THE ROLE OF PALAEOLIMNOLOGY IN IMPLEMENTING THE WATER FRAMEWORK DIRECTIVE IN IRELAND

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ABSTRACT

The EU Water Framework Directive has created research opportunities and challenges for water-quality managers and palaeolimnologists alike. Opportunities have arisen through increased attention to water-quality issues, and these in turn have led to enhanced funding for palaeolimnological research. Scientific challenges include identifying aquatic-system pressures, assessing risks, defining non-impacted reference conditions and developing new indicator and classification systems. These challenges have provided the aquatic science research communities with a range of highly relevant and urgent research questions. Addressing these questions requires a collaborative, systematic, whole-catchment approach that, in addition to palaeolimnologists, involves modellers and scientists from other disciplines, water-quality managers, policy-makers and the general public.

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INTRODUCTION

Incorporation of Directive 2000/60/EC (European Parliament and Council 2000), or the EU Water Framework Directive (WFD), into national legislation throughout the EU has established a new legislative framework and agreed protocols for European waters. Specifically with regard to surface waters in river basin districts (RBDs), the basis for water management under the WFD, member states are required to identify, delimit and differentiate waterbodies and to establish hydromorphological, physico–chemical and biological type-specific reference conditions (European Parliament and Council 2000). According to Table 1.2 in Annex V of the WFD and to REFCOND (2003), biological reference conditions equate to high ecological status and show no or very minor deviation from this as a result of human activity. They can therefore be viewed as a baseline, or the equivalent of conditions that existed prior to the onset of the current period of significant human impact.

Biological reference conditions can be established through several pathways (European Parliament and Council 2000; Andersen *et al.* 2004). In the absence of long-term data, the WFD (Annex II, 1.3) states that reference conditions may be derived through modelling, using hindcasting methods, and also through palaeolimnology, the scientific study of past conditions in freshwater bodies and their catchments (European

Parliament and Council 2000). The role of modelling in facilitating implementation of the WFD has been enhanced of late, following greater appreciation of human activity in current and future climate changes and of the aquatic-ecosystem impacts of these changes (e.g. Intergovernmental Panel on Climate Change 2007). Palaeolimnology also has a potentially important role to play here. Palaeolimnology can generate data that can then be used to calibrate models that simulate past aquatic impacts of climate- and catchment-induced changes at the drainage-basin scale, as well as providing a context for predictions of future conditions (Anderson *et al.* 2006; Bennion and Battarbee 2007).

The WFD has created opportunities and challenges for palaeolimnologists (Bennion and Battarbee 2007). This paper begins by outlining the science of palaeolimnology, providing examples of the contribution of palaeolimnology to implementation of the WFD in Ireland, including an approach in which studies of past and current aquatic and catchment conditions are linked with dynamic modelling, and ends with a look towards future opportunities and challenges for palaeolimnologists in Ireland.

PALAEOLIMNOLOGY

Palaeolimnology utilises lake sediments to reconstruct past drivers of environmental

change and their effects, and it is a particularly useful approach where other forms of time series information, particularly instrumental data, are incomplete or lacking.

Lake sediments contain datable records of past environmental conditions. Sediment-based archives represent accumulations of autochthonous and allochthonous material, in the form of biological, chemical and physical components. These components can be used as indicators, or proxies, of environmental conditions over various spatial scales, and therefore as a basis for reconstructing past environments (Table 1). The length of a lake-sediment record is a function of the time period over which sediments have accumulated, of the rate of accumulation and of the number and duration of any hiatuses. Sediment-accumulation rates are often determined by factors such as lake productivity and the degree of catchment disturbance, and hence the amount of material eroded and transported to a lake. As these factors vary on a site-by-site basis, it is not surprising that rates of sediment accumulation are known to be highly variable (Appleby 2001; Leira et al. 2006) and therefore notoriously difficult to predict. Fortunately, sediments preserve the isotopic (or radiometric) basis for establishing absolute ages (e.g. ^{14}C, ^{210}Pb and ^{137}Cs). Radiocarbon (^{14}C) dating is useful for sediments up to 40,000 years of age, while ^{210}Pb and ^{137}Cs are the preferred isotopes for sediments forming the uppermost part of the record and dating to the last 100–200 years or

so (Appleby 2001; Björck and Wohlfarth 2001). In those cases where it has not been possible to establish an absolute chronology, marker horizons of distinctive events that are synchronous across regions—for example, pollen representing vegetation change (Douglas 2007), and spheroidal carbonaceous particles (SCPs) (Rose and Appleby 2005)—can be used. SCPs are released from power stations into the atmosphere as a by-product of the combustion of fossil fuels, and they are deposited according to prevailing meteorological conditions and topographic factors. Down-core variations in abundances of SCPs have a profile that is distinct for a particular region, and can therefore provide a means of chronological control that is cheaper, although less accurate and precise, than the radiometrically based equivalent (Rose and Appleby 2005).

Sediments used in palaeolimnological research are usually retrieved using a coring device, although samples of surface sediments may also be obtained using various forms of mechanical grabs. The length of sediment record extracted from a lake, the sampling equipment used and the way in which recovered sediments are subsequently handled depend upon the nature of the research questions being addressed. A variety of different sediment corers and grabs are available to the palaeolimnologist, each of which is suited to a particular type of sediment or study (see Glew et al. 2001). For example, a piston corer (e.g. Chambers and Cameron 2001) can be used to extract long cores of sediment that extend

Table 1—Palaeolimnological proxies, their environmental conditions and their WFD quality elements for classification.

