INTEGRATING OBSERVED, INFERRED AND SIMULATED DATA TO ILLUMINATE ENVIRONMENTAL CHANGE: A LIMNOLOGICAL CASE STUDY

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ABSTRACT

Effective management of aquatic ecosystems requires knowledge of baseline conditions and past variations in stressors and their effects in order to mitigate the impacts of future variability and change. This study utilizes combined monitoring, sedimentary and hindcast computer model data to reconstruct and examine the eutrophication history of a lake in southwest Ireland over a *c.*60-year period and uses computer models to simulate future responses in water quality as a result of projected changes in land use and climate. The study site, Lough Leane, has major national and international importance, but is currently regarded as 'at significant risk' of not meeting the water quality objectives of the EU Water Framework Directive. Palaeolimnological reconstructions and hindcast modelling results confirmed that current eutrophication in the lake dates at least to the 1950s, and particularly from the 1970s. When used to simulate future conditions the same computer models indicated that climate change will likely worsen the current situation. The approach described, synthesising data from a range of sources, can inform future-proofing of lake management plans and objectives by enabling the accommodation of future changes in catchment and climate conditions.

INTRODUCTION

Human-induced (or cultural) eutrophication, generally linked to increased inputs of phosphorus (P) and nitrogen (N) from human sources, remains the principal pressure on lake water quality in many parts of the world (Schindler, 2012; Woodward *et al.*, 2012), including Europe (Lyche-Solheim *et al.*, 2013). As P and N are generally limiting to phytoplankton growth in freshwater, increased availability of these elements may lead to elevated primary productivity (Moss 2012; Azevedo *et al.*, 2013) and related effects, including oxygen depletion (Müller *et al.*, 2012). Climate and weather variations can also influence aquatic conditions substantively, including increasing eutrophication effects (Hering *et al.*, 2013), as can other factors, or stressors, linked to human activity (Vörösmarty *et al.*, 2013; Crockford *et al.*, 2014).

The aquatic impacts of the complex of stressors linked to human activity may now far exceed the amplitude of natural variability (Moss, 2010); their extent and scale have stimulated development and implementation of legislation at national and international levels aimed at mitigating and in some cases reversing anthropogenic effects. The Water Framework Directive (WFD) (European Parliament and Council, 2000) provides an example of a legislative response at international level to persistent water quality problems over a large geographic area (Kaika, 2003). The WFD requires that all freshwater bodies in European Union (EU) member states achieve at least good ecological status, representing little or no human impact, by the end of the first implementation period (2015) (Kirilova *et al.*, 2010) or six-year cycles thereafter.

Establishing the relative contributions of the various stressors affecting water quality, an important early step in the development of plans aimed at effective remediation, can be problematic (Battarbee *et al.*, 2012). For example, some stressors act together to have synergistic effects, while others may have impacts that are cumulative (Palmer and Yan 2013; Mollina-Navarro *et al.*, 2014). Moreover, attempts at separation are often practically impossible due to incomplete or lacking observational records (Jennings *et al.*, 2013) and understanding of the nature of the interactions involved (Palmer and Yan, 2013). Palaeolimnology is the science of using sediment-based proxies to reconstruct past conditions in a lake and its catchment and as a basis for inferring the quality and quantity of influencing factors. Dynamic computational models and sediment-based proxies can be used separately to plug data

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gaps and extend observational records to accommodate the amplitude and frequency of ecological variability (Scheffer and Carpenter, 2003). Their individual application to lake management problems is now relatively well established (e.g. Jennings *et al.*, 2009, 2013; Sayer *et al.*, 2012). However, rarely have the two been used together in a combined approach (Anderson *et al.*, 2006), despite their complementarity. The few exceptions include an acidification model used in conjunction with lake water acidity reconstructions (Battarbee *et al.*, 2005), combinations of sedimentary, instrumental and model output data to inform management decisions (Barr *et al.*, 2013; Murnaghan *et al.*, 2015) and lake core records and limnological models to evaluate lake response to past climate change (Bracht-Flyr and Fritz, 2016).

Effective management of aquatic ecosystems under changing environmental conditions requires data from a variety of sources (Pullin, 2012), ideally over long, ecologically meaningful time periods. The current research integrates a combination of information types including empirical data (monitoring), sedimentary data (inferred) and simulated data (hindcast and forecast) using dynamic modelling, to examine the recent (*c.*60-year) eutrophication history of a lake, i.e. *c.*1945–2007. The same dynamic computer models used in the first part of the research are then run with a selection of scenarios describing different projected climate and catchment land use. Here the focus is on determining the possible trophic effects of future changes, and on disentangling the relative contributions of individual stressors, using a series of models tested against evidence of past conditions. The simulations referred to in this paper, as output from an approach that integrates a range of scales, data and modes of enquiry, are used to illuminate not only the potential effects on water quality of future changes in land use and climate change but also areas deserving of further research.

MATERIALS AND METHODS

STUDY SITE

Lough Leane (Fig. 1) (Irish Grid V 931 891) is a deep (mean 13.4m, maximum 67m), large (1987ha) and moderately alkaline (15–28mg l^{-1} $CaCO_3$) lake, draining a catchment area of 553km^2. The area is subjected to a cool temperate, oceanic climate, and variable weather strongly influenced by conditions in the North Atlantic (Jennings *et al.*, 2000; Jennings and Allott 2006). The hydrological catchment is broadly divided into upland mountain peat and forest over Devonian Old Red Sandstone in the south and west, and pasture, largely for cattle, on lower-lying Lower Carboniferous Limestone in the north and east. Three main rivers drain into Lough Leane (Deenagh, Flesk and Long Range), while the Laune provides the only outflow. The catchment includes the largest extent of semi-natural woodland in Ireland (Mitchell, 1990), with heathland vegetation extensive on base-poor peatland (Quirke, 2001). The town of Killarney lies on the eastern shore of the lake: the population (13,497; Central Statistics Office (CSO), 2012) increases markedly in summer months as a result of an influx of tourists, as is the case in southwest Ireland generally (Fáilte Ireland, 2011). Sewage from Killarney passes through a waste water treatment plant (WWTP) before being discharged into Lough Leane via the Folly stream (Jennings *et al.*, 2013). Rainfall varies considerably across the catchment, from approximately 1000mm yr^{-1} in the northeast to 2700–3200mm yr^{-1} in the southwest (Allott *et al.*, 2008). The Flesk and Deenagh subcatchments account for about 60% of the hydraulic loading to the lake, while the bulk of the remainder is supplied by the Upper subcatchment (Twomey *et al.*, 2000). External loading of total phosphorus (TP) has high inter-annual variability, driven largely by variations in precipitation. More than 60% of TP inputs in 2010 (the year for which the most recent data are available) came from the Flesk subcatchment (Lenihan, 2013).

