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Water quality and water availability variations in an upland Galloway
loch with special reference to dissolved organic matter and the
distribution of benthic diatoms

Final report to SNH Research and Technical Support Programme

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Cover photograph: Round Loch of Glenhead, South-west Scotland, April 2007
Photo: Hong Yang

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Water quality and water availability variations in an upland Galloway loch with special reference to dissolved organic matter and to the distribution of benthic diatoms

Summary

Upland waters in acid sensitive regions of Scotland are vulnerable to several disturbance processes that most importantly include atmospheric pollution and climate change as well as to local land use. Monitoring in the Round Loch of Glenhead (RLGH) since 1988 has shown that both water acidity and sulphate concentration have declined while the concentration of dissolved organic matter (DOM) has steadily increased. Currently, it is unclear if increasing DOM reflects climate change effects or relief from acid pollution. This report concerns recent research at the RLGH on relating seasonal changes in water supply and coloured dissolved organic matter (cDOM) to the distributions of benthic algae (diatoms). Diatoms are primarily limited by light which in turn varies according to season, water depth and water transparency. cDOM in lake water strongly influences water transparency and our central hypothesis is that benthic diatom distributions are influenced by changes in cDOM concentrations and light availability.

Temporal variation of diatoms and chlorophyll a along depth transects indicated that the abundances of motile diatoms increased in summer and autumn and declined in winter and spring. This seasonal effect indicates that light and temperature influence the epipelagic diatom distributions. Diatoms and chlorophyll a peaked at about 2 m depth. Although the euphotic depth varied during the different seasons, motile diatom abundances were always very low or zero below the euphotic depth (about 6 m). Correlation analysis of environmental variables and diatoms from around the whole lake showed that the total diatom abundance, the diatom ratio and individual diatom species were all mainly controlled by light. Species such as *Navicula leptostriata* were commonly found living on shallow water surface sediments but they can occur down to a depth about 7 m. Light clearly has a major controlling influence on diatom spatial distributions in the RLGH. Stones and plants within the loch generally occur in the upper 3 m of water depth and additional sampling of aquatic macrophytes indicated that these substrata supported attached diatom species such as *Tabellaria flocculosa* and *Achnanthes* taxa. The shallow water species are different from those common in the 1980s and indicate a recovery in acidity of the loch. Work is continuing of the effects of light and DOC on diatom species occurrences.

1. Introduction

Upland waters in acid sensitive regions of Scotland are vulnerable to a variety of disturbance processes that relate not only to local land-use practices but also to regional atmospheric pollution and to global climate change (Monteith *et al.*, 2007). The Round Loch of Glenhead (RLGH) in the Galloway Hills has been investigated by environmental scientists at UCL's Environmental Change Research Centre (ECRC) since 1980 and together with Lochnagar in the Cairngorms (Rose, 2007) these two sites are the most carefully researched upland acidified upland lochs in Scotland.

In order to examine the nature and implications of contemporary environmental changes at the RLGH, a research student from China (Hong Yang) applied successfully in 2005 for a DHPA fellowship to undertake this study. The research has focused on water colour, light and the distribution of living and sedimentary diatoms in the loch during 2006 and 2007. Fieldwork finished in October 2007 and the resulting thesis is due for completion in September 2008. A supplementary grant from SNH was instrumental in permitting Mr Yang and colleagues to undertake fieldwork visits to the RLGH during 2006 and 2007. This report presents the main results of the work so far (to January 2008).

1.1 Environmental background

In the 1980s acid upland lochs in the Galloway region of south-west Scotland were a major focus for UK acid rain research (Battarbee *et al.*, 1990). Since that time non-marine sulphur deposition has declined but other environmental changes are becoming manifest; these include those associated with global warming, with land-use practices and deposition of other air pollutants. Consequently, regular monitoring of the Galloway lochs as part of the UK Acid Waters Monitoring Network has continued since 1988. Following the DHPA award to Mr Yang more intensive study of one Galloway loch, the Round Loch of Glenhead (RLGH), was begun in late 2005. This report builds upon the summary report presented to SNH in January 2007 and concerns the preliminary research results, especially over the period April 2006 to October 2007.

1.2 Project rationale

As acidification of sensitive surface water became less acute in the 1990s as acid emissions declined, concern increased about the effects of global climate change in relation to the acidification recovery processes. Many acid sensitive upland waters are now showing signs of ecological recovery but climate change effects are becoming stronger and nitrogen oxide emissions are showing little evidence of decline. Since the Round Loch of Glenhead (RLGH) is monitored (since 1988) for water quality and ecology (see <http://www.ukawmn.ucl.ac.uk/report>), there was considerable benefit for selecting this site for specific study. Monitoring has shown that both water acidity and sulphate concentration declined since the 1990s whereas the concentration of dissolved organic matter (DOM) has increased steadily. Several publications have pointed out the effects of climate-pollution interactions on DOM and other water quality variables in UK acid lakes (Freeman *et al.*, 2001, Evans *et al.*, 2005) but Monteith *et al.* (2007) concluded that relief from acid pollution exerts a strong effect by raising DOM concentrations in many upland acid-sensitive lakes.

In this work, research at the RLGH has focused on relating seasonal changes in water supply and coloured dissolved organic matter (cDOM) to benthic diatom distributions. Diatoms on subaquatic sediment surfaces are primarily limited by light which in turn varies according to season, water depth and water transparency. cDOM in lake water strongly influences water transparency and our central hypothesis is that benthic diatom distributions are influenced by changes in cDOM concentrations and light availability. In addition to the specific diatom

work at the RLGH, several other linked activities were also initiated in late 2005 to early 2006. They were (i) use of field time to service a buoy-mounted weather and water quality metering station (donated by Dr G. George, CEH) and deployed on the loch by Ensis Ltd. staff in October 2005; (ii) collection of soil water samples and inflow/outflow water samples for stable isotope measurements (by Dr T Heaton, NIGL, Keyworth); (iii) measurement of loch water level changes; (iv) development of an automatic sediment trap (built by CEH) for deployment in the RLGH.

2. Field and laboratory activities undertaken

After a preliminary visit to the RLGH in October 2005, regular research fieldwork visits began in April 2006 and finished in October 2007. The activities undertaken are summarized below. In addition to literature survey and site mapping, water (quality and flow), and living diatom algae (from stones, sands and deeper sediments) collected on each fieldwork visit were analysed in the laboratory during 2007. However, the research work is not scheduled to finish until late 2008.

Fieldwork:

Initial fieldwork included the establishment of sampling routines and designation of sampling protocols and georeferencing sampling locations including:

- GIS mapping of the site and installation of 10 markers (wooden stakes) around the periphery of the loch to locate sample points for repeat diatom sampling
- Establishment of a depth gradient diatom sampling transect
- Installation of a rain gauge (on the island), two 'Dataflow' water level loggers, one in the lake and one in the outflow, and a stage board
- Installation of six soil water samplers (Figure 2, upper left) and six dip well samplers
- Emplacement of a depth transect of artificial substrata (0.3-10m depth) to assess diatom colonization (Figure 2, lower left)

After initial trials, routine sampling activities were carried out on seven occasions (April 2006-October 2007) and comprised:

- Determination of outflow stream flow by dilution gauging
- Collection of water samples from loch inflow and outflow and soil water samples
- Collection of 10 shallow water epilithon and epipsammon samples (c. 20 cm depth) at each marked point around the loch
- Collection of 10 shallow water depth epipelon samples (c. 60 cm depth) at each marked point around the loch (Figure 2, upper and lower left)
- Collection of 19 surface sediment samples (for diatom and chlorophyll analysis) along a depth transect from ca 0-9 m depth along a transect (T2, Figure 1, lower right and Figure 4)
- Measurement of Secchi disc depth and of the light extinction coefficient (for photosynthetically active radiation, PAR)
- Download water level data from loggers

Spatial sampling activities were focused on two extended sampling occasions in April 2006 and in April 2007 and included:

- Bathymetric mapping of the RLGH
- Collection of surface sediment samples according to a stratified random sampling protocol
- Collection of seven sediment cores for stratigraphic analysis (Figure 1, lower left)

Poor weather conditions interfered with sampling and data collection on several occasions so much so that the sampling designed was changed after August 2006. Consequently, sampling of deep water epipelagic diatoms was restricted to April 2006 and April 2007. Wet conditions frequently caused data downloading problems but these were later avoided by returning the loggers overnight to the field laboratory for servicing on each visit.

Associated field activities included collection of monthly samples for total organic carbon (TOC) measurements by the Freshwater Research Services Laboratory at Pitlochry as part of their regional monitoring of Galloway lochs. These will be used to calibrate the absorbance measurements made routinely on the loch and soil water samples. Water temperature and meteorological variables at the RLGH are being recorded by the weather station located in the loch and work by Mr. D. Monteith (at that time of Ensis Ltd.) remains on-going.

Sediment cores were collected with a Renberg corer (Figure 1, lower left). Two cores were collected in April 2006 and were used for DOM release experiments as conducted in the UCL laboratory cold room. In April 2007 a transect line of short cores was collected along the surface sediment diatom sampling transect (T2) and in October 2007 another short core (ca 35 cm) sediment core was collected beyond the T2 at 12 m depth (near to the deepest point (14 m) in the loch).

Both light meter and Secchi disc data are being compiled and related to DOM concentrations.

Despite some problems in downloading data, the two water level loggers and stage boards are being used to monitor water levels. It is hoped to relate flow and climate related changes to DOC levels in the loch water.

Laboratory activities

Water samples: These were collected for routine measurements of acidity, conductivity and light absorbance, and also for stable isotope analysis by NERC Isotope Geosciences Laboratory (NIGL). Ratio changes of ^{15}N and ^{13}C in these water samples could indicate the extent of seasonal differences in organic matter sources for the RLGH. After initial problems of fungal growths in stored samples, samples were filtered and frozen shortly after collection.

Diatom samples: These have been collected for diatom analysis primarily from epilithic, epiphytic and epipelagic environments in a manner that should reflect the underwater light regime in the loch. On each field visit diatoms were collected from georeferenced points in and around the loch and along the 9 m transect (T2). Together with the spatial survey samples, samples were used for a variety of measurements. Sediment samples were measured for lithography (organic content and % dry weight), chlorophyll *a* (for total algal biomass and for estimating diatom abundances). Specifically three ways were used to assess diatom cell abundances:

- the proportion of living diatoms was estimated by counting cell abundances in fresh untreated sediment
- the number of motile living diatoms (the epipelagic) was estimated by lens tissue harvesting
- the total abundance of diatoms in each sample was estimated by counting acid cleaned samples

To ensure replicability of results regarding the living communities of mobile diatoms, a number of experiments were performed to determine the optimum time for collecting this community in laboratory conditions. The results indicated that most diatoms can be collected

on to lens tissue squares in the early afternoon of the day following sampling. In addition, quantitative samples of epilithon were collected at three replicated points in the loch.

Data were and are being related to space and time and to substratum type. Spatial distributions are mapped using ArcGIS. By quantitatively sampling the living diatom communities we hope to establish a relationship between living cell abundances and water depth. Light must be a major limiting factor on deeper water communities and this in turn must be related to DOM in the water. If this can be demonstrated, then there is a possibility of using diatom analysis of lake sediment cores to infer water colour change (and other water quality attributes) in the past. This should help inform the debate on the causes of the long-term increases in DOC, and in turn be related to climate and land-use changes.