	Example sediment indicators	*Example environmental conditions*	*WFD quality elements*
Biological	Pollen, macrofossils	Terrestrial and aquatic vegetation	Aquatic flora
	Algae (e.g. diatoms, chrysophytes, desmids, pigments)	Aquatic chemistry, microhabitats, water quality	Phytoplankton
	Zooplankton (e.g. protozoa, Cladocera, ostracods, copepods)	Aquatic chemistry, microhabitats	Benthic invertebrate fauna, fish fauna
Chemical	Isotopes (e.g. C and N)	Catchment processes, palaeoclimate, palaeoproductivity	Hydromorphological and chemical condition supporting biological elements
	Geochemistry	Catchment processes, erosion, palaeoclimate, palaeoproductivity	
Physical	Organic matter content	Composition (inorganic/ organic ratio)	Hydromorphological and chemical condition supporting biological elements
	Grain size	Sediment source	
	Magnetic properties	Sedimentation, erosion	

over several metres and that potentially record changing environmental conditions over post–glacial timescales. By comparison, gravity corers (e.g. Renberg and Hansson 2008) are used to extract much shorter sequences of sediments from the uppermost part of a profile, and are therefore used when recent environmental changes are the focus.

One of the greatest challenges facing palaeo-limnologists is the interpretation of information extracted from the sediment record. Here, recourse to other sources of temporally overlapping information, notably instrumental and documentary records, can be extremely useful as a means of calibrating palaeolimnological data (e.g. Lotter 1998; Battarbee *et al.* 2005). More often than not, however, the interpretation of biological remains preserved in lake sediments (e.g. pollen, diatoms, Cladocera, chironomids) requires reference to ecological knowledge (Anderson 1995). Generally, this is developed from contemporary ecological studies that focus on extant equivalents of those taxa that are preserved in lake sediments and on their environmental ranges and optima (ter Braak and van Dam 1989).

Over the past two to three decades the interpretation of palaeolimnological data has been greatly enhanced through the development of statistical techniques that facilitate the extraction of values for environmental parameters directly from sediment-based remains (Birks 1998). One such technique involves the use of transfer functions, which are the quantifications of relationships between the composition of samples of surface sediment and current environmental conditions—otherwise known as a calibration training set (e.g. ter Braak 1987). Once constructed, transfer functions can be used to infer past measures of important environmental variables through their application to samples from deeper within a sediment profile. Thus, when applied to the remains of diatoms, transfer functions can be used as a basis for inferring the trophic and/or acidification histories of lakes (Birks 1998; Smol 2008). For example, transfer functions can be used to infer past levels of epilimnic total P (TP) from the remains of diatoms preserved in lake sediments (diatom-inferred TP, or DI-TP) (e.g. Bennion *et al.* 1996). Recent research has enabled the determination of transfer functions for the Irish ecoregion (Chen *et al.* 2008), thus improving quantitative reconstructions of epilimnic water quality from palaeolimnological data. Weighted averaging (WA) regression and calibration (ter Braak and van Dam 1989) and its extension, WA partial least squares (ter Braak and Juggins 1993), are

the most widely used statistical techniques in the reconstruction of past environmental variables based on transfer functions (Birks 1998).

ESTABLISHING REFERENCE CONDITIONS

In those situations where there is some uncertainty over the level of impairment of lake water quality and where long time series of monitoring data are unavailable, palaeolimnology can be used as a basis for reconstructing conditions that existed prior to human impact. Reference conditions can be established directly in terms of biological assemblages and indirectly through the use of transfer functions to calculate former levels of nutrients, pH, temperature, dissolved organic carbon, etc. Palaeolimnology also provides a means of reconstructing the amplitude and rate of past variability in lake conditions, in terms of both biological composition and ecological functioning, as well as the main causes of change, or ecological pressures. The approach thus provides a means not only of defining a reference state in the absence of extant examples of baseline conditions or long time series of data from water-quality monitoring, but also of quantifying how far a waterbody has changed relative to a defined reference state, as well as the cause(s) and rate of that change. Palaeolimnology therefore, inter alia, potentially provides some indication of the efforts that might be required to restore a particular lake, or type of lake. Moreover, palaeolimnology can also provide a means of establishing and examining past periods of chemical and ecological recovery, and therefore an insight into ecosystem resilience.

The question of whether lakes that currently appear to be in good condition provide extant examples of reference conditions can also be verified through palaeolimnology. IN-SIGHT (Identification of reference status for Irish lake typologies using palaeolimnological methods and techniques), a largely palaeolimnology-based study funded by the Environmental Protection Agency (EPA), which ran from 2003 to 2006, aimed to validate the state of a representative selection of lakes in Ireland that on the basis of expert opinion were deemed to be candidate reference lakes (CRLs) or possible examples of extant reference conditions (Leira *et al.* 2006). The study also set out to establish biological reference conditions for examples of the main types of impacted lakes in the Irish ecoregion (Taylor *et al.* 2006). The status of the sampled CRLs was based on a comparison of sediment composition

between core-top and core-bottom samples that focused on proxies of biological, water-quality and catchment conditions. Focusing on the differences between sediment core-top and core-bottom samples provides a relatively efficient and effective means of establishing changes based on sedimentary records from a large number of sites. This approach is based on the assumption that sediment core-top and core-bottom samples represent, respectively, the date of coring and the pre-impact, or reference, conditions (Smol 2008). Indications of the actual ages of core-bottom samples in IN-SIGHT were provided by absolute (isotope-based) techniques and relative dating using SCPs.