Little historical limnological information is available for Lough Leane before the 1970s. However, a preliminary sediment study undertaken by Douglas and Murray (1987) suggested that the lake experienced nutrient enrichment from the late 1950s. Measurements of water quality, dating to the early 1970s, revealed temporal variations in trophic status (Twomey *et al.*, 2000; Lenihan, 2013) (Fig. 2). The lake was mesotrophic (WFD Good to Moderate status) for most of the period to the early 1980s and moderately eutrophic in 1983 (marked by an algal bloom) and 1984, while the chemical status of the lake improved following upgrade of the WWTP on the Folly stream in the mid 1980s. Reverting to mesotrophic conditions for most of the 1990s, the lake became hypereutrophic (poor to bad status) in the summer of 1997, when a peak in chlorophyll concentrations was again associated with the occurrence of cyanobacteria bloom, and highly eutrophic in 1998. The lake recovered, and from 1999 TP concentrations were generally in the mesotrophic range, possibly as a result of the implementation in the late 1990s nationally of restrictions on the application of fertilisers (O'Dwyer *et al.*, 2013). Towards the end of 2001 TP concentrations increased again, although trophic conditions overall remained within the mesotrophic range. Since 2006 measured concentrations of TP and chlorophyll a (chl-a) have declined, and transparency has increased. Rising chl-a concentration maxima are evident in measurements from 2010 to 2012

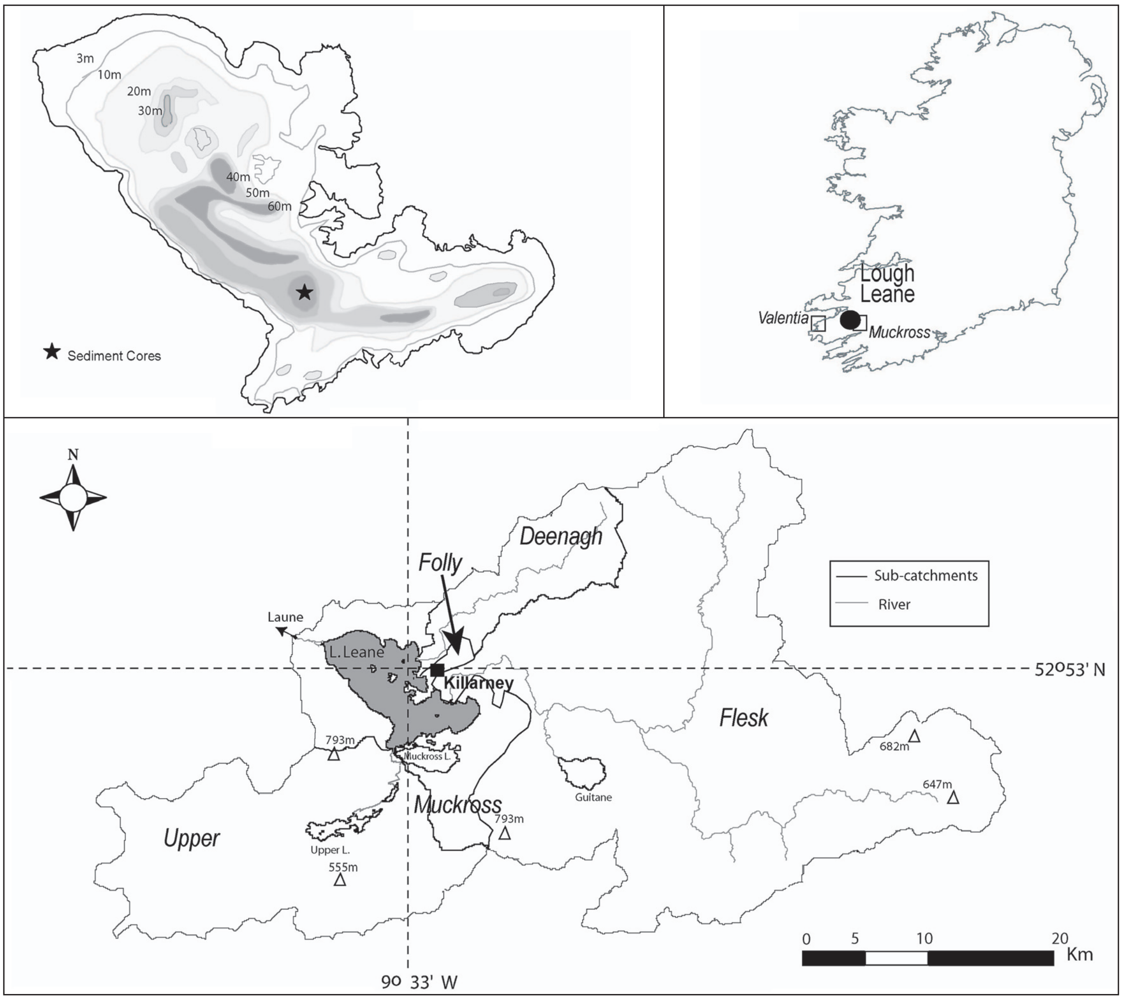

Fig. 1—Location map, showing Lough Leane and its catchment in southwest Ireland. Also shown are the boundaries of the four subcatchments (including that of the Folly stream) and the main rivers draining into and out of the lake, bathymetric variations (including the deepest point coring site), and the location of the meteorological stations at Muckross and Valentia.

(Lenihan, 2013) but have since declined. Persistent cultural eutrophication has meant that Lough Leane continues to be viewed as 'at significant risk' of not meeting the water quality objectives of the WFD (www.wfdireland.ie).

LAKE SEDIMENT-BASED ANALYSES

Four sediment cores (45, 52, 57 and 57cm) were obtained from the deepest point of Lough Leane using a Renberg gravity corer (Renberg and Hansson, 2008). Chronological control was established on a 45cm core based on measured activity levels of the radioactive isotopes ^{210}Pb and ^{137}Cs and estimates of sediment accumulation rate (SAR) (Appleby, 2001). Determination of % organic matter in sediment core samples (Heiri *et al*., 2001) provided a basis for cross-matching the relatively minor differences with the adjacent shorter sediment cores, enabling extension of the chronology. Up-core variations in a range of geochemical elements were determined on the 57cm core using flame atomic absorption spectrometry (Jordan *et al*., 2001). Concentrations of seven plant pigments (chl-a, chlorophyll b, diatoxanthin, fucoxanthin, lutein, phaeophytin a and zeaxanthin) preserved in sediment samples were established on the 52cm core using mass spectrometry high-pressure liquid chromatography (Airs *et al*., 2001) and are assumed to represent productivity of different algal groups (McGowan, 2013). The sedimentary remains of diatoms and Cladocera, an order of zooplankton, were separated from sediment samples (in the 57cm core) in accordance with, respectively, Battarbee *et al*. (2001) and Frey (1986). Multivariate ordination techniques were employed using CANOCO (version 4.5) (ter Braak and Šmilauer 2002) to summarise the main patterns of variation in the diatom data. Estimation of enrichment factors (EFs) provides a basis for distinguishing between natural and

