THE PALAEOLIMNOLOGY OF LOUGH MURREE, A BRACKISH LAKE IN THE BURREN, IRELAND

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ABSTRACT

Lough Murree, a rock/karst barrier lagoon, is superficially isolated from the sea and seasonal variations in lake water level reflect precipitation and groundwater variation. Lake salinity is influenced by subsurface saline intrusions, occasional barrier overwash together with precipitation and groundwater inflow, leading to poikilohaline conditions. Palaeolimnological reconstructions in Murree support the supposition that the lagoon was once superficially connected to the sea around the mid-nineteenth century. Physical, chemical and biological proxies suggest an evolution to more freshwater conditions. Uncertainties about the timing of the transition persist because of an unresolved sediment chronology. The isolation of Murree from the Atlantic Ocean has promoted the formation of dense charophyte beds composed of lagoonal specialist species, which are able to tolerate large variations in salinity.

INTRODUCTION

Coastal lagoons are typically shallow coastal water bodies located at the transition between terrestrial and marine ecosystems (Viaroli et al. 2004). In particular, lagoons are unstable and dynamic environments in the ecotone between inland freshwater and marine systems. Lagoon hydrology depends on climate variability, which exerts control on both freshwater (e.g. precipitation) and seawater (e.g. tides and sea level). Variations in water volume, salinity, temperature and water chemistry characterise lagoons, and such changes are greater than in most other aquatic environments (Healy 2003; Kennish and Paerl 2010).

Lagoons are considered to be among the most productive natural ecosystems in the world (Levin et al. 2001). However, few species are generally permanent inhabitants of such systems, and low biodiversity is generally evident in coastal lagoons (Healy 2003). This is explained by the environmental stress that is principally represented by salinity fluctuations (Bamber et al. 1992), and only euryhaline species are able to withstand such harsh conditions. In particular, some opportunistic species, largely restricted to coastal saline lakes and absent in estuaries or salt marshes, are defined lagoonal specialists (e.g. Chara canescens, Lamprothamnium papulosum) (Bamber et al. 2001) and are generally rare and legally protected (Oliver 2005).

Lagoons play an important ecological role. As many lagoons are shallow, the photic zone can sometimes extend to most of the lagoonal floor and benthic primary producers represent a large fraction of the total primary production (McGlathery et al. 2007). Shallow lagoons tend to be dominated by seagrasses, benthic algae and macrophytes, and as a result, benthic primary production often exceeds phytoplankton production (Kennish and Paerl 2010). The formation of dense benthic macroalgae and macrophyte beds leads to considerable nutrient uptake with a consequent reduction in water column nutrients (Tyler et al. 2003; Lloret et al. 2008).

Coastal lagoon ecosystems are sensitive to natural pressures (e.g. progressive sea level rise, floods and storms) as well as anthropogenic influences (e.g. land reclamation, aquaculture and eutrophication) (Airoldi and Beck 2007). Thus, these systems represent unique habitats of high conservation value, which have been included in both the EU Habitats Directive (92/43/EC) and the EU Water Framework Directive (WFD; 2000/60/EC). The WFD aims to prevent further deterioration of inland and coastal water bodies and achieve a good ecological status by 2015. Additionally, the directive requires a baseline of reference conditions prior to anthropogenic impact to be identified.

Aquatic sediments represent excellent archives of past environmental conditions as they record both autochthonous (in lake) and allochthonous (terrestrial) inputs. Palaeolimnological multidisciplinary studies have been successfully applied to coastal environments by using a wide range of
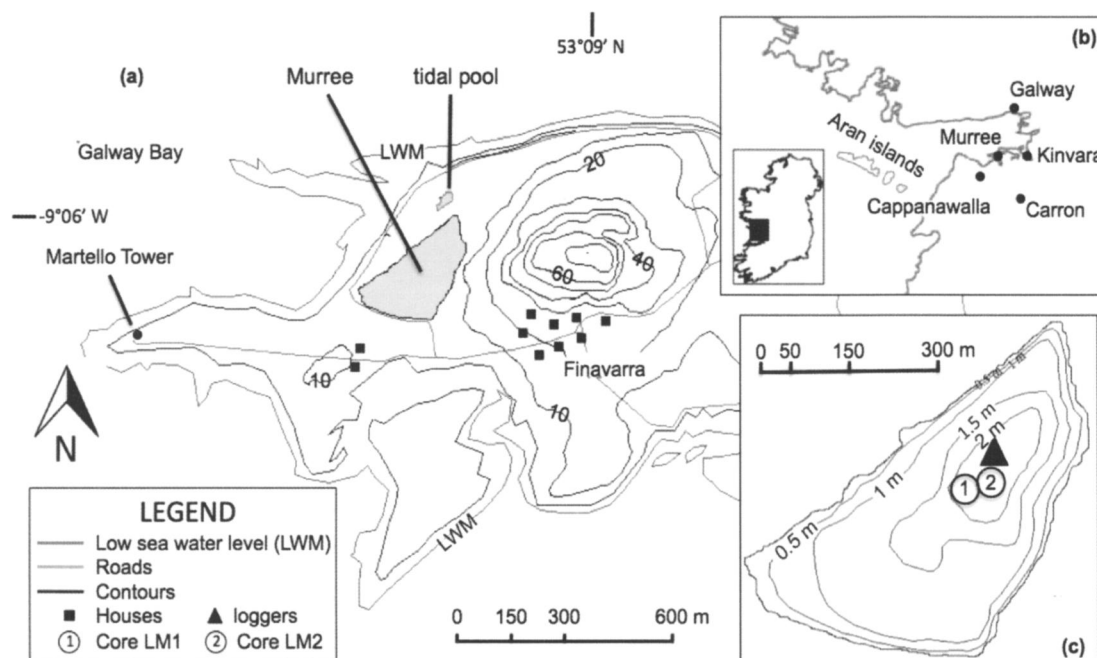
Fig. 1—(a) Map of Murree showing its location, contour lines (m) and low sea water level (LWM); (b) location of Murree, Galway, Carron, Kinvara, Cappanawalla and Aran Islands and (c) Murree bathymetry, (1) long and (2) superficial sediment cores and monitoring station position (triangle).

sediment proxies (e.g. Müller and Voß 1999; Lloyd and Evans 2002; Cearreta et al. 2003; Holmes et al. 2007; Dolukhanov et al. 2010; Savage et al. 2010), permitting inference of development and change of these coastal water systems over time. Only a few sediment studies have been conducted on coastal lagoons in Ireland (Buzer 1981; Holmes et al. 2007; Cassina et al. 2013).

The purpose of this study is to provide a detailed understanding of Lough Murree (Co. Clare), a karst lagoon on the western coast of Ireland, from a palaeolimnological perspective. Lithology, stable isotopes and a number of biological fossils (e.g. diatoms, foraminifera and ostracoda) have been analysed to track the ecological history of the lagoon in response to coastal influence. Reconstructing the past requires a detailed understanding of the current hydrological regime (e.g. salinity) in order to understand system evolution through time. Thus, palaeolimnological reconstruction was augmented by monitoring modern hydrology (i.e. salinity and temperature) through the water column over a two-year period in order to accurately delineate the hydrological changes of these coastal ecosystems and support inferences of lagoon ontogeny.