3. Preliminary results

Some general observations were made about the RLGH following the initial visits. These were reported previously and include the recovery of the near loch catchment from peat erosion and the increase in aquatic macrophyte communities (particularly *Sparganium angustifolium* and *Juncus bulbosus*). Some management of heathland has been practised in recent years with cutting as well as burning of the *Molinia* grass land. As yet there is little evidence that *Calluna* growth has been promoted. On the other hand, removal of sheep from the near catchment area has resulted in more growth of seedlings including *Myrica* and *Sorbus*. Although cattle have been introduced to the upland area around the RLGH few seem to be using land in the catchment area.

Water samples and water quality: Basic measurements of water quality and transparency were made using water samples collected during field visits to the RLGH in 2006 and 2007. Water samples from the main inflow and the outflow streams together with samples of soil drainage water were measured. Water pH and conductivity for the RLGH open water are measured as part of the UKAWMN and these routine measurements on inflow and outflow samples were begun in this study in June 2007. Two sites within the RLGH catchment blanket peats were also used to obtain samples of peat drainage water. Drainage water was collected by inserting 50 cm lengths of PVC guttering into the peat and capping one end where a pipe conducted collected water into a bottle partly buried in the peat (Figure 2). Site 1 is near the inflow stream (co-ordinates: 55.09251N, 4.42695W) and the other is on the west side of the loch (co-ordinates: 55.09364N, 4.43335, lower; 55.09363N, 4.43382W, upper). Site 1 has one collection bottle (lower) at the base of a blanket peat covered slope and one about 3 m up-slope. Site 2 has two pairs of collection bottles, one pair is located up-slope, about 1 m above the loch level, and the other pair is about 4 m above the loch level. The individual bottles at each level are indicated as left and right since it was noticed that collected water colour was different even between replicate pairs only 1 m apart.

Water conductivity and pH was measured using Meittler Toledo calibrated probes. After these routine measurements, the water samples were passed through GF/C filters and frozen to prevent deterioration of cDOM. Water colour (caused by DOM) was measured by absorbance at a wavelength of 254 nm prior to sample freezing. These absorbance results will be related to DOC values when available. On several occasions poor weather interrupted sampling and several soil water sample bottles were not recovered. At intervals, the samples were despatched to the National Geological Isotope Laboratory (NERC, Keyworth, England) for determination of ^{13}C and subsequently ^{15}N activities.

Results of basic measurements of water quality made as a result of the field visits are indicated in Tables 1-3. Water pH and conductivity for RLGH open water are measured as part of the UKAWMN and routine measurements of pH and conductivity on the soil water samples were begun in this study in June 2007. Water colour caused by DOM was assessed by absorbance at a wavelength of 254 nm (these will be related to DOC values when

calibrated). On several occasions poor weather interrupted sampling and several soil water sample bottles were not recovered.

During the sampling period acidity of inflow and out-flowing water (Table 1) was similar but the out-flowing water was always slightly more acid and the most acid samples were in April 2007. Water conductivity was less consistent from April 2007 showing large differences but with the outflow being the most dilute on each occasion. Absorbance was similarly inconsistent but particularly high values occurred in the inflow samples in August 2006 and April 2007; both samplings followed heavy rain.

The seasonal changes in cDOM concentration at soil water sites 1 and 2 are expected to be primarily due to changes in seasonal temperature and hydrological pathways linked to the amount of antecedent precipitation. From the limited data it is apparent that the variation in adjacent replicate samples at Site 2 showed more variation than between the upper and lower samples. This indicates significant small-scale variations in groundwater drainage patterns. For example, the lower 1 sample was always the least acidic and usually the least dilute compared with either the other 'replicate' sample or the two upper samples. Site 1 samples showed no clear trend in acidity or conductivity but, except for October 2007, the upper sample was always the least acid and the least dilute. Similarly, the upper sample was always the most coloured and had the highest absorbance. These latter differences are attributed to hydrology, the down-slope sample (lower) receiving relatively more drainage water. This agreed with casual observations of water flow from the collector which indicated that a greater flux of water occurred in the lower samples at sites 1 and 2.

Table 1. Water quality in the outflow and main inflow streams at the RLGH during 2006/7. pH, conductivity and water colour (absorbance at 254 nm) were measured.

Sample	pH	Conductivity $\mu\text{S cm}^{-1}$	Absorbance at 254 nm	$d^{15}\text{N}$	%N	Date
Inflow	5.96	36.4	0.099	1.7	0.7	28.04.06
Outflow	5.98	48	0.135	0.9	1.5	
Inflow			0.112	3.7	0.8	1.06.06
Outflow		31	0.132	0.9	1.6	
Inflow			0.346	1.0	1.0	1.08.06
Outflow		35	0.159	0.1	1.3	
Inflow	5.61	24.4	0.257	1.7	0.9	18.10.06
Outflow	5.34	24.7	0.202	-0.1	1.0	
Inflow	5.92	44.3	0.152	2.0	1.0	11.01.07
Outflow	5.77	40.1	0.154	1.4	1.1	
Inflow	4.87	58.9	0.263	4.0	2.0	27.04.07
Outflow	4.83	35.6	0.103	0.9	1.1	
Inflow	5.83	32.3	0.183			30.07.07
Outflow	5.21	30.3	0.174			
Inflow	5.80	26.9	0.259			16.10.07
Outflow	5.45	28.1	0.189			

Table 2. Water quality measurements on soil water collected at Site 1 on the south-east side of the Round Loch of Glenhead near the main inflow stream about 60 m from the loch. The upper sample was about 3 m up-slope from the stream edge. The lower sample was from the edge of the stream about 0.7 m above stream level. (See Table 1 for other details)

Sample Site 1	pH	conductivity $\mu\text{S cm}^{-1}$	Absorbance at 254 nm	D ¹⁵ N	%N	Date
upper			0.906	2.4	1.6	1.08.06
lower			0.402	0.4	1.2	
upper	4.40	37.8	0.538	5.6	1.1	18.10.06
lower	4.62	29.7	0.398	0.1	1.2	
upper	4.80	45.8	0.353	17.0	1.4	11.01.07
lower	4.95	49.7	0.242	1.3	1.0	
upper	4.28	60.7	0.601	3.5	1.6	27.04.07
lower	4.45	38.7	0.363	6.3	0.9	
upper	4.61	25.6	1.234			30.07.07
lower	4.75	21.1	0.558			
upper	4.65	49.1	0.757			16.10.07
lower	4.73	29.7	0.444			

Table 3: Water quality measurements on soil water collected at Site 2 on the west side of the Round Loch of Glenhead. Two replicate upper samples were about 1 m apart up-slope and about 4 m above the loch level. The two replicate lower samples were about 1.5 m apart and about 1 m up-slope from the loch level. See Table 1 for other details.

Sample Site 2	pH	conductivity $\mu\text{S cm}^{-1}$	Absorbance at 254 nm	D ¹⁵ N	%N	Date
upper 1			0.864	26.7	1.6	1.08.06
upper 2			1.497	35.5		
lower 1			0.699	42.2	1.2	
lower 2						
upper 1	4.43	36.3	0.970			18.10.06
upper 2	4.43	33.7	0.589			
lower 1	5.15	26.8	0.992			
lower 2						
upper 1	4.85	33.2	1.030	-0.1	1.5	11.01.07
upper 2	4.96	44.2	0.545	3.8	1.4	
lower 1	5.24	73.1	0.433	9.9	0.8	
lower 2	4.73	37.2	0.657	1.4	0.8	
upper 1	4.71	35.7	0.576	1.4	1.6	27.04.07
upper 2	4.14	57.8	0.651	18.3	1.6	
lower 1	4.69	53.7	0.350	71.4	0.7	
lower 2	4.23	51.5	0.482	8.6	1.3	
upper 1	4.37	31.6	1.941			30.07.07
upper 2	4.54	29.4	1.043			
lower 1	5.10	52.1	2.076			
lower 2	4.66	31.5	1.608			
upper 1	4.25	43.1	1.277			16.10.07
upper 2	4.35	39.4	2.331			
lower 1	5.04	48.1	1.171			
lower 2	4.79	28.9	0.916			

An initial hypothesis was that base-flow conditions should reflect catchment run-off that contributes proportionately more from deep peats; conversely, high runoff conditions should reflect more surface flows. However, no consistent trend differences in the measured variables over the sampling period were apparent from the data in Tables 1-3. Casual observations on water flow rates from each sample collected indicated that water flux was greatest for the lower samples, especially the lower Site 2 sample 2. Clearly very local variations in soil drainage hydrology were influencing drainage water quality.

Preliminary ^{15}N data results are also displayed in Tables 1-3. Delta ^{15}N values were nearly all positive and tended to be generally higher in inflow samples compared with outflow samples but variations were relatively small. Some very high $\delta^{15}\text{N}$ values were found in the soil waters (particularly in April 2007). Some of these values were outside the range expected for natural terrestrial materials (-20 to +30; see Kendall & McDonnell, 1998) and indicate some unnatural source of ^{15}N enriched material.

Transect sampling and diatom analysis: Diatoms and other algae colonizing artificial substrates placed in the loch along a depth range from 25 cm to 10 m are under investigation but preliminary observations of the substrata retrieved after 15 months (Figure 3, left) show large variations in cell cover according to water depth. The results for the abundance estimates of living diatoms on surface sediment along the depth transect line (T2) were carried out at approximately quarterly intervals during the sampling period and these are displayed in Figures 5 to 11. These figures display light availability, sample distance from the shore, sediment texture and diatom abundances, first as the total number of mobile diatoms then numbers for individual common species on each occasion. Chlorophyll *a* concentrations indicate algal biomass.

Light compensation depth was between about 5 and 7 m depending on the season. The sediment was sandy in nature up to about 1 m water depth. Below this depth the organic content sharply increased and usually peaked around 2 – 2.5 m depth before slightly declining in deeper water. Seasonally, both chlorophyll *a* and the abundance of motile diatoms increased in summer and autumn and were lower in winter and spring. During the study period, motile diatom abundance peaked in July 2007. This temporal variation indicated the influence of temperature and light on the epipelagic diatom distribution (DeNicola, 1996). Although the euphotic depth varied during the different seasons, motile diatom abundances were always very low or zero below the euphotic depth, indicating the overall role of light in controlling diatom spatial distributions (Kirk, 1994; Hill, 1996).

Both chlorophyll *a* and diatom abundance also typically showed a typical bi-modal distribution with depth with lower values around 2 m depth. Only the January 2007 sampling did not show this bimodal trend and on this occasion no increase in cell abundance was found beyond 2 m depth. Chlorophyll *a* was about four times higher in the July 2007 samples than at other times. Below about 4 m depth the motile diatom abundance was comparatively very low. Elsewhere, Stevenson & Stoermer (1981) showed that epipelagic algae in Lake Michigan were relatively scarce at shallow depths (<9 m), increased at intermediate depths (9-15 m), then declined at greater depths (>23 m) where light intensity was <6% of surface irradiance. Research in Northern Lake Michigan also supported this spatial distribution (Kingston et al., 1983). Clearly the oligotrophic acidic and peat stained water of the Round Loch of Glenhead strongly curtails benthic diatom growth compared with that in the Great Lakes. The decline in diatom cover at around 2 m depth is more difficult to explain; this depth coincided with a change of slope of the transect line, and also macroalgae and some aquatic macrophytes were more common around this depth. These distributional data need further evaluation.