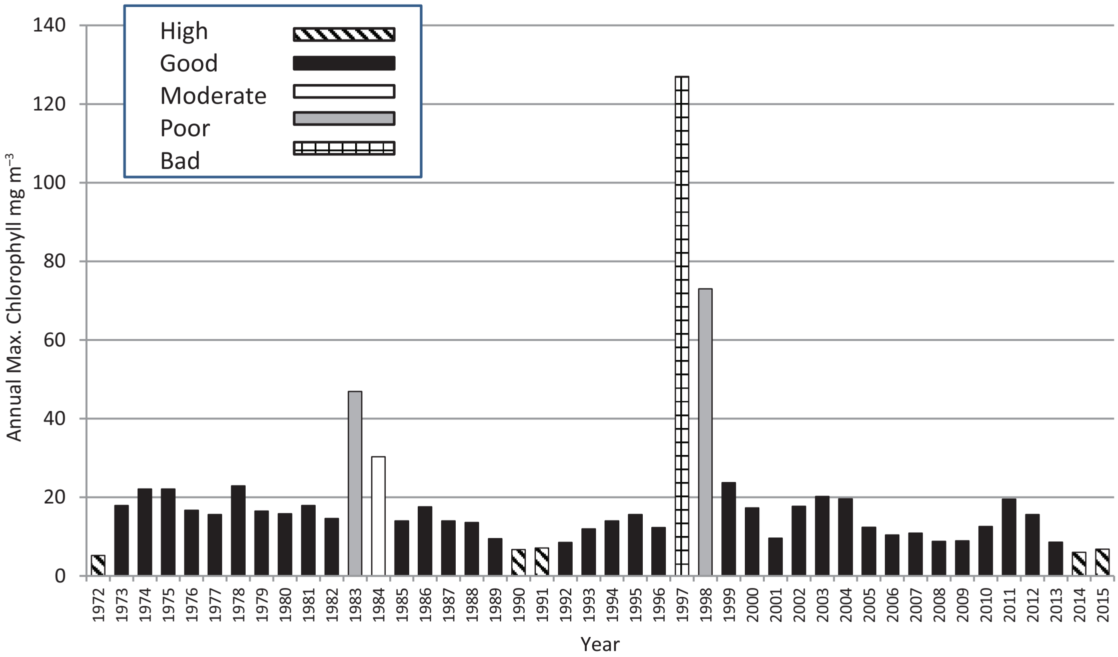

Fig. 2—Annual maximum chl-a (mg m^{-3}) concentrations between 1972 and 2015. Approximate WFD water quality status indicated. Data from Kerry County Council.

anthropogenic sources of geochemical elements: EFs were determined in the current research according to Binford (1990). Stratigraphically constrained, incremental sum of squares cluster analysis (CONISS) (Grimm, 1987) and the broken-stick model (Bennett, 1996) were used to establish the optimum number of groupings (or zones) of sediment core data. Diatom abundance data were converted to diatom-inferred estimates of TP (DI-TP) using the transfer function approach (Dalton *et al.*, 2009), and in particular a 70-lake diatom TP model ($r^2_{jack} = 0.74$; RMSEP = 0.21 ($\log_{10}$ μg l^{-1} TP)) for the Irish Ecoregion (Chen *et al.*, 2008).

COMPUTER-BASED MODEL SIMULATIONS

Modelling was used to simulate variations in lake water quality, in both the past (hindcast) and the future (forecast), driven by changes in climate, catchment land use and population density. Comparisons with empirical and inferred sedimentary data provided a basis for assessing both the potential of model output to complement observational data and the possibility of using the approach to simulate future aquatic conditions under different environmental change scenarios.

The Generalised Watershed Loading Functions (GWLF) model (Haith and Tubbs, 1981) was used to simulate daily values for catchment discharge and sediment and nutrient loading. The version of GWLF used (Schneiderman *et al.*, 2002) was optimised for local hydrological conditions and land cover (Jennings *et al.*, 2009, 2013) and driven by daily precipitation and air temperature data from stations at Muckross (from 1970) and Valentia (from 1941 to 1969). Information on catchment population, livestock and land use was obtained from the CSO. GWLF was calibrated for each of the three subcatchments using observed discharge and water quality data. The average annual precipitation for Valencia for the period 1970 to 2005 was 1512mm yr^{-1}. For comparison, the annual average for the same time period for Muckross was 1691mm yr^{-1}, slightly higher than for Valentia. The hydrology subroutine in GWLF 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. This factor was recalibrated to account for any differences between stations for each time period. Daily water quality monitoring data collected using autosamplers deployed by Kerry County Council at each inflow (daily composite sample based on three eight-hourly samplers per day) from 1 January 2000 to 31 December 2004 were used for model calibration and validation. Nutrient loads from the WWTP were calculated as described in Jennings *et al.* (2013). Temporal trends were assessed using the coefficient of determination (r^2) calculated over time, and residuals were examined for any breaches of assumptions. Change points were statistically assessed using the cumulative deviations test (Buishand, 1982).

Daily output from GWLF for hindcast periods was used as input to DYRESM-CAEDYM, a dynamically coupled model of in-lake physical, chemical and biological processes (Imberger and Patterson, 1981), together with required meteorological data. DYRESM, a one-dimensional hydrodynamics model for predicting the vertical distribution of temperature and density in lakes (Imerito 2007), was driven by local weather data, and measured and simulated inflows. It was validated using spot sample temperature profile data from 1976 to 2005 (weekly to monthly) and some additional high-resolution data (averaged to daily) from a thermistor chain deployed at the deepest point of the lake (May to October 1997, and June to September 2000). Stream flow, sediment concentrations, and nutrient concentrations calculated from GWLF outputs were used as input for CAEDYM, a process-based model of the biological effects of variations in lake water quality (Hipsey *et al.*, 2006). Five phytoplankton groups were simulated, based on available species data for 1996, 1999/2000 and 2007: diatoms, cyanobacteria, chlorophytes, cryptophytes and dinoflagellates. As seasonal variations in phytoplankton could not be replicated without also accommodating grazing effects, two zooplankton groups (cladocerans and copepods) were also included based on available data (Twomey *et al.*, 2000). CAEDYM was validated using measured surface water chl-a data from 1972 to 2005 and dissolved P data from 1984 to 2005.

Possible impacts of future changes in local weather and credible variations in population and land use (Jennings *et al.*, 2009) on both catchment loading and in-lake ecological responses were projected for the period 2071 to 2100. Simulations were based on output from three combinations of a regional climate model (RCM) (either the Rossby Centre RCM (RCAO) or the Hadley Centre RCM (HadRM3p)) run using boundary conditions based on either the HadAM3p general climate model (GCM) (the Hadley Centre, UK) or the ECHAM4/OPYC3 GCM (Max Planck Institute, Germany). The three GCM-RCM combinations therefore were ECHAM4/OPYC3 + RCAO, HadAM3p + RCAO and HadAM3p + HadRM3p. Data were produced for each combination for both the A2 and B2 special reports on emission scenarios (SRESs) (Samuelsson, 2010). It should be noted that the most recent climate projections have been based on more complex models and on representative concentration pathways rather than the SRES scenarios; however, these have been shown to provide projected changes that are similar in magnitude and pattern globally (Knutti and Sedláček, 2013) and for Ireland (Nolan, 2015) to those based on the SRES scenarios. A weather generator (Climate Research Unit, UK) was used to downscale the GCM–RCM output for 2071–2100 to the catchment scale (Kilsby *et al.*, 2007). One hundred 30-year simulations of local weather were output for a reference period (1961–1990) and for each climate model–scenario combination.

GWLF was run for each of the 100 scenarios for the reference period (1961–1990) and future (2071–2100) for (1) current population and land-use levels, and (2) a scenario that assumed changes in population and land use. These changes were population growth in line with estimated projections (CSO, 2008) with an increase from 5582 persons in 2000 to 7497 persons in 2071, an increase in area of forestry to 17% (Department of Agriculture, Food and Forestry (DAFF), 1996) and a 10% increase in cattle numbers, requiring conversion of 1910ha of low-productivity pasture to high-productivity pasture (Sweeney, 2003). For these simulations, the nutrient load from the WWTP was kept at the levels in the observed period from 2000 to 2005 (that is, no change in discharged nutrient loading). The combined DYRESM–CAEDYM model was run for the reference period (1961–1990) and future (20712100) for six randomly selected 30-year future climate simulations for the reference period, and for each of the three GCM–RCM combinations for both the A2 and B2 SRESs and for both population and land-use scenarios. Simulated data from the model runs were output at a daily time step and monthly means were then calculated. The interquartile ranges for these monthly means were calculated for the reference period and for the combined simulations for the A2 and B2 scenarios ($n = 540$).

