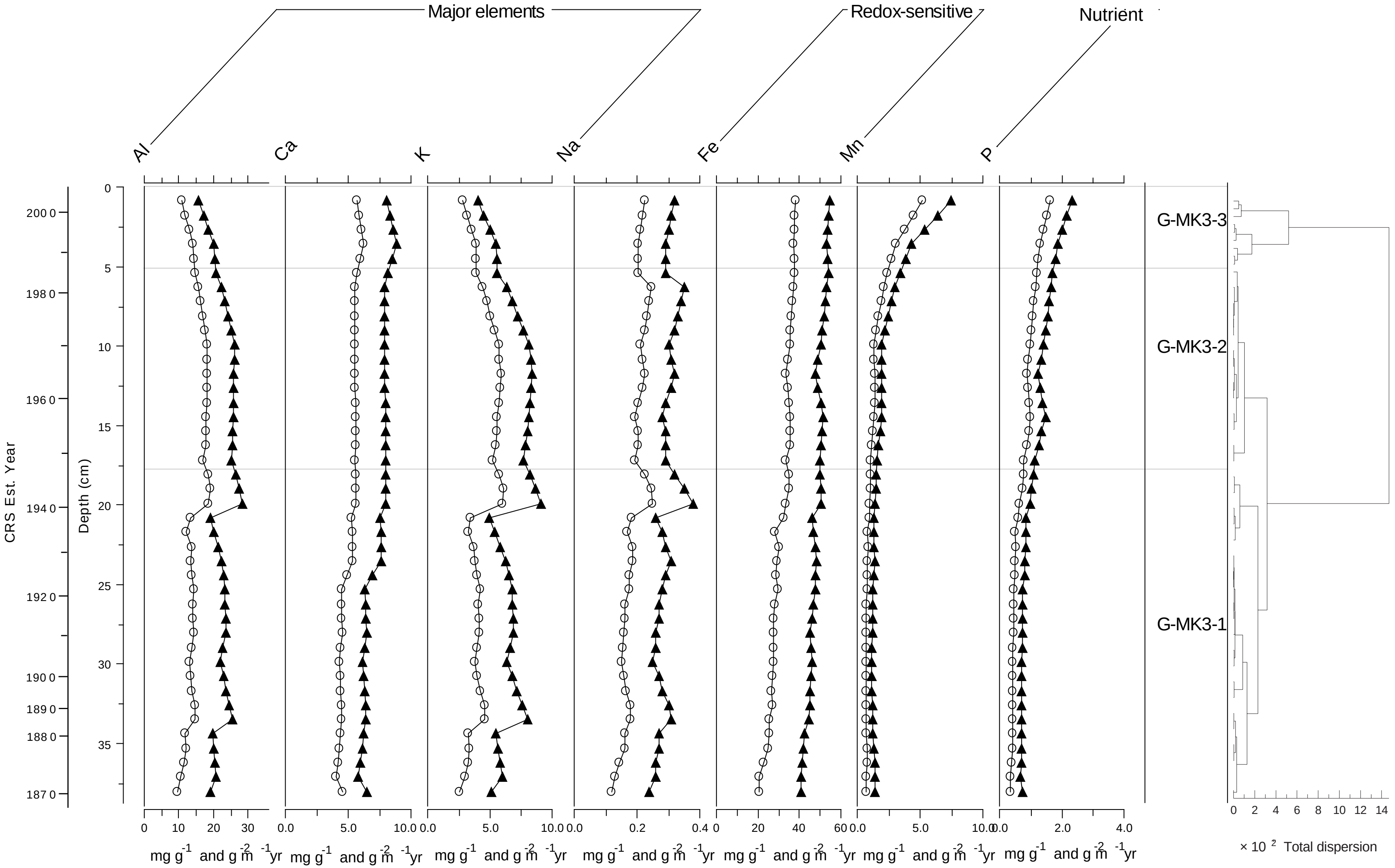


Figure 3.40a Mask coring site 3 (southwest): up-core variations in concentration (▲) and accumulation rate (○) data for chemical elements.

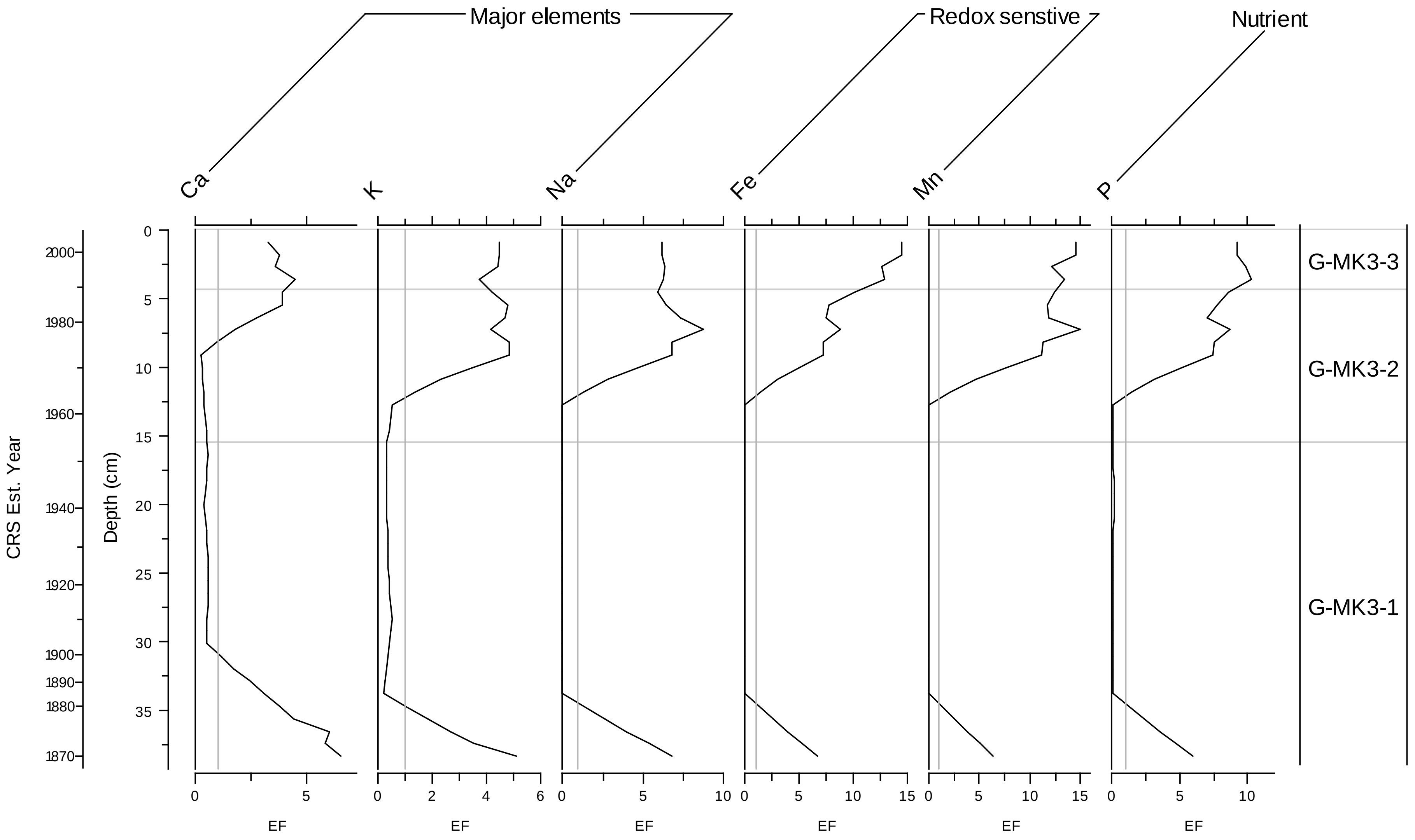


Figure 3.40b Mask coring site 3 (southwest): up-core variations in EFs. EF = 1 is highlighted.

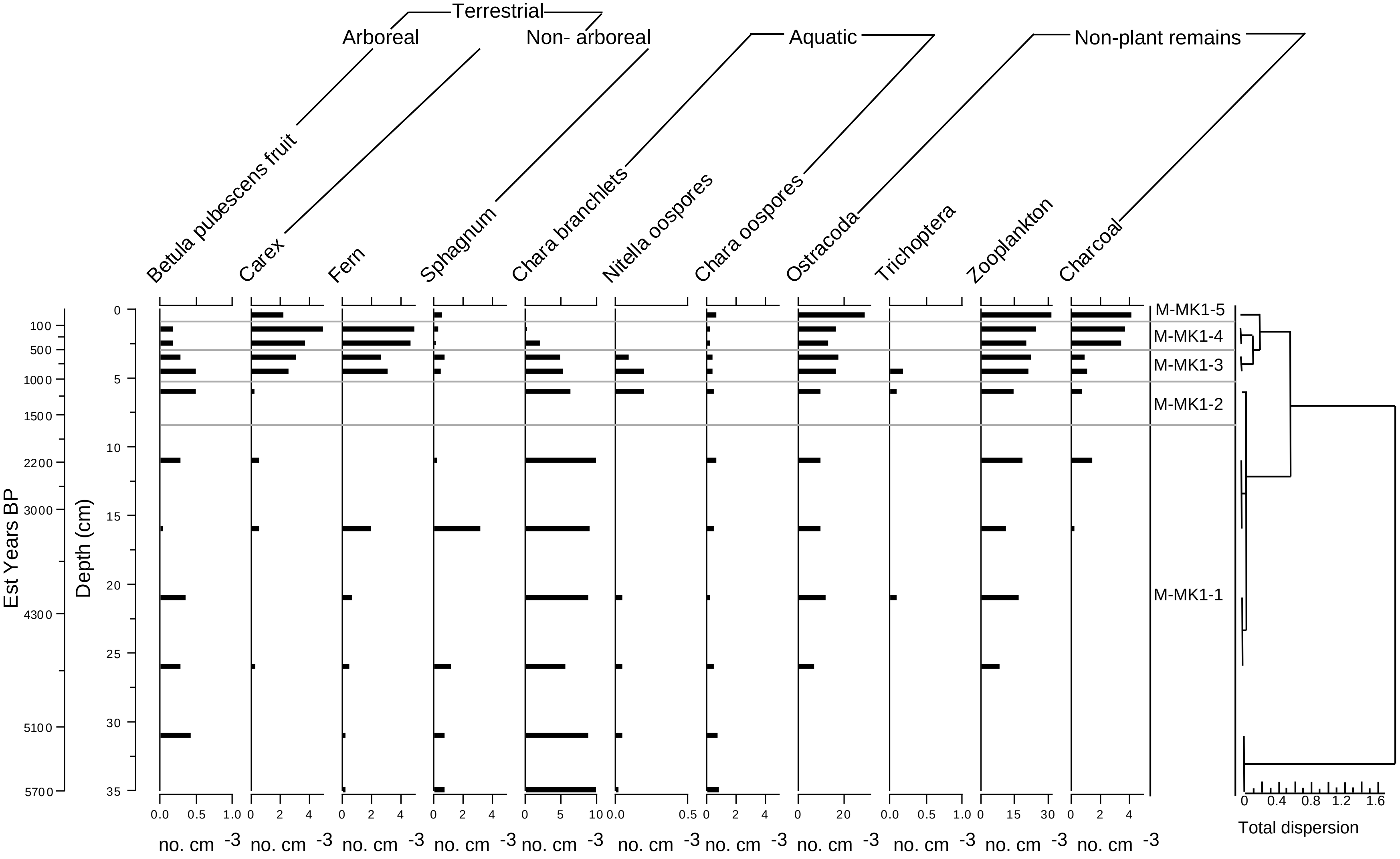


Figure 3.41 Mask coring site 1 (deepest point): up-core variations in macrofossil remains.

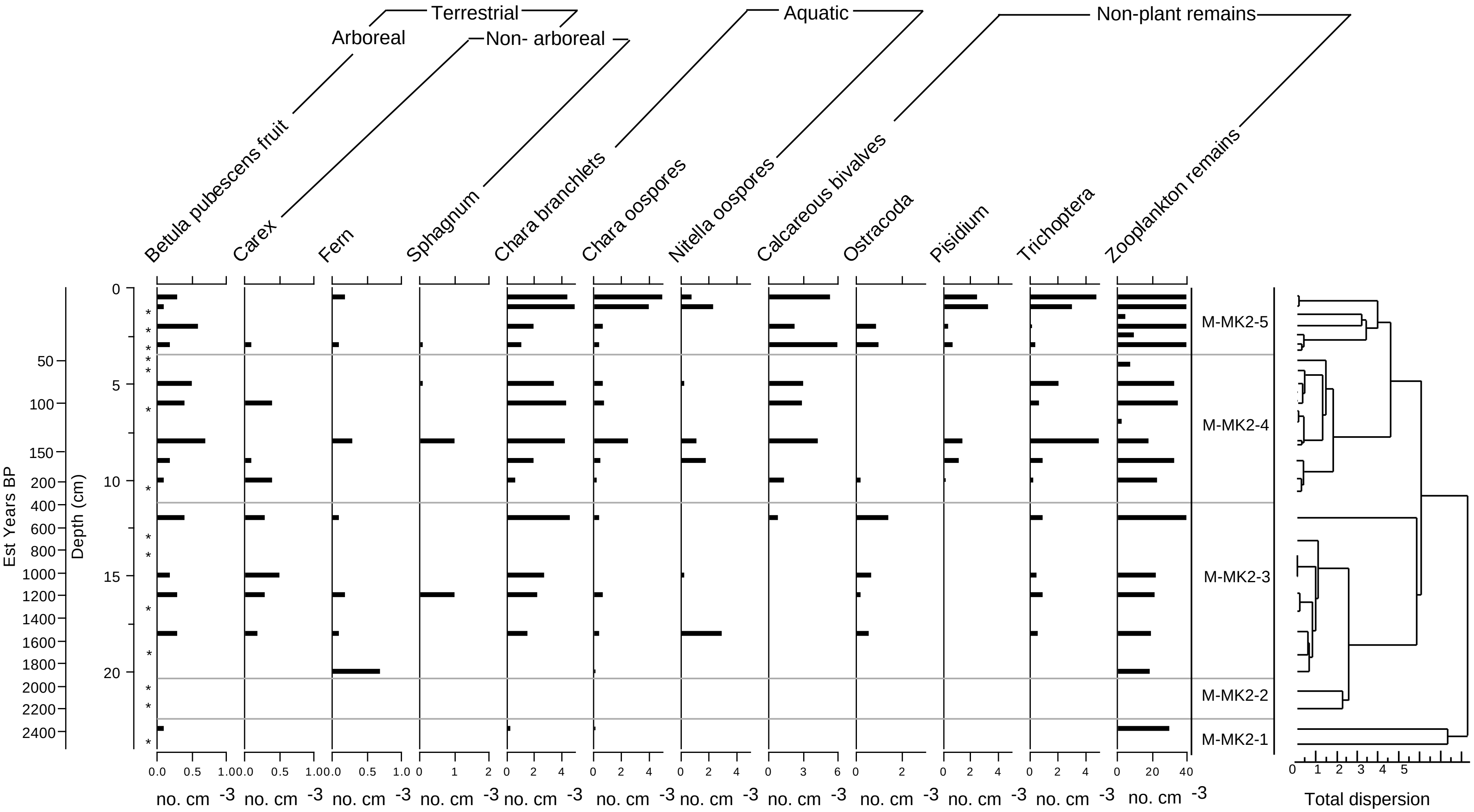


Figure 3.42 Mask coring site 2 (eastern Robe): up-core variations in macrofossil remains. *****denotes depths from which samples were analysed but were found to have very low abundances of or no macrofossils.

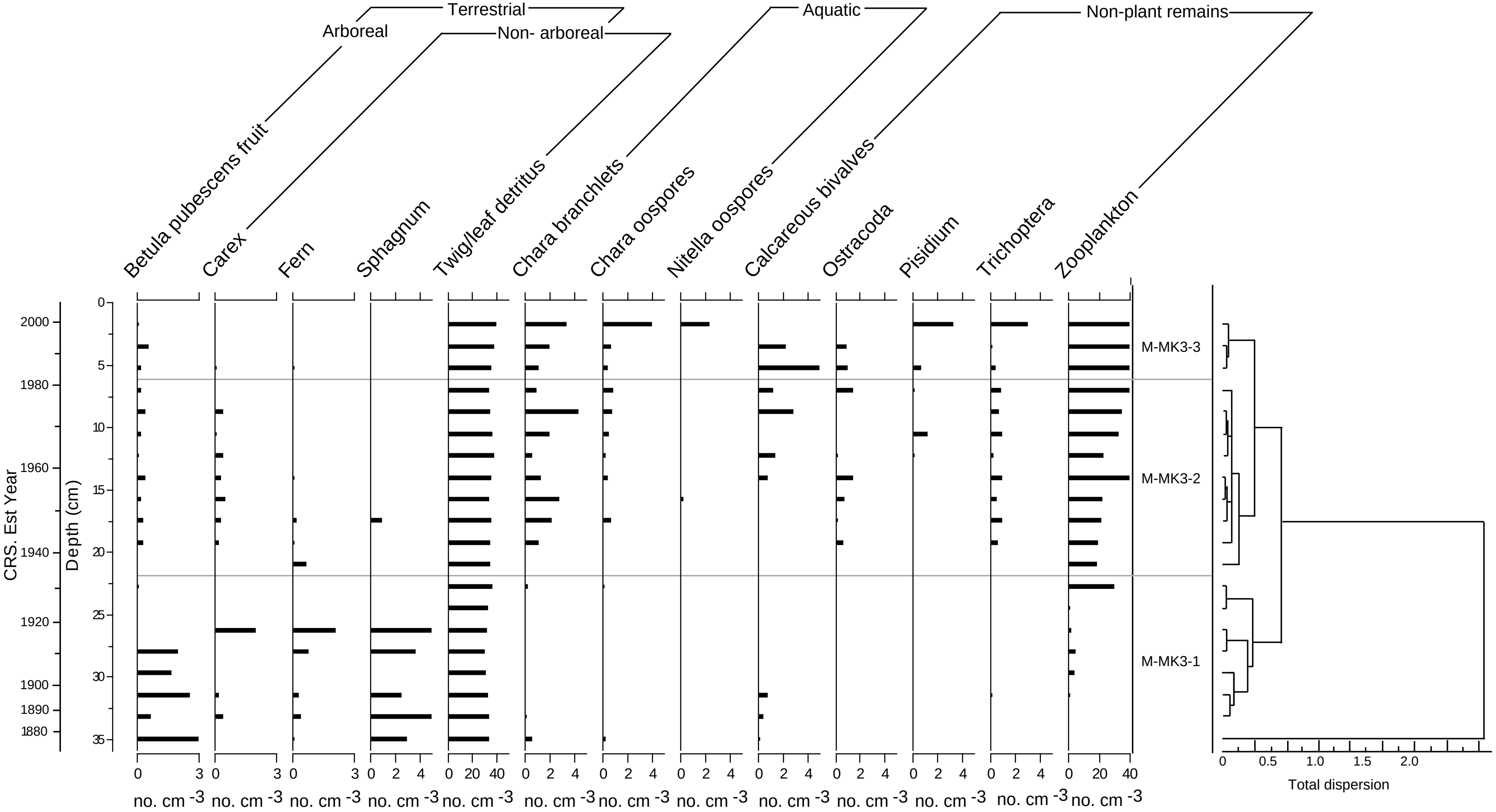


Figure 3.43 Mask coring site 3 (southwest): up-core variations in macrofossil remains.

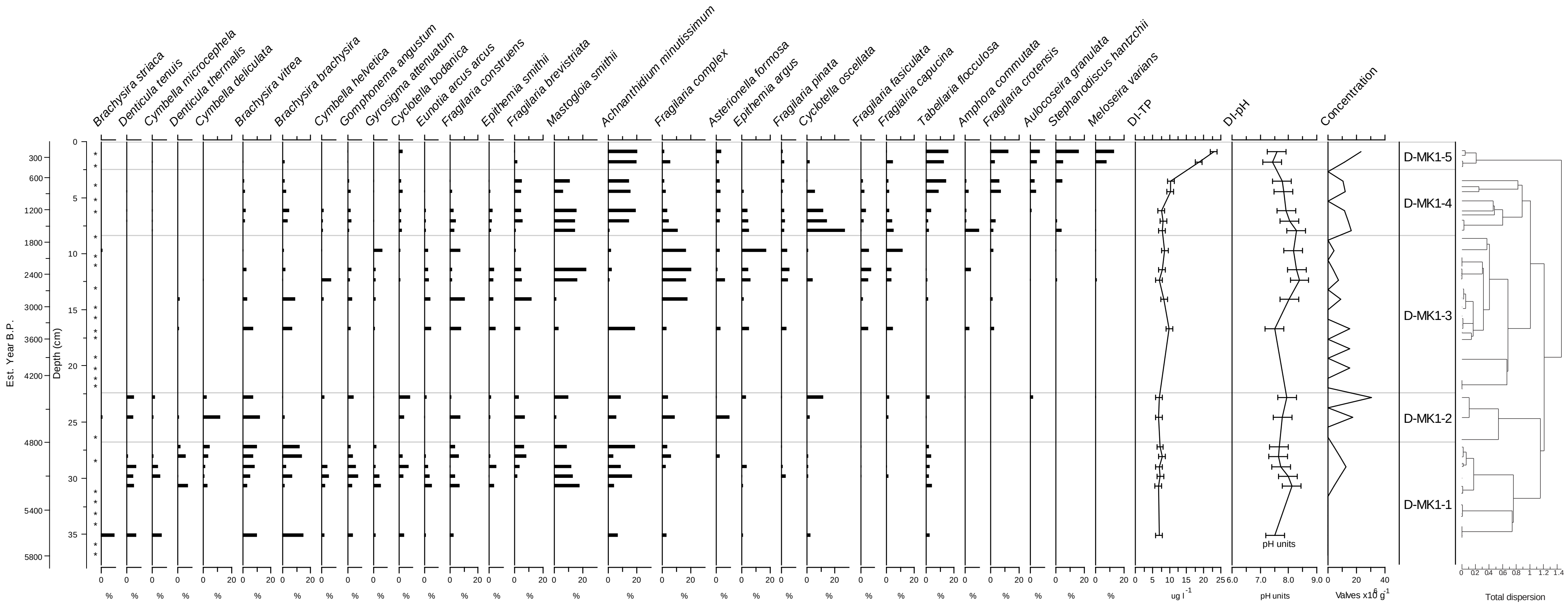


Figure 3.44 Mask site 1 deepest point: up-core variations in diatom abundances, DI-TP, DI-pH and diatom concentrations. Note the vertical axis is in estimated years BP. *****denotes depths from which samples were analysed but were found to have very low abundances of or no diatoms.

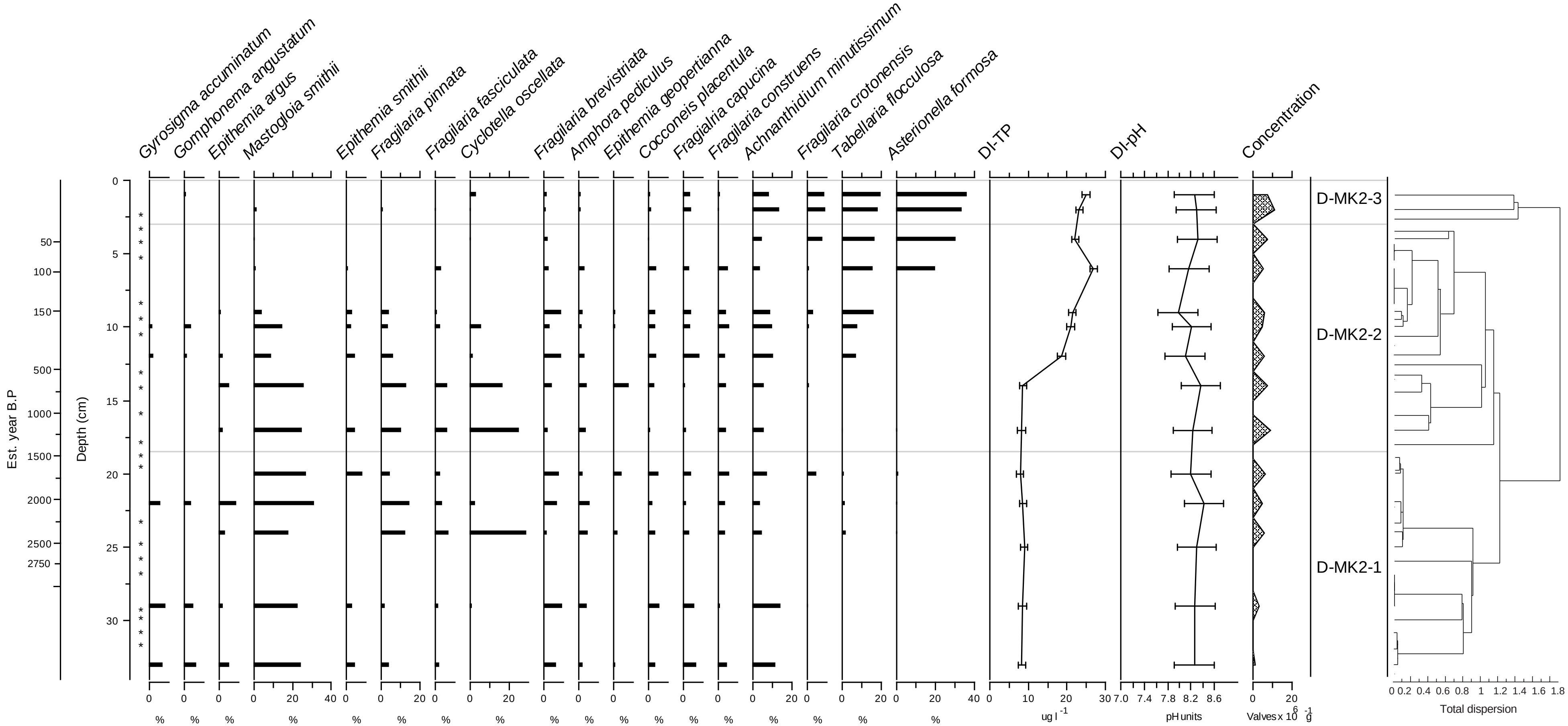


Figure 3.45 Mask coring site 2 (eastern Robe): up-core variations in diatom abundances, DI-TP, DI-pH and diatom concentrations. Note the vertical axis is in estimated years BP, and that these diatom data are from a core that was longer than the one dated. ***denotes depths from which samples were analysed but were found to have very low abundances of or no diaoms.

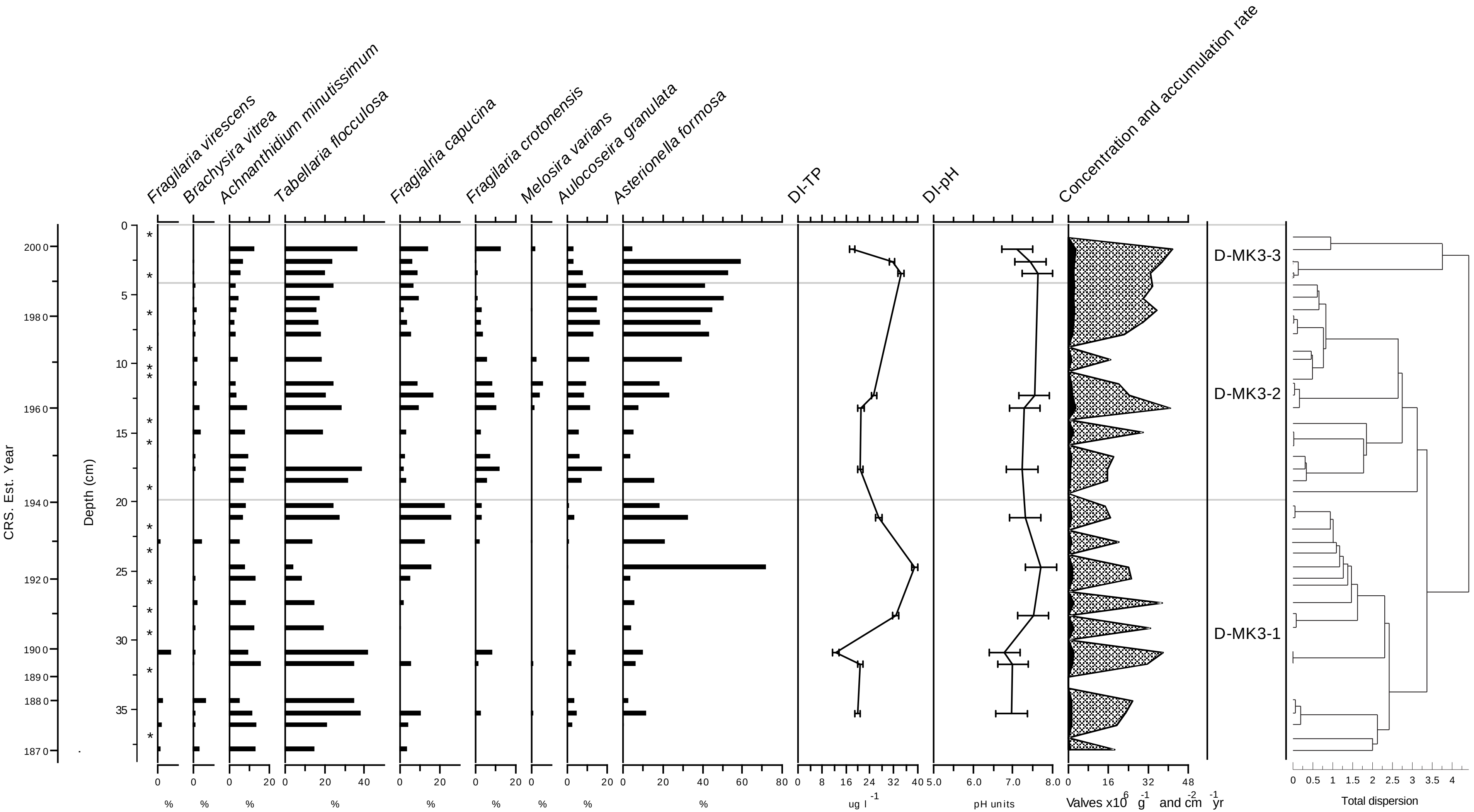


Figure 3.46 Mask coring site 3 (southwest): up-core variations in diatom abundances, DI-TP, DI-pH, concentrations (black silhouette) and flux (grey silhouette). ***denotes** depths from which samples were analysed but were found to have very low abundances of or no diatoms.

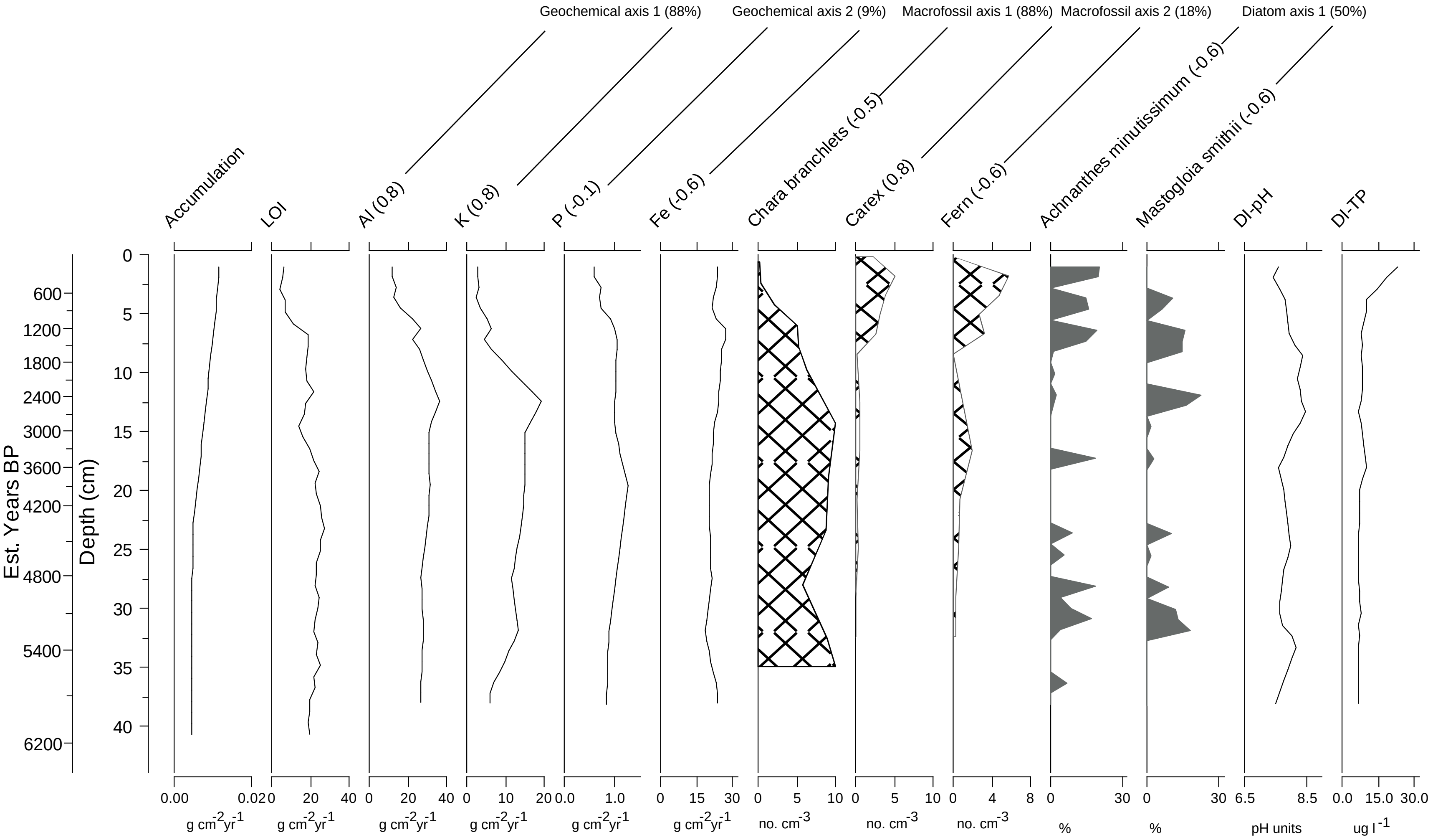


Figure 3.47 Mask coring site 1 (deepest point): synthesis of multi-proxy palaeolimnological data.

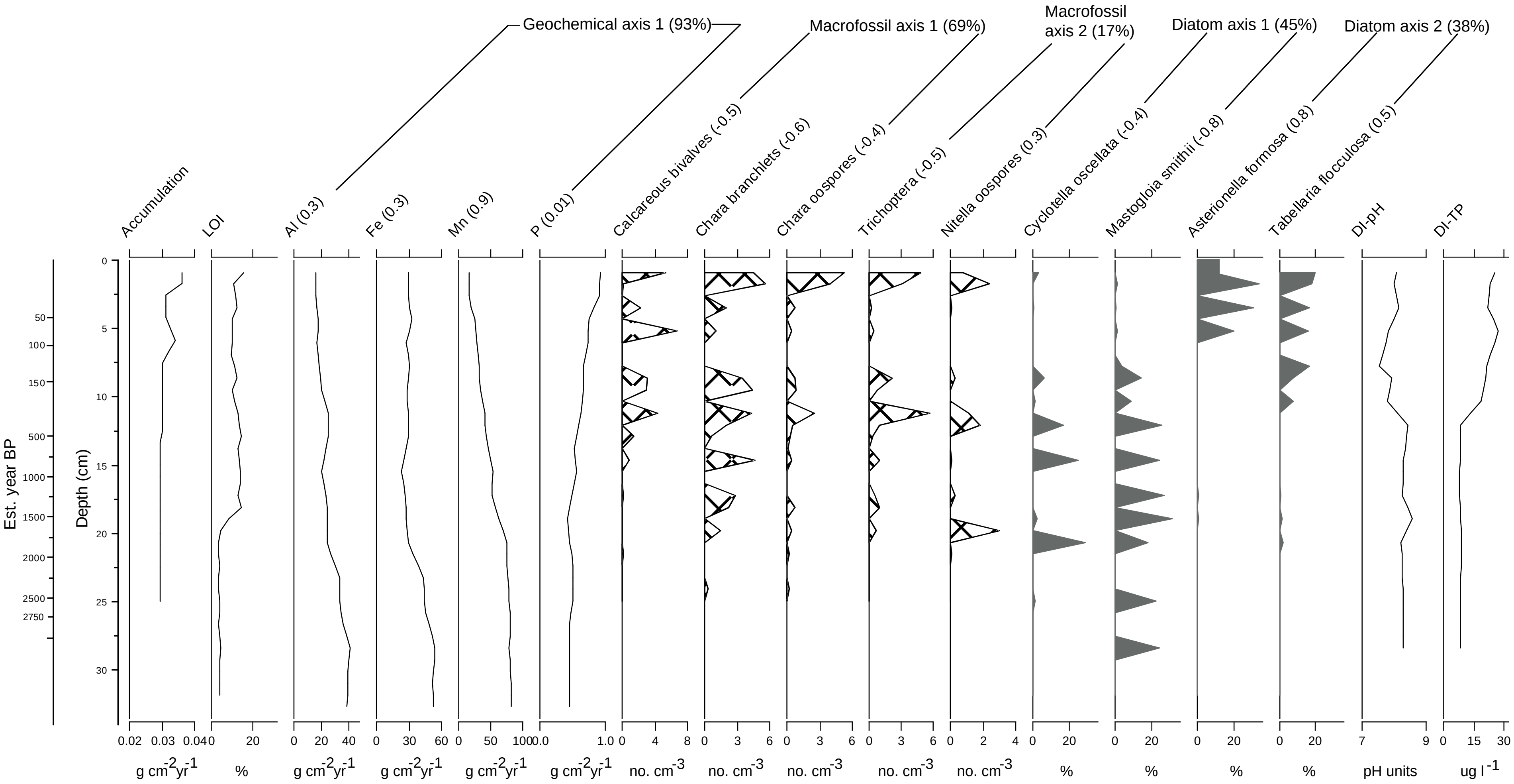


Figure 3.48 Mask coring site 2 (eastern Robe): synthesis of multi-proxy palaeolimnological data.

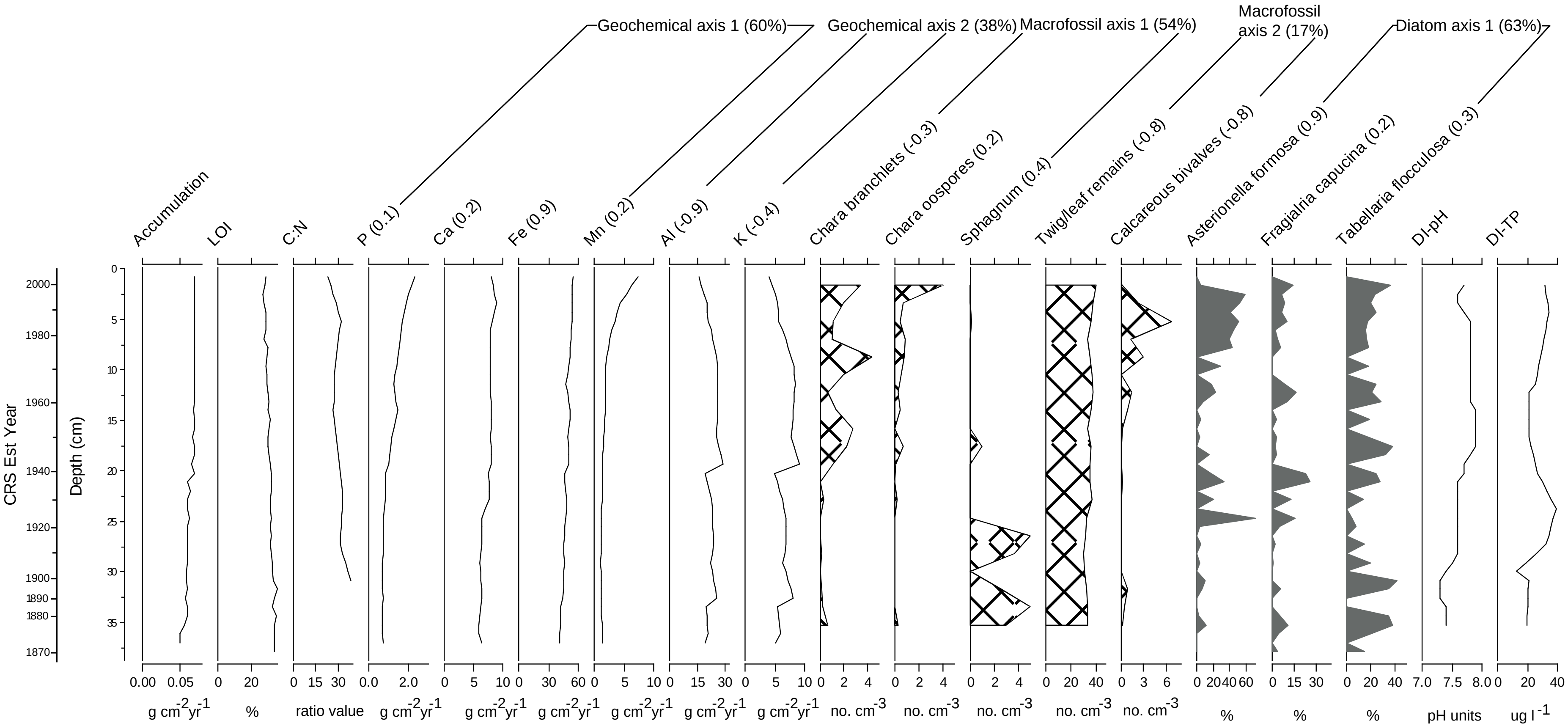


Figure 3.49 Mask coring site 3 (southwest): synthesis of multi-proxy palaeolimnological data.

Chapter 4. Catchment Modelling

4.1 Introduction

The overall aim of WP 3 was to demonstrate the use of dynamic modelling in meeting WFD requirements, in particular to reduce uncertainty in risk characterisation and to explore future changes in pressures and ecological responses. The initial characterisation exercise for Irish water bodies described the probability of meeting the WFD requirement for good ecological status by 2015, as required under Annex II section 1.5 of the WFD (Anon 2005). The report also identified the main threats to water quality at each site. However, for many sites there was a high degree of uncertainty, both in the assigned risk status and in the identification of the major pressures, mainly due to limited availability of data on which to base these assessments (Anon 2005). WP 3 explored the potential of a modelling approach to reduce uncertainty in future characterisations. In addition, models were used to quantify future ecological responses to simulated changes in pressures, for example, in local population, industrial and agricultural practices, and climate, thus providing a tool to explore potential management options.

Models of catchment nutrient export range from simple regression models (e.g. Donohue et al. 2006) and export coefficient functions (e.g. Johnes 1996) to complex process based models such as SHETRAN (e.g. Ewen et al. 2000) and SWAT (e.g. Arnold et al. 1998). Semi-empirical nutrient loading models offer a compromise between simple export coefficients and more complex models: these mechanistically describe the hydrologic and sediment components and estimate nutrient loads based on relationships between flow and concentration. A version of one semi-empirical model, the GWLF model (Schneiderman et al. 2002), was used in ILLUMINATE to simulate daily values for catchment discharge, sediment and nutrient loading. This work built on simulations of climate change impacts on catchment loading in several European catchments carried out through CLIME (2003-2006) (Moore et al. 2009; Pierson et al. 2009). These simulations included the Flesk subcatchment of Leane and the Glenamong subcatchment of Feeagh. Models of in-lake response also range from simple models, i.e. those based on empirical relationships between nutrient loading and chlorophyll-a (Vollenweider 1968; OECD 1982; Foy 1992), to more complex models of in-lake productivity that include equations for a range of physical, chemical and biological processes (e.g. Elliot et al. 2006; Trolle et al. 2008). The daily output from GWLF was used in ILLUMINATE as input to DYRESM-CAEDYM, a dynamically coupled model of in-lake physical, chemical and biological processes (Figure 4.1). However, annual values from GWLF were also used as input to a simple modified Vollenweider model for shallow Irish lakes (Foy 1992) to obtain estimates of past in-lake TP concentrations.

The chosen models were used to explore pressures and ecological responses in three lakes, one in each of the three study catchments: Leane, Feeagh and Mask. All modelling approaches are restricted by the availability of historical input and validation data. The models were therefore run for the period for which suitable data were available (Table 4.1). Thirty-seven years of monitoring data were available for Leane, probably the longest historical data set for any lake in the Republic of Ireland. In addition, the Leane catchment has been the subject of an intensive monitoring and management programme, instigated by Kerry County Council in 1999, which has included high frequency monitoring of nutrient concentrations for all the major inflows to the lake (KMM 2000, 2003). The availability of these data sets provided a high degree of certainty in the initial at risk characterisation of Leane. The availability of this relatively long time series of monitoring data also facilitated validation of a range of modelling techniques.

In contrast to Leane, where the major historical pressures have been nutrient loading from both municipal sewage and from agricultural sources (Twomey et al. 2000; Jennings et al. 2008), changes in livestock densities and afforestation have been the main pressures on water quality in Feeagh (Allott et al. 2005; Leira et al. 2006). On-going high frequency monitoring at the site includes suspended sediment and DOC concentrations; a more limited data set exists for nutrients, chlorophyll-a and plankton species composition. While Feeagh was initially designated a CRL for the WFD, subsequent palaeolimnological investigations indicated that the lake had possibly been impacted both by acidification and nutrient enrichment in the more recent past (Leira et al. 2006). Mask has similar catchment pressures to Leane (municipal sewage and diffuse agricultural inputs). Water quality in the lake has deteriorated from oligotrophic to mesotrophic over the last twenty years (Toner et al. 2005); however, the availability of monitoring data is again lower than for Leane.

Where long-term monitoring data for catchment nutrient loading and in-lake phytoplankton biomass are rare, palaeolimnological data may provide the only means of validating long-term model behaviour (Bennion et al. 2005; Anderson et al. 2006). The application of the models in the project was validated by a combination of monitoring and palaeolimnological data. The chosen models were then run to hindcast catchment pressures and in-lake responses. The output of these simulations was used to identify the main drivers of catchment pressures in all three study catchments and to assess the potential for a range of approaches to reduce uncertainty in risk classification. In addition, a set of simulations was carried out to explore the impact of projected changes in climate and possible management scenarios on nutrient export and in-lake responses.

4.2 Model descriptions and validation

4.2.1 GWLF

GWLF description

GWLF is a loading model originally developed by Haith & Tubbs (1981) and validated by Haith & Shoemaker (1987) to simulate monthly dissolved and total P and N loads in stream flow in US catchments. Several adaptations of the original GWLF model are currently in use. The version used in the current research was originally created by New York City Department of Environmental Protection in the Vensim visual modelling software package (Ventana Systems Inc.) (Schneiderman et al. 2002). The model is driven by daily temperature and precipitation data and water balances are calculated on a daily interval. Streamflow consists of surface runoff and fast and slow subsurface flow components. Modelling of diffuse nutrient loads is a function of land use and runoff. Dissolved nutrient loads are derived by multiplying runoff by a land use-specific nutrient concentration. Sediment loading is based on the Universal Soil Loss Equation (USLE) (Wischmeier & Smith 1978). Particulate nutrient loads are calculated according to stream flow on that day using information on sediment yield and a soil nutrient concentration for each land use. The contribution of nutrients from septic systems is based on population and estimates of system performance. Point source loadings, for example STPs, are also input and accounted for in the overall estimates of nutrient flux.

Developments during CLIME included an improved optimisation procedure for the hydrology model that minimises the sum of the residuals between simulated and measured stream flow (Schneiderman et al. 2009). A further change was the use of European CORINE level 3 land cover classes for land use classification (EEA 2000). Pasture was further divided into high, mixed, and low productivity, and peat bogs were classified as unexploited or exploited, to allow for differences in land management. A land use for farmyards was also included. In addition, GWLF was coupled with a process driven model of DOC developed by the Centre for Ecology and Hydrology, UK (Naden et al. 2009). DOC from peat soils has implications for the ecology and productivity of receiving waters, the quality and treatment costs of water used for human consumption and the global carbon cycle (Jennings et al. 2009a).

GWLF application

Model driving data (daily precipitation and air temperature) were available for the Leane catchment from the meteorological station at Muckross House (Figure 1.1) from 1969 to present. Precipitation data were also available from the synoptic station at Valentia (Figure 1.1) from 1941 to present. Driving data for the Feeagh catchment included data from the Newport meteorological station, which is located close to the shore of Furnace (1960 to present) (Figure 1.1). Additional data were available from 1956 to present for the Belmullet synoptic station from Met Éireann. Data from 1900 to 1952 were transcribed from paper records for the Blacksod weather station, an earlier station located at the Belmullet site, by the ILLUMINATE project team. Data from the synoptic station at Claremorris (1950 to present) were used to drive the model for Mask, while the data from Blacksod were used for earlier simulations. Data from the synoptic station at Claremorris, which is 40 km west of Burrishoole, were used for the Feeagh simulations for 1953 to 1955. A precipitation correction factor is used in the model to make a correction to the available precipitation data based on measured stream flow for the subcatchment. Where precipitation data were used from a more remote station, the precipitation correction factor was recalibrated to account for any differences between the sites. Air temperature data were also compared and corrected where required.

The model also requires data on the catchment population and land use. Population data were obtained from the CSO for the DEDs within the three study catchments. These were available for all census years from 1901 to present. Where a catchment included only part of a DED, the population within that part of the DED was determined on a proportional area basis that also accounted for the locations of any large centres of population. This approach was necessary for the larger and more populated Leane and Mask catchments, the subcatchments of which comprise, respectively, 31 and 48 DEDs: by contrast, the Feeagh catchment consists mainly of one DED, Srahmore. Following consultation with MI staff, human residents of the Srahmore DED were assigned to the Black subcatchment; none were assigned to the Glenamong subcatchment. In GWLF, houses outside of sewered areas were presumed to have septic tanks. Septic tanks are assigned in the GWLF septic tank subroutine to one of four categories; normal, short-circuited, ponded and direct (Schneiderman et al. 2002). Results from the special study area on septic tanks in the Leane catchment indicated that depth of overburden was the critical factor controlling the loss of nutrients from septic tank soak-away areas (KMM 2003) and concluded that no nutrients were retained by soils in areas with <3 m of overburden. All persons in areas with <3 m soil depth were assigned to the short-circuited class. As peat soils also do not have the capacity to fix or store applied P (Daly & Styles 2005), households in areas of peat soil were also assigned to the short-circuit class. All others were assigned to the normal category. Households were assumed to have relied upon cesspits prior to the introduction of septic tanks or other small on-site treatment systems. The losses from these were classed as for septic soak-away systems, with no retention in areas with <3 m soil depth or in areas with peat soils.

CORINE land cover values were available for the three catchments for 1990 and 2000. Additional data were available for agricultural land use from years in which agricultural censuses were undertaken from 1900, while forestry data were available from the FIPS database. These were combined to give estimates of historical land use changes over time. The area for farmyards was estimated based on the number of farms multiplied by 0.5 ha. Coefficients of soil erodibility and vegetation cover, required for USLE calculations in the model, were based on Wischmeier & Smith (1978). Average slope length and slope gradient were calculated for each land use using GIS and ordnance survey maps. Soil nutrient concentrations, used in the calculation of particulate nutrient loads, were based on literature values for sites in Ireland (Appendix 4.1). A value based on monitoring data from a small stream draining Killarney in the Leane catchment was used for urban land use classes. A catchment average concentration, weighted for land use area, was used for the roads class. Land use specific dissolved nutrient concentrations were based on results from a study in the Leane catchment on areas representing agricultural land uses (KMM 2003), while values from Cummins & Farrell (2003) were used for coniferous forestry. In the original model, slurry or manure spreading is incorporated through applying a dissolved nutrient concentration representative of post-spreading runoff conditions to selected land uses (Schneiderman et al. 2002). Dissolved P losses after experimental application of slurry range from 0.29 to 34.0 mg dissolved P l^{-1}, with relative increases in concentration of between 5- and 60-fold (Withers et al. 2001; Kleinman et al. 2003; McGechan et al. 2005; Vadas et al. 2007). A value of 0.42 mg dissolved P l^{-1} was applied to runoff events during the slurry season in the GWLF simulations, representing an average relative increase in concentration. This increase in concentration was applied to high productivity pasture. The slurry spreading period was set to the dates stipulated in the good agricultural practice regulations (S.I. No. 378 of 2006. European Communities (Good Agricultural Practice for Protection of Waters) Regulations 2006). These prohibit spreading of slurry between 15th October and the following 15th January. No data were available to validate Si loading from the catchments. However loads were required as input to the biological response model CAEDYM. In GWLF, Si loads are a simple function of flow and an applied concentration. This concentration in ILLUMINATE was based on limited data available for Leane and Mask.

Livestock module development

In the original GWLF model, the spreading of livestock slurry and manure on land was accounted for through a simple increase in the dissolved nutrient concentration values applied to specified land uses, while land use area and the unsewered population, a requirement of the septic tank module, were input as constants. Available historical data for the ILLUMINATE catchments included human population, land use and livestock numbers from national and agricultural census returns on approximately a decadal basis. The following modifications of the original model were made to allow use of these data as time series rather than constants in model simulations, thus producing a more realistic estimate of hindcast nutrient loads:

1. The data for the ‘unsewered population’ and the ‘seasonal unsewered population’ (population plus tourists) in the septic tank module were changed from fixed values to variables.

2. The land use areas were changed from fixed values to variables. These land use area values are used in model equations calculating runoff, evapotranspiration, sediment yield, sediment nutrient concentration and dissolved nutrient concentration.

3. The calculation of dissolved nutrient loads based on an adjusted nutrient concentration, as in the original model, was not used in hindcast load estimates. Instead a new livestock module for sheep and cattle was created that included slurry spreading calculations (Figure 4.2). The time series input to the livestock module included total and over-wintering livestock numbers. Livestock remaining on the land over winter are referred to as grazers. In the three study catchments, all sheep were assumed to over-winter in the field. Nutrient outputs per day for sheep and cattle were based on an output per head specified in S.I. 378 of 2006. Up until the late 1950s, cattle were fed exclusively on a grass diet. Nutrient outputs from cattle fed on grass have been reported to be c. 70% of those from cattle fed with artificial concentrates (Cerosaletti et al. 2004; Maguire et al. 2007). Cattle were assumed to have been fed on a traditional grass-based diet until 1965, with a subsequent increase in nutrient output as the use of concentrated feeds became more widespread. The nutrient output per head was therefore varied for cattle, from values based on traditional feeding to values specified in S.I. 378 of 2006 from 1965 to 1990. The number of grazing livestock was multiplied by the nutrient output per head to give a potential livestock load. A portion of this load was lost during grazing in surface runoff based on the loss rates for cattle and sheep assumed for export coefficient calculations (Johnes 1996; Jones & Heathwaite 1997).

All nutrients from over-wintering cattle were added to a slurry load that accumulated over the winter housing period. The dates for the start and end of the winter housing period were set in the module using a lookup table. The slurry spreading season was based on the dates specified in S.I. 378 of 2006; on wet days, losses from slurry were related to any slurry spread in the previous days. A loss rate was applied to the slurry load based on available literature (Stevens et al. 1997; Withers et al. 2001; Hyde and

Carton 2005; Vadas et al. 2007). Losses were also proportional to runoff on that day. The loss rate on dry days was set to zero. Both daily slurry and livestock loads were apportioned into particulate and dissolved forms based on published values (Stevens et al. 1997; Withers et al. 2001).

GWLF calibration and validation

The GWLF hydrology model was calibrated and validated for all subcatchments using observed flow data, prior to running hindcast and future scenarios. The Nash-Sutcliffe coefficient of model efficiency, NS (Nash and Sutcliffe 1970), was used to measure model performance. Ideally, model performance is characterised by a NS value close to one (Schneiderman et al. 2002).

$$\mathrm{NS} = 1 - \frac{\sum (\text{measured - modelled})^2}{\sum (\text{measured – mean modelled})^2}$$

Daily discharge data were available for the three inflows to Leane for 1960 to present from OPW gauging sites. The daily stream flow data from 1996 to 2000 were used to calibrate the hydrology model, while those from 2001 to 2004 were used for model validation (see Appendix 4.2 for parameter values). Values of NS for daily and monthly stream flow indicated a good model fit for catchment hydrology for all three subcatchments (Figure 4.3 and Table 4.2). Water quality data, available from locations on the three main inflows to Leane, have been collected by autosamplers, set to take six samples in each 48 hour period that are then pooled, since 1999. These samples are analysed for TP and NO_3-N+NO_2-N. Weekly/bi-weekly data are available for the same locations for suspended solids and PO_4-P and NH_4-N. The monitoring data from 2000 to 2004 were used for model calibration and validation. Estimates of sediment yield and sediment P concentration were optimised as described in Schneiderman et al. (2002). NS values for monthly TP loads for the calibration period (2002 to 2004) and the validation period (1999-2001) for the Flesk subcatchment were 0.84 and 0.79, respectively. The equivalent values for the Deenagh subcatchment were 0.70 and 0.65, while those for the Upper subcatchment were 0.65 and 0.68.