Spatial sampling and diatom analysis: Spatial attributes of the RLGH are reported for April 2007 and Figure 12 shows the distribution of light arriving at the underwater surface sediment in relation to water depth. This figure also shows the surface sediment characteristics of

percentage dry weight and organic matter at 61 locations within the loch. As expected, light shows a rapid decline with depth but indicates that much of the surface sediment in the western sector of the loch is within the euphotic zone. Because of the exponential decline in underwater light, relatively small differences in depth are attributable to different light intensities at the sediment surface (Figure 12). There is, however, no simple relationship with depth and surface sediment characteristics, and although shallow water sediment tends to have a high dry weight and low organic content (because of its sandy nature and soft sediment redistribution processes), some deep water samples also have high dry weight and low organic content. This latter feature is because late glacial clays and gravels remain exposed at the sediment surface and are kept free of recent sediment by the hydrodynamic circulation of the loch. Hence, the organic content of deep water surface sediment in the south-western part of the basin (where the deepest point occurs at 14 m) is >20%. At around 11 m in the south-eastern part of the loch organic values are much less at <10%.

Figures 13 to 16 show the spatial variation in the abundance of living diatoms (cells mm⁻²) in 61 profundal surface sediments and 10 shore samples (at water depth 0.6 m).

Clearly, living diatom abundances in shallow water are greater than deep water (Figure 13) and similarly the proportions of living diatoms in these shallow water samples are larger. Correlation analysis clearly showed that the total diatom abundance, the diatom ratio and the individual diatom species were all mainly controlled by light (cf. Kirk, 1994; Hill, 1996). In terms of living diatom species abundance, the spatial distribution of *Eunotia denticulata* was concentrated on the middle and east of the loch. *Navicula leptostriata* appeared in the north, south and west but was seldom in the eastern part. *Eunotia naegeli* occurred mostly in the north and middle parts. *Eunotia incisa* and *Navicula madumensis* were distributed mainly in northern and southern regions of the loch. *Frustulia rhomboides* and *Eunotia bactriana* were distributed mainly in the southern part of the loch. *Eunotia vanheurckii* var 1 was mainly found in the north and east. *Tabellaria* sp., *Frustulia rhomboides* var *saxonica*, *Eunotia* sp. and *Peronia fibula* occurred around the entire loch but mainly in shallower water.

Species such as *Navicula leptostriata* were common on shallow water surface sediments and can occur down to a depth about 7 m. Stones and plants within the loch generally occur in the upper 3 m of water depth and additional sampling of aquatic macrophytes indicated that these plants supported attached diatom species such as *Tabellaria flocculosa* and *Achnanthes* taxa. The shallow water species are different from those common in the 1980s and indicate a recovery in acidity of the loch (cf. Jones & Flower 1986); however, spatial distributions with regard to depth were not assessed in this earlier 1980s work.

Hydrology: Despite problems downloading the water level loggers a good record of water level changes in the RLGH outflow stream was retrieved for 2006 (Figure 2, lower). Stream flow gauging during each field visit will allow stream discharge to be estimated from a water depth – water flow rating curve.

Available data from the lake water level and outflow water level loggers are shown in Figures 17 and 18 and although some data were lost due to equipment failures there is a good record for summer 2006 and autumn 2007. Both periods show strong fluctuations in lake and outflow stream levels. Taking August 2007 as an example of where the two data sources are coeval, three distinct peaks in water level are clearly shown for each location. For both locations, the peaks increase in magnitude during this month with the lake level indicating a fluctuation of 40 cm depth and the outflow level indicating a fluctuation of about 10 cm. The loch and its drainage system is clearly a close coupled dynamic system with lake level rising extremely rapidly (in a matter of several hours) after rain events. This hydrological response, with water levels showing a rapidly ascending limb followed by a moderated decline is typical of a 'flashy' upland system dominated by rain induced surface run-off water (e.g. Storry, 1991). Further work will attempt to demonstrate the temporal linkage between rainfall, lake level and stream level changes by using secondary precipitation data from the nearby

Loch Dee catchment. Furthermore, stream discharge was measured on eight occasions, so this will permit calculation of lake volume changes from loch level fluctuations and of the efflux of dissolved organic matter. The latter is made possible by measurements of total dissolved organic carbon made monthly by staff at the Fisheries Research Service Freshwater Laboratory, Pitlochry.

4. Associated activities

These concern the meteorological station moored near the centre of the RLGH and development of the automatic sediment trap.

The sediment trap (Figure 3, right), constructed by engineers at CEH Lancaster, was deployed in the loch in April 2007. It consists of 12 collection tubes held in a carousel and rotation of a closing plate was set for 2 weekly intervals. Power is provided by a 12 v rechargeable battery held in a timer pod that is suspended below the collection device. This trap is a mark II version of a simpler trap developed earlier but which proved to have an unreliable timing mechanism. The new trap was retrieved in October 2007 but was disappointingly found still to be malfunctioning; only one chamber had rotated before stopping (after 2 weeks). The problem seems to be the frictional adjustment to the timing mechanism which was set too firmly to operate effectively in the colder deeper water. Nevertheless, it is still considered a priority to be able to collect regularly the sedimenting material within the loch to get a record of particulate dynamics and to monitor over time periods that are relevant to plankton development and to peat erosion episodes.

The experimental weather station provided by CEH is supplying continuous data about light and weather, as well as about loch water temperature and conductivity (as reported earlier). Water temperature data are collected as a profile over 10 m depth using a thermistor chain. The shallow water trace displayed higher values in the summer months as the water column temporarily stratified and the water temperature difference approached 10°C. Water temperature data were recorded throughout the RLGH water column using a chain of thermistors suspended from the moored weather station (D. Monteith, pers. comm). The temperature traces for each depth zone (1- 12 m depth) are shown in Figure 19 for the period April 2006 to December 2007. The traces clearly show that isothermal conditions existed during much of the year and stratification was transient depending on wind conditions and only occurred during the summer months. It may be expected that as climate changes so does the extent and strength of summer stratification, and water warming will be facilitated by increased amounts of cDOM. Clearly, deployment of the automatic sediment trap would allow us to monitor the ecological effects of changes in thermal conditions through the interception of (*inter alia*) sinking plankton.

5. Outputs

The main output is still anticipated to be a research thesis at the end of 2008, and associated papers. At a wider level, results will be incorporated into web sites maintained by the ECRC.

6. Overview and Implications

The work on the RLGH was initiated to extend and develop understanding of aquatic ecology in an acid upland loch that is recovering from acidification. Previous work through palaeolimnology and aquatic monitoring has demonstrated that the increasing acidity trend began in the mid 19th century (as a result of atmospheric pollution) ceased in the 1990s. A slight recovery, first in water quality and then in aquatic plants (including diatoms), began in the late 1990s. As acidification has declined, other environmental changes have become manifest, first at the catchment level where regeneration of vegetation has resulted from removal of sheep from the area in the 1990s, and second at the global level where climate

change is causing milder winters. The marked increase in water colour (increasing cDOM) in the loch since 1988 revealed by regular monitoring (UKAWMN) is a result both of alleviation from acid deposition and climate change. The relative importance of these two drivers is as yet unclear. What is even more unclear is how this mix of changing environmental conditions that involves both pollution and climate change is affecting the ecology of the loch.

Since the EC Water Framework Directive was adopted as the regulatory guide for maintaining good ecological quality in Britain's inland waters, the emphasis for management has shifted from water quality standards to ecological conditions and ecological quotients based on a comparison with reference or pre-disturbance conditions. Clearly, for the RLGH a consideration of sedimentary diatom records and biomonitoring data shows that not only is the current ecology of the loch well removed from that which prevailed in the mid 19th century but also that change is continuing on a trajectory that is as yet unpredictable. This current study was conceived with the primary aim of mapping diatom diversity and setting baseline data for the 2006/07 period, and secondary aims of relating living benthic diatom communities, most notably the epipelton, to current environmental conditions that relate to spatial attributes such as water depth and light availability. The regular field campaigns have established the spatial distribution of living diatoms throughout the loch in April 2007 and have monitored the distribution of epipellic diatoms on a seasonal basis over a depth transect line of 0 to 9 m depth. At the same time information on water levels and cDOM will enable loss rates of cDOM to be calculated.

In order to generate initial results research was needed on sampling techniques both in the field and in the laboratory. Hence, a new shallow water surface sediment diatom epipelton sampler was developed and harvest methods for repeatable harvesting of diatom epipelton were devised through experimentation with fresh sediments and their communities. The initial results indicate that seasonally there are large changes in the abundance of epipellic diatoms both with depth and with season. Highest numbers of epipelton reached in the summer period, in late July (rather than in spring). Maximum abundance occurs at around 4 m depth and very little is growing below 6 m depth where light levels are much diminished. In less than 1 m depth cell abundance is also low and this is associated with a change in substratum (from organic mud to sand and silt) and with increased turbulence. A similar pattern of growth was observed on the artificial substrata. Grazing seemed to have little effect in controlling cell abundance.

Unexpectedly, there was relatively little zonation in the diatom communities below 1 m depth: the same species were generally present and the most significant changes were in the abundances of living diatom cells. Spatial sampling in April 2007, however, did reveal a strong variation in cell abundance in different parts of the loch. Some species such as *Frustulia rhomboides* var *saxonica* were more abundant on the east side of the loch while *Navicula leptostriata* was more common in the northern sector of the loch. The data are currently being explored in order to try to establish relationships between water depth and light availability and aspect location. Although not exclusively found in one habitat type (soft sediment surfaces, for example) some of the mobile diatoms such as *F. rhomboides* and *N. leptostriata* are indicative of such a substratum whereas other diatoms such as *Tabellaria* and *Eunotia* are much more common on sand grains and rock surfaces. By defining habitat preference groups another approach to reconstructing past variations in light availability can be explored in sediments. In October 2007 a short sediment core was collected from about 12 m depth and close to the end of the regular transect line (T2). This core is being analysed for diatoms at high resolution intervals (2.5 mm or about every 2-3 years) for apportioning to habitat groups. This approach is complicated by the fact that diatom communities have been changing in response to factors other than light availability in recent decades. Nevertheless, a habitat-related influence of species abundance should be detectable. An independent method is also being used to explore water colour changes in the loch. We hope to use a near infra-red spectrophotometric (NIRS) technique for dated sediments, as developed in Sweden, to

reconstruct cDOM concentrations in surface waters of the RLGH. We know that the water level of the RLGH is unlikely to have fluctuated beyond present values in the recent past so any changes in water colour should be related to release rates of cDOM from the catchment peats. Furthermore we can hypothesise that if atmospheric acidity is mainly driving the current rise in cDOM, the NIRS technique should reveal higher values in the pre-acidification phase prior to about 1850.