Statistical techniques in the form of squared chord distance, detrended correspondence analysis, and TP and pH transfer functions enabled quantification of the nature and degree of biological (diatoms) and chemical changes at each of the CRLs studied. Sediment chemistry and land-cover data (European Environment Agency 2009) were used to identify possible human-induced pressures, particularly processes of acidification, eutrophication and sediment inwash, in those cases where biologically important floristic changes were evident from the diatom data.

Fig. 1 summarises results of the test of reference status for a representative group of CRLs from different lake types in Ireland, carried out through the IN-SIGHT project. The results revealed marked temporal and spatial differences in reference condition, and they supported reference status in only 32% of CRLs studied (Leira et al. 2006). Marked differences were also evident in the commencement of anthropogenic impact, with significant impacts in some locations dating to before the mid nineteenth century, thus calling into question the basis for a generally applicable date for the onset of significant human-induced effects on aquatic ecosystems (Taylor et al. 2006). These differences are much greater when expanded to include the rest of Europe, and they represent some of the difficulties in defining a temporal start point for the commencement of major anthropogenic impact, and thus an end-point for reference conditions. Scientists in the UK (e.g. Battarbee 1999; Bennion et al. 2004; Simpson et al. 2005) have suggested c. AD 1850 as a possible terminus for pre-impact conditions upon which to base restoration targets and catchment management. By comparison, Anderson and Battarbee (1994) and Anderson (1997) maintain that c.1950—i.e. just prior to the period when cheap fertilisers became widely available to farmers in many parts of Europe—is
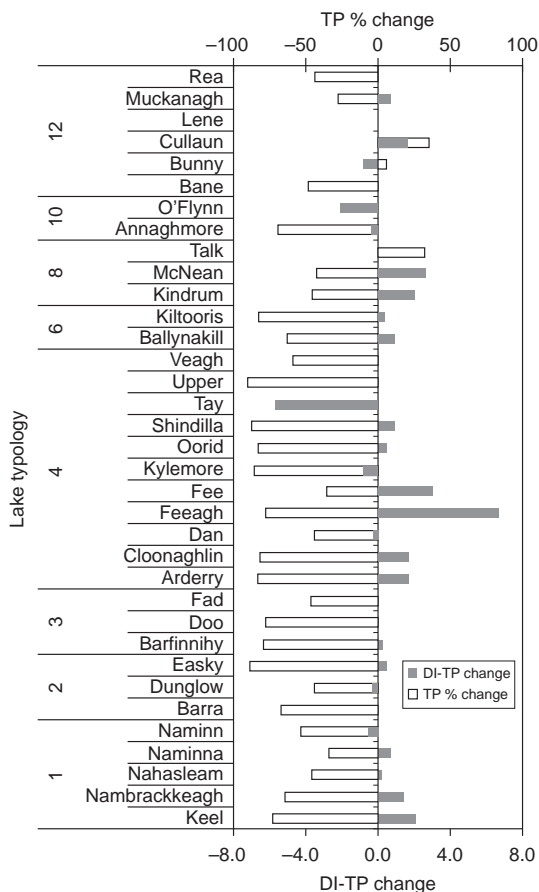
Fig. 1—Differences between core-bottom and core-top samples in accumulation-rate changes for DI-TP and sediment TP. CRLs are ordered according to typology class.

probably more realistic, particularly in view of the dramatic changes in climate that have occurred in the period since World War II.

SYSTEM CHANGE

The main pressures, or stressors, on aquatic ecosystems are changes in land use and inputs of nutrients, acidity and toxic pollutants that interact with local weather conditions. Changes in the weather linked to global-scale variations in climate—for example, the North Atlantic Oscillation—have a major effect on the dynamics of lakes throughout Europe (Blenckner et al. 2007). Many water-quality problems that were once assumed to be driven by the local weather are now known to be influenced by climatic events that operate on a global scale (e.g. Jennings and Allott 2006). Superimposed on this variability are projected changes in climate due to global warming, including increases in temperature, increased rainfall and changes in the seasonality

of precipitation. These in turn influence other variables, such as the volume and type of material delivered to a lake. The potential impacts of these changes will be both direct and indirect and may include reduced transparency of water and increased frequency and severity of algal blooms (e.g. Elliot *et al.* 2006; Weyhenmeyer *et al.* 2007; Naden *et al.* in press).

Eutrophication is currently considered to be the principal pressure on water quality globally. In Ireland (Jennings *et al.* 2003) nutrient enrichment is thought to be responsible for a large part of the documented decline in water quality over the last *c.*30 years (Toner *et al.* 2005). Eutrophication pressures are likely to be increased as a result of changes in rainfall patterns and ambient temperatures associated with global warming (Marshall and Randhir 2008). Excess P is the primary cause of increased nutrient inputs, with these inputs being commonly attributed to discharges of municipal and industrial waste (Smith *et al.* 1999; Foy *et al.* 2003) and to agricultural intensification, with diffuse agricultural sources often being the main contributor (Lucey *et al.* 1999; Jennings *et al.* 2003; Smith *et al.* 2005).