Water level data have been collected for the two main inflows to Feeagh, the Glenamong and Black, by the MI from 2002 to present. Rating curves for these sites were completed by MI staff during the project. The daily stream flow data from 2004 to 2006 were used to calibrate the hydrology model for the small Glenamong subcatchment, while the data from 2002 to 2004 were used for model validation. Values for NS for daily stream flow indicated a good model fit for catchment hydrology, with values of 0.77 and 0.82 for the calibration and validation periods, respectively (Figure 4.3 and Table 4.2). However, the best fit was obtained using data from a set of rain-gauges situated in the subcatchment. The fit with data from the meteorological station at Newport was much lower for the Glenamong (0.42), due in particular to periods of localised precipitation that were not captured by the Newport station (Appendix 4.3). Optimisation for the larger Black subcatchment produced similar values of NS with both the Newport data and catchment rain-gauge data. However, a high level of uncertainty is attached to all modelling carried out for this subcatchment owing to problems with the rating curve and, therefore, for the loading estimates produced for Feeagh in this project (Appendix 4.3). As available data on nutrient inputs to Feeagh were sparse, TP and TN were measured on the two main inflows between June 2007 and June 2009 on a weekly basis. The area of eroded peat due to over-grazing in the catchment in 1995 was estimated in accordance with Weir (1996), and was included in the CORINE land cover category sparsely vegetated in model simulations. The model performance was calibrated using the 2007 to 2009 data. The NS values for the Black and Glenamong were lower than for the other subcatchments (Table 4.2). This, however, related to the impact of several high measured loading values in the relatively short calibration dataset. The NS statistics for the ten month period prior to one of these events for the Black, for example, was 0.60, while that in a seven month period prior to an event in the Glenamong was 0.52.

High DOC concentrations have implications for both water treatment and for the ecology of surface waters (Jennings et al. 2009a). DOC must be removed from drinking water because of health concerns related to the formation of trihalomethanes (THMs), carcinogenic compounds that are produced when water with a high DOC concentration is disinfected using chlorine (WHO 2005). The release of DOC from peat soils in GWLF is modelled as a two stage process: peat decomposition produces DOC compounds that are then washed out of the soil column (Naden et al. 2009). The rate of peat decomposition is assumed to be a function of soil moisture and temperature. An in situ instrument, measuring chromophoric dissolved organic matter (CDOM) fluorescence (a proxy for DOC) in stream water was installed on the Glenamong River in 2003. The availability of these high frequency data facilitated optimisation and validation of the DOC module of GWLF for this site. The NS value for measured and modelled DOC concentration was 0.49, which is similar to that quoted for other models of DOC concentration (Taugbøl et al. 1994; Futter et al. 2007).

Daily stream flow was successfully calibrated and validated for the Mask subcatchments using measured flow data obtained from the OPW and EPA and from BUFFER (Donohue pers. comm). Values of NS ranged from 0.69 to 0.83 (Figure 4.3 and Table 4.2). Sediment yield, sediment, TP, TN, dissolved P and dissolved N loads were also successfully validated using data from 2001 to 2003 from BUFFER. Modelled TP data compared well with measured data, with values for NS ranging from 0.61 for the Owenbrin subcatchment to 0.81 for the Robe subcatchment.

Historical changes in nutrient loading to lakes are driven by changes in nutrient sources. Cumulative deviations plots (Buishand 1982) were used to identify any significant change points in the reconstructed TP loads. Identified change points were assessed in relation to changes in P sources. In this test, the cumulative deviations from the overall mean are calculated and are rescaled using the overall standard deviation. Change points in a plot of these values are indicated by an alteration in direction. The statistical significance of the change point with the maximum cumulative score can be assessed as a Q value, as defined by Buishand (1982). As the test assumes normal distribution and independence, all data sets were first checked for normality and serial correlation using, respectively, the Ryan-Joiner and Durbin Watson tests in MINITAB 13.1.

4.2.2 DYRESM

DYRESM description

Periods of warm, calm weather result in thermal stratification in lakes, while increases in wind speed and, at times, heavy precipitation can result in entrainment of hypolimnetic waters or complete mixing of the lake water column (Imberger & Patterson 1989; Wetzel 2001). In Ireland ice-cover is rare and most lakes are either monomictic, in that they experience one period of mixing and one of stratification in an annual cycle, or polymictic, with several shorter periods of stratification and mixing during summer months. The intensity of stratification, the length of the stratified period and the mixing depth all have implications for phytoplankton productivity and seasonal succession (Wetzel 2001). In general, for example, diatoms are abundant in spring before or in the early stages of stratification, and in autumn when stratification breaks down. Cyanobacterial blooms are in contrast associated with warmer, calmer weather conditions and more intense thermal stratification in the lake (Jöhnk et al. 2007; Wilhelm & Adrian 2008).

Because of the importance of stratification for phytoplankton production, simulation of the physical structure of a lake is essential if in-lake biological responses are to be modelled. DYRESM is a one-dimensional hydrodynamics model for predicting the vertical distribution of temperature, salinity and density in lakes. DYRESM can be coupled to an ecological model, which includes process descriptions of primary production, secondary production, nutrient cycling and oxygen dynamics, therefore providing a means of predicting seasonal and interannual variation in lakes and reservoirs, as well as investigating the sensitivity to long-term changes in environmental factors or catchment properties (Imerito 2007). The model and software are currently available at no charge from the Centre for Water Research (CWR), University of Western Australia (Imberger & Patterson 1981).

A graphical user interface (GUI), Modeller, is also available from CWR to facilitate model application and interpretation of results. The model can be run at daily or subdaily time-steps. Model input data requirements are, however, more extensive than for GWLF and include daily solar radiation, cloud cover, wind speed, vapour pressure, air temperature, and precipitation. Data are also required on lake bathymetry, inflow volume and inflow water temperature. DYRESM model outputs include water temperature and density. The results can be interpolated to provide a high resolution two-dimensional output of the modelled water temperature at the deepest point in a lake over time. Model inputs and outputs and measured data from the site can also be graphed within the Modeller GUI. The model relies on parameterisations derived from detailed process studies (both from the field and in the laboratory) and is unique in that reliable predictions are obtained without calibration (Imerito 2007).

DYRESM application

As the meteorological data requirements are much greater for DYRESM than for the catchment loading model, GWLF, the physical model could only be run for shorter time periods. However, for all three lakes, these periods coincided with the time since the onset of significant catchment pressures, as identified in the catchment modelling simulations and from palaeolimnological data. Available driving data for Leane included precipitation, air temperature and sunshine hours from the meteorological station at Muckross, and solar radiation/sun hours, cloud cover, relative humidity and wind speed from Valentia from 1941 to present. Data from the stations at Newport and Belmullet were used in model simulations at Feeagh, and from Claremorris and Belmullet/Blacksod for Mask, and were available from 1957 and 1905, respectively. Relative humidity values were converted to vapour pressure (Imerito 2007). Where solar radiation data were not available, sunshine hours were converted to solar radiation using a version of the Angstrom equation, with empirical constants defined for Ireland (McEntee 1980). A range of meteorological parameters, including solar radiation and wind speed data, were also available for some periods from a high frequency monitoring buoy that operated on Leane between 1996 and 2003. Similar data were available from a buoy that has been in operation on Feeagh by the MI from 1996 to present. A comparison of wind speed data from these buoys with wind data from the stations at Valentia and Belmullet showed that both data sets had similar values at low speeds. At higher wind speed, however, values measured at the two coastal stations tended to be greater than those measured on Leane and Feeagh.

Wind speed data from the meteorological station were corrected based on the regression relationship between meteorological station and buoy data. A similar correction, based on output from the lake monitoring buoys, was made to solar radiation data. Where measurements of stream flow were not available, simulated stream flow data were generated using the hydrology subroutine of the GWLF model (Schneiderman et al. 2002). A five day average air temperature was used as a surrogate for stream water temperature (Imerito 2007). Data for surface water temperature (SWT) (0.5m) and deep water temperature (DWT) (40m or 50m) were output from model simulations, and compared: the difference between SWT and DWT for the same site at the same time was taken as a proxy for the degree of stratification. Both SWT and DWT datasets were assessed for long-term trends.

The NAO is a north-south oscillation in barometric pressure in the North Atlantic that is most pronounced from December to February (Hurrell 1995). NAO is expressed as an index based on the pressure difference at locations representative of the strength of the Azores high and of the Icelandic low atmospheric pressure cells. Highly positive index values are associated with an increase in the occurrence of westerly winds and increased wind speeds, temperatures and rainfall in northern Europe. The influence of the NAO is generally greatest in western Europe, bordering the Atlantic Ocean (Blenckner et al. 2007). In common with lakes across Europe, temperatures in Leane and Feeagh have been shown to be strongly correlated with the NAO (Jennings et al. 2000; Blenckner et al. 2007). The correlation with the NAO was also assessed for each month, once the SWT and DWT data and the NAO had been detrended to remove any long-term trend (Blenckner et al. 2007). All data sets were also assessed for normality and serial correlation prior to analysis, as described in section 4.4.1.

DYRESM validation

DYRESM is based on a description of internal physical processes in a body of water and does not therefore have constant values that are calibrated. DYRESM was validated for Leane using weekly/fortnightly surface temperature data from 1976 to 2005 (Figure 4.4 a) and high resolution data (averaged to daily) from a thermistor chain (May to October 1997) (Figure 4.5 a and b). A good fit, with a NS of 0.96, between modelled and measured long-term surface water data was clear (Figure 4.4 a). The simulations for Feeagh were validated using a long-term record (1974 to 1990), measured at a site situated close to the lake outflow using a Negretti chart recorder (Figure 4.4 b) and data from the buoy thermistor chain (Figure 4.5 c and d). The fit between measured and modelled data was again good, with a NS value of 0.98. No long-term temperature records existed for Mask prior to commencement of ILLUMINATE. A thermistor chain was installed as part of the current project, with loggers (ONSET TidbiT) placed at 15 depths between the surface and 50 m, and providing data from March 2007 to the end of the project. Hindcast lake surface temperature data were successfully validated using two years of daily measured temperature from March 2007 to March 2009, and, with a NS of 0.98, compared well with measured values.

4.2.3 CAEDYM

CAEDYM description

CAEDYM is a process-based model of the major processes influencing lake water quality (Hipsey et al. 2006). The model was developed by CWR and the software is also available free of charge from the CWR, University of Western Australia (Imberger & Patterson 1981). CAEDYM simulates the C, N, P, and Si cycles along with inorganic suspended solids, phytoplankton, and optional biotic compartments (e.g. bacteria, fish and zooplankton). The model can be dynamically coupled to hydrodynamic drivers, including DYRESM, and can be run in a nutrients-phytoplankton-zooplankton (N-P-Z) configuration. CAEDYM can also simulate a range of other in-lake processes, however. Seven phytoplankton groups can be simulated, including freshwater diatoms, cyanobacteria, chlorophytes, cryptophytes and dinoflagellates. The model operates on any subdaily time step, but is generally run at the same time interval as the hydrodynamic model. Additional model data requirements include time series data on inflow concentrations for nutrients and a range of other parameters (Hipsey et al. 2006). Compulsory state variables include dissolved and particulate labile nutrient concentrations for C, N and P, together with dissolved oxygen concentrations and, if diatoms are simulated, Si. The model produces simulations of the selected parameters for each time-step for a profile at the deepest point of the lake.

CAEDYM validation

The principal aim of the CAEDYM simulations was to explore and demonstrate the potential of a dynamic model of in-lake biological responses as a tool in lake management. The model was used to simulate past in-lake responses of the main phytoplankton groups to changes in meteorological drivers and nutrient loading described earlier, and to explore future impacts due to projected changes in climate and catchment management. CAEDYM (V4.0.0-b2) was run in N-P-Z configuration on a daily time step. Where inflow nutrient data were not available, data based on the output from GWLF was used for suspended solids and dissolved and particulate nutrient concentrations. Particulate organic C concentrations were estimated based on simulated levels of suspended solids using GWLF and the record of historic organic matter loading provided by the sediment core data.

Validation data for Leane included chlorophyll-a data from 1976 to present. Data on the phytoplankton species composition in Leane were available for 1996 (Irvine et al.

2001) and from April 1999 to December 2000 (Twomey et al. 2001). Additional species counts were carried out as part of ILLUMINATE (Chapter 2). Validation data for Mask included fortnightly to monthly chlorophyll-a data from 2001 to 2003 (Donohue pers. comm), and 1996 to 2003 (Gallagher pers. comm). Unpublished monthly data on phytoplankton species composition in Mask were available for 1975, 1984 and 1986 from the CFB (Trevor Champ pers. comm). Owing to problems encountered in finalising the rating curve for the Black River and the uncertainty in simulated flow and nutrient loads for that site, CAEDYM simulations were not carried out for Feeagh.

Leane

Data from 1999 and 2000 were used to validate the seasonal succession of the five phytoplankton groups in Leane. Although some studies simulate only the most dominant phytoplankton groups (e.g. Schladow & Hamilton 1997; Trolle et al. 2008), all five groups were included in the Leane simulations, as they had been noted in all years for which species composition data were available. The optimum temperature for the phytoplankton groups was set at the 90th percentile of temperature for the time of peak growth, to reflect the fact that phytoplankton communities show site-specific temperature acclimation (Staehr & Sand-Jensen 2005). Phytoplankton parameters, with the exception of maximum growth rates, were optimised using a stepwise manual adjustment based on the 1999/2000 data (Schladow & Hamilton 1997; Trolle et al. 2008). Maximum growth rates were then optimised in a similar stepwise manner based on the historical chlorophyll-a data from 1972 to 2005. The optimised model was run from 1941 to 2005.

As the seasonal pattern for phytoplankton groups, in particular for chlorophytes, could not be replicated without allowing for the effects of grazing, two generic zooplankton groups (cladocerans and copepods) were included in Leane simulations. Twomey et al. (2001) reported spring and autumn peaks in cladocerans (mainly *Daphnia* spp.), which suggested they were grazing mainly on diatoms. Copepod numbers rose from spring to August 1999, and fell during winter and rose again in late March 2000. These two groups, cladocerans and copepods, were included in CAEDYM simulations for Leane. The main grazing preference for cladocerans was set for diatoms, while copepods were set to graze on several groups and on labile particulate C. The parameter set used for these groups in simulations for Lake Ravn, Denmark (Trolle et al. 2008), was applied with the exception of optimum temperature (22 ^{o}C) and grazing rates.

The observed seasonal succession of phytoplankton in an open lake site in Leane in 1999 and 2000 was similar in both years (Twomey et al. 2001). Diatoms were abundant in the spring, with a second peak occurring in the autumn (Figure 4.6). The most important diatom taxon, in terms of biomass, was *Aulacoseira* sp. Various cyanobacteria dominated the phytoplankton in late summer and autumn: *Anabaena flos-aquae* was the most important contributor in 1999 and in the following year was numerically co-dominant along with *Aphanizomenon flos-aqua* and *Oscillatoria aghardii*. Chloropytes, cryptophytes and dinoflagettates contributed to a lesser extent to total biovolume. A similar seasonal succession was noted in the 1996 survey (Irvine et al. 2001) and in the 2007 data collected in the present study, although the cyanobacterial peak in August was lower in 2007 than 1999/2000. In general, the optimised species composition was similar to that observed in the 1999/2000 study, with diatoms the most abundant taxonomic group in the spring and autumn and cyanobacteria in July and August (Figure 4.6). As with monitoring data, chlorophytes, cryptophytes and dinoflagellates were less abundant than diatoms and cyanobacteria likewise during the annual cycle. However, an observed seasonal optimum in cryptophytes in May 1999 was not replicated in the modelled data.

The nutrient loading data used in the CAEDYM validation for Leane included both the load from the catchment and an estimated daily load from the STP at Killarney. The seasonal and long-term patterns in dissolved P in the lake were largely replicated, with a distinct seasonal draw-down of P during summer months (Figure 4.7 a). The long-term trend in measured chlorophyll-a was also largely replicated by the model, with peaks in concentration in the late 1970s and the early 1980s (Figure 4.7 b). However, a large algal bloom in 1997, when hypertrophic conditions were recorded in the lake, was not replicated. This event could have been driven by incidental losses of P, for example from slurry spreading, which the model could not simulate.

Mask

The observed chlorophyll-a concentration in Mask, as indicated by unpublished historical monitoring data, was variable and displayed an unusual annual pattern, with two peaks over the year, the highest in summer (up to c. 12 μg l^{-1}) and a smaller one in winter (up to c. 7 μg l^{-1}). This pattern was evident in both CFB and BUFFER monitoring datasets for Mask. The observed seasonal trend for phytoplankton community composition in Mask was also unusual. Diatoms were abundant for most of the year (40 % to 100 % of total phytoplankton). Two peaks were apparent, however, the highest in spring and a smaller peak in autumn. Chlorophytes were the next most abundant group and peaked in late summer, after the diatom peak, and again in late autumn, before a second diatom peak. Cyanobacteria numbers were low for most of the year, but displayed a distinctive peak in late autumn, characterised by abundant *Oscillatoria agardii*. Hindcast phytoplankton community composition data (Figure 4.8) were validated with data from the CFB for 1983, 1984 and 1986 (Trevor Champ pers.comm). The hindcast data compared best with measured data for the months March to September. Hindcast data for the winter months (November to February), however, did not replicate measured phytoplankton composition well. Hindcast in-lake TP concentrations (Figure 4.9 a) also compared well with measured values, while total chlorophyll-a values were close to measured data from late spring to early autumn (March to September) (Figure 4.9 b). The model did not replicate the winter chlorophyll-a peak evident in the monitoring data.

4.3 Hindcast modelling

4.3.1 Hindcast modelling of catchment export

Trends in simulated nutrient export

The combined hindcast TP loading from the three Leane subcatchments ranged from 15 to 20 tonne TP $year^{-1}$ in the 1940s to 25 to 33 tonne TP $year^{-1}$ in recent years. The load was dominated by export from the Flesk for both total and dissolved forms (Figure 4.10 a and b; Appendix 4.4). The modelled TP loads from the Flesk ranged from c. 11 tonne TP $year^{-1}$ in the 1940s to over 20 tonne $year^{-1}$ in the more recent past (Figure 4.10 a), while dissolved P loads ranged from 4.5 tonne $year^{-1}$ to over 7 tonne $year^{-1}$ over the same period. TN loads followed similar trends to P and were again dominated by export from the Flesk, although an order of magnitude higher (Figure 4.10 c and d). Modelled TN loads from the Flesk rose from c. 280 tonne to c. 400 tonne TN $year^{-1}$ over the period of the simulations. Modelled nutrient loads from the other two main subcatchments, Upper and the Deenagh, were similar to each other in magnitude despite their three-fold difference in area. This was due, in part, to the higher human and livestock populations in the Deenagh when compared with the Upper subcatchment (Chapter 2). The simulated sediment loading (Figure 4.10 e) reflected differences in erosion rates for the three subcatchments: the low-lying Deenagh, dominated by pasture, had consistently low loads, while loading was highest for the Flesk with its extensive upland peaty areas and coniferous forestry, both of which had higher estimated erosion rates in the model. The changes in Si loads reflected variability in discharge rates and included higher values in the period from 1970 to 2005, during which precipitation increased (Figure 4.10 f).

Hindcast nutrient loads from the two Feeagh subcatchments (Black and Glenamong) were relatively stable until the 1960s, after which they increased (Figure 4.11 a to d). The TP load from the larger Black subcatchment in the first ten years of the simulations (1900 to 1910) was c. 0.3 tonne TP year^{-1}, and increased by >50% to 0.48 tonne TP year^{-1} in the 1995 to 2004 period (Figure 4.11 a). Simulated TP loads from the smaller Glenamong subcatchment rose from c. 0.15 tonne TP year^{-1} to 0.23 tonne TP year^{-1}, a 78% increase. The TN load for the Black increased from c. 41 to 53 tonne year^{-1} over the same period. The increase over time in both TP and TN was due in part to an increase in flow rates, resulting in a concurrent increase in sediment yield (Figure 4.11 e). However, sediment yield also increased during the later years of the model simulations, owing to changes in land use, in particular increases in the extents of afforested and eroded peat. This was also reflected in a change over time in the contribution of dissolved P to the TP load from c. 70% in the early 1900s to c. 55% in more recent decades. DOC concentration, which is dependent in the model on soil temperature, soil moisture levels and flow rates, showed no overall trend over time, with relatively little variability (values between 6 and 10 mg DOC l^{-1}) occurring over the period of the simulation (Figure 4.11 f).

Hindcast annual TP loads to Mask were relatively low and stable from 1900 to 1972, with an average load of 35 tonne TP year^{-1} (Figure 4.12 a). From the early 1970s, catchment TP loading increased sharply, with the annual TP load increasing to c. 74 tonne year^{-1} in the period 1972 to 2006, peaking at c. 113 tonne year^{-1} in 1999. This change in TP load mainly reflected changes in livestock numbers in the catchment, and to some extent human population over the same period. Between 1900 and 1950, the majority of the TP load to Mask came from the Robe subcatchment (c. 41 % of the total TP load). Approximately 35 % of the TP load was accounted for by the western subcatchments combined (total area 151 km^2), and c. 24 % by the Carra subcatchment. Between 1951 and 2006, however, a higher portion of the TP loading was sourced from the western subcatchments (c. 45 %), while the contribution from the Robe subcatchment in the east dropped to c. 27 %. The remaining contribution, from the Carra subcatchment, was relatively unchanged at c. 25 %. Hindcast catchment dissolved P loading followed a similar trend to that of TP loading (Figure 4.12 b).

Hindcast annual catchment TN loadings to Mask (Figure 4.12 c) did not show as much variability over time as TP loadings. Average annual TN loads were relatively stable between 1900 and 1940. From 1941, TN loads increased and became stable again until 1970, after which they increased slightly until the late 1990s. Average annual TN loads between 1900 and 1950 were c. 1367 tonne TN year^{-1}, compared with c. 1718 tonne TN year^{-1} between 1951 and 2006. The Robe and western subcatchments accounted for approximately equal amounts of the TN loading to Mask (c. 40% each) in the first half of the last century. However, in the latter half of the century the western subcatchments accounted for almost half of the TN load (c. 48 %), while the contribution from the Robe subcatchment fell to c. 30 %. Again hindcast annual dissolved N loads for Mask followed a similar trend to that of TN loads (Figure 4.12 d).

The modelled TP loads for all three catchments were statistically assessed for the presence of change points using the cumulative deviations test (Figure 4.13). A significant change point was identified in hindcast catchment TP loading at all sites (Figure 4.13). For Leane, a significant change point was indicated for 1973 ($Q = 2.6$; $p \leq 0.01$) (Figure 4.13 a), a date that roughly coincided with an increase in cattle numbers evident in the 1971 agricultural census (Figure 4.13 d). Also associated with 1973 was a change point in annual precipitation that led to an increase in loading from land use. For Feeagh, a change point was identified at c. 1960 ($Q = 3.7$; $p \leq 0.01$) (Figure 4.13 b), therefore shortly following the commencement of afforestation in the catchment, but just prior to an increase in sheep numbers that commenced in the 1970s and peaked in the 1990s. The change point in the simulated TP load from the Mask subcatchments was 1978 ($Q = 4.2$; $p \leq 0.01$) (Figure 4.13 c): here the factor responsible was increasing livestock numbers (Figure 4.14 f).

Modelled variations in TP load from the catchment and measured TP content of lake sediment were in close agreement for all three lakes (Figure 4.14: note that loads in this figure are expressed in kg TP km^{-2} to allow inter-site comparisons). The total TP loading to Leane in Figure 4.14 (a) is the sum of the modelled catchment load, using GWLF, and estimates for the load from the Killarney STP (Jennings et al. 2008). The long-term trend in the STP load reflected changes in the population of Killarney, tourist numbers, and sewage treatment methods (Jennings et al. 2008). Before 1971, untreated sewage was discharged directly into the lake. From 1977, sewage received secondary treatment, while P removal using ferric chloride was fully implemented in 1984/1985. STP inputs represented 68 % of a total TP load of 30 tonne TP year^{-1} in 1982, but decreased to under 2 tonne TP year^{-1} following implementation of P removal technologies. Modelled TP loading and measured sediment P are highly variable for the period of interest for Leane. However, variations in both comprised a period of increase from the 1940s to the 1980s, a subsequent decrease to the early 1990s and a further increase in the more recent past (Figure 4.14 a). While modelled loads to Feeagh were lower than those to Leane, as might be expected for a catchment with little intensive agriculture and low population, both modelled TP loads and sediment P accumulation indicated relatively stable conditions until the 1960s, with subsequent increases evident (Figure 4.14 b). The increase in the sediment P and in modelled TP loads for Mask was more recent, occurring over the last 30 years or so. Sediment P values for Mask followed a similar trend to hindcast annual TP loads for the period 1900 to 2006. However, increases in sediment P, though gradual, commenced earlier (late 1950s) than TP loading (mid 1970s) (Figure 4.14 c)..

4.3.2 Hindcast modelling of lake thermal structure

Trends in simulated lake water temperatures

Simulated daily water temperatures (SWT and DWT) were of similar magnitude during months in which the lakes were fully mixed (generally from late autumn to early summer) in both Leane and Feeagh, but differed in summer depending on the intensity of thermal stratification in that year (Figure 4.15 a and b). The difference between

SWT and DWT was, however, lower in Mask in the early part of the simulation period than for more recent years (Figure 4.15 c). The mean difference for the months of June, July and August in Mask for the 1950s and 1960s were, respectively, 1.4 ^{o}C and 1.3 ^{o}C, and 3.5 ^{o}C for the period 1990 to 2000, indicating a possible increase in the degree of stratification in Mask over time. The equivalent mean values for Leane were 5.4 ^{o}C, 5.6 ^{o}C and 5.7 ^{o}C, while those for Feeagh for the 1960s and the 1990s were, respectively, 4.4 ^{o}C and 5.2 ^{o}C. The results indicate that while Mask was only weakly stratified or unstratified for much of the period from 1950 to the mid 1960s, the lake was stratified for the period between the mid 1960s and the late 1970s and in the more recent past. Both periods of strengthened stratification at Mask are associated with higher solar radiation values.

Differences were also evident in the long-term trends in the simulated water temperatures for Leane and Feeagh when compared with Mask for the period 1960 to 2005 (Figure 4.16 a, b and c). A significant upward trend in mean annual SWT is evident in all three lakes. In Leane, an upward trend in SWT occurred during the spring and early summer periods but not in autumn/winter, with the exception of December; an upward trend in SWT was apparent in most months in Feeagh, with the exception of January, April and June. Moreover, no warming trend in simulated DWT in summer months was evident for Leane and Feeagh. The warming trend in summer was, however, stronger in the simulations for Mask than in the other two lakes, and was apparent in both SWT and DWT.

Simulated water temperature datasets were also assessed for relationships to the NAO. Significant positive relationships between the NAO and modelled SWT and DWT were found for all three lakes for the months of January, February and March (Figure 4.16 d, e and f), reflecting a link between the NAO and local variability in weather that has been identified in previous studies. The relationships were stronger and advanced farther into the year in DWT in the two more coastal sites, Leane and Feeagh, but not in SWT. This difference between simulated trends in SWT and DWT is believed to be due to a separation of the deeper hypolimnetic waters from the influence of changes in input variables during stratification.

4.3.3 Hindcast modelling of in-lake biological responses

Trends in biological responses

Leane

The hindcast CAEDYM runs for Leane for 1941 to 2005 showed increasing maximum chlorophyll-a levels from 1941 to the early 1970s, the period prior to available records (Figure 4.17 a; Appendix 4.5). For most of this period, the chlorophyll-a concentration was between 8 and 25 mg m^{-3}, and therefore more-or-less within the mesotrophic range. Cyanobacterial chlorophyll-a was the main contributor to the total maximum in-lake chlorophyll-a (Figure 4.17 a). As noted earlier, the model replicated the subsequent decreases after 1984 and the increase to the late 1990s, but not the hypertrophic conditions that were recorded in 1997 (KMM 2003). The overall increases from the 1940s reflected the trend in dissolved P and TP described in section 4.3.2 for hindcast GWLF loading. These data were used as input for the CAEDYM simulations. Zooplankton biomass (Figure 4.17 b) was a function of phytoplankton abundance and the assigned grazing preferences used in the simulations. Diatom abundances generally peaked in spring in the simulations and did not show the same long-term increase as total and cyanobacterial chlorophyll-a (Figure 4.17 d).

Mask

Hindcast annual maximum chlorophyll-a concentrations in Mask were relatively low and stable between 1905 and 1950. After 1950 concentrations were more variable, increasing by up to five times levels pre-1950 (Figure 4.18 a). Hindcast annual maximum chlorophyll-a peaked in 1968 (at 44 μg m^{-3}) before declining in the late 1990s. In the early 1900s, phytoplankton community composition was dominated, numerically, by chlorophytes, with very few diatoms and cyanobacteria. This community structure changed from the 1920s onwards, when diatoms became more abundant (Figure 4.18 b). From 1950, diatoms were the most common group (comprising 40% to 98% of total algae) in the phytoplankton community hindcast for Mask. Between 1950 and the late 1970s, chlorophytes were generally the second most common algal group, with cyanobacteria comprising a very small minority (less than 5% of total phytoplankton abundance) (Figure 4.18 c and d). The contribution to total chlorophyll-a from cyanobacteria increased in the early 1990s, with peaks in 1992, 1994 and 1995. However, both chlorophyte and cyanobacteria chlorophyll-a concentrations were relatively low from the late 1990s onwards (Figure 4.18 c and d).

4.4 Impacts of future climate and management change

Possible impacts of future climate change, and possible changes in population and management, on catchment loading and in-lake ecological responses were simulated for the three study lakes. These simulations comprised an assessment of the impacts of climate change on catchment loading for the Flesk (Leane), Black (Feeagh) and Robe (Mask) subcatchments for the period 2021-2060 using data provided by the C4I project based at Met Éireann. In addition, a more detailed study covering possible impacts from changes in land use and management, was carried out on loading from the Flesk subcatchment for the period 2071 to 2100 (Jennings et al. 2009b) and on the ecological responses in Leane. A set of GWLF simulations was also carried out for this time period on the impacts of changes in climate on DOC concentrations using data for the Glenamong subcatchment (Feeagh, Burrishoole catchment). These simulations for 2071 to 2100 used future climate data downscaled for the Leane and Burrishoole catchments during the EU-funded CLIME project. An assessment of future climate and salmon population management on salmon survival in the Burrishoole catchment was also undertaken, using a combination of an ecogenetic response model developed during the project and the lake physical model DYRESM, although the results of this assessment are not included here (but see McGinnity et al. 2009).

The impacts of projected changes in climate were assessed using data produced by global climate models (GCM). These models have high computational and technical requirements and are usually run in specialised centres. However, GCMs operate on a coarse spatial scale when compared with the scale of most environmental impact assessments (Räisänen et al. 2004; Samuelsson 2009). Output from GCMs can, however, be downscaled to a more relevant scale using, for example, a regional climate model (RCM). An additional consideration in modelling the impacts of climate change is uncertainty related to differences in model structure between different GCMs and uncertainty in future global population behaviour. The former uncertainty is addressed by using output from more than one GCM or GCM/RCM combination. The latter is incorporated into GCM simulations using a range of greenhouse gas emission concentrations based on scenarios of population behaviour (Table 4.3) (Nakicenovic et al. 2000).

In order to accommodate uncertainty, future climate data used in ILLUMINATE comprised a range of model combinations and greenhouse gas emission scenarios. The data from the CLIME project for the future period 2071 to 2100 were based on simulations from two RCMs, the Rossby Centre RCM (RCAO) and the Hadley Centre RCM (HadRM3p), which were run using boundary conditions based on either the HadAM3p GCM, from the Hadley Centre (UK), and ECHAM4/OPYC3 GCM, from the Max Planck Institute (Germany), for the A2 and B2 SRES emissions scenarios (tables 4.3 and 4.4). The use of two GCMs and two SRES scenarios gave two combinations for the period 2021 to 2060, while the combination of two GCMs, two RCMs and the two scenarios gave six future climate projections for the future period 2071 to 2100 (Table 4.4).

A weather generator developed by the Climate Research Unit (UK) (Kilsby et al. 2007) was also used in CLIME to downscale the GCM-RCM output for 2071-2100 to catchment level. One hundred 30-year simulations were carried out for a control period and for each future climate model-scenario combination for both a present and a projected future population and land use scenario.

An alternative method for assessing the effects of future climate, the Delta Change (DC) or Incremental Scenario approach (Hay et al. 2000; Andreasson et al. 2004), was used with the 2020 to 2060 data. In the DC approach, the observed weather is perturbed by the mean monthly change in temperature and precipitation between the control and the chosen future scenario. The temperature change is applied as an addition or subtraction, whereas the rainfall change is applied as a ratio. DC has the drawback that the same sequence of weather (i.e. pattern of wet and dry periods) occurs in both the control and the future climate. A resampling method was derived during CLIME in order to generate alternative weather sequences (Moore et al. 2008; Naden et al. 2009). This works on a monthly basis: a year is chosen at random to provide that month’s daily data. This may give some discontinuity between months but preserves the integrity of the weather within a month. For the present research, 100 alternative weather sequences were generated for each future climate scenario based on a 30 year time series of observed meteorological data for each site.

A set of catchment loading simulations was carried out for the period 2021 to 2060 (Table 4.5; Appendix 4.7). For all three study sites, both dissolved P and TP loading were projected to decrease for most months between February and July and increase in the January/February period. Although the overall pattern was similar in the three sites, with decreases in loading during summer and increases in some winter months, there were differences between the three sites in the autumn months. For the Flesk subcatchment (Leane), the increases in dissolved P loading in the model simulations are driven by changes in stream flow, while that in TP was also related to changes in sediment loading (Figure 4.19 a, b). Moreover, both dissolved and total loads increased for the months of August, September and October. The increase for October relative to the control period was 26 % for the A2 scenario and 29 % for the B1 scenario. In contrast to the Flesk, decreases in TP loading were projected for all months for the Black subcatchment (Feeagh) with the exception of October, when increases of 15% and 17% in loading were indicated for the A2 and B1 scenarios, respectively. The increases in dissolved P loads were 6% (A2) and 7% (B1). The Robe subcatchment (Mask) had increases in dissolved P for both climate scenarios in the autumn. These were highest for the A2 scenario: a 54% and 44% increase in loading in September and October, respectively.

GWLF was also used in a more extensive exploration of the potential impacts of climate change and possible changes in land use and population on nutrient export from the Flesk subcatchment (Jennings et al. 2009b). The projected future population for the catchment was estimated based on projections from the CSO (CSO 2005; 2008). These projections are available only until 2041. The population for 2071 was estimated based on a further 0.37 % growth per five-year period (CSO 2008). Tourist numbers were estimated on a pro-rata basis. In addition a scenario for a change in land use was formulated based on possible economic and policy influences. This scenario consisted of two changes: an increase in forestry and an increase in high productivity pasture. In 1996, the Irish government set an objective of increasing the forest cover from 8% to 17 % by 2030, with broad-leaved forest comprising at least 20% of this area (Department of Agriculture, Food & Forestry 1996). The strategic forestry plan for the south west of

Ireland includes establishment of half of the proposed forestry on land already owned by the industry and half from farm partnerships (Coillte 2006). The scenario assumed an increase in forestry of 3000 ha by 2070, with 50% of the increase on low productivity grassland (as mixed forest) and 50 % on unexploited bog. The second scenario assumed that a projected shift to arable land use in the eastern part of the country (Sweeney et al. 2003) would lead to further intensification in dairy and dry stock farming in the southwest. This was assumed to result in a 10 % increase in cattle numbers requiring the conversion of 1910 ha of low productivity pasture to high productivity pasture. In addition, a slurry management scenario was included: the optimum period for slurry spreading in Ireland is the period from spring to autumn, during the peak grass growing season (Hyde & Carton 2005). The model was run with the slurry season set from 16th January to 14th October, as described earlier. However, to explore the impact of changes in the extent of the spreading season, the model was also run with the open season set to 1st April to 30th September.

All future climate model-scenario combinations showed an increase in projected annual air temperature in the catchment for the period 2071 to 2100. This increase was greater for each A2 emissions scenario than for its respective B2 equivalent, reflecting the higher CO_2 emissions associated with the A2 storyline. The annual increases for the overall A2 and B2 scenarios were 2.9 ^{o}C and 2.3 ^{o}C, respectively. The increase was higher in summer and autumn than in winter for both emission scenarios (Figure 4.20 a and b). Overall the A2 scenario showed a small decrease in annual precipitation of -26 mm year^{-1}, while the B2 scenario resulted in a slight increase of +69 mm year^{-1}. There was, however, a similar change in the seasonal pattern of precipitation for both emission scenarios, with increases in precipitation between October and March and drier weather from late spring to autumn (Figure 4.20 c and d). The greatest predicted increases were for the month of January: these were 2.0 mm day^{-1} (20%) and 2.4 mm day^{-1} (24%) for the A2 and B2 scenarios, respectively. The decrease in rainfall between June and September was greater for the A2 scenario than the B2 scenario. The decrease in precipitation for the month of August for the A2 scenario was -2.2 mm day^{-1} (-22%), while that for the B2 scenario for August was -1.8 mm day^{-1} (-19%).

The increase in temperature resulted in higher rates of actual evapotranspiration (AET) in all months between October and May (Figure 4.20 e and f). However, AET decreased between July and September owing to a combination of lower rainfall and higher rates of potential evapotranspiration, leading to decreases in soil moisture levels. This seasonal pattern was similar for both the A2 and B2 scenarios, but the decrease in rates was greater for A2. The net effect of the changes in precipitation and AET on annual stream flow was a significant positive change for both scenarios. The overall changes in stream flow reflected the seasonal pattern in precipitation (Figure 4.20 g and h): higher discharge rates were indicated for the months between October and April, with more pronounced increases for the B2 scenario in the early months of the year. Streamflow was lower between April and September for both scenarios, remaining below the control level for the months of October and November, despite increases in precipitation, until the soil moisture store in the model replenished after the summer drought.

The changes in the annual dissolved P load based on future climate alone were in general agreement with those for stream flow. The overall change for the B2 scenario was an increase of 1.5 kg dissolved P km^{-2} year^{-1}, representing a 9% increase from the control period, while there was no significant change for the combined A2 scenario. The inclusion of scenarios for future land use and population change in the model simulations resulted in further increases in the annual dissolved P load for both scenarios (Figure 4.21 a; Table 4.6; Appendix 4.8). The increase for the combined A2 scenario was 3.3 kg dissolved P km^{-2} year^{-1}, representing a 20% increase from the control period, while the increase for the B2 scenario was 5.3 kg dissolved P km^{-2} year^{-1}, an increase of 31%. In both cases, 1.1 kg P km^{-2} year^{-1} (equivalent to 7% of the control load) was attributable to the projected increase in the septic tank population. The remaining increase was due to the reassignment of land to uses with higher dissolved P concentrations (e.g. high productivity pasture), combined with an increased potential for export owing to higher levels of precipitation. P loads were lower between June and October based on climate change alone. In particular, both scenarios indicated potential decreases in dissolved P export in the June to September period, the time of peak algal growth in Leane, together with increases in the early part of the year, particularly for the B2 scenario.

The addition of land use and population changes to the simulations led to increases in the dissolved P load in all months relative to the climate change only simulations.

However, loads in August and September were still lower than the control period. The simulations with future land use and population estimates, but with an adjustment of the open slurry spreading period from the period stipulated in national regulations to 1st April to 30th September, indicated substantial decreases in dissolved P loads for the early months of the year, highlighting the contribution of this source to the overall dissolved P load (Figure 4.21 c and d). Decreases in annual load relative to the original control value were -3.0 and -2.0 kg dissolved P km^{-2} year^{-1} for the A2 and B2 scenarios, respectively: decreases relative to the climate simulations with the January to October spreading season were -6.3 dissolved P km^{-2} year^{-1} (A2) and -7.3 kg dissolved P km^{-2} year^{-1} (B2). Slurry spreading contributed 5.1 kg to the simulated control dissolved P load of 16.1 kg km^{-2} year^{-1}.

In contrast to dissolved P, all model combinations resulted in increases in projected annual TP load. The median value increased from 49.3 kg TP km^{-2} year^{-1} for the control period to 53.8 and 58.3 kg TP km^{-2} year^{-1} for the combined A2 and combined B2 scenarios, respectively. Adjustments for future land use and population led to additional increases of 4.6 and 4.9 kg TP km^{-2} year^{-1}. The seasonal results for the set of simulations based on climate change reflected changes in stream flow, showing increases in TP loads in the winter and early summer and decreases between June and November. The addition of potential land use changes to the simulations resulted in increases in TP loads in all months, but with the same overall seasonal pattern of increased loads in the winter and spring and decreases in the spring and early autumn (Figure 4.21 e and f; Table 4.6). The open slurry spreading period in these simulations was that stipulated in national regulations for County Kerry. Of the increase in the annual TP load for the combined A2 scenario (9.1 kg TP km^{-2} year^{-1}), 12% was attributable to the increase in the septic tank population, 49% was due to changes in climate alone, while 39% was due to potential land use change (Figure 4.22). The change in the septic tank population represented 8% of the 13.9 kg TP km^{-2} year^{-1} increase for the combined B2 scenario; 65% was attributed to climate change and 27% to the impact of potential land use change.

The ecological response model DYRESM-CAEDYM was run for the control and future (2071 to 2100) periods for the A2 and B2 scenarios to assess the impact of the projected changes in climate and catchment nutrient loading on ecological responses in Leane.

The model was run using: 1) nutrient concentration based on the impact of changes in climate alone (that is, population and land use were set at current values); and 2) nutrient concentrations based on climate change combined with the population and land use change scenarios described earlier. In addition to changes in air temperature and precipitation, data on projected changes in radiation and wind speed were required for these simulations (Figure 4.23). These data were also available from the weather generator output. Little change in projected global radiation or wind speed was evident for the B2 scenario, with the exception of a marginal increase in wind speed in January and February of 11% and 8%, respectively. There was, however, a decrease of 12% in mean wind speed in summer months for the A2 scenario, together with an increase of c. 4% in mean global radiation for months between January and August. Nutrient loads were calculated for the entire Leane (Figure 4.24) catchment to provide input for the ecological response model. For these calculations, the nutrient load from the STP for Killarney was kept at levels similar to those in the more recent past (i.e.1 tonne TP year^{-1}).

While the seasonal pattern in SWT was similar for the control period and for the simulations for the A2 and B2 scenarios, an increase in monthly mean SWT was simulated for Leane in all months of the year (Figure 4.25 a and b). Maximum increases occurred in June for both scenarios and were 3.0 ^{o}C and 2.3 ^{o}C for the A2 and B2 scenarios, respectively. The months with the lowest increases (1.7 ^{o}C in both cases) were December for the A2 scenario and January for the B2 scenario. Dissolved P in the in-lake model simulations represents the net availability as a function of dissolved P inflow, dissolved P produced through sediment release of mineralised particulate organic labile P and uptake by phytoplankton. In all simulations, the concentration of dissolved P had a seasonal pattern, with highest concentrations in the winter and spring and lowest values in the summer (Figure 4.25 c and d), reflecting the seasonal pattern in simulated loading to Leane, which was highest in the autumn and winter months, and possibly also algal uptake. Dissolved P concentrations were, however, higher for both future climate scenarios than for the control: mean concentration for January to March was 10 μg l^{-1} for the A2 scenario and 11 μg l^{-1} for the B2 scenario, but was 8 μg l^{-1} for the control, again reflecting differences in P loading. The minimum mean monthly dissolved P concentration occurred in the August/September period in all three sets of simulations. The relative decrease from high spring values to the minimum was, however, greater for the A2 than for the B2 scenario.

Differences in dissolved P concentrations between the control and future simulations probably reflect differing uptake by phytoplankton groups. There was little difference in simulated phytoplankton biomass, as measured by mean monthly chlorophyll-a, between the control and 2071-2100 periods (Figure 4.25 e and f). Maximum mean monthly chlorophyll-a concentrations for the control and the A2 and B2 scenarios were, respectively, 8.2 mg m^{-3}, 9.4 mg $m^{-3}$and 9.0 mg m^{-3} (Figure 4.25 g and h). Cyanobacterial chlorophyll-a made the largest contribution to this summer maximum in all cases, while a smaller peak in spring was due to diatom chlorophyll-a. However, there was a shift in the peak mean chlorophyll-a from July to June for the A2 scenario, together with a longer period (June to September) with high mean values. More importantly, there was an increase in median maximum chlorophyll-a concentration for both scenarios, from below 20 mg m^{-3} in the control simulations to c. 25 mg m^{-3} for the A2 and 24 mg m^{-3} for the B2 scenarios.

A set of simulations was also undertaken with nutrient concentrations based on both future climate data (B2) and the future scenarios for land use and population change described earlier. These simulations showed an increase in surface water dissolved P concentrations that were 5-6 μg l^{-1} higher than the control (Figure 4.26 a and b). While the maximum value for mean chlorophyll-a was similar for both sets of simulations, values in the early summer and the overall variability were higher (Figure 4.26 c and d). Maximum chlorophyll-a was higher, but there was no seasonal shift in occurrence (Figure 4.26 e and f). Given these results, and the similarity in dissolved P concentrations for the A2 and B2 scenarios with the original land use and population levels, the shift in chlorophyll-a peaks from July to June described earlier for the A2 simulations was probably not due to increased availability of dissolved P. There was, however, an earlier onset of stratification for the A2 scenario, owing to a combination of higher temperatures, higher solar radiation and lower summer wind speed. For example, stratification commenced 12 days earlier for the A2 simulations based on the ECHAM4 GCM than for the equivalent B2 simulations (Figure 4.27). In addition, the earlier and more prolonged period of phytoplankton growth was probably a response to higher temperatures in the early summer in the A2 simulations.

In contrast, the increase in maximum chlorophyll-a in both simulations was probably caused by an increase in the availability of dissolved P.

The change in climate projected for the Feeagh (Burrishoole) catchment showed a similar pattern to that for Leane, with an increase in temperature of between 1.5 ^{o}C and 4 ^{o}C and a shift towards wetter winters and drier summers (Figure 4.28 a to d; Appendix 4.8). These changes resulted in increases in summer soil moisture deficits in model runs, which extended well into the autumn. The increases in temperature and soil moisture deficits contributed to projected increases in DOC concentration for both emission scenarios (Figure 4.28 e and f). This effect was more pronounced for the simulations based on the A2 scenario than for the B2 scenario. Annual mean DOC concentrations in the Glenamong were projected to increase from a median value of 8.7 mg l^{-1} (25 and 75 percentiles: 7.7 mg l^{-1} and 9.8 mg l^{-1}) to 10.5 mg l^{-1} (25 and 75 percentiles: 7.8 mg l^{-1} and 12.5 mg l^{-1}) for the B2 scenario and 11.2 mg l^{-1} (25 and 75 percentiles: 8.6 mg l^{-1} to 14.3 mg l^{-1}) for the A2 scenario. For both emissions scenarios, the increase was lowest in the spring and most pronounced in the autumn and early winter (Figure 4.28 e and f).

Table 4.1 Time periods for which the models were run for Leane, Feeagh and Mask Shading indicates that models were run for that period (note: these periods were dictated by the availability of model driving data).

Model	**Lake**	**1900**	**1910**	**1920**	**1930**	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**2000**	**2021 - 2060**	**2071 - 2100**
GWLF	Leane					▨	▨	▨	▨	▨	▨	▨	▨	▨
	Feeagh	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	Mask	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
DYRESM	Leane					▨	▨	▨	▨	▨	▨	▨		▨
	Feeagh						▨	▨	▨	▨	▨	▨		▨
	Mask	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
CAEDYM	Leane					▨	▨	▨	▨	▨	▨	▨		▨
	Feeagh	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		
	Mask	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		

Table 4.2 Values of Nash-Sutcliffe coefficients (NS) for calibration (cal) and validation (val) periods: daily stream flow and TP loads for subcatchments for Leane, Feeagh and Mask.

Lake	**Subcatch.** *(area km^2)*	**Hydrology cal**	**Hydrology val**	**TP cal**	**TP Val**
Leane	**Flesk** ***(325)***	0.79	0.76	0.84	0.79
	Deenagh ***(31)***	0.69	0.65	0.70	0.65
	Upper ***(125)***	0.80	0.83	0.65	0.68
Feeagh	**Black** ***(47)***	0.79	0.79	0.30	
	Glenamong ***(18)***	0.77	0.82	0.37	
Mask	**Robe** ***(620)***	0.80	0.83	0.81	0.80
	Carra ***(151)***	0.77	0.74	0.63	0.62
	Owenbrin ***(23)***	0.69	0.69	0.62	0.61

Table 4.3 SRES emission storylines used in ILLUMINATE (Nakicenovic et al. 2000).

B1	The B1 storyline and scenario family describes a convergent world with low population growth, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.
A2	The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in high population growth. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines.
B2	The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with moderate population growth, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

Table 4.4 GCM and RCM models and SRES emission scenarios used in ILLUMINATE.

GCM	**RCM**	**SRES**	**Time**
ECHAM4/OPYC3	RCAO	A2	2071-2100
ECHAM4/OPYC3	RCAO	B2	2071-2100
HadAM3p	RCAO	A2	2071-2100
HadAM3p	RCAO	B2	2071-2100
HadAM3p	HadRM3p	A2	2071-2100
HadAM3p	HadRM3p	B2	2071-2100
ECHAM5/OPYC3	RCA	A2	2021-2060
ECHAM5/OPYC3	RCA	B1	2021-2060

Table 4.5 Flesk (Leane), Black (Feeagh) and Robe (Mask) subcatchments: % difference between monthly median values for the control (n = 3000) and the A2 and B1 simulations (n = 9000) for dissolved P (dis P) and TP loads 2021-2060: shaded squares indicate negative changes.

			J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
			% change											
Dis P	***Flesk***	A2	22	-28	-12	-1	-5	-6	-8	2	11	25	-5	-9
		B1	16	-35	-26	-4	-4	-6	-6	2	2	21	-17	-9
	Black	A2	11	2	-4	-16	-22	-17	-20	-9	-12	6	-18	-6
		B1	3	-1	-10	-17	-22	-19	-20	-9	-11	7	-17	-7
	Robe	A2	6	11	2	-2	-16	-16	-8	-24	-17	54	44	6
		B1	2	8	-3	-7	-15	-16	-6	-17	1	25	13	-7
TP	***Flesk***	A2	26	-8	-1	-1	-12	-12	-18	5	13	29	1	-7
		B1	17	-17	-17	-8	-10	-12	-14	6	3	26	-18	-8
	Black	A2	25	12	-3	-29	-43	-37	-41	-25	-23	15	-32	-8
		B1	6	5	-18	-31	-42	-40	-42	-24	-21	17	-32	-10
	Robe	A2	16	24	0	-6	-19	-19	-8	-27	-10	44	36	11
		B1	6	18	-10	-13	-21	-17	-6	-17	6	23	5	-8

Table 4.6 Flesk (Leane): % difference between monthly median values for the control (n = 3000) and the A2 and B2 simulations (n = 9000) for dissolved P and TP loads. P loads are presented for two population and land use scenarios (pop-lu): present levels (pres) and a future population and land use scenario (fut). Dissolved P results are also presented with the slurry spreading season set to 16th January to 14th October (J-O) and 1st April to 30th September (A-S). Shaded squares indicate negative changes.

			J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
	pop-lu		% change											
Dis P	***pres; J-O***	A2	45	-14	-8	2	-3	-15	-19	-35	-48	-5	-4	12
	pres; J-O	B2	31	-6	53	6	0	-14	-20	-49	-73	1	-7	10
	fut; J-O	A2	54	17	3	16	14	6	4	-29	-60	8	5	21
	fut; J-O	B2	43	19	44	18	15	8	5	-20	-36	13	2	17
	fut; A-S	A2	-14	-39	-15	17	14	6	3	-20	-38	-11	4	23
	fut; A-S	B2	-12	-36	7	22	18	9	5	-16	-27	-8	2	21
TP	***pres; J-O***	A2	51	-1	9	5	-6	-33	-39	-58	-64	-12	0	28
	pres; J-O	B2	54	9	69	14	1	-27	-35	-52	-47	-6	-4	25
	fut; J-O	A2	54	9	69	14	1	-27	-35	-52	-47	-6	-4	25
	fut; J-O	B2	66	24	83	26	12	-13	-21	-45	-42	-1	0	31

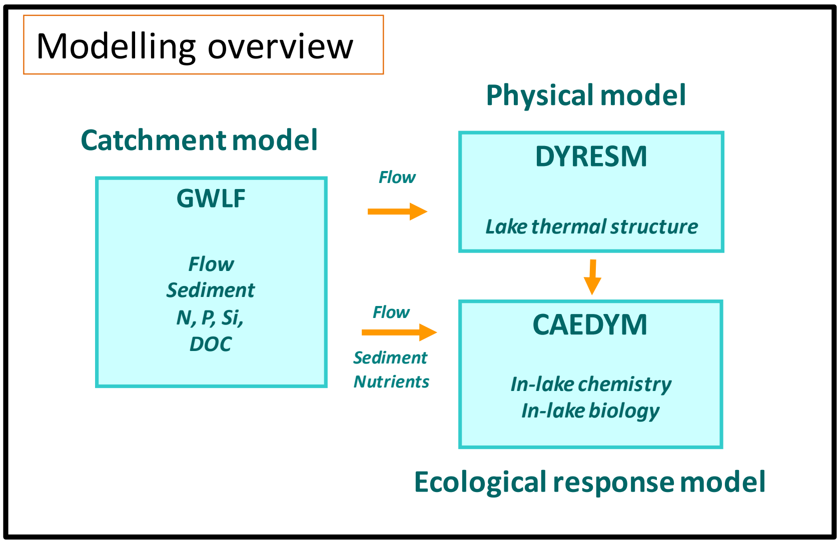


Figure 4.1 Overview of modelling approach taken in the project.

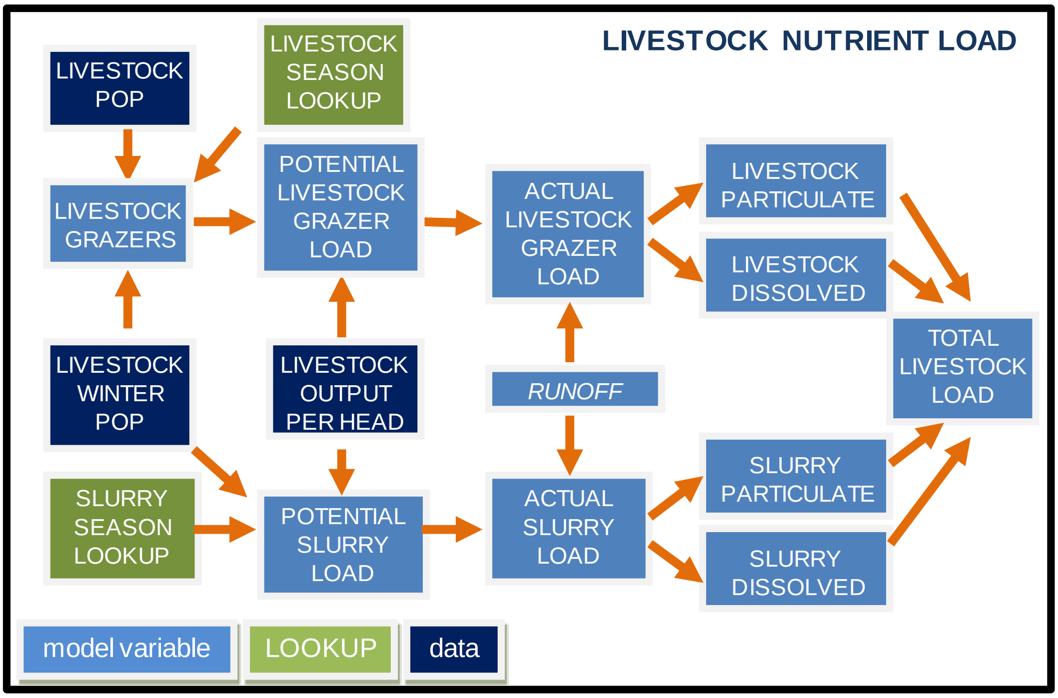


Figure 4.2 Schematic diagram of new GWLF livestock nutrient load module (POP = population).