References

- Battarbee, R. W., Mason, J., Renberg I. & Talling J.F. (eds.) (1990) *Palaeolimnology and Lake Acidification*. University Press, Cambridge.
- DeNicola, D.M. (1996) Periphyton responses to temperature at different ecological levels, in: Stevenson, R.J., Bothwell, M.L., & Lowe, R.L. (Eds.), *Algal Ecology: Freshwater Benthic Ecosystems*. Academic Press, San Diego, pp. 149-181.
- Evans, C.D., Monteith, D.T. & Cooper, D.M. (2005) Long-term increases in surface water dissolved organic carbon: observations, possible causes and environmental impacts. *Environmental Pollution*. 137, 55-71.
- Freeman, C., Evans, C.D., Monteith, D.T., Reynolds, B. & Fenner, N. (2001) Export of organic carbon from peat soils. *Nature* 412, 785.
- Jones, V. & Flower, R. J. (1986) Spatial and temporal variation in periphyton communities: palaeoecological significance in an acidified lake. in: Smol, J. P., Davies, R. B., Battarbee, R. W., & Merilainen J. (Eds), *Diatoms and Lake Acidity*. Dr W. Junk Publishers, Dordrecht. pp. 87-96.
- Hill, W.R. (1996) Effects of light, in: Stevenson, R.J., Bothwell, M.L., & Lowe, R.L. (Eds.), *Algal Ecology: Freshwater Benthic Ecosystems*. Academic Press, San Diego, pp. 121-148.
- Kendall, C. & McDonnell, J.J. 1998. *Isotope Tracers in Catchment Hydrology*. Elsevier, Amsterdam.
- Kingston, J.C., Lowe, R.L., Stoermer, E.F., & Ladewski, T.B. (1983) Spatial and temporal distribution of benthic diatoms in northern Lake Michigan. *Ecology* 64, 1566-1580.
- Kirk, J.T. (1994) *Light and Photosynthesis in Aquatic Ecosystems*. Cambridge University Press, New York.
- Monteith D.T., Stoddard J.L., Evans C.D., de Wit H.A., Forsius M., Hogasen T., Wilander A., Skjelkvale B.L., Jeffries D.S., Vuorenmaa J., Keller B., Kopacek J. and Vesely J. (2007) Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. *Nature* 450: 537-540.
- Rose, N. (2007) *Lochnagar: The Natural History of a Mountain Lake*. Springer, Dordrecht, The Netherlands.
- Stevenson, R.J., & Stoermer, E.F. (1981). Quantitative differences between benthic algal communities along a depth gradient in Lake Michigan. *Journal of Phycology* 17, 29-36.
- Storry, T., 1991. *British White Water*. Constable, London.

Appendix A: Health and Safety Requirements for the Project Work

UCL H&S regulations were followed for all field and laboratory work. Because one participant is a DHPA research student, risk assessment protocols were drawn up accordingly and submitted to the Departmental safety officer. They are entered on the Departmental intranet

1. *Evidence of competency:* Relevant information has already been supplied or is available under staff descriptions on the ECRC website <http://www.ecrc.ucl.ac.uk/>
2. *Health and Safety Policy Statement:*

Statement of Safety Policy for the Department of Geography, University College London

Policy

1. The policy of the Department is to promote the safety, health and welfare of all its staff, students, visitors, contractors and members of the public on the Department's premises and to protect them elsewhere from any adverse effect on their health or safety arising from the activities of the Department.
2. The Department is committed to ensuring that risk assessments are carried out as required by the Management of Health and Safety at Work Regulations 1999 and other regulations. These risk assessments will be made by the staff responsible for the work, set out in writing and signed by the relevant manager or supervisor. No work is permitted to start unless it is covered by a suitable and sufficient assessment of the risks involved in the work.
3. The Department arranges for all work activities to be performed by persons competent to perform those activities. To this end, the Department is committed to ensuring that all members of the Department receive such training as required for them to be able to discharge their tasks and duties in a competent manner.
4. The Department arranges for staff activities and work activities to be supervised by competent people.
5. A person can only be competent in discharging a duty if they accept that duty, understand the responsibility of that duty and are allocated sufficient time to be able to discharge that duty.
6. The Department is a Department of University College London, and as such is responsible to the Provost for the implementation of the arrangements in the College Statement of Safety Policy.
7. To give effect to this policy, the organisation and arrangements as described in this document have been approved and authorised by the Head of Department upon whom rests the ultimate responsibility for the standard of safety within the Department.
8. It is a legal duty for **all** staff, students and visitors in the Department to co-operate with the arrangements for safety set out in this document.

9. This policy is intended to reflect the current state of affairs within the Department. To this end, it will be revised upon any substantial change of organization or arrangements within the Department, and in any case, annually. This policy and its revision will be communicated to all persons affected by the activities of the Department.

ENSIS Statement of Safety Policy

Background

ENSIS was established in 1986 and specialises in the management of multidisciplinary research programmes, particularly those concerned with environmental monitoring. ENSIS is affiliated with University College London (UCL) and operates from the Department of Geography at UCL.

As part of UCL, ENSIS complies with the Safety Policies of both the University and the Department of Geography. This document refers specifically to activities carried out by ENSIS. Full Safety Statements and Policies are available from UCL and Department of Geography, and can be found on the following web sites.

http://www.safety.ucl.ac.uk/public/policies/ssp_65-UC-2.pdf

<http://www.geog.ucl.ac.uk/safety/>

Safety Policy

1. ENSIS is committed to achieving best practice in the management of health and safety by fully controlling risk to health and safety and preventing harm to its staff, students, visitors and all those who may be affected by all its activities.
2. Risk assessments will be carried out as required by the Management of Health and Safety at Work Regulations 1999 and other regulations. These risk assessments will be made by the staff responsible for the work, set out in writing and signed by the relevant project leader or supervisor. No work should start unless it is covered by a suitable and sufficient assessment of the risks involved in the work.
3. All work activities are performed by persons competent to perform them. To this end, ENSIS is committed to ensuring that all staff members receive such training as required for them to be able to discharge their tasks and duties in a competent manner.
4. Staff activities and work activities are supervised by competent people.
5. A person can only be competent in discharging a duty if they accept that duty, understand the responsibility of that duty and are allocated sufficient time to be able to discharge that duty.
6. It is a legal duty for all ENSIS staff, students and visitors to co-operate with the arrangements for safety set out in this document.
7. This policy is intended to reflect the current state of affairs within the company. To this end, it will be revised upon any substantial change of organisation or arrangements within the company, and in any case, annually. This policy and its revision will be communicated to all staff members.

Appendix B: Figures

This figure appendix accompanies the 2008 report on the Round Loch of Glenhead, Galloway and Dumfriesshire. It comprises four sections: field work activities during 2006 and 2007, results of surface sediment diatom analyses along a depth gradient in the loch, results of an assessment of the spatial distributions of diatom species in surface sediments within the loch and measurements of water level change in the loch and its outflow.

1. Fieldwork activities 2006-2007 – Round Loch of Glenhead.

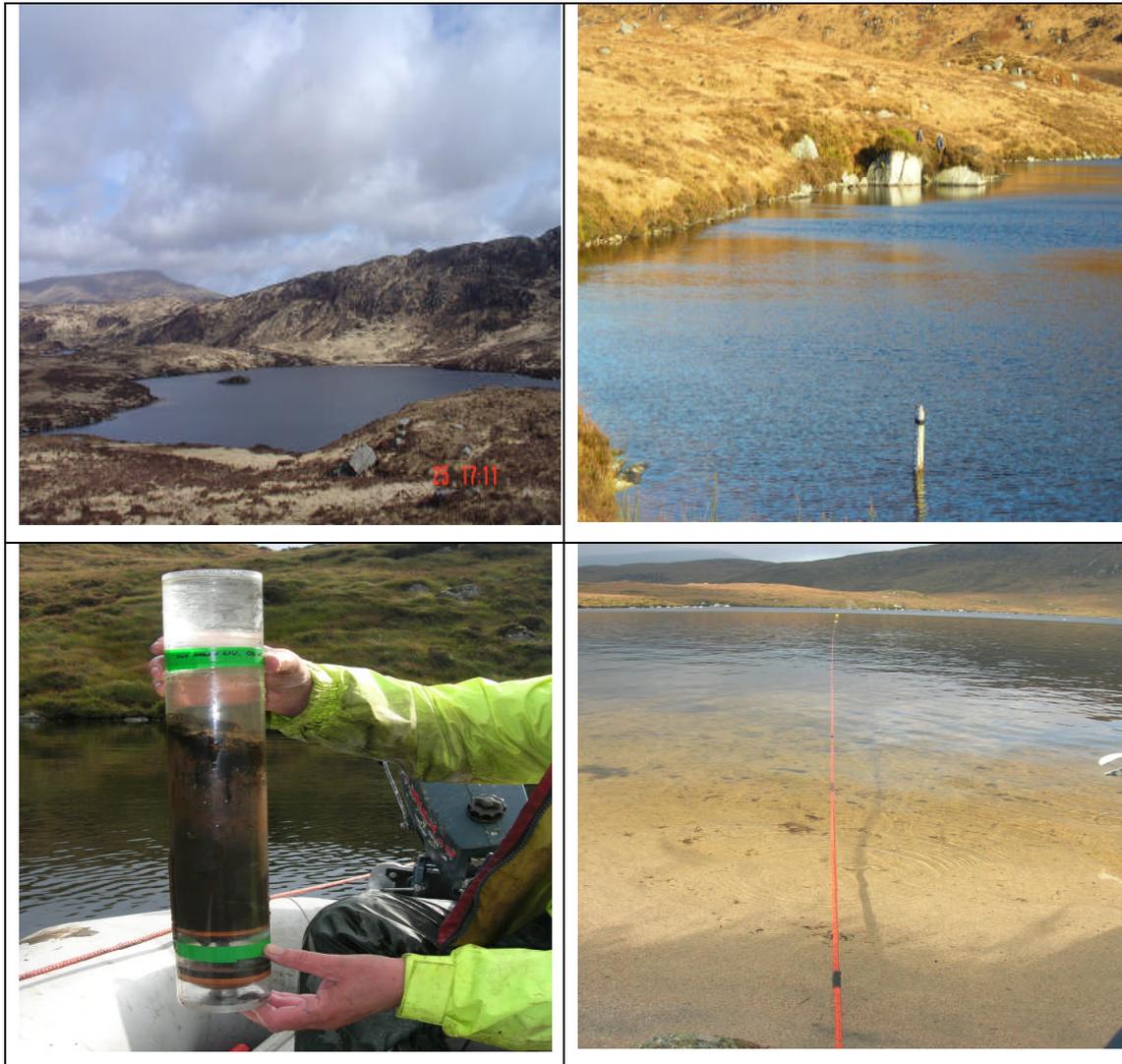


Figure 1. The Round Loch of Glenhead. Upper left: The loch from a southern aspect. Upper right: The stage board for recording water level changes. Lower left: a sediment core collected from the loch in October 2007. Lower right: The surface sediment diatom sampling transect (T2) on the southern shore



Figure 2: The Round Loch of Glenhead. Upper left: soil (peat) water collectors. Upper right: sampling the diatom biofilm (the epipelon) on shallow water sediment. Lower left: retrieving artificial substrates for attached diatoms in October 2008 after 17 months exposure. Lower right: collecting the diatom epipelon sample from within the specially developed sediment sampling device.

Experimental techniques:

Artificial substrata (Sterilin tubes) for diatom colonization were retrieved after more than 15 months exposure at different depths in the loch. An automatic sediment trap was placed in the RLGH in 2007 to intercept sedimenting material at 15 day intervals.