RESULTS AND ANALYSIS

SEDIMENTARY ANALYSES

Excess ^{210}Pb activity declines with depth to a minimum of 5.37 DPM g^{-1} (DPM = disintegrations per minute), thus background levels were not reached. The estimated SAR, based on the application of the Continuous Rate of Supply model (Appleby, 2001) to ^{210}Pb activity in sediment samples (Fig. 3), indicates that the sedimentary record obtained from Lough Leane covers the period since the mid 1940s with an average sediment accumulation rate of 0.33g cm^2 yr^{-1} or 0.85cm yr^{-1}. Levels of ^{137}Cs activity confirm these estimates, with peaks in activity evident at 32–33cm and 20–21cm. Levels of organic matter content generally fluctuate around 20%.

Up-core variations in levels of chemical elements were grouped into four significant zones: G (Geochemistry)-L (Leane)-1 (pre-*c.*1958), G-L-2 (*c.*1958–*c.*1968), G-L-3 (*c.*1968–*c.*1987) and G-L-4 (post-*c.*1987) (Fig. 4). The lowermost sediments (pre-*c.*1958) were characterised by relatively low levels of all elements. Peaks in levels of trace and nutrient elements were apparent for the 1960s, with

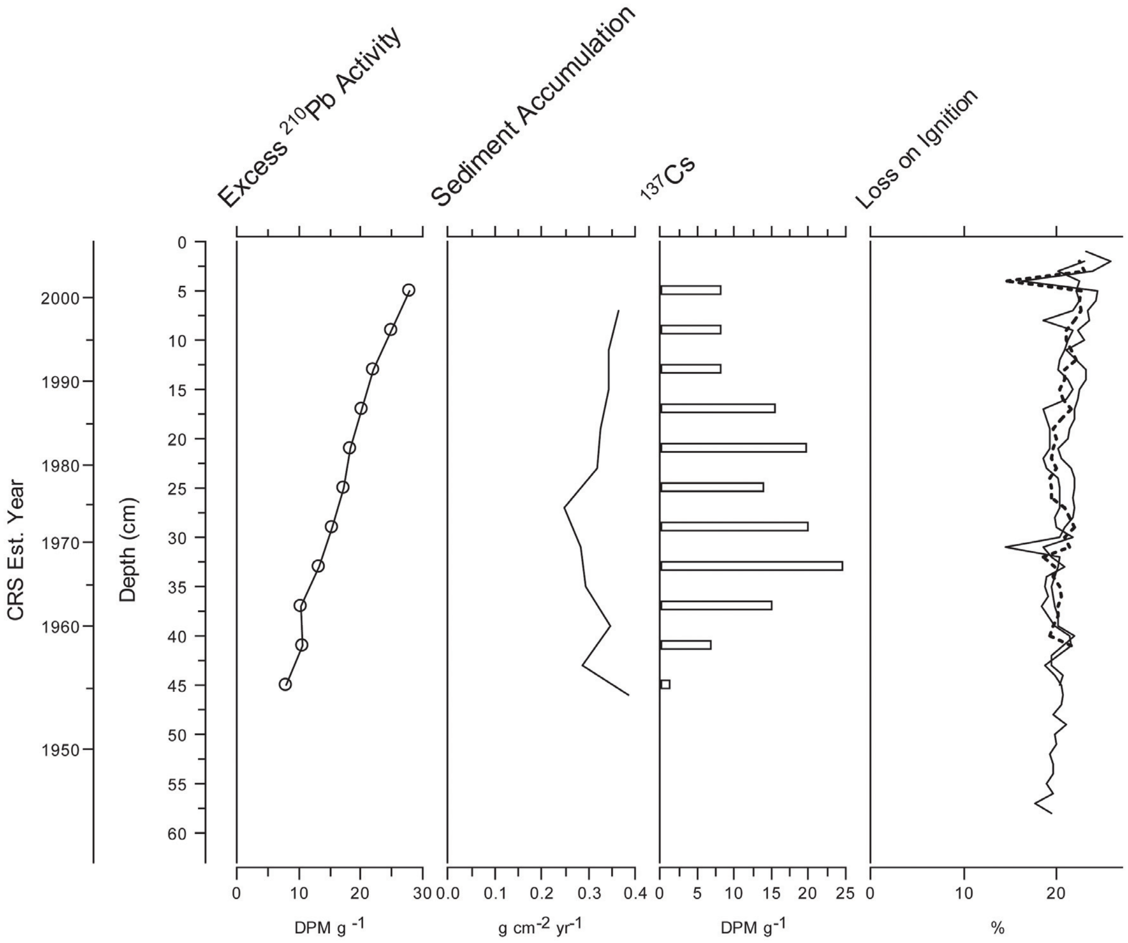

Fig. 3—Age-depth information for sediments collected from Lough Leane, based on ^{210}Pb, ^{137}Cs activity, sediment accumulation (determined using the constant rate of supply model (CRS) in DPM (disintegrations per minute) units) and up-core variations in % loss on ignition.

increased accumulation rates apparent from the mid 1970s. Anthropogenic enrichment by P ($EF > 1$) was evident in the sedimentary record from the early 1950s, and particularly from *c.*1970. Zoning of pigment data produced three significant zones (AP (Algal Pigments)-L-1 (*c.*1950–1955), AP-L-2 (*c.*1955–1995) and AP-L-3 (1995–2007)), while the chl-a–phaeophytin a (phaeo-a) ratio indicates reasonably good preservation throughout the cored sediments, with the exception of the basal samples. Diatom abundance data for a total of 234 diatom taxa from 38 sediment core samples were grouped into three significant zones, although only the earliest of these (D (Diatoms)-L-1 (*c.*1945–1955)) had a similar time range to the equivalent pigment zone, which was characterised by very low concentrations for all pigments analysed. Relatively high abundances of the remains of oligotrophic and mesotrophic species of diatoms (e.g. *Cyclotella comensis* Grunow 1882 and *C. radiosa* Grunow Lemmermann 1900) and benthic/epiphytic diatom species *Achanthidium* minutissium (Kütz.) Czarnecki were conspicuous components of D-L-1 and D-L-2 (respectively, *c.*1945–1955 and *c.*1955–1962). Positive PCA axis 1 loadings are also evident in this period. Pigment concentrations increased from *c.*1955, particularly from the early 1970s and more so from *c.*1995, peaking *c.*2000. Two earlier peaks are also evident, for the early 1970s and mid to late 1980s. The three peaks may relate to algal (cyanobacterial) blooms, given their timing and prominence of the pigment zeaxanthin.

An increasing availability of nutrients in the epilimnion is reflected in rising abundances of planktonic species *Aulacoseira subarctica* (O.Muller) Simonsen and *Stephanodiscus neoastraea* Hakansson et Hickel. Diatom inferred-total phosphorus (DI-TP) values increase from the late 1950s, reaching a sustained high from the early 1970s that lasted to the early 2000s. This trend is also captured in negative PCA axis 1 loadings. This equates to a shift from relatively good WFD status to moderate status. A major DI-TP peak is evident in the mid 1990s, possibly recording the same eutrophication