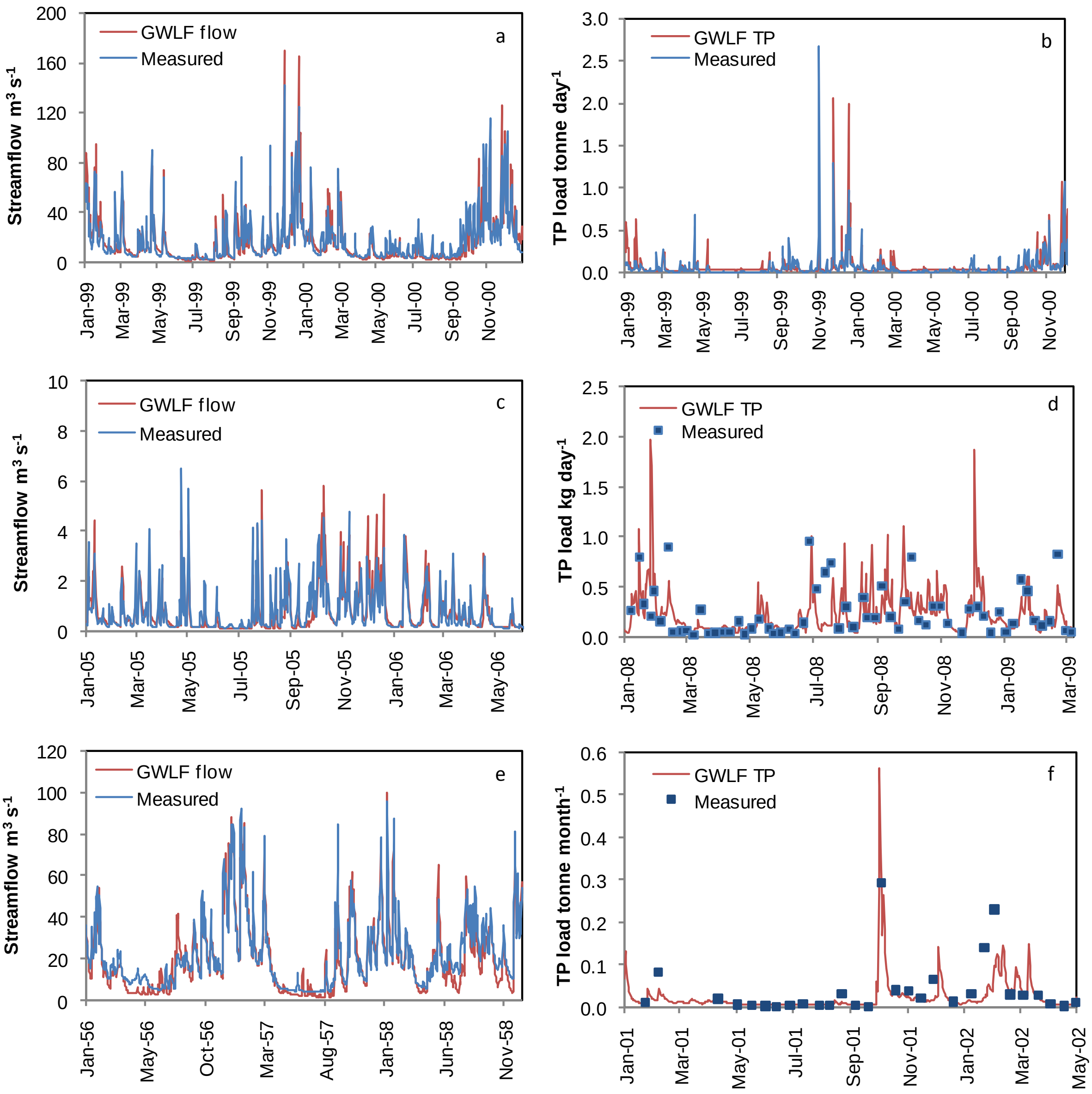


Figure 4.3 Modelled and measured stream flow and TP loads for the Flesk subcatchment, Leane (a and b), the Glenamong subcatchment, Feeagh (c and d), and the Robe subcatchment, Mask (e and f).

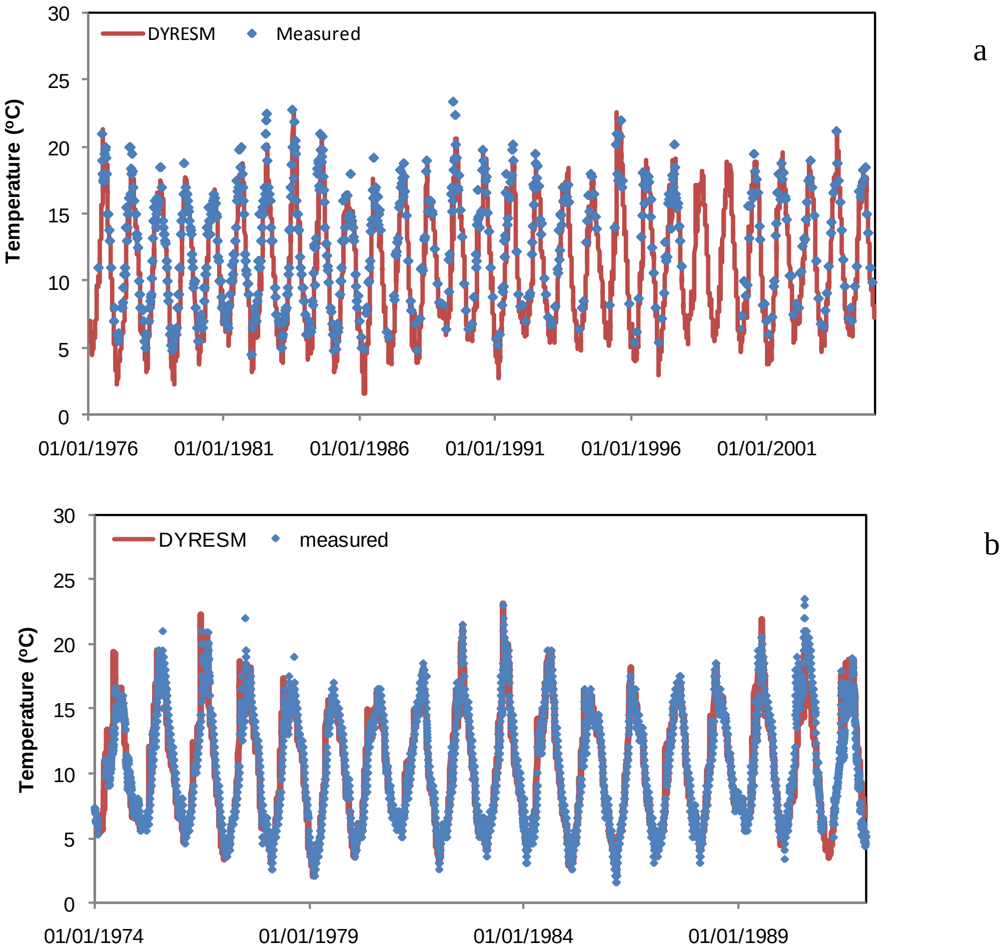


Figure 4.4 Measured and modelled surface water temperature Leane 1976-2001 (a) and Feeagh 1974-1990 (b).

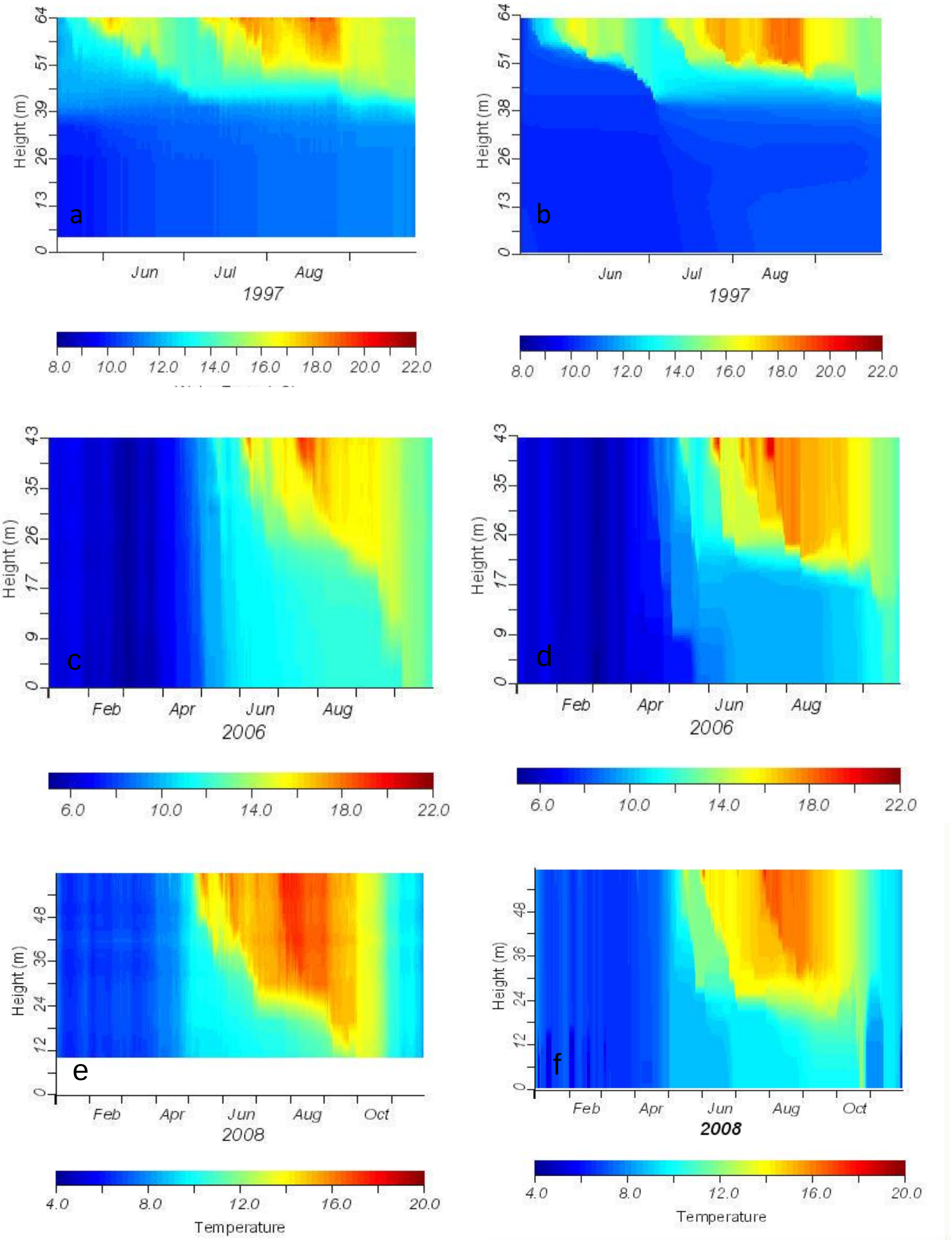


Figure 4.5 Leane, May to September 1997: measured (12 depths between surface and 60m) (a) and DYRESM modelled water temperature profile (b); Feeagh, January to October 2006: measured (10 depths between the surface and 43m) (c) and DYRESM modelled water temperature (d); Mask, January to October 2008: (e) measured (15 depths between surface and 60m) and (f) DYRESM modelled water temperature profile.

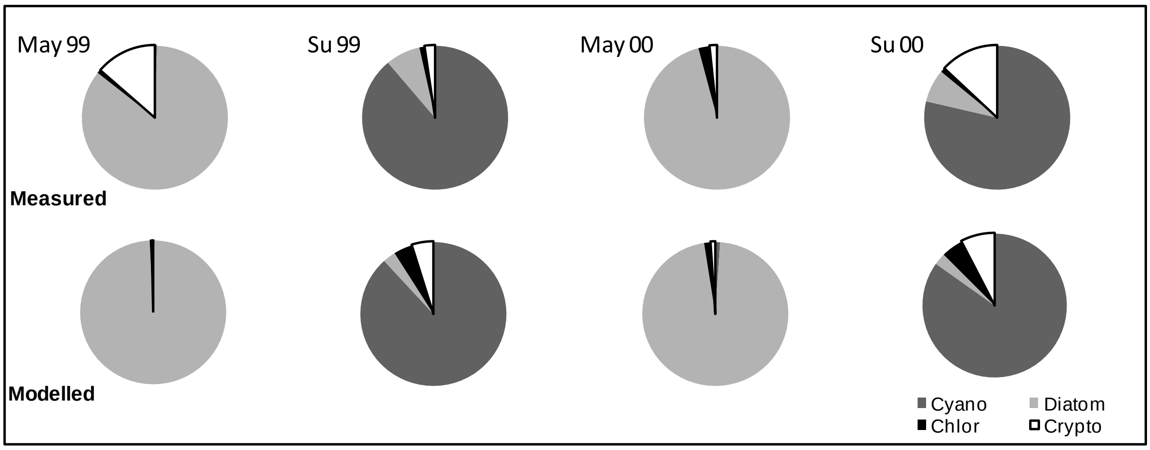


Figure 4.6 Leane: measured and CAEDYM modelled species composition in May and summer (July/August) 1999 and 2000.

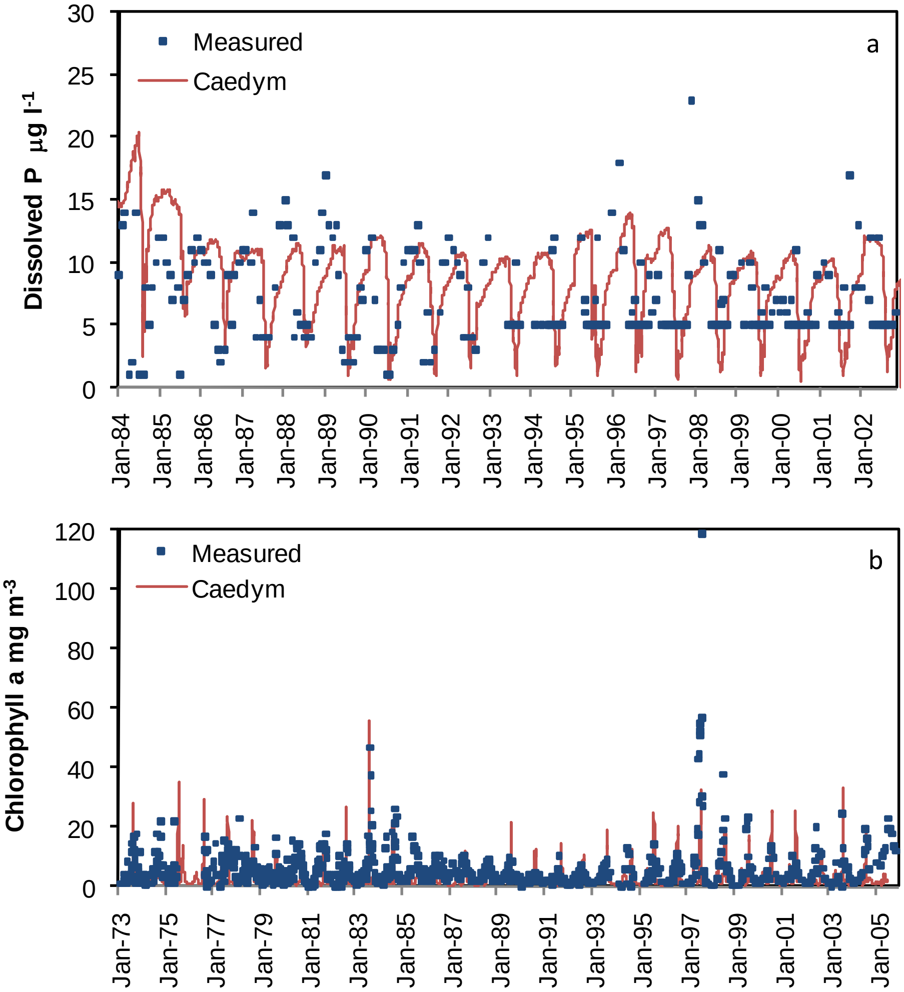


Figure 4.7 Leane: measured and modelled dissolved P concentrations, 1984-2002 (a, and note that the reported limit of detection for the monitoring data changed in 1993 to 0.05 mg L^{-1}); measured and modelled chlorophyll-a, 1973 to 2005 (b).

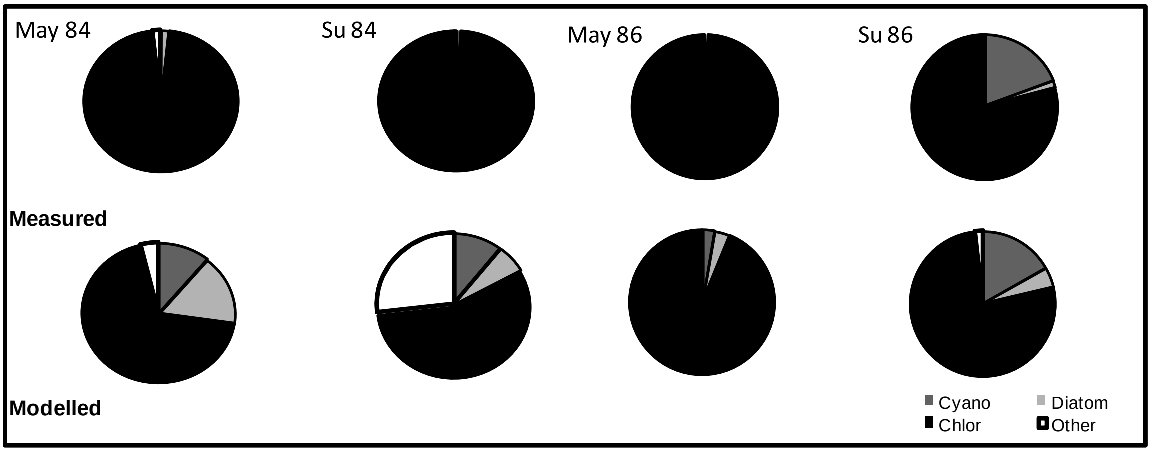


Figure 4.8 Mask: measured and CAEDYM-modelled species composition, May and summer (July/August) 1984 and 1986.

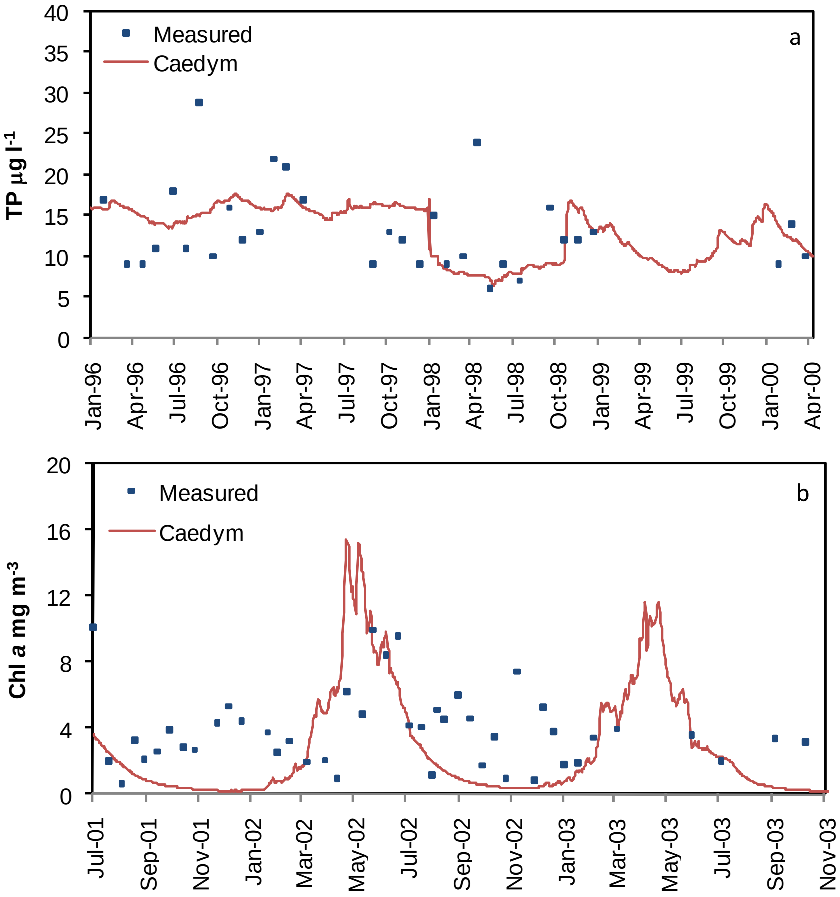


Figure 4.9 Mask: measured and modelled TP concentration (µg l^{-1}) 1996 to 2000 (a); and chlorophyll-a (mg m^{-3}) 2001 to 2003 (b).

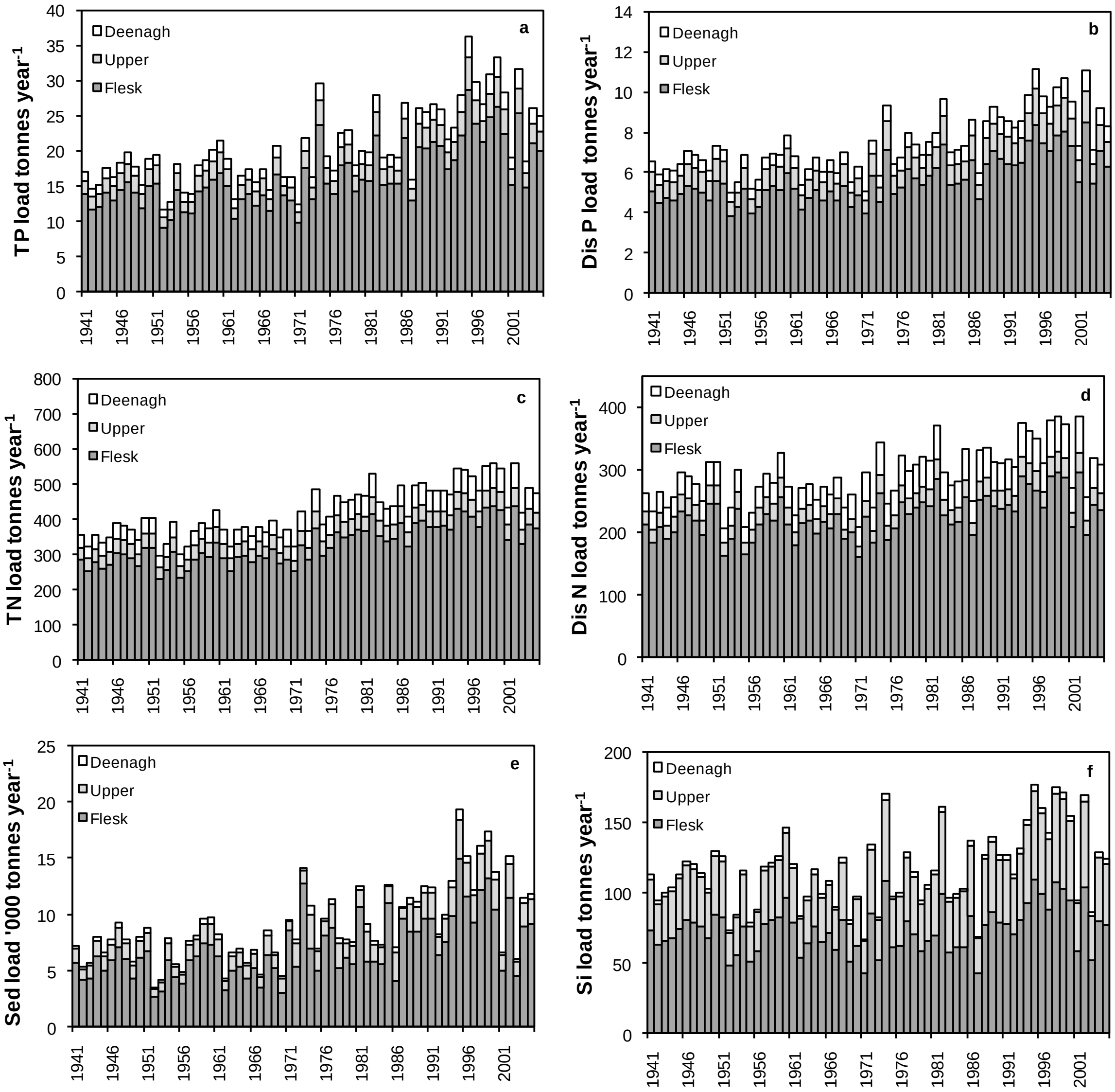


Figure 4.10 Leane, 1941-2006: modelled annual TP (a), dissolved P (b), TN (c), dissolved N (d) sediment (e) and Si (f) loads from the Flesk, Deenagh and Upper subcatchments.

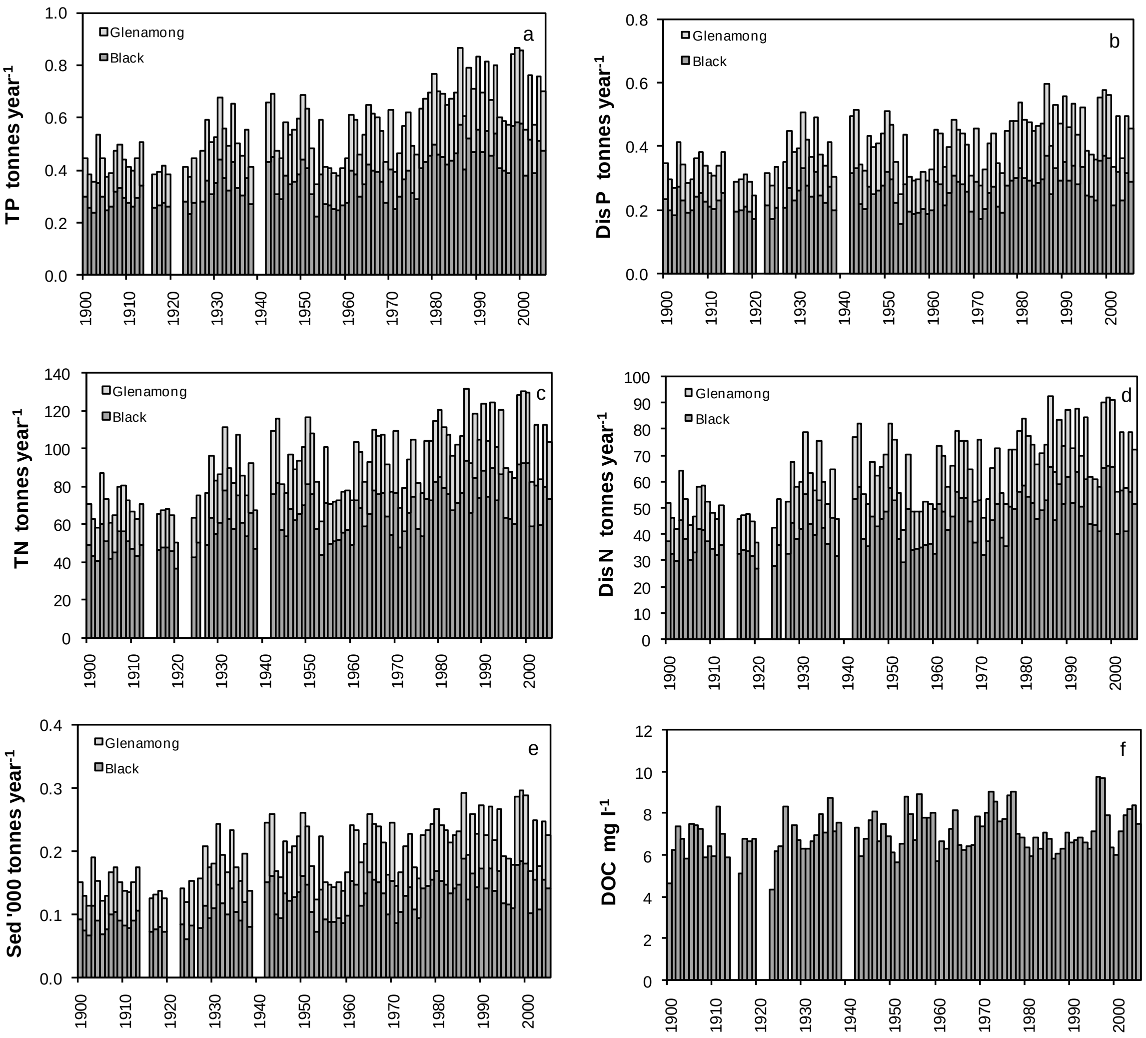


Figure 4.11 Feeagh, 1900-2006: annual TP load (a), dissolved P load (b), TN load (c), dissolved N load (d), sediment load (e) from the Glenamong and Black subcatchments and DOC concentration from the Glenamong subcatchment (f).

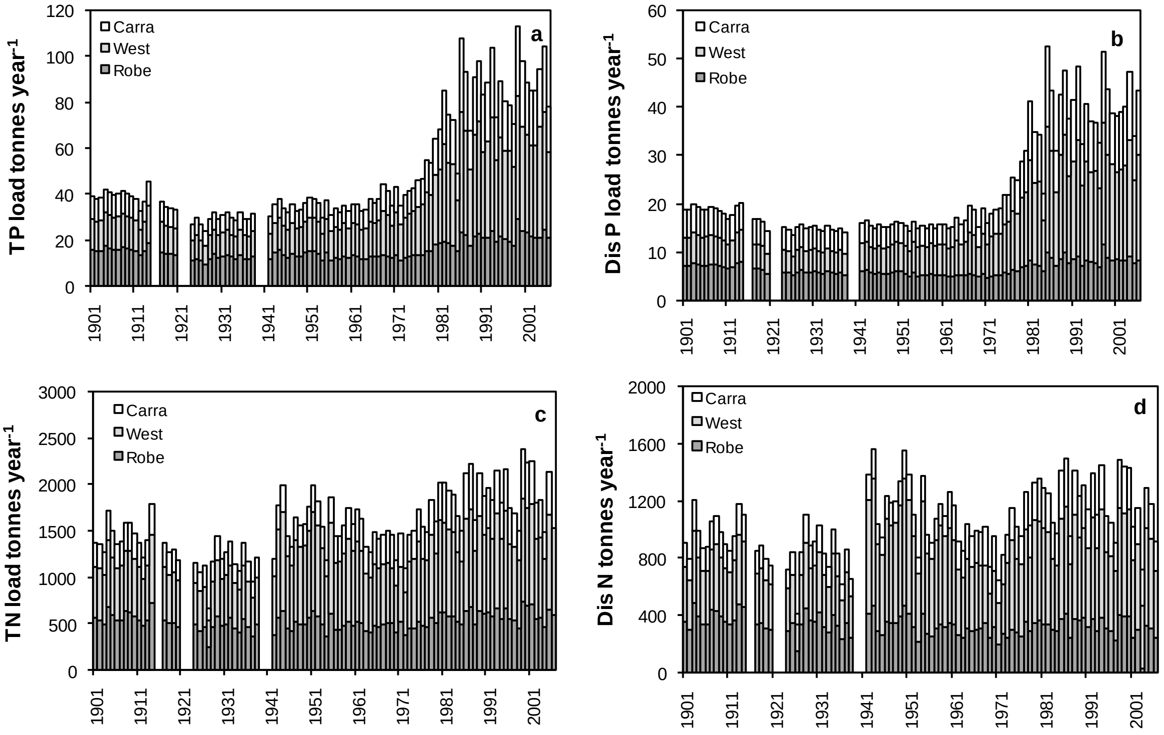


Figure 4.12 Mask, 1900-2006: annual TP (a), dissolved P (b), TN (c) and dissolved N (d) loads from the Robe, Carra and combined western subcatchments.

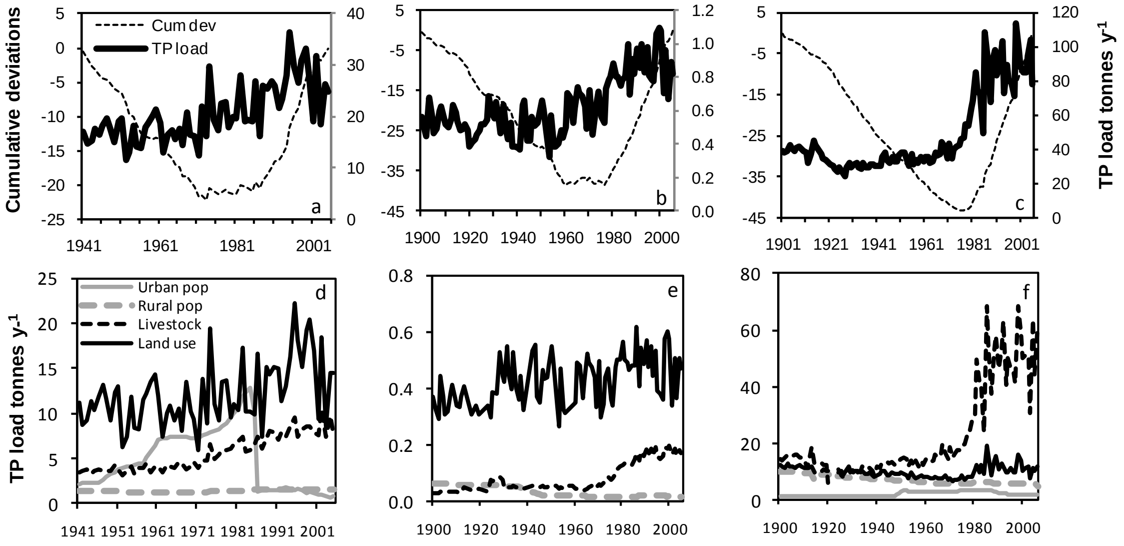


Figure 4.13 Leane (a, d), Feeagh (b, e) and Mask (c, f): cumulative deviation plots of modelled TP loads (tonne year^{-1}) (a to c) and the main sources of the TP load (d to f).

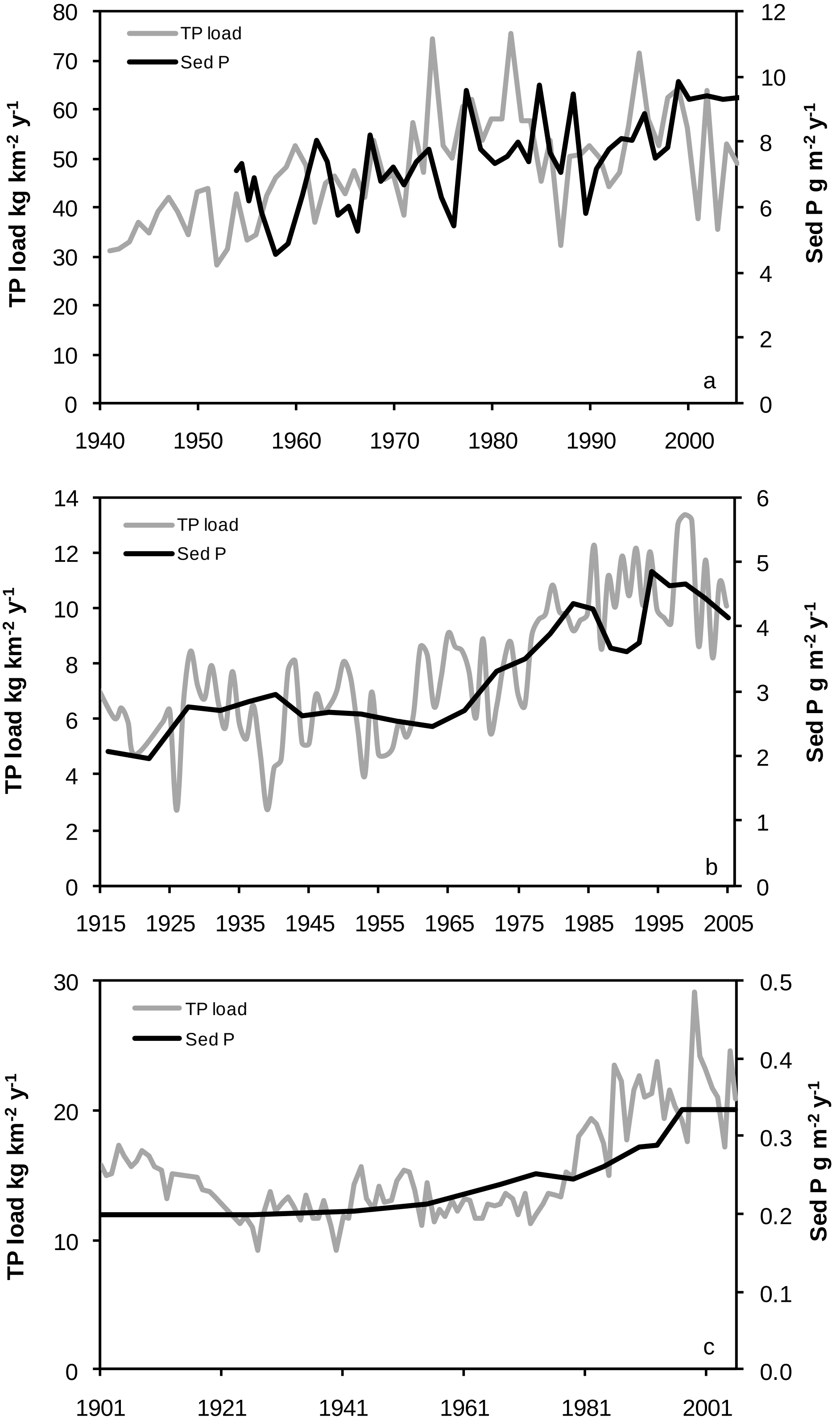


Figure 4.14 Leane, 1941-2005 (a); Feeagh, 1900-2005 (b); Mask, 1900-2005 (c): modelled TP loads and sediment P accumulation.

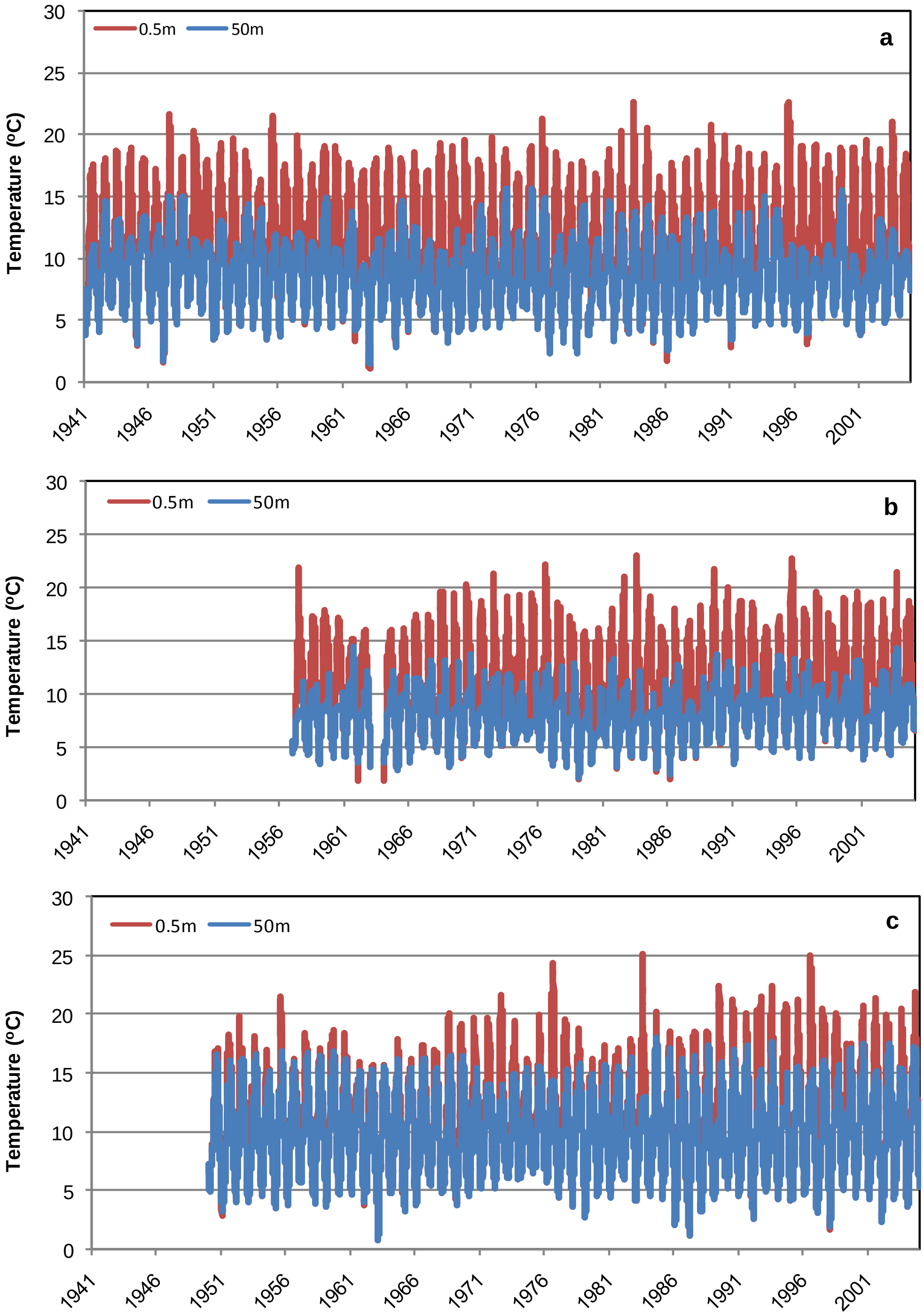


Figure 4.15 Leane, 1941-2005 (a); Feeagh, 1957-2005 (b); Mask, 1950 to 2005 (c): simulated surface water temperature (SWT) and deep water temperature (DWT).

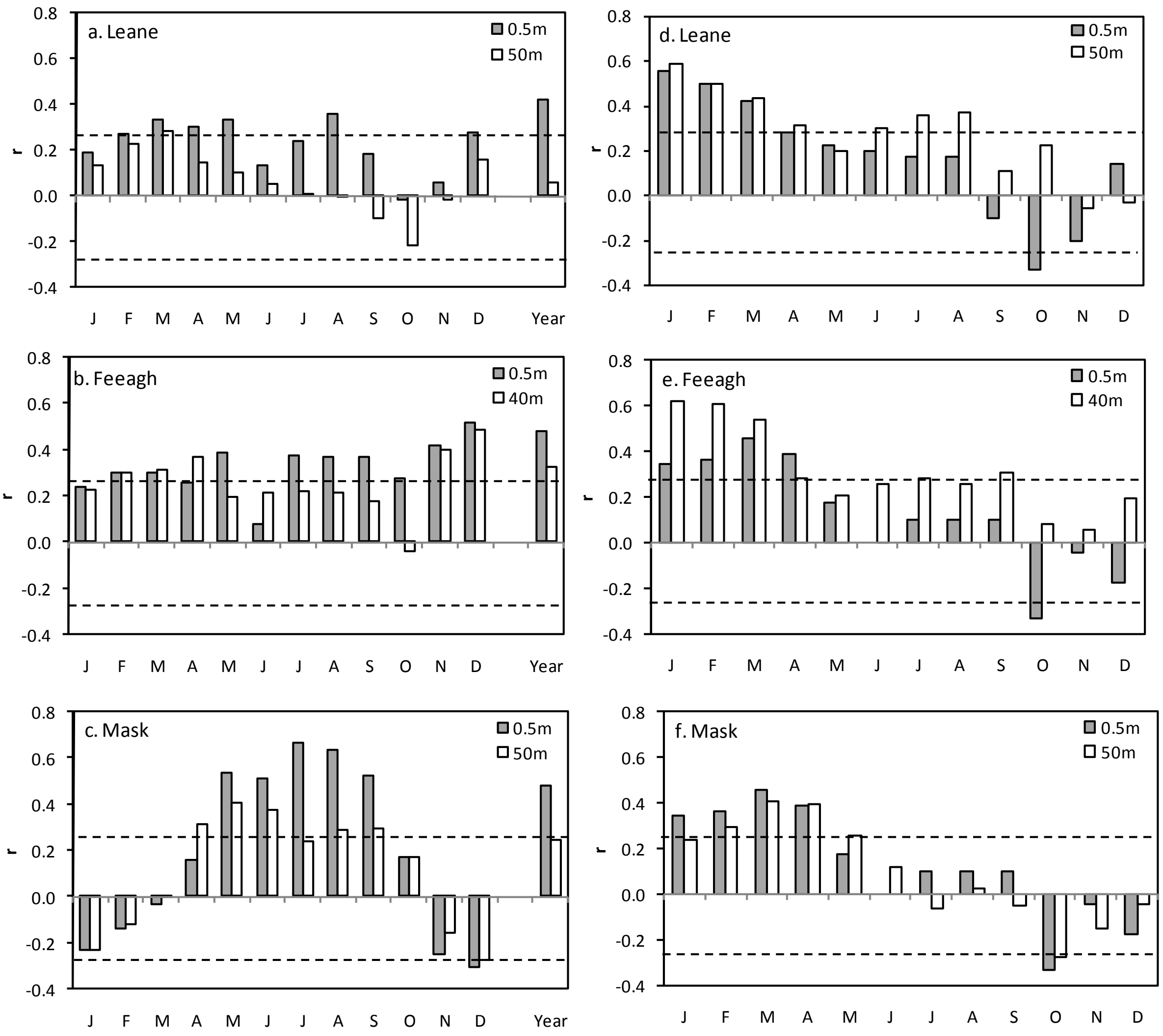


Figure 4.16 Correlation coefficient (r) between SWT (grey bars) and DWT (clear bars) and year for mean annual (year) and mean monthly (J-D) temperature for Leane (a), Feeagh (b) and Mask (c); correlation coefficient (r) between mean monthly SWT and DWT for each month and the North Atlantic Oscillation (1960-2005) for Leane (d), Feeagh (e) and Mask (f). The dashed lines indicate the 5% significance level.

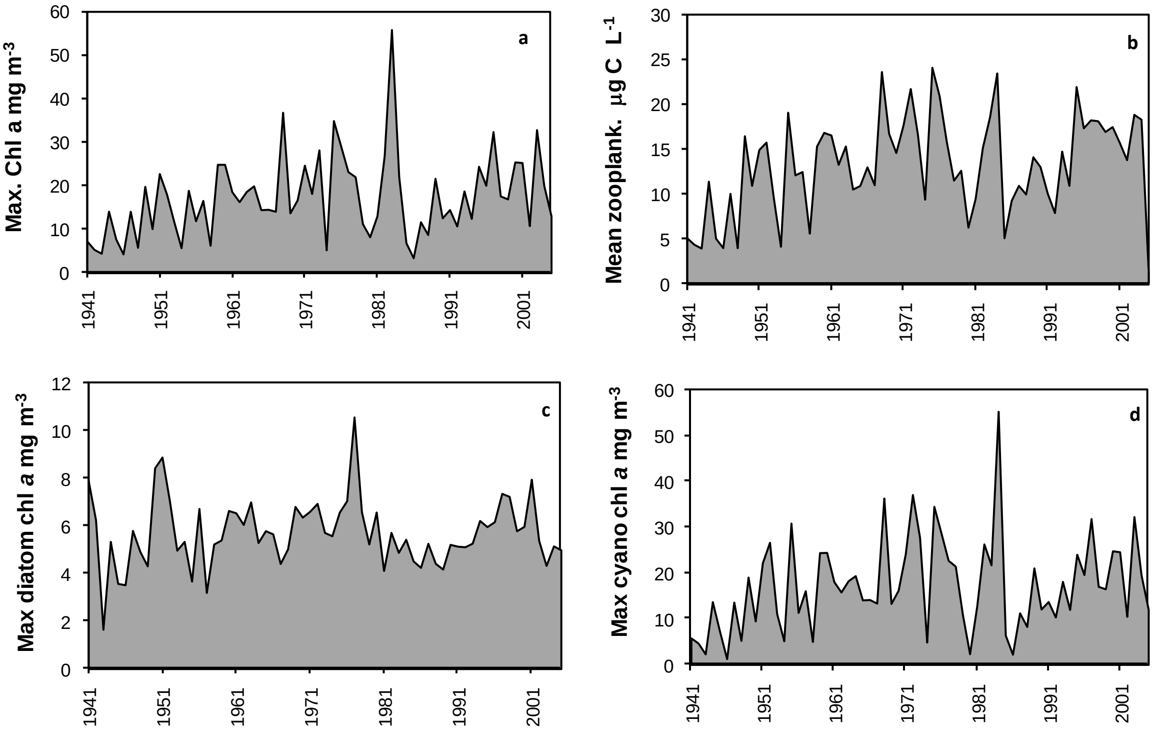


Figure 4.17 Leane, 1941-2005: hindcast annual maximum chlorophyll-a (total) (mg m^{-3}) (a); annual mean zooplankton biomass (µg C l^{-1}) (b); annual maximum diatom chlorophyll-a (c); annual maximum cyanobacterial chlorophyll-a (d).

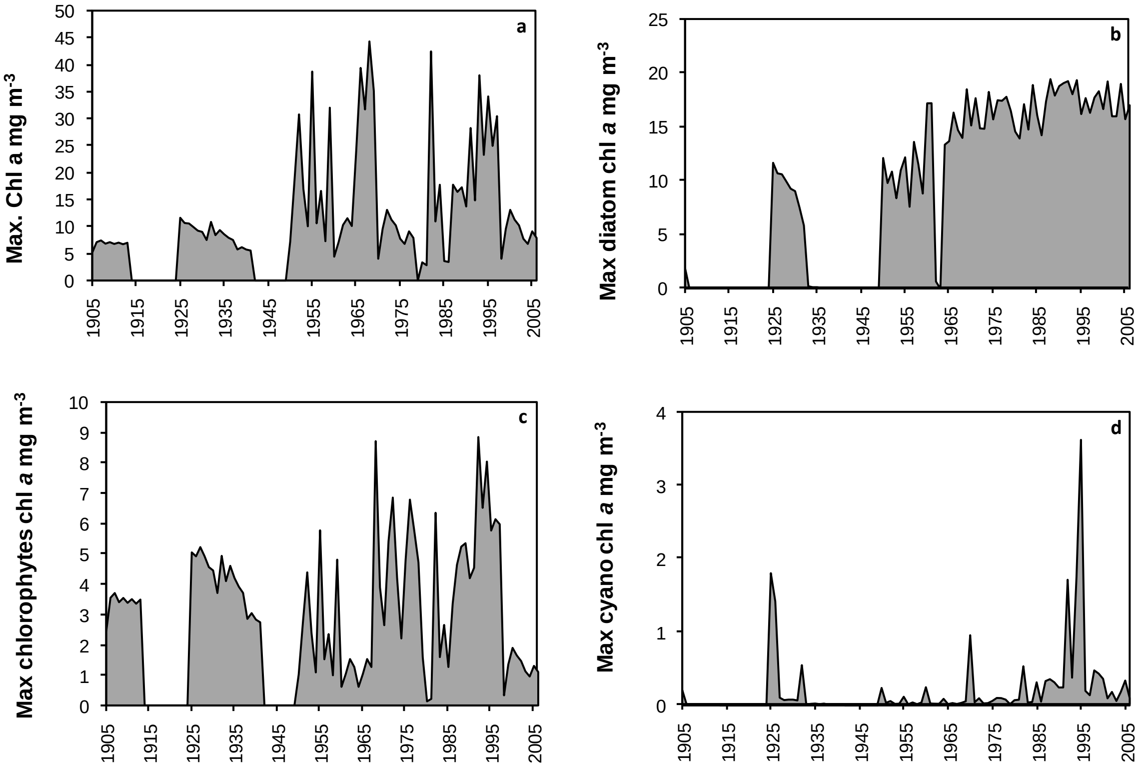


Figure 4.18 Mask, 1905-2005: hindcast annual maximum chlorophyll-a (total) (mg m^{-3}) (a); annual maximum diatom chlorophyll-a (b); annual maximum chlorophyte chlorophyll-a (c), annual maximum cyanobacterial chlorophyll-a (d).

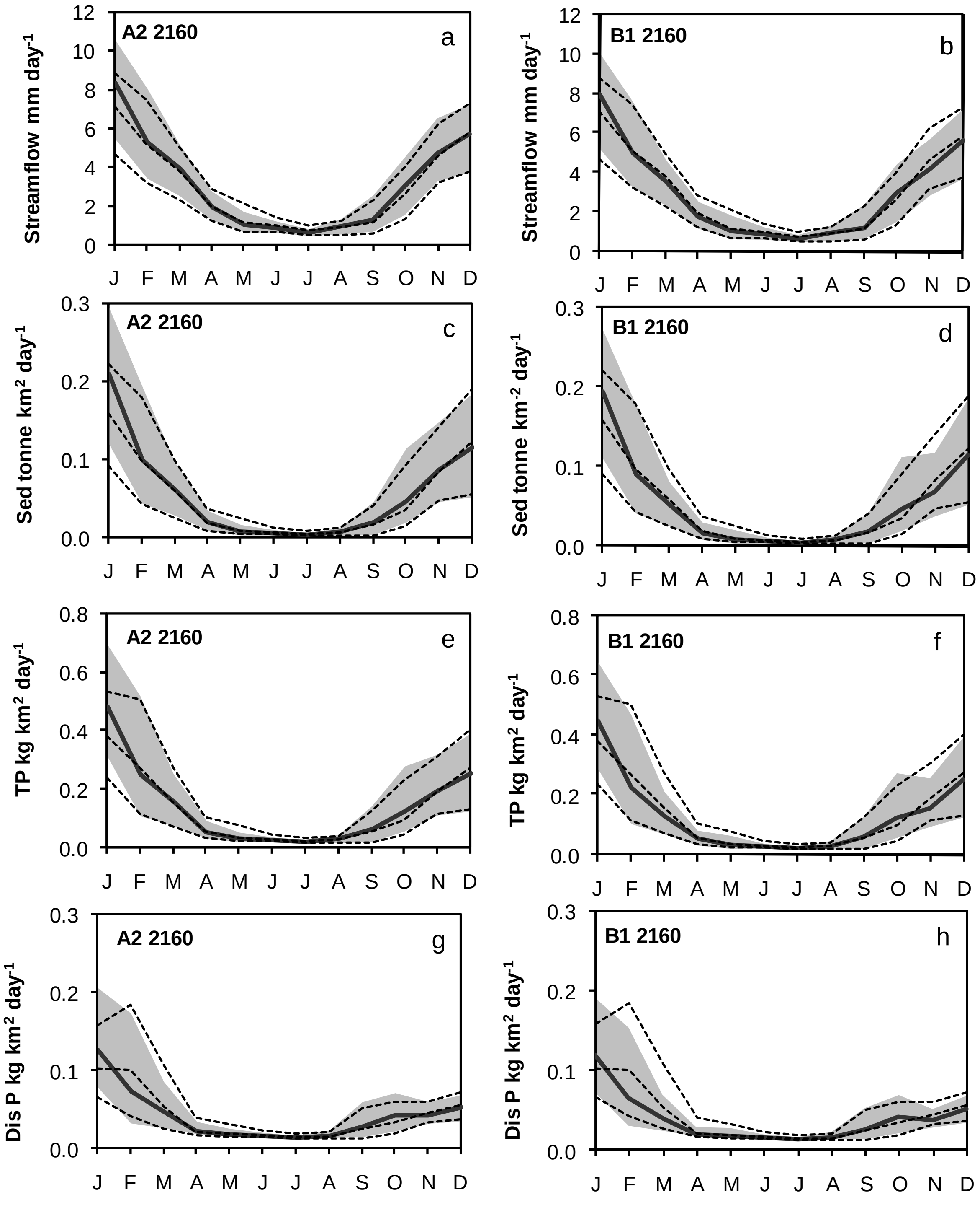


Figure 4.19 Examples of simulations of future climate impacts on P loadings. Flesk subcatchment, Leane: median and interquartile range for the control period (dashed lines, n = 3000) and for the A2 and B1 scenarios (2021-2060) (grey line and grey area, n = 9000): stream flow (mm day^{-1}) (a and b) sediment load (kg P km^{-2} day^{-1}) (c and d) dissolved P load (kg P km^{-2} day^{-1}) (e, f), TP load (kg P km^{-2} day^{-1}) (g, h).