Figure 3. Diatom sampling in the Round Loch of Glenhead. Left: diatom growth on artificial substrata after 17 months exposure at depths 40 cm (left) to 2m. Right: the automated sediment trap removed from the loch in October 2007 after 6 months exposure (see main text).

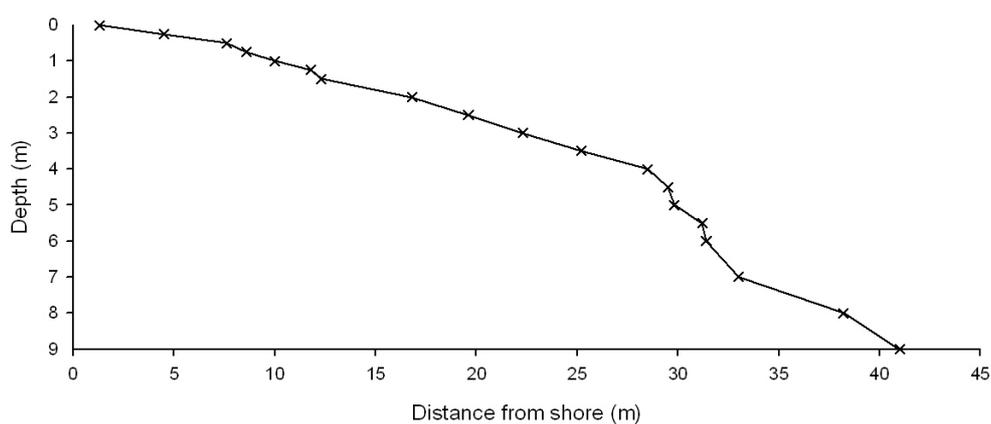


Figure 4. The water depth profile of the sampling transect used to deploy the artificial substrata for diatom colonization. The transect was near transect 2 (see Fig 1) and extended across the littoral area from the southern shore of the Round Loch of Glenhead to a depth of 9 m.

2. Preliminary results of diatom analyses of surface sediments along the depth transect, T2 - Round Loch of Glenhead

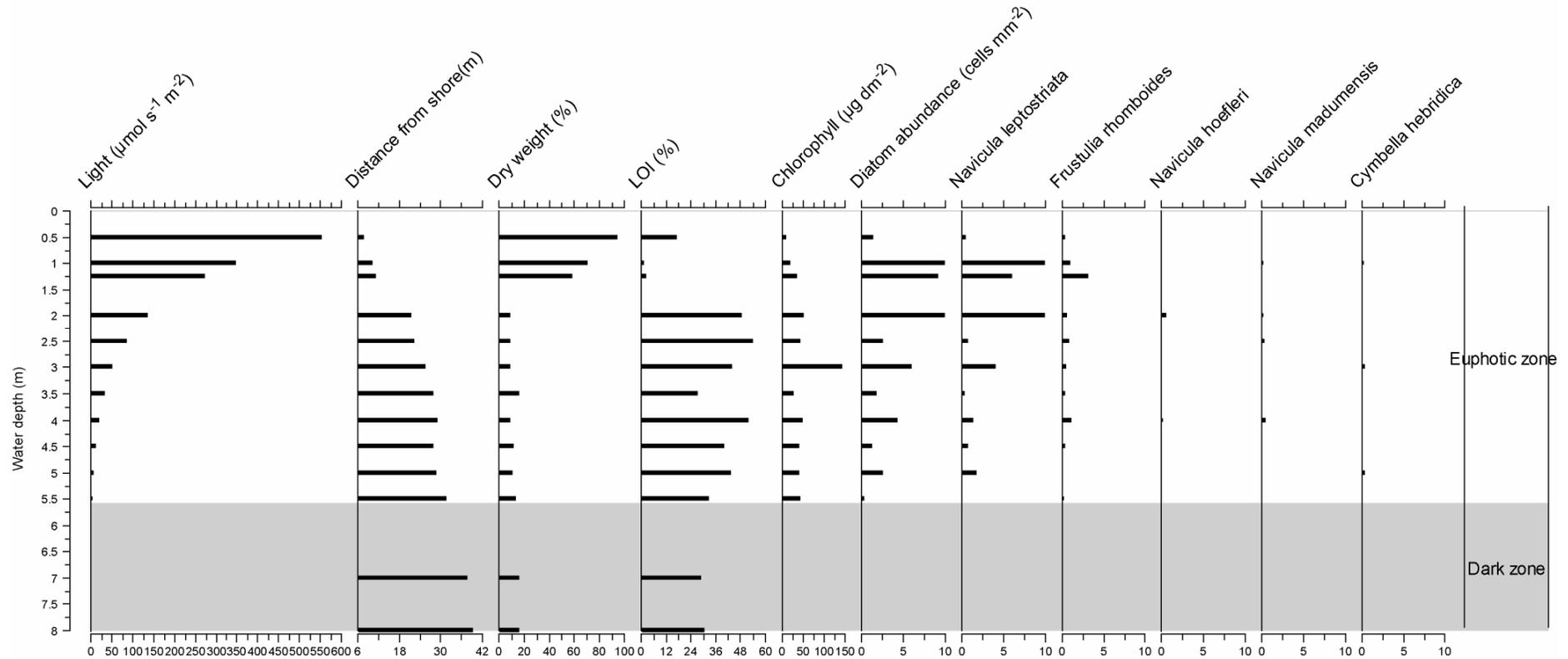


Figure 5. Distribution of motile diatom (cells mm^{-2}) and environmental variables along transect in the Round Loch of Glenhead in April 2006. From left to right: light attenuation, distance, sediment % dry weight of the wet weight, organic matter, chlorophyll concentration, number of motile diatoms cells mm^{-2} , numbers of individual common diatom species.

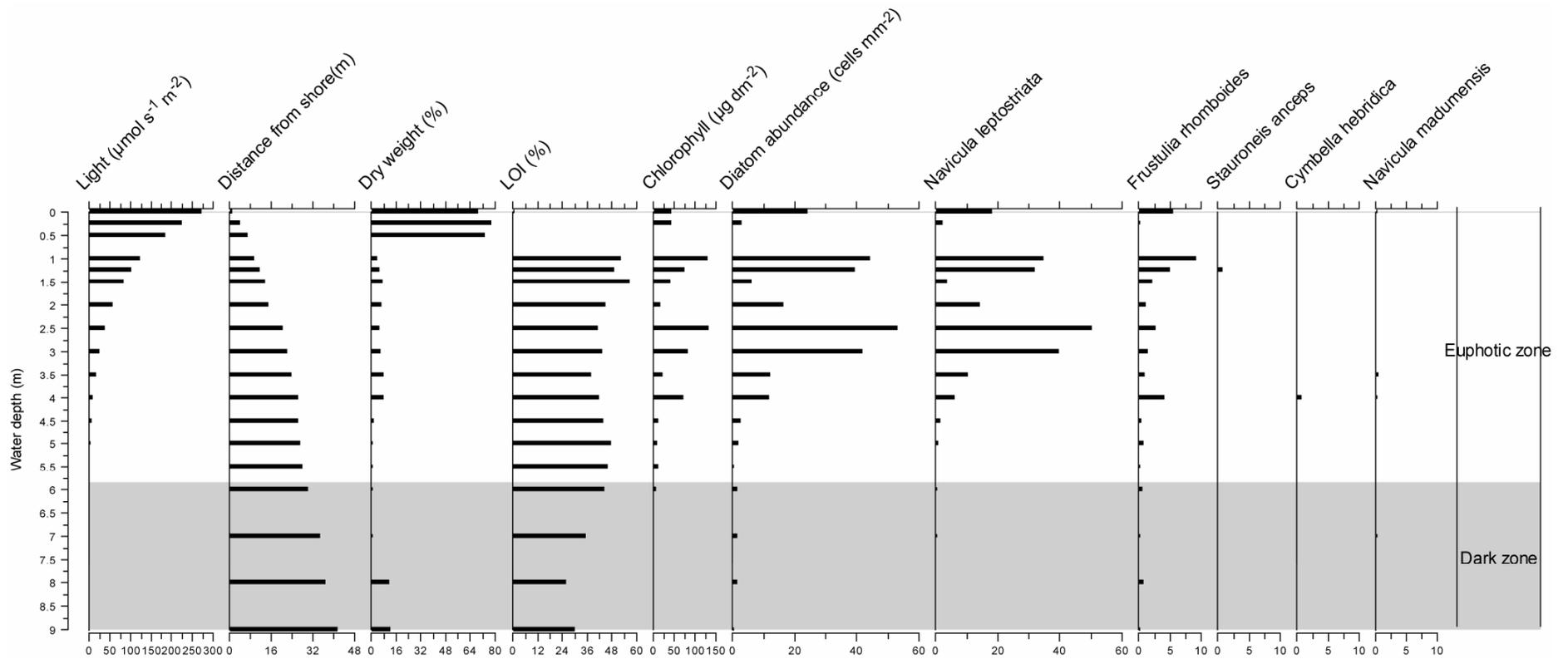


Figure 6. Distribution of motile diatom (cells mm^{-2}) and environmental variables along transect in the Round Loch of Glenhead in July 2006. Details as for Figure 5.

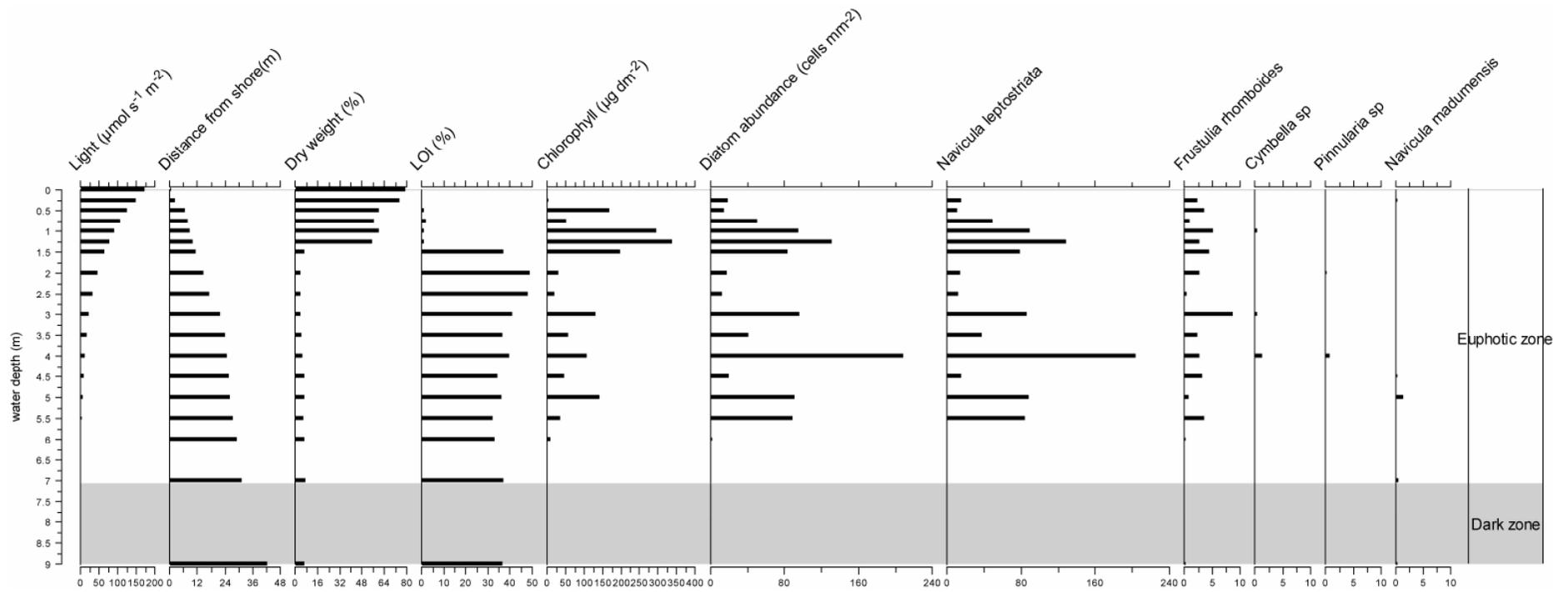


Figure 7. Distribution of motile diatom (cells mm^{-2}) and environmental variables along transect in the Round Loch of Glenhead in October 2006. Details as for Figure 5.