The acidification of sensitive surface waters through the deposition of strong acids from industrial and other sources has declined as a result of emission-reduction protocols (Battarbee *et al.* 1990). The recovery of acidified sites may in some cases be delayed by climate change (Aherne *et al.* 2008). In other cases, climate change may enhance the mineralisation of catchment soils, thus contributing to the recovery of acidified lakes through increased supplies of cations (Larsen *et al.* 2006). Acidification effects in Ireland are limited when compared with some neighbouring parts of western Europe, owing to the relatively recent onset of industrialisation and to the prevalence of largely pollution-free, westerly airflows originating over the Atlantic Ocean (Bowman 1991; Flower *et al.* 1994; Bowman and Harlock 1998; Aherne and Farrell 2002). Acid deposition varies spatially, however, with hot spots associated with high rainfall—upland areas in the east, west and south-west of the country (Aherne and Curtis 2003). Superimposed upon an east-west gradient of declining levels of deposition across Ireland, which reflects differential atmospheric fallout from sources located in Britain and continental Europe (Bowman and McGettigan 1994; Bowman and Harlock 1998; Aherne *et al.* 2002; Rippey and Douglas 2004), are inputs from localised sources, generally power stations in and around Dublin in the east and on the Shannon Estuary in the west (Bowman and Harlock 1998; de Kluizenaar *et al.* 2001). For lakes in base-poor,

acid-sensitive catchments, the deposition of material originating as emissions from power stations that burn fossil fuels can be a source of both acidifying ions and increased buffering, while heightened levels of acidity have led to increased mobilisation of heavy metals in soils (Johansson *et al.* 1995) and lake sediments (Borma *et al.* 2003). In addition, lakes that are naturally low in pH show limited recovery (Smol *et al.* 1998). Perhaps most worryingly to policy-makers and managers of waterbodies in acid-sensitive catchments, the recovery of acidified ecosystems does not necessarily immediately follow reduced depositions of atmospheric pollutants (Futter *et al.* 2007).

Palaeolimnological studies of system change have been particularly important in terms of tracking impacts of acidification and eutrophication. Reconstructions of past environments have enabled hindcast tests of the different hypotheses concerning the possible causes of lake water acidification—long-term natural acidification, land-use management and change, and anthropogenically sourced acid deposition (Battarbee *et al.* 1990). Examination of sediment archives has enabled the determination of reference conditions and of the timing and rate of changes in biological communities. Convincing evidence was found linking acid deposition with surface water acidification (e.g. Flower *et al.* 1987; Fritz *et al.* 1990; Cumming *et al.* 1994). Palaeolimnology has similarly provided long-term records that help elucidate past trophic states (e.g. diatom reconstructions are reviewed in Hall and Smol 1999), and thus contribute important information on the response of aquatic ecosystems to variations in nutrient inputs. An example of such an application in the Irish ecoregion is provided below, while an example of the potential effects of interactions between climate and other ecological pressures on waterbodies is described in the section on modelling.

Palaeolimnological techniques have been used to examine system changes in lakes in Ireland that have been disturbed by humans; such lakes are generally moderately to highly alkaline, are situated in intensively farmed catchments and no longer display reference conditions. Research on a selection of impacted lakes in Ireland, as part of the IN-SIGHT project, found the lakes to have been oligomesotrophic or mesotrophic at the onset of the sedimentary records retrieved—sediment core-bottom samples ranged in age from the late eighteenth century to after *c.*1950 (Taylor *et al.* 2006). Basal samples were characterised by a relatively diverse diatom flora, with DI-TP ranging from 12 to 21µg l^{-1}, and

diverse littoral cladoceran assemblages generally indicative of abundant aquatic macrophyte cover. In other words, conditions prior to human impact were very different from those found at the same sites today.

Crans Lough, an 8.5ha lake located in the Oona River catchment in Co. Tyrone, provides an excellent example of a lake in the Irish ecoregion that, on the basis of results from a palaeolimnological study, experienced anthropogenic impacts at an early date, and that in the period since has had a complex history that equates to substantial changes in socio-economic conditions in its small and tightly constrained catchment. The Oona River drains into the River Blackwater and eventually into Lough Neagh. Crans Lough is eutrophic according to published TP data (Gibson 1991). On the basis of analyses of three short cores of sediment (31, 39 and 40cm), Crans Lough has experienced varying human-induced stresses since at least the early nineteenth century (Taylor et al. 2006). The preliminary palaeolimnological reconstructions initially presented in Taylor et al. (2006) were significantly added to by Erdil (2008) and Erdil and Taylor (submitted), who were able to work on a longer core of sediment (57cm), collected in June 2008. Palaeolimnological results from this longer core of sediment from Crans Lough are summarised in Fig. 2; more-detailed figures are available in Erdil (2008) and Erdil and Taylor (submitted). Based on a rate of sediment accumulation of 0.028 ± 0.007g cm^2 yr^{-1}, established through radiometric dating using ^{210}Pb and ^{137}Cs and application of a constant rate of supply of ^{210}Pb model (Appleby 2001), basal sediments in the 57cm-long core were calculated to date to c.1700. DI-TP reconstructions on seventeen samples of sediment from the core show a protracted history of anthropogenic