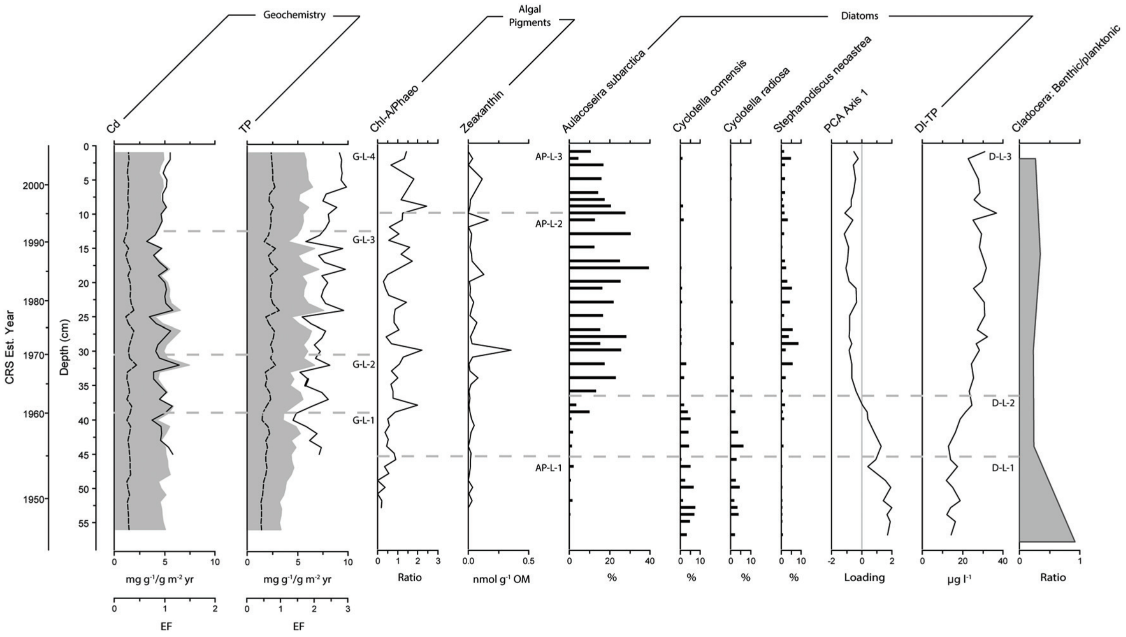

Fig. 4—Summary plot showing the key changes in the multiproxy palaeolimnological (sedimentary) data collected from Lough Leane. Up-core variations in (from left to right): concentrations (dashed line), accumulation rates (solid line) and EFs (grey silhouettes) for geochemical data; algal pigment data (ratio of chl-a to phaeophytin and zeaxanthin); diatom remains expressed as relative abundances (%), ordination (principal components analysis (PCA) axis 1 sample scores and diatom-inferred total phosphorus (DI-TP)); ratio of benthic–planktonic Cladocera.

event as the pigment concentration maxima (and Poor to Bad status), with both products of the algal bloom observed in 1997. The differences in dating are likely due to minor differences in SAR between sediment cores. Minor peaks in DI-TP are also evident for the early to mid 1970s and in the surface sample (*c.*2006). Absolute values of DI-TP should be treated with some caution, owing to the influence of differential preservation (Ryves *et al.*, 2013) and predictive ability (Juggins *et al.*, 2013; 2015; Murnaghan *et al.*, 2015), especially in the current research as the transfer function used appears to overestimate in-lake levels of TP. Thus, for example, the surface sediment sample had a DI-TP estimate of 30µg l^{-1} TP compared with measured mean TP for the year when the sediment core was collected of 22µg l^{-1} TP (Lenihan, 2013). Analyses of cladocera remains also indicate increasing productivity over the period represented by the sedimentary record: an impoverished benthic fauna characterises basal sediments, with planktonic taxa becoming more prominent from the early 1960s.

PAST TRENDS AND HINDCAST MODEL SIMULATIONS

Although there was no overall trend in measured annual precipitation, there was a low but significant increase in annual totals in the more recent period from 1970 to 2005 ($r^2 = 0.15$, $p < 0.005$) (Fig. 5a). There was also a significant increase in precipitation for the Muckross station for this time period ($r^2 = 0.20$, $p < 0.01$). Similarly, a highly significant increase in air temperature occurred during the period 1970 to 2005 ($r^2 = 0.31$, $p < 0.0005$) (not shown). Cattle numbers, which reflect agricultural activity in the catchment, were relatively stable from the 1940s to the late 1960s, but increased between the 1960 and 2000 censuses (from 33 to 48 head km^{-2}), after which numbers declined slightly (Fig. 5b). The human population declined from the 1940s and was followed by an increase from the 1960s (not illustrated). The increase in measured air temperature since the 1970s referred to above was reflected in simulated mean summer surface water temperature (SWT) in Lough Leane. This trend was not apparent in simulated mean summer deep water temperature below the thermocline (DWT) (Fig. 5c).

Simulated TP loading from the subcatchments fluctuated from the 1940s to the 1960s, prior to the commencement in the early 1970s of an upward trend from the Flesk and Deenagh subcatchments in particular (Fig. 5d). The overall rate of simulated TP export levelled off in the 2000s and declined in the later years of the run. The estimated load from the WWTP increased from the 1940s until the facility was upgraded in the mid-1980s (Jennings *et al.*, 2013). The hindcast TP loading data from all sources exhibited a similar profile to the measured sedimentary P concentrations (Fig. 6). Exports from the catchment have dominated loadings in the more recent past, reflecting diffuse losses from land use