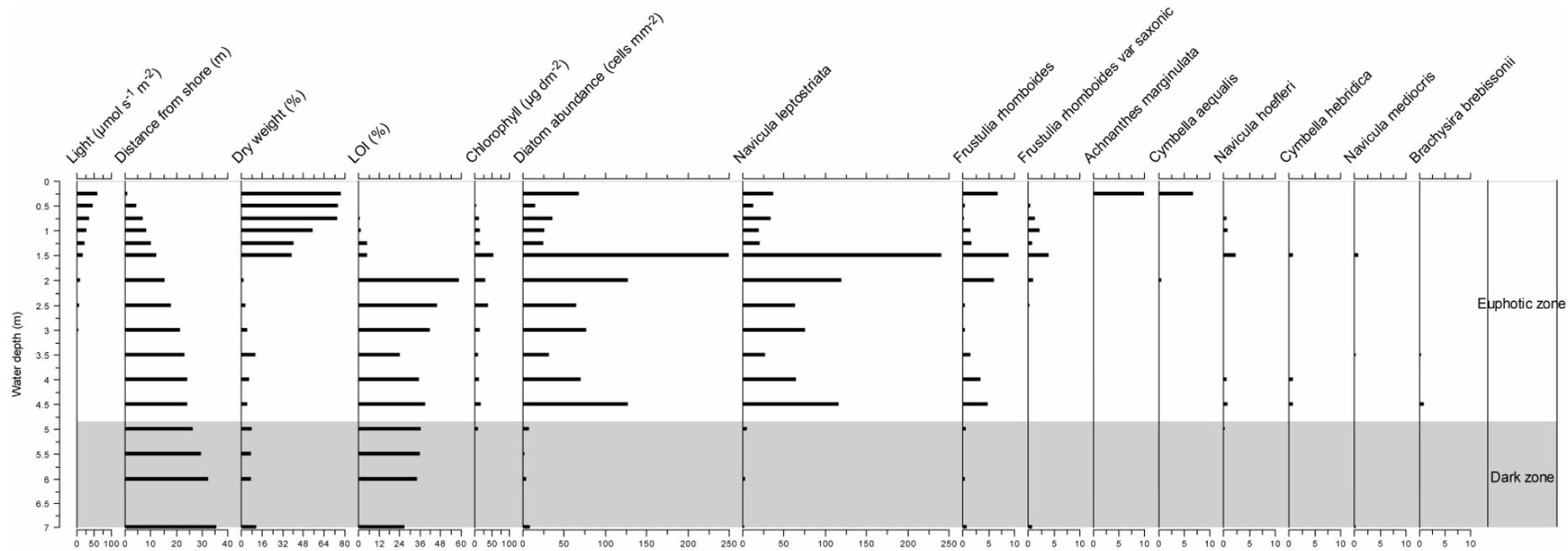


Figure 8. Distribution of motile diatom (cells mm^{-2}) and environmental variables along transect in the Round Loch of Glenhead in January 2007. Details as for Figure 5.

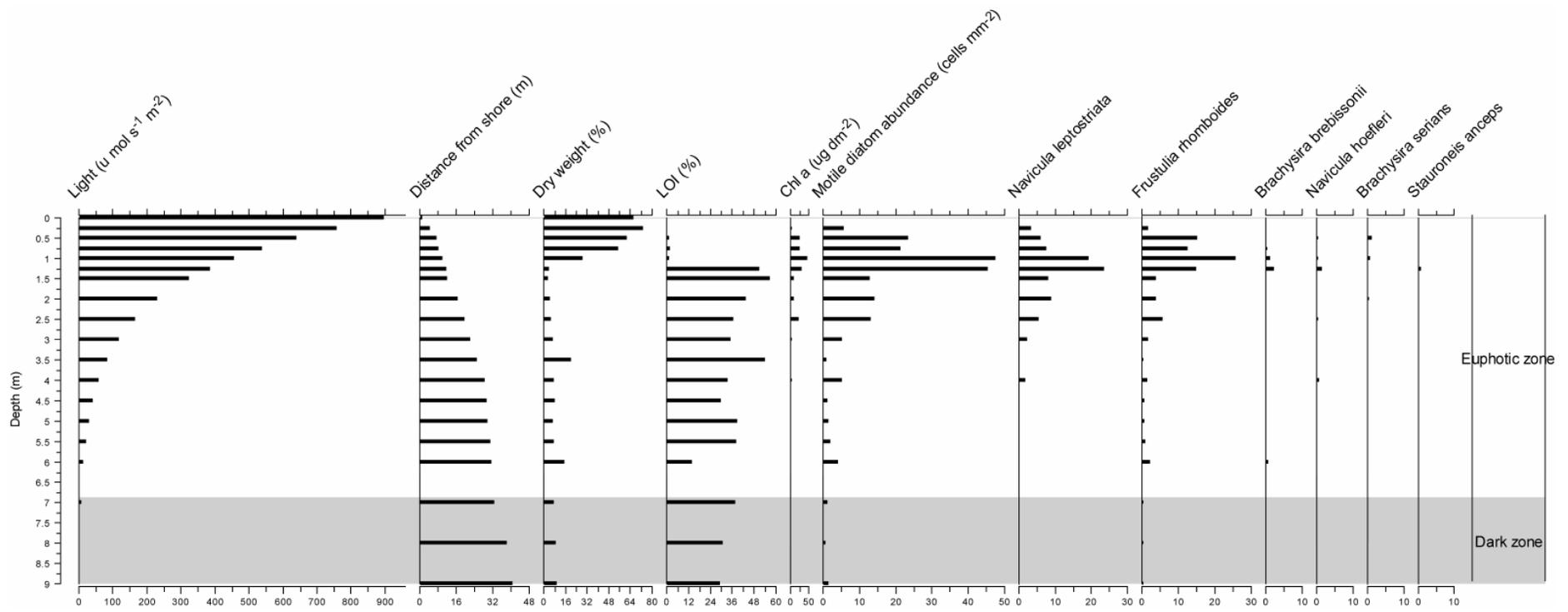


Figure 9. Distribution of motile diatom (cells mm^{-2}) and environmental variables along transect in the Round Loch of Glenhead in April 2007
 Details as for Figure 5.

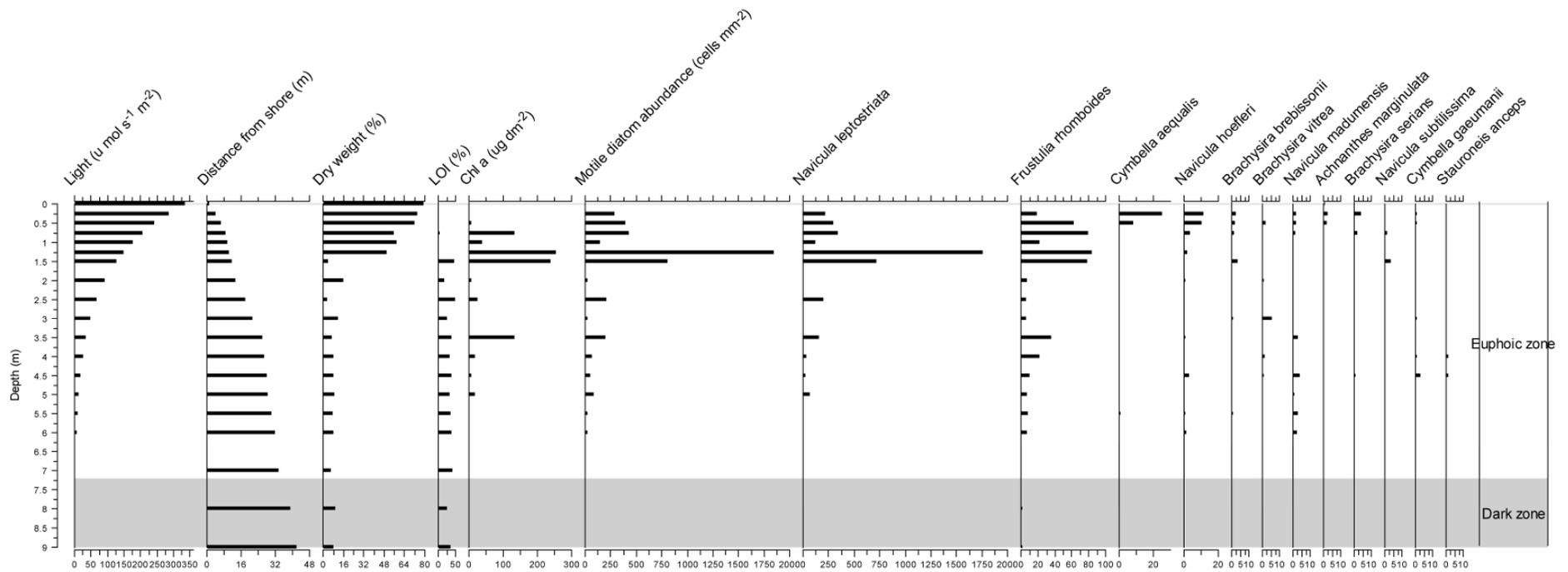


Figure 10. Distribution of motile diatom (cells mm^{-2}) and environmental variables along transect in the Round Loch of Glenhead in July 2007. Details as for Figure 5.