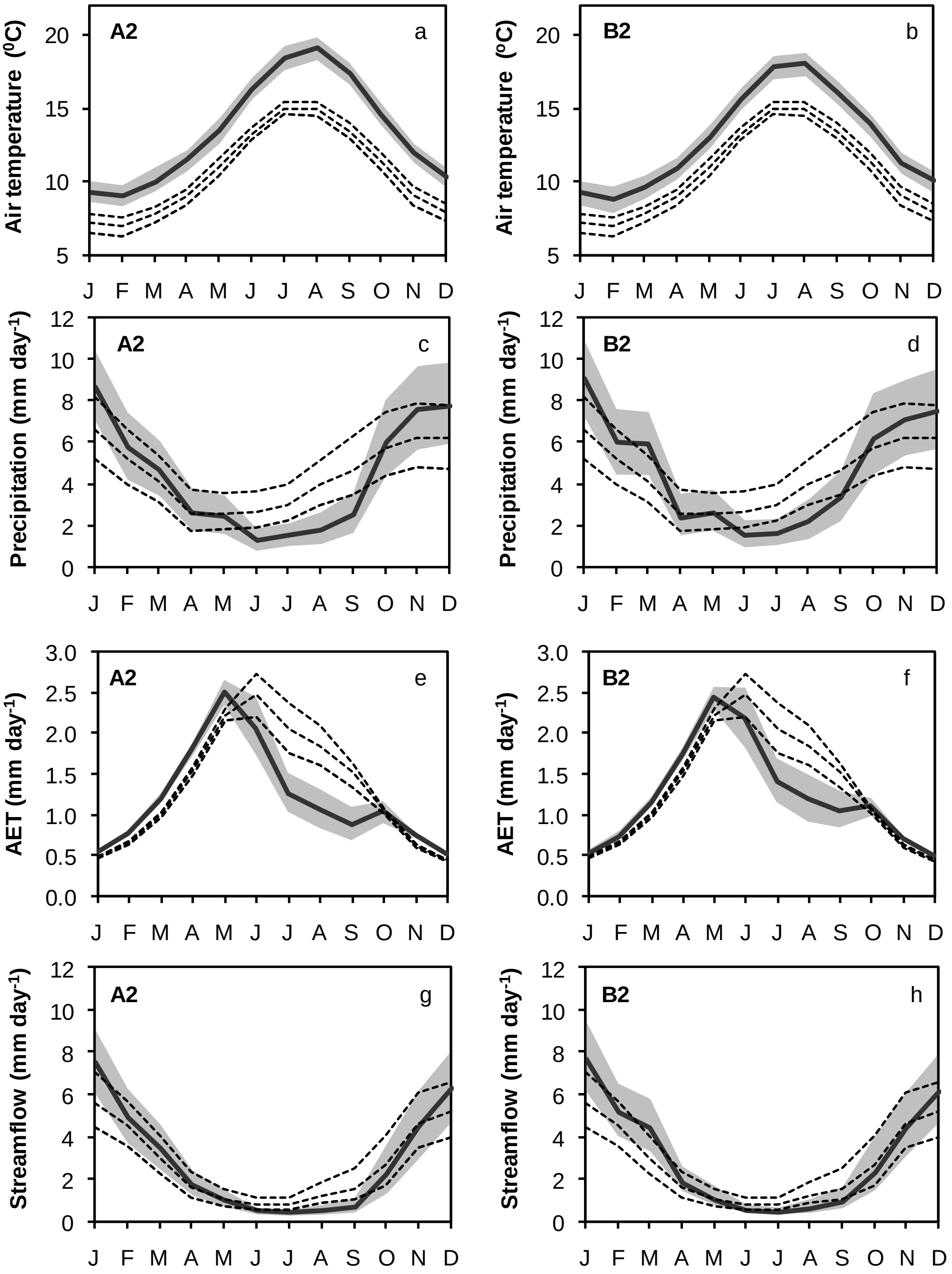


Figure 4.20 Flesk subcatchment, Leane: median and interquartile range for the control period (dashed lines, n = 3000) and for the overall A2 and B2 scenarios (2071-2100) (grey line and grey area, n = 9000): air temperature (^{o}C) (a, b), precipitation (mm day-1) (c, d), AET (mm day^{-1}) (d, e) and stream flow (mm day^{-1}) (g, h).

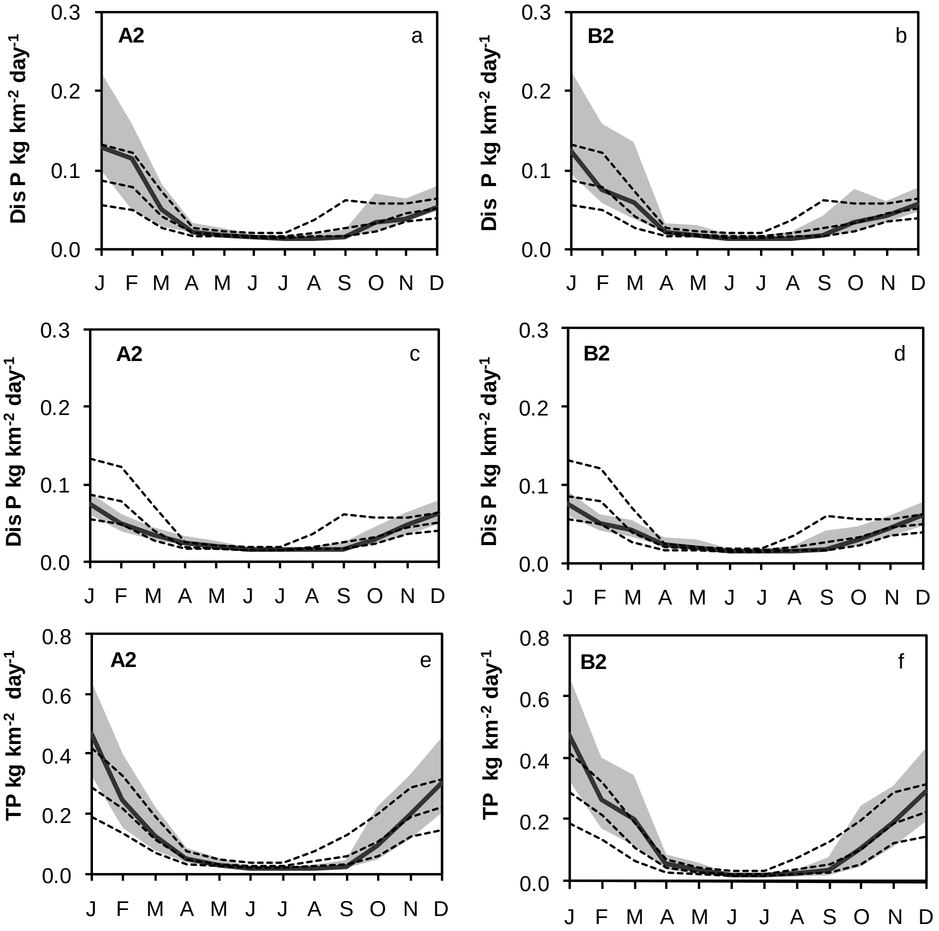


Figure 4.21 Flesk subcatchment, Leane: median and interquartile range for the control period (dashed lines, n = 3000) and for the A2 and B2 scenarios (2071-2100) (grey line and grey area, n = 9000); dissolved P load with open slurry spreading season set at 16th January to 14th October (a, b), dissolved P load with slurry season at 1st April to 30th September (c, d), TP load with open slurry spreading season set at 16th January to 14th October (e, f) (all kg P km^{-2} day^{-1}).

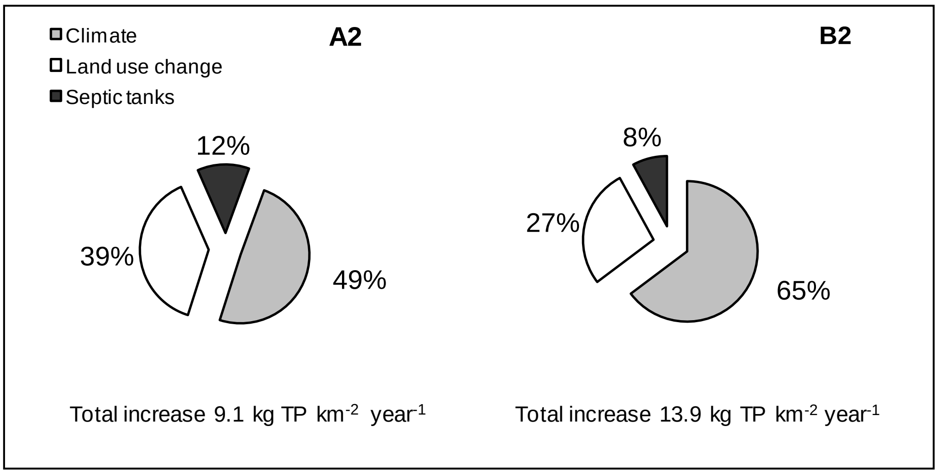


Figure 4.22 Source of the increase in TP load for the A2 and B2 SRES scenarios and projected changes in landuse and population.

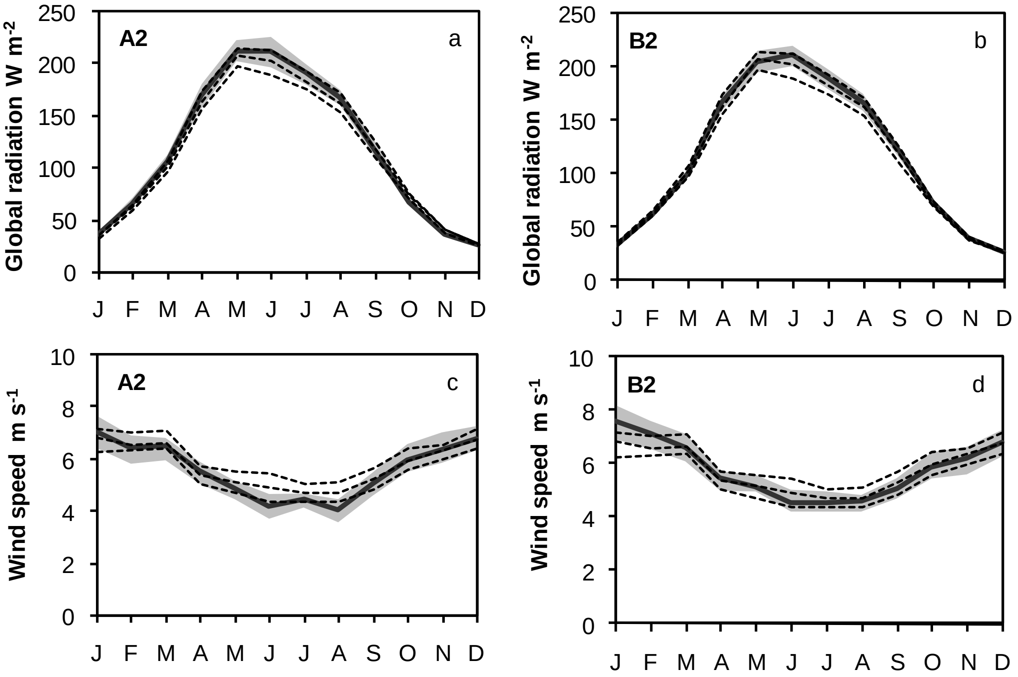


Figure 4.23 Leane: median and interquartile range for the control period (dashed lines, n = 200) and for the A2 and B2 scenarios (2071-2100) (grey line, grey area, n = 200) for global radiation (W m^{-2}) (a, b) and wind speed (m s^{-1}) (c, d).

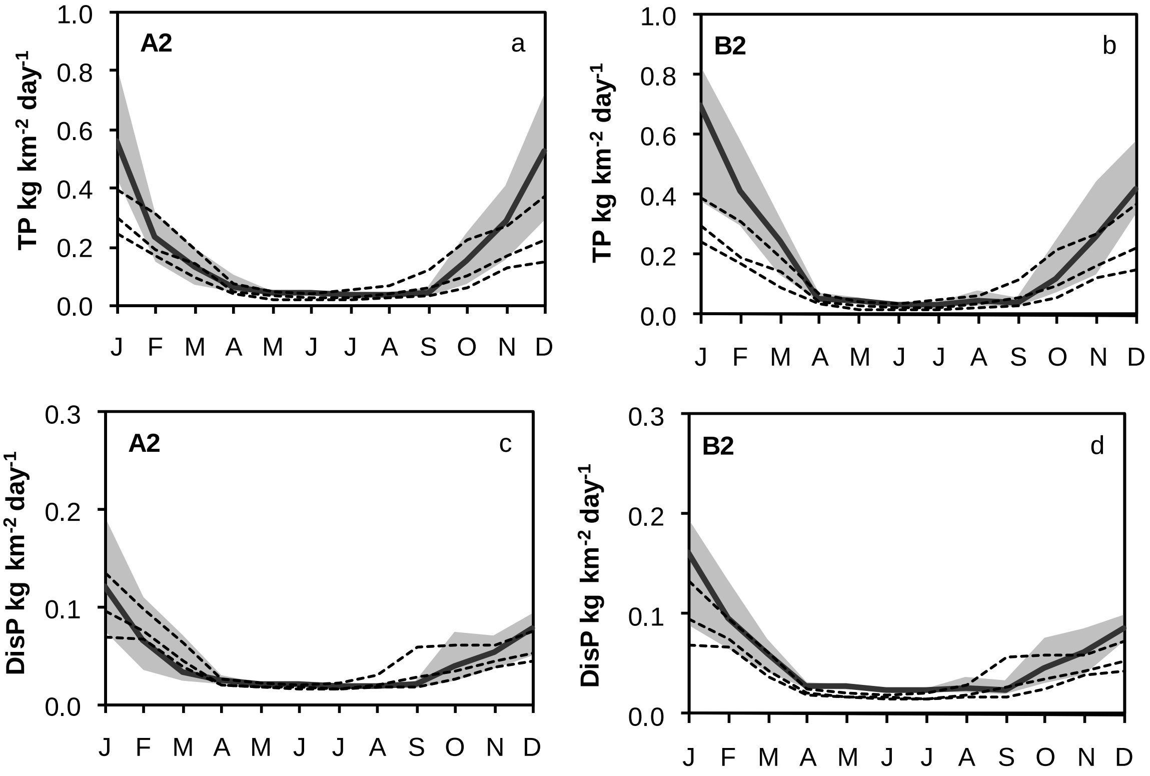


Figure 4.24 Leane: median and interquartile range for the control period (dashed lines, n = 90) and for the overall A2 and B2 scenarios (2071-2100) (grey line and grey area, n = 180) for total catchment TP load (a, b) and dissolved P load (c, d) (all kg km^{-2} day^{-1}).

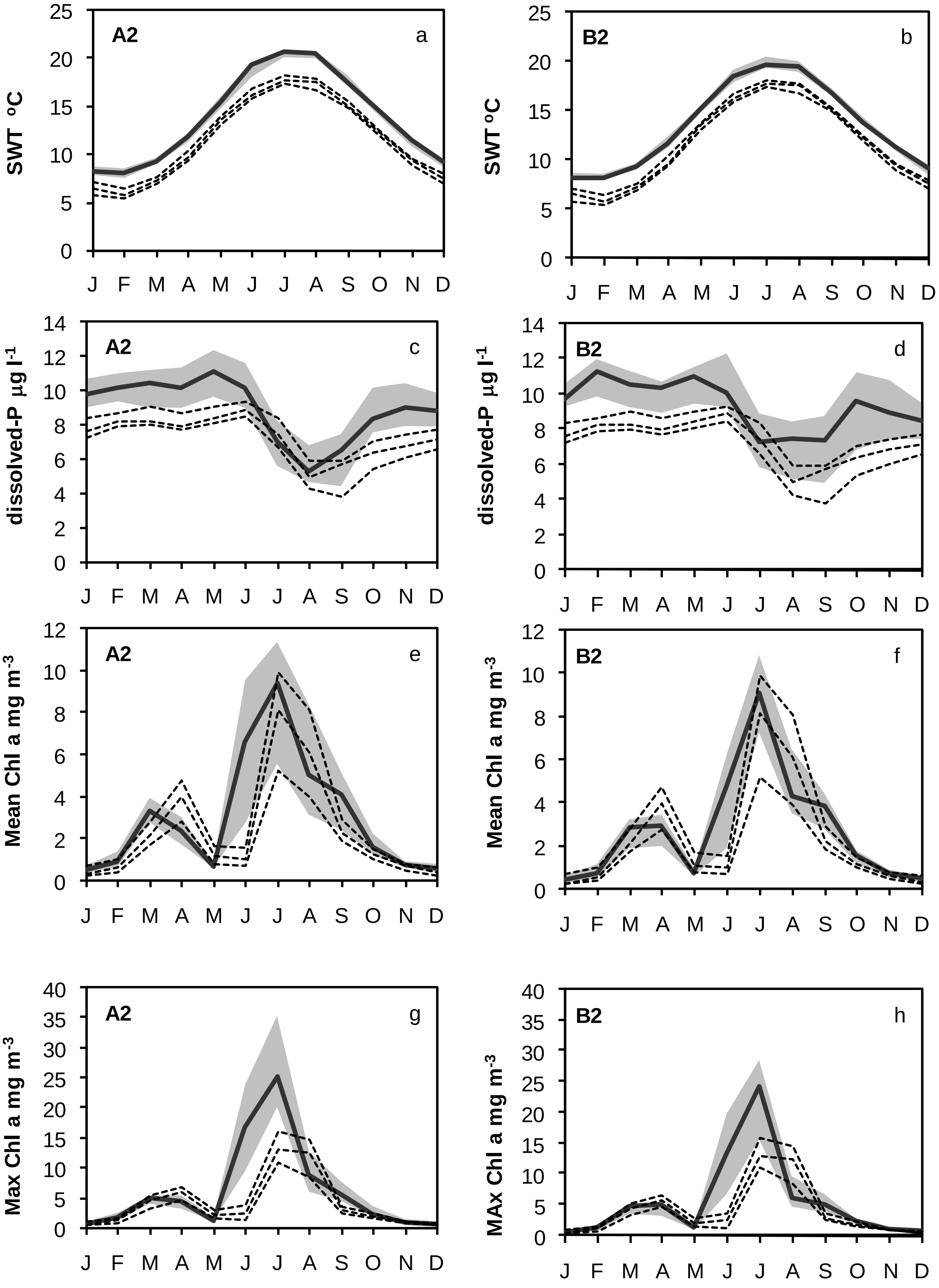


Figure 4.25 Leane: median and interquartile range for the control period (dashed lines, n = 90) and the A2 and B2 scenario (2071-2100) (grey line and grey area, n = 180); SWT (a and b), in-lake dissolved P concentrations (µg l^{-1}) (c and d), mean chlorophyll-a for April to September (mg m^{-3}) (e and f), maximum annual chlorophyll-a (mg m^{-3}) (g and h).

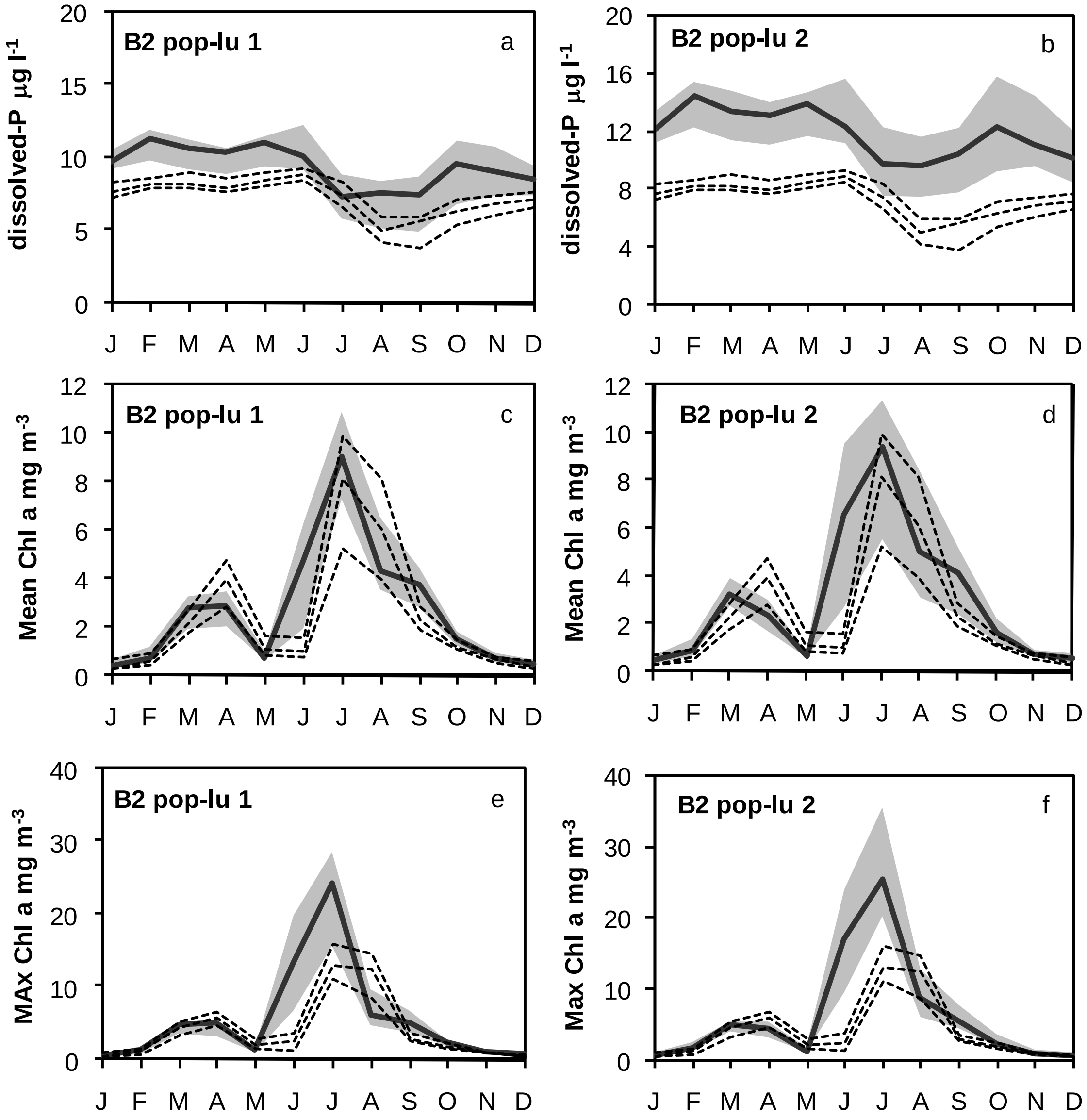


Figure 4.26 Leane: median and interquartile range for the control (dashed lines, n = 20) and for B2 scenario (grey line and grey area, n = 200), dissolved P concentrations (µg l^{-1}) (a and b), mean chlorophyll-a (mg m^{-3}) (c and d), and maximum chlorophyll-a (mg m^{-3}) (e and f).

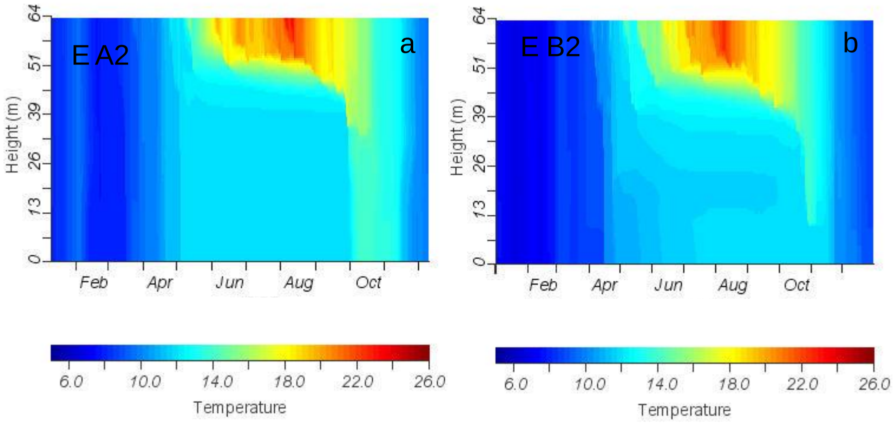


Figure 4.27 Leane: examples of thermal profile A2 (a) and B2 (b) for the ECHAM4 GCM; in each case a year that reflected the median period of stratification was chosen.

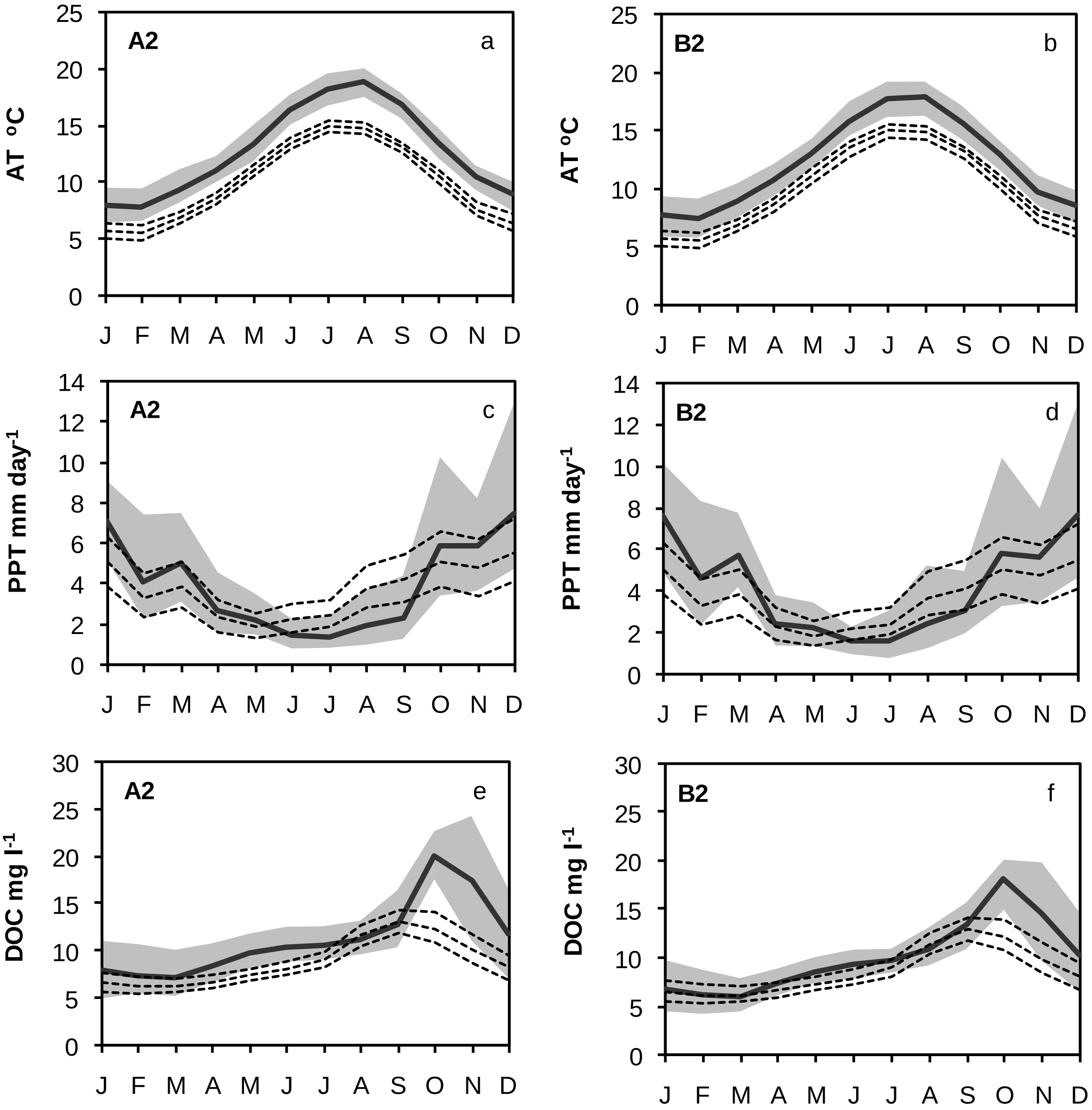


Figure 4.28 Glenamong subcatchment, Feeagh: median and interquartile range for the control period (dashed lines, n = 9000) and the A2 and B2 scenario (2071-2100) (grey line and grey area, n = 3000); air temperature (ºC) (a and b), precipitation (mm day^{-1}) (c and d), DOC (mg l^{-1}) (e and f).

Chapter 5 Discussion

ILLUMINATE had two key aims. First, the project aimed to establish reference conditions and to quantify and evaluate the historical ecological responses of lakes in the three study catchments to particular and combined pressures. Second, ILLUMINATE aimed to use coupled dynamic ecological pressure-response models combined with broadly-based, integrated datasets to produce and evaluate simulations of past and future environmental scenarios that can be used to demonstrate key ecological pressures and responses of direct relevance to the implementation of the WFD in Ireland. A third, lesser, aim was to provide informed comment on the at risk characterisation of the lakes studied in detail, where possible. The following discusses the findings of ILLUMINATE in the context of these aims.

5.1 Reference conditions and catchment pressures

Reference status, i.e. conditions showing no or minimal anthropogenic impact, can be established for aquatic systems in several ways (Anderson et al. 2006), including palaeolimnological approaches. Palaeolimnology provides a means of not just determining anthropogenically-induced effects, however; lake sediments also provide a basis for unravelling the multitude of causal drivers and pressures (Smol 2010). Recent palaeolimnological research carried out as part of IN-SIGHT, which was completed in 2006, confirmed the current reference status of a selection of oligotrophic and meso-oligotrophic lakes in Ireland (Leira et al. 2006). These lakes are in catchments where human-induced drivers of aquatic ecosystem changes are thought to be minimal. Lakes in catchments supporting intensive agriculture and sizable human populations are unlikely to be in reference condition at present, however, because of combined anthropogenic pressures (Ormerod et al. 2010), as was recently borne out by the results of a largely sediment-based study of six lakes in intensively farmed catchments in the Irish Ecoregion (Taylor et al. 2006a). According to this study, modification of the lakes studied has continued over various periods of time, with the effects of anthropogenic pressures evident for at least 200 years in the case of Crans Lough, Northern Ireland (and see Dalton et al. (2009) for an updated discussion of the palaeolimnological record from Crans Lough).

Differences in the length of time over which lakes in Ireland have been modified by humans highlight the difficulties of applying *a priori* a temporal end-point for reference conditions, such as the c. 1850 suggested by Battarbee (1999) and Bennion et al. (2004), and the benefits – where the data permit – of fixing reference state according to local factors. If a general end-point for reference conditions is desirable, then Anderson (1997: 438) argues that a 'realistic background' state is probably a relatively recent one, immediately prior to 1950 and therefore before widespread agricultural applications of synthetic fertilisers. This more recent date also coincides with the onset of major increases in fossil fuel use (Hansen et al. 1998) and a phase of relatively cool temperatures globally, preceding the onset of the current period of major global warming that commenced c. 1970 (Parmesan & Yohe 2003).

Firm dating control and the use of multi-proxy evidence are essential requirements if reference conditions are to be established through a palaeolimnological approach. The two lakes in the Leane catchment examined in the current research revealed contrasting rates of sediment accumulation and levels of intra-coring site variations in sedimentation. At Muckross, rates of sediment accumulation were found to be very low, with the last century or so of record captured in the uppermost few cm of sediments, while the level of intra-coring site variations in sedimentation was relatively high. This combination led to difficulties in establishing chronological control, and in carrying out a detailed (i.e. high resolution, multi-proxy, sediment-based) study of more recent changes in lake and catchment conditions. By comparison, the rate of sediment accumulation at Leane, both relative to Muckross and for a lake in Ireland generally, was found to be high, as previously reported by Linnane (2001). Up-core variations in sediment composition were also similar between cores of sediment collected from proximate locations at the coring site. Both these sedimentary characteristics for Leane facilitated chronological control, and the use of multi-proxies in the reconstruction of past environmental conditions at relatively high temporal resolution.

Because of the difficulties in establishing chronological control and the availability of only a poorly resolved sedimentary record of the last c. 150 years, palaeolimnological investigations at Muckross were curtailed relatively early in the project. However, results indicate that Muckross has been close to the threshold between oligotrophic and oligo-mesotrophic conditions and has oscillated between slightly acidic and slightly alkaline throughout the period of time represented by the analysed sediments. As was the case for a second lake in the same catchment (Upper) that was included in IN-SIGHT (Leira et al. 2006), Muckross can be regarded as currently close to or in reference state, and its characterisation as ‘probably not at significant risk’ thus appears justified. Moreover, as there is evidence for catchment changes during the period of time represented by the sedimentary record analysed, both from up-core variations in sediment composition (organic matter content, geochemistry and pollen) and from secondary data (see below), Muckross may be relatively resistant to human-induced pressures, notably those of inwash and eutrophication.

By comparison, the base of the longest of the several sediment cores obtained and analysed from Leane dated only to the early to mid 1940s. The high rate of sedimentation at Leane is partly a reflection of productivity in the lake. However, sediment inwash from the catchment must also be significant, given the highly inorganic nature of the cored sediments. According to palaeolimnological and hindcast model data, Leane was in a recovery phase in the early to mid 1940s, following a relaxation of human-induced pressures, and may actually have been close to reference. This is evident in the relative abundance of oligtrophic and circumneutral species of diatoms (e.g. *Achnanthidium minutissimum*, *Cyclotella comensis* and *C. radiosa*), reconstructed epilimnic (or DI-) TP in the oligo-mesotrophic range, and the low concentrations of remains of pigments for the early part of the sedimentary record analysed. Further up the food chain the benthic/planktonic cladocerans ratio for Leane was relatively high in c. 1945, indicative not only of a relatively rich benthic fauna but also abundant macrophytes and high transparency, and corresponding to high ecological status according to the WFD definition (de Eyto et al. 2003). Low concentrations of many geochemical elements, and EFs less than 1.0, also attest relatively stable catchment conditions and low rates of sediment inwash (Bindford 1990) from the early 1940s.

One reason for concluding that Leane was in a process of recovery in the 1940s is evidence that human-induced pressures were relaxed relative to the present, but particularly when compared with the preceding period. For example, rural population levels in the catchment had declined by the 1940s relative to the 19th century (CSO 2005), while cattle and sheep numbers remained largely unchanged. Consequently hindcast model data show low and relatively stable sediment, TP and TN loadings to the lake and relatively low in-lake TP concentrations.

According to meteorological records from the Valentia Observatory, air temperature and rainfall in southwest Ireland have increased significantly since the mid 20th century (temperature from the 1960s, rainfall from the 1940s). Human-induced and related pressures have also increased substantially in the same period, notably those related to agriculture, urbanisation and tourism, and associated infrastructure (Quirke 2001). Human population levels have increased from the 1960s, with numbers in urban areas showing the greatest rise (the population of Killarney has almost doubled) (CSO 2005). Numbers of tourists visiting the area have also risen sharply, especially during the spring and summer months. Large increases in stocking densities of cattle and sheep have also occurred from, respectively, the 1970s and in the 1980s and 1990s (CSO 1997). Afforestation commenced in the Leane catchment in the early 1970s, as is evident in an increase in conifer-type pollen and a concomitant decline in Poaceae pollen in the sediment record from the mid 1970s. Increased pressures have been translated into effects on water quality, with impacts possibly magnified by warmer temperatures and increased rainfall-induced runoff from the catchment.

Concern for water quality at Leane was expressed first in the late 1960s (Fehily & Shipman 1967) and led to a commencement of monitoring of lake water quality in the early 1970s. Periods of enrichment are evident in the monitoring data, with the early records suggesting a mesotrophic status for Leane. The sedimentary data suggest that enrichment could have commenced somewhat earlier (in the mid-1950s), with peak levels of DI-TP in the 1990s and 2000s twice what they were in the late 1940s and early 1950s, with a stepped increase in nutrient levels occurring in the early 1960s. A sustained period of nutrient enrichment since the mid 1950s is also evident in changes in phyto (diatoms and algal pigments) and zooplankton remains preserved in sediments. Changes in phytoplankton remains indicated increased productivity, while the replacement of benthic chydorids by planktonic Daphniidae and Bosminidae suggested reduced water transparency and availability of macrophyte habitat (Duigan & Birks 2000; Jeppesen et al. 2001). Levels of sediment P are also indicative of increasing nutrient enrichment from anthropogenic sources (Binford 1990) from the early to mid 1950s, and particularly from the 1990s.

P inputs from the STP at Killarney were most likely the major driver of nutrient enrichment of Leane until the mid-1980s, evident in the sedimentary evidence. Measures to reduce P inputs, introduced in the late 1970s with the installation of secondary treatment facilities, were completed in the mid 1980s and led to a more than ten-fold decline in P inputs to the lake from the STP. These improvements have meant that high nutrient loadings to the lake from the late 1980s are almost certainly from diffuse agricultural sources (Jennings et al. 2008). A catchment monitoring and management programme was implemented in the late 1990s with the aim of reducing loadings from diffuse sources. The lake has been classified as mesotrophic in all years since that time. However, recent nutrient enrichment events, in addition to a shift in the trophic status of the lake back towards the mesotrophic-eutrophic boundary, highlight the difficulties in controlling inputs from diffuse sources and add support to the current 'at significant risk' designation for Leane.

The situation in the Burrishoole catchment is and has been somewhat different to Leane, as was expected at the outset of ILLUMINATE. Aside from extensive peatlands, which are rough grazed, land cover in the catchment also comprises small areas of regenerating woodland and commercial forestry (conifer) plantations. Commercial plantations were first established in 1951 and were extended between 1960 and 1969; a programme of clear felling commenced in the early 1990s. The number of people currently residing in the Burrishoole catchment is small, and has fallen by about 75% since 1900. Livestock (cattle and sheep) numbers were also low throughout most of the 1900s. Sheep numbers increased rapidly from the early 1970s (from c. 7 km^{-2} to c. 88 km^{-2}) however, but have declined over the past decade.

The two lakes in the Burrishoole catchment that were the focus of ILLUMINATE research both yielded sedimentary records that facilitated the compilation of well-dated, relatively high resolution, multi-proxy evidence of past environmental conditions since the late 1800s. For both Bunaveela and Feeagh, relatively stable, oligotrophic conditions are indicated during the early and middle parts of the records. At least one phase of inwash of material from the catchment is evident during this period of relative stability, however, dated to the mid to late 1920s at Feeagh. Conditions begin to change in Feeagh from the mid 1950s, with evidence of catchment inwash associated with nutrient enrichment indicating increased erosion. Nutrient enrichment becomes more pronounced at Feeagh from the late 1960s, with reconstructed epilimnic P levels suggesting the occurrence of mesotrophic conditions in the lake from this time. Nutrient enrichment is indicated in both qualitative and quantitative changes in the remains of diatoms, from assemblages numerically dominated by oligotrophic *Achnanthidium* and *Cyclotella* species to those characterised by increased abundances of nutrient tolerant taxa, notably species of *Asterionella* and *Aulacoseira*. Moreover, the remains of Cladocera extracted from sediment samples suggest reduced transparency and macrophyte habitat (Duigan & Birks 2000; Jeppesen et al. 2001) from the early 1970s. The situation at Bunaveela is similar, although the onset of pronounced catchment disturbance and associated nutrient enrichment was delayed until the early to mid 1980s, with the appearance of mesotrophic conditions dating to the late 1980s/early 1990s. A fall in abundance of *Isoetes* pollen from the early 1980s could reflect reduced transparency as a result of inwash and increased DOM in the lake. Afforestation in the catchment is reflected in the pollen records from the two lakes, with initial increases in conifer-type pollen dating to the mid-1970s and to the late 1950s at, respectively, Bunaveela and Feeagh. No clear acidification effect is evident, however: the pH of water in the two poorly-buffered lakes oscillating between slightly alkaline and slightly acidic.

Hindcast model data for Feeagh, indicating relatively stable catchment conditions and low in-lake TP concentrations pre-1960, largely accord with the palaeolimnological evidence. Afforestation and overgrazing by livestock over the last c. five decades are the most likely pressures impacting aquatic conditions in Bunaveela. Afforestation, currently accounting for about 23% of land cover, targeted unproductive upland parts of the catchment (Allott & Brennan 1993). Soils in these areas were also susceptible to erosion, especially during initial planting and subsequent harvesting. Adverse impacts of afforestation locally are therefore likely to comprise alteration of catchment hydrology, erosion, siltation, acidification and eutrophication (Harriman & Morrison 1982; Ormerod et al. 1991). The sharp increase in sheep numbers from the 1970s, particularly in the western upland regions and driven largely by EU subsidies (Gillmor & Walsh 1993), and subsequent over-grazing of erosion-sensitive substrates are likely to have further added to sediment loadings to streams draining into the two lakes (Allott et al. 2005; May et al. 2005). A significant upward trend in temperature from the 1960s combined with increases in precipitation and sediment load over the last 50 years are suggested by hindcast model data, although a trend of increasing rainfall is not supported by the available meteorological data, and heightened modelled particulate N and P loads are evident post-1960s.

Palaeolimnological evidence therefore indicates that both Bunaveela and Feeagh in the Burrishoole catchment have been impacted by human-related activities, with the effects on Bunaveela beginning later and currently less pronounced than at Feeagh. The main drivers in both cases appear to be catchment erosion and nutrient enrichment associated with afforestation from the 1950s and over-grazing from the 1970s, with their aquatic impacts possibly enhanced by climate change. The sedimentary evidence therefore provides confirmation of an earlier claim that current conditions in Feeagh are nutrient enriched relative to reference (Leira et al. 2006). Moreover, the evidence calls into question the characterisation of Feeagh as a category 2a site, or ‘probably not at significant risk’ of meeting the requirements of the WFD (Anon 2005).

Mask and its catchment comprised the most complex of the sites studied in ILLUMINATE. Mask is commonly referred to in the literature as a marl, or calcite-precipitating, lake (e.g. McGarrigle and Champ 1999; Toner et al. 2005). In reality, marl precipitation characterises only the northern and eastern part of the lake, where the influence of run-off from the Carra and Robe subcatchments is greatest. Elsewhere the lake is much less alkaline in nature, owing to the influence of run-off from the acidic, western parts of the catchment. Cores of sediment were collected from three coring sites at Mask. Problems of preservation, in part caused by differential rates of Si dissolution, were a factor at all three coring sites. Moreover, only cores from the southwest part of the lake permitted a reasonably well-dated, high resolution sediment-based study of changes in aquatic pressures and their effects over the last c. 150 years. The rate of sediment accumulation at the other two coring sites proved to be very low. Thus although the deepest point and the eastern basin coring sites yielded sedimentary records covering the last c. 6200 years and >2700 years, respectively, in both cases the last c. 150 years were compressed into the uppermost few cm of sediments. Varying levels of the degree of preservation of sediment-based proxies observed at all three coring sites are themselves worthy of further study. These variations were expressed on an apparently cyclical basis, and may have been driven by changes in lake water chemistry that had a climatic cause.

Sedimentary evidence from sites 1 and 2 at Mask indicate the onset of nutrient enrichment could date to as long as the middle of the last millennium, and is reflected in distinct changes in diatom and macrophyte remains and sediment geochemistry, and in increased DI-TP. Although the evidence of early nutrient enrichment at Mask is poorly resolved and dated, early eutrophication has been detected in the sediment records from other lakes in Ireland (Dalton et al. 2009). Moreover, nutrient enrichment appears to have been a factor by the late 19th century, according to the more finely resolved and firmly dated sedimentary evidence in the core from the southwestern part of the lake. Levels of reconstructed epilimnic TP are in the highly mesotrophic range at the beginning of the 20th century. Nutrient enrichment in the late 19th/early 20th century is also marked in the sedimentary record by an absence of the remains of *Chara*, possibly as a result of eutrophication-induced, reduced transparency (although differential preservation may also have been a factor). A period of recovery, or oligotrophication, appears to have taken place during the early part of the 20th century, with eutrophication impacts returning by the late 1950s. The latter is marked by increased abundances of diatom taxa having TP optima outside the oligotrophic range (e.g. *Asterionella formosa* and, to a lesser extent, *Tabellaria flocculosa*). Levels of sediment P also increase sharply from the late 1970s. Preservation of sediment-based proxies was particularly problematic in the uppermost part of the sedimentary record from the southwest part of Mask, with the most recently deposited sediments analysed dating to the late 1990s. Diatoms extracted from these sediments indicate some recovery of lake water quality.

Nutrient enrichment pressures and their impacts at Mask may therefore have commenced at a relatively early date. Increased nutrient loadings from the mid 20th century are likely to be both point and diffuse sources, while their effects may have been enhanced by increased water temperatures over the last five decades. Diffuse sources of eutrophication pressures are likely to have become more prominent as a result of improvements to sewage treatment facilities and, initially at least, a reduced level of human population. Raw sewage from Ballinrobe was discharged to the Robe until 1948, when primary treatment was installed (K. Shally pers. comm.). Further improvements, in the form of a new secondary treatment system (with P removal), were implemented in 1996 and reduced annual P loading to the lake by at least 3 tonne P yr^{-1} (McGarrigle & Champ 1999). Reduced inputs from point sources have only partially compensated increased loadings from diffuse agricultural sources, however. In particular, stocking densities of cattle and sheep rose sharply from the early 1960s. Although diffuse nutrient loadings are likely to have increased in all three of the Mask subcatchments as a consequence, the Robe subcatchment remains prominent as a source and was responsible for up to c. 85% of the total P loading to Mask in the late 1990s (McGarrigle & Champ 1999). Afforestation on upland peats in the western part of the catchment, beginning c. 1990, is also likely to have led to increased nutrient loadings to the lake.

Although problems concerning the differential preservation of palaeolimnological evidence at Mask cannot be discounted, enhanced nutrient loadings by the early 1950s are in line with simulations from hindcast modelling. Moreover, a significant change point occurs in the hindcast data in 1978, corresponding to increased cattle and sheep stocking densities in the catchment. Numbers of cattle and sheep have since fallen, and reconstructed epilimnic P shows some improvement in trophic status, possibly linked to reduced stocking densities in the catchment. However, diffuse sources of nutrients continue to pose a threat to the successful implementation of the WFD at Mask, thereby justifying the current ‘at significant risk’ characterisation of the lake.

5.2 Hindcast trophic status

The modelling exercises carried out in Chapter 4 provide several different parameters that can be used to assign an annual trophic status to the study lakes for the time period prior to available monitoring data. These include two estimates of in-lake TP concentrations (DI-TP and GWLF TP), together with simulated chlorophyll-a levels from CAEDYM. The availability of long-term monitoring data for Leane since the early 1970s allows these estimates to be validated. Although the annual TP concentration in Leane was generally over-estimated by DI-TP values, there was good agreement between the TP estimates based on input of loads from GWLF to CAEDYM and with the simpler approach based on Foy’s (1992) modified Vollenweider model (Table 5.1). The agreement between the latter two estimates of TP concentrations suggests that the potential of the simpler approach, using Foy (1992), for estimating past lake trophic status is equal to the more complex dynamic modelling of in-lake processes. However, the original equation of Foy (1992) was based on a limited number of lakes in Ireland: an update of this work could provide a useful management tool. In addition to TP, good agreement also existed between trophic status based on CAEDYM-simulated chlorophyll-a levels and that derived from in-lake measured values. However, as with trophic status based on monitoring data, high chlorophyll-a levels did not occur in all years in which TP concentrations were in the higher parts of the eutrophic range.

All available evidence suggests that Leane was mesotrophic from the 1940s. An oligotrophic status is also indicated for some years prior to 1960, based on modelled chlorophyll-a. Before 1971, untreated sewage was discharged directly into the lake and STP inputs were estimated to have accounted for 68% of the load in 1982: this contribution decreased substantially after the plant was upgraded, however (Jennings et al. 2008). In contrast, modelling indicates that catchment loads continued to increase and accounted for 98% of 30 tonne TP year^{-1} in 1998 (Jennings et al. 2008). For the period after the early 1980s, catchment load was dominated by the larger Flesk subcatchment. An intensive sampling programme in the Leane catchment between 1999 and 2000 supports the modelling results: according to measured data, the Flesk accounted for 80% of the TP load to Leane during the sampling period (KMM 2003).

These results, together with hindcast in-lake modelling using both a simple empirical method and the CAEDYM model, confirm that the TP concentration in Leane increased from the 1950s to present. While there is some over-estimation of TP concentrations using DI-TP, all estimates agree that Leane was in a potentially mesotrophic state from the 1940s to the 1960s and indicate that these methods have potential for hindcasting trophic status in lakes. An additional advantage of the modelling approach is that it allows exploration of the main drivers of changes in TP loading, and therefore concentration, over time. The changes in the historical data (Chapter 2 and Table 5.1), together with the change point analyses for the catchment loads for Leane, indicated a significant change in TP loadings in 1971, coincident with an increased number of cattle in the catchment.

In-lake response simulations could not be conducted for Feeagh and fewer monitoring data exist for both Feeagh and Mask when compared with Leane. For Feeagh, measurements of proxies of trophic status were consistently different throughout the monitoring period, with measured chlorophyll-a indicating an oligotrophic status in all years despite TP concentrations in the low mesotrophic range (Table 5.2). This may be due to high water colour levels in the lake suppressing algal photosynthesis and growth (Jones 1992). Differences also existed between reconstructed epilimnic TP and hindcast in-lake TP concentrations using the simpler approach based on Foy's (1992) modified Vollenweider model. Despite these differences, all approaches indicated that the lake was potentially oligotrophic until the 1960s. Again a significant change point in loading was indicated for this period, which coincided with a major phase of afforestation in the catchment.

Results from both the hindcast modelling and from the sediment investigations at Mask also support recent concern relating to deteriorating water quality, notably an elevation of trophic status from oligotrophic to mesotrophic (Toner et al. 2005). In particular, results confirm nutrient enrichment in the Robe inflow, evident in previous studies (McGarrigle & Champ 1999; Donohue & Irvine 2003; Irvine et al. 2003). Results also indicate anthropogenically sourced P inputs as the sole driver of nutrient enrichment. Modelling output suggests that nutrient enrichment has been driven primarily by agricultural activity, including changes in livestock population and agricultural practices.

While the hindcast TP levels indicate that Mask has been in a potentially mesotrophic or eutrophic condition for much of the last century (Table 5.3), nutrient enrichment did not commonly lead to high levels of chlorophyll-a. The model simulations also indicate that an alteration of phytoplankton community composition may have occurred over time. Evidence for an increase in the abundance of cyanobacteria and, in some months, chlorophytes accords with results from a recent study of the phytoplankton composition in Mask (McCarthy et al. 2001). Cyanophytes are known to out-compete other algae for resources when nutrients are relatively freely available and cause toxic algal blooms (Wetzel 2001). Increased stratification, indicated in the modelling results, could possibly have favoured cyanobacterial species (Jöhnk et al. 2007; Wilhelm & Adrian 2008). Such changes in primary producers could ultimately affect higher trophic levels and lead to critical changes in the ecological dynamics of Mask. Hindcast in-lake responses highlight the sensitivity of the lake to catchment pressures, particularly agricultural activity and possible climate change. This study also highlights the threat posed to the future of Mask, in terms of its ecology and viability as a local water supply, and the risk of it failing to meet WFD objectives by 2015.

5.3 Future simulations: implications for catchment management

If no further action is taken to reduce greenhouse gas emissions, the global average surface temperature is likely to rise by a further 1.1 to 6.4°C this century (IPCC 2007). Although the WFD does not explicitly refer to climate change, future climate variability has obvious implications for the long-term implementation of the Directive and for the formulation and review of management plans (Wilby et al. 2006; Ulén & Weyhenmeyer 2007). The pressing need for more studies investigating the potential impacts of these changes on freshwater systems, in particular impacts on water quality and the coupling of climate model output with land-use change, was emphasised in the latest IPCC report (Kundzewicz et al. 2007). These studies can only be undertaken through a combination of climate and catchment modelling similar to that carried out in ILLUMINATE.

Exploration of the impacts of projected climate changes on catchment pressures and ecological responses in ILLUMINATE identified several key impacts that would have major implications for catchment management, both in Ireland and in similar freshwater systems in other regions (Figure 5.1). These included changes in the seasonal pattern of nutrient loading to lakes and subsequent changes in the phytoplankton biomass, together with the potential for seasonal shifts in peak biomass driven by changes in stratification. Simulations of the impacts of combined projected climate, land-use and population changes highlighted the potential for increases in P export from catchments (Jennings et al. 2009b) (Figure 5.1 1). Similar changes in the seasonal pattern of rainfall and air temperature to those used in the current research are projected across Ireland and Britain (Samuelson 2009). Thus the findings from ILLUMINATE have relevance beyond the three study catchments, and probably beyond the Irish Ecoregion. This wider relevance would appear to be borne out by available published data. For example, a comparable pattern of change in stream flow and dissolved P export was found for a grassland catchment in the UK (Pierson et al. 2009), while simulations using the SWAT model in another UK catchment reported potential increases in winter and decreases in summer TP export (Bouraoui et al. 2002). Both of these studies were based solely on changes in climate. The projected increases in loading for the more immediate time period of 2021 to 2060 were also based on changes in climate alone. Interestingly, while the increase in loading was lower than that expected for the later time period of 2071 to 2100, the months when increases of greatest magnitude were expected included the late summer and early autumn period. Slurry spreading is currently permitted during this period, which is also often the time of maximum algal growth. Both Leane and Mask are currently considered to be impacted by agriculturally-derived loadings of P (KMM 2003; Toner et al. 2005).

The more detailed investigation in the Flesk subcatchment indicated substantial increases in P loadings in the January/February period in particular (Jennings et al. 2009b), and highlighted the potential influence over climate change impacts by concurrent changes in population, land use and land management. More importantly, the results show that the increase in annual TP loads attributable to climate change is greater than that arising from population increase or potential land-use change. The results also clearly indicate that changes in practice at farm, local authority and national levels could be used to mitigate these increases. Decisions made as part of management plans can have far-reaching consequences that impact on the spatial and temporal patterns in P loss rates over a range of time-scales (Daly et al. 2001; Cummins & Farrell 2003). Projected changes in climate should therefore be considered in tandem with changes arising from planning and policy decisions in the management of RBDs.

Of greatest significance was the substantial increase in dissolved P loading indicated for the months between January and April, especially when climate change was combined with land-use and population change. This increase was due mainly to cattle slurry spreading and represents substantially enhanced supplies of labile P just prior to the onset of spring and therefore during a critical part of the seasonal cycle. Modelling of the impact of these changes on lake chlorophyll-a in Leane showed the potential for increased eutrophication pressures, therefore posing a significant threat to the successful, long-term implementation of the WFD. More importantly, results indicated that the addition of potential changes in land use and population could lead to further increases in chlorophyll-a levels (Figure 5.1 2). Once again, this threat is generally applicable to catchments where nutrient management is a problem. Projected increases in chlorophyll-a in the Leane simulations resulted mainly from an increase in cyanobacteria, which thrive under calm, warm conditions (Jöhnk et al. 2007; Wilhelm

& Adrian 2008). In the model simulations, this numerical dominance of cyanobacteria was due in part to the optimisation using available phytoplankton species data, which indicated that the species composition was dominated by diatoms in spring and by cyanobacteria in summer. However, projected increases in cyanobacteria as a result of climate change have also been indicated for other lakes (Elliot et al. 2006; Shatwell et al. 2008; Elliot 2009). Utilising climate projections based on the same set of GCM-RCM simulations used for Leane with the PROTECH model, Elliot et al. (2006) reported that annual mean phytoplankton biomass increased as a result of warming and nutrient enrichment in eutrophic Esthwaite Water (UK), although nutrients had the larger effect. As with the results using the A2 scenarios in the present study (Figure 5.1 3), they also reported that the phenology of the dominant phytoplankton taxa changed with increasing water temperature, with a simulated summer bloom of *Anabaena* occurring earlier in the year. More recently, Elliot (2009) reported that projected changes in climate led to enhanced abundances and longevity of *Anabaena* in model simulations. Cyanobacterial biomass in the simulations exceeded the WHO derived risk thresholds (10 and 50 mg m^{-3}) for safe drinking water. Projected changes in climate may therefore have implications not just for the trophic status of lakes but also human health, particularly where lakes are used as water sources.