impact at the site, characterised by eutrophication followed by partial recovery (oligotrophication). Accordingly, the earliest increases in DI-TP concentrations date to the early 1700s (Erdil 2008; Erdil and Taylor submitted), and are concomitant with the arrival of plantation settlers (Battarbee 1986; Crawford 1998). DI-TP concentrations began to rise steadily from the mid eighteenth century, presumably because of reported increases in livestock numbers and an expansion in the area devoted to the production of grass seed (Census Office 1882–1912; Crawford 1998; Campbell and Rice 2000). According to analyses of the sediment-based remains of diatoms, Crans Lough has been eutrophic since the early nineteenth century, with a brief period of recovery from 1820 to 1860, when human population densities were also lower across Co. Tyrone because of the impacts of repeated famines during the mid nineteenth century (Macafee 2000). Productivity of the lake increased rapidly during the late nineteenth century but fell back during the early twentieth century before increasing once more post–1950, reaching a peak at 68µg TP l^{-1} in 1997. Eutrophication appears to have occurred earlier at Crans Lough than at other lakes in Northern Ireland: eutrophication commenced in the late nineteenth century at Heron (Anderson 1997) and Neagh (Battarbee 1978; Foy et al. 2003) and at the beginning of the twentieth century at Upper Lough Erne (Battarbee 1986). The results from a single sub-region illustrate the variations in the onset of anthropogenic impacts and in the timing of ecosystem responses, and therefore the difficulties in extrapolating for lake types and across entire ecoregions.

RESTORATION

Palaeolimnology can provide information on ecological, chemical and hydromorphological targets that can guide restoration efforts. This can be done directly: restoration can be based on knowledge of pre-impact reference conditions established for the same lake using palaeolimnological approaches (Bennion et al. 2004; Leira et al. 2006; Bennion and Simpson in press). Palaeolimnology can also be used in a less direct way through, for example, the critical loads approach (Battarbee et al. 1996) and analogue matching (e.g. Simpson et al. 2005).

Attempts to reverse surface water acidification and its associated ecological effects have been aided by the critical loads approach to the reduction of atmospheric pollutants. The approach requires the establishment of target levels of acid deposition for sites that are regarded as being sensitive to acidification, so that
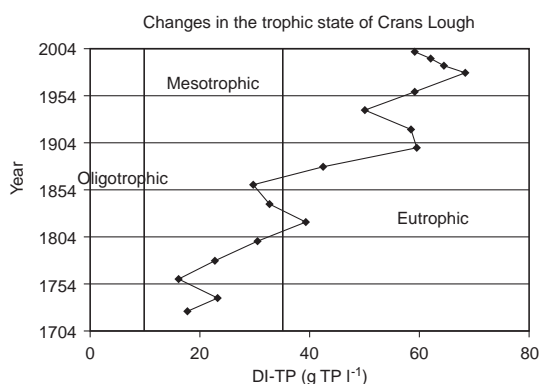
Fig. 2—DI-TP reconstruction for Crans Lough, Co. Tyrone, based on up-core variations in diatom remains and excess ^{210}Pb (figure based on data from Taylor *et al.* (2006) and Erdil (2008)).

ecological impairment does not occur and that sites already impaired can recover (Aherne and Curtis 2003). Diatom-based palaeolimnological analyses enabled calibration of the critical loads model (Battarbee *et al.* 1996). Application of this model is based on the assumption that susceptibility to acidifying ions varies between sites. The measure of susceptibility adopted is the ratio of Ca to S ions, with the former being a proxy of buffering capacity and the latter being a proxy of acidifying pressure. Establishing target levels for deposition has the effect of setting limits on atmospheric emissions of potentially acidifying substances. Palaeolimnology has enabled validation of the critical loads model through the reconstruction of acidification histories (Smol *et al.* 1998). More recently, monitoring records were compared with palaeolimnological reconstructions in limed lakes in Sweden (Norberg *et al.* 2008), and results indicate that some lakes had never acidified in the first place, suggesting the need to set realistic mitigation goals.

Palaeolimnology can also be used via analogue matching, particularly through the Modern Analogue Technique (MAT). MAT compares fossil assemblages in the sediment record with contemporary community compositions in surface sediments from different reference lakes (e.g. Flower *et al.* 1997; Simpson *et al.* 2005). A key assumption is that if close analogues are found to exist between modern and past assemblages, then the similarities should extend to other taxonomically unrelated groups, such as fish and benthic macroinvertebrates. MAT provides a mathematical means of matching fossil assemblages with present-day assemblages, and therefore of identifying extant examples of reference conditions for impacted lakes that have preserved in their sediments a record of pre-impact environments. To date, MAT has been used in the UK to identify restoration targets for lakes based on diatoms and Cladocera (Flower *et al.* 1997; Simpson *et al.* 2005). In order for MAT to work optimally, relatively large data sets—far larger than those currently available to palaeolimnologists working in Ireland—are required; for example, the training data sets used by Flower *et al.* (1997) and Simpson *et al.* (2005) to identify modern analogues for lakes impacted by acidification comprised 194 and 83 lakes, respectively.