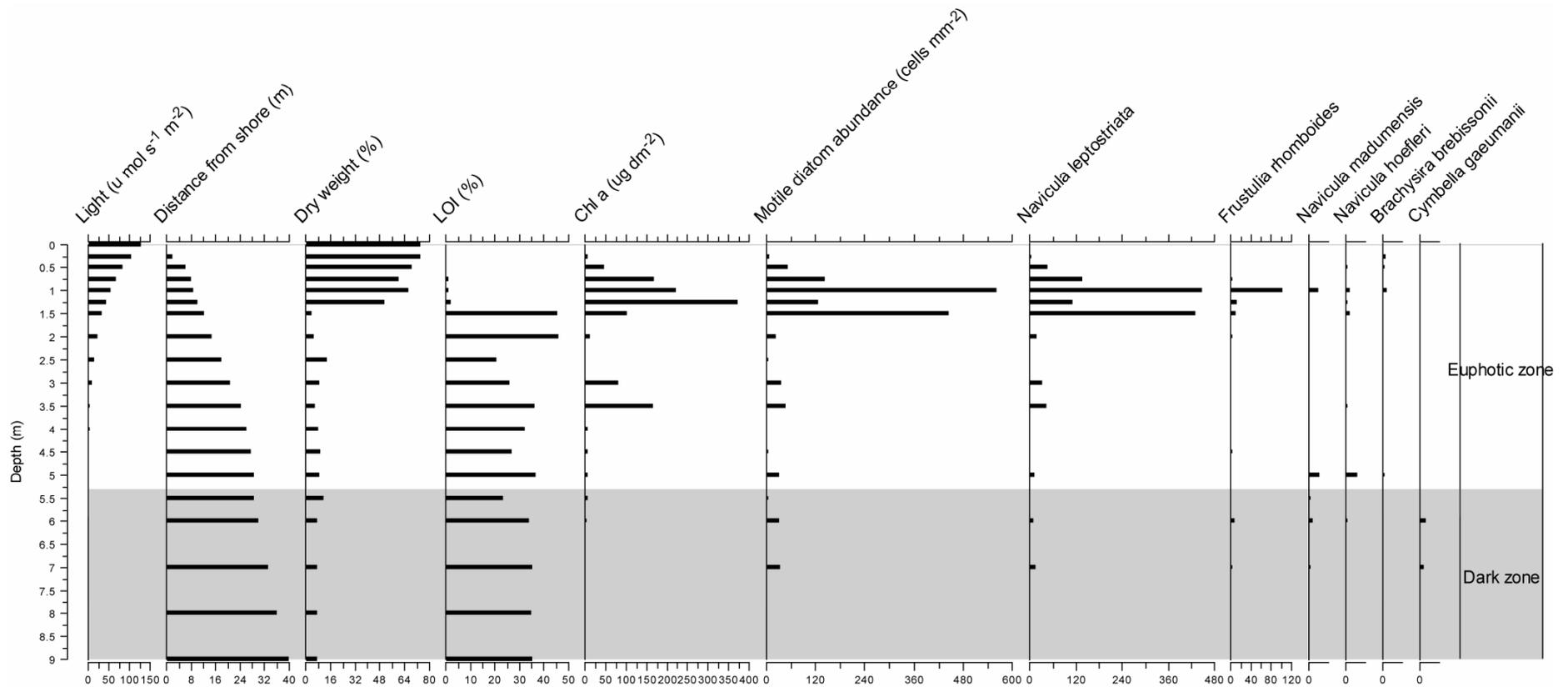


Figure 11. Distribution of motile diatom (cells mm^{-2}) and environmental variables along transect in the Round Loch of Glenhead in October 2007. Details as for Figure 5

3. Spatial environmental characteristics and surface sediment diatom distributions - Round Loch of Glenhead

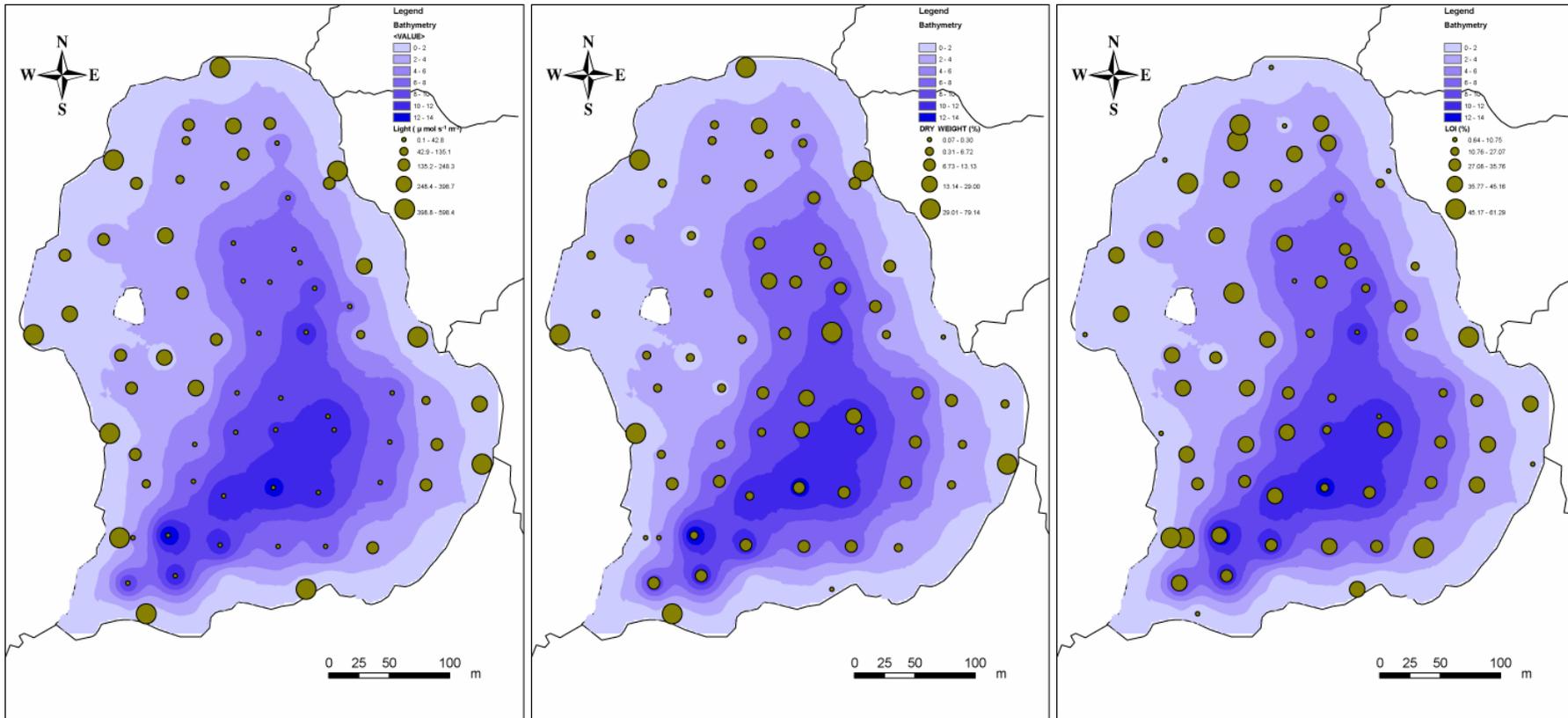


Figure 12. Bathymetric map of the Round Loch of Glenhead showing depth zones. Left: the spatial distribution of light. Middle: sediment % dry weight. Right: % organic content (LOI). The environmental variables were measured in April 2007

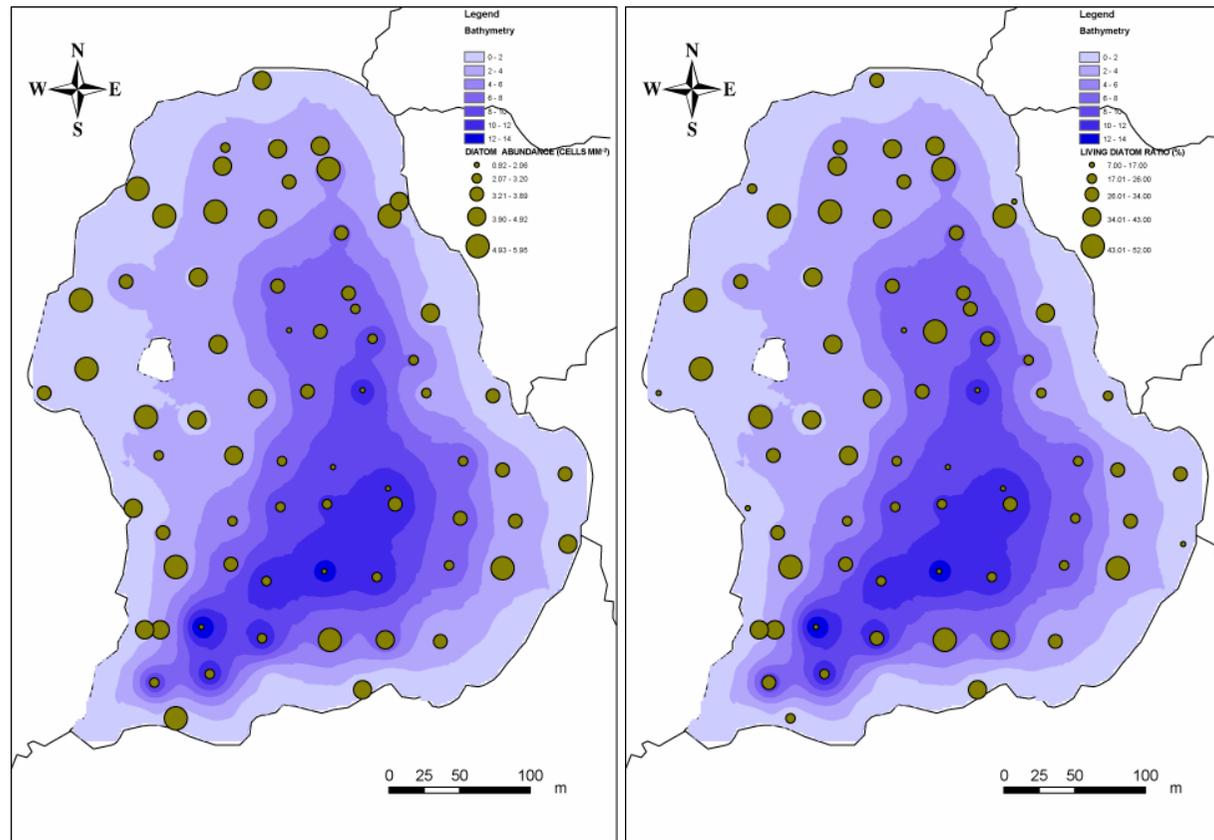


Figure 13. Spatial distribution of living diatoms in Round Loch of Glenhead surface sediment, April 2007. Left: the abundance of cells mm⁻². Right: the living diatom to total diatom ratio (%).