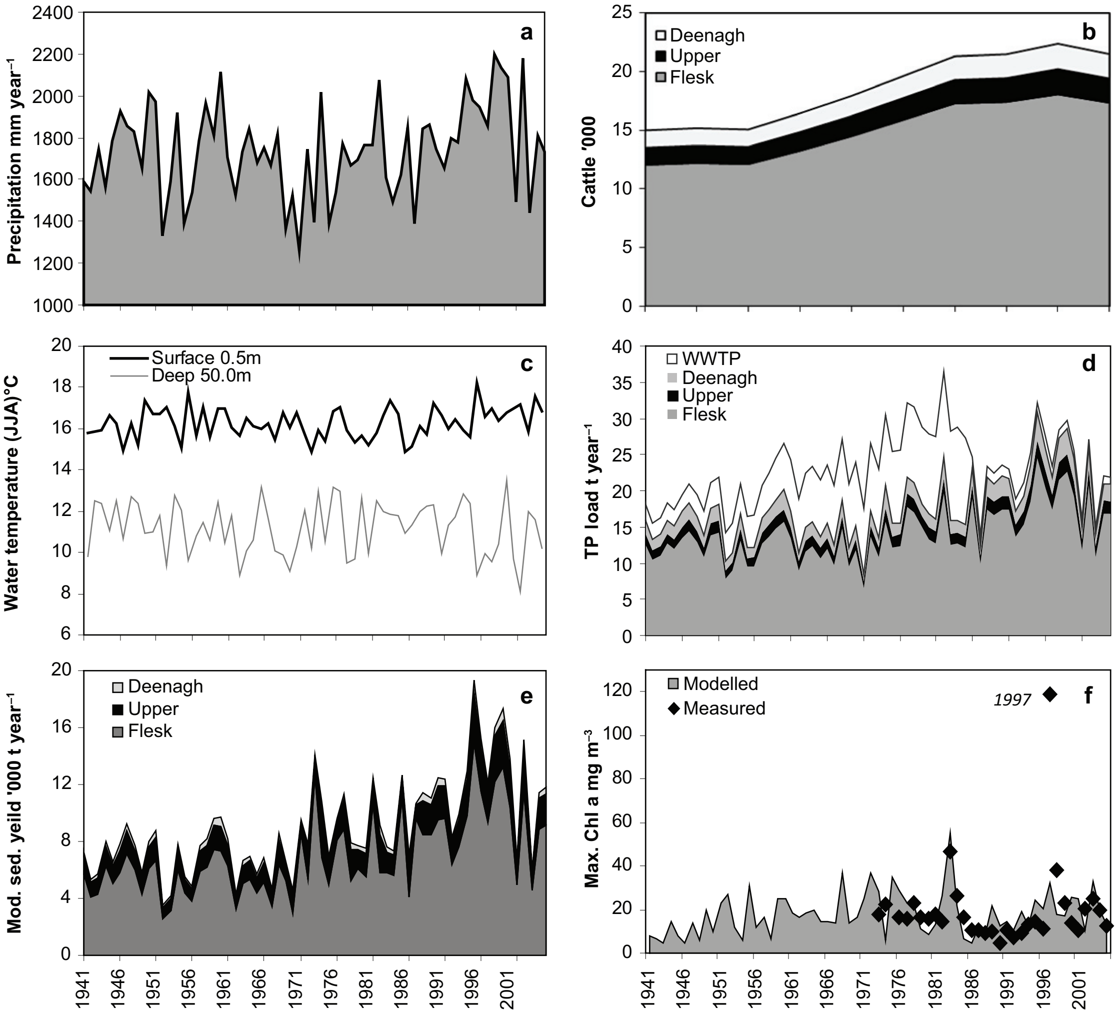

Fig. 5—(a) Annual precipitation from Valencia (mm yr^{-1}); (b) cattle numbers in the three subcatchments (1000s yr^{-1}); (c) modelled surface water (0.5m) and deep water (50m) temperature (°C), (d) modelled catchment TP load for the subcatchments and the WWTP (t yr^{-1}); (e) modelled catchment sediment load (tonnes yr^{-1}); (f) modelled and measured maximum annual chl-a in Lough Leane (mg m^{-3}), 1941–2005.

and livestock, especially cattle, as has been reported elsewhere in Ireland and Europe (May *et al.*, 2012; Carson *et al.*, 2015). The simulated TP loads from the catchment (excluding the WWTP loads) had a significant change point for 1973 ($Q = 2.6$; $p \leq 0.01$), roughly coinciding with increases in cattle numbers, evident in the 1971 agricultural census, and the increase in annual precipitation. Several measured sediment proxies (e.g. geochemistry, diatoms and pigments) also indicated the early to mid 1970s as a period of substantial change.

Hindcast model runs for Lough Leane showed increasing maximum chl-a levels from 1941 to the early 1970s (Fig. 5f), the period prior to available observations but paralleling the lower part of the sedimentary record obtained. For most of this period, simulated maximum chl-a concentrations remained more or less within the mesotrophic range for the modified OECD scheme used by the Environmental Protection Agency (maximum chl-a of 8–25μg L^{-1}; McGarrigle *et al.*, 2010). Cyanobacterial chl-a was the main contributor to the maximum values for simulated in-lake chl-a. Hindcast model runs replicated an algal bloom in the early to mid 1980s, and an increase in chl-a overall to the late 1990s, but not the hypertrophic and highly eutrophic conditions observed in, respectively, 1997 and 1998 (Jennings *et al.*, 2013; Lenihan 2013).

FUTURE SIMULATIONS

Air temperature was projected to increase for the period 2071 to 2100 in all months relative to the reference period (1961–1990) for both the A2 and B2 emissions scenarios (Fig. 7a and 7b). This increase was greater for A2, reflecting higher CO_2 emissions. Increases in projected air temperature

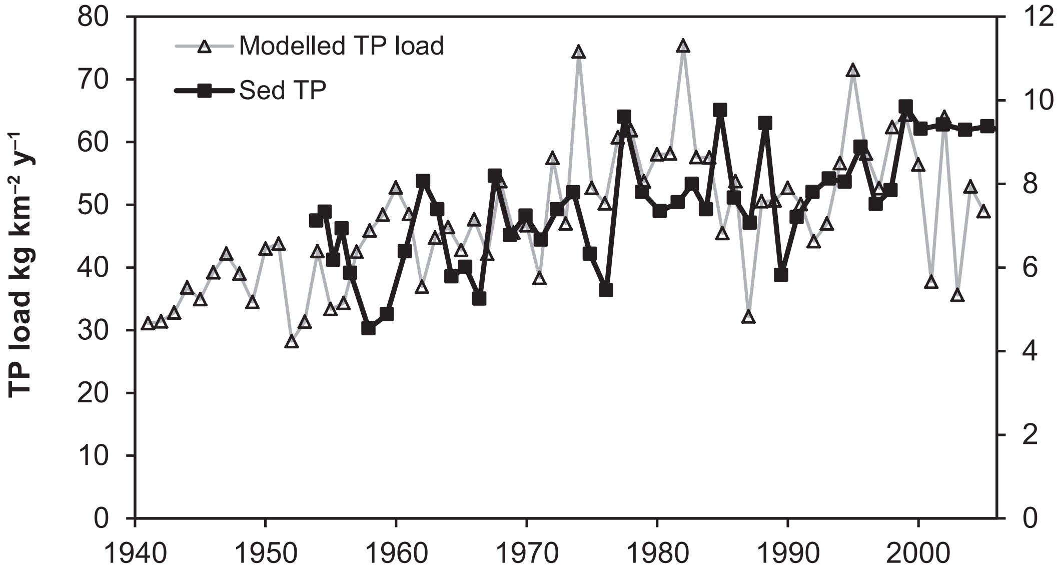

Fig. 6—Modelled TP loads and sediment P accumulation for Lough Leane 1941–2005.

were also higher in summer and autumn than in winter for both scenarios. The overall changes in projected stream flow reflected a change in the seasonal pattern in precipitation: higher discharge rates in the months between October and April, with more pronounced increases for the B2 scenario in the early months of the year. Streamflow was then lower between April and September for both scenarios (Fig. 7c and 7d). There was no overall change in mean daily wind speeds for most months, with the exception of a decrease during summer for the A2 scenario (Fig. 7e and 7f). The projected changes in the seasonal SWT in the lake (Fig. 7g and 7h) mirrored those for air temperature and were again higher for the A2 scenario than for the B2 scenario.

Projected changes in the seasonal pattern of dissolved P export from the catchment based on future climate alone reflected changes for stream flow, with lower loading in the late summer and autumn for both the A2 and B2 scenarios with population and land use set to levels in the 2000–2005 period (Fig. 8a and 8b). The overall change in the annual loading for the B2 scenario represented a 9% increase from the reference period; however, there was no projected change in annual dissolved P load for the combined A2 scenario. The inclusion of future land use and population change into the scenario resulted in further increases in the annual dissolved P load that were most pronounced for the B2 scenario. The seasonal pattern for this scenario had higher median mean monthly values for all months from January to June, while the median annual load for all runs ($n = 9000$) was 31% above the reference period. Of this increase in the annual load 1.1kg P km^{-2} yr^{-1} (equivalent to 7% of the reference period load) was attributable to the change in human population, with the remaining change attributable to the land use change in the scenario (Jennings *et al.*, 2013).

Simulated dissolved P concentrations in Lough Leane varied seasonally, with highest concentrations in the winter and spring and lowest values in the summer, for both the future climate period of 2071 to 2100 and reference period simulations (Fig. 7d and 7e). The projected concentrations for both future climate scenarios exceeded those for the reference period in most months (with the exception of June and July for the A2 scenario), and months between June and September for the B2 scenario. However, for the B2 scenario, with the changes in land use and human populations included, concentrations were higher than the reference period in all months (Fig. 8f). There was little difference in simulated phytoplankton biomass, as measured by mean monthly chl-a, between the reference period and 2071 to 2100 for the B2 scenario; however, a temporal shift in peak chl-a from July to June was indicated for the A2 scenario, together with a longer time period (from June to September) with high mean values, and greater variability between years (Fig. 8g and 8h). Although there was some indication of projected increases in mean monthly chl-a levels in the spring for the B2 scenario with land use and population change, and the overall variability in chl-a was higher, the midsummer peak in chl-a concentration did not show any seasonal shift (Fig. 8i) as was projected for the A2 scenario (Fig. 8a).