STUDY SITE

Lough Murree is a shallow coastal lake situated on the south shoreline of Galway Bay (N53°09′13″,

W09°06′46″) on Finavarra Peninsula and the northern edge of the Burren, a karst-landscape region in northwest County Clare (Fig. 1b). The lake is included in the Galway Bay complex Special Area of Conservation (SAC; site code 268) under the EU Habitats Directive (92/43/EEC). The Burren, together with the Aran Islands, constitutes an exceptional karstic limestone region in Atlantic Europe with glacial deposits, high flora diversity and archaeological evidence of human occupation from the Neolithic (4000 year BC) onwards (Molloy and O'Connell 2004). The area is characterised by Carboniferous limestone that fringes the southern sides of Galway Bay and extends into the sublittoral zone. Kinvara (c. 12km from Murree) represents the focal point for a large part of the underground drainage from the north Burren lowlands (Cave and Henry 2011). Submarine and intertidal karst springs can be observed along the coastline and groundwater resurgences have been identified (Mullan 2003; Cave and Henry 2011).

The lagoon catchment is small (c. 4.3km^2), with a maximum altitude of 67m to the north-east. Most of the surrounding region is classified as improved pasture and rough grazing (cattle) predominates (CORINE 1990). Surface drainage is limited due to the karstic nature of the bedrock. Murree is isolated from the sea, and its morphology resembles isolation basins present along the rocky shores of Scotland and Norway (e.g. Lloyd and Evans 2002; Balascio et al. 2011). Lough Murree is

312

formed in limestone bedrock on which a cobble barrier has been deposited along the coastal boundary (Healy et al. 1997). The stretch of land separating the lake from the sea is generally above the highest tidal level with the exception of the south-western edge, which dips below the level of the coastal road. To the north, karst landforms prevail with a fissured limestone pavement and a small tidal pool, which fills and empties at each tidal cycle illustrating underground connections with the sea (Pybus and Pybus 1980). Pybus and Pybus (1980) suggested that Murree had a surface communication with the adjacent ocean at its south-western shore in the past.

Murree is classified as a karst lagoon (Oliver 2007), and it lies on a north-east–south-west transect. It is approximately 600m long and 300m wide with a total area of c. 13.6ha. The bathymetry, determined in 2009 as part of this study, shows a shallow basin with a mean depth of 1.3m. The deepest area is located to the north-east with a maximum depth of 2.2m. The lake water level is below the high spring tide level, thus enabling seawater intrusion into the lake at high tide (Geoff Oliver, pers. comm.) Therefore, it can be assumed that the lake water level approximates the height of mean low tide (i.e. 0m OD).

The lake was described in 1965 as a naturally eutrophic lake with dense algal mats and algal blooms (Lansbury 1965). However, low annual average phosphorus ($10\mu g\ P\ l^{-1}$) and nitrogen concentrations ($0.1 mg\ N\ l^{-1}$) were reported in 1980 (Pybus and Pybus 1980) and recently confirmed by Roden and Oliver (2010). During spring, summer and autumn, the water column is highly transparent with an abundance of macrophytes and macroalgae. Murree has a high conservation rating because it is an unusual lagoon morphological type with a rich aquatic flora (20 floral taxa) (Healy et al. 1997; NPWS 2001). Typical brackish water plants characterise the lake including tasselweeds (Ruppia cirrhosa and Ruppia maritima) and Potamogeton pectinatus, which cover large areas of the lake surface (Healy et al. 1997). Additionally, two rare charophytes, Lamprothamnion papulosum and Chara canescens, form dense beds in the shallower areas (Oliver 2005). Poor faunal diversity is evident in Murree despite the presence of diverse habitats and substrates (Healy et al. 1997; Oliver 2007). In total 25 taxa (mainly hydrobidae and isopoda) were recorded, and most of them were classified as poly-mesohaline and euryhaline species. Some species were listed as lagoonal specialists such as the Sigara stagnalis and the beetle Enchorus halophilus (Healy et al. 1997). Empty shells of barnacles on rocks indicate that a more saline environment existed in the past.

MATERIALS AND METHODS

MODERN HYDROLOGY

A monitoring station composed of three DST CT Star-Oddi Data Storage sensors was installed to monitor temperature and salinity in the water column of Murree (Fig. 1c). Recorders were positioned at 0.5m, 1m and 1.5m depths, and hourly measurement intervals were set for both parameters. Data retrieval was carried out by means of Sea Star 4.3.8 (Star-Oddi 2001) software. Data were collected between February–October 2009 and February–July 2010. Rainfall and air temperature data are from Carron (Co. Clare; N53°02′19″, W09°03′18″; c. 13km from Murree; Met Éireann, unpublished data), while tidal data are from the Galway Port (N53°16′08″, W09°02′53″; c. 12km from Murree; Met Éireann, unpublished data) (Fig. 1b).

PALAEOLIMNOLOGY

Two sediment cores were collected from the deepest part of the lake in 2009 (Fig. 1c). A surface sediment core (35cm; LM1) was collected using a gravity corer (Renberg and Hansson 2008), and a 116cm long core (LM2) was collected using a Livingstone corer (1955) from the same area. Sediment cores were extruded and subsampled at 1cm resolution.

Sediment chronology

LM1 core was dated using radiometric technique (^{210}Pb, ^{137}Cs and ^{241}Am) at the Bloomsbury environmental isotope facility (BEIF), University College London. Samples were analysed using an ORTEC HPGe GWL detector. Dates were determined using the constant rate supply (CRS) model (Krishnaswami et al. 1971; Appleby and Oldfield 1978), while sediment accumulation rates (SARs) were calculated using unsupported ^{210}Pb and expressed both as $g\ cm^{-2}\ year^{-1}$ and $cm\ year^{-1}$.

Accelerated mass spectrometry (AMS) radiocarbon analysis was performed at the CHRONO Centre, Queen's University Belfast. A range of macrofossils from the core LM2 were analysed (wood, charcoal and carbonate fossils such as foraminifera tests and Cerastoderma glaucum shells) with appropriate pre-treatments as no single fossil occurred repeatedly over the core sequence. Calibration of radiocarbon dates was conducted using Calib 6.0 software (Stuiver et al. 2005). Radiocarbon results are expressed as radiocarbon age BP and calibrated results as calibrated years BP (cal. year BP). Radiocarbon ages from terrestrial fossils (i.e. wood and charcoal) were calibrated using IntCal09 calibration curve, while Marine09 was adopted to calibrate carbonate samples (Reimer

313

et al. 2009). The marine reservoir effect ($\Delta R = -111 \pm 18$) from the site DL3 (Connemara Coasts) proposed by Ascough *et al.* (2009) was assumed. A mixed calibration curve (Reimer *et al.* 2009) was additionally run for carbonate samples. Two sigma (2σ) age ranges were utilised as recommended by Björck and Wolhlfarth (2001).

Lithostratigraphy and stable isotopes

Variations in lithological composition were initially identified through sediment cores by visual inspection. Loss on ignition was measured shortly after collection to estimate organic matter and carbonate content (LOI_{550} and LOI_{950}) (Heiri *et al.* 2001).

Carbon and nitrogen stable isotopes sample preparation was based on the combination of methods proposed by Talbot (2001) and Wolfe (2001). The analysis was carried out at the Geochemistry Laboratory, Trinity College, Dublin, using a thermo delta continuous flow isotope ratio mass spectrometer (CF-IRMS) and International Atomic Energy Authority reference standards. Elemental weight percentage composition of organic carbon (C_{org}) and total nitrogen (N_{tot}) was used to calculate the C/N ratio. Stable isotope results are reported as organic carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$). Correlations between $\delta^{15}N$, C/N ratio and nitrogen (%) were calculated to test for the presence of sediment diagenetic processes (Thornton and Mc Manus 1994) using SigmaPlot 11.0. Salinity reconstruction was derived from $\delta^{13}C$ measurements according to the equation: salinity ‰ $= (\delta^{13}C + 30.5)/0.54$ (Emeis *et al.* 2003).