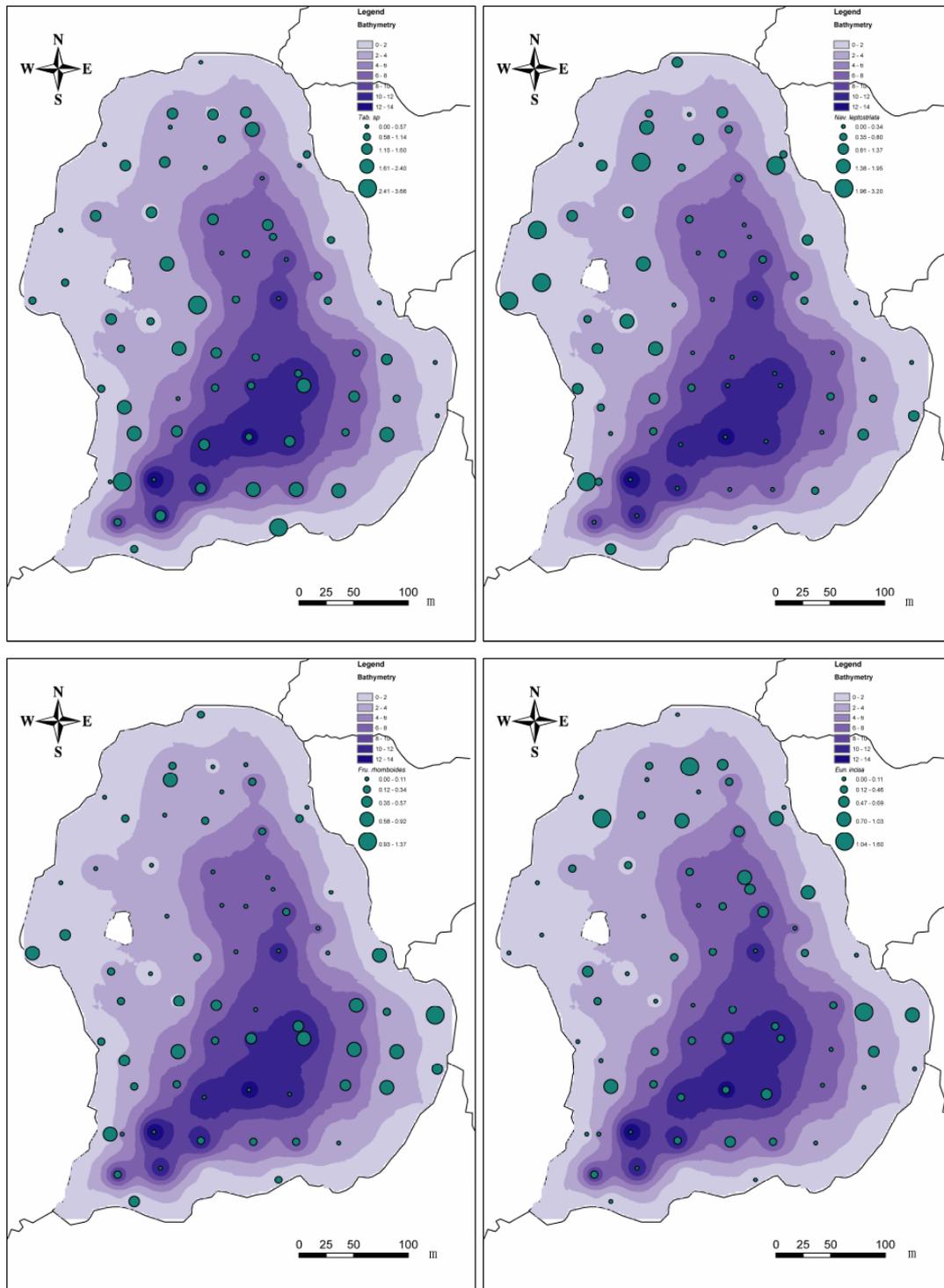


Figure 14. Spatial distribution of individual species of living diatoms as cells mm⁻² in fresh sediments in the Round Loch of Glenhead in April 2007. Upper left, *Tabellaria* sp. Upper right, *Navicula leptostriata*. Lower left, *Frustulia rhomboides*. Lower right, *Eunotia incisa*.

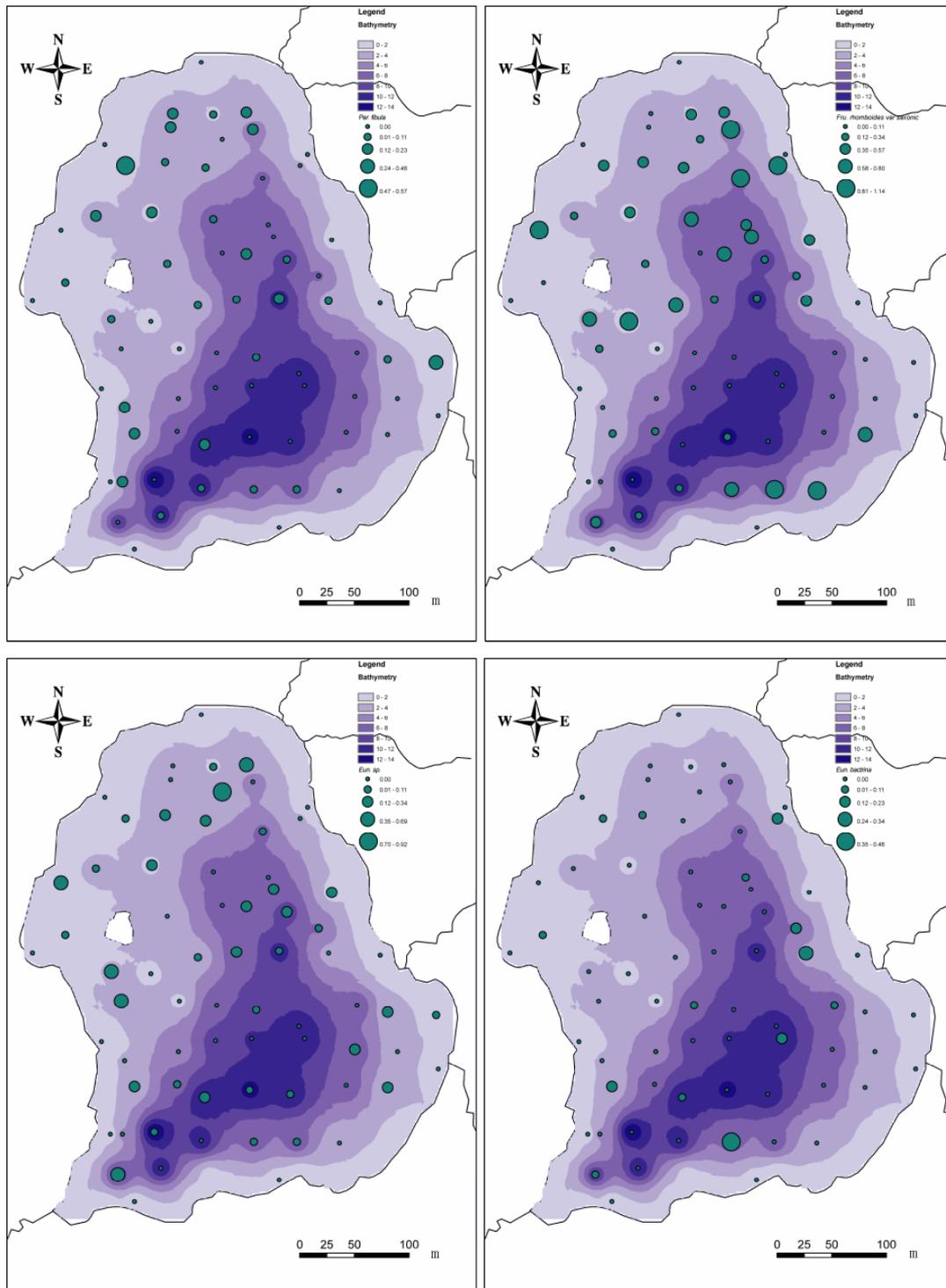


Figure 15. Spatial distribution of individual species of living diatoms as cells mm^{-2} in fresh sediments in the Round Loch of Glenhead in April 2007. Upper left, *Peronia fibula*. Upper right, *Frustulia rhomboides var saxonica*. Lower left, *Eunotia sp.* Lower right, *Eunotia bactriana*.

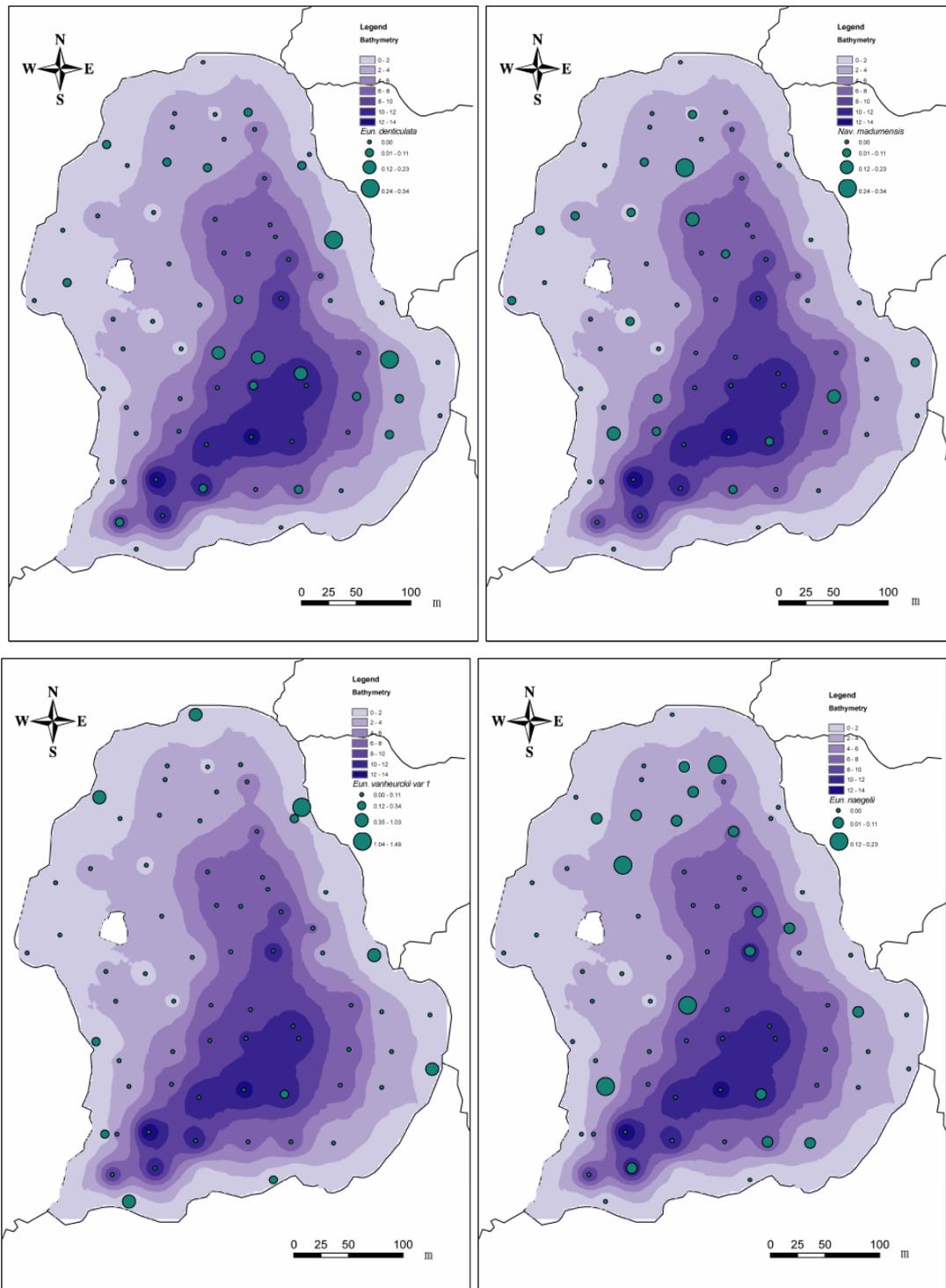


Figure 16. Spatial distribution of individual species of living diatoms as cells mm⁻² in fresh sediments in the Round Loch of Glenhead in April 2007. Upper left: *Eunotia denticulata*. Upper right: *Navicula madumensis*. Lower left, *Eunotia vanheurckii* var f. Lower right, *Eunotia naegelii*.

4. Water level and temperature changes in the Round Loch of Glenhead.