Projected increases in DOC concentrations also have implications both for the ecology of lakes and for human health where water is sourced from peat catchments (Figure 5.1 5). Feeagh is an important fish habitat, especially for the freshwater stages of salmon and sea trout. Many highly coloured lakes like Feeagh exhibit net heterotrophy, owing to the central role of catchment-derived DOC in fuelling the upper trophic levels via the bacterioplankton-protozoan link (e.g. Tranvik 1992; Kankaala et al. 1996). The projected increases in DOC may, therefore, alter the food-web dynamics in these lakes; the impact of these changes on the C dynamics could be a topic for further research (Figure 5.1 6). Reduced light intensity also lowers the reactive distance of fish and their ability for size-selective predation (Wissel et al. 2003), while the hypolimnion can become anoxic during periods of intense stratification and decomposition of DOC (Salonen et al. 1984). This anoxic zone can provide a refuge for prey species that are less sensitive to oxygen availability than fish (Wissel et al. 2003). Darkly coloured water also absorbs solar radiation more effectively, resulting in a steepening of temperature stratification and increased thermal stability, particularly in small and sheltered lakes (Eloranta 1978, Jones and Arvola 1984).

In addition to these local impacts, projected increases in DOC concentration may have implications for water treatment and supply, and for the global C cycle. DOC must be removed from drinking water because of the aforementioned health concerns relating to THMs. THMs are one of six parameters that continue to be of concern in drinking water supplies in Ireland (Page et al. 2009). In 2007-2008, monitoring in Ireland indicated that THM levels were in excess of the parametric value in almost 10% of public water supplies (Page et al. 2009). The projected depletion in water availability in the early autumn in both the Leane and Feeagh catchments could also lead to difficulties in meeting water supply requirements. A positive feedback mechanism between decomposition in organic soils and climate change has been suggested, with changes in climate driving increases in the export of DOC that in turn would increase atmospheric CO_2 concentrations and contribute to further global warming (Knorr et al. 2005; Davidson & Janssens 2006).

Work completed during ILLUMINATE also included an assessment of the potential impact of projected changes in water temperature on salmon survival in the Burrishoole catchment (McGinnity et al. 2009) (Figure 5.1 7). This work was based on a unique 37 year datasets relating to salmon populations in the catchment. A dearth of such long time series datasets for key taxonomic groups, including fish, and a shortage of studies on ecological responses to combined pressures, were identified as major knowledge gaps in research supporting the WFD by Heiskanen and Solimini (2005). Adult Atlantic salmon in the Burrishoole river system typically spawn in December and juveniles generally spend three winters in freshwater, including the winter when eggs are buried in the gravel bed of the water body, before migrating to sea in May or June as smolts. A total trapping system for the counting of returning adults and migrating smolts has operated at Burrishoole since 1969, allowing the quantification of all fish entering and leaving the system and the estimation of egg numbers. Egg estimates included egg deposition from an experimental captive breeding and smolt release (ranching) programme established between 1960 and 1964. Returning ranched-adults, surplus to the requirements of the captive breeding programme, were allowed to ascend the river system between 1960 and 1997 and could therefore interbreed with wild fish

(Thompson et al. 1998). Numbers of ranched fish entering the river have been curtailed in recent years to prevent such interbreeding.

Multiple regression analyses of these data produced an ecogenetic model of egg-to-smolt survival for salmon in the Burrishoole catchment (McGinnity et al. 2009). The model indicated that 76% of the variability in egg-to-smolt survival in the salmon population was explained by five climate-related factors and the proportion of eggs in the natural spawning population contributed by ranched fish. The proportion of eggs from ranched fish in the spawning population had a significant negative impact on survival. Higher water temperatures in the first winter, when eggs were incubating in gravel beds, and during the second winter, when fish were in the parr stage, had negative impacts on survival. The impact of higher winter water temperatures was, however, significantly greater when there was a larger cohort of ranched fish in the total population, suggesting that the progeny of ranched fish are more sensitive to projected temperature increases. Higher water temperatures in the first winter were possibly problematic because earlier hatching in a warmer winter is not always correlated with earlier phytoplankton or macroinvertebrate production, thus leading to insufficient food supplies for recently hatched parr. In the case of parr survival, higher water temperatures increase fish metabolism, so juvenile fish may deplete their energy reserves before the spring food supply becomes available (McGinnity et al. 2009).

Future changes in water temperature were simulated for Feeagh using DYRESM. Future egg-to-smolt survival was then estimated based on the regression model and projected changes in water temperature and precipitation. This indicated no reduction in egg-to-smolt survival when the proportion of eggs from ranched fish was low. However, poor outcomes and considerably lower egg-to-smolt survival were predicted for the population when the proportion of eggs originating from ranched fish was high with zero smolt recruitment in some years. The study concluded that ranched fish capable of breeding in the wild, even where strains have been established from local or progenitor stocks, should not be deliberately introduced into natural salmon rivers, and that measures must be found to reduce the numbers of escaped farm salmon in nature, if wild salmon populations are to adapt successfully to climate change (McGinnity et al. 2009).

The 4th IPCC assessment report confirms that global warming is strongly affecting biological systems and that 20-30% of species risk extinction from projected future increases in temperature. Any measures taken to conserve individual species against climate mediated declines, while often pressing, must be appropriate, and not themselves constitute a further threat to survival. The release of captive bred animals to augment wild populations is a widespread management strategy but has proven controversial. The study concluded that many species could adapt to projected climate change if given sufficient scope to do so. Rather than imposing an additional genetic load on wild populations by releasing captive bred animals, McGinnity et al. (2009) propose that conservation efforts should focus on optimising conditions for adaptation to occur by reducing exploitation and protecting critical habitats.

Table 5.1 Leane: hindcast and measured trophic status based on the modified OECD classification as described in S.I. No. 258 of 1998.

Year	TP DI-TP	TP GWLF/DC	TP GWLF/Foy	Chl-a GWLF/DC	Chl-a Measured	TP Measured
2005	🟧	🟧	🟨	🟨	🟨	🟨
2004	🟧	🟨	🟨	🟨	🟨	🟨
2003		🟨	🟨	🟧	🟨	🟨
2002	🟧	🟨	🟨	🟨	🟨	🟧
2001		🟨	🟨	🟨	🟨	🟨
2000	🟧	🟨	🟨	🟨	🟨	🟨
1999	🟧	🟨	🟨	🟨	🟨	🟨
1998	🟧	🟨	🟨	🟨	🟧	🟧
1997	🟧	🟨	🟧	🟧	🟥	🟧
1996	🟧	🟨	🟨	🟨	🟨	🟧
1995	🟧	🟧	🟧	🟨	🟨	
1994	🟧	🟨	🟨	🟨	🟨	
1993	🟧	🟨	🟨	🟨	🟨	🟧
1992	🟧	🟨	🟨	🟨	🟩	🟨
1991	🟧	🟨	🟨	🟨	🟨	🟨
1990		🟨	🟨	🟨	🟩	🟨
1989		🟨	🟨	🟨	🟨	🟨
1988	🟧	🟨	🟨	🟨	🟨	🟧
1987	🟧	🟨	🟨	🟨	🟨	🟨
1986	🟧	🟨	🟨	🟩	🟨	🟨
1985	🟧	🟧	🟧	🟩	🟨	🟧
1984	🟧	🟧	🟧	🟨	🟧	🟧
1983	🟧	🟧	🟨	🟧	🟧	
1982	🟧	🟧	🟧	🟧	🟨	
1981		🟧	🟧	🟨	🟨	
1980	🟧	🟨	🟧	🟨	🟨	
1979	🟧	🟧	🟧	🟨	🟨	
1978		🟧	🟧	🟨	🟨	
1977	🟧	🟧	🟧	🟨	🟨	
1976	🟧	🟧	🟧	🟧	🟨	
1975	🟧	🟧	🟧	🟧		
1974	🟧	🟧	🟨	🟩	🟨	
1973		🟧	🟧	🟧	🟨	
1972	🟧	🟧	🟨	🟨		
1971	🟧	🟧	🟧	🟨		
1970	🟧	🟧	🟨	🟨		
1969	🟧	🟨	🟧	🟨		
1968	🟧	🟨	🟨	🟧		
1967		🟨	🟨	🟨		
1966	🟧	🟨	🟨	🟨		
1965	🟧	🟧	🟨	🟨		
1964	🟧	🟨	🟨	🟨		
1963	🟧	🟧	🟨	🟨		
1962	🟧	🟨	🟨	🟨		
1961	🟧	🟨	🟨	🟨		
1960		🟨	🟨	🟨		
1959	🟧	🟨	🟨	🟨		
1958	🟨	🟨	🟨	🟩		
1957	🟨	🟨	🟨	🟨		
1956	🟨	🟨	🟨	🟨		
1955	🟨	🟨	🟨	🟨		
1954	🟨	🟨	🟨	🟩		
1953	🟨	🟨	🟨	🟨		
1952	🟨	🟨	🟨	🟨		
1951	🟨	🟨	🟨	🟨		
1950	🟨	🟨	🟨	🟨		
1949	🟨	🟨	🟨	🟨		
1948	🟨	🟨	🟨	🟩		
1947	🟨	🟨	🟨	🟨		
1946	🟨	🟨	🟨	🟩		
1945		🟨	🟨	🟩		
1944		🟨	🟨	🟨		
1943		🟨	🟨	🟩		
1942		🟨	🟨	🟩		
1941		🟨	🟨	🟩		

🟥 Hypertrophic	🟧 Eutrophic
🟨 Mesotrophic	🟩 Oligotrophic

Table 5.2 Feeagh: hindcast and measured trophic status based on the modified OECD classification as described in S.I. No. 258 of 1998.

Feeagh **Year**	**TP** **DI-TP**	**TP** **GWLF/Foy**	**Chl-a** **Measured**	**TP** **Measured**
2007	🟨		🟩	🟩
2006		🟩		
2005	🟨	🟩		🟨
2004	🟨	🟩		🟨
2003		🟩	🟩	🟩
2002	🟨	🟩	🟩	
2001		🟩		
2000	🟨	🟩		
1999	🟨	🟩		
1998	🟨	🟩	🟩	🟩
1997	🟨	🟩	🟩	🟨
1996		🟩		
1995	🟨	🟩		
1994	🟨	🟩		
1993	🟨	🟩		
1992	🟨	🟩		
1991	🟨	🟩		
1990	🟨	🟩		
1989		🟩		
1988	🟨	🟩		
1987	🟨	🟩		
1986	🟨	🟩		
1985		🟩		
1984	🟨	🟩		
1983	🟨	🟩		
1982		🟩		
1981	🟨	🟩		
1980	🟨	🟩		
1979		🟩		
1978	🟨	🟩		
1977		🟩		
1976	🟨	🟩		
1975		🟩		
1974	🟨	🟩		
1973	🟨	🟩		
1972	🟨	🟩		
1971		🟩		
1970	🟨	🟩		
1969		🟩		
1968		🟩		
1967	🟨	🟩		
1966		🟩		
1965	🟨	🟩		
1964		🟩		
1963	🟩	🟩		
1962		🟩		
1961		🟩		
1960	🟩			
1959				
1958				
1957	🟩	🟩		
1956		🟩		
1955	🟩	🟩		
1954		🟩		
1953		🟩		
1952	🟩	🟩		
1951		🟩		
1950	🟩	🟩		
1949		🟩		
1948	🟩	🟩		
1947		🟩		
1946	🟩	🟩		
1945		🟩		
1944	🟩	🟩		
1943		🟩		
1942	🟩	🟩		
1941		🟩		
1940	🟩	🟩		
1939		🟩		
1938	🟩	🟩		
1937		🟩		
1936	🟩	🟩		
1935		🟩		
1934	🟩	🟩		
1933		🟩		
1932	🟩	🟩		
1931		🟩		
1930	🟩	🟩		
1929		🟩		
1928	🟩	🟩		
1927				
1926		🟩		
1925	🟩	🟩		

🟥 Hypertrophic	🟧 Eutrophic
🟨 Mesotrophic	🟩 Oligotrophic

Table 5.3 Mask: hindcast and measured trophic status based on the modified OECD classification as described in S.I. No. 258 of 1998.

Year	TP DI-TP	TP GWLF/DC	TP GWLF/Foy	Chl-a GWLF/DC	Chl-a Measured	TP Measured
2005	🟨	🟨	🟧	🟨	🟨	🟨
2004	🟨	🟨	🟨	🟩	🟩	🟨
2003	🟨	🟨	🟧	🟩	🟨	🟨
2002	🟨	🟨	🟨	🟨	🟨	🟧
2001	🟨	🟨	🟧	🟨	🟨	🟨
2000	🟨	🟨	🟨	🟨	🟨	🟨
1999	🟨	🟨	🟨	🟨	🟨	🟨
1998	🟨	🟨	🟨	🟩	🟨	🟨
1997	🟨	🟨	🟧	🟧	🟨	🟨
1996	🟨	🟧	🟨	🟨		
1995	🟨	🟧	🟧	🟧		
1994	🟨	🟧	🟨	🟨		
1993	🟨	🟧	🟧	🟧		
1992	🟨	🟧	🟨	🟨		
1991	🟨	🟧	🟨	🟧		
1990	🟨	🟧	🟨	🟨		
1989	🟨	🟧	🟨	🟨		
1988	🟨	🟨	🟨	🟨		
1987	🟨	🟨	🟧	🟨		
1986	🟨	🟨	🟨	🟩		
1985	🟨	🟨	🟨	🟩		
1984	🟨	🟨	🟨	🟨		
1983	🟨	🟧	🟨	🟨		
1982	🟨	🟨	🟨	🟧		
1981	🟨	🟨	🟨	🟩		
1980	🟨	🟨	🟨	🟩		
1979	🟨	🟨	🟨	🟩		
1978	🟨	🟨	🟨	🟩		
1977	🟨	🟧	🟨	🟨		
1976	🟨	🟧	🟨	🟩		
1975	🟨	🟧	🟨	🟩		
1974	🟨	🟧	🟨	🟨		
1973	🟨	🟧	🟨	🟨		
1972	🟨	🟧	🟨	🟨		
1971	🟨	🟧	🟨	🟨		
1970	🟨	🟧	🟨	🟩		
1969	🟨	🟧	🟨	🟧		
1968	🟨	🟧	🟨	🟧		
1967	🟨	🟧	🟨	🟧		
1966	🟨	🟧	🟨	🟧		
1965	🟨	🟨	🟨	🟨		
1964	🟨	🟧	🟨	🟨		
1963	🟨	🟧	🟨	🟨		
1962	🟨	🟧	🟨	🟨		
1961	🟨	🟧	🟨	🟩		
1960	🟨	🟨	🟨	🟩		
1959	🟨	🟨	🟨	🟧		
1958	🟨	🟧	🟨	🟩		
1957	🟨	🟧	🟨	🟨		
1956	🟨	🟧	🟨	🟨		
1955	🟨	🟧	🟨	🟧		
1954	🟨	🟧	🟨	🟨		
1953	🟨	🟧	🟨	🟨		
1952	🟨	🟧	🟨	🟧		
1951	🟨	🟧	🟨	🟨		
1950	🟨	🟧	🟨	🟩		
1949	🟨		🟨			
1948	🟨		🟨			
1947	🟨		🟨			
1946	🟨		🟨			
1945	🟨		🟨			
1944	🟨		🟨			
1943	🟨		🟨			
1942	🟨		🟨			
1941	🟨	🟨	🟨	🟩		
1940	🟨	🟨		🟩		
1939	🟨	🟨		🟩		
1938	🟨	🟨		🟩		
1937	🟨	🟨	🟨	🟩		
1936	🟨	🟨	🟨	🟩		
1935	🟨	🟨	🟨	🟩		
1934	🟨	🟨	🟨	🟩		
1933	🟨	🟨	🟨	🟩		
1932	🟨	🟨	🟨	🟩		
1931	🟨	🟨	🟨	🟩		
1930	🟨	🟨	🟨	🟩		
1929	🟨	🟨	🟨	🟩		
1928	🟨	🟨	🟨	🟩		
1927	🟨	🟨	🟨	🟩		
1926	🟨					
1925	🟨	🟨	🟨	🟩		
1924	🟨	🟨	🟨	🟩		
1923	🟨		🟨			
1922	🟨		🟨			
1921	🟨		🟨			
1920	🟨		🟨			
1919	🟨		🟨			
1918	🟨		🟨			
1917	🟨		🟨			
1916	🟨					
1915	🟨					
1914	🟨		🟨			
1913	🟨	🟨	🟨	🟩		
1912	🟨	🟨	🟨	🟩		
1911	🟨	🟨	🟨	🟩		
1910	🟨	🟨	🟨	🟩		

🟥 Hypertrophic	🟧 Eutrophic
🟨 Mesotrophic	🟩 Oligotrophic

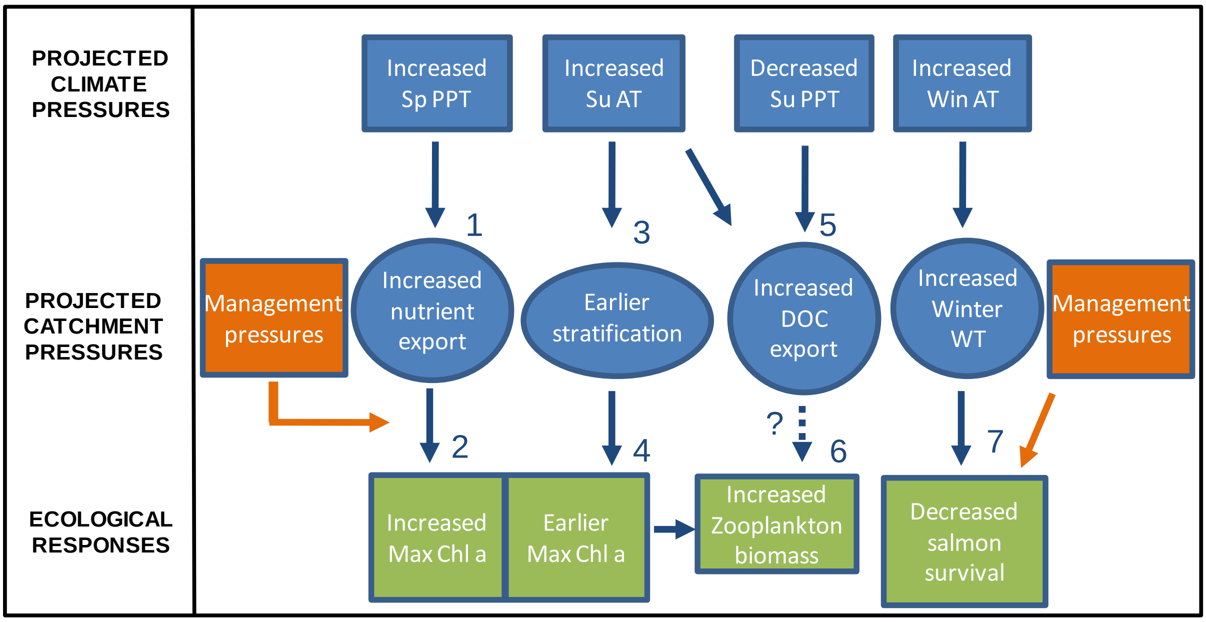


Figure 5.1 Summary diagram of the potential impacts of projected changes in climate and catchment management. Sp PPT = spring precipitation; Su AT = summer air temperature; Win AT = winter air temperature; Winter WT = winter water temperature

Chapter 6 Conclusions

Focusing on three study catchments and associated lakes and divided into four, integrated WPs, ILLUMINATE aimed to: establish reference conditions and determine aquatic ecological responses to particular and combined past pressures; use coupled dynamic ecological pressure-response models in combination with existing and new environmental information to simulate past and future scenarios of direct relevance to implementation of the WFD in Ireland; and provide informed comment on the at risk characterisation of the study lakes, where possible**.** The ILLUMINATE mandate to make best use of existing research infrastructure and available data guided the choice of the study catchments. The mandate also required ILLUMINATE to engage as closely as possible with previously funded research projects of a similar nature, such as IN-SIGHT and CLIME, with relevant, contemporaneous research projects, for example EURO-LIMPACS and with the activities of the WRBD and SWRBD. Arriving at the conclusions that follow, which relate directly to the above aims, was greatly facilitated through engagement with previous and ongoing relevant research and with those directly involved in the management of water bodies in the three study catchments.

1. Quantitative reconstructions of historical in-lake TP using fossil diatom assemblages and computer-based modelling of past conditions enabled the trophic status of the study lakes to be established for the time period prior to available monitoring data. While there is some over-estimation of TP concentrations using DI-TP, all estimates are in general agreement and provide a basis for confidence in the value of the approach adoped in ILLUMINATE.
2. Dynamic modelling of individual and combined ecological pressures, in the form of projected climate, land-use and population changes and their in-lake physical effects, highlighted the potential for increases in P export from the study catchments. Projected increases in transfers of P attributable to climate change potentially could be mitigated via changes in practice at farm, local and national levels, highlighting the desirability of including consideration of future changes in climate when undertaking modelling in support of decision making in catchment management.

3. Modelling of the in-lake responses to projected changes in nutrient and sediment loading and climate indicated the potential for increases in phytoplankton biomass and a shift in maximum biomass to earlier in the year.
4. Palaeolimnology-based reconstructions and model output representing past conditions support the current ‘at significant risk’ designation for Leane and Mask and ‘probably not at significant risk’ designation for Muckross. The characterisation of Feeagh as ‘probably not at significant risk’ is not supported, however. Continued catchment pressures, leading to nutrient levels being maintained above reference, severely jeopardise successful attainment of the WFD objectives for this site by the end of the current implementation period (i.e. 2015).
5. Climate change is now confounding and potentially exacerbating existing problems and represents a major challenge for how freshwaters might be managed sustainably in future. The case for considering climate change in tandem with changes arising from planning and policy decisions in the management of RBDs is compelling.
6. Aside from meeting the main research aims, ILLUMINATE acts as a demonstration of the utility and potential benefits of combining computer-based modelling of catchment and associated lake ecosystem condition and linkages with other sources of information. In ILLUMINATE, the latter comprised existing documentary and instrumental evidence and data from ecological and sedimentological analyses. This information can be used to fine-tune model output, and as a basis for realistic future scenarios. Moreover, the approach adopted in ILLUMINATE is flexible, readily updatable as new technologies and data become available, and highly portable.

References

Airs, L.R., Atkinson, J.E. & Keely, B.J. 2001. Development and application of a high resolution liquid chromatographic method for the analysis of complex pigment distributions. Journal of Chromatography A 917: 167-177.

Allott, N. & Brennan, M. 1993. Stream chemistry and biota, Galway-Mayo Region. In Evaluation of the effects of forestry on surface-water chemistry and fishery potential in Ireland. Vol. 2 Eolas, Dublin, 109 pp.

Allott, N. McGinnity, P. & O’Hea, B. 2005. Factors influencing the downstream transport of sediment in the Lough Feeagh catchment Burrishoole, Co. Mayo, Ireland. Freshwater Forum 23: 126-13.

Allott, N., Jennings, E. & Duffey, A. 2008. Rainfall distribution in a catchment in SW Ireland, implications for catchment modelling. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 30(4): 431-434.

Allott, N., McGinnity, P. & O'Hea, B. 2005. Factors influencing the downstream transport of sediment in the Lough Feeagh catchment, Burrishoole, Co. Mayo, Ireland. Freshwater Forum 23: 126-138.

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

Amoros, C. 1984. Introduction pratique a la Systematique des organismes des eaux continentales françaises. Bulletin de la Société Linnéene de Lyon 53: 72-145.

Anderson, J.N. 1997 Historical changes in epilimnetic phosphorus concentrations in six rural lakes in Northern Ireland. Freshwater Biology 38: 427–40.

Anderson, J. N., Bugmann, H., Dearing, J. A., & Gaillard, M-J. 2006. Linking palaeoenvironmental data and models to understand the past and to predict the future. Trends in Ecology and Evolution 21: 696-704

Anderson, N.J. & Korsman, T. 1990. Land-use change and lake acidification: Iron Age de-settlement in northern Sweden as a pre-industrial analogue. Philosophical Transactions of the Royal Society, London, B 327: 373-376.

Andréasson, J., Bergström, S., Carlsson, B., Graham, L.P. & Lindström, G. 2004. Hydrological Change – Climate change impact simulations for Sweden. Ambio 33: 228-234.

Anon 2005. Article 5 The characterisation and analysis of Ireland's river basin districts. In accordance with Section 7 (2 & 3) of the European Communities (Water Policy) Regulations 2003 (SI 722 of 2003). National Summary Report (Ireland). Compendium of public submissions and responses.

Appleby, P.G. & Oldfield, F. 1978. The calculation of ^{210}Pb dates assuming a constant rate of supply of unsupported ^{210}Pb to the sediment. Catena 5: 1-8.

Appleby, P.G. 2001. Chronostratigraphic Techniques in Recent Sediments. In: W. M. Last & J.P. Smol, Tracking Environmental Change Using Lake Sediments. Vol. 1: Basin Analysis, Coring and Chronological Techniques. Dordrecht, The Netherlands, Kluwer Academic Publishers pp. 155_202.

Arnold, J. G., Srinivasan, R. Muttiah, R. S. & J. R. Williams. 1998 Large area hydrological modelling and assessmnet Part I: Model development. Journal American Water Works Association 34: 73-89

Barbiero, R.P. 2000. A multi-lake comparison of epilithic diatom communities on natural and artificial substrates. Hydrobiologia 438: 157-170.

Battarbee, R., Carvalho, L., Jones, V.J., Flower, R.J., Cameron, N.G., Bennion, H. & Juggins, S. 2001. Diatoms. In: J.P. Smol, H.J.B. Birks & W.M. Last, Tracking

Environmental Change Using Lake Sediments. Vol. 3: Terrestrial, Algal and Siliceous Indicators Kluwer Academic Publishers, Amsterdam, pp. 155-202.

Battarbee, R.W. 1984. Diatom analysis and the acidification of lakes. Philosophical Transactions of the Royal Society, London, B 305: 451-477.

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

Bennett, K. D. 1996. Determination of the number of zones in a biostratigraphic sequence. New Phytologist 132: 155-179.

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

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

Bennion, H., Johnes, P., Ferrier, R., Phillips., G. & Haworth, E. 2005. A comparison of diatom phosphorus transfer functions and export coefficient models as tools for reconstructing lake nutrient histories. Freshwater Biology 50: 1651-1670.

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

Binford, M.W. 1990. Calculation and uncertainty analysis of ^{210}Pb dates for PIRLA project lake sediment cores. Journal of Paleolimnology 3: 253-267.

Birks, H.H. & Birks, H.J.B. 2006. Multi-proxy studies in paleolimnology. Vegetation History and Archaeobotany, 15: 235-251.

Birks, H.H. 2001. Plant Macrofossils. In: J.P. Smol, H.J.B. Birks & W.M. Last (eds.) Tracking Environmental Change using Lake Sediments. Vol. 3: Terrestrial, Algal and Siliceous Indicators, pp. 49-74. Kluwer, Dordecht, The Netherlands.

Birks, H.H. 2007. Plant macrofossil methods and studies. In: S.A. Elias (ed.) Encyclopedia of Quaternary Science. Elsevier, Amsterdam, The Netherlands.

Björck, S. & Wohlfarth, B. 2001. ^{14}C chronostratigraphic techniques in paleolimnology. In: W.M. Last & J.P. Smol, (eds.), Tracking Environmental Change Using Lake Sediments. Vol. 1: Basin Analysis, Coring and Chronological Techniques pp. 205-245. Kluwer, Dordecht, The Netherlands.

Blenckner, T., Adrian, R., Livingstone, D.M., Jennings, E., Weyhenmeyer, G.A., Nic Aonghusa, C., George, D.G., Jankowski, T., Järvinen, M., Nõges, T., Straile, D., & Teubner, K. 2007. Large-scale climatic signatures in lakes across Europe, a meta-analysis. Global Change Biology 13: 1314-13.

Boorman, D. 2005. REBBECA Newsletter # 2. Relationships between ecological and chemical status of surface waters - REBECCA C-EH, UK.

Bouraoui, F., Galbiati, L., & Bidoglio, B. 2002. Climate change impacts on nutrient loads in the Yorkshire Ouse catchment UK. Hydrology and Earth System Sciences 6: 197-209.

Boyle, J.F. 2001. Inorganic geochemical methods in palaeolimnology. In: W.M. Last & J.P. Smol (eds.) Tracking Environmental Change Using Lake Sediments, Vol. 2 Physical and Geochemical Methods, pp 83-141. Kluwer, Dordecht, The Netherlands.

Bracken, J.J. 1998. The Killarney Valley. In: C. Moriarty (ed.) Studies of Irish rivers and lakes. Dublin, Marine Institute pp. 145-167.

Brancelj, A., Sisko, M., Muri, G., Appleby, P., Lami, A., Shilland, E., Rose, N.L., Kamenik, C., Brooks, S.J. & Dearing, J.A. 2002. Lake Jezero v Ledvici (NW Slovenia) - changes in sediment records over the last two centuries. Journal of Paleolimnology 28: 47-58.

Brennan, M.T., Wilson, J.G., Jeffrey, D.W., Dowley, A., Jennings, E. & Hussey, M. 1994. Particulate Nutrient Inputs and Their Role in Macroalgal Development in Dublin Bay. Report to STRIDE Measure 3 Environment Sub-programme. Department of the Environment. Dublin.

Brugam, R. McKeever, K. & Kolesa, L. 1998. A diatom-inferred water depth reconstruction for an Upper Peninsula, Michigan lake. Journal of Paleolimnology 20: 267-276.

Buishand, T.A. 1982.Some methods for testing the homogeneity of rainfall records, Journal of Hydrology 58:1-27.

Carol, D., Dearing, J. & Roberts, R. 1998. Land-use history and sediment flux in a lowland lake catchment: Grotby Pool, Leicestershire, UK. The Holocene 8: 383-394.

Carvalho, L. & Defew, L.H. 2005. Eutrophication pressures. In: A.S. Heiskanen & A.G. Solimini (eds.) Relationships between pressures, chemical status and biological quality elements: analysis of the current knowledge gaps for the implementation of the Water Framework Directive. REBECCA Report D4.

Carvalho, L., Maberly, S. May, L., Reynolds, C. Hughes, M. Brazier, R., Heathwaite, L., Liu, S., Hilton, J., Hornby, D., Bennion, H., Elliot , A., Willby, N. Dils, R., Pope, L., Fozzard I. & Phillips, G. 2004. Risk Assessment methodology for determining nutrient impacts in surface freshwater bodies. Environment Agency & Scottish Environment Protection Agency, R&D technical report P2-260/9, Bristol.

Cerling, T.E. 1999. Paleorecords of C4 plants and ecosystems. In: Sage, R.F. & Monson, R.K. (eds.) C4 Plant Biology, London, Academic Press pp. 445-469.

Cerosaletti, P.E. Fox, D.G. & Chase L.E. 2004. Phosphorus reduction through precision feeding of dairy cattle. J. Dairy Sci. 87: 2314–2323.

Chambers, F. & Blackford, J.J. 2001. Mid- and late-Holocene climatic changes: a test of periodicity and solar forcing in proxy-climate data from blanket peat bogs. Journal of Quaternary Science 16(4): 329-338.

Chen, G., Dalton, C., Leira, M., & Taylor, D. 2008. Construction of diatom-inferred pH and total phosphorus (TP) transfer functions for the Irish Ecoregion using palaeolimnological techniques. Journal of Paleolimnology 40:143-163.

CLC (CORINE Land Cover) 2000. Seamless vector database. http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2000-clc2000-seamless-vector-database (accessed throughout duration of ILLUMINATE)

Coillte 2006. District Strategic Plan 2006 - 2010 District S4 South West Peninsulas. Coillte, Wicklow, Ireland.

Confer, J. L., Howick, G. L., Corzette, M. H., Kramer, S. L., Fitzgibbon, S. & Landesberg, R. 1978. Visual predation by planktivores. Oikos 31: 27-37.

CSO (Central Statistics Office) 1970. Census for the island of Ireland. Stationery Office, Dublin

CSO (Central Statistics Office) 1980. Census for the island of Ireland. Stationery Office, Dublin

CSO (Central Statistics Office) 1991. Census for the island of Ireland. Stationery Office, Dublin

CSO (Central Statistics Office) 1997. Farming since the famine. Stationery Office, Dublin.

CSO (Central Statistics Office) 2000. Census for the island of Ireland. Stationery Office, Dublin

CSO (Central Statistics Office) 2005. Regional Population Projections 2006-2021. Stationary Office, Dublin.

CSO (Central Statistics Office) 2006. Census 2006. Volume 1: Population classified by area. Stationary Office, Dublin.

CSO (Central Statistics Office) 2008. Population and labour force projections 2011-2041. Stationary Office, Dublin.

Cummins, T. & Farrell, E.P. 2003. Biogeochemical impacts on blanket peatland streams of clearfell harvesting and reforestation I: phosphorus. Forest Ecology and Management 180: 545-555.

Dalton, C., Jennings, E. & Taylor, D. (2009). Palaeolimnology and the Water Framework Directive. Special Issue Biology and the Environment. Proceedings of the Royal Irish Academy, 109B(3): 161-174 (2009).

Daly, K., Jeffrey, D. & Tunney, H. 2001. The effect of soil type on phosphorus sorption capacity and desorption dynamics in Irish grassland soils. Soil Use and Management 17: 12-20 6575.

Daly, K. & Styles, D. 2005. Eutrophication from Agricultural Sources – Phosphorus Chemistry of Mineral and Peat Soils in Ireland (2000-LS-2.1.1b-M2) Final Report. EPA.

Davidson, E.A. & Janssens, I.A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440: 165-173.

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. & Moss, M. 2003. The distribution of chydorids (Branchiopoda, Anomopoda) in European shallow lakes and its application to ecological quality monitoring. Archiv Fur Hydrobiologie156: 181-202.

de Freitas, H.A., Pessenda, L.C.R., Aravena, R., Gouveia, S.E.M., Ribeiro, A d-S. & Boulet, R. 2001. Late Quaternary vegetation dynamics in the southern Amazon basin inferred from carbon isotopes in soil organic matter. Quaternary Research 55: 39-46.

De Meeus, C., Eduljee, G.H. & Hutton, M. 2002. Assessment and management of risks arising from exposure to cadmium in fertilizers. The Science of the Total Environment 291: 167-187.

Department of Agriculture, Food and Forestry 1996. Growing for the Future, Strategic Plan for the Development of the Forestry Sector in Ireland.

Donohue, I. & Irvine, K. 2003. BUFFER ‘Key nutrient transport mechanisms important for the prediction of nutrient and phytoplankton concentrations in European standing waters’ Trinity College Dublin.

Donohue, I. McGarrigle, M. & Mills. P. 2006. Linking catchment characteristics and water chemistry with the ecological status of Irish rivers. Water Research 40: 91-98.

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

Duigan, C. & Birks, H.H. 2000. The late-glacial and early-Holocene palaeoecology of cladoceran microfossil assemblages at Kråkenes, western Norway, with a quantitative reconstruction of temperature changes. Journal of Paleolimnology 23: 67-76.

Eakins, J.D. & Morrison, R.T. 1978. A new procedure for the determination of lead-210 in lake and marine sediments. International Journal of Radiation and Isotopes 29: 531-536.

Eloranta, P. 1978. Light penetration in different types of lakes in Central Finland, Holarcic. Ecology 1: 362-366.

Elliot A. 2009. The seasonal sensitivity of Cyanobacteria and other phytoplankton to changes in flushing rate and water temperature. Hydrobiologia 559: 401-411.

Elliott, A. Jones, I.D. & Thackeray, S.D. 2006. Testing the sensitivity of phytoplankton communities to changes in water temperature and nutrient load in a temperate lake. Hydrobiologia 559: 1573-5117.

EEA (European Environment Agency) 2000. CORINE land cover technical guide Addendum 2000. EEA technical Report No. 40 prepared by M. Bossard, J. Feranec and J. Ptahel. Copenhagen, May 2000 105pp.

Ewen, J., Parkin, G. & O'Connell, E. 2000. SHETRAN: distributed basin flow and transport modelling system. J. Hydrol. Eng. 5: 250-258.

Fehily, J. & Shipman, P. 1967. The Killarney Valley survey. An Forás Forbartha Teoranta (The National Institute for Physical Planning and Construction Research), Dublin.

Flanagan, P.J. & Toner, P.F. 1975. A preliminary survey of Irish lakes. An Foras Forbartha, pp. 164.

Foged, N. 1977. Freshwater diatoms in Ireland. Bibliotheca Phycologica 34: 221.

Foy, R.H. 1992. A phosphorus loading model for Northern Irish lakes. Water Res. 26: 633-638.

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: B.E. Berglund (ed.) Handbook of Holocene Paleoecology and Paleohydrology. John Wiley and Sons, pp. 667-692.

Futter, M. N., Starr M., Forsius M. & Holmberg, M. 2007. Modelling the effects of climate on long-term patterns of dissolved organic carbon concentrations in the surface waters of a boreal catchment. Hydrol. Earth Syst. Sci. Discuss 4: 3175–3207.

Gervais, F. 1997. Diel vertical migration of *Cryptomonas* and *Chromatium* in the deep chlorophyll maximum of a eutrophic lake. J. Plankton Res. 19: 533-550

Gillmor, D.A. & Walsh, J.A. 1993. County level variations in agricultural adjustment in Ireland in the 1980s. Geographical Viewpoint 21: 25-44

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.

Grimm, E.C. 1987. CONISS: a fortran 77 programme for stratigraphically constrained cluster analysis by the method of incremental sum of squares. Computers and Geosciences 13: 13-35.

Haith D.A., Mandel R. & Shyan Wu R. 1996. GWLF Generalized Watershed Loading Functions model. Version 2.0. User's Manual. Department of Agricultural & Biological Engineering, Cornell University, Itica, NY.

Haith, D. A. & Shoemaker, L. L. 1987. Generalized watershed loading functions for stream flow nutrients. Water Resources Bulletin 23: 471-478.

Haith, D. A. & Tubbs, L. J. 1981. Watershed Loading Functions for Nonpoint Sources. ASCE. Journal of Environmental Engineering 107(EE1):121-137.

Hall, R.I. & Smol, J.P. 1992. A weighted-average regression and calibration model for inferring total phosphorus concentration from diatoms in British Columbia (Canada) lakes. Freshwater Biology 27: 417-434.

Hammer, A., Schumann, R. & Schubert, H. (2002). Light and temperature acclimation of Rhodomonas salina (Cryptophyceae): photosynthetic performance. Aquatic Microbial Ecology 29: 287-296.

Hammer, Ø., Harper, D.A.T. & Ryan, P.D. 2001. Past: Paleonological statistic software package for education and data analysis. Palaeontologica Electronica 4: 9pp., http://palaeo-electronica.org/2001_1/past/issue1-01.htm.

Hansen, J.E., Sato, M., Lacis, A., Ruedy, R., Tegen, I. & Matthews, E. (1998). Climate forcings in the industrial era. PNAS, 95: 12753-12758

Hari, R.E., Livingstone, D.M., Siber, R., Burkhardt-Holm, P. & Güttinger, H. 2006. Consequences of climatic change for water temperature and brown trout populations in Alpine rivers and streams. Global Change Biology 12: 10-26.

Harriman, R. & Morrison, B.R.S. 1982. Ecology of streams draining forested and non-forested catchments in an area of central Scotland subject of acid precipitation. Hydrobiologia 88: 251-263.

Hay, L.E., Wilby, R.L. & Leavesley, G.H. 2000. A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States. J. Am. Water Resources Assoc. 36: 387-397.

Heiri, O., A.F. Lotter & G. Lemcke. 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. Journal of Paleolimnology 25: 101-110.

Heiskanen, A.-S. & Solimini, A.G. (eds.) 2005. Relationships between pressures, chemical status and biological quality elements. Analysis of the current knowledge gaps for the implementation of the Water Framework Directive. Report to the EU JRC # EUR 21497 EN.

Hillebrand, H.D., Kirschtel, C.D., Pollingher, D. & Zohary, T. 1999. Biovolume calculation for pelagic and benthic microalgae. Journal of Phycology 35: 403-424.

Hipsey, M.R., Romero, J.R., Antenucci, J.P. & Hamilton, D. 2006. Computational Aquatic Ecosystem Dynamics Model. v. 2.3 Science Manual. Centre for Water Research, the University of Western Australia (online). http://www.cwr.uwa.edu.au/ services/models/legacy/model/dyresmcaedym/

Holland, C.H. 2009. The geology of Ireland. Edinburgh: Dunedin Academic. 2nd Edition.

Horkan, J.P.K. 1976. Algal Studies in the Killarney Lakes. In: Final Report on the Killarney Valley Lake Survey 1971-1975 by Limnological Research Unit, University College, Dublin. Unpublished report to N.S.C., O.P.W. and Board Failte.

Hurrell, J.W. 1995. Decadal trends in the North Atlantic Oscillation, regional temperatures and precipitation. Science 269: 676-79.

Hyde, B. & Carton, O. 2005. Manure management facilities on farms and their relevance to efficient nutrient use. Proceedings of the Fertiliser Association of Ireland. No.42. http//www.fertilizer-assoc.ie/publications.htm.

ICES 2009 a. Report of the Working Group on North Atlantic Salmon (WGNAS), 30 March 8 April, Copenhagen, Denmark. ICES CM 2009/ACOM:06. 282 pp.

ICES 2009 b. Report of the 2009 Session of the Joint EIFAC/ICES Working Group on Eels (WGEEL), 7-12 September 2009, Göteborg, Sweden. ICES CM 2009/ACOM:15. 137 pp.

Imberger, J. & Patterson, J.C. 1981. In Transport models for inland and coastal waters. Fischer HB editor. New York: Academic Press. pp. 310-61.

Imberger, J. & Patterson, J.C. 1989. Physical limnology p 303-475 In Advances in applied mechanics, volume 27, Academic Press.

Imerito, A. 2007. DYRESM v4.0 Science Manual. Perth: Centre for Water Research, University of Western Australia.

IPCC (Intergovernmental Panel on Climate Change) 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 104 pp.

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., Donohue, I., Wemaëre, A., Styles, D. & Hobbs, W. 2003. Connecting land-use with water quality: sources, sinks and time-bombs. In M. Bruen (ed.) Diffuse pollution and basin management pp. 56-60. Proceedings of the 7th IWA international conference, Dublin, Ireland.

Jennings, E. & Allott, N. 2006. Influence of the Gulf Stream influences lake nitrate concentrations in SW Ireland. Aquatic Sciences 68: 482-489.

Jennings, E., Allott, N., Arvola, L. Jarvinen, M., Moore, K., Naden, P., Nic Aongusa, C., Noges, T. & Weyhermeyer, G. 2009a. Impacts of climate on the flux of dissolved organic carbon from catchments. In D. G. George (ed.) The Impact of Climate Change on European Lakes. Aquatic Ecology Series, Vol. 4, Springer pp. 199-220.

Jennings, E., Allott, N., Pierson, D., Schneiderman, E., Lenihan, D., Samuelsson, P. & Taylor, D. 2009b. Impacts of climate change on phosphorus loading from a grassland catchment – implications for future management. Water Research 43: 4316-4326.

Jennings, E., N. Allott, P. McGinnity, R. Poole, B. Quirke, H. Twomey & D. G. George, 2000. The North Atlantic Oscillation: implications for freshwater systems in Ireland. Biol. Env. Proc. R. Irish Acad. 100B: 149-158.

Jennings, E., Dalton, C., Olas, M., de Eyto, E., Allott, N. Bosch, K., Murnaghan, S. & Taylor, D. 2008. Reconstruction of the recent past in a west of Ireland catchment. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 30: 512-514.

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

John, D., Whitton, B.A. & Brook, A.J. 2002. The freshwater algal flora of the British Isles. Cambridge University Press. Cambridge

Johnes, P.J. 1996. Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach. Journal of Hydrology 183: 323-349.

Johnes P.J. & Heathwaite A.L. 1997. Modelling the impact of land use changes on water quality in agricultural catchments. Hydrological Processes 11: 269-286.

Jöhnk, K.D., Huisman, J., Sharples, J., Sommeijer, B., Viser, P.M. & Stroom, M. 2007. Summer heatwaves promote blooms of harmful cyanobacteria. Global Change Biology 14: 495-512.

Jones, R.I. 1992. The influence of humic substances on lacustrine planktonic food chains. Hydrobiologia 229: 73-91.

Jones, R.I. & Arvola, L. 1984. Light penetration and some related characteristics in small forest lakes in southern Finland. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 22: 811-816.

Jones, V.J., Stevenson, A.C. & Battarbee, R.W. 1986. Lake acidification and the land-use hypothesis: a mid-post-glacial analogue. Nature 322: 157-158.

Jordan, P., Rippey, B. & Anderson, N.J. 2001. Modelling diffuse phosphorous loads from land to freshwater using the sedimentary record. Environmental Science and Technology 35: 815-819.

Kankaala, P., Arvola, L., Tulonen, T. & Ojala, A. 1996. Carbon budget for the pelagic food web of the euphotic zone in a boreal lake (Lake Pääjärvi). Canadian Journal of Fisheries and Aquatic Sciences 53: 1663-1674.

Kiely, J., Diamond, S., Burke, P.J. & Collins, T. (1974). The soil map of West Mayo. National Soil Survey, Soils Division, An Foras Taluntais.

Kilsby, C.G., Jones, P.D., Burton, A., Ford, A.C., Fowler, H.J., Harpham, C., James. P., Smith, A. & Wilby, R.L. 2007. A daily weather generator for use in climate change studies. Environmental Modelling and Software 22: 1705-1719.

Kleinman, P.J.A. & Sharpley, A.N. 2003. Effect of broadcast manure on runoff phosphorus concentrations over successive rainfall events, J. Environ. Qual. 32: 1072-1081.

KMM (Kirk McClure Morton) 2000. A catchment based approach for reducing nutrient inputs from all sources to the Lakes of Killarney – interim report. Kerry County Council, Tralee.

KMM (Kirk McClure Morton) 2003. A catchment based approach for reducing nutrient inputs from all sources to the Lakes of Killarney - final report. Kerry County Council, Tralee.

Knorr, W., Prentice, I. C., House, J. I. & Holland, E. A. 2005. Long-term sensitivity of soil carbon to warming. Nature 433: 298-301.

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

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

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

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

Kundzewicz, Z.W., Mata, L.J., Arnell, N.W., Döll, P., Kabat, B., Jiménez, K.A. Miller, T., Oki, Z., Sen, I.A. & Shiklomanov, 2007. Freshwater resources and their management. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden & C.E. Hanson, eds., Cambridge University Press, Cambridge, UK, 173-210.

Lami, A., Guilizzoni, P. & Marchetto A. 2000 High resolution analysis of fossil pigments, carbon, nitrogen and sulphur in the sediment of eight European Alpine lakes: the MOLAR project. Journal of Limnology, 59 (Suppl. 1): 15-28.

Lange-Bertalot, H., & Metzeltin, D. 1996. Indicators of oligotrophy: 800 taxa representative of three ecologically distinct lake types: carbonate buffered-oligodystrophic-weakly buffered soft water (Vol. 2). Königstein, Koeltz Scientific Books.

Leavitt, P.R. & Hodgson, D.A. 2001. Sediment Pigments. In: J.P. Smol, H.J.B. Birks & W.M. Last, Tracking Environmental Change Using Lake Sediments. Vol. 3: Terrestrial, Algal and Siliceous Indicators Kluwer Academic Publishers, Amsterdam, pp. 1-32.

Leira, M., Jordan, P., Taylor, D., Dalton, C., Bennion, H. & Irvine, K. 2006. Recent histories of the main types of candidate reference lakes in Ireland: a palaeolimnological approach. Journal of Applied Ecology 43: 816-827.

Linnane, S. 2001. Recent changes in lakes in the Shannon and Laune catchments - a palaeolimnological study on lake sediment chemistry and selected pigment biomarkers. Unpublished Ph.D. thesis. University College Dublin, Ireland.

Livingstone, D.M. & Dokulil, M.T. 2001. Eighty years of spatially coherent Austrian lake surface temperatures and their relationship to regional air temperature and the North Atlantic Oscillation. Limnology and Oceanography 46: 1220-1227.

Lohse, L., Kloosterhuis, R.T., de Stigter, H.C., Helder, W., van Raaphorst, W. & van Weering, T.C.E. (2000). Carbonate removal by acidification causes loss of 20 nitrogenous compounds in continental margin sediments. Marine Chemistry 69: 193 201

Long, C.B., MacDermot, C.V., Morris, J.H., Sleeman, A.G., Tietzsch-Tyler, D. Aldwell, C.R., Daly, D., Flegg, F.M., McArdle, P.M. & Warren, W.P. 1992. Geology of North Mayo. Geological Survey of Ireland.

Lund, J.W.G., Kipling, C. & Le Cren, E.D. 1958. The inverted microscope method for estimating algal numbers and the statistical basis of estimations by counting. Hydrobiologia 11: 143-170.

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

Maguire, R.O, Crouse, D.A. & Hodges, S.C. 2007. Diet modification to reduce phosphorus surpluses: a mass balance approach. Journal of Environmental Quality 36: 1235-1240.

Mauquoy, D. & B. van Geel 2007. Plant macrofossil methods and studies: Mire and peat macros. In: S.A. Elias (ed). Encyclopedia of Quaternary Science. Elsevier, Amsterdam, The Netherlands.

May, L., Place, C., O'Hea, B., Lee, M., Dillane, M. & McGinnity 2005. Modelling soil eroision and transport in the Burrishoole catchment, Newport, Co. Mayo, Ireland. Freshwater Forum 23: 139-154.

McCarthy, T.K., Barbiero, R., Doherty, D., Cullen, P., Ashe, P., O'Connell, M., Guiry, M., Sheehy-Skeffington, M., King, M. & O'Connor, B. 2001. Investigations of Eutrophication Processes in the Littoral Zones of Western Irish Lakes. Environmental Protection Agency, Wexford, Ireland.

McEntee, M.A. 1980. A revision of the equation relating sunshine hours to radiation income for Ireland. Irish Journal Agriculture Research 19:119-125.

McGarrigle, M.L. & Champ, W.S.T. 1999. Keeping pristine lakes clean: Loughs Conn and Mask. Hydrobiologia 395/396: 455-69

McGechan, M.B., Lewis, D.R. & Hooda, P.S. 2005. Modelling through-soil transport of phosphorous to surface waters from livestock agriculture at the field and catchment scale. Sci. Total Environ. 344: 185-199.

McGinnity, P., Jennings, E., deEyto, E., Allott, N., Samuelsson, P., Rogan, G., Whelan, K. & Cross, T. 2009. Impact of naturally spawning captive-bred Atlantic salmon on wild populations: depressed recruitment and increased risk of climate-mediated extinction. Proceedings of the Royal Society B: Biological Sciences 276: 3601-3610.

Meyers, P.A. 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. Chemical Geology 114: 289-302.

Meyers, P.A. 2003. Applications of organic geochemistry to paleolimnological reconstruction: A summary of examples from the Laurentian Great Lakes. Organic Geochemistry 34: 261-289.

Meyers, P.A. 2006. An overview of sediment organic matter records of human eutrophication in the Laurentian Great Lakes Region. Water, Air and Soil Pollution: Focus 6: 453-463.

Mitchell F.J.G. & T. Cooney 2004. Vegetation history in the Killarney valley. In: W. O'Brien (ed.) Ross Island: Metal, mining and society in early Ireland. National University of Ireland, Galway.

Mitchell, F.J.G. 1988. The vegetational history of the Killarney oakwoods, S.W. Ireland: evidence from fine spatial resolution pollen analysis. Journal of Ecology 76: 415-436.

Mitchell, F.J.G. 1990. The impact of grazing and human disturbance on the dynamics of woodland in S.W. Ireland. Journal of Vegetation Science 1: 245-254.

Moore, K., Jennings, E., May, L., Jarvinen, M., Allott, N., Arvola, L., Tamm, T., Jarvet, A., Noges, T, Pierson D. & Schneidman, E. (2009) Modelling the effects of climate change on inorganic nitrogen transport from catchments to lakes. In D. G. George (ed.) The Impact of Climate Change on European Lakes. Aquatic Ecology Series , Vol. 4, Springer pp. 179-197.

Moore, K., Pierson, D., Pettersson, K., Schneiderman, E. & Samuelsson, P. 2008. Effects of warmer world scenarios on hydrologic inputs to Lake Mälaren, Sweden and implications for nutrient loads. Hydrobiologia 599: 191-199.

Moore, P.D., Webb, J.A. & Collinson, M.E. 1991. Pollen analysis. London, Blackwell

Mullins, E. 2003. Statistics for the Quality Control Chemistry Laboratory. Royal Society of Chemistry, Cambridge, pp 247-260.

Naden, P., Allott, N., Arvola, L., Jarvinen, M., Jennings, E., Moore, K., Nic Aongusa, C., Pierson, D. & Schneidermen, E. 2009. Modelling the effects of climate change on dissolved organic carbon. In D.G. George (ed.) The Impact of

Climate Change on European Lakes. Aquatic Ecology Series, Vol. 4. Springer pp. 221-252.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J., Gaffin, S., Gregory, K., Gru¨ bler, A., Jung, T.Y., Kram, T., La Rovere, E.L., Michaelis, L., Mori, S., Morita, T., Pepper, W., Pitcher, H., Price, L., Raihi, K., Roehrl, A., Rogner H-H., Sankovski, A., Schlesinger, M., Shukla, P., Smith, S., Swart, R., van Rooijen, S., Victor, N. & Dadi, Z. 2000. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge pp 599.

Nash, J.E. & Sutcliffe, J.V. 1970. River flow forecasting through conceptual models part I - A discussion of principles. Journal of Hydrology 10 (3): 282-290.

Nowlan, N.V., Mitchell, P.I., Murray, D.A., Leon-Vintro, L. & 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 für Theoretische und Angewandte Limnologie 27: 2303-2306.

O'Connor, M. 2000. Action Plan for Blanket Bog and Wet Heath: Technical Aspects. Draft report to NPWS, Dept. Environment, Heritage and Local Government, Dublin, Ireland.

O'Sullivan, A. 1993. Site synopsis, Owenduff/Nephin complex. ASI survey. National Parks and Wildlife Service. Unpublished.

OECD (Organisation of Economic Co-operation and Development) 1982. Eutrophication of Waters; Monitoring and Assessment, pp.154. OECD, Paris.

Ormerod, S. J., Dobson M., Hildrew A. G. & Townsend, C. R. 2010. Multiple stressors in freshwater ecosystems. Freshwater Biology 55 (Suppl. 1), 1–4.

Ormerod, S., Rutt, G., Weatherly, N. & Wade, K. 1991. Detecting and managing the influence of forestry on river systems in Wales: results from surveys, experiments and models. In: M.W. Steer (ed.) Irish Rivers - Biology and Management. Royal Irish Academy, Dublin.

Page, D., Burke, D., Wall B., & O'Leary G. 2009. The Provision and Quality of Drinking Water in Ireland. A Report for the Years 2007 - 2008. EPA, Wexford.

Parker, M.M. 1977. Lough Furnace, County Mayo; Physical and chemical studies of an Irish saline lakes, with reference to the biology of *Neomysis integer*. PhD. Trinity College Dublin, Dublin.

Parmesan, C. & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. Nature, 421: 37-42

Patrick, S.T. & Stevenson, A.C. (1990). Acidified Welsh lakes: the significance of land-use and management. In: R.W. Edwards, A.S. Gee & J.H. Stoner (eds.) Acid waters in Wales. Kluwer Academic Publishers, the Netherlands.

Pierson, D.C., Arvola, L., Allott, N., Järvinen, M., Jennings, E., May, L., Moore, K., Naden, P. & Schneiderman, E. 2009. Modelling the effects of climate change on the supply of phosphate-phosphorus. In D.G. George (ed.) The Impact of Climate Change on European Lakes. Aquatic Ecology Series, Vol. 4. Springer pp. 139-159.

Poole, W. R., Dillane, M., de Eyto, E., Rogan, G., McGinnity, P., & Whelan, K. 2007. Characteristics of the Burrishoole Sea Trout Population: Census, Marine Survival, Enhancement and Stock-Recruitment Relationship, 1971-2003. In N. M. Graeme Harris (ed.) Sea Trout: Biology, Conservation and Management pp. 279-306.