Fossil diatoms

Fossil diatoms were prepared according to Battarbee *et al.* (2001). Identification and enumeration were achieved using a Leica DME microscope with oil immersion objective at $1000 \times$ magnification. Fossil records were biased by preservation and dissolution issues, with a minimum count of just 200 valves achieved for each sample. Taxonomic identification was derived using the Snoejis series (Snoeijs 1993; Snoeijs and Vilbaste 1994; Snoeijs and Potapova 1995; Snoeijs and Kasperovièienë 1996; Snoeijs and Balashova 1998) and Krammer and Lange-Bertalot (Krammer and Lange-Bertalot 1986; 1988; 1991a; 1991b; 2000) floras. A total of 11 and 30 taxa had abundances $>1\%$ and occurred in more than two samples in LM1 and LM2 cores, respectively. Problems were experienced in classifying many genera to species level. The diatom morphological dissolution index (F index) (Flower and Lokhoshway 1993; Ryves *et al.* 2006) was calculated to quantify frustule dissolution. Diatom taxa were divided into groups according to their salinity tolerance and life forms. Zonation of diatoms was performed with constrained cluster analysis (CONISS) by means of Psimpoll 4.27 software (Bennett 2008), and the number of significant zones was identified by applying the broken-stick model (Bennett 1996).

Foraminifera and ostracoda analysis

Foraminifera and ostracoda sample preparation followed the methods in De Deckker (1982) and Holmes (2001). Specimens were picked and transferred to Chapman slides under a Meiji optical stereoscope at $45 \times$ magnification. Concentrations were calculated for foraminifera (tests g^{-1} WW) and ostracoda (shells g^{-1} WW). Foraminifera were classified to species level following Murray (1979), Horton and Edwards (2006) and Scott *et al.* (2007). The percentage of noded valves of *Cyprideis torosa* was calculated (Keatings *et al.* 2007); however, due to very low concentrations in the deeper sediments only samples above *c.* 40cm were examined. Population structure was also investigated by measuring biometric dimensions (i.e. length and height) of the dorsal view of at least 120 shells at three example core intervals. Subdivisions between adults and juvenile instars were derived according to Heip (1976) and Meisch (2000). Charcoal particles and Characeae oospores were encountered during the work and were also enumerated with concentrations expressed as number per g^{-1} WW.

RESULTS

MODERN HYDROLOGY

Salinity ranged from 0‰ to 30‰ over the study period, and its stratification to the lake bottom was evident despite the shallow nature of the Murree Basin (Fig. 2c). Salinity stratification, however, was interrupted by a number of temporary isohaline events. In particular, salinity close to freshwater conditions (0.5‰) is evident in March and April 2009. Salinity stratification reached values of 16‰–18‰ in April 2009, and a further reduction (salinity $< 10‰$) was apparent in May 2009. Permanent stratification is then evident from approximately mid-June to the end of October with salinities up to 25‰ at the base of the water column and *c.* 10‰ in the mixolimnion. A similar trend occurred in 2010 with the lowest salinity ($< 1‰$) recorded from February to the beginning of April. Rapid salinity shifts were also recorded with changes from 15‰ to almost freshwater conditions ($< 1‰$) in only six days.

Rainfall was undoubtedly a key influencing factor on water column salinity levels; however, a comparison between salinity and rainfall (Fig. 2a) suggested an indirect relationship. This could indicate that salinity shifts are principally driven by underground freshwater flows in Lough Murree. Tidal influence was additionally explored for the

314
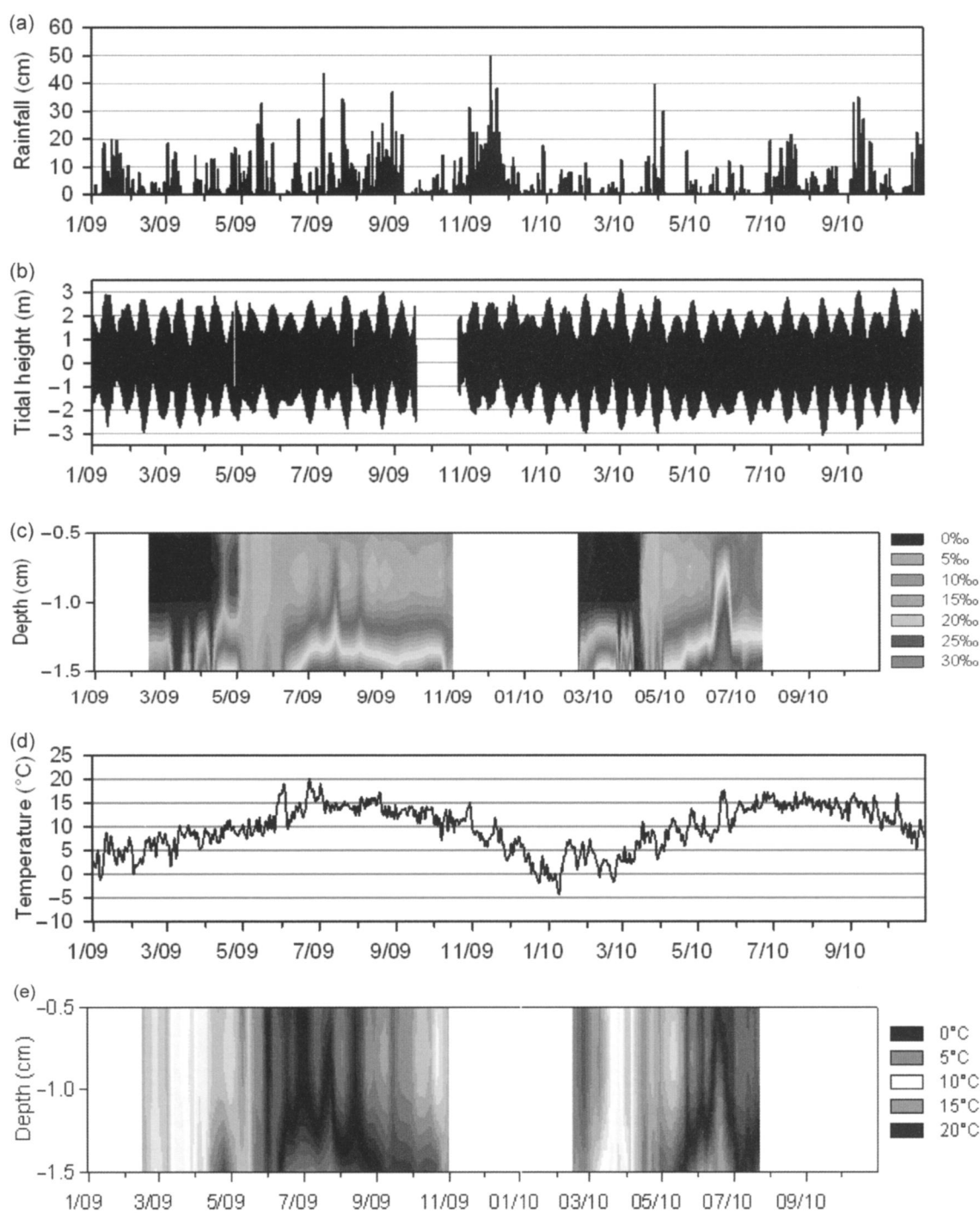
Fig. 2—(a) Rainfall from Carron (cm), (b) tidal range from Galway Port (m), (c) Murree water salinity (‰), (d) air temperature from Carron (°C) and (e) Murree water temperature (°C) in 2009 and 2010.

whole recording period, and no direct association with water column salinity was found even during spring tides. A complex hydrology due to the karst bedrock and the presence of underground communication with the tidal pool might buffer the tidal effect on the water column.

Lake water temperature ranged between 0°C and 21°C and appeared to be closely related to air temperature (Fig. 2d and e). Water temperatures were higher than air temperature with differences up to 7°C. Water temperature is related to salinity stratification. Isothermal conditions from February to June 2009 are interrupted by a temporary increase in temperatures to 14°C at the lake bottom at the end of April, which corresponds to a temporary salinity peak. Warming of the basal

315

Fig. 3—^{210}Pb age-depth model and sediment accumulation rates (SARs) (g cm^{-2} year^{-1}) from LM1 core.