DISCUSSION

Good agreement in general exists between reconstructions of past changes in the trophic status of

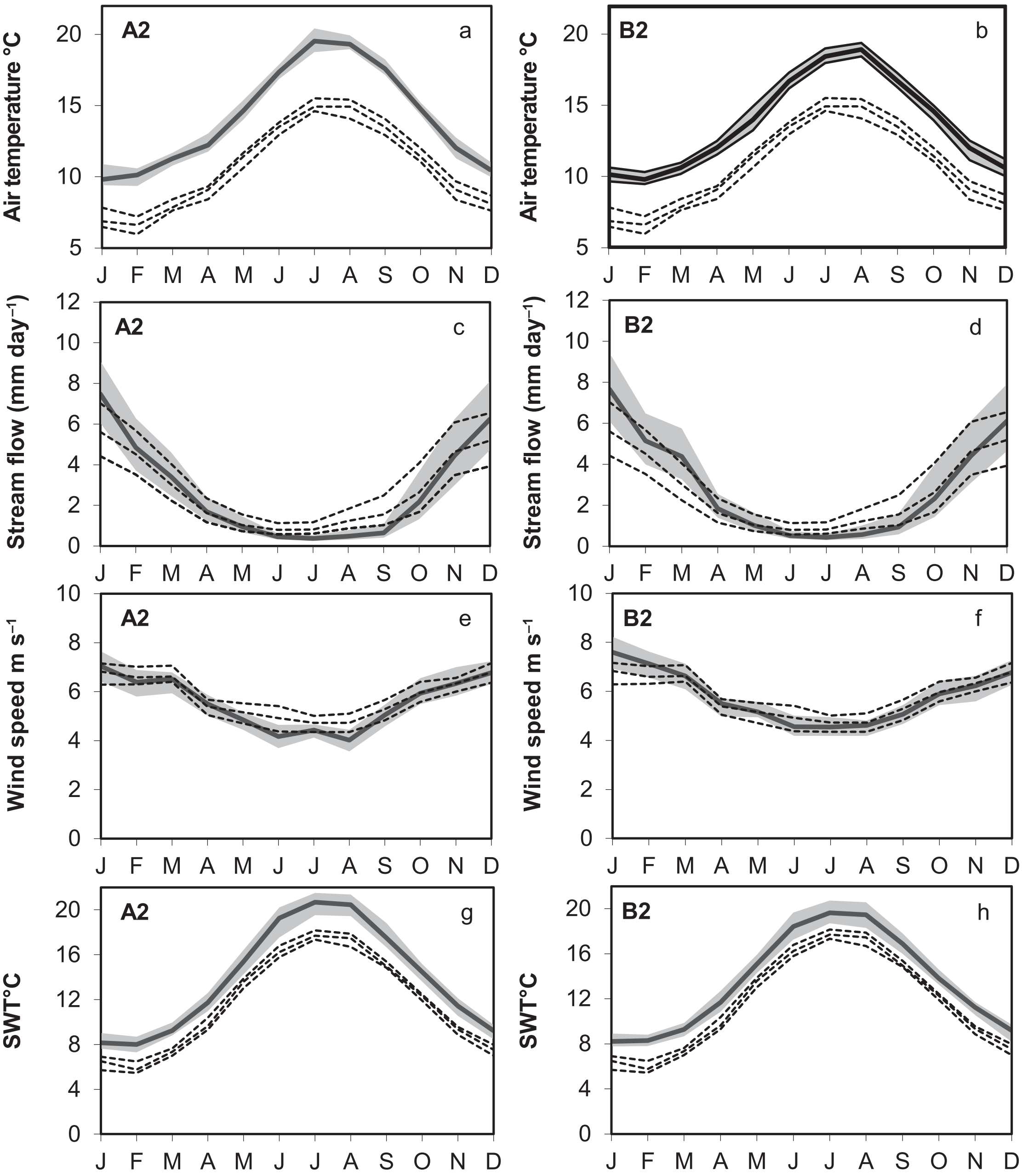

Fig. 7—Median and interquartile range for each month for the reference period 1961–1990 (dashed lines) and for the A2 and B2 scenarios, 2071–2100 (black line and grey area) for (a, b) air temperature, (c, d) stream flow, (e, f) wind speed and (g, h) surface water temperature (SWT) (a–f—reference: $n = 3000$; A2, B2: $n = 9000$; g, h—reference: $n = 180$; A2, B2: $n = 540$).

Lough Leane based on empirical and hindcast modelling and inferences from the sedimentary record: minor inconsistencies in the timing and magnitude most likely reflect differences in chronological control and weaknesses in some of the statistical relationships used, notably the diatom transfer function. This divergence between reconstructions using dynamic modelling and palaeolimnological approaches based on Irish transfer functions has also been noted by Murnaghan *et al.* (2015). Overall, however, results support the use of both palaeolimnology and hindcast modelling in supplementing missing or impoverished records of lake water quality to infer past nutrient loading and lake trophic status. They also provide a basis for improved confidence in the use of computer models to simulate water quality variations for different climate and catchment scenarios.

Relatively rapid mean SAR at Lough Leane likely reflects high levels of both in-lake productivity and catchment in-wash. While the core encapsulates only sediment from *c.*1945 onwards,

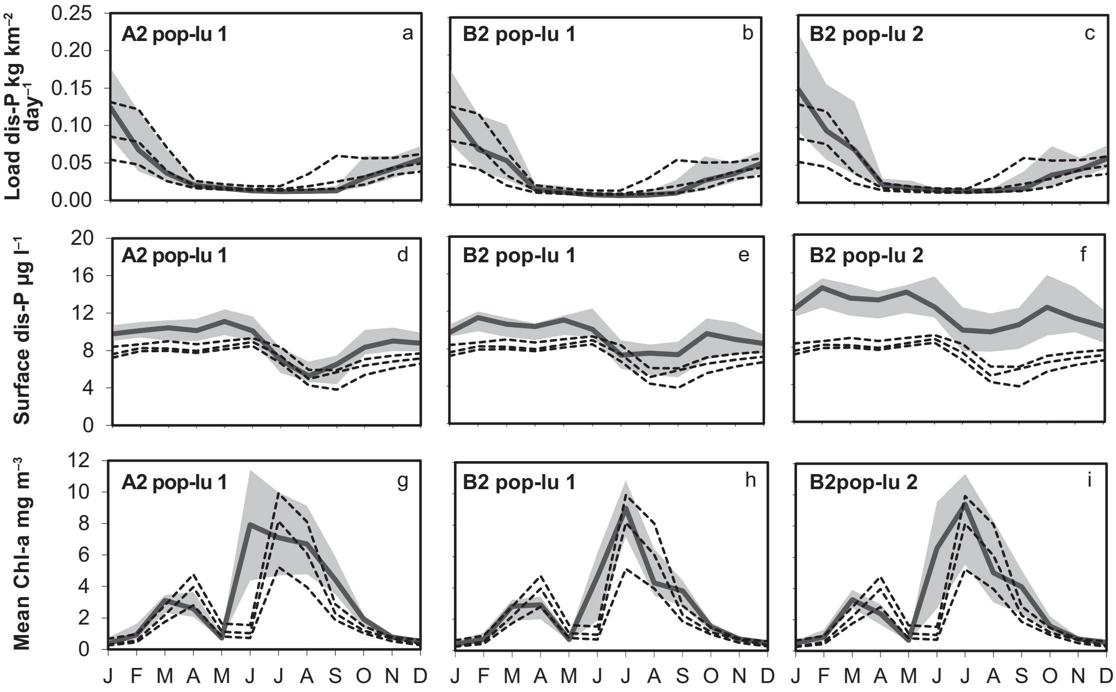

Fig. 8—Median and interquartile range for each month for the reference period 1961–1990 (dashed lines) and for the A2 and B2 scenarios, 2071–2100, (black line and grey area) with population and land-use at current levels (pop-lu 1) and with projected land use and population change (pop-lu 2): (a, b, c) dissolved P export from the catchment (reference: *n* = 3000; A2, B2: *n* = 9000); (d, e, f) in-lake dissolved P concentration; (g, h, i) mean chl-a at 0.5m (reference: *n* = 180; A2, B2: *n* = 540).