Quirke, B. (ed.) 2001. Killarney national park: a place to treasure. The Collins Press, Cork.

Raisanen, R., Hansson, U., Ullerstig, R., Doscher, R., Graham, L.P., Jones, C., Meier, H.E.M., Sammuelsson, P. & Willen, U. 2004. European climate in the late twenty-first century: regional simulations with two driving global models and two forcing scenarios. Climate Dynamics 22: 13-31

Reimer, P.J. et al. (2004). IntCal04 terrestrial radiocarbon age calibration, 26–0 ka BP. Radiocarbon 46:1029-1058

Renberg, I. & Hansson, H. 2008. The HTH sediment corer. Journal of Paleolimnology 40: 655-659.

Roberts, N. 1998. The Holocene: An Environmental History, 2nd ed., Oxford: Blackwell.

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

Rose, N.L. 2001. Fly-ash particles. In: W.M. Last & 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., 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.

Ruiz-Fernandez, A. C., Hillaire-Marcel, C., Paez-Osuna, F., Ghaleb, B. & Caballero, M. 2007. ^{210}Pb chronology and trace metal geochemistry at Los Tuxtlas, Mexico, as evidenced by a sedimentary record from the Lago Verde crater lake. Quaternary Research 67: 181-192.

Salonen, K., Arvola, L. & Rask, M. 1984. Autumnal and vernal circulation of small forest lakes in Southern Finland, Verh. Internat. Verein. Limnol. 22: 103-107.

Samuelsson, P. 2009. Using regional climate models to quantify the impact of climate change on lakes. In D.G. George (ed.) The Impact of Climate Change on European Lakes Springer. Aquatic Ecology Series, Vol. 4. Springer pp. 15-32.

Scheer, H. 1991. Structure and occurrence of chlorophylls. In: Scheer, H. (ed) Chlorophylls. CRC Press, Boca Raton, Florida, pp 3-30.

Schladow, S.G. & Hamilton, D.P., 1997. Prediction of water quality in lakes and reservoirs. Part II. Model calibration, sensitivity analysis and application. Ecol. Model. 96:111-123.

Schneiderman, E., Järvinen, M., Jennings, E., May, L., Moore, K., Naden, P. & Pierson, D.C. 2009. Modeling the effects of climate change on catchment hydrology with the GWLF model. In D.G. George (ed.) The Impact of Climate Change on European Lakes. Aquatic Ecology Series, Vol. 4. Springer. pp 33-49.

Schneiderman, E.M., Pierson, D.C., Lounsbury D.G. & Zion, M.S. 2002. Modeling the hydrochemistry of the Cannonsville Watershed with the Generalized Watershed Loading Functions GWLF. Journal of the American Water Resources Association 38: 1323-1347.

Scourfiels, D.J. & Harding, J.P. 1994. A Key to the British Freshwater Cladocera. Freshwater Biological Association, 5 (3th ed.)

Shatwell, T., Köhler, J. & Nicklisch, A. 2008. Warming promotes cold-adapted phytoplankton in temperate lakes and opens a loophole for Oscillatoriales in spring. Global Change Biology 14: 2194-2200.

S.I. 378 2006. European Communities Good agricultural practice for protection of waters. Government Publication Office, Dublin.

S.I. 258 1998. Local Government (Water Pollution) Act, 1977 (Water Standards for Phosphorus) Regulations. Government Publications Office, Dublin.

Simms, M.J. 2005. The Great Western Lakes. In P. Coxon (ed.). The Quaternary of central western Ireland: Field Guide, Quaternary Research Association, London, pp 71-78.

Smith, B.N. & Epstein, S. 1971. Two categories of 13C/12C ratios for higher Plants. Plant Physiology 47: 380-384.

Smol, J.P. 2010. The power of the past: using sediments to track multiple stressors on lake ecosystems. Freshwater Biology 55 (Suppl. 1), 43–59.

Staehr, P.A. & Sand-Jensen, K. 2005. Seasonal changes in temperature and nutrient control of photosynthesis, respiration and growth of natural phytoplankton communities. Freshwater Biology 51: 249 - 262

Stefánsson, A., Gunnarsson, I., & Giroud, N. 2007. New methods for the direct determination of dissolved inorganic, organic and total carbon in natural waters by Reagent-Free Ion Chromatography and inductively coupled plasma atomic emission spectrometry. Anal. Chim. Acta 582 (1): 69-74.

Stevens, R. J., Laughlin, R. J., O'Bric, C. J., Carton, O. T. & Lenehan, J. J. 1997. The efficiency of nitrogen in cattle slurry acidified with nitric acid for grass production. Journal of Agricultural Science 129: 335-342.

Stuiver, M. & Reimer, P.J. 1993. Extended 14C Data Base and Revised Calib 3.0 14C Age Calibration Program. Radiocarbon 35: 215-230.

Sun, J. & Liu, D. 2003. Geometric models for calculating cell biovolume and surface area for phytoplankton. Journal of Plankton Research 25(11): 1331-1346.

Sweeney, J. (ed.) 2003. Climate Change, Scenarios and Impacts for Ireland. Johnstown Castle, Wexford, Environmental Protection Agency. 229pp.

Talbot, M.R. 2001. Nitrogen isotopes in palaeolimnology. In: W.M. Last & J.P. Smol (eds.) Tracking Environmental Change Using Lake Sediments Vol. 2 Physical and Geochemical Methods, Kluwer Academic Publishers, Amsterdam, pp 401-439.

Taugbøl, G., Seip, H.M., Bishop, K. & Grip, H. 1994. Hydrochemical modelling of a stream dominated by organic acids and organically bound aluminium. Water, Air and Soil Pollution, 78: 103-139.

Taylor, D., Dalton, C., Leira, M., Jordan, P., Chen, G., León-Vintró, L., Irvine, K., Bennion, H., & Nolan, T. 2006a. Recent histories of six productive lakes in the Irish Ecoregion based on multiproxy palaeolimnological evidence. Hydrobiologia 571: 237-259.

Taylor, D., Dalton, C., Leira, M., Jordan, P., Irvine, K., Bennion, H., Magee, E. & León-Vintró, L. 2006b. Identification of Reference Status for Irish Lake Typologies Using Palaeolimnological Methods and Techniques (IN-SIGHT, EPA/ERTDI Project # 2002-W-LS/7). Final Report to the EPA. EPA, Dublin, Ireland

ter Braak C.F.G. & Prentice, I.C. 1988. A theory of gradient analysis. Advances in Ecological Research 18: 271-317.

ter Braak, C.J.F. & Šmilauer, P. 2002. CANOCO reference manual and CanoDraw for Windows. User’s guide: software for canonical community ordination (version 4.5). Microcomputer Power, Ithace, New York, USA.

Thompson, C. E., Poole, W. R., Matthews, M. A. & Ferguson, A. 1998. Comparison, using minisatellite DNA profiling, of secondary male contribution in the fertilisation of wild and ranched Atlantic salmon (Salmo salar) ova. Can. J. Fish. Aquat. Sci. 55: 2011–2018.

Toner, P., Bowman, J., Clabby, K., Lucey, J., McGarrigle, M., Concannon, C., Clenaghan, C., Cunningham, P., Delaney, J., O’Boyle, S., MacCáthaigh, M., Craig, M. & Quinn. R. 2005. Water Quality in Ireland 2001-2003. Environmental Protection Agency, Wexford, Ireland.

Tranvik, L.J. 1992. Allochthonous dissolved organic matter as an energy source for pelagic bacteria and the concept of the microbial loop, Hydrobiologia 229: 107-114.

Trolle, D., Skovgaard, H. & Jeppesen, E. 2008. The Water Framework Directive: Setting the phosphorus loading target for a deep lake in Denmark using the 1D lake ecosystem model DYRSEM CAEDYM. Ecological Modelling 219: 138-152.

Twomey, H., Quirke, B. & Allott N. 2000. A report on the monitoring of the Killarney Lakes 1967-1997 and other related studies. Conservation Services, Glenflesk, Co. Kerry.

Twomey, H., Quirke, B., Allott N. & Irvine 2001. Biological monitoring of Lough Leane catchment lakes and rivers – report for Lough Leane Catchment Monitoring & Management System Project Results of the 1999-2000 Investigations. Conservation Services, Glenflesk, Co. Kerry.

Ulén, B.M. & Weyhenmeyer, G.A. 2007. Adapting regional eutrophication targets for surface waters – influence of the EU Water Framework Directive, national policy and climate change. Environmental Science and Policy 10: 734-742

Vadas, P.A., Harmel, R.D. & Kleinman, P.J.A. 2007. Transformations of soil and manure phosphorus after surface application of manure to field plots. Nutrient Cycling in Agroecosystems 77: 83-99.

Villanueva, J., Grimalt, J.O., Dewit, R., Keely, B.J. & Maxwell, J.R. 1994. Sources and transformations of chlorophylls and carotenoids in a monomictic sulphate-rich karstic lake environment. Organic Geochemistry 22:739-757

Vollenweider, R.A. 1968. Scientific fundamentals of the eutrophication of lakes and flowing waters with particular reference to nitrogen and phosphorus as factors in eutrophication. OECD Technical Report No. DAS/DST/88, 182 pp. OECD, Paris.

Ward, J. 1955. A description of a new zooplankton counter. Quarterly Journal of Microscopic Science 96: 371-373.

Weir, G. 1996. Sheep overgrazing in the Nephin Begs. MSc Thesis. Trinity College, Dublin.

West, W. & West G.S. 1906. A comparative study of the plankton of some Irish lakes. Trans. R. Ir. Acad. 33B: 77-116.

Wetzel, R.G. & Likens, G.E. 1991. Limnological analysis. Springer Verlag, New York: 391 pp.

Wetzel, R.G. 2001. Limnology: Lake and River Ecosystems. 3rd Edition Academic Press San Diego CA USA

Whelan K.F., Poole, W.R., McGinnity, P., Rogan, G. & Cotter, D. 1998. The Burrishoole System. In: C. Moriarty (ed.) Studies of Irish Rivers and Lakes, Marine Institute, Dublin, pp. 279.

WHO (World Health Organisation) 2005. Trihalomethanes in drinking water, WHO/SDE/WSH/05.08/64. World Health Organisation, Geneva. 35 pp.

Wilby, R.L, Orr, H.G., Hedger, M., Forrow, D. & Blackmore, M. 2006. Risks posed by climate change to the delivery of Water Framework Directive objectives in the UK. Environ. Int. 32: 1043-1055.

Wilhelm, S. & Adrian, R. 2008. Impact of summer warming on the thermal characteristics of a polymictic lake and consequences for oxygen nutrients and phytoplankton. Freshwater Biology 53: 226-237.

Wischmeier, W.H. & Smith, D. 1978. Predicting rainfall erosion losses: a guide to conservation planning. USDA-ARS Agriculture Handbook N° 537, Washington DC. 58 pp.

Wissel, B. Goeing, W.J. & Ramcharan, C.W. 2003. Effects of water color on predation regimes and zooplankton assemblages in freshwater lakes. Limnology and Oceanography 48: 1965-1976.

Withers, P.J.A., Clay, S.D. & Breeze, V.G. 2001. Phosphorus transfer following application of fertilizer, manure and sewage sludge. J. Environ. Qual. 30: 180-188.

Wolfe, B.B., Edwards, T.W.D., Beuning, K.R.M. & Elgood, R.J. 2001. Carbon and oxygen isotope analysis of lake sediment cellulose: methods and applications. In: W.M. Last & J.P. Smol (eds.) Tracking Environmental Change Using Lake Sediments, Vol. 2 Physical and Geochemical Methods, Kluwer Academic Publishers, Amsterdam, pp 373-400.

Wu, Y., Hou, X., Cheng, X., Yao, S., Xia, W. & Wang, S. 2007. Combining geochemical and statistical methods to distinguish anthropogenic sources of metals in lacustrine sediment: a case study in Dongjiu lake, Taihu lake catchment, China. Environmental Geology 52: 1467-1474.

Young, A.J. 1991 The photoprotective role of carotenoids in higher plants. Physiol. Plant. 83: 702-708.

Appendix 1

Appendix 1.1: ILLUMINATE metadatabase and database

An ILLUMINATE project and metadatabase and database were designed in ACCESS with the help of Dr Peter Mooney (EPA) in line with EPA requirements for the SAFER archive. Meta- and project- databases were populated as part of ILLUMINATE (and the Marine Institute/Sea Change-funded RESCALE project) and will be uploaded to SAFER archive. The master metadatabase file was stored on an ftp site to facilitate input by multiple users. In the project database each core has a code indicating site, sampling location, date collected, core number and parameter examined. Parameters include all measurements e.g. LOI, diatom species. Each is classified as a parameter type e.g. 'Sediment_diatom'.

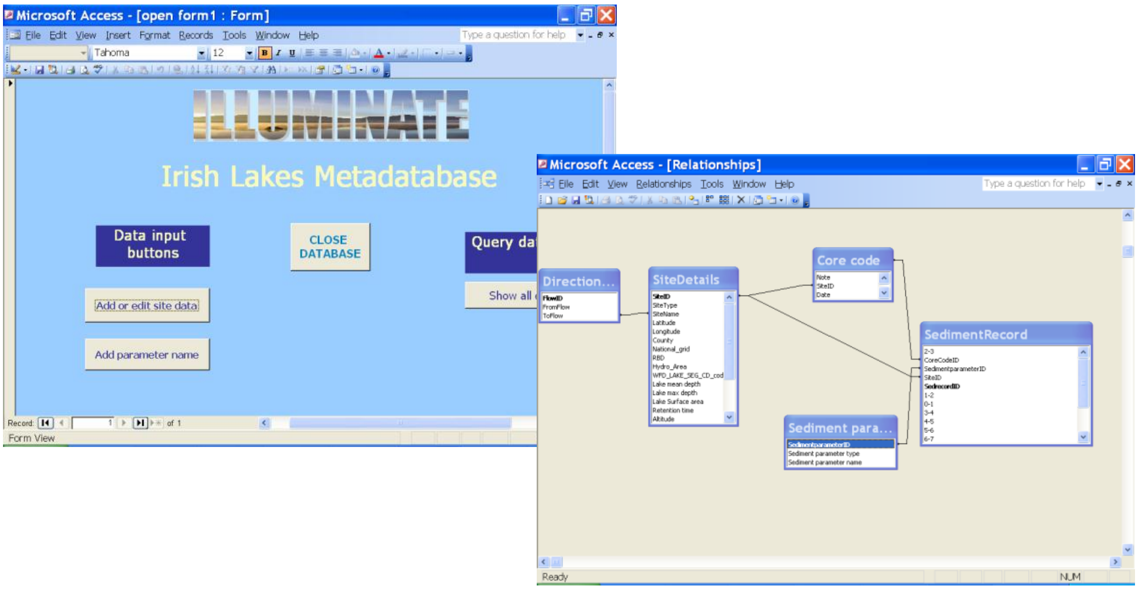
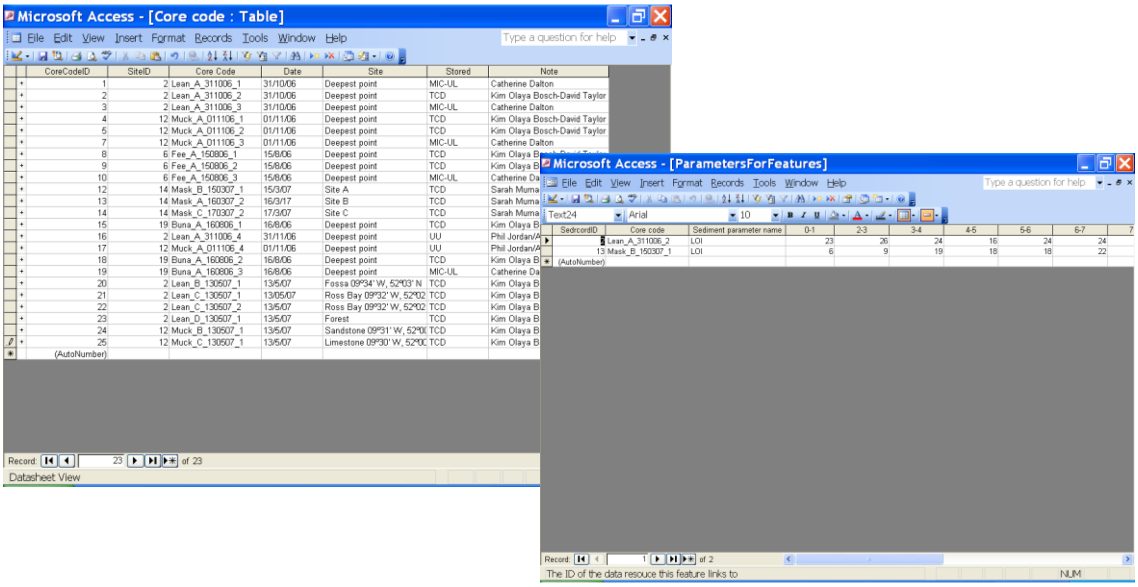


Figure 1.1 Schematic of the metadatabase



CoreCodeID	SiteID	Core Code	Date	Site	Stored	Note
1	2	Lean_A_311006_1	31/10/06	Deepest point	MIC-UL	Catherine Dalton
2	2	Lean_A_311006_2	31/10/06	Deepest point	TCD	Kim Olaya Bosch-David Taylor
3	2	Lean_A_311006_3	31/10/06	Deepest point	MIC-UL	Catherine Dalton
4	12	Muck_A_011106_1	01/11/06	Deepest point	TCD	Kim Olaya Bosch-David Taylor
5	12	Muck_A_011106_2	01/11/06	Deepest point	TCD	Kim Olaya Bosch-David Taylor
7	12	Muck_A_011106_3	01/11/06	Deepest point	MIC-UL	Catherine Dalton
8	6	Fee_A_150806_1	15/8/06	Deepest point	TCD	Kim Olaya B
9	6	Fee_A_150806_2	15/8/06	Deepest point	TCD	Kim Olaya B
10	6	Fee_A_150806_3	15/8/06	Deepest point	MIC-UL	Catherine Da
12	14	Mask_B_150307_1	15/3/07	Site A	TCD	Sarah Muma
13	14	Mask_A_160307_2	16/3/17	Site B	TCD	Sarah Muma
14	14	Mask_C_170307_2	17/3/07	Site C	TCD	Sarah Muma
15	19	Buna_A_160806_1	16/8/06	Deepest point	TCD	Kim Olaya B
16	2	Lean_A_311006_4	31/11/06	Deepest point	UU	Phil Jordan/A
17	12	Muck_A_011106_4	01/11/06	Deepest point	UU	Phil Jordan/A
18	19	Buna_A_160806_2	16/8/06	Deepest point	TCD	Kim Olaya B
19	19	Buna_A_160806_3	16/8/06	Deepest point	MIC-UL	Catherine Da
20	2	Lean_B_130507_1	13/5/07	Fossa 09º34' W, 52º03' N	TCD	Kim Olaya B
21	2	Lean_C_130507_1	13/05/07	Ross Bay 09º32' W, 52º02	TCD	Kim Olaya B
22	2	Lean_C_130507_2	13/5/07	Ross Bay 09º32' W, 52º02	TCD	Kim Olaya B
23	2	Lean_D_130507_1	13/5/07	Forest	TCD	Kim Olaya B
24	12	Muck_B_130507_1	13/5/07	Sandstone 09º31' W, 52º0	TCD	Kim Olaya B
25	12	Muck_C_130507_1	13/5/07	Limestone 09º30' W, 52º0	TCD	Kim Olaya B
(AutoNumber)						

SedrcordID	Core code	Sediment parameter name	0-1	2-3	3-4	4-5	5-6	6-7	7
2	Lean_A_311006_2	LOI	23	26	24	16	24	24	
13	Mask_B_150307_1	LOI	6	9	19	18	18	22	
(AutoNumber)									

Figure 1.2 Schematic of the project database

Appendix 2

Appendix 2.1: CORINE 2000 subcatchment land cover (ha) (CLC 2000)

	Leane			Feeagh		Mask		
CORINE land cover (ha)	Flesk	Deenagh	Upper	Black	Glen	Robe	Carra	Owenbrin
High Prod. Pastures	5011.4	1218.5				28911.9	5021.2	115.2
Mixed pasture		599.0	48.6			9011.6	22667.0	72.8
Low Prod. Pastures	4625.9	379.1				6344	1892.4	
Complex cultivation	81.8	44.7	276.4			449.8	31.3	
Principally agriculture	1421.8	119.6		122.1				1328.5
Non-irrigated arable land						21742.7		
Farmyards	380.0	148.0	70					
Broad leaved forest	179.5	83.5	743.6			88.4	119.8	
Mixed forest						532.3	44.0	
Coniferous forest	2102.1	83.5	18.4	1319	411.6	2711.7	260.1	130.3
Natural grasslands	258.6	27.5	630.6	582.5		45.3		84.5
Transitional wood/shrub	1348.9			119.2	34.6	1444.9	589.56	136.3
Sparsely vegetated areas	348.0		232.4	400	540			
Inland marshes	56.9	58.4				205.3	258.4	
Moors heath		27.5						
Exploited Peat bogs	5638.6					214.8	2532.4	446.4
Unexploited Peat bogs	10024.3	276.4	5398	2145.0	540	21509.0	337.9	8200.5
Sport and leisure facilities	22.0					169.2		
Continuous urban	1.3	4.3						
Discontinuous urban	220.2	43.6				280.9		
Road and rail networks	170.0	17.5	70					
Mineral extraction sites	135.3					29.7		
Water bodies	299.0	20	295.1	47	2.2	8604.7	3243.1	840.8

Appendix 2.2: Ecological Sampling Methods

Field Methods

Open water samples were collected from the Burrishoole and Leane catchments. Open water samples were collected over 6 months spread across three seasons (spring, summer and autumn) to capture a broad range of species diversity. Phytoplankton samples were collected in deep open waters in months between April and October 2007. Two litres of open water samples were collected from the top 1 m of the water column with a plastic tube (30 mm x 1 m). The tube was filled vertically a number of times and transferred to a sample bottle. Samples were preserved with Lugol's solution (c. 50 ml). Open water zooplankton samples were collected from the deepest point of each lake with a conical net (53 µm mesh size) by vertical hauls through the water column. The sampling depth was approximately 50% of the maximum depth in each lake. The samples were transferred to 250 ml sample bottles. Fifty ml of 90% alcohol was added to give a sample/alcohol ratio of 1:5. A digital flowmeter attached to the net mouth enabled calculation of the water volume passing through the net (in the Burrishoole lakes only) and thus estimation of the mean numbers and proportional abundance of individual species per litre of water (individuals l^{-1}). No water volume data were available for Leane and thus zooplankton data are reported as % abundance of counts for this lake.

Phytoplankton Enumeration

Phytoplankton samples were analysed in the laboratory following the sedimentation technique developed by Utermöhl (1958) and Lund et al. (1958) and published as a European standard (EN 15402 2006). Preserved samples were mixed uniformly by gentle inversion and then poured into sedimentation chambers (volumes of 3, 5, 10 and 25 ml). The size of the chamber used depended on the density of organisms present. The chambers were filled to the top with sufficient excess to permit the water to bead upward. A cover was gently placed across the top of the chamber to remove excess water and an exact volume sample was enclosed without entrapping air bubbles. In order to ensure complete sedimentation of all organisms, sedimentation time in hours was at least three times the height of the sedimentation chamber (Wetzel & Likens 1991). Identification and enumeration of the phytoplankton communities was conducted under an inverted microscope (Brunel SP-95-I) at a magnification of x400. Identification of taxa to genus, and, when possible, to species level was achieved primarily through the use of John et al. (2002) and the associated interactive CD-Roms. Photographic images were taken using a Leica DFC 290 attached to the microscope during sample enumeration.

Enumeration of at least 400 individuals of the more abundant species in each sample was conducted. Small (4-8 µm diameter) organisms were counted along transects, and larger species (>8 µm diameter) together with all algal colonies were counted from 50% of the sedimentation chamber. More detailed analyses of phytoplankton populations in terms of algal biovolume were estimated by multiplying the number of cells of a given species counted in a sample by its average cell volume. Total sample/community biomass was obtained by summing the biomasses of the individual species. Cell volume was estimated from measurements of mean cell dimensions and the correspondence of cell shape to geometric shapes or combinations of shapes (e.g. spheres, cones, truncated cones, cylinders) (Hillebrand et al. 1999; Sun & Lui 2003). Photographs were taken of each species and linear dimensions measured with a computerised image analysis systems program (Leica Application Suite). Estimated biovolume values were then multiplied by cell density values to produce total biomass values for each species in a sample. The results were compared with literature-based studies from the UK (e.g. Carvalho et. al. 2007).

Zooplankton Enumeration

Zooplankton samples were washed gently under a tap through a 53 µm sieve. All the material rinsed from the mesh was collected and diluted with deionised water. A wide-bore pipette was used to transfer a 5 ml sub-sample onto a Ward rotary counting chamber (Ward 1955), and any zooplankton present allowed to settle out for 15 minutes. Samples were examined under a Meiji stereoscopic microscope with a magnification of x45. The cladocera in the subsample were identified to the lowest possible taxonomic level using Amoros (1984) and Scourfiels & Harding (1994). A minimum of 100 individuals of the most common species was recorded. The total number of copepods and nauplii present in each subsample were also noted, but these taxa were not differentiated into species. In Feeagh and Bunaveela a digital flowmeter enabled the calculation of mean numbers of individual species l^{-1} which are subsequently reported as percentage abundance while counts from Leane and Muckross are reported as percentages (no water volume measurements were available).

Appendix 2.3: Algal species, density and biomass calculations

Table 2.3.1 Leane: Algal density (cells ml^{-1}) for each genus/species (March to October 2007)

CYANOPHYTA	**Mar**	**May**	**Jul**	**Aug**	**Oct**
Anabaena sp.	0	0	16	26	15
Aphanocapsa sp.	128	4720	532	16272	1588
Aphanothece sp.	0	0	0	2968	0
Gomphospheria sp.	0	430	395	0	0
Merismopedia tenuissima	0	6	18	37	22
Oscillatoria limnetica	0	1083	17	93696	50280
Oscillatoria agardhii	7	324	4566	245	2544
CHLOROPHYTA					
Botryococcus brunii	6	3	74	0	37
Closteriopsis acicularis	10	10	2	6	13
Closterium acculare	3	10	0	0	0
Closterium acutum var. *variabile*	36	10	0	8	3
Closterium gracile	0	0	2	0	0
Closterium sp.	5	10	0	0	0
Coelastrum microporum	0	0	0	0	8
Cosmarium sp.	0	0	0	2	0
Crucigenia tetrapedia	0	0	2	0	0
Crucigeniella rectangularis	2	2	32	150	5
Dictyosphaerium sp.	0	96	0	394	23
Elakatothrix gelatinosa	0	2	2	10	0
Eudorina sp.	0	6	0	0	0
Kirchneriella sp.	0	1	2	16	2
Monoraphidium arcuatum	0	4118	198	0	1788
Monoraphidium contortum	151	1300	0	243	0
Monoraphidium convolutum	42	0	314	177	634
Oocystis cfr. *Lacustris*	0	0	0	8	3
Pediastrum boryanum	0	0	33	0	0
Scenedesmus sp.	2	20	25	34	13
Sphaerocystis schroeteri	0	13	388	98	0
Staurastrum sp.	0	0	7	1	0
CHRYSOPHYTA					
Dinobryon sp.	0	0	10	1	0
BACILLARIOPHYCEAE					
Asterionella formosa	92	345	45	222	51
Aulacoseira cfr. *granulata*	988	2525	400	446	403
Navicula sp.	0	3	1	0	0
Rhizosolenia sp.	0	312	4	2	10
Synedra actinastroides	0	4	11	39	64
Synedra sp.	0	52	4	1	0
Stephanodiscus astriae.	447	114	152	214	104
Tabellaria fenestrata	0	0	3	0	12
Tabellaria flocculosa var. *asterionelloides*	45	18	328	0	230
Tabellaria flocculosa	0	136	60	0	0
CRYPTOPHYTA					
Cryptomonas sp.	10	697	0	0	96
Chroomonas minuta	0	2766	77	25	681
Chroomonas acuta	6542	3494	0	6	665
DINOFLAGELLATA					
Ceratium hirundinella	0	0	32	7	0

Table 2.3.2 Leane: algal biomass (mm^3 m^{-3}) and biovolume (μm^3) for each genus/species (March to October 2007)

	Mar	May	Jul	Aug	Oct	Biovolume (μm^3)
CYANOPHYTA						
Anabaena sp.	0.0	0.0	3.1	5.0	2.9	193.51
Aphanocapsa sp.	0.3	11.5	1.3	39.7	3.9	2.44
Aphanothec sp	0.0	0.0	0.0	10.4	0.0	3.49
Gomphospheria sp.	0.0	9.9	9.1	0.0	0.0	23.09
Merismopedia tenuissima	0.0	0.0	0.0	0.1	0.1	2.4
Oscillatoria limnetica	0.0	40.1	0.6	3466.8	1860.4	37
Oscillatoria agardhii	0.3	12.0	168.9	9.1	94.1	129
CHLOROPHYTA						
Botryococcus braunii	0.0	0.0	0.1	0.0	0.1	1.85
Closteriopsis acicularis	0.7	0.7	0.1	0.4	0.9	69.22
Closterium aciculare	10.9	36.2	0.0	0.0	0.0	3623.5
Closterium acutum var. *variabile*	23.8	6.6	0.0	5.3	2.0	660.23
Closterium gracile	0.0	0.0	7.0	0.0	0.0	3502.3
Closterium sp.	0.3	0.6	0.0	0.0	0.0	59.5
Coelastrum microporum	0.0	0.0	0.0	0.0	0.0	
Cosmarium sp.	0.0	0.0	0.0	18.5	0.0	9232
Crucigeniella rectangularis	0.1	0.1	1.2	5.4	0.2	36.4
Dictyosphaerium sp.	0.0	3.8	0.0	15.6	0.9	39.6
Elakatothrix gelatinosa	0.0	0.1	0.1	0.4	0.0	35.11
Eudorina sp.	0.0	34.8	0.0	0.0	0.0	5804.4
Kirchneriella sp.	0.0	0.0	0.0	0.2	0.0	11.52
Monoraphidium arcuatum	0.0	298.4	14.3	0.0	129.6	72.46
Monoraphidium contortum	1.7	14.4	0.0	2.7	0.0	11.06
Monoraphidium convolutum	3.0	0.0	22.6	12.8	45.7	72.09
Oocystis cfr. *Lacustris*	0.0	0.0	0.0	2.7	1.0	321.12
Scenedesmus sp.	0.0	0.5	0.6	0.8	0.3	23.75
Sphaerocystis schroeteri	0.0	1.1	33.1	8.4	0.0	85.3
Staurastrum sp.	0.0	0.0	2.1	0.3	0.0	307
CHRYSOPHYTA						
Dinobryon sp.	0.0	0.0	1.2	0.1	0.0	116.64
BACILLARIOPHYCEAE						
Asterionella formosa	72.9	272.2	35.5	174.8	40.2	789
Aulacoseira cfr. *granulata*	1458.1	3727.8	590.5	659.0	595.0	1476.36
Rhizosolenia sp.	0.0	133.3	1.7	0.9	4.3	427.3
Synedra actinastroides	0.0	0.2	0.7	2.3	3.8	59.19
Synedra sp.	0.0	205.8	15.8	3.2	0.0	3957
Stephanodiscus neoastraea	621.9	158.6	211.4	298.0	144.7	1391
Tabellaria flocculosa var. *asterionelloides*	66.4	26.6	484.2	0.0	339.6	1476.35
Tabellaria flocculosa	0.0	74.8	33.0	0.0	0.0	550
CRYPTOPHYTA						
Cryptomonas sp.	21.3	1480.6	0.0	0.0	204.0	2125.3
Chroomonas minuta	0.0	67.5	1.9	0.6	16.6	24.4
Chroomonas acuta	251.2	134.2	0.0	0.2	25.6	38.4
DINOFLAGELLATA						
Ceratium hirundinella	0.0	17.8	1425	311.8	0.0	44536

Table 2.3.3 Feeagh: algal density (cells ml^{-1}) for each genus/species (April to October 2007)

CYANOPHYTA	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**
Anabaena flos aquae	0	0	62	152	9	7	0
Oscillatoria agardhii	0	0	22	1451	179	283	83
Spirulina sp.	1	0	0	0	1	0	0
CHLOROPHYTA							
Botryococcus braunii	644	428	431	324	614	1878	371
Chlorolobion braunii	1	6	5	1	0	0	0
Closterium acutum var *variabile*	83	42	0	135.2	16	255	73
Closterium gracile	0	0	1	0	0	0	0
Closterium kuetzingii	0	1	0	1	0	1	0
Coenococcus planctonicus	0	0	0	364	0	52	0
Cosmarium sp.	0	1	0	0	0	0	0
Euastrum sp.	0	0	1	0	0	0	0
Kirchneriella sp.	13	0	6	15	1	29	60
Monoraphidium arcuatum	31	21	17	42	10	73	39
Monoraphidium pusillum	0	0	0	281	120	62	29
Mougeotia sp.	24	24	11	60	3	19	1
Oocystis sp.	2	1	36	109	28	29	9
Planktosphaeria sp.	0	33	332	396	173	197	44
Scenedesmus sp.	0	0	0	187	0	1009	44
Sphaerocystis schroeteri	4	13	459	101	33	226	66
Staurastrum sp.	0	0	1	0	1	0	0
CHRYSOPHYTA							
Chrysochromulina parva	104	52	0	0	31	0	0
Dinobryon sp.	0	0	74	345	13	2	0
Mallomonas sp.	0	0	0	0	57	42	3
BACILLARIOPHYTA							
Achnantes minutissima	0	0	183	23	8	58	2
Asterionella formosa	380	897	179	199	606	332	84
Aulacoseira cfr. *distans*	182	79	7	34	195	1231	996
Aulacoseira cfr. *italica*	1143	109	7	123	195	351	236
Cyclotella kuetzingiana	239	125	87	125	31	42	36
Navicula sp.	0	0	0	9	0	7	2
Rhizosolenia sp.	6	23	3	69	1	11	9
Tabellaria flocculosa var. asterionelloides	90	113	35	37	71	183	72
Tabellaria flocculosa	197	103	0	382	143	285	19
Tabellaria sp.	5	2	9	37	0	7	7
Cymbella sp.	0	0	0	0	0	0	2
CRYPTOPHYTA							
Cryptomonas cfr. *acuta*	0	21	0	0	0	0	0
Cryptomonas cfr. *ovata*	52	135	520	145.6	31	42	18
Chroomonas acuta	7851	6904	5528	2989	2516	2761	265
Chroomonas minuta	281	125	87	3442	36	2407	990
DINOFLAGELLATA							
Ceratium hirundinella	0	1	3	11	1	0	0
Gymnodinium sp.	0	1	0	1	1	0	0
OTHERS							
Unknown unicells 2 µm	0	312	884	0	0	0	0
Unknown unicells 4 µm	250	0	0	333	166	0	3
OTHERS							
Unknown unicells 2 µm	0	312	884	0	0	0	0
Unknown unicells 4 µm	250	0	0	333	166	0	3

Table 2.2.4 Feeagh: algal biomass (mm^3 m^{-3}) and biovolume (µm^3) for each genus/species (April to October 2007)

	Apr	May	Jun	Jul	Aug	Sep	Oct	Biovolume (µm^3)
CYANOPHYTA								
Anabaena flos aquae	0.0	0.0	22.7	55.6	3.4	2.4	0.0	366.0
Oscillatoria agardhii	0.0	0.0	3.6	235	29.1	45.9	13.4	162.0
CHLOROPHYTA								
Botryococcus braunii	1.2	0.8	0.8	0.6	1.1	3.5	0.7	1.9
Chlorolobion brunii	0.0	0.3	0.3	0.0	0.0	0.0	0.0	55.88
Closterium acutum var. *variabile*	5.1	2.6	0.0	8.3	1.0	15.7	4.5	61.5
Coenococcus planctonicus	0.0	0.0	0.0	59.3	0.0	8.5	0.0	162.8
Kirchneriella sp.	0.1	0.0	0.0	0.1	0.0	0.2	0.4	6.29
Monoraphidium arcuatum	1.0	0.7	0.6	1.4	0.3	2.4	1.3	33.3
Monoraphidium pusillum	0.0	0.0	0.0	73.5	31.3	16.3	7.5	261.6
Mougeotia sp.	126	125.7	55.9	314	17.5	101	6.3	5237.4
Oocystis sp.	0.6	0.5	12.7	38.6	9.9	10.4	3.1	353
Planktosphaeria sp.	0.0	0.5	5.0	6.0	2.6	3.0	0.7	15.2
Scenedesmus sp.	0.0	0.0	0.0	15.6	0.0	84.2	3.7	83.5
Sphaerocystis schroeteri	0.9	3.3	117	25.7	8.5	57.5	16.8	254.4
Staurastrum sp.	0.0	0.0	0.4	0.0	0.4	0.0	0.0	307
CHRYSOPHYTA								
Chrysochromulina parva	15.2	7.6	0.0	0.0	4.6	0.0	0.0	146
Dinobryon sp.	0.0	0.0	30.6	143	5.4	0.8	0.0	413.6
Mallomonas sp.	0.0	0.0	0.0	0.0	1013	737	46.0	17709
BACILLARIOPHYTA								
Achnantes minutissima	0.0	0.0	9.9	1.3	0.4	3.1	0.1	53.8
Asterionella formosa	311	734	147	162	495.5	271	69.0	817.7
Aulacoseira cfr. *Distans*	12.4	5.4	0.5	2.3	13.3	83.9	67.9	68
Aulacoseira cfr. *Italic*	572.0	54.5	3.5	61.5	97.6	176	118	500.4
Cyclotella kuetzingiana	427.0	223.2	155	223	55.7	74.3	65.0	1785.4
Navicula sp.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0
Rhizosolenia sp.	2.2	8.9	1.0	27.0	0.4	4.3	3.6	393
Tabellaria flocculosa var. *asterionelloides*	69.1	86.8	26.9	28.4	54.5	140	55.0	767.8
Tabellaria flocculosa	42.9	22.5	0.0	83.3	31.2	62.1	4.1	218
Tabellaria sp.	17.4	7.0	31.3	129	0.0	23.2	23.6	3477.2
CRYPTOPHYTA								
Cryptomonas cfr. *acuta*	0.0	4.8	0.0	0.0	0.0	0.0	0.0	229.1
Cryptomonas cfr. *Ovate*	164.9	428.1	1649	462	98.9	132	57.7	3171
Chroomonas acuta	330.5	290.7	233	126	105.9	116	11.2	42.1
Chroomonas minuta	9.8	4.4	3.0	120	1.3	84.0	34.6	34.9
DINOFLAGELLATA								
Ceratium hirundinella	0.0	59.4	149	475	44.5	0.0	0.0	44536
Gymnodinium sp.	0.0	0.4	0.0	0.4	0.6	0.0	0.0	580
OTHERS								
Unknown unicells 2 µm	0.0	1.3	3.7	0.0	0.0	0.0	0.0	4.18
Unknown unicells 4 µm	8.4	0.0	0.0	11.2	5.6	0.0	0.1	33.5

Appendix 3

Appendix 3.1: Diatom taxa and authorities

Table 3.1.1 Diatom taxa enumerated in lake sediment samples. Only those taxa with abundance > 3% in at least one sediment sample are shown. Authorities are also provided, as is information on the lakes where a particular taxon was encountered (B = Bunaveela; F = Feeagh; L = Leane; M = Muckross; MK-1, MK-2, MK-3 = Mask coring sites one, two and three)

Taxon Name and Authority			**Lake**
Achnanthes	*capitata*	(Kuetz)	M
Achnanthes	*buccola*	Cholnoky	L
Achnanthes	*helvetica*	(Hustedt) Lange-Bertalot, Kusber & Metzeltin	B, F
Achnanthes	*oblongella*	Oestrup	B
Achnanthes	*rhombica*	Oestrup	M
Achnanthes	*pusilla*	(Grunow) De Toni	B, F
Achnanthes	*subatomides*	(Hustedt) Lange-Bertalot et Archibald	B, F
Achnanthidium	*affine*	(Grun) Czarnecki	F
Achnanthidium	*caledonicum*	(Lange-Bertalot)Lange-Bertalot	L, B
Achnanthidium	*clevei*	(Lange-Bertalot) Lange-Bertalot	L, M, F
Achnanthidium	*eutrophilum*	(Lange-Bertalot)Lange-Bertalot	L, B, F
Achnanthidium	*microcephalum*	Kuetzing	L, B, F
Achnanthidium	*minutissimum*	(Kütz.) Czarnecki	L, B, M, F, MK-1, MK-2, MK-3
Amphora	*commutata*	Grunow	MK-1
Amphora	*inariensis*	Krammer	L, B, F
Amphora	*pediculus*	(Kuetzing) Grunow	L, MK-2
Asterionella	*formosa*	Hassall	L, M, B, F, MK-1, MK-2, MK-3
Aulacoseira	*alpigena*	(Grunow) Krammer	L, M, F
Aulacoseira	*ambigua*	(Grunow) Krammer	L, M, F
Aulacoseira	*granulate*	(Ehr.) Simonsen	B, F, MK-1, MK-3
Aulacoseira	*islandica*	(O.Muller) Simonsen	L
Aulacoseira	sp.		M
Aulacoseira	*subarctica*	(O.Muller) Simonsen	L, B, F
Brachysira	*garenssis*	(Lange-Bertalot & Krammer) Lange-Bertalot	L, B, F
Brachysira	*brachysira*		MK-1
Brachysira	*neoexilis*	Lange-Bertalot	L, B, F
Brachysira	*striaca*	(Grunow) Ross in Hartley	B
Brachysira	*vitrea*	(Grunow) Ross in Hartley	M, MK-1, MK-3
Cocconeis	*neothumensis*	Krammer	L, B, F
Cocconeis	*placentula*	Krammer	L, M, B, F, MK-1, MK-2
Cyclotella	*atomus*	Hustedt	L, F
Cyclotella	*bodanica*	Grunow	L, B, F, MK-1
Cyclotella	*comensis*	Grunow in Van Heurck	L, M, B, F
Cyclotella	*comta*	(Ehr.)Kutzing	L, M, B, F
Cyclotella	*distinguenda*	Hustedt	L, B, F, MK-1
Cyclotella	*distingunda var. unipunctuata*	Hustedt	L, M, F
Cyclotella	*kuetzingiana*	Thwaites	L, M, B, F
Cyclotella	*meneghiniana*	Kuetzing	L
Cyclotella	*michiganiana*	Kuetzing	MK-1
Cyclotella	*oscellata*	Pantocsek	F, MK-1, MK-2, MK-3
Cyclotella	*pesudostelligera*	Hustedt	L
Cyclotella	*planctonica*	Hustedt	MK-1
Cyclotella	*radiosa*	(Grunow) Lemmermann	L, M, B, F
Cyclotella	*rossii*	Hakansson	M, F
Cyclotella	sp.		M
Cymbella	*affinis*	Kuetzing	L, B, F
Cymbella	*deliculata*	Kuetzing	MK-1
Cymbella	*gracilis*	(Ehr.)Kuetzing	L, M, B, F

Cymbella	*helvetica*	Kuetzing	L, M, F, MK-1
Cymbella	*microcephala*	Grunow	L, M, B, F, MK-1
Cymbella	*minuta*	Grunnow	L, M, B, F
Cymbella	*silesiaca*	Bleisch in Rabenhorst (Encyonema)	L, M, B, F
Cymbella	*sinuate*	Gregory	L, B, F
Denticula	*tenuis*	Kuetzing	L, F, MK-1
Denticula	*thermalis*	Kuetzing	MK-1
Diatoma	*moniliformis*	Kuetzing	L, M, B, F
Diatoma	*tenuis*	Agardh	L, B, F
Diploneis	*elliptica*	(Kuetzing) Cleve	L, M, MK-1
Epithemia	*argus*	(Ehrenberg) Kutzing	MK-1, MK-2
Epithemia	*geoppertianna*	Hilse	MK-2
Epithemia	*smithii*	Carruthers 1864	MK-1, MK-2
Eunotia	*arcus*	Ehrenberg	MK-1
Fragilaria	*brevistriata*	Grunnow	L, M, B, MK-1, MK-2
Fragilaria	*capucina*		F, MK-1, MK-2, MK-3
Fragilaria	*capucina var. rumpens*	(Kütz.) Lange-Bert. ex Bukht.	L, M, B, MK-1, MK-2, MK-3
Fragilaria	*complex*		MK-1
Fragilaria	*construens*		MK-1, MK-2
Fragilaria	*crotonensis*	(Ehrenberg) Kitton	L, M, MK-1, MK-2, MK-3
Fragilaria	*exigua*	Grunow	L, M, B, F
Fragilaria	*fasciculata*		MK-1, MK-2
Fragilaria	*gracilis*	Østrup	L, M, B, F
Fragilaria	*pinnata*	Ehrenberg	L, M, B, F, MK-1, MK-2
Fragilaria	*tenera*	(W.Smith) Lange-Bertalot	L, M, B, F
Fragilaria	*virescens*	Ralfs	L, F, MK-3
Frustulia	*rhoimboides*	(Ehr.)De Toni	L, M, B, F
Gomphonema	*angustum*	Agardh	L, M, B, F, MK-1
Gomphonema	*angustatum angustatum*	(Kuetz) Rabenhorst	MK-2
Gyrosigma	*acuminatum*	(Kuetz) Rabenhorst	L, MK-2
Gyrosigma	*attenuatum*	(Kuetz) Rabenhorst	F, MK-1
Mastolgloia	*smithii*	Thwaites	MK-1, MK-2
Meloseira	*varians*	Agardh	L, MK-1, MK-3
Stephanodiscus	*hantzschii*	Grunow in Cl. & Grun. 1880	L, MK-1
Stephanodiscus	*neoastrea*	Hakansson et Hickel	L
Stephandiscus	*parvus*	Stoermer et Hakansson	L
Tabellaria	*flocculosa*	(Roth) Kuetzing	L, M, B, F, MK-1, MK-2, MK-3

Appendix 3.2: Cladocera taxa and authorities

Table 3.2.1 Cladocera taxa and authorities listed in alphabetical order

Taxon Name	Authority
Acroperus harpae	Baird, 1834
Alona affinis	Leydig, 1860
Alona costata	G.O. Sars, 1862
Alona guttata	G.O. Sars, 1862
Alona guttata var *tuberculata*	
Alona guttata/rectangular	G.O. Sars, 1862/G.O. Sars, 1862
Alona intermedia	G.O. Sars, 1862
Alona quadrangularis	O.F. Müller, 1776
Alona rectangular	G.O. Sars, 1862
Alona rectangula var *pulchra*	
Alona rustica	G.O. Sars, 1862
Alona sp.(small)	
Alonella excise	Fischer, 1854
Alonella exigua	Lilljeborg, 1853
Alonella nana	Baird, 1834
Alonopsis elongate	G.O. Sars, 1862
Anchistropus emarginatus	G.O. Sars, 1862
Bosmina coregoni	Baird, 1857
Bosmina longirostris	O.F. Müller, 1776
Bosmina longispina	Leydig, 1860
Bosmina sp.	
Camptocercus rectirostris	Schödler, 1862
Ceriodaphnia sp.	
Chydorus piger	G.O. Sars, 1862
Chydorus sp.	
Chydorus sphaericus	
Daphnia longispina group	
Eurycercus lamellatus	O.F. Müller, 1776
Eurycercus sp.	
Graptoleberis testudinaria	S. Fischer, 1848
Kurzia latissima	Kurz, 1875
Leydigia acanthocercoides	S. Fischer, 1854
Leydigia leydigii	Schödler, 1862
Monospilus dispar	G.O. Sars, 1862
Oxyurella tenuicaudis	G.O. Sars, 1862
Phrixura rostrata	Koch, 1844
Pleuroxus aduncus	Jurine, 1820
Pleuroxus denticulatus	Birge, 1879
Pleuroxus laevis	G.O. Sars, 1862
Pleuroxus sp.	
Pleuroxus trigonellus	O.F. Müller, 1785
Pleuroxus truncates	O.F. Müller, 1785
Pleuroxus uncinatus	Baird, 1850
Rhynchotalona falcata	G.O. Sars, 1862
Tretocephala ambigua	Lilljeborg, 1900

Appendix 3.3: Sequence Slotting (core-correlation)

The unpublished computer programme CSPLOT (Malcolm Clarke pers. comm.) was used in cross-correlation of deepwater sediment cores from Leane and Feeagh. The following provides an example of the technique, as applied to material from Feeagh.

3.1.1 Feeagh: sequence (core) comparison

Four sediment sequences (cores) (F-1, F-2, F-3, F-4) were collected from the deepest point (c. 45 m water depth) in Feeagh. Percentage LOI was measured on all cores, while additional analyses (geochemistry, diatoms, pollen, cladocera) were conducted on F-2, F-3 and F-4. Core F-2, the longest core, was radiometrically dated and therefore was selected as the master sequence (64 levels/cm) (F2 = Sequence A) for core correlation using LOI sediment profile data. Cores F-1, F-3 and F-4 have 41, 51 and 53 levels, respectively (i.e. are, respectively, 41, 51 and 53 cm long).

Sequence comparison was conducted by comparing all cores with the master sequence (F-2). First, variations in LOI data were plotted against depth for each core, including the master sequence. Second, a piano plot was constructed to give a visual indication of how well the core sequences matched up (not illustrated). For a good match, the black and white keys should be roughly the same size. A sensitivity curve was used to detect any unusual observations in the master core, and the depth scales in each core were compared with those in the master core (figures 3.1a, 3.2a and 3.3a). This is equivalent to comparing sedimentation rates between cores. Lastly, cubic and linear polynomial curve fits were examined to summarise the level of correlation between any two cores (figures 3.1b, 3.2b and 3.3b).

Comparison of master core F-2 with F-1 (41 levels/cm)

CSPLOT comparisons of depth scales of F-1 and F-2 (the master sequence) were very similar (Figure 3.1a). Examination of both cubic and linear polynomial fits suggest that the latter is better for core F1 (Figure 3.1b), suggesting that sedimentation rates are proportional to one another (for each 1 cm increase in the depth in sequence F-1, the depth in the master sequence (F-2) increases by 0.6361 cm).

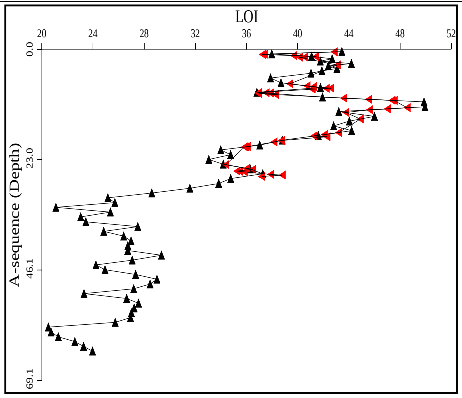


Figure 3.1a.

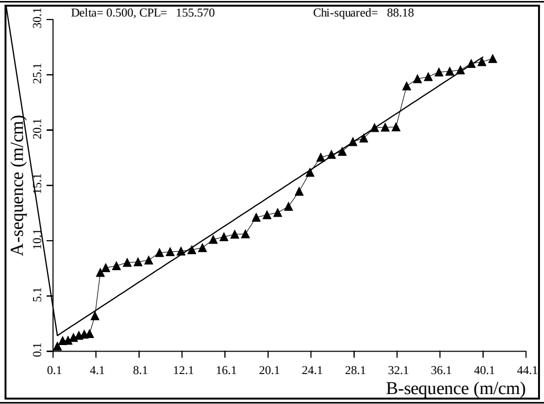


Figure 3.1b

Figure 3.1 LOI versus Depth (black symbols correspond to F-2 the master sequence, while the red symbols correspond to core F-1) (Figure 3.1a); Straight line fit with equal weights: Fitted Polynomial, with 2 terms, n=46, Chi-squared = 88.18, Normalised SD= 0.62502 (Figure 3.1b).

Comparison of master core F2 with F-3 (51 levels/cm)

CSPLOT comparison of depth scales of F-3 and F-2 (the master sequence) indicates an excellent match (Figure 3.2a) across the full 51 cm-long sequence. Examination of both cubic and linear polynomial fits suggest that the latter is better for core F3 (Figure 3.2b), suggesting that sedimentation rates are proportional to one another.

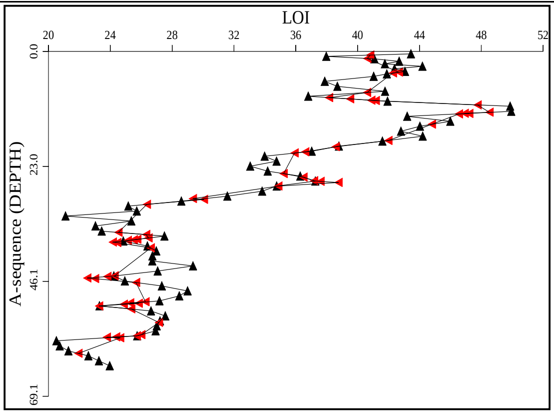
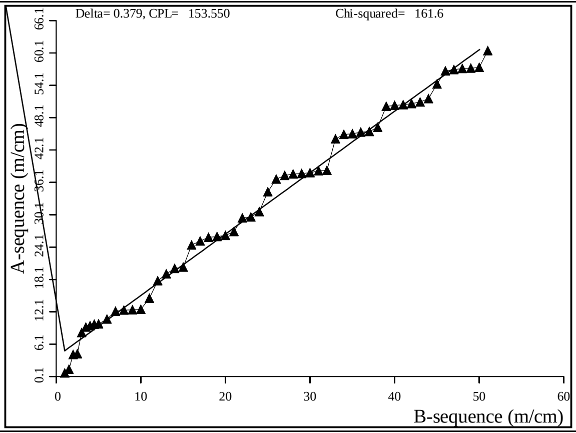
	

Figure 3.2a:	**Figure 3.2b**

Figure 3.2 LOI versus Depth (black symbols correspond to F-2 the master sequence, while the red symbols correspond to core F-3) (Figure 3.2a); Fitted straight line: Fitted Polynomial, with 2 terms, n=55, Chi-squared = 161.6, Normalised SD= 0.14897 (Figure 3.2b).

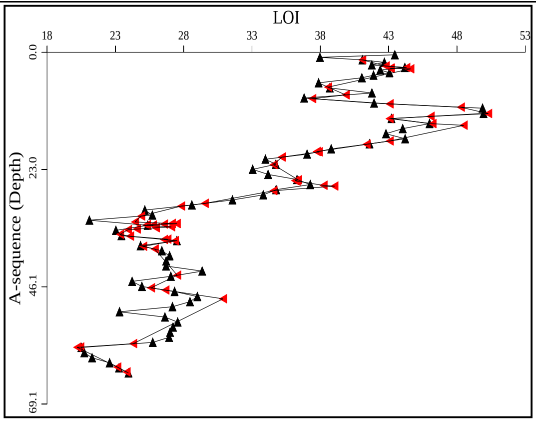
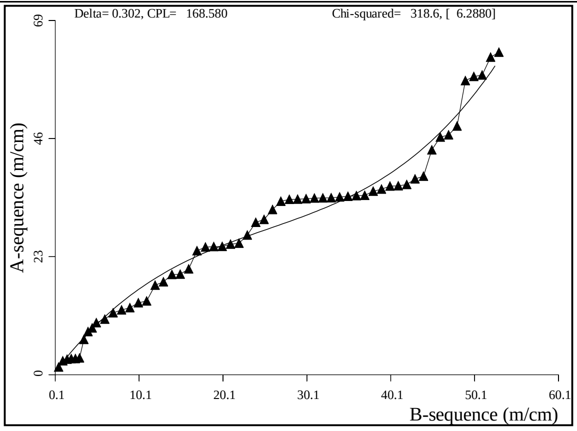
	

Figure 3.3a:	**Figure 3.3b**

Figure 3.3 LOI versus Depth (black symbols correspond to F-2 the master sequence, while the red symbols correspond to core F-4) (Figure 3.3a); Fitted Polynomial, with 4 terms, n=58, Chi-squared = 318.6, Normalised SD= 0.17070 (Figure 3.3b).

Comparison of master core F-2 with F-4 (53 levels/cm)

CSPLOT comparison of depth scales of F-4 and F-2 (the master sequence) indicate close similarity in the uppermost levels (Figure 3.3a). Examination of both cubic and linear polynomial fits suggests that a cubic fit is better for core F-4 (Figure 3.3b). The relative sedimentation varies, which is in contrast to the first two comparisons (F-1 and F-3), where the sedimentation rates were found to be proportional to one another.