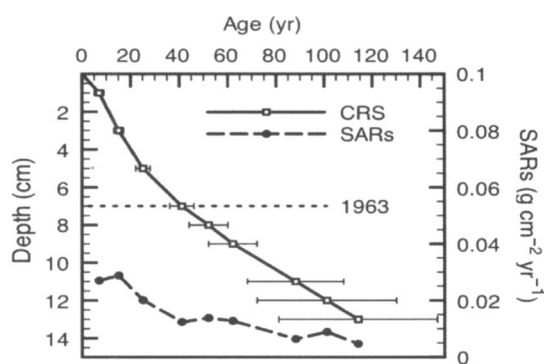water column is evident from May to October coincident with salinity stratification and maximum air temperatures (Met Éireann, unpublished data). Similar trends are evident in 2010.

PALAEOLIMNOLOGY

Chronology and SARs

Establishing a chronology for Murree proved complex as two dating methods were applied to two adjacent but separate sediment cores and additional problems arose during sample selection for ^{14}C analysis.

^{210}Pb radiometric analysis was carried out on LM1 core as it retained an intact sediment water interface. The equilibrium between the total and supported ^{210}Pb activity is evident at approximately 15cm depth, while the CRS model suggested that the top 13cm represents the past 115years (Fig. 3). Artificial radionuclides were used as independent tracers and are in good agreement with ^{210}Pb. Both ^{137}Cs and ^{241}Am place the 1963 layer at 7cm, while the CRS model places it at 8cm. SARs are low, and a progressive increase is evident from 0.057cm year^{-1} (0.0047g cm^{-2} year^{-1}) at 13cm to 0.095cm year^{-1} (0.012gcm^{-2} year^{-1}) at 7cm. A further rise is present from 5cm up to the core top with the highest rates reached at 3cm depth (0.245cm year^{-1}; 0.0028g cm^2 year^{-1}) (Fig. 3).

Radiocarbon dating was carried out on four macrofossil samples through LM2 core to reconstruct older time periods. The core top was disturbed during coring, therefore, a surface sediment date could not be inferred. Radiocarbon dates for Murree are listed in Table 1, and unusually all samples date to c. 4100–4600 year BP.

No coherent sediment chronology was established due to age similarities of the radiocarbon samples. Extrapolation of the ^{210}Pb-derived accumulation rates to 111cm sediment depth suggests an age of c. 1380 cal. year BP and is thus well below the dates derived using radiocarbon methods.

Many attempts were conducted to establish a temporal overlap between LM1 and LM2 using proxies, but finding an unequivocal match proved impossible.

A possible temporal overlap between LM1 and LM2 is evident in lithology and stable isotopes suggesting that c. 17 cm of the top of LM2 might have been lost. A comparison of diatoms in the sediment cores illustrated many differences while no foraminifera were common to both cores. Only *Cyprideis torosa* and charcoal concentrations appeared similar in both cores. Thus, while the sediment cores were collected from adjacent areas (< 2m^2), and it was estimated that a relatively small amount of sediment (c. 15–20cm) was disturbed or lost in LM2 the results suggest complex sediment responses or patchiness in a relatively small geographical area. Sediment data are presented stratigraphically on a depth scale for both cores, while ^{210}Pb chronology is also shown for LM1.

Lithology and stable isotopes

The lagoon sediments were mainly organic mud with brownish black colour (Hue 10YR 3/2; Oyama and Takehar 1967), while the surface core had a mixture of mud and sand at the top. Abundant *Hydrobia* cf. *ventrosa* shells characterised LM1 sediments.

Marked variations in LOI$_{550}$ are shown in core LM1 (Fig. 4a). A sharp decrease in the organic content to c. 5% is evident mid-core. An abrupt peak follows at c. 15cm depth with values up to c. 50%, while the core top averages 27%. A similar

Table 1—δ ^{13}C, ^{14}C dates and calibrated 2σ ranges in LM2.

Depth (cm)	Sample	δ^{13}C (‰)	^{14}C age (year BP)	Calibration curve	2σ range (cal. year BP)
39	Charcoal	−24.9	4163 ± 22	IntCal09	4589–4827
43	Foraminifera	−0.5	4550 ± 31	Marine09	4502–4776
				Mixed	4880–5236
86	C. glaucum	−0.4	4527 ± 33	Marine09	4435–4767
				Mixed	4861–5213
111	Wood	−27.9	4475 ± 21	IntCal09	4980–5284

316
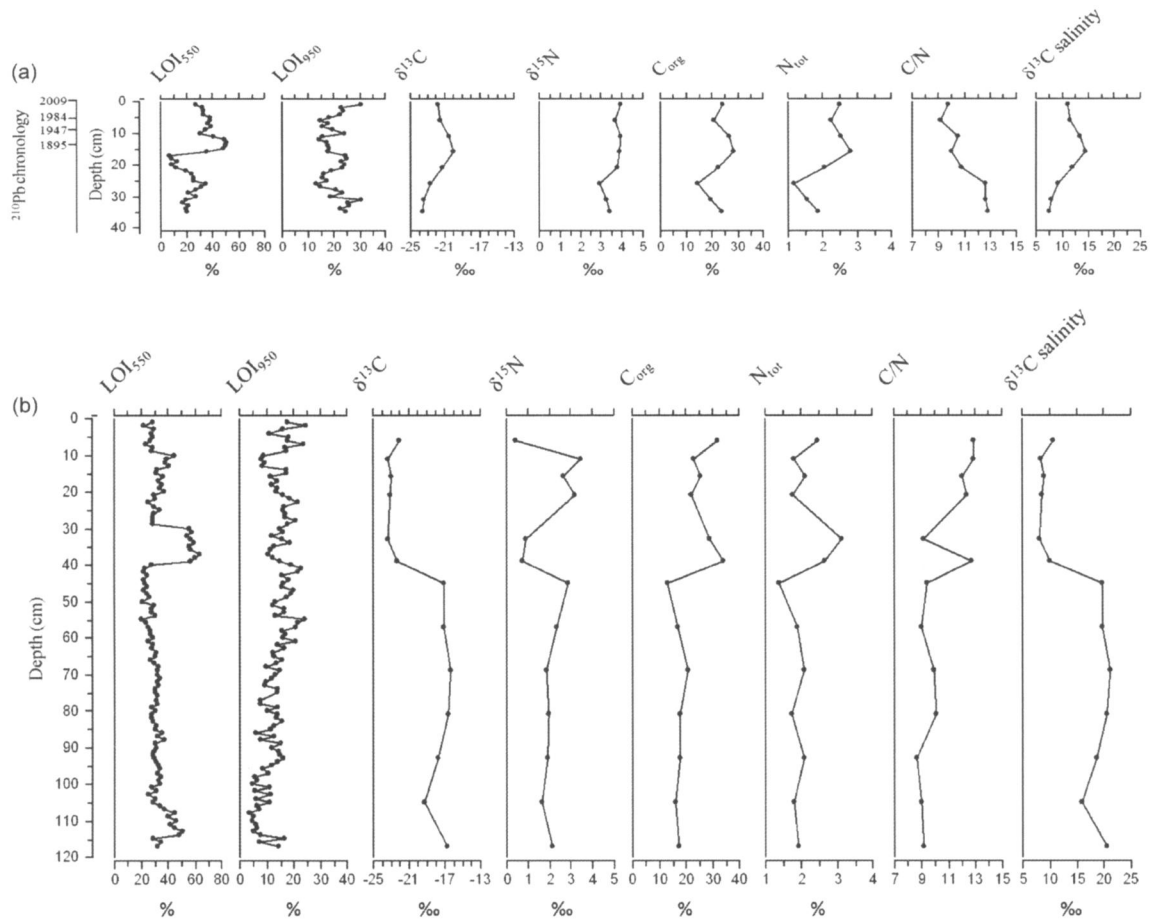
Fig. 4—(a) Organic matter content (LOI_{550}), carbonates (LOI_{950}), stable isotopes ($\delta^{13}C$ & $\delta^{15}N$), organic carbon (C_{org}) total nitrogen (N_{tot}) and $\delta^{13}C$-inferred salinity in LM1; (b) Organic matter content (LOI_{550}), carbonates (LOI_{950}), stable isotopes ($\delta^{13}C$ & $\delta^{15}N$), organic carbon (C_{org}) total nitrogen (N_{tot}) and $\delta^{13}C$-inferred salinity in LM2.