FROM THE PAST TO THE FUTURE—MODELLING APPROACHES

Annex II, 1.3, of the WFD states that in addition to hindcast modelling techniques, such as those used in association with palaeolimnology, type-specific reference conditions may also be derived using predictive models, while Annex II, 1.5, states that EU member states may use modelling techniques to assist in the assessment of whether waterbodies will meet environmental quality objectives. Models are simplified representations of reality that describe a complex system in a way that is more manageable and more easily understood. Once calibrated and validated for a system, a model can be used to increase and evaluate understanding of that system and to predict and explore management scenarios. Models include qualitative models, such as spatial models that assign a risk classification to a given field or catchment, and quantitative models, which use mathematical relationships to simulate and quantify the magnitude of ecosystem processes and responses (Fig. 3). Quantitative models range in complexity from simple empirical equations to models that include linked equations for the main processes within a system. Models with no temporal dimension are described as static or steady-state, while dynamic models repeat on a defined time-step. In general, the more complex a model, the higher the requirement for input data, technical support and computer power, with dynamic, process-driven quantitative models having the greatest requirements. Irvine *et al.* (2004) note, however, that the development of simple models tends to evolve towards greater complexity, while that of more-complex, process-driven models evolves towards greater simplicity.

The use of dynamic quantitative models of catchment nutrient export linked to models of in-lake chemical and physical conditions and biological responses (Fig. 3) has the potential to assist implementation of the WFD, provided output from trial runs of the models compares well with existing empirical data in the form of information generated from palaeolimnological and contemporary monitoring studies. 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 (Ewen *et al.* 2000) and SWAT (Arnold *et al.* 1998) models. The simpler regression and export coefficient models simulate on an annual time-step, restricting the use of their outputs to simple regression-based, in-lake models. More complex models of in-lake processes require input data based on a daily time-step. All of these modelling approaches are, however, restricted by the availability of historical input and validation data. Long-term monitoring data for catchment nutrient loading

TIME STEP	CATCHMENT	LAKE	WFD APPLICATION

Static — A

QUALITATIVE/QUANTITATIVE SPATIAL MODEL → SPATIAL RISK

WFD APPLICATION: SPATIAL RISK ASSESSMENT; SCENARIO TESTING

Dynamic (Annual) — B

REGRESSION-BASED MODEL; EXPORT COEFFICIENT MODEL → NUTRIENT LOAD/CONC → LOAD/RESPONSE REGRESSION MODEL → ANNUAL CHL A/BIOMASS; TRANSFER FUNCTION MODEL ← SEDIMENT DIATOM DATA

WFD APPLICATION: TEMPORAL or SPATIAL RISK ASSESSMENT

Dynamic (Daily/Sub-daily) — C

HYDROLOGY MODEL → COEFFICIENT/REGRESSION NUTRIENT LOAD MODEL; PROCESS-DRIVEN NUTRIENT LOAD MODEL → NUTRIENT LOAD/CONC → BIOLOGICAL PROCESS MODEL → DAILY CHL A/BIOMASS; THERMAL PROFILE ← LAKE PHYSICAL MODEL

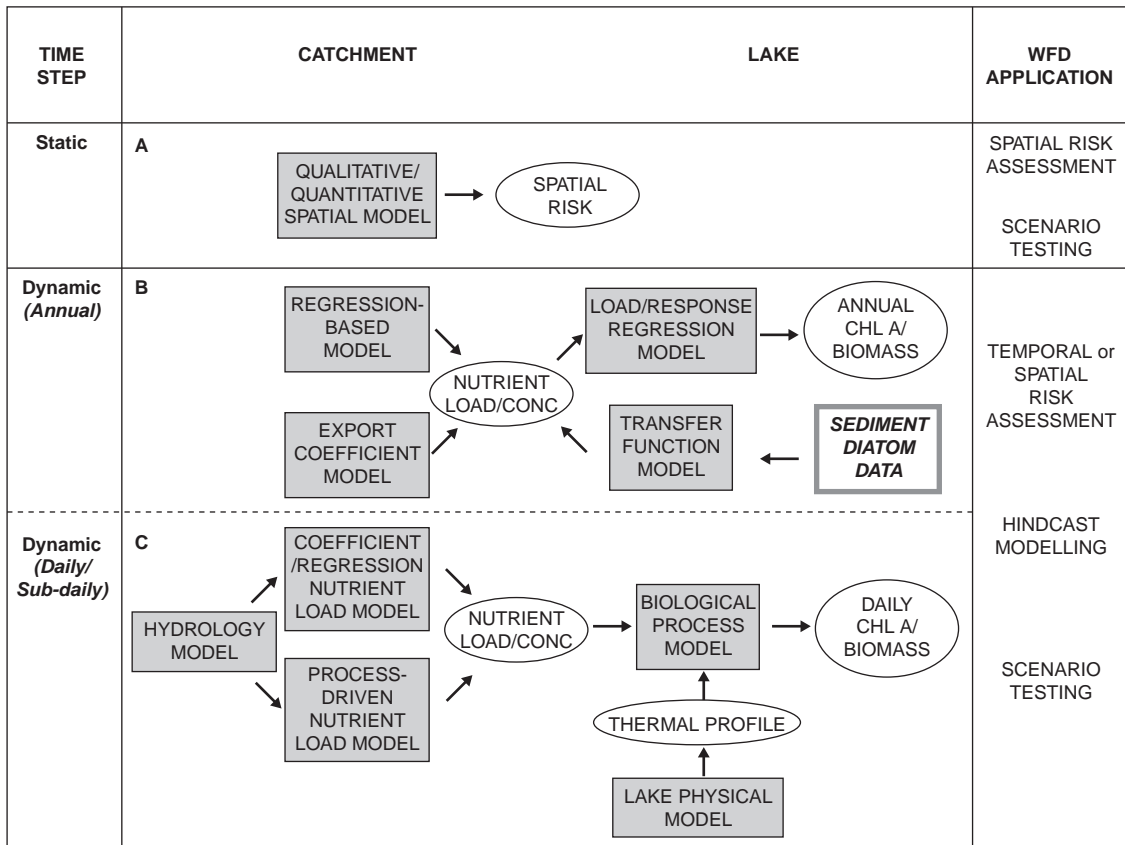WFD APPLICATION: HINDCAST MODELLING; SCENARIO TESTING