Appendix 3.4: Fossil diatom percentages

Table 3.4.1 Leane fossil diatoms (>3% abundance in at least one sample).

Depth (cm)	*Achnanthidium minutissimum*	*Achnanthidium caledonicum*	*Achnanthidium eutrophilum*	*Asterionella formosa*	*Aulacoseira ambigua*	*Aulacoseira subarctica*	*Cocconeis placentula*	*Cyclotella bodanica*	*Cyclotella kuetzingiana*	*Cyclotella comensis*	*Cyclotella meneghiniana*	*Cyclotella pesudostelligera*	*Cyclotella radiosa*	*Fragilaria brevistriata*	*F. capucina var# rumpens*	*F. capucina var# vaucheriae*	*Fragilaria construens*	*Fragilaria crotonensis*	*Fragilaria pinnata*	*Fragilaria robusta*	*Fragilaria tenera*	*Stephanodiscus hantzschii*	*Stephanodiscus neoastrea*	*Stephanodiscus parvus*	*Tabellaria flocculosa*
0.5	6.9	0.0	0.0	0.9	37.4	10.7	2.8	0.0	0.0	0.0	0.0	0.3	0.0	0.0	4.7	1.9	2.5	0.0	4.7	0.0	3.8	0.0	1.3	0.0	2.2
1.5	9.2	0.0	0.0	7.2	43.5	4.6	2.9	0.0	0.0	1.2	0.0	0.0	0.0	0.0	1.2	0.3	0.0	0.0	1.4	0.0	5.5	0.0	4.9	1.2	3.2
2.5	7.5	0.0	0.9	3.7	30.0	17.0	2.0	0.0	2.0	0.0	0.0	0.0	0.6	0.0	3.2	0.3	3.5	0.0	1.4	0.0	0.0	0.0	2.0	2.6	3.2
4.5	9.2	0.0	0.0	4.4	24.9	15.9	2.8	0.0	1.0	0.0	0.0	0.0	0.5	0.8	5.1	0.8	0.3	1.5	3.6	0.0	0.0	0.5	1.8	3.8	3.8
6.5	12.7	0.0	0.0	4.5	38.9	14.3	2.5	0.3	0.0	0.3	0.3	0.0	0.0	0.0	1.9	0.0	0.0	0.0	0.6	0.0	1.3	1.9	1.9	5.4	1.3
7.5	7.2	0.3	1.1	4.5	38.0	17.4	2.1	0.0	0.0	0.3	0.0	0.3	0.5	0.0	1.6	1.1	0.0	0.0	0.0	0.0	2.9	0.0	0.8	2.9	4.0
8.5	11.1	0.0	0.0	3.8	37.0	20.6	1.6	0.0	0.0	1.3	0.6	0.0	0.0	0.0	3.5	0.3	0.6	0.0	1.6	0.0	0.3	1.9	1.3	3.2	1.9
9.5	2.8	0.0	0.0	6.0	26.8	27.9	0.9	0.0	0.0	0.0	0.3	0.3	0.0	0.0	2.6	0.9	0.0	5.1	5.7	0.0	0.0	0.6	1.7	4.0	0.6
10.5	8.8	0.0	0.0	5.2	42.0	12.7	2.0	0.0	0.0	1.6	1.0	0.0	0.0	0.0	1.3	0.3	0.3	0.0	1.3	0.0	0.3	1.0	3.3	3.9	2.0
12.5	3.4	0.6	0.3	0.9	33.9	30.5	2.3	0.0	0.6	0.0	0.0	3.2	0.3	0.0	2.0	1.1	0.0	0.0	1.4	0.0	2.9	0.3	1.4	2.3	0.0
14.5	8.0	0.0	0.0	0.7	48.4	12.5	2.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7	1.0	0.0	4.3	2.2	0.0	0.0	0.0	0.5	2.9	4.3
16.5	7.8	0.0	0.0	0.9	35.2	25.1	5.1	0.9	0.0	0.3	2.7	0.0	0.0	0.0	0.9	0.0	0.3	0.0	1.2	0.0	0.0	0.9	1.8	3.6	4.8
17.5	5.2	0.0	1.0	0.0	17.8	39.4	1.8	0.5	0.0	0.5	0.0	0.8	0.5	0.0	0.5	0.3	0.0	0.0	0.8	0.0	1.3	0.0	2.4	3.9	4.2
19.5	5.8	0.0	0.0	6.0	22.7	25.5	2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5	0.3	0.0	0.0	7.1	0.0	0.0	0.5	3.0	5.8	4.4
20.5	17.3	0.0	0.0	1.6	27.7	16.5	2.1	1.0	0.0	0.8	0.0	0.0	0.0	0.3	0.0	0.3	0.3	0.0	1.3	0.0	0.0	0.8	5.5	6.3	6.5
22.5	6.0	0.0	0.0	2.3	12.0	22.1	3.4	0.0	0.0	0.9	0.0	0.0	1.1	0.0	1.4	1.4	3.4	0.0	2.0	0.0	2.0	5.2	4.3	10.9	0.6
24.5	8.5	0.0	0.0	3.2	27.1	16.8	3.2	0.0	0.0	0.0	0.0	3.2	0.0	0.0	1.8	0.3	0.0	4.7	0.0	0.0	0.0	0.0	1.5	9.7	2.4
26.5	8.6	0.0	0.0	4.6	44.8	15.4	3.4	0.6	0.0	0.6	0.3	0.0	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.9	0.9	5.6	4.0	2.8
27.5	5.4	0.3	0.0	1.2	19.8	28.2	3.6	0.0	0.3	0.6	0.3	0.0	0.3	0.0	0.0	0.0	2.1	0.0	0.6	0.0	2.1	1.2	3.9	3.3	2.7
28.5	8.9	0.0	0.0	2.3	37.4	15.2	1.0	0.0	0.0	0.7	0.0	0.0	1.7	0.0	1.7	1.7	0.0	0.0	1.0	0.0	1.3	0.7	8.6	4.3	1.3
29.5	9.0	0.0	0.0	2.5	23.3	25.6	2.5	0.0	0.3	0.0	0.0	0.8	0.0	0.0	0.8	0.8	0.0	1.0	1.0	0.0	0.0	0.0	2.3	11.5	2.8
31.5	7.6	0.0	0.0	1.3	34.9	17.5	3.2	1.0	0.0	2.9	1.0	0.0	0.0	0.3	2.2	0.6	0.6	1.0	1.6	0.0	0.0	1.0	5.7	7.6	2.5
33.5	6.4	0.6	0.3	0.0	30.6	22.9	4.8	0.0	0.0	1.9	0.3	0.6	1.6	0.0	0.6	0.6	0.0	0.0	0.3	0.0	1.9	0.6	2.2	6.7	2.2
35.5	11.4	0.0	0.0	0.3	28.1	13.2	4.5	0.3	0.3	0.3	0.0	0.3	1.5	0.0	0.3	0.3	0.0	5.7	3.3	0.0	0.0	0.0	0.9	7.8	2.4
37.5	14.2	0.0	0.0	3.9	42.9	3.3	9.1	2.4	0.0	1.8	0.6	0.0	0.0	0.3	0.9	0.6	0.0	0.0	0.9	0.0	0.6	0.0	1.8	2.7	3.0
38.5	13.8	0.6	1.1	2.9	17.5	10.1	8.6	0.0	0.3	3.7	0.0	0.6	2.3	0.6	0.6	0.0	0.6	0.0	1.1	6.3	5.7	0.6	0.9	3.7	1.4
39.5	16.1	0.0	0.0	2.5	39.6	0.9	11.4	1.6	0.0	5.1	0.0	0.0	0.0	0.0	1.3	0.6	0.0	2.2	0.3	0.0	4.4	0.6	1.3	0.6	2.2
41.5	17.3	0.0	0.0	7.5	27.5	1.8	4.5	0.0	0.9	4.2	0.0	1.2	3.6	0.0	1.5	0.9	0.0	3.6	7.2	0.0	0.0	0.0	0.0	0.0	4.8
43.5	18.9	2.9	1.4	2.9	8.3	1.4	4.9	0.0	3.1	4.3	0.0	2.3	6.3	0.0	1.4	0.9	0.9	0.0	0.6	0.0	2.3	1.7	1.1	4.3	3.7
45.5	22.7	0.0	0.0	3.8	35.6	0.0	1.1	0.0	3.0	0.5	0.0	2.7	3.0	0.0	5.8	0.8	0.0	0.5	3.3	0.0	0.0	0.0	0.0	3.6	1.6
46.5	17.8	0.0	0.0	3.3	38.0	2.1	3.6	1.5	0.0	5.1	0.0	0.0	0.0	0.6	1.8	0.0	0.0	0.0	0.6	0.0	0.3	0.0	0.6	4.2	4.5
48.5	14.7	6.2	4.2	6.5	5.9	0.8	2.5	0.6	4.2	2.5	0.0	1.4	2.5	4.0	1.4	4.2	0.0	0.0	1.7	0.0	0.8	0.8	0.0	2.8	4.0
49.5	30.8	0.0	0.0	8.7	2.4	0.3	3.9	4.8	0.0	6.9	1.5	0.0	4.5	0.0	4.5	1.2	0.9	0.0	3.0	0.0	1.5	0.3	0.6	1.5	3.0
51.5	31.4	0.0	0.0	2.3	5.0	1.5	4.7	0.0	0.0	1.5	0.0	2.6	1.8	0.3	0.3	1.2	0.0	0.6	10.0	0.0	0.0	0.0	0.6	4.7	4.4
52.5	36.0	0.0	0.0	3.5	3.5	0.0	4.5	1.0	0.0	7.6	1.9	0.0	3.5	0.0	0.3	0.3	0.0	0.0	2.5	0.0	1.3	1.0	0.6	3.2	2.5
53.5	14.7	2.6	4.3	4.0	3.4	0.6	2.9	0.0	2.3	6.9	0.0	1.7	4.0	1.7	0.6	2.3	1.1	0.0	5.5	0.0	0.6	0.6	0.6	7.5	2.0
54.5	38.1	0.0	0.0	7.1	3.5	0.0	3.9	1.6	0.0	4.8	3.5	0.0	0.0	0.3	2.3	0.3	1.0	0.0	2.3	0.0	1.9	0.6	0.6	4.8	6.1
56.5	28.2	0.0	0.0	3.2	9.4	0.0	0.5	0.0	4.6	3.2	0.3	2.1	2.1	1.6	2.1	0.0	3.2	0.0	5.9	0.0	3.2	0.0	0.8	2.9	2.4

Table 3.4.2 Muckross fossil diatoms (>3% abundance in at least one sample).

Depth (cm)	*Achnanthidium minutissimum*	*Achnantes capitata var# jackii*	*Achnanthes rhombica*	*Achnanthes minutissima var# scotica*	*Achnantes pusilla*	*Asterionella formosa*	*Aulacoseira sp#*	*Brachysira vitrea*	*Cocconeis placentula*	*Cyclotella comensis*	*Cyclotella distinguenda var# unipunctata*	*Cyclotella kuetzingiana*	*Cyclotella radiosa*	*Cyclotella rossii*	*Cyclotella sp#*	*Cymbella gracilis*	*Cymbella microcephala*	*Cymbella minuta*	*Cymbella silesiaca*	*Fragilaria capucina var# rumpens*	*Fragilaria exigua*	*Fragilaria gracilis*	*Fragilaria tenera*	*Frustulia saxonica*	*Frustulia viridula*	*Gomphonema minutum*	*Nitzschia sp*	*Stephanodiscus alpinus*	*Stephanodiscus sp*	*Stephanodiscus/Cyclotella*	*Tabellaria flocculosa*
1	15.3	0.0	0.0	0.0	0.0	4.3	0.0	3.2	0.0	7.2	0.0	0.0	6.4	12.1	0.0	1.7	1.2	0.0	1.2	0.0	0.0	2.0	1.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.0
8	23.0	0.0	0.0	0.0	1.1	1.1	0.0	3.4	0.0	3.0	0.0	0.0	14.7	5.7	6.0	1.9	2.3	1.5	1.1	2.6	1.5	3.8	0.0	0.4	0.8	0.8	0.0	1.5	0.0	0.0	2.3
11	33.5	3.2	0.0	0.0	1.6	0.0	0.0	6.8	2.4	6.8	0.0	0.0	0.0	0.0	10.0	1.6	0.0	0.0	2.0	0.0	0.0	3.2	0.0	0.0	0.0	2.0	0.4	0.0	4.8	0.0	1.6
14	34.1	0.0	2.8	0.0	1.2	0.0	0.0	5.7	0.8	3.3	0.0	0.0	4.9	10.6	0.0	1.6	4.1	2.8	2.4	0.8	2.0	0.8	0.0	0.8	0.0	0.0	1.6	0.0	0.0	0.0	5.3
21	35.0	0.0	0.0	0.0	0.4	0.0	0.0	8.5	0.0	0.4	0.0	2.2	0.0	10.8	0.4	2.2	3.6	0.0	0.0	0.0	0.0	0.9	0.0	0.9	0.0	0.0	2.2	0.0	0.0	10.3	6.3
34	21.1	0.0	0.0	3.6	0.0	0.0	6.8	8.4	0.0	3.6	8.0	0.0	13.5	4.0	0.0	1.6	2.4	0.0	0.0	0.0	0.0	2.0	0.0	1.6	0.8	0.8	0.4	2.4	0.0	0.0	1.6
41	24	0	0	0	0.9	0.5	0.2	8.8	0	7.9	5.8	0	21	3.9	0	1.6	2.8	0.2	1.8	0.5	0	1.8	0	2.1	0.5	0	0	0.5	0	0	0.9
45	23	0	0	0	2.1	0	0	9.4	0.7	16	9.7	0	11	0	0.7	1	0.7	0	0	0	2.1	0	0	0	2.1	2.1	0	0.3	0	0	0
52	20	0	0	0	0.6	1.5	0.3	4.1	0.9	13	4.1	0	11	10	0.3	0.6	2.7	0	3.6	1.2	0.6	0.3	2.4	0.6	0.6	0.6	0	0	0	0	1.5

Table 3.4.3 Bunaveela fossil diatoms (>3% abundance in at least one sample).

Depth (cm)	*Achnanthidium caledonicum*	*Achnanthidium minutissimum*	*Achnanthes oblongella*	*Achnanthes pusilla*	*Asterionella formosa*	*Aulacoseira ambigua*	*Aulacoseira granulata*	*Aulacoseira subarctica*	*Brachysira garenssis*	*Brachysira neoexilis*	*Cocconeis placentula*	*Cyclotella sff# Comta*	*Cyclotella comensis*	*Cyclotella radiosa*	*Cymbella affinis*	*Cymbella minuta*	*Cymbella silesiaca*	*Cymbella sinuata*	*Diatoma tenuis*	*Eunotia implicata*	*Eunotia incise*	*Fragilaria brevistriata*	*Fragilaria capucina var# rumpens*	*Fragilaria caupucina var# vaucheriae*	*Fragilaria construens*	*Fragilaria exigua*	*Fragilaria pinnata*	*Fragilaria tenera*	*Frustulia rhoimboides*	*Gomphonema angustum*	*Gomphonema parvulum*	*Navicula cocconeiformis*	*Nitzschia fonticola*	*Synedra ulna*	*Tabellaria flocculosa*
1	1.3	4.8	1.3	1.3	2.2	1.0	2.2	41.5	0.0	0.0	1.3	0.0	0.0	4.8	0.0	1.6	3.2	0.3	0.0	0.6	2.2	0.0	0.6	1.3	0.3	1.9	2.9	0.6	0.0	0.0	1.0	0.0	0.0	1.0	5.1
6	0.0	16.2	1.6	0.0	3.6	0.3	10.0	5.2	2.3	0.0	2.3	0.0	0.6	5.8	0.6	2.3	1.0	0.0	0.3	0.3	0.6	0.0	1.6	1.6	0.0	1.0	2.9	1.3	4.5	1.0	2.9	0.0	0.0	2.6	5.5
10	0.0	15.0	1.3	0.7	3.6	1.3	14.4	12.4	1.0	0.0	2.0	0.0	0.7	3.3	0.3	0.7	0.7	0.3	0.3	0.7	0.3	0.7	0.7	2.9	0.0	0.7	3.3	0.7	1.3	0.3	0.7	0.7	0.3	0.7	7.2
14	0.0	18.2	0.3	0.0	14.9	0.0	0.7	0.3	3.6	0.0	0.7	1.3	3.3	0.7	0.3	0.0	1.0	0.3	3.6	2.0	0.3	0.0	3.3	3.0	0.0	1.7	2.3	2.3	1.3	1.0	1.7	0.7	0.0	1.7	7.6
22	0.0	18.6	1.0	0.3	0.7	2.3	3.7	1.0	2.7	0.0	3.3	1.0	2.3	6.0	0.3	0.0	2.0	0.7	0.0	1.7	1.7	1.0	0.0	1.7	1.0	2.3	3.0	1.3	5.6	1.0	0.7	3.3	0.0	1.7	9.3
26	0.0	12.0	1.5	1.5	0.8	0.8	9.0	0.0	0.0	0.0	1.5	5.3	2.3	1.5	2.3	0.0	3.8	2.3	0.8	2.3	1.5	2.3	1.5	4.5	0.0	8.3	3.0	1.5	0.8	0.8	2.3	1.5	0.0	3.0	7.5
34	0.0	10.1	2.3	0.0	7.5	0.0	3.3	1.3	2.6	0.0	3.3	1.3	1.6	1.6	0.7	0.3	0.7	0.7	0.3	1.6	1.6	2.0	0.3	2.3	0.3	3.6	8.8	1.0	1.0	0.7	0.7	3.9	0.0	2.0	9.4
49	11.9	11.9	0.6	2.2	0.0	0.0	0.0	0.3	0.3	2.9	2.2	0.0	1.9	6.4	0.6	2.6	1.6	2.6	1.0	0.3	2.9	1.3	0.0	4.2	3.2	3.5	4.8	1.3	0.0	2.9	0.6	0.0	2.2	0.0	6.4

Table 3.4.4 Feeagh fossil diatoms (>3% abundance in at least one sample).

Depth (cm)	*Achnanthes buccola*	*Achnanthes helvetica*	*Achnanthidium minutissimum*	*Achnanthidium microcephalum*	*Achnanthes oblongella*	*Achnanthes subatomides*	*Asterionella formosa*	*Aulacoseira alpigena*	*Aulacoseira ambigua*	*Aulacosiera granulata*	*Aulacoseira subarctica*	*Brachysira garrensis*	*Cocconeis placentula*	*Cyclotella comensis*	*Cyclotella kuetzingiana*	*Diatoma moniliformis*	*Eunotia incisa*	*Eunotia minor*	*Fragilaria capucina*	*Fragilaria capucina var# rumpens*	*Fragilaria capucina var# vaucheriae*	*Fragilaria gracilis*	*Fragilaria pinnata*	*Fragilaria tenera*	*Frustulia rhomboides*	*Gomphonema parvulum*	*Synedra ulna*	*Tabellaria flocculosa*
1	0.0	0.0	16.6	0.0	4.5	4.5	4.5	2.7	0.0	2.7	14.5	0.6	0.3	0.0	4.8	0.3	0.6	0.0	0.3	6.0	0.9	1.5	0.3	0.3	0.0	1.8	1.2	2.7
3	0.0	2.6	14.4	0.0	4.2	0.3	1.9	2.6	5.1	9.9	10.6	0.6	2.2	3.8	2.6	0.3	0.0	0.0	0.0	2.9	0.0	5.4	0.6	0.0	0.3	1.0	1.3	8.3
5	0.0	0.0	14.3	0.0	2.5	4.4	7.4	1.6	1.9	4.9	11.5	0.5	1.9	0.0	4.9	1.1	1.4	0.0	0.0	5.2	0.5	1.4	1.1	0.3	0.0	1.9	1.4	8.2
7	0	3.8	17	0	2.6	0.3	5.4	2.2	0	7.1	2.9	1	0.6	1	3.2	0	1.9	0	0	1.3	1.3	4.8	1.3	0.6	0	4.5	3.5	11
9	0.3	0	13	0	4.3	3.4	12	2	0	5.7	13	0	3.4	0	1.1	0.9	1.1	0	0	0.9	0.9	5.7	0.9	0	0	2	1.7	1.4
11	0	1.6	15	0	1.6	0	1.6	3.8	0	20	4.7	0.9	1.6	0	5.9	0.6	2.8	0	0	3.1	0.3	1.9	0	0	0	3.1	1.6	3.1
13	0.3	0.3	15	0	6.7	2.9	11	0.6	0.6	3.8	9.3	1.5	0.9	0.9	2	2	0.3	0	0	2.3	1.7	2.3	4.7	0	0.3	2.9	1.5	5.5
15	0	1.6	13	0	3.6	1	6.8	0	2.6	11	4.9	1.3	0	6.5	4.5	0	1.3	0	0	6.5	1.9	1.3	0	0.6	3.6	1.9	1.3	4.5
17	3.4	0	14	0	1.5	2.8	22	4.3	0	2.8	5.2	0.3	2.2	0.6	2.2	1.2	0.3	0	0	2.2	0.9	3.4	0.6	0.3	0	2.8	0.3	2.8
20	0	3.8	14	0	0.6	0.6	18	1.9	1.9	4.8	0.3	0.6	1.3	0.6	5.8	0	0.6	0	0	4.5	0.3	0.6	1	1.3	1.3	3.2	0.6	12
22	0	0	10	0.9	1.7	2.6	27	6.1	0	5.5	0.3	0.6	2.3	2.3	2	3.2	1.4	0.6	0	5.8	2	0	0	1.4	0	2.9	0	3.2
24	0	2.6	16	0	1.9	0	16	3.2	3.2	4.2	1	0.6	1	3.2	2.3	0	2.3	0	0	3.5	1.3	0.3	0.3	1.3	0	1.9	1.6	13
26	0.3	0	16	0	0	1.5	27	3.9	0	0.6	0.3	0.9	1.5	2.1	4.2	0.6	2.1	0	0	2.7	2.7	0.6	0	0.9	0	0.9	1.5	5.7
30	0	0	21	0	1.2	0.3	5	5.9	0	0.6	0.3	1.5	1.2	4.4	12	0	2.9	0	0	1.8	3.2	1.2	0	2.3	0	2.1	0	12
32	0	1.3	19	0	1.3	0	3.4	1.7	0	3.4	0	3	0.7	4.7	10	0	2.7	0	0	4	1	0.3	0.3	0.7	0	3	1.7	14
34	0	0	21	0	1	2	6.3	3.6	0	0	0.7	2	1.3	4.6	9.2	1	2.3	0	0	1.3	1	3.6	0.3	0.7	0	0.7	0	9.6
36	0	0.6	27	0	1.2	0	3.1	2.5	0	1.9	0.3	2.5	0.6	2.2	9.9	0	3.1	1.2	0	3.7	3.4	0	0.9	0.6	0	2.2	0.6	15
38	0	0	19	0.3	0.3	3.8	2.2	8.5	0	0.6	0	0.9	0.6	7.2	7.9	0	1.6	0	0	1.6	3.1	0.9	0.3	1.3	0	1.3	0.3	6.9
40	0	0.3	32	0	0.6	0.6	0.6	0.6	0	2.6	0.3	4.8	0.3	5.5	12	0.3	2.6	0.6	0	3.9	0.6	1	1	1	0	3.2	1	5.2
42	0	0.7	26	0	0	2.3	1.3	1.6	0	0.7	0	2.6	0.3	7.5	15	0.3	2	3.6	0	0.7	3.3	1	0	2	0	1.6	1	3.6
44	0	0.7	31	0	0.3	0	0.3	1.3	0	2	0	4	0.3	7	8.3	0	1	0	0	4.3	0.7	0.3	0	1.3	0	2	0.7	7.3
46	0	0	19	3.6	0.6	2.4	2.1	3	0	0	0.3	2.4	1.5	9.6	7.5	0.9	0.6	0.6	0	0.9	1.8	2.4	0.3	1.5	0	1.2	0	6.9
48	0	1.3	31	0	0	0	1.3	5	0	0	0	3.3	0	7.3	8.7	0	3	0.7	1.3	1.7	0.7	0.7	0	1.3	0	1.3	1.3	5.7
50	0	0	30	0	0	3.4	0.9	1.9	0	0	0.6	2.2	0.6	12	5.6	2.2	0.6	0.3	0	1.2	0.3	0.9	0	3.1	0	0.9	0.3	4.9
51	0	0	22	0	0	1	0	4.9	0	0	0	3.3	1.3	10	13	0	1.3	0.7	3	1.3	2	0	1.3	2.6	0	2.3	2	8.2
54	0	0	22	0	0	1.2	0.3	7.3	0	0	0	4.2	0	7.6	10	0.6	1.8	1.8	4.5	0.6	0.9	0.9	0.3	1.8	0	3.3	0.6	7
56	0	0.6	25	0	0	1	1.3	6.7	0	0	0	5.7	0	6.3	6.7	3.2	1.6	0.3	0.6	1.3	3.2	3.5	0	3.2	0	2.5	1	7.6
58	0	0	27	0.3	0.3	1.8	0.8	4.2	0	0	0	2.6	0	6.3	7.1	0.8	1	1.3	2.4	0.8	1.6	2.6	0	2.1	0.3	2.6	0.3	5.5
60	0	1.9	29	0	0	0.6	0.9	3.7	0	0	0	2.5	0	10	4.3	2.8	1.5	0	0	0.3	0.6	1.5	0	4	0	1.5	0.9	9
62	0	0	25	1.3	1.9	1.6	1.6	5.7	0	0	0	1.6	0	5.7	7.9	0	0	0	2.8	0.3	2.2	2.2	0.9	2.5	0	0.6	0.6	9.1

Table 3.4.5 Mask (deepest point) fossil diatoms (>3% abundance in at least one sample).

Depth (cm)	*Achnanthes minutissima*	*Amphora commutata*	*Asterionella formosa*	*Aulocoseira granulata*	*Brachysira brachysira*	*Brachysira vitrea*	*Cocconeis placentula*	*Cyclotella michiganiana*	*Cyclotella oscellata*	*Cyclotella bodanica*	*Cyclotella distingunda*	*Cyclotella planctonica*	*Cymbella deliculata*	*Cymbella helvetica*	*Cymbella microcephela*	*Denticula tenuis*	*Denticula thermalis*	*Diploneis elliptica*	*Epithemia argus*	*Epithemia smithii*	*Eunotia arcus arcus*	*Fragilaria brevistriata*	*Fragilaria crotensis*	*Fragialria capucina*	*Fragilaria construens*	*Fragilaria fasiculata*	*Fragilaria pinata*	*Gomphonema angustum*	*Gyrosigma attenuatum*	*Mastogloia smithii*	*Meloseira varians*	*Stephanodiscus hantzchii*	*Tabellaria flocculosa*
0.5	20.7	0.0	3.5	6.7	0.0	0.1	1.0	0.0	0.0	2.9	0.3	0.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.3	12.5	0.8	0.0	0.0	0.8	0.5	0.0	0.0	13.0	16.4	16.3
1	19.9	0.0	2.3	4.9	1.4	0.6	3.2	0.0	2.0	0.0	0.3	0.0	0.0	0.0	0.7	0.0	0.0	0.0	0.0	0.0	0.0	2.3	3.1	4.6	0.0	0.0	2.1	0.8	0.0	0.0	7.9	5.4	12.8
1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	14.8	1.3	2.8	3.2	1.7	1.3	0.0	0.0	0.8	1.9	0.5	0.0	0.0	0.0	0.2	0.2	0.0	0.0	0.0	0.5	0.0	5.4	6.5	1.6	0.8	1.8	2.3	1.2	0.6	10.9	0.0	4.9	14.4
2.5	16.0	2.5	3.0	4.0	2.7	1.5	0.8	0.0	6.0	2.7	0.8	0.0	0.0	0.0	0.5	0.3	0.0	0.0	1.4	0.8	0.4	4.7	7.6	2.1	1.7	2.5	1.0	2.0	0.3	6.3	0.0	0.0	9.0
3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3.5	19.4	1.2	2.9	1.0	4.6	2.1	2.0	0.0	11.8	1.8	0.1	0.0	0.2	1.7	0.6	0.7	0.2	0.0	4.4	2.5	1.1	4.5	0.0	2.0	2.6	4.0	1.9	2.4	0.2	15.7	0.3	0.0	3.8
4	14.8	1.3	2.4	0.0	3.7	1.7	1.5	0.0	14.7	1.5	0.0	0.0	0.0	1.1	0.4	0.5	0.0	0.0	4.7	2.1	0.9	5.7	3.7	4.5	4.2	2.3	2.6	3.0	0.8	14.8	0.0	1.0	1.7
4.5	1.3	10.0	0.0	0.0	0.0	0.0	1.8	0.0	27.1	2.2	0.0	0.0	0.1	0.9	0.4	0.0	0.1	0.0	5.1	1.4	1.0	1.2	2.3	5.5	3.1	0.3	2.1	1.3	0.1	14.8	0.5	4.0	2.3
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	1.9	0.0	2.6	0.0	1.1	0.4	0.0	0.0	1.1	1.1	0.0	0.0	0.0	0.4	0.0	0.0	0.0	0.4	17.4	0.0	2.6	1.1	1.9	11.9	7.8	5.9	4.1	0.0	6.7	16,4	0.7	0.7	0.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	2.4	4.2	1.2	0.0	2.3	2.7	3.6	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	4.7	3.7	2.7	4.8	0.0	3.7	1.4	7.5	5.8	2.5	1.4	22.6	0.0	0.0	0.8
9	1.1	0.0	6.5	0.4	0.4	0.0	0.9	0.0	4.5	1.2	0.5	0.0	0.7	6.9	0.0	0.2	0.0	3.3	6.5	2.9	3.1	5.3	0.0	3.9	1.8	5.5	4.7	1.6	1.5	16.5	0.9	1.1	1.1
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	9.2	3.1	3.1	0.0	0.0	0.0	3.1	3.1	0.0	1.5	0.0	0.0	1.5	0.0	1.5	3.1	4.6	12.3	1.5	0.0	10.8	1.5	0.0	3.1	1.5	1.5	0.0	0.0	1.5
12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	18.9	3.2	2.9	0.0	6.8	7.8	3.7	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	1.3	0.0	5.1	4.6	5.1	4.0	2.7	4.7	7.9	5.8	3.6	2.0	1.3	3.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	9.1	0.4	0.6	1.9	0.6	7.8	2.5	0.0	11.7	8.1	0.1	0.0	2.6	2.2	1.9	5.2	0.0	1.0	3.1	1.6	1.4	2.9	0.1	2.3	1.0	0.1	0.7	4.2	0.6	10.2	0.3	0.0	2.6
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	5.7	0.0	9.7	0.0	1.6	12.2	0.0	0.0	2.4	4.1	0.0	0.0	12.2	0.0	0.8	4.9	0.8	0.0	0.0	0.8	0.8	7.3	0.0	1.6	7.3	0.0	0.0	0.0	0.0	1.6	0.0	0.0	0.8
24	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	19.0	0.0	0.0	0.0	12.7	10.0	3.7	0.0	0.0	0.0	0.0	0.0	4.7	0.0	0.0	0.0	2.3	0.0	0.0	0.1	0.2	6.9	0.0	0.0	3.7	0.6	0.5	2.1	2.3	8.9	0.0	0.0	1.9
27	3.8	0.0	2.6	0.0	14.1	7.7	0.0	3.9	1.3	2.6	1.3	0.0	3.9	0.0	1.3	1.3	5.8	0.0	0.0	1.3	1.3	8.3	0.0	0.0	6.4	0.0	0.0	3.9	0.0	0.0	0.0	0.0	3.9
28	8.8	0.0	0.0	0.0	2.8	8.6	1.6	0.0	1.3	7.2	0.9	0.0	1.6	4.0	4.1	6.6	0.0	0.0	3.7	5.0	2.7	3.5	0.0	0.4	0.5	0.4	1.3	5.9	1.9	12.0	0.0	0.0	2.9
29	17.0	0.0	0.0	0.0	6.9	5.2	2.7	3.0	1.0	3.4	0.2	0.0	1.2	5.0	5.7	4.9	0.7	0.0	0.7	0.4	3.7	2.3	0.0	1.4	3.7	0.6	2.9	7.6	4.5	13.0	0.0	0.0	2.3
30	4.2	0.0	0.0	0.0	1.5	3.0	2.0	0.0	0.0	0.0	0.0	0.0	3.4	2.5	0.0	5.3	7.4	2.4	0.8	3.9	5.8	0.0	0.0	0.0	6.9	0.0	0.0	3.4	5.3	18.0	0.0	0.0	4.5
31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35	6.7	0.0	0.0	0.0	15.2	10.5	0.0	0.0	2.9	3.8	1.0	0.0	0.0	1.9	6.7	6.7	0.0	0.0	1.0	0.0	1.0	0.0	0.0	0.0	2.9	0.0	0.0	3.7	1.9	0.0	0.0	0.0	2.9
36	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3.4.6 Mask (eastern Robe) fossil diatoms (>3% abundance in at least one sample).

Depth (cm)	*Achnanthes minutissima*	*Amphora pediculus*	*Asterionella formosa*	*Cocconeis placentula*	*Cyclotella oscellata*	*Epithemia argus*	*Epithemia geopertianna*	*Epithemia smithii*	*Fragilaria brevistriata*	*Fragialria capucina*	*Fragilaria construens*	*Fragilaria crotensis*	*Fragilaria fasiculata*	*Fragilaria pinata*	*Gomphonema angustatum*	*Gyrosigma accuminatum*	*Mastogloia smithii*	*Tabellaria flocculosa*
0.5	8.4	1.0	36.5	1.0	3.4	0.0	0.0	0.0	1.4	3.8	1.3	8.9	0.0	0.0	1.2	0.0	0.0	19.8
1	13.8	1.2	33.8	1.5	0.3	0.0	0.0	0.0	0.9	4.4	0.7	9.4	0.4	1.2	0.0	0.0	1.5	18.3
1.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	4.7	0.0	30.7	0.4	0.5	0.0	0.0	0.0	2.1	0.0	0.0	7.9	0.0	0.0	0.0	0.0	0.6	16.8
2.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	3.6	3.4	19.9	4.1	0.0	0.0	0.0	1.3	2.5	3.0	5.4	1.2	3.2	0.0	0.0	0.0	1.3	15.8
3.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.5	8.9	2.1	0.0	3.8	0.0	1.2	1.2	3.2	8.9	4.3	4.3	3.4	1.2	4.3	0.0	0.0	4.0	16.5
5	9.9	1.8	0.0	3.9	6.0	0.0	0.8	2.7	3.2	3.6	5.8	1.0	2.7	3.7	3.7	1.5	14.8	8.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	10.3	3.2	0.0	4.2	1.5	2.1	0.0	4.6	8.9	8.5	3.7	0.0	0.0	6.4	1.5	2.1	8.9	7.6
8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	5.7	4.0	0.0	3.0	17.0	5.4	8.1	0.0	4.0	1.1	4.0	1.3	6.2	13.2	0.0	0.0	26.1	0.0
10	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	5.7	3.9	0.3	0.9	25.3	1.9	0.0	4.5	2.3	1.7	4.0	0.0	6.2	10.5	0.0	0.0	24.8	0.3
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	7.6	1.9	0.8	5.3	0.0	0.0	4.0	8.5	7.8	4.0	6.0	4.5	2.7	4.5	0.0	0.0	27.0	0.9
16	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	3.6	5.7	0.5	2.1	2.6	8.9	0.0	0.0	6.8	1.6	3.6	0.0	3.6	14.6	3.6	5.7	31.3	1.6
18	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	4.9	4.6	0.3	3.8	29.2	3.0	1.9	0.0	1.6	3.3	3.8	0.0	7.1	12.8	0.0	0.0	18.3	2.2
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	14.3	4.2	0.0	5.7	1.2	2.1	0.0	3.4	9.5	5.8	0.9	0.5	1.6	2.3	4.8	8.2	23.0	0.0
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	11.6	2.3	0.0	3.7	0.0	5.3	1.2	4.7	6.4	6.9	4.7	0.0	2.1	4.2	6.3	6.7	24.7	0.0
29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table 3.4.7 Mask (southwest) fossil diatoms (>3% abundance in at least one sample).

Depth (cm)	*Achnanthes minutissima*	*Asterionella formosa*	*Aulocoseira granulata*	*Brachysira vitrea*	*Cyclotella oscellata*	*Fragialria capucina*	*Fragilaria virescens*	*Fragilaria crotensis*	*Melosira varians*	*Tabellaria flocculosa*
0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	12.7	4.8	3.0	0.1	0.0	14.1	0.2	12.6	1.9	36.7
1.5	6.6	59.2	3.3	0.4	0.0	6.3	0.0	0.4	0.0	23.8
2	5.8	53.2	8.0	0.3	0.0	8.7	0.0	1.1	0.0	20.3
2.5	3.2	41.3	9.6	1.2	0.1	6.7	0.1	0.0	0.0	24.7
3	4.8	50.8	15.1	0.6	0.0	9.7	0.0	1.2	0.0	17.7
3.5	3.7	45.2	14.9	1.4	0.1	2.0	0.1	3.2	0.4	15.7
4	2.7	39.4	16.5	0.9	3.0	3.6	0.0	2.5	0.0	16.8
4.5	3.0	43.2	13.2	1.2	2.6	6.0	0.4	3.7	0.2	18.3
5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	4.3	29.6	11.3	2.1	3.7	0.0	0.1	5.8	2.4	18.7
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	3.4	18.4	9.3	1.7	2.8	8.9	0.1	8.3	5.9	24.3
9	3.9	23.5	8.5	0.0	3.1	16.7	0.0	9.4	4.4	20.8
10	9.1	8.1	11.4	3.3	0.5	9.7	0.0	10.4	1.7	28.7
11	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	7.8	5.3	5.8	3.7	0.6	3.0	0.1	2.4	0.0	19.3
13	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	9.5	3.8	6.2	1.2	1.3	2.7	0.4	7.5	0.0	25.6
15	8.3	0.1	17.2	0.8	0.7	2.2	0.0	11.9	0.0	39.0
16	7.4	16.0	7.3	0.0	0.0	3.0	0.2	5.8	0.2	32.1
17	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	8.3	18.5	1.0	0.0	0.0	22.5	0.2	3.1	0.1	24.7
19	6.6	33.1	3.6	0.0	0.0	25.9	0.0	3.0	0.0	27.7
20	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	5.0	21.0	1.2	4.0	0.0	12.6	1.5	2.3	0.3	13.6
22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	7.8	72.0	0.4	0.0	0.0	15.6	0.0	0.0	0.0	4.3
24	13.4	3.5	0.1	1.3	0.0	5.0	0.0	0.0	0.0	8.3
25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	8.5	5.7	0.0	2.3	0.0	2.3	0.0	0.1	0.0	15.0
27	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	12.7	4.0	0.0	1.0	0.0	0.6	0.0	0.0	0.0	19.8
29	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	9.5	9.9	4.2	1.0	3.1	0.0	6.7	8.6	0.0	42.2
31	15.7	6.3	2.0	0.6	0.0	5.7	0.0	1.5	1.3	35.0
32	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
33	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
34	5.0	2.5	3.8	6.3	0.0	7.3	2.6	0.0	0.0	35.2
35	11.8	11.9	4.7	1.2	0.3	10.4	0.0	2.4	1.3	38.2

36	13.6	0.3	2.5	0.8	0.0	4.0	2.1	0.0	0.0	21.3
37	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
38	13.4	0.0	0.0	3.2	0.0	3.5	1.6	0.0	0.0	14.8

Appendix 3.5: AMS ^{14}C dates

Table 3.3.1 AMS radiocarbon ages for selected samples.

Beta ID	**Lake**	**Sample Depth (cm)**	**Radio-carbon age BP**	**Conventional radiocarbon age BP**	**Cal. Yrs. BP (1 sigma)***	**$\delta\ ^{13}C$**
Beta-220583	Bunaveela Core B-1	49-50	2810 +/- 40	2760 +/- 40	2862-2957	-28.3 ‰
Beta-220584	Feeagh Core F-1	62-63	3960 +/- 50	3930 +/- 50	4299-4518	-26.8 ‰
Beta-251237	Mask Site 1 Core MK-8	20-21	3860 +/- 40	3830 +/- 40	4184 - 4406	-26.6 ‰
Beta-245605	Mask Site 1 Core MK-8	40-41	5410 +/- 60	5370 +/- 60	6125-6290	-27.5 ‰
Beta-251239	Mask Site 2 Core MK-5	24-25	2580 +/- 40	2550 +/- 40	2618-2757	-26.2‰

*According to Calib 5.01 and the Intcal04.14c dataset (Stuiver & Reimer 1993; Reimer et al. 2004).

Appendix 4

Appendix 4.1: Soil nutrient concentration (mg kg^{-1} dry weight soil) and dissolved and particulate nutrient concentrations used in catchment modelling

CORINE land cover	**Soil TP mg kg^{-1}**	**Soil TN mg kg^{-1}**	**Dissolved P mg l^{-1}**	**Dissolved N mg l^{-1}**
High Productivity Pastures	1291	5100	0.015	1.49
Low Productivity Pastures	798	3100	0.010	0.86
Complex cultivation patterns	798	3100	0.010	0.86
Principally agriculture	798	3100	0.010	0.86
Farmyards	6000	34800	1.828	10.60
Broad leaved forest	800	19844	0.004	0.34
Coniferous forest	600	11700	0.009	0.34
Natural grasslands	600	11700	0.001	0.06
Transitional woodland shrub	600	11700	0.001	0.06
Sparsely vegetated areas	400	11700	0.001	0.06
Inland marshes	600	11700	0.001	0.06
Unexploited Peat bogs	400	11700	0.001	0.06
Sport and leisure facilities	1291	5100	0.015	1.49
Continuous urban	2944	31800	0.034	13.30
Discontinuous urban	2944	31800	0.034	13.30

Appendix 4.2: Optimised GWLF hydrology parameters for the subcatchments

		Ppt correction factor unitless	Recess coeff. (1/day)	Slow Recess coeff (1/day)	Runoff Recess coeff (1/day)	Soil water capacity (cm)	Deep GW capacity (cm)	Unsat Leak unitless
Leane	Flesk	1.07	0.04	0.059	0.77	12	13.7	0.35
	Deenagh	0.81	0.044	0.0025	0.50	12	20	-
	Upper	1.57	0.12	0.0189	0.55	25	3.8	0.28
Feeagh	Black	0.81	0.15	0.02	0.92	20	11.18	-
	Glena	1.10	0.13	0.004	0.86	20	20.0	-
Mask	Robe	1.35	0.10	0.01	0.32	12	7.16	0.004
	Carra	1.23	0.05	0.01	0.10	12	1.5	0.11
	Owenbrin	1.36	0.16	0.005	0.23	15	13.22	0.30

Appendix 4.3: Uncertainty in dynamic modelling

All modelling exercises include varying levels of uncertainty in the estimates produced. These relate to the errors associated with model structure and with input and calibration data. Models are by design simplifications of reality and their structure will generally only include the dominant processes contributing to the parameters of interest. The sources of uncertainty in the catchment modelling carried out in ILLUMINATE included the selection of appropriate meteorological data, inaccuracies in the measured flow data used for model calibration, and error related to input nutrient data. The latter includes the combined error associated with sample collection and analysis and, where catchment specific data were not available, the selection of appropriate input data from the literature. This uncertainty in the modelling of stream flow and nutrient loads was then carried forward in the input data used to run CAEDYM, and were therefore potentially propagated. Additional uncertainty was also associated with the model parameter values used for phytoplankton and zooplankton groups in CAEDYM, which were based on a combination of literature optimised values.

The meteorological data used to drive the catchment loading model, GWLF, are precipitation and air temperature. The hydrology subroutine includes a precipitation correction factor, which is optimised during the calibration process, to correct input data based on differences between modelled and measured stream flow. Whilst air temperature is generally coherent on a regional scale (Hari et al. 2006; Livingstone & Dokulil 2001), precipitation is highly variable. All three catchments contain a meteorological station operated by Met Éireann. In addition, tipping bucket rain-gauges were deployed across both the Leane and Burrishoole catchments to assess the spatial variability in rainfall levels (Allott et al. 2005; Allott et al. 2008). A comparison of GWLF modelled stream flow was carried out for the Leane catchment using spatially averaged rain-gauge data and data from the Muckross station at Leane for both the Flesk and Upper subcatchments (Allott et al. 2008). The results indicated that simulations using the Met Éireann site had an equal or better fit between measured and modelled flow data than those based on subcatchment specific data. However, as noted earlier (Section 4.2), the fit between modelled and measured stream flow for the small, upland Glenamong subcatchment in Burrishoole was poorer when precipitation data from the Met Éireann site were used than when subcatchment-specific rain-gauge data were used. The difference between the rain-gauge data and the meteorological station data related to variability in the occurrence of daily rainfall and to overall levels. The latter could be accounted for in simulations by adjusting the precipitation correction factor. The difference in the occurrence of precipitation on any day would, however, have resulted in errors in modelled daily stream flow for any given date, when data from the meteorological station were used for long-term simulations.

Measured stream flow data were available for calibration of the hydrology subroutine of GWLF from the Office of Public Works for inflows to Leane and Mask. These data are quality controlled (QC) prior to distribution and QC comments were taken into account when selecting data for model calibration and validation. The MI have been collecting water level data for the Glenamong and Black rivers, the main inflows to Feeagh, since 2001 and 2003, respectively, and have constructed rating curves for these sites. Rating curves constructed for the Glenamong River in both 2007 and 2008 were almost identical, suggesting a high level of confidence in the resulting stream flow estimates. The production of a reliable rating curve for the Black River has proved problematic, however, due to difficulties in measuring flow at the higher end of the scale and to backwash in the lower reaches of the river when the lake level was high (De Eyto pers comm.). Flow measurements were only available for water level readings up to 0.84 m. Based on water level data from the site, water levels were above 1 m for approximately 2-4% of the time. This would represent a significantly greater percentage of total flow to the lake. In addition, a comparison of estimated flow values for the Black River using rating curves based on both salt dilution measurements and measurements taken using a flow meter produced very different results, with higher flow estimates being produced by the curve based on flow meter measurements. For example, flow estimates for a water level of 1 m were 11.5 $m^3 s^{-1}$ and 18.5 $m^3 s^{-1}$ for the salt dilution method and the flow meter method, respectively, a 60% difference. This difference increased with water level, with highest water levels recorded at the site in any given year ranging from c. 2 m to over 6 m.

In order to select the most appropriate rating curve to calculate estimated flow for this project, an area weighted maximum flow for each curve was compared with a similar value for the Long Range, the small channel draining the Upper catchment and flowing into Leane (a similar upland peat catchment but with higher rainfall) and for the Glenamong River. The value for the Long Range and Glenamong rivers were 1.4 and 0.8 $m^3 s^{-1} km^{-2}$, respectively. The value for Black for the salt dilution method was 1.4 $m^3 s^{-1} km^{-2}$, while that based on flow meter measurements was 2.3 $m^3 s^{-1} km^{-2}$. The stream flow measurements based on salt dilution rating curve were used to calibrate GWLF for the Black River. However, given the issues described above, a high level of uncertainty should be attached to all modelling carried out for this subcatchment and therefore for the loading estimates produced for Feeagh in ILLUMINATE.

Uncertainty relating to nutrient input data relates to the constant values used in the model to calculate daily loads. These include values for particulate and dissolved nutrients for each land use and per capita nutrient output per head for the human and animal populations. The impact of this uncertainty on model nutrient loads will be a function of the sensitivity of the model to changes in parameter levels. A sensitivity analysis of the impact on a 10% change in values on P loads for the Flesk subcatchment of Leane, for example, indicated that the TP load was most sensitive to a change in the TP concentration applied to the sediment load for each land use and to a change in precipitation (Table 4.3.1). The dissolved P load was most sensitive to a change in surface runoff concentrations and precipitation. The level of sensitivity will, however, also differ between subcatchments depending on the contribution of each component to the total load for that site.

Additional uncertainty in loading from the human and livestock populations was related to population estimates between census years and to the percentage of total nutrient output per head that reaches surface or subsurface flow. The population trend between census years was assumed to be linear in the catchment model. The P load per capita for the population using septic tanks was based on the results of a study carried out in the Leane catchment as part of the catchment monitoring and management study (KMM 2003). This is one of very few studies that have produced estimates of P losses from this source (Carvalho et al. 2004). The estimate was almost identical to that suggested in the GWLF manual, based on a study carried out in the US (Haith et al. 1996). Values based on literature estimates can be up to c. 40% higher or lower (Carvalho et al. 2004), indicating potential uncertainty in this estimate. The nutrient output per head of livestock was based on values included in Irish regulations on agricultural practice (S.I. 378 of 2006). These values are lower than similar values quoted for the UK (Carvalho et al. 2004). The percentage loss from this output for grazing livestock was based on values used in export coefficient calculations of only 2.9% and 3% of TP output per head for cattle and sheep, respectively (Johnes & Heathwaite 1997). There is, therefore, a potential large margin of error in these estimates, but one that is comparable to export coefficient models (e.g. Johnes 1996; Bennion et al. 2005). A similar large margin of error would be associated with the loss of nutrients in cattle slurry applied to land.

Table 4.3.1 percentage change in total P (TP) and dissolved P (Dis P) load from the Flesk subcatchment for a 10% change in model input value.

Source	TP load	Dis P load
Surface runoff (dissolved P concentration)	1.3	3.8
Subsurface flow (dissolved P concentration)	0.6	1.9
Surface runoff (particulate P concentration)	8.1	-
Livestock (P output per capita)	3.1	3.0
Septic systems (P output per capita)	0.6	1.8
Precipitation	14.3	9.2

Appendix 4.4: Annual values for hindcast nutrient and sediment loads

Table 4.4a Hindcast loads to Leane (Flesk, Deenagh and Upper subcatchments), 1941 to 2005 (tonne y^{-1}) for TP, dissolved P, TN, dissolved N, sediment and silica.

Year		TP			Dissolved P			TN			Dissolved N			Sediment			Silica	
tonne y-1	Flesk	Deen	Upper	Flesk	Deen	Upper	Flesk	Deen	Upper	Flesk	Deen	Upper	Flesk	Deen	Upper	Flesk	Deen	Upper
1941	13.9	1.9	1.3	5.0	1.0	0.6	283.5	33.6	36.7	211.9	21.1	29.4	5683.9	256.6	512.3	72.9	2.9	36.7
1942	11.6	1.8	1.2	4.5	0.9	0.5	253.3	33.8	35.2	183.3	21.2	28.0	4121.5	272.7	391.6	62.7	2.7	28.7
1943	12.0	1.9	1.3	4.7	0.9	0.6	277.5	36.4	40.0	207.4	23.8	32.8	4284.3	303.7	449.1	65.6	2.5	31.8
1944	14.1	2.1	1.4	4.6	0.9	0.5	261.0	34.7	35.9	188.8	21.9	28.4	6260.2	372.6	555.3	67.2	3.0	33.4
1945	13.0	2.0	1.4	4.9	1.0	0.6	271.5	36.2	39.5	200.7	23.4	32.1	5017.5	301.1	500.7	73.7	2.9	36.7
1946	14.4	2.5	1.5	5.3	1.1	0.6	304.8	40.0	44.1	233.3	26.9	36.5	5851.0	441.8	595.4	80.8	3.3	38.4
1947	15.6	2.6	1.5	5.2	1.1	0.6	299.9	39.9	42.7	227.3	26.7	34.9	7108.6	508.2	657.1	79.1	3.4	38.0
1948	14.1	2.3	1.4	5.0	1.0	0.6	290.0	38.0	41.4	218.4	24.8	33.7	5961.3	396.7	558.0	75.7	3.2	35.3
1949	11.9	2.0	1.3	4.6	0.9	0.5	266.1	35.8	37.9	196.4	22.6	30.3	4314.7	311.6	468.9	67.9	2.6	32.5
1950	15.0	2.4	1.5	5.6	1.1	0.6	317.1	41.8	45.9	245.6	28.4	38.1	6082.5	430.9	611.2	84.5	3.4	41.6
1951	15.4	2.5	1.5	5.4	1.1	0.6	318.6	41.3	45.1	246.7	27.9	37.2	6711.4	479.2	642.0	82.5	3.3	40.1
1952	9.1	1.5	1.0	3.8	0.7	0.5	230.4	32.9	31.9	162.7	19.6	24.3	2612.6	183.1	283.7	48.3	1.9	22.8
1953	10.2	1.6	1.1	4.3	0.8	0.5	256.8	34.5	36.7	188.8	21.2	29.1	3144.2	189.9	332.4	55.4	1.9	26.9
1954	14.4	2.4	1.5	5.2	1.0	0.6	308.6	40.6	44.1	237.8	26.9	36.1	5955.7	441.5	576.3	76.2	3.2	36.4
1955	11.3	1.6	1.2	3.9	0.7	0.5	233.1	33.2	32.8	163.7	19.8	25.1	4364.5	219.4	381.9	50.8	2.1	25.5
1956	11.0	1.7	1.2	4.3	0.8	0.5	252.6	34.3	35.4	183.0	20.8	27.7	3806.5	219.2	351.0	58.0	2.4	27.8
1957	14.3	2.2	1.5	5.1	1.0	0.6	285.6	39.1	41.3	213.4	25.4	33.3	5877.0	361.0	576.1	78.0	3.2	37.6
1958	14.9	2.3	1.5	5.3	1.0	0.6	302.4	40.6	44.8	229.3	26.9	36.7	6225.6	407.7	604.4	80.2	3.2	38.3
1959	16.0	2.6	1.6	5.1	1.1	0.6	294.0	39.4	41.6	219.3	25.6	33.5	7407.3	495.4	688.4	82.6	3.6	40.2
1960	16.8	3.0	1.7	6.0	1.3	0.7	332.9	44.2	48.6	257.0	30.3	40.3	7287.2	596.0	722.1	95.9	3.9	46.3
1961	14.9	2.5	1.5	5.2	1.1	0.6	289.4	40.0	41.0	213.2	26.4	32.9	6261.1	456.0	595.1	79.0	3.2	38.5
1962	10.4	1.5	1.2	4.1	0.8	0.5	253.4	33.9	35.4	178.8	20.6	27.6	3256.8	182.1	340.2	54.0	2.1	27.2
1963	13.1	2.1	1.4	4.7	0.9	0.6	292.0	37.5	40.4	214.2	24.1	32.4	5019.2	357.3	505.7	63.8	2.7	30.8
1964	13.9	2.1	1.4	5.1	1.0	0.6	297.6	38.5	42.2	217.8	25.2	34.2	5300.7	320.1	529.8	75.5	3.1	37.8
1965	12.3	1.9	1.3	4.6	0.9	0.6	278.3	35.5	38.7	198.4	22.3	30.8	4334.2	285.3	439.8	65.2	2.7	31.2
1966	13.8	2.3	1.4	5.0	1.0	0.6	297.6	38.9	40.7	215.7	25.6	32.6	5172.7	409.6	515.6	70.8	3.0	34.5
1967	11.4	1.7	1.2	4.6	0.8	0.6	287.8	35.9	39.1	206.6	22.8	31.3	3475.5	246.3	361.1	59.1	2.2	28.5
1968	16.6	2.5	1.6	5.3	1.1	0.6	314.9	39.1	42.1	228.4	25.7	33.9	6396.0	454.2	673.6	80.4	3.4	40.9
1969	13.7	1.4	1.3	4.3	0.7	0.5	274.6	29.4	42.4	188.6	16.4	33.9	5232.3	156.7	471.8	50.5	2.1	27.7
1970	13.0	1.9	1.4	4.9	0.9	0.6	287.0	35.0	47.8	199.2	21.5	39.0	2968.3	277.9	518.5	62.2	2.4	33.0
1971	9.8	1.4	1.1	3.9	0.7	0.5	250.3	31.5	39.7	160.8	17.3	31.0	8564.7	141.5	311.3	43.0	1.6	22.5
1972	17.6	2.5	1.8	5.8	1.1	0.7	325.6	40.0	55.2	225.9	24.7	44.9	5350.7	412.9	815.5	85.3	3.6	45.1
1973	13.1	1.8	1.4	4.5	0.8	0.5	283.8	35.9	45.5	183.2	20.0	35.6	12694.9	251.3	457.5	52.2	2.1	28.5
1974	23.7	3.6	2.4	7.1	1.4	0.8	374.8	47.5	64.6	262.1	30.1	52.5	6886.7	772.8	1230.4	108.2	4.7	57.5
1975	15.4	2.2	1.6	4.9	0.9	0.6	298.0	39.4	47.1	188.0	22.1	36.1	4992.0	327.6	666.5	61.3	2.6	33.6
1976	13.9	1.9	1.5	5.2	0.9	0.6	317.4	39.0	49.8	206.4	21.6	39.1	8107.9	220.4	500.2	61.8	2.4	35.6
1977	18.0	2.6	1.9	6.1	1.2	0.7	364.3	45.4	58.7	248.0	27.6	47.2	8826.8	432.9	842.1	79.6	3.2	45.5
1978	18.3	2.6	1.9	5.7	1.1	0.7	348.7	43.0	54.8	229.1	25.1	43.2	5243.6	461.0	877.9	70.6	3.2	40.6
1979	14.4	2.0	1.6	5.3	0.9	0.6	357.4	42.3	55.8	238.8	24.4	44.9	6080.1	300.5	545.0	57.9	2.3	34.0
1980	15.9	2.3	1.8	5.8	1.0	0.7	368.9	44.5	58.6	247.3	26.5	47.3	5504.4	363.1	645.9	65.6	2.6	37.6
1981	15.8	2.2	1.8	6.2	1.0	0.8	364.9	44.1	58.2	242.4	26.2	46.9	10658.4	279.4	611.0	69.6	2.5	43.8
1982	22.2	3.3	2.4	7.4	1.4	0.8	414.6	49.5	67.0	285.8	31.2	54.6	5804.2	598.2	1079.7	98.9	4.1	58.2
1983	15.3	2.2	1.7	5.4	0.9	0.7	352.3	42.6	54.3	227.2	24.5	43.1	5803.0	318.3	591.1	57.8	2.4	35.9
1984	15.5	2.2	1.7	5.4	1.0	0.7	338.2	41.6	50.4	211.7	23.5	39.2	5605.8	316.2	567.9	61.4	2.6	34.9
1985	15.4	1.9	1.8	5.6	0.9	0.7	343.9	41.0	53.3	216.3	23.1	41.9	11015.6	203.7	574.4	61.4	2.3	39.5
1986	21.8	2.8	2.3	6.6	1.2	0.8	390.2	45.8	61.8	256.0	27.5	49.4	4055.8	468.1	1014.5	83.2	3.6	50.3
1987	13.0	1.6	1.5	4.7	0.7	0.6	323.8	38.2	46.2	195.2	20.3	35.2	9581.9	149.8	381.3	43.0	1.7	24.3
1988	20.6	3.2	2.3	6.4	1.3	0.8	387.3	46.9	62.6	251.9	28.5	50.3	8452.4	596.9	953.1	77.2	3.3	46.5
1989	20.3	2.9	2.3	7.1	1.4	0.9	394.5	46.5	61.2	258.7	28.2	49.0	8452.4	456.8	864.7	86.5	3.7	49.8
1990	21.2	3.2	2.3	6.7	1.3	0.8	378.9	44.8	57.5	240.8	26.4	45.1	9560.8	594.7	946.4	78.3	3.7	45.0
1991	20.8	2.9	2.2	6.4	1.3	0.8	376.8	46.0	57.0	238.2	27.8	44.6	9594.4	469.1	942.5	78.1	3.5	45.1
1992	17.5	2.3	2.0	6.3	1.1	0.8	379.9	43.6	59.5	244.2	25.6	47.8	6371.6	286.4	643.7	70.1	2.8	39.7
1993	18.7	2.6	2.1	6.5	1.3	0.8	369.5	43.4	57.7	232.8	25.4	45.6	7577.3	353.5	795.6	80.5	3.5	47.3
1994	22.3	3.2	2.5	7.6	1.4	0.9	428.6	49.3	67.9	289.4	31.1	55.3	9815.1	575.9	1035.5	93.0	3.8	54.9
1995	28.8	4.6	2.9	8.4	1.8	1.0	422.1	52.0	66.0	277.4	33.4	52.5	14913.4	972.5	1388.9	109.1	5.2	62.9
1996	23.8	3.4	2.6	7.4	1.5	0.9	407.4	48.6	65.1	266.5	30.5	52.0	11537.9	605.1	1219.6	98.7	4.4	57.3
1997	21.4	2.9	2.3	7.1	1.3	0.9	377.9	43.4	59.5	238.9	25.5	47.1	9316.8	461.4	938.1	87.9	3.9	50.5
1998	24.8	3.3	2.7	7.8	1.5	0.9	431.7	49.0	70.6	290.1	31.0	57.4	12183.7	583.0	1305.7	107.7	4.7	62.4
1999	26.4	4.2	2.8	8.0	1.7	1.0	437.8	51.9	70.5	295.1	33.7	57.2	13204.3	863.3	1316.0	103.2	4.7	63.8
2000	22.4	3.5	2.4	7.3	1.4	0.9	426.7	49.3	68.2	286.8	31.3	55.6	10365.9	689.5	1090.2	94.8	3.9	55.7
2001	15.2	2.2	1.7	5.5	1.1	0.7	341.8	42.0	50.7	207.5	24.5	39.3	4999.5	281.7	539.3	57.9	2.5	34.3
2002	25.3	3.5	2.8	8.5	1.6	1.0	437.7	49.8	70.8	296.0	31.8	57.8	11480.0	627.7	1205.2	103.9	4.6	60.6
2003	14.8	2.0	1.7	5.4	1.0	0.7	330.8	39.6	49.0	196.8	22.2	37.7	4550.9	225.1	491.6	52.3	2.2	31.5
2004	21.2	2.8	2.2	7.1	1.3	0.9	383.6	44.2	59.6	244.6	26.5	47.5	8892.9	417.9	843.4	79.4	3.5	46.1
2005	20.1	2.8	2.1	6.3	1.2	0.8	374.6	43.8	57.4	236.1	26.0	45.3	9128.5	454.1	893.1	76.6	3.4	44.1

Table 4.4b Hindcast loads to Feeagh (Glenamong (Glen) and Black subcatchments), 1900 to 2005 (tonne y^{-1}) TP, dissolved P, TN, dissolved N, sediment and DOC (mg l^{1}).