pattern is shown by core LM2 (Fig. 4b), where LOI_{550} content progressively decreases from c. 50%–20% at 40cm. An abrupt shift to over 60% is evident between 40cm and 30cm. The jelly-like sediment consistency of this section possibly suggests the development of microbial mats (Ladakis et al. 2006). A sample almost entirely composed of sand is also evident at 33 cm. LOI_{550} declined to 30% at the core top. No clear trends of LOI_{950} are evident through LM1 core, ranging between 15% and 30% (Fig. 4a). An overall increase in LOI_{950} is evident in core LM2 from c. 5% at the bottom to c. 20% at 40cm, while the core top averages 15% (Fig. 4b).

A major change at c. 40 cm depth is evident in $\delta^{13}C$, $\delta^{15}N$, C_{org} and N_{tot} in core LM2 (Fig. 4b). Below this depth, $\delta^{13}C$ is stable with values averaging around −17.0‰, while in the upper part of the core a reduction to c. −23.0‰ is apparent. An increase in $\delta^{13}C$ to −19.9‰ is evident in LM1 with a reduction to the top (−21.7‰) (Fig. 4a). $\delta^{15}N$ measured at the base of the LM2 core is around 2.0‰ and lows in $\delta^{15}N$ are

evident between 40cm and 30cm and at the core top with values of 0.7‰ on average. In LM1 $\delta^{15}N$ is stable around 3.5‰. A parallel trend is evident for C_{org} and N_{tot} in LM2 with values of c. 17% and 2% below 40cm, respectively. Above this depth, an increase is evident for both C_{org} (c. 25%) and N_{tot} (c. 2%). Similar trends are evident in LM1. Through the core LM2, the C/N ratio is stable around 9 C/N and an increase to c. 13 C/N characterises the core top above 40cm. Similar values are found in LM1 followed by a reduction to c. 9 which characterises the most recently deposited sediments. $\delta^{13}C$-inferred salinity indicates a reduction from 19‰ to 9‰ at this stratigraphic change-point.

Diatoms

Fossil diatom identification and enumeration proved difficult because of poor preservation with up to 60% of taxa unclassified. Diatom preservation was biased by silica dissolution process, determined by a number of possible factors (e.g. low concentrations of dissolved silica in water, alkalinity and bioturbation) determining selective dissolution

317

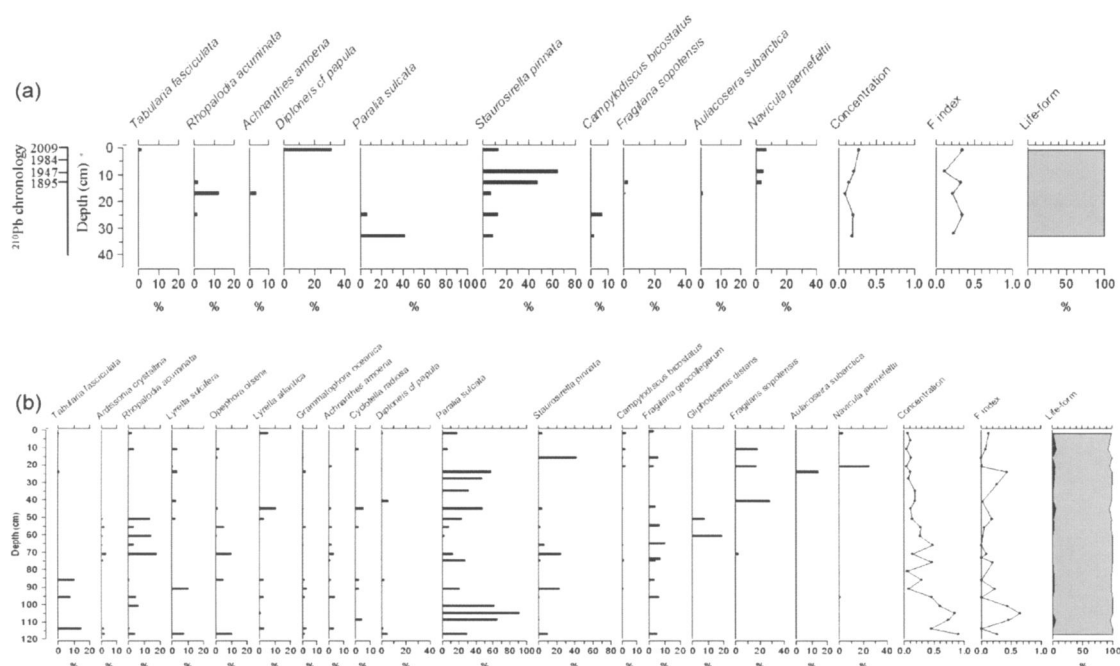Fig. 5—(a) Summary of select diatom taxa (*n* = 10; > 10%) in Murree LM1 sediment cores, concentration (frustules × 10^5 g^{-1} WW), F index, salinity groups and life-form (black: planktonic; grey: benthic); (b) Summary of select diatom taxa (*n* = 10; > 10%) in Murree LM2 sediment cores, concentration (frustules × 10^5 g^{-1} WW), F index, salinity groups and life-form (black: planktonic; grey: benthic).

(Reed 2007; Flower and Ryves 2009). Only robust and strongly silicified valves (e.g. *Paralia sulcata, Lyrella atlantica, Rhopalodia acuminata*) were generally preserved intact in Murree sediments, while other taxa presented a strong degree of silica dissolution, often limiting taxonomical classification to genera level (Fig. 5a and b). The F dissolution index was generally < 0.5 in both cores, confirming poor frustule preservation, which precluded the application of quantitative reconstructions using transfer functions and core correlation. Diatom frustule concentrations are low and range between 0.06 × 10^5 frustules g^{-1} WW to 9.00 × 10^5 frustules g^{-1} WW. However, despite preservation issues, a clear upcore decrease in valve concentrations is evident in LM2 core and is confirmed in LM1 core.

No significant zones of change were identified in the fossil assemblages. *P. sulcata* is the dominant species with highest abundances (90%) at the base of LM2 core along with *Tabularia fasciculata, Opephora olsenii, Rhopalodia acuminata* and *Staurosirella pinnata*. The core top (40–0cm) is dominated by *Staurosirella pinnata* (40%), *Fragilaria cf. sopotensis* (18%), *Navicula jaernefeltii* (24%) and *Aulacoseira subarctica* (13%), while *P. sulcata* reduces to 18%. LM1 core also captures the *Staurosirella pinnata* expansion and the decline in *P. sulcata*. *Diploneis cf. papula* and *Rhopalodia acuminata* are also important. Brackish and marine species dominate the bottom of LM2 core, while brackish-freshwater species increase to

the core top. Brackish taxa characterise the recent sediments in LM1 (*c.* 115 years). Benthic taxa characterise the Murree sediment cores, while planktonic taxa are less abundant in LM2 and are absent in LM1.