the lowermost samples suggest that the lake may have had good quality in this period. The lake may have been in a reasonable state relative to the preceding period: rural population levels in the catchment had declined by the 1940s relative to the nineteenth century (CSO, 2005), while cattle and sheep numbers remained largely unchanged. Results may therefore be in keeping with those from lakes in other parts of Ireland, indicating relatively complex eutrophication histories over the past *c.*200 years characterised by cycles of nutrient enrichment and subsequent recovery (Taylor *et al.*, 2006; Dalton *et al.*, 2009; Donohue *et al.*, 2010; O'Dwyer *et al.*, 2013; Carson *et al.*, 2015; Murnaghan *et al.*, 2015), and in other parts of the world, for example northwest Europe (Bennion *et al.*, 2012) and North America (Estepp and Reavie, 2015).

According to the sedimentary and hindcast model data, enrichment of Lough Leane (with periods of moderate status) had commenced by the mid 1950s, a finding comparable with evidence presented in Douglas and Murray (1987). High levels of P in the lake were sustained from the early 1970s, leading to increased algal productivity and a series of blooms: peak levels of DI-TP were attained 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 1970s and shifts in WFD class status. Changes in phytoplankton remains (*Aulacoseira* and *Stephanodiscus* spp.) indicated increased productivity, while the replacement of benthic chydorids by planktonic Daphniidae and Bosminidae suggested reduced water transparency and availability of littoral macrophyte habitat (Jeppesen *et al.*, 2001). Levels of sediment P are also indicative of increasing nutrient enrichment from anthropogenic sources from the mid 1950s, and particularly from the 1990s. Human population levels generally increased from the 1960s, as did numbers of tourist visitors, with the number staying in urban areas showing the greatest rise (CSO, 2005). A change in the rate of increasing pressures on water quality, evident in results of change point analysis, would appear to reflect changes in catchment conditions. Thus large increases in stocking densities of cattle and sheep occurred, respectively, from the 1970s and in the 1980s and 1990s (CSO, 1997); afforestation commenced in the early 1970s (Quirke, 2001); and fertiliser use increased nationally from the mid 1950s, with the aim of increasing productivity of pastureland, peaking in the early 1970s and remaining high until restrictions were introduced in the late 1990s (Humphreys, 2008). Furthermore, eutrophication stresses on Lough Leane from the 1970s as a result of changes in population and farming are likely to have been amplified by warmer and wetter climate conditions. Similar studies combining palaeolimnological and archival study (McGowan *et al.*, 2012; Moorhouse *et al.*, 2014) demonstrated regional agricultural intensification in the mid-nineteenth century, with lake nutrient enrichment enhanced in response to meteorological change.

Exports of P from the WWTP made an important contribution to nutrient enrichment of the lake until the mid 1980s. Improvements to the WWTP completed in the mid 1980s mean that high nutrient loadings to the lake from the late 1980s are almost certainly from diffuse agricultural sources (Jennings *et al.*, 2008, 2013), and are therefore likely to vary with changes in precipitation, land use and stocking densities (Greene *et al.*, 2013), with loading from the WWTP relatively important during the summer months (Jennings *et al.*, 2013). A catchment monitoring and management programme, implemented in the late 1990s with the aim of reducing loadings from diffuse sources, may have had some success, as the lake has been classified as mesotrophic in all years since 1998. However, recent evidence of a decline in water quality, in the form of a shift in the trophic status of the lake towards the mesotrophic–eutrophic boundary (Lenihan, 2013), highlights the difficulties in controlling inputs from diffuse sources and adds support to the current 'at significant risk' designation for the lake.

Global mean surface temperature looks set to rise by 1.5°C by the end of this century, when compared with the average for the period 1850–1900, and to be more than 4°C warmer without effective mitigation (IPCC, 2013). In contrast with predicted temperature changes, which are generally positive, the situation regarding future precipitation levels is variable (IPCC, 2013). Moreover, the WFD does not explicitly mention risks posed by climate change to the achievement of its environmental objectives despite the implementation period overlapping climate model projected changes (Wilby *et al.*, 2006). For Ireland in coming years, output from ten RCMs used in the ENSEMBLES project indicated drier summers overall, with a rising risk of more frequent extreme precipitation events throughout the rest of the year (Rajczak *et al.*, 2013). Climate change thus has obvious implications for the long-term success of the WFD (Hering *et al.*, 2010; Henriques *et al.*, 2015), for the formulation and review of related management plans (Ulén and Weyhenmeyer, 2007) and for the definition of reference conditions (Logez and Pont 2013) for Ireland as in other EU member states, and for water quality more generally (Batterbee *et al.*, 2012). The increase in annual TP loads attributable to climate change in the future has been shown to be greater than that arising from population increase or an intensification of agriculture for the Leane catchment (Jennings *et al.*, 2009). The future simulations adopted in this study thus not only provide additional insight into past eutrophication events, but also have potentially serious implications for implementation of the WFD. Similar innovative climate modelling and ecological state predictions have been conducted by Nielsen *et al.* (2014) and Trolle et al (2015), who suggest that reduced loadings are necessary to maintain present ecology status given future warming scenarios.

The results also suggest that changes in practice at farm, local authority and national levels could be used to mitigate these increases. Further research would indicate the extent to which the findings are catchment-specific or more widely representative. Not only are the stressors leading to eutrophication expected to increase as a result of climate change; the nature of enrichment effects is also likely to alter. Thus, significant increases in loadings of dissolved P to Lough Leane indicated for the period January–April, especially when climate change was combined with land-use and population change and due mainly to cattle slurry spreading, represent substantially enhanced supplies of labile P during an ecologically critical part of the seasonal cycle. Modelling the impact of these changes showed an increase in algal biomass, and a shift to an earlier peak biomass for the warmer A2 scenario. Monomictic lakes, such as Lough Leane, tend to stratify in summer because generally stable meteorological conditions preclude deep mixing. These peaks in simulated biomass were dominated by cyanobacteria, which thrive under calm, warm, nutrient-enriched conditions (Posch *et al.*, 2012). Projected increases in cyanobacteria as a result of climate change have also been indicated for other lakes, particularly in temperate latitudes (e.g. Elliot *et al.*, 2010; Taranu *et al.*, 2012; Persaud *et al.*, 2014; Thomas and Litchman, 2016). Simulations for Lough Leane described and discussed here highlight the important role potentially played by variations to the onset and duration of stratification as a result of future changes in climate.

In conclusion, this combination of data from a range of sources relating to past, present and future aquatic conditions reveals the complexity of aquatic effects of climate both in the past and for projected changes when operating in conjunction with other lake water pressures. Moreover, the synthesising approach adopted here can ensure that lake management plans and objectives are future-proofed by providing a means of accounting for future changes in climate and catchment conditions.

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