Fig. 3—Summary diagram of model types (boxes) and model outputs (ovals), together with potential applications in support of the WFD. Commonly used models of catchment processes include static models (A) and dynamic models at annual (B) and daily or sub–daily (C) time steps. The output from dynamic models can also be used to assess in–lake biological responses.

and in-lake phytoplankton biomass are rare, and at many sites palaeolimnological data may provide the only means for validating long-term model behaviour (Anderson *et al.* 2006). Bennion *et al.* (2005) recommended that diatom models should be employed to reflect the nature and timing of in-lake responses and that a catchment-loading model, such as an export coefficient model, could be used to establish the origins and extent of changes in the external load. Comparisons of palaeoecological data and model outputs can be mutually advantageous and complementary. However, both approaches have limitations, the former in terms of taphonomy and uncertain chronologies, the latter in terms of the quality of input data.

To date, the use of combined dynamic modelling and palaeolimnological approaches to model the trophic status of lakes in Ireland has been limited to work undertaken in the Lough Mask and Carra catchments in Mayo, as part of the EU-funded BUFFER project

(EVK1-1999-00094), and to ongoing work in three catchments in the south–west and west of Ireland (Burrishoole and Mask in Co. Mayo, and Lough Leane in Co. Kerry), as part of the EPA-funded ILLUMINATE (Past, current and future interactions between pressures, chemical status and biological quality elements for lakes in contrasting instrumented catchments in Ireland) project. In the BUFFER project two export coefficient models (Johnes 1996; Jordan *et al.* 2000) were used to estimate a present-day annual TP loading for Lough Carra in Co. Mayo (Irvine *et al.* 2003). Predicted loads were then used to calculate simulated in-lake TP concentrations using a mass-balance, Vollenweider-type empirical model developed by Foy (1992) for lakes in the Irish ecoregion. There were, however, discrepancies between measured loads and those simulated by the export coefficient models, and these were attributed to variation among land-use categories, scaling effects and possibly a multiplication effect of inappropriate

weighting of export coefficients (Irvine *et al.* 2003). No comparison of hindcast model output and sediment data was carried out in the project, although lake-sediment profiles indicated progressive eutrophication, with associated reductions in Fe:P ratios indicative of impact from diffuse P loads.

The use of complex, process-driven models of nutrient exports from catchments to hindcast previous nutrient loading is often restricted by the high data requirements of these models. Semi-empirical models offer a compromise between simple export coefficients and more complex models: semi-empirical models mechanistically describe the hydrologic and sediment components and estimate nutrient loads based on simple relationships between flow and concentration. A version of one such model, the Generalised Watershed Loading Functions (GWLF) model (Schneiderman *et al.* 2002), is being used in the ILLUMINATE project to simulate nutrient loading in three catchments in the west of Ireland. As part of ILLUMINATE, the GWLF model has been adapted to use time series data for population, land use and livestock numbers (Jennings *et al.* 2008) in order to hindcast TP loads for the period 1941–2005 for Lough Leane (Jennings *et al.* 2008). The annual loads from these simulations were then used to estimate in-lake TP concentrations based on the model of Foy (1992). The hindcast TP concentrations suggested that Lough Leane was mesotrophic from 1941 to the early 1970s, a period for which historical water-quality data were absent. A comparison of these data with preliminary estimates of DI-TP indicated reasonable agreement between the two approaches (see Jennings *et al.* 2008). The daily output from GWLF is also being used as input to DYRESM CAEDYM (Trolle *et al.* 2008), a dynamically coupled model of in-lake physical, chemical and biological processes, to hindcast the biological responses of phytoplankton groups to past environmental pressures. A data set spanning 34 years of measurements is available for chlorophyll *a* from Lough Leane, allowing validation of both the palaeolimnological data and the hindcast model output. Historical monitoring data are relatively limited at the other two sites (Burrishoole and Mask), and palaeolimnological data are therefore being used to provide long-term validation data for the model.