Foraminifera

Foraminifera test preservation was generally good. Low biodiversity characterised Murree sediments with seven foraminiferal species found (Fig. 6a and b). Most of the taxa are infaunal, and all are benthic calcareous forms typical of marginal marine environments of Europe and are dominant in brackish waters (Murray 2006). The species in Murree are all herbivores (Murray 2006). The most common species are *Ammonia aberdoveyensis* (Haynes 1973) and *Elphidium williamsoni* (Haynes 1973). The former is dominant at the base of LM2, while the latter dominates more recent sediments in LM2 (above 30cm) and LM1. *Haynesina germanica* (Ehrenberg 1840) is generally subdominant. *Elphidium crispum* (Linné) and *Elphidium macellum* (Fitchel and Moll) are generally evident in the middle part of the core LM2. *A. aberdoveyensis* is dominant in the surficial sediments of the core LM1. Differences between the cores include low concentrations of *H. germanica* and the presence of *Cibicides lobatulus* (Walker and Jacob 1798) in LM1. Foraminifera concentrations fluctuate but are generally higher in LM2 bottom with the highest concentration (395 tests g^{-1} WW) recorded. Between 40cm and 30cm

318

Fig. 6—(a) Foraminifera distribution (%) and concentration (tests g^{-1} WW), *Cyprideis torosa* concentration (shells g^{-1} WW), *C. torosa* noded shell abundance (%), *Chara* oospores (oosp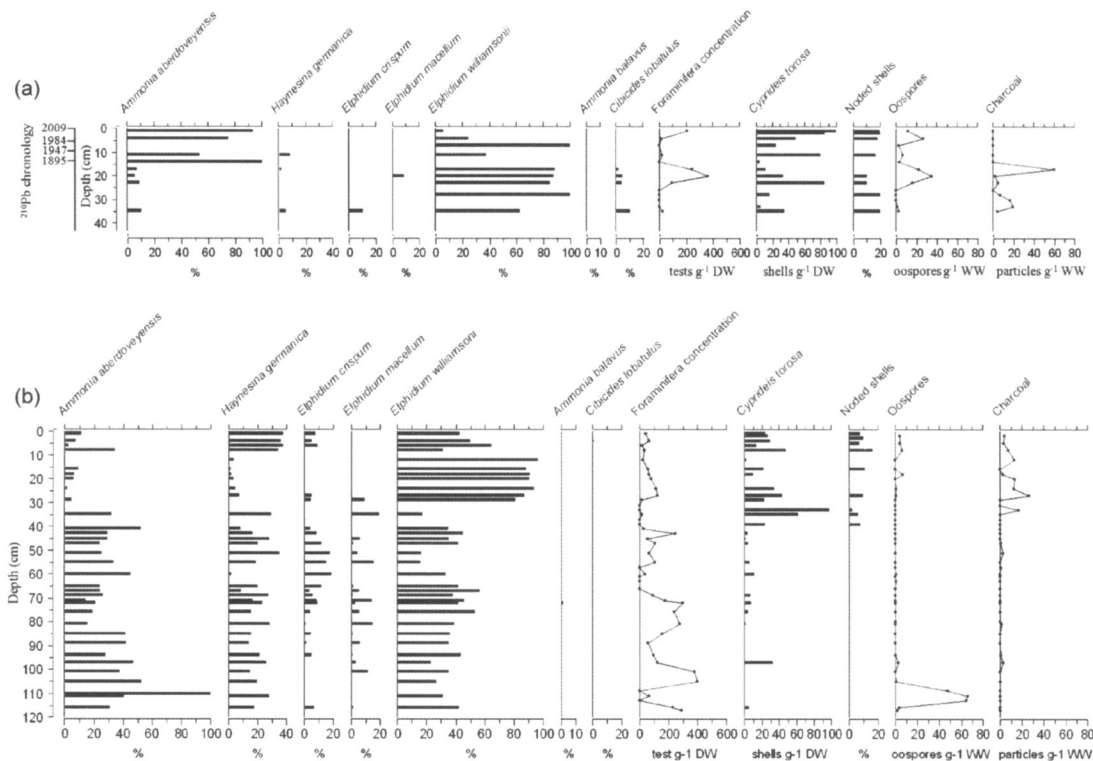ores g^{-1} WW) and charcoal (particles g^{-1} WW) in LM1; (b) Foraminifera distribution (%) and concentration (tests g^{-1} WW), *Cyprideis torosa* concentration (shells g^{-1} WW), *C. torosa* noded shell abundance (%), *Chara* oospores (oospores g^{-1} WW) and charcoal (particles g^{-1} WW) in LM2.

foraminifera are almost absent, while above 30cm concentrations are generally below 100 tests g^{-1} WW. Test concentration in LM1 is also low but peaks of up to 360 tests g^{-1} WW are evident.

Ostracoda

Monospecific populations of *Cyprideis torosa* (Jones 1950) were found in both sediment cores (Fig. 6a and b). Concentrations increase upcore in LM2. Below 40cm, shells are generally absent in many samples and concentrations increase from this point onwards. High concentrations (> 80 shells g^{-1} WW) are recorded above 40cm in LM2 and more frequently in LM1.

Biometric dimensions of the different moults were measured to explore potential changes in population structure (Holmes 2001; Ruiz *et al.* 2003) at three core intervals. In LM2 juvenile instars are only present at 54cm, while the population structure at 34cm depth is composed of both juvenile stages and adults. Juveniles and adults were evident at the top of core LM1. Noded shells ranged between 0% and 20% in both cores with slightly higher values in the core LM1 and no clear trends are evident. Equal proportions of left- and right-oriented valves are present in both sediment cores.

Oospores and charcoal

Charophyte species produce oospores that are preserved in the sediment as propagule banks, representing a regenerative strategy for repopulating lakes (Bonis and Grillas 2002; Combroux and Bornette 2004). Oospores were found at the bottom of core LM2 with a peak up to 66 oospores g^{-1} WW (Fig. 6b). Few oospores were found in the remainder of the core. Concentrations up to 35 oospores g^{-1} WW are evident in LM1 (Fig. 6a).

Charcoal particles are indicative of either natural or anthropogenic fire activity. Particles are evident in LM1 and at the top of LM2 with concentrations ranging between 10 and −60 particles g^{-1} WW (Fig. 6a and b).

DISCUSSION

MODERN HYDROLOGICAL DYNAMICS AND ECOLOGY

The contemporary hydrology in Murree reflects the karst limestone geology, which is subject to submarine groundwater discharge with inputs of fresh water to coastal zones and recharge with saline incursions (Cave and Henry 2011). Ground-water discharge and saline recharge help to maintain water

319

budgets of coastal lakes and dissolved chemical constituents affect the salinity and play a role in the biological species composition and productivity (Barlow 2003).

It is clear from the hourly time series data that Murree is predominantly dependent on underground freshwater inflow. The trend of salinity stratification appears similar in both years, while higher salinity at the bottom of the water column (up to 30‰) is evident in 2010 as a result of reduced precipitation. Extreme variations in salinity were found seasonally in the lake and are reliant on the amount of winter precipitation. Isohaline conditions through the water column appeared five times from March to June 2009, while lower precipitation patterns in 2010 determined reduced salinity events from April to May. The speed of salinity change, for example, six days, at the sediment-water interface is additionally noteworthy. These dynamic conditions can prove difficult for benthic invertebrates, as documented by a recent biological survey of 18 Irish lagoons (Roden and Oliver 2010).