Year	TP tonne y^{-1}		Dissolved P tonne y^{-1}		TN tonne y^{-1}		Dissolved N tonne y^{-1}		Sediment tonne y^{-1}		DOC mg l^{-1}
	Glen	Black	Glen	Black	Glen	Black	Glen	Black	Glen	Black	Glen
1900	0.15	0.30	0.11	0.23	21.2	49.4	14.8	37.1	59.8	91.9	4.6
1901	0.13	0.25	0.10	0.20	19.5	43.3	13.6	32.5	54.6	74.0	6.2
1902	0.12	0.24	0.09	0.18	17.6	40.5	12.1	29.8	48.7	65.9	7.4
1903	0.18	0.35	0.14	0.27	26.7	60.4	18.8	45.4	75.9	114.4	6.7
1904	0.15	0.30	0.11	0.23	22.1	51.2	15.4	38.0	62.2	91.0	5.8
1905	0.13	0.25	0.09	0.19	18.8	41.8	13.0	30.4	52.2	69.5	7.5
1906	0.13	0.26	0.10	0.20	19.4	45.4	13.4	33.1	53.9	75.6	7.4
1907	0.16	0.32	0.12	0.24	23.3	56.4	16.3	41.9	65.7	100.5	7.2
1908	0.17	0.33	0.13	0.26	24.4	56.0	17.2	41.5	69.5	104.7	5.9
1909	0.15	0.29	0.11	0.23	21.7	50.8	15.2	37.3	61.2	90.4	6.4
1910	0.14	0.27	0.10	0.21	19.9	46.9	13.9	34.3	56.1	82.1	5.9
1911	0.14	0.26	0.10	0.20	19.7	43.1	13.9	31.9	56.6	77.8	8.3
1912	0.15	0.29	0.11	0.23	21.5	48.9	15.1	35.6	61.3	89.7	7.0
1913	0.17	0.34	0.13	0.26							
1914											
1915											
1916	0.13	0.26	0.09	0.19	18.9	46.7	13.1	32.7	52.4	72.9	5.1
1917	0.13	0.26	0.10	0.20	19.3	47.8	13.4	33.9	53.9	76.8	6.8
1918	0.14	0.28	0.10	0.21	20.4	47.8	14.2	33.4	57.0	80.3	6.7
1919	0.13	0.26	0.09	0.19	18.6	45.9	12.8	31.8	51.6	73.1	6.8
1920			0.07	0.17	13.9	36.3	9.8	27.0	39.7	62.0	
1921											
1922											
1923	0.14	0.28	0.10	0.21							
1924	0.14	0.23	0.11	0.17	21.1	42.2	14.6	27.9	58.9	60.3	6.2
1925	0.17	0.27	0.13	0.21	24.9	50.6	17.6	35.7	71.5	81.7	6.4
1926											
1927	0.19	0.28	0.15	0.21	27.8	49.0	19.6	32.7	79.3	78.1	
1928	0.23	0.36	0.18	0.27	32.8	63.7	23.3	44.4	94.4	113.9	7.4
1929	0.20	0.31	0.15	0.23	28.2	54.8	19.9	38.2	80.9	93.9	6.7
1930	0.18	0.35	0.13	0.26	25.2	61.0	17.7	42.1	71.4	109.0	6.3
1931	0.23	0.44	0.18	0.33	33.1	77.9	23.4	55.3	95.0	147.9	6.3
1932	0.19	0.37	0.14	0.28	27.1	62.8	19.1	44.0	77.5	117.3	6.6
1933	0.17	0.32	0.13	0.24	24.1	57.6	16.9	39.8	68.1	99.5	7.0
1934	0.22	0.43	0.17	0.32	31.9	75.1	22.6	52.8	91.6	141.8	7.9
1935	0.17	0.33	0.13	0.25	24.6	60.8	17.3	42.6	69.7	104.3	7.0
1936	0.15	0.30	0.12	0.22	22.1	53.4	15.4	36.2	62.1	90.2	8.7
1937	0.19	0.37	0.14	0.27	26.5	65.9	18.7	46.1	75.6	120.3	7.2
1938	0.14	0.27	0.11	0.20	20.1	47.1	14.1	31.6	56.6	79.7	7.6
1939											
1940											
1941											
1942	0.23	0.43	0.18	0.32	32.8	76.2	23.3	53.5	94.5	150.2	7.3
1943	0.24	0.45	0.18	0.33	34.2	81.8	24.3	57.9	98.5	160.4	5.9
1944	0.17	0.31	0.13	0.22	24.0	57.1	16.8	38.2	67.7	100.8	6.7
1945	0.16	0.29	0.12	0.20	22.9	53.3	16.0	35.5	64.6	94.6	7.7
1946	0.21	0.38	0.16	0.28	29.1	67.9	20.6	46.8	83.5	132.9	8.1
1947	0.19	0.34	0.15	0.25	27.2	62.0	19.2	42.9	78.0	120.9	6.7
1948	0.20	0.36	0.15	0.26	28.1	65.3	19.9	45.6	80.8	126.6	7.5
1949	0.22	0.38	0.16	0.28	30.6	70.1	21.6	48.6	87.8	135.8	6.9
1950	0.25	0.44	0.19	0.32	34.9	81.3	24.8	57.5	100.7	160.7	6.1
1951	0.23	0.41	0.17	0.30	32.3	75.9	22.9	53.0	93.0	146.9	5.6
1952	0.17	0.31	0.13	0.22	25.0	57.3	17.5	38.3	70.9	104.8	6.5
1953	0.12	0.22	0.09	0.16	17.8	43.8	12.3	29.2	49.7	73.3	8.8
1954	0.21	0.38	0.16	0.28	29.4	71.1	20.8	49.7	84.3	138.6	8.0

Table 4.4c Hindcast loads to Mask (Robe, Carra and Owenbrin subcatchments), 1901 to 2006 (tonne y^{-1}) TP, dissolved P, TN, dissolved N, sediment and silica.

Year	TP tonne y-1			Dissolved P tonne y-1			TN tonne y-1			Dissolved N tonne y-1			Sediment tonne y-1			Silica tonne y-1		
	Robe	Carra	Owenbrin	Robe	Carra	Owenbrin	Robe	Carra	Owenbrin	Robe	Carra	Owenbrin	Robe	Carra	Owenbrin	Robe	Carra	Owenbrin
1901	15.7	9.7	13.5	7.3	5.8	5.8	555.8	270.8	550.3	359.2	169.7	378.8	0.7	0.1	48.7	37.0	14.7	19.5
1902	15.0	9.5	13.2	7.2	5.8	5.8	531.3	260.0	559.5	303.6	149.6	337.7	0.5	0.0	42.4	16.4	9.6	10.2
1903	15.1	9.7	13.7	7.8	5.8	6.2	486.5	245.8	531.0	485.7	214.5	502.0	0.3	0.0	34.4	15.1	7.6	10.1
1904	17.3	10.1	14.7	7.5	5.8	6.0	685.0	317.8	709.2	396.3	184.2	410.5	1.0	0.1	75.1	37.1	16.6	23.2
1905	16.5	10.1	14.4	7.3	5.7	5.8	594.3	287.7	617.8	338.7	157.8	368.8	0.7	0.1	51.6	27.2	12.6	15.2
1906	15.7	9.8	13.9	7.3	5.7	5.9	528.4	257.5	568.1	338.7	163.5	375.0	0.5	0.1	42.9	23.3	10.0	12.1
1907	16.0	10.0	14.3	7.5	5.7	6.0	537.8	268.3	584.1	435.5	193.1	427.0	0.5	0.1	43.5	19.2	9.6	11.1
1908	16.8	10.0	14.6	7.4	5.6	5.9	640.9	299.8	642.1	434.2	197.8	459.7	0.8	0.1	55.6	29.6	13.1	16.4
1909	16.4	9.7	14.0	7.2	5.6	5.8	626.7	298.4	659.4	389.0	179.9	412.5	0.9	0.1	68.1	38.8	16.2	22.7
1910	15.7	9.6	13.8	7.0	5.5	5.6	581.2	280.4	614.0	355.9	168.4	374.8	0.6	0.1	51.6	28.7	13.2	17.0
1911	15.3	9.4	13.2	6.6	5.2	5.1	540.1	264.5	567.1	333.5	150.1	362.9	0.7	0.1	51.1	30.3	12.8	16.7
1912	13.2	8.2	11.0	6.9	5.4	5.5	474.4	223.5	508.7	368.5	172.1	414.4	0.7	0.1	49.1	34.2	12.9	16.4
1913	15.2	9.1	12.6	7.7	5.7	6.3	540.3	261.6	591.6	475.3	215.3	487.2	1.0	0.1	65.8	39.8	15.6	22.2
1914	18.6	10.7	16.2	8.1	5.5	6.5	714.8	340.3	736.5	459.5	190.8	453.6	1.0	0.1	71.7	41.6	16.4	21.3
1915																		
1916																		
1917	14.8	9.1	13.1	6.5	5.1	5.2	539.8	260.3	576.2	336.9	157.9	355.1	0.5	0.1	46.7	15.5	10.1	11.4
1918	13.9	8.6	12.1	6.5	5.1	5.2	501.8	244.0	527.5	348.6	159.0	383.9	0.6	0.1	40.8	15.7	8.0	9.9
1919	13.7	8.4	11.8	6.3	5.0	5.0	505.2	241.0	547.0	309.5	143.2	338.5	0.6	0.1	52.0	28.8	12.2	16.8
1920	13.3	8.3	11.6	5.6	4.6	4.2	463.7	223.9	499.9	297.3	138.2	315.5	0.5	0.1	40.0	22.5	9.6	12.5
1921																		
1922																		
1923																		
1924	11.3	6.8	8.7	5.9	4.7	4.6	485.2	225.6	448.4	288.4	131.2	300.5	0.9	0.1	48.6	32.6	14.2	16.8
1925	11.8	7.5	10.2	5.8	4.5	4.4	417.2	198.9	435.2	348.7	160.7	328.9	0.4	0.0	32.3	17.7	7.2	9.3
1926	10.9	6.9	9.1	5.2	4.5	4.0	457.9	217.5	442.4	146.8	75.8	187.6	0.5	0.1	37.9	20.4	10.6	12.1
1927	9.2	6.6	8.2	5.9	4.6	4.6	246.4	128.0	293.5	338.5	155.6	347.7	0.1	0.0	11.4	2.7	1.8	1.6
1928	11.9	7.4	10.1	6.2	4.6	4.9	465.7	222.0	480.6	445.8	195.7	463.6	0.5	0.1	41.4	31.8	13.4	17.8
1929	13.8	7.6	10.7	5.8	4.5	4.5	582.1	265.4	601.0	360.2	158.9	371.9	1.3	0.1	79.0	60.1	21.4	27.8
1930	12.2	7.2	9.7	5.9	4.5	4.7	481.8	221.7	495.6	358.6	165.0	393.3	1.0	0.1	55.9	38.5	15.0	20.3
1931	12.8	7.6	10.5	6.1	4.5	4.8	495.2	236.0	533.1	423.8	185.0	416.4	1.0	0.2	61.4	30.6	13.6	16.5
1932	13.3	7.7	10.9	5.7	4.4	4.5	567.0	258.8	563.4	321.4	148.5	358.9	1.0	0.1	60.6	38.1	16.7	19.8
1933	12.6	7.2	9.8	5.6	4.4	4.4	447.2	212.9	485.4	278.9	137.7	317.8	1.2	0.2	61.6	47.8	15.9	21.9
1934	11.5	7.2	9.9	6.1	4.5	4.8	407.8	205.2	453.5	404.9	172.9	424.7	0.5	0.1	38.1	25.7	11.0	13.7
1935	13.5	7.7	11.1	5.7	4.4	4.5	550.1	247.8	572.9	323.2	152.5	351.7	1.0	0.1	65.9	39.2	15.5	22.8
1936	11.7	7.3	10.2	5.5	4.4	4.4	456.2	221.6	491.3	234.0	111.6	273.8	0.4	0.1	41.2	17.3	9.7	10.4
1937	11.6	7.3	10.2	5.8	4.4	4.6	365.9	180.9	412.0	341.7	155.3	358.1	0.4	0.0	30.8	28.1	9.4	14.3
1938	13.0	7.6	10.7	5.4	4.3	4.3	483.9	229.0	504.2	243.4	118.6	288.3	0.9	0.1	52.5	38.3	14.3	18.7
1939	11.1	7.1	9.8	4.9	4.2	3.8	369.9	184.7	420.8	134.8	70.0	168.6	0.4	0.1	33.4	21.3	10.2	12.2
1940	9.2	6.5	8.4	5.5	4.4	5.0	239.1	125.3	279.5	240.7	117.4	546.4	0.0	0.0	7.7	3.8	2.2	2.3
1941	11.8	7.4	11.5	5.4	4.3	4.9	377.9	189.2	692.4	238.4	118.8	493.0	0.4	0.0	60.5	23.4	9.3	12.6
1942	11.6	7.3	11.1	6.0	4.4	5.7	372.5	189.1	634.4	408.2	174.3	798.5	0.4	0.0	52.3	30.3	10.2	11.9
1943	14.3	7.9	13.2	6.2	4.4	6.0	562.0	253.4	957.2	466.4	202.6	887.8	1.2	0.1	111.9	51.7	17.4	25.6
1944	15.6	8.3	14.0	5.7	4.4	5.3	634.1	288.6	1062.5	293.2	136.3	606.7	1.5	0.2	132.5	45.2	19.5	86.8
1945	13.2	8.0	12.8	5.6	4.3	5.1	451.5	219.2	774.5	262.7	125.9	558.7	0.5	0.1	68.1	21.0	10.1	51.1
1946	12.3	7.7	12.2	5.8	4.3	5.5	411.5	204.4	716.5	357.3	157.5	722.1	0.3	0.0	54.7	18.1	8.5	50.3
1947	14.1	8.0	13.2	5.6	4.2	5.3	514.2	238.8	885.6	347.5	161.5	679.8	1.0	0.1	102.1	45.4	17.0	75.1
1948	12.9	7.5	12.3	5.6	4.2	5.3	492.0	236.5	832.1	349.7	153.7	692.6	0.7	0.1	88.2	32.4	14.5	70.6
1949	13.1	7.5	12.4	5.9	4.2	5.7	493.8	228.8	843.6	391.8	170.7	773.8	0.8	0.1	86.5	37.2	14.3	65.2
1950	14.5	8.1	13.8	6.1	4.2	6.0	556.8	256.0	947.7	467.3	199.9	884.5	1.0	0.1	106.8	39.3	16.4	76.8
1951	15.4	8.3	14.5	6.0	4.2	6.0	639.6	288.9	1064.8	407.5	176.5	794.5	1.2	0.1	121.5	41.9	17.7	85.0
1952	15.2	8.4	14.6	5.6	4.2	5.8	581.0	266.9	974.7	316.4	147.7	640.7	1.0	0.1	103.0	40.0	14.9	72.2
1953	13.9	8.1	13.9	5.0	4.0	5.3	488.6	237.7	823.4	217.5	106.5	477.1	0.7	0.1	77.2	28.8	13.0	60.4
1954	11.1	7.1	11.8	5.8	4.1	6.5	366.2	184.7	637.0	415.2	179.9	781.9	0.1	0.0	38.3	7.9	5.1	31.0
1955	14.4	8.0	14.6	5.1	3.9	5.9	604.5	278.2	981.1	269.1	125.1	565.8	1.0	0.1	106.3	41.1	16.1	72.8

Table 4.4c (cont.)

Year	TP tonne y-1			Dissolved P tonne y-1			TN tonne y-1			Dissolved N tonne y-1			Sediment tonne y-1			Silica tonne y-1		
	Robe	Carra	Owenbrin	Robe	Carra	Owenbrin	Robe	Carra	Owenbrin	Robe	Carra	Owenbrin	Robe	Carra	Owenbrin	Robe	Carra	Owenbrin
1956	11.3	7.2	12.5	5.2	4.0	6.1	427.1	285.7	733.2	249.7	116.2	540.8	0.3	0.1	53.8	22.9	9.5	48.9
1957	12.3	7.7	13.6	5.1	3.8	6.0	430.8	282.4	732.8	312.2	142.8	615.2	0.3	0.1	48.0	15.9	7.0	39.7
1958	11.8	7.4	12.6	5.4	3.9	6.4	472.3	300.5	785.8	338.0	148.7	686.9	0.6	0.3	70.5	20.9	10.3	52.1
1959	13.0	7.9	14.2	5.1	3.8	6.1	525.2	337.9	884.8	314.1	136.3	639.8	0.5	0.2	70.5	31.3	11.9	55.5
1960	12.2	7.6	13.0	5.4	4.0	6.4	476.0	292.0	809.9	343.9	247.0	667.6	0.6	0.3	73.3	28.6	26.8	54.2
1961	13.2	8.4	14.2	5.3	4.2	6.3	523.3	344.5	858.6	333.5	245.3	590.6	0.6	0.3	78.6	25.3	29.3	84.7
1962	13.0	8.6	14.1	5.0	4.1	5.9	509.1	340.1	778.0	263.9	196.9	451.7	0.6	0.3	76.8	32.1	30.5	142.0
1963	11.6	7.8	13.0	4.9	4.1	6.0	421.3	281.3	619.4	242.3	184.7	419.1	0.3	0.1	54.4	22.5	22.9	152.3
1964	11.6	8.1	13.4	5.4	4.8	7.0	405.1	272.4	592.4	312.1	245.7	479.6	0.2	0.1	47.0	17.1	16.9	147.0
1965	12.8	9.5	15.4	5.1	4.3	6.5	482.7	337.7	662.5	288.8	219.7	446.9	0.4	0.2	71.0	28.5	26.1	272.7
1966	12.7	8.7	14.8	5.2	4.5	6.9	464.1	314.1	634.1	303.1	227.6	462.8	0.5	0.2	66.2	22.3	21.8	280.3
1967	12.8	9.2	15.6	5.5	5.6	8.5	483.2	324.6	655.4	312.3	234.1	438.6	0.3	0.1	61.2	16.1	18.7	304.1
1968	13.6	11.4	19.2	5.3	5.2	8.4	508.9	341.1	650.6	343.9	273.2	401.4	0.3	0.2	61.3	13.6	18.3	348.1
1969	13.1	10.5	18.0	4.9	4.1	6.3	510.9	364.8	580.2	238.6	187.4	309.9	0.8	0.4	86.6	39.2	32.1	549.9
1970	12.0	8.3	14.5	5.5	5.4	8.3	409.9	279.6	492.6	321.6	248.4	386.9	0.3	0.2	92.4	20.8	17.8	352.2
1971	13.6	11.0	18.7	4.7	4.3	6.9	516.9	354.5	596.6	195.8	162.3	285.7	0.4	0.2	127.1	20.9	21.2	461.8
1972	11.3	8.4	15.3	5.0	4.8	8.1	369.4	255.4	472.2	273.0	204.3	345.7	0.1	0.1	64.6	10.5	11.2	292.0
1973	12.0	9.5	18.0	5.2	5.0	8.6	453.0	298.1	710.5	246.2	202.1	518.7	0.3	0.1	113.7	21.4	19.4	442.2
1974	12.8	9.9	18.6	5.3	5.0	8.6	452.7	313.5	740.7	302.9	225.4	620.8	0.2	0.1	94.4	16.3	16.1	382.8
1975	13.6	10.4	18.7	5.7	6.0	10.1	524.7	345.7	858.5	284.5	233.2	505.6	0.5	0.3	132.7	17.5	17.8	439.2
1976	13.5	11.8	20.8	5.6	5.8	10.6	481.0	340.7	715.9	256.3	196.5	500.4	0.5	0.3	123.2	22.2	23.0	452.7
1977	13.3	11.2	22.1	6.2	6.9	12.3	459.2	306.3	720.5	351.0	263.3	648.8	0.3	0.1	99.5	16.1	16.3	403.7
1978	15.2	14.0	25.6	6.1	7.0	11.8	569.2	383.7	885.8	293.5	227.7	509.5	0.6	0.4	146.9	20.0	23.2	506.3
1979	14.9	13.9	24.9	6.9	7.5	14.3	507.9	344.8	742.2	349.6	263.2	712.5	0.4	0.2	122.8	19.3	22.1	482.7
1980	18.0	15.7	30.5	7.2	8.4	15.2	613.8	407.5	997.7	362.6	296.7	695.6	0.6	0.3	152.1	19.0	21.3	500.3
1981	18.5	17.4	32.1	8.2	12.1	21.0	617.3	437.1	971.1	333.6	280.1	676.9	0.8	0.4	186.2	25.5	30.7	624.8
1982	19.4	23.6	42.2	7.6	10.4	16.9	576.3	416.0	944.6	337.6	264.7	645.9	0.4	0.2	140.5	59.4	23.5	517.1
1983	18.9	20.7	34.9	7.2	9.9	17.3	580.3	399.5	909.7	295.7	250.9	502.2	0.7	0.3	163.8	68.6	26.6	581.1
1984	17.5	19.4	35.5	6.0	5.6	10.6	522.7	376.8	752.8	287.3	219.8	462.6	0.4	0.2	123.2	59.5	23.8	491.7
1985	14.9	11.5	22.6	10.1	16.6	26.0	492.4	331.6	681.8	371.3	334.8	701.2	0.6	0.3	117.2	55.2	21.3	470.6
1986	23.4	32.2	52.2	8.8	12.5	22.2	636.2	485.3	994.4	411.4	332.0	750.9	0.6	0.2	183.9	79.3	31.2	630.9
1987	22.2	25.3	45.6	7.1	8.3	15.4	683.8	485.2	1049.2	240.4	197.6	517.7	0.9	0.5	211.8	85.2	33.4	700.9
1988	17.8	16.8	32.8	8.5	12.2	21.7	490.9	334.0	790.6	375.9	313.4	724.9	0.2	0.1	80.8	36.7	12.7	323.1
1989	21.5	24.7	44.5	9.9	13.2	24.4	638.7	460.7	1014.1	363.6	290.0	584.1	0.8	0.4	191.0	74.7	30.2	644.9
1990	22.7	26.1	49.0	7.8	12.0	17.9	604.3	426.3	851.3	378.7	298.6	629.8	0.7	0.4	166.8	73.0	27.7	625.0
1991	21.0	24.8	37.5	8.5	12.9	20.1	626.9	440.6	895.4	315.4	272.0	555.6	1.4	0.8	215.8	91.0	36.8	685.0
1992	21.2	25.7	41.8	9.2	15.2	23.9	574.7	417.6	839.3	371.1	302.7	715.8	0.7	0.3	142.0	65.8	28.6	517.5
1993	23.7	30.4	49.5	7.3	8.7	16.5	657.4	463.3	1029.5	288.2	236.9	578.1	0.8	0.3	182.0	76.6	30.9	594.2
1994	19.4	18.2	35.6	8.2	11.8	20.6	553.3	382.2	865.5	387.3	300.5	756.5	0.5	0.3	143.4	61.4	23.4	518.2
1995	21.5	24.3	43.2	8.1	10.6	18.4	658.7	453.8	1054.1	306.0	251.9	535.4	0.8	0.4	186.5	70.9	28.1	626.7
1996	20.3	21.5	38.5	7.7	9.8	19.1	553.2	390.4	806.9	293.0	230.7	521.1	0.7	0.4	139.0	62.4	25.7	506.8
1997	19.2	19.6	39.7	7.0	9.4	16.3	536.8	364.6	789.6	224.0	197.2	489.0	0.4	0.2	115.2	55.3	21.5	485.8
1998	17.6	18.8	34.2	11.7	14.6	25.2	447.3	319.9	729.3	402.2	335.7	750.1	0.3	0.1	95.9	46.6	16.2	396.1
1999	29.1	30.6	53.4	8.8	13.5	21.3	735.7	522.7	1114.9	394.4	324.7	716.4	0.9	0.5	207.7	85.2	35.1	659.9
2000	24.1	28.1	45.5	8.4	10.4	19.7	695.9	492.2	1046.1	389.6	291.5	746.2	1.1	0.5	215.5	94.1	37.3	684.2
2001	23.1	22.5	42.8	8.4	11.7	18.0	699.8	463.8	1083.5	244.3	225.9	543.9	0.8	0.5	172.7	59.7	24.6	553.4
2002	21.7	23.8	39.2	8.2	11.9	18.9	544.6	392.3	869.1	299.3	253.8	593.5	0.2	0.1	90.3	44.2	18.2	344.2
2003	21.0	23.9	40.0	6.4	6.2	11.1	558.6	398.3	875.6	202.1	155.5	442.2	0.5	0.2	137.5	59.4	23.4	509.4
2004	17.2	13.2	25.7	9.2	13.9	24.0	465.3	294.9	728.5	326.6	277.1	681.5	0.1	0.0	53.6	26.7	9.0	244.0
2005	24.5	28.5	51.2	7.8	9.2	17.1	646.4	455.3	1032.2	310.0	243.5	620.7	0.5	0.2	148.8	62.7	23.4	528.8
2006	20.9	19.5	37.5	8.4	13.5	21.6	597.5	400.7	929.5	245.7	210.1	462.7	0.5	0.2	67.0	47.6	18.5	426.3

Appendix 4.5: Annual values for hindcast in-lake responses

Table 4.5a Hindcast maximum chlorophyll-a Leane (mg m^{-3}) and mean annual zooplankton biomass (µg C l^{-1}), 1941 to 2005.

Year	Total Max Chl_a	Total Diatom Chl_a	Cyano Max Chl_a	Zoo biomass
1941	7.3	5.8	7.9	5.8
1942	5.4	4.7	6.3	4.7
1943	4.5	2.3	1.7	2.3
1944	14.1	13.7	5.4	13.7
1945	7.7	7.3	3.6	7.3
1946	4.3	1.3	3.5	1.3
1947	14.1	13.6	5.8	13.6
1948	5.8	5.2	4.9	5.2
1949	19.8	19.0	4.3	19.0
1950	10.1	9.5	8.4	9.5
1951	22.7	22.2	8.9	22.2
1952	18.0	26.6	7.1	26.6
1953	11.7	11.1	5.0	11.1
1954	5.8	5.2	5.4	5.2
1955	18.9	30.8	3.7	30.8
1956	11.9	11.3	6.7	11.3
1957	16.6	16.1	3.2	16.1
1958	6.3	5.0	5.2	5.0
1959	24.8	24.4	5.4	24.4
1960	24.8	24.4	6.7	24.4
1961	18.6	18.0	6.6	18.0
1962	16.3	15.8	6.1	15.8
1963	18.7	18.2	7.0	18.2
1964	19.9	19.3	5.3	19.3
1965	14.5	14.1	5.8	14.1
1966	14.5	14.1	5.7	14.1
1967	14.1	13.4	4.4	13.4
1968	36.8	36.3	5.0	36.3
1969	13.7	13.3	6.8	13.3
1970	16.7	16.2	6.4	16.2
1971	24.6	24.1	6.6	24.1
1972	18.2	37.0	7.0	37.0
1973	28.2	27.7	5.7	27.7
1974	5.3	4.9	5.6	4.9
1975	34.9	34.5	6.6	34.5
1976	29.1	28.6	7.1	28.6
1977	23.2	22.7	10.6	22.7
1978	22.0	21.4	6.6	21.4
1979	11.3	10.9	5.2	10.9
1980	8.3	2.3	6.6	2.3

Table 4.5b Hindcast maximum chlorophyll-a Feeagh (mg m^{-3}) and mean annual zooplankton biomass (µg C l^{-1}), 1981 to 2005.

Year	Total Max Chl_a	Total Diatom Chl_a	Cyano Max Chl_a	Zoo biomass
1981	13.1	12.7	4.1	12.7
1982	26.8	26.3	5.7	26.3
1983	55.7	21.7	4.9	21.7
1984	22.1	55.2	5.4	55.2
1985	6.9	6.4	4.5	6.4
1986	3.5	2.2	4.3	2.2
1987	11.7	11.2	5.3	11.2
1988	8.8	8.3	4.4	8.3
1989	21.7	21.0	4.2	21.0
1990	12.6	12.1	5.2	12.1
1991	14.5	13.7	5.2	13.7
1992	10.7	10.3	5.1	10.3
1993	18.8	18.1	5.3	18.1
1994	12.5	12.0	6.2	12.0
1995	24.4	24.0	6.0	24.0
1996	20.1	19.6	6.2	19.6
1997	32.3	31.8	7.4	31.8
1998	17.6	17.0	7.2	17.0
1999	16.9	16.5	5.8	16.5
2000	25.4	24.8	6.0	24.8
2001	25.3	24.6	8.0	24.6
2002	10.8	10.5	5.4	10.5
2003	32.8	32.2	4.3	32.2
2004	20.0	19.5	5.2	19.5
2005	13.0	12.0	5.0	12.0

Table 4.5c Hindcast maximum chlorophyll-a Mask (mg m^{-3}), 1905 to 2006.

Year	Total Max Chl_a	Total Diatom Chl_a	Total Cyano Chl_a	Total Chloro Chl_a
1905	5.17	1.93	0.21	2.42
1906	7.13	0.02	0.01	3.54
1907	7.46	0.03	0.01	3.70
1908	6.85	0.03	0.01	3.40
1909	7.13	0.03	0.01	3.54
1910	6.80	0.02	0.01	3.38
1911	7.05	0.02	0.01	3.50
1912	6.75	0.03	0.01	3.35
1913	7.02	0.02	0.01	3.48
1925	11.66	11.66	1.81	5.03
1926	10.68	10.68	1.42	4.91
1927	10.60	10.60	0.11	5.21
1928	9.94	9.94	0.07	4.91
1929	9.26	9.26	0.08	4.55
1930	9.04	9.04	0.08	4.44
1931	7.53	7.53	0.07	3.70
1932	10.90	5.86	0.55	4.92
1933	8.43	0.24	0.01	4.09
1934	9.37	0.15	0.02	4.59
1935	8.59	0.15	0.03	4.19
1936	7.95	0.10	0.02	3.91
1937	7.54	0.09	0.03	3.70
1938	5.78	0.05	0.01	2.85
1939	6.20	0.09	0.02	3.04
1940	5.76	0.07	0.02	2.82
1941	5.58	0.07	0.02	2.74
1950	7.25	12.11	0.24	1.01
1951	18.89	9.79	0.04	2.75
1952	30.86	10.85	0.06	4.38
1953	16.98	8.38	0.02	2.38
1954	10.08	10.97	0.02	1.09
1955	38.81	12.17	0.12	5.76
1956	10.64	7.59	0.02	1.52
1957	16.65	13.60	0.04	2.35
1958	7.31	11.52	0.02	0.99
1959	32.10	8.82	0.04	4.80
1960	4.44	17.17	0.25	0.61
1961	7.14	17.17	0.03	1.04
1962	10.32	0.68	0.02	1.53
1963	11.58		0.02	1.26
1964	10.13	13.34	0.09	0.61
1965	24.15	13.66	0.02	1.04
1966	39.48	16.31	0.03	1.53
1967	31.78	14.68	0.02	1.26
1968	44.41	13.96	0.04	8.69
1969	35.18	18.47	0.06	3.89
1970	4.05	15.11	0.96	2.64
1971	9.60	17.64	0.04	5.40
1972	13.13	14.84	0.10	6.84
1973	11.31	14.81	0.03	4.21
1974	10.25	18.22	0.03	2.20
1975	7.75	15.68	0.06	4.79
1976	6.81	17.45	0.10	6.77
1977	9.15	17.40	0.10	5.76
1978	7.92	17.77	0.08	4.70
1979	5.38	16.47	0.02	1.58
1980	3.39	14.55	0.07	0.14
1981	2.84	13.91	0.08	0.22
1982	42.55	17.08	0.54	6.34
1983	10.98	14.74	0.04	1.59
1984	17.79	18.86	0.05	2.65
1985	3.62	16.04	0.32	1.26
1986	3.45	14.21	0.05	3.35
1987	17.80	17.34	0.33	4.63
1988	16.46	19.40	0.36	5.22
1989	17.32	17.88	0.32	5.34
1990	13.76	18.76	0.25	4.18
1991	28.32	19.03	0.25	4.53
1992	14.89	19.22	1.72	8.83
1993	38.12	18.01	0.38	6.50
1994	23.34	19.31	1.76	8.02
1995	34.19	16.17	3.63	5.75
1996	25.01	17.65	0.20	6.13
1997	30.52	16.28	0.14	5.96
1998	4.05	17.70	0.48	0.33
1999	9.60	18.28	0.44	1.35
2000	13.13	16.63	0.36	1.89
2001	11.31	19.19	0.10	1.64
2002	10.25	15.96	0.18	1.46
2003	7.75	15.96	0.06	1.12
2004	6.81	18.96	0.18	0.95
2005	9.15	15.69	0.34	1.30
2006	7.92	16.99	0.10	1.10

Appendix 4.6 Incremental change values for future climate simulations 2021-2060.

Table 4.6.1 Incremental change values for future climate simulations 2021 to 2060 for the Leane, Feeagh and Mask catchments provided by the C4I project: note that the temperature value is additive, while precipitation is a ratio between the reference and future climate period.

		J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**
Leane													
AT +°C	A2	1.24	1.01	0.5	0.46	0.78	0.78	1.21	0.86	0.89	0.70	0.64	0.59
	B1	0.49	0.60	0.08	0.35	0.57	0.73	0.84	0.52	0.63	0.37	0.59	0.37
PPTratio	A2	1.17	1.11	1.00	0.88	0.92	0.94	0.83	1.05	1.03	1.17	1.10	1.02
	B1	1.14	1.03	0.93	0.87	0.95	0.93	0.89	1.06	1.02	1.09	0.96	0.99
Feeagh													
AT +°C	A2	1.15	1.02	0.57	0.46	0.76	0.66	1.14	0.79	0.84	0.67	0.63	0.54
	B1	0.32	0.5	0.2	0.39	0.58	0.60	0.84	0.60	0.59	0.37	0.56	0.24
PPTratio	A2	1.13	1.08	1.01	0.86	0.90	0.89	0.82	0.98	1.00	1.16	1.09	1.03
	B1	1.06	1.07	0.94	0.86	0.90	0.88	0.88	0.98	1.00	1.10	0.93	0.98
Mask													
AT +°C	A2	1.19	1.00	0.58	0.47	0.78	0.70	1.17	0.83	0.86	0.70	0.63	0.54
	B1	0.34	0.50	0.18	0.37	0.58	0.65	0.86	0.60	0.61	0.41	0.57	0.24
PPTratio	A2	1.17	1.11	1.00	0.88	0.92	0.94	0.83	1.05	1.03	1.17	1.10	1.02
	B1	1.14	1.03	0.93	0.87	0.95	0.93	0.89	1.06	1.02	1.09	0.96	0.99

Appendix 4.7: TP and dissolved P loads for a control period and the A2 and B1 scenarios 2021 to 2060.

Table 4.7.1 Flesk subcatchment, Leane, Black subcatchment, Feeagh, and Robe subcatchment, Mask: dissolved TP loads (kg day^{-1}) for a control period and the A2 and B1 scenarios 2021 to 2060 (25th, median and 75th percentiles of mean monthly and annual values).

			J	F	M	A	M	J	J	A	S	O	N	D	year
Flesk	Ctl	25%	77.95	37.28	22.55	11.03	6.83	6.99	5.88	5.60	6.26	15.03	37.30	43.43	42.67
		med	124.26	88.24	50.82	17.64	10.99	9.87	7.61	8.55	17.71	31.35	62.06	88.80	52.18
		75%	172.18	163.02	88.71	32.62	24.73	14.37	10.62	13.15	40.55	74.66	99.48	130.84	62.97
	A2	25%	101.13	35.15	24.24	10.90	6.40	6.40	5.24	5.66	6.52	18.53	36.18	40.54	44.61
		med	156.74	81.24	50.19	17.52	9.64	8.67	6.21	8.99	19.99	40.49	62.79	82.41	55.40
		75%	224.83	167.46	81.84	29.99	17.10	11.83	7.77	14.68	46.15	90.21	103.31	126.49	67.58
	B1	25%	93.06	33.32	22.01	9.95	6.35	6.41	5.40	5.71	6.37	18.15	30.11	40.28	41.34
		med	145.99	72.94	42.08	16.15	9.92	8.69	6.54	9.05	18.17	39.39	50.79	81.73	51.53
		75%	209.16	151.91	68.37	26.10	20.50	11.91	8.44	14.79	40.79	88.52	82.89	127.00	62.93
Black	Ctl	25%	14.58	9.44	4.83	1.24	0.27	0.31	0.29	0.43	0.71	4.51	16.25	16.00	11.81
		med	27.43	14.91	15.03	3.66	1.02	0.73	0.64	1.28	2.49	11.94	29.38	27.41	15.43
		75%	44.53	24.81	27.22	9.77	4.89	1.59	1.77	6.67	10.23	28.94	42.29	52.56	19.79
	A2	25%	18.68	9.83	4.68	0.99	0.21	0.24	0.22	0.36	0.52	4.79	10.55	14.61	11.30
		med	34.20	16.64	14.63	2.61	0.58	0.46	0.38	0.96	1.92	13.69	19.94	25.21	15.14
		75%	57.34	29.34	26.92	6.40	2.86	0.94	0.96	5.71	8.10	34.51	32.39	50.81	19.77
	B1	25%	16.39	9.25	4.07	0.95	0.22	0.24	0.21	0.37	0.53	4.93	10.74	14.29	10.67
		med	29.07	15.64	12.31	2.52	0.59	0.44	0.38	0.97	1.96	13.94	20.06	24.64	14.31
		75%	49.22	27.51	22.69	6.22	2.90	0.87	0.96	5.72	8.17	34.89	32.54	49.66	18.74
Robe	Ctl	25%	12.39	7.18	8.13	3.73	2.21	1.46	1.30	1.19	1.29	1.60	5.96	9.60	8.41
		med	19.07	15.64	10.42	5.81	4.25	2.02	1.51	1.91	2.66	5.98	14.71	14.88	10.23
		75%	27.17	23.78	15.44	10.34	6.50	3.76	4.18	5.11	10.16	20.59	25.43	25.64	13.54
	A2	25%	14.09	8.12	8.20	3.39	1.91	1.38	1.24	1.13	1.18	1.54	8.34	11.50	9.66
		med	22.21	19.33	10.38	5.49	3.45	1.64	1.40	1.38	2.40	8.64	20.01	16.46	11.82
		75%	33.40	29.67	17.83	10.00	5.45	2.84	2.70	4.53	11.31	26.33	40.55	27.41	15.68
	B1	25%	13.05	7.75	7.42	3.28	1.90	1.38	1.24	1.15	1.21	1.57	6.87	8.77	8.69
		med	20.26	18.53	9.39	5.05	3.37	1.68	1.42	1.57	2.82	7.34	15.49	13.65	10.42
		75%	29.87	28.10	15.85	8.90	5.26	2.87	3.16	4.90	12.32	24.91	32.76	23.86	14.21

Table 4.7.1 (cont.) Flesk subcatchment, Leane, Black subcatchment, Feeagh, and Robe subcatchment, Mask: dissolved P loads (kg day^{-1}) for a control period and the A2 and B1 scenarios 2021 to 2060 (25th, median and 75th percentiles of mean monthly and annual values).

			J	F	M	A	M	J	J	A	S	O	N	D	year
Flesk	Ctl	25%	21.26	13.36	8.28	5.55	4.69	4.67	4.27	4.09	4.19	6.02	10.58	11.98	13.79
		med	33.32	32.51	17.29	6.96	5.73	5.45	4.72	4.91	8.06	10.96	14.42	18.31	16.83
		75%	51.24	59.64	34.54	12.62	10.06	6.85	5.77	6.37	16.38	19.35	19.36	23.11	20.11
	A2	25%	24.98	10.01	7.95	5.53	4.58	4.51	4.07	4.10	4.27	6.65	9.85	10.87	0.00
		med	40.81	23.55	15.17	6.92	5.43	5.12	4.36	5.00	8.94	13.66	13.72	16.64	16.77
		75%	66.59	55.98	27.27	10.62	7.72	6.06	4.80	7.02	18.86	22.66	19.02	21.71	20.47
	B1	25%	23.29	9.58	7.57	5.31	4.56	4.52	4.12	4.12	4.22	6.56	8.85	10.81	12.80
		med	38.60	21.01	12.72	6.65	5.49	5.12	4.44	5.02	8.24	13.28	12.03	16.66	15.72
		75%	61.84	49.58	22.25	9.05	8.70	6.05	4.98	7.05	16.86	22.12	16.40	21.78	19.13
Black	Ctl	25%	0.85	0.66	0.49	0.24	0.12	0.13	0.12	0.15	0.18	0.45	0.89	0.87	0.62
		med	1.18	0.90	0.84	0.44	0.22	0.19	0.19	0.25	0.33	0.77	1.22	1.24	0.71
		75%	1.67	1.17	1.23	0.70	0.48	0.27	0.30	0.51	0.72	1.21	1.49	1.57	0.80
	A2	25%	0.93	0.68	0.50	0.21	0.11	0.12	0.11	0.14	0.16	0.43	0.72	0.82	0.59
		med	1.31	0.91	0.81	0.37	0.17	0.16	0.15	0.22	0.29	0.82	1.00	1.17	0.68
		75%	1.89	1.21	1.19	0.57	0.37	0.21	0.22	0.46	0.63	1.30	1.28	1.48	0.77
	B1	25%	0.88	0.66	0.46	0.21	0.11	0.12	0.11	0.14	0.17	0.44	0.73	0.82	0.57
		med	1.22	0.89	0.75	0.36	0.17	0.16	0.15	0.22	0.30	0.83	1.01	1.16	0.67
		75%	1.75	1.18	1.10	0.56	0.37	0.20	0.22	0.46	0.64	1.31	1.28	1.47	0.75
Robe	Ctl	25%	6.68	4.84	4.86	3.02	2.00	1.43	1.27	1.16	1.22	1.49	4.24	5.56	4.71
		med	8.21	7.40	5.72	4.20	3.32	1.88	1.46	1.78	2.55	4.56	8.41	7.28	6.09
		75%	9.59	9.15	7.20	5.89	4.51	3.09	3.86	4.55	9.16	14.66	16.65	9.99	8.30
	A2	25%	6.95	5.18	5.03	2.83	1.78	1.35	1.21	1.11	1.16	1.46	5.60	6.02	5.27
		med	8.71	8.22	5.84	4.11	2.79	1.58	1.33	1.35	2.12	7.03	12.10	7.74	7.06
		75%	10.34	10.23	7.84	5.70	4.14	2.49	2.47	4.17	10.29	20.73	27.21	11.21	9.41
	B1	25%	6.71	5.09	4.81	2.74	1.78	1.35	1.21	1.12	1.18	1.47	4.69	5.39	4.87
		med	8.41	7.96	5.57	3.90	2.83	1.58	1.36	1.47	2.58	5.72	9.53	6.78	6.28
		75%	9.84	9.98	7.46	5.37	3.95	2.49	2.77	4.50	10.57	18.45	21.21	9.75	8.53

Appendix 4.8: TP and dissolved P loads for a control period and the A2 and B2 scenarios 2071 to 2100.

Table 4.8 Flesk subcatchment, Leane: TP loads (kg day^{-1}) for a control period and the A2 and B2 scenarios 2071 to 2100 for the ECHAM4/RCAO (E), HadAM3/HadRM3 (H) and HadAM3/RCAO (Had) GCM/RCM combinations (25th, median and 75th percentiles of mean monthly values). Annual loads were calculated as the sum of daily values for each year prior to the calculation of the percentiles.

		J	F	M	A	M	J	J	A	S	O	N	D	Year
Scenario		kg day^{-1}												tonnes yr^{-1}
	25%	62	44	22	10	7	6	6	8	10	18	41	48	13.8
ctl	med	94	70	36	14	10	8	8	13	18	34	62	73	16.7
	75%	136	105	61	24	15	12	12	25	43	66	94	103	19.9
Present population and landuse														
	25%	97	36	18	9	6	4	4	5	5	16	44	86	15.5
E A2	med	139	56	27	14	8	5	5	6	7	35	77	128	18.9
	75%	194	87	45	28	11	6	6	11	16	81	131	184	23.0
	25%	105	66	39	11	6	5	5	7	6	23	42	78	18.7
E B2	med	151	98	66	15	8	5	6	12	9	49	72	116	22.1
	75%	210	142	108	21	11	6	9	26	19	108	121	167	26.3
	25%	104	72	34	12	6	5	4	4	5	15	26	53	15.5
H A2	med	143	108	54	16	8	5	5	4	6	31	49	82	18.5
	75%	192	154	87	24	12	6	6	6	12	70	88	124	22.1
	25%	79	48	34	12	7	5	4	4	5	15	42	50	14.3
H B2	med	117	75	57	16	9	5	5	5	8	32	67	74	17.4
	75%	164	114	98	25	16	7	5	6	16	68	109	109	21.0
	25%	100	37	24	10	8	5	4	5	5	12	38	55	14.3
Had A2	med	144	55	40	15	13	6	5	6	6	24	62	79	17.1
	75%	196	86	70	25	30	7	6	10	11	58	97	114	20.6
	25%	100	37	24	10	8	5	4	5	5	12	38	55	16.0
Had B2	med	168	60	60	20	16	7	5	6	15	21	42	87	19.3
	75%	196	86	70	25	30	7	6	10	11	58	97	114	23.2
Projected population and landuse														
	25%	105	39	19	11	7	5	5	6	6	17	46	89	16.7
E A2	med	152	61	29	16	9	6	6	7	8	38	79	131	20.3
	75%	178	127	108	27	17	8	6	6	18	72	112	113	22.6
	25%	113	72	43	13	7	6	6	8	7	24	45	81	20.2
E B2	med	164	109	73	16	9	6	7	13	10	52	75	120	24.0
	75%	231	160	121	22	12	8	10	30	21	117	125	171	28.6
	25%	112	80	37	13	7	6	5	5	5	16	28	56	16.7
H A2	med	155	120	58	17	9	6	6	5	7	32	51	85	19.9
	75%	209	172	96	27	13	7	7	7	13	73	91	127	23.9
	25%	85	53	37	13	8	6	5	5	6	16	44	53	15.5
H B2	med	126	83	62	17	10	6	6	6	9	34	70	77	18.8
	75%	178	127	108	27	17	8	6	6	18	72	112	113	22.6
	25%	106	46	25	12	9	6	5	6	5	13	40	62	15.7
Had A2	med	154	71	41	16	15	7	6	7	7	25	64	88	18.8
	75%	211	108	75	27	33	8	7	11	12	60	100	124	0.1
	25%	133	48	36	15	10	7	6	6	8	12	27	65	17.5
Had B2	med	180	73	64	22	17	8	6	7	16	23	45	94	21.0
	75%	244	108	109	41	37	11	7	11	46	51	71	131	25.2

Table 4.8 (cont.) Flesk subcatchment, Leane: dissolved P loads (kg day^{-1}) for a control period and the A2 and B2 scenarios 2071 to 2100 for the ECHAM4/RCAO (E), HadAM3/HadRM3 (H) and HadAM3/RCAO (Had) GCM/RCM combinations (25th, median and 75th percentiles of mean monthly values).

		J	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Year**
Scenario		kg day^{-1}												tonnes yr^{-1}
	25%	18	16	8	5	5	4	4	5	5	7	11	13	4.6
ctl	med	28	25	13	6	5	5	5	6	8	10	14	16	5.4
	75%	43	40	23	8	7	6	6	12	19	18	18	20	6.4
Present population and landuse														
	25%	25	10	7	5	4	4	4	4	4	7	11	17	4.4
E A2	med	38	16	9	6	5	4	4	4	4	11	16	22	5.2
	75%	56	27	14	10	6	4	4	6	7	22	22	29	6.2
	25%	25	18	11	6	4	4	4	4	4	8	11	16	5.3
E B2	med	38	29	20	6	5	4	4	6	5	14	15	21	6.2
	75%	57	46	36	8	6	5	5	12	9	28	21	27	7.4
	25%	30	24	10	6	5	4	4	4	4	6	8	12	4.9
H A2	med	42	37	16	7	5	4	4	4	4	10	12	17	5.7
	75%	58	56	28	9	6	5	4	4	6	20	17	22	6.7
	25%	23	17	11	6	5	4	4	4	4	6	11	12	4.6
H B2	med	35	27	19	7	5	4	4	4	5	11	14	16	5.4
	75%	50	42	35	9	7	5	4	4	8	20	20	20	6.4
Projected population and landuse														
	25%	29	12	8	6	5	5	5	5	5	8	12	18	5.2
E A2	med	48	19	10	7	6	5	5	5	5	13	17	23	6.3
	75%	61	53	43	10	8	6	5	5	9	23	21	21	7.7
	25%	28	21	13	7	5	5	5	5	5	9	12	17	6
E B2	med	47	37	25	7	6	5	5	7	6	17	16	22	8
	75%	74	60	47	9	7	6	6	15	11	33	22	28	9
	25%	35	29	11	7	5	5	5	4	5	7	9	14	5.7
H A2	med	50	46	18	8	6	5	5	5	5	12	13	18	6.8
	75%	71	70	34	10	7	6	5	5	7	23	18	23	8.1
	25%	26	20	12	7	6	5	5	5	5	7	12	14	5.4
H B2	med	41	33	22	8	6	5	5	5	5	12	16	17	6.5
	75%	61	53	43	10	8	6	5	5	9	23	21	21	7.7

Appendix 5

Appendix 5.1 Email addresses of all project team members as of June 1 2010

Team member	**Email address**	**Team member**	**Email address**
Norman Allott	nallott@tcd.ie	Paddy Kavanagh	Paddy.kavanagh@esbi.ie
Helen Bennion	hbennion@geog.ucl.ac.uk	David Lenihan	dlenihan@kerrycoco.ie
Kim Bosch	boschk@tcd.ie	Phil McGinnity	phil.mcginnity@marine.ie pmcginnity@ucc.ie
Catherine Dalton	Catherine.dalton@mic.ul.ie	Sarah Murnaghan	murnaghs@tcd.ie
Elvira de Eyto	Elvira.deeyto@marine.ie	Barry O'Dwyer	odwyerb@tcd.ie
Eleanor Jennings	Eleanor.jennings@dkit.ie	Karin Sparber	karin.sparber@mic.ul.ie
Phil Jordan	p.jordan@ulster.ac.uk Phil.Jordan@teagasc.ie	David Taylor	taylord@tcd.ie