Once validated for a system, dynamic models can also be used to inform and direct future management of RBDs by exploring the impacts of potential mitigation measures. Most importantly, models allow managers to assess these impacts in the light of projected changes

in catchment pressures; for example, changes in local population, industrial and agricultural practices, and climate. Model simulations of projected climate-change impacts on nutrient loading in several European catchments have indicated that changes in the seasonal pattern of export, rather than in the magnitude of annual losses, are likely to be the most significant consequence of future climate changes for lakes (Moore *et al.* in press; Pierson *et al.* in press). These catchments included the River Flesk catchment of Lough Leane, where increased nutrient loading was projected for the winter and early spring, raising nutrient availability in the lake just prior to the main algal-growing season. However, the simulations also projected reductions in loading in mid to late summer. A further set of simulations undertaken as part of the ILLUMINATE project has explored the combined impacts of these changes and potential changes in land use and population in the River Flesk catchment (Jennings *et al.* 2009). The simulations highlighted the importance of exploring proposed management initiatives in the light of projected changes in other pressures. They indicated, for example, that a change in the open slurry-spreading season, from that stipulated in present regulations to the period between 1 April and 1 September, could potentially mitigate projected increases in export of P in the early months of the year driven by higher precipitation rates. They also showed, however, that a reduction in export of P in summer could be negated by increases in the population served by septic tanks, and thus support the adaptation of catchment-wide management strategies. Ongoing work in the project includes the use of the daily output from these model simulations to explore potential in-lake responses. Comparisons of palaeoecological data and model outputs to date have provided analogous scenarios. However, further exploration and development of palaeoenvironmental reconstructions and model predictions would benefit greatly from verification using high-quality data from contemporary ecological surveys and environmental monitoring (Battarbee *et al.* 2005).

CONCLUSIONS AND FUTURE DIRECTIONS

Effective palaeolimnological research requires clearly stated research questions or problems, undisturbed sedimentary sequences that accommodate the time period(s) of interest, good chronological control and proxies of variables of

interest to provide the basis for the reconstruction of past environments. Palaeolimnologists now command a vast array of techniques for the acquisition, analysis and interpretation of sediment-based information, and they are increasingly making use of sophisticated statistical and modelling approaches. The range of sediment-based proxies that can potentially be used in palaeolimnological studies has greatly increased over the last two to three decades. Multi-proxy studies, however, can require many specialists, be time-consuming, demand significant resources and generate large amounts of data (Smol 2008).

The WFD has provided great challenges and opportunities for palaeolimnologists, as well as further encouragement for aquatic scientists and environmental policy-makers and regulators to work more closely together (e.g. Bjerring *et al.* 2008). The WFD has also been a source of research questions and problems, and it has contributed to palaeolimnology becoming a much more applied and systematic science than was previously the case. The challenges have been that much greater in Ireland, where fewer systematic palaeolimnological studies were carried out in the decades leading up to the current millennium than in many other parts of Europe. In the Republic of Ireland palaeolimnology is still very much in its infancy, and palaeolimnologists there have found themselves combining very basic research with highly applied research in the same project—not so much running before they can walk, but attempting to walk and run at the same time!

Palaeolimnological investigations have succeeded in elucidating in considerable detail the recent histories of lakes. This has provided invaluable information for catchment and water-quality management and monitoring in parts of Europe (e.g. Ayres *et al.* 2004; Bennion *et al.* 2004), although there are still very few detailed, well-dated histories of changes in aquatic conditions, and of the drivers of these, for lakes in Ireland. Palaeolimnology also potentially offers a relatively inexpensive and effective means of filling in the gaps within, and of extending the period of time covered by, monitoring records. Thus, rotation sampling of surface sediment samples in lakes every four years has been proposed as a substitute for traditional water-sampling approaches for lake monitoring (Smol 2008). Palaeolimnological reconstructions have additionally made an important contribution to setting targets for control of anthropogenic pressures and strategies for lake restoration. Once again, this aspect of palaeolimnology remains underdeveloped in the Irish ecoregion.

The Government of Ireland's response to challenges associated with implementing the WFD, largely expressed through the EPA, has helped to drive an expansion of research capacity in palaeolimnology, to improve taxonomic expertise, to foster an increase in national and international collaboration and to encourage dissemination of findings through diverse forums, including publications in the scientific literature. These developments are especially significant given that current international science strongly favours the development of collaborative and relevant palaeolimnological research, not least because of the importance of this research in relation to climate-change studies; one example is LIMPACS, a PHAROS (Past Human–Climate–Ecosystem Interactions) project of the International Geosphere-Biosphere Programme's PAGES (Past Global Changes) initiative (PAGES 2009), which is concerned with understanding how and why lake ecosystems have changed, are changing and might change in the future, especially on decadal timescales. Climate influences, directly and indirectly, every water-quality issue, impacting both the strengths of other stressors and the ability of aquatic ecosystems to recover. Future concerns centre on whether the combined effects of climate and other stressors of aquatic ecosystems will be cumulative, thus exacerbating environmental impacts and further compromising recovery (e.g. Blenckner *et al.* 2007; George *et al.* 2007; ter Heerdt *et al.* 2007; Moss 2008; Wright and Dillon 2008; Futter *et al.* 2009; Kirilova *et al.* 2009). The challenge in Ireland, as in many parts of the world, is to secure the necessary resources and to optimise collaborative links, thus enabling palaeolimnologists to continue to contribute in a significant way towards addressing these concerns.

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