Despite its shallowness, Murree appeared to undergo thermal stratification during summer months mainly due to decreased precipitation, increased evaporation and underground saltwater inflow. Up to 7°C differences between water and air temperatures were evident during summer lake stratification. Warming at the sediment-water interface, coincident with salinity stratification, is potentially enhanced by the sun's irradiance that penetrates shallow and highly transparent waters (Gale et al. 2006). Hearn and Robson (2001) suggest that dissolved oxygen is influenced by vertical mixing of the surface water and the sediment oxygen demand. When extended salinity stratification appears, vertical mixing is inhibited and the consumption of oxygen by the sediments dominates. Pybus and Pybus (1980) demonstrated that surface waters in Murree contained more oxygen than the sediment/water interface, which was described as deoxygenated and characterised by hydrogen sulphide gas. Colonies of anoxigenic Chromatium sp. (purple sulphur bacteria) were observed on the sediment surface on many occasions during fieldwork and anoxic/suboxic conditions can be assumed at the sediment-water interface even in the shallow littoral zone. This is confirmed by the absence of the ostracod Cyprideis torosa in recent surveys (Roden and Oliver 2010), which does not tolerate low dissolved oxygen concentration (Holmes et al. 2007). Therefore, the reduction of oxygen at the sediment/water interface coupled with poikilohalinity constitutes a natural stressor for benthic fauna.

Murree has been described as a eutrophic coastal lake (e.g. Lansbury 1965; Healy et al. 1997), but chemical analyses suggest that the lake

lies at the boundary between oligotrophic and mesotrophic conditions (Pybus and Pybus 1980; Roden and Oliver 2010). Therefore, Murree should be considered as a highly productive rather than a nutrient rich coastal lake. The formation of dense macroalgal beds, principally composed by Chara canescens and Lamprothamnion pauplosum, highlights the importance of the habitat (Bamber et al. 1992) and are responsible for the high degree of water clarity. In fact, macroalgae are capable of rapid nutrient uptake and influence the movement of dissolved nutrients across the sediment-water interface (Tyler et al. 2003) affecting phytoplankton production (McGlathery et al. 2001).

Recent climatic predictions indicate a possible relative sea level (RSL) rise of 0.5m by 2100 (IPCC 2000; Sweeney et al. 2002; Fealy et al. 2010). A progressive increase in the RSL together with land submergence (Gehrels 2010) might lead to increased seawater overwash to Murree in the near future. Additionally, a permanent superficial connection with the sea might form to the south-west of the lake. This will potentially see a dramatic shift in lagoon hydrology and ecology.

PALAEOECOLOGICAL RECONSTRUCTION

Palaeolimnological reconstructions revealed a complex chronology and sedimentation regime in Lough Murree. The dating of the sediment confirms differences between adjacent cores, while a large gap in sedimentation and poorly preserved proxies (e.g. diatoms) limits historical inferences. However, despite these limitations the proxy data are indicative of coastal influences and suggest a hydrological shift from marine-brackish conditions to a poikilohaline system as described by modern hydrology.

Chronology

Establishing a sediment core chronology using a variety of dating methodologies and materials can be useful in palaeoenvironmental reconstructions (Enters et al. 2006; Saulnier-Talbot et al. 2009). However, in Murree, the chronological reconstruction was complicated because the two methods were performed on different sediment cores, and it was necessary to use a range of terrestrial and aquatic materials for ^{14}C AMS dating. Additionally, radiocarbon dates can be potentially biased by factors such as sediment reworking, marine reservoir effect (Ascough et al. 2009) and the hard water effect (Björck and Wohlfarth 2001; Pigati et al. 2010). Core LM1 was successfully dated using ^{210}Pb methodologies indicating that the top 13cm have been deposited during the past 115 years. Lagoons are considered to be among the most productive natural ecosystems in the world (Levin et al. 2001; Kennish and Paerl 2010) and high SARs

320

were expected. However, modern chronology suggests exceptionally low SARs (0.014g cm^2 year^{-1}, 0.126cm year^{-1}). Radiocarbon dates for four different materials in LM2 date to between 4100 year BP and 4600 year BP. The divergence between dating systems and the uniformity of the radiocarbon dates, therefore, suggest that there must be a hiatus in sedimentation in the lagoon.

The evolution of Murree

Rock/cobble barrier lagoons form as a result of incident wave energy, swash dynamics and tidal range and permit water exchange via percolation (Carter and Orford 1980; Orford 2005). Rock barriers can have both overground and underground hydrological connection to the sea and can isolate lagoons from the sea with falls in sea level and land uplift (Westman and Hedenström 2002; Lamb et al. 2006). Physical, chemical and biological sediment proxies from Murree generally suggest an evolution to more freshwater conditions, while a notable change point at c. 40cm sediment depth is evident and may be coincident with the sediment hiatus. Changes in relative sea level, hydrological communication, open and enclosed basin formation and possible forcing mechanisms are explored in the following sections.

Past change in RSL over NW Europe is spatially complex and still unclear (Tooley 1993; Edwards 2006) and no detailed reconstruction of Galway Bay RSL is available. However, primary index points included in the Sea Level Database of Ireland (Brooks and Edwards 2006) suggest a rise from c. -6m c. 7000 cal. year BP to c. -2 m approximately 5000 cal. year BP. A lower palaeo mean sea level of -2.27m is suggested from Cork and -1.68m for Donegal (the extreme north and south of the country) for the mid-Holocene period. Sand mixed with mud through core LM2 could suggest a constant contribution from the sea. However, a lower RSL would potentially correspond to lower lake salinity, lower sediment accumulation and more freshwater influence similar to modern conditions. Lower salinity, however, is not supported by the sediment proxies, which suggest brackish-marine conditions in the older LM2 sediments. High δ^{13}C-inferred salinity (19%) could be indicative of an open or semi-enclosed coastal basin with constant or intermittent seawater inflow, while organic matter at the base of LM2 (c. 9 C/N) is most likely derived from algal sources, which have C/N values typically between 4 and 10 (Müller and Voß 1999; Yamamuro 2000). C/N ratios of c. 9 have been attributed to benthic algal communities in shallow water sediments (Sundbäck et al. 2000). Algae and macrophytes have a wide range of δ^{15}N (Finaly and Kendall 2007) and values of c. 2‰ at the base of LM2 core are possibly representative of phytoplankton (Maksymowska et

al. 2000; Rossi et al. 2010). Basal core diatom records have relatively high concentrations (9.00 $\times$ 10^5 frustules g^{-1} WW), are mainly composed of benthic species and assemblages comprising marine and brackish taxa, including high levels of Paralia sulcata. Fossil foraminifera assemblages from Murree are typical of marginal marine environments (Murray 2006) and resemble those found in other lagoons (e.g. Cearreta et al. 2002; Avramidis and Kontopoulos 2009; Lloyd and Evans 2002; Horton and Murray 2007). The lower core foraminifera assemblages in Murree also suggest a more saline environment. Food availability is another key factor controlling foraminifera abundance (Altenbach 1992; Gooday 1994) and freshly deposited phytoplankton are known to stimulate foraminifera population growth (Lee 1980; Anderson et al. 1991). Higher foraminifera concentrations in LM2 are coincident with high diatom concentrations.

Therefore, older sediments in LM2 between 116cm and 40cm depth, dating to c. 4100–4600, were clearly more marine influenced in character. This could be explained by a superficial connection to the sea, or a breach/storm surge between the sea and lagoon, which subsequently led to sediment erosion and a hiatus in the lagoon sediment chronology.

A dramatic change point is evident in all physical, chemical and biological proxies at approximately 40cm or 1500AD with extrapolation of the ^{210}Pb-derived accumulation rates. The change point is characterised by peaks in LOI$_{550}$, C_{org}, C/N and elemental nitrogen, declines in δ^{13}C and a trough in δ^{15}N suggesting a major change in sediment source. A sediment hiatus postulated above and/or basin isolation are possible explanations. Increases in productivity, change in allochthonous inputs and/or sediment reworking are possible consequences. Following the change point, the Murree sediments are clearly more organic and carbonate rich, while diatom and foraminifera concentrations decline and δ^{13}C-inferred salinities are lower.

Isolation of Murree from the adjacent ocean would have determined major changes in hydrochemistry. The lagoon would have been rendered more susceptible to underground freshwater influence. The increase in sediment carbonate (as LOI$_{950}$) in LM2 could reflect a shift to a more hydrologically closed (endorheic) system, as the high carbonate content is typical of karstic lakes (Reed et al. 2008). Additionally, the formation of large charophyte beds might have enhanced sediment carbonates via calcification of plant stems and oospores during photosynthetic activity (Andrews et al. 2004). The reduction in organic δ^{13}C may also reflect increased freshwater inflow via groundwater and superficial runoff.

321

Increased lagoon productivity is suggested by high carbonates, organic matter (LOI_{550}) and $\delta^{15}N$. Today, Murree is a highly productive coastal lake with dense macrophytes, macroalgal mats and recurrent algal blooms (e.g. Pybus and Pybus 1980; Oliver 2005). The increase in $\delta^{15}N$ evident after the change point and recorded through LM1 could be a response to this increase in primary production. This supposition is consistent with the presence of both charcoal and C/N ratios. Moreover, transfer of nitrogen to the sediment may additionally be as a result of the development of macroalgal beds evidenced by increases in Characeae oospores in the recent sediments. Microbial mats are concurrent with modern poikilohaline conditions in Murree today; however, no sediment proxies were used to directly infer their historical development. The development of microbial mats is made possible with the activity of N_2-fixing organisms (Bergman et al. 1997) in protected, shallow, warm waters, with fluctuations in temperature and in salinity (Friedman and Sanders 1972; Walter 1976; Stal et al. 1996; Villbrandt and Stal 1996). The role of benthic macrophytes in coastal lagoon nutrient cycles has been discussed by many authors (e.g. Tyler et al. 2003; McGlathery et al. 2007; Lloret and Marin 2009). McGlathery et al. (2007) outline the importance of benthic macrophytes in coastal lagoon resistance to eutrophication via nutrient sequestration into plant biomass. A progressive increase in algal mats in Murree as a result of basin isolation might, therefore, account for the upcore reduction in diatom concentration.

Reduced $\delta^{13}C$-inferred salinity (9‰), after the change point, is coincident with biological responses in the diatom, foraminifera and ostracod assemblages. While diatom records were biased by poor frustule preservation that made the fossil record fragmentary low valve concentrations and assemblages in the recent sediments confirm brackish-freshwater tolerant species. Similar species assemblages were found in infilled coastal lagoons (Robinson 1982; Cearreta et al. 2003), while P. sulcata was common and particularly abundant in organic rich coastal sediments (Zong 1997; Gebühr et al. 2009). In parallel, the foraminifera assemblages confirm a less saline environment. Additionally, progressive declines in foraminifera concentrations are evident, and this generally reflects a shift from marine/brackish to freshwater conditions in coastal transitional zones (e.g. Scott and Medioli 1980; Patterson et al. 1985; Cearreta et al. 2007). The decreases in foraminifera are paralleled by decreases in diatom concentrations also suggesting a change in the food base.

The abundance of Cyprideis torosa in LM1 and LM2 core top might be indicative of the formation of poikilohaline conditions. C. torosa is a euryhaline species capable of withstanding a wide salinity range

(0.4‰–150‰) (e.g. Heip 1976; Schiewer 2008; Primavera et al. 2011). In particular, low diversity assemblages with a few or a single dominating species generally indicate stressed and unstable conditions (e.g. Mazzini et al. 1999; Frenzel and Boomer 2005; Mischke et al. 2010). Moreover, it is noteworthy that C. torosa cannot tolerate low oxygenated waters (Holmes et al. 2007). Therefore, the expansion of monospecific populations of C. torosa in Murree could be a response to basin isolation. This is supported by the population structure which, in older sediments, is represented by small juvenile instars only and is typical of exposed conditions (Whatley 1983; Penney 1987), while the presence of adults together with larval stages in the upper core sediments are typical of more protected systems (Penney 1987). Equal proportions of left- and right-oriented valves (Schellenberg 2007) and the presence of shell noding in response to reduced water salinity (e.g. van Harten 2000; Keyser 2005) support this hypothesis.

A further explanation for the change point could be an increase in land-derived material. A possible input from the catchment is suggested by increased C/N ratio (c. 9–13 C/N) evident in LM2 core top suggesting a possible contribution allochthonous organic matter (Müller and Voß 1999; Sundbäck et al. 2000; Balascio et al. 2011). $\delta^{13}C$ values reflect C_3 plants which are generally comprised between −30‰ and −23‰ (Michener and Kaufman 2007; Li et al. 2008). The increase of charcoal particles in the upper part of the Murree core also supports the idea of enhanced external loads of land-derived material and, furthermore, could indicate the presence of enhanced anthropogenic activity. In fact, firing may have played an important role in woodland clearance as described by Molloy and O'Connell (2004) on Inis Oírr (Aran Islands) between 4900–3690 cal. year BP and at Cappanawalla (c. 10km from Murree; Fig. 1b) from 3520 cal. year BP (Feeser and O'Connell 2010). An upcore decreasing trend in the C/N ratio is also evident through core LM1. The reduction might indicate a more recent decline in land-derived organic material; additionally, sediment reworking might also be a possible cause. The C/N ratio decrease at the top of LM1 indicates a possible reduction of land-derived material during the past 115 years.

Lagoon isolation has been inferred for Norwegian (Mills et al. 2009; Balascio et al. 2011) and Scottish (Mackie et al. 2005; Mackie et al. 2007) basins, which transformed into freshwater coastal lakes as a result of isostacy or land uplift. However, natural forcing is unlikely since Irish coasts, with the exception of a small portion of Northern Ireland, are submergent (Gehrels 2010). Anthropogenic forcing is, therefore, more likely. A

322

significant anthropogenic influence is evident in the northern Burren area since the Iron Age (c. 600 BC–AD 500) (Feeser and O'Connell 2010). Holmes et al. (2007) highlighted effects of Neolithic clearance of land on salinity and water level in An Loch Mór, a coastal lake on the nearby Inis Oírr (Aran Islands). In Murree, anthropogenic forcing is reflected by the increase in charcoal particles at the top of LM2 and in LM1. The construction of a coastal road on the Finavarra Peninsula (Pybus and Pybus 1980) and the erection of the Martello Tower between 1811 and 1814 AD (Kerrigan 1982) are other potential sources of disturbance causing isolation of the lake from the adjacent ocean.

CONCLUSIONS

This research tracked the ecological history of Lough Murree a modern-day brackish coastal lagoon in a karst limestone landscape. Modern hydrological data collected over two years explored salinity change due to coastal influence and tracked freshwater inputs. Hourly time series data revealed wide seasonal salinity variation, saline and temperature stratification and abrupt system change over the course of days. The detailed record of current hydrological change was extended through palaeo-limnological reconstructions, which permitted inference of development and change of over c. 4500 years. Interpretation of historical change was limited by a complex chronology, which limits what can be said about the timing of evolutionary change. However, in general, the interpretation of sediment proxies in Murree conforms with the supposition by Pybus and Pybus (1980) that the lagoon was once surficially connected to the sea. Many physical, chemical and biological process and responses parallel those of isolation basins in Northern Europe, which transformed into freshwater coastal lakes as a result of land uplift. Natural forcing and anthropogenic influence are both posited as possible explanations. The surficial isolation of the lake from the ocean has potentially rendered Murree a more productive system with the formation of dense macroalgal beds mostly composed of lagoonal specialist species, which are able to tolerate poikilohaline conditions (Bamber et al. 1992).

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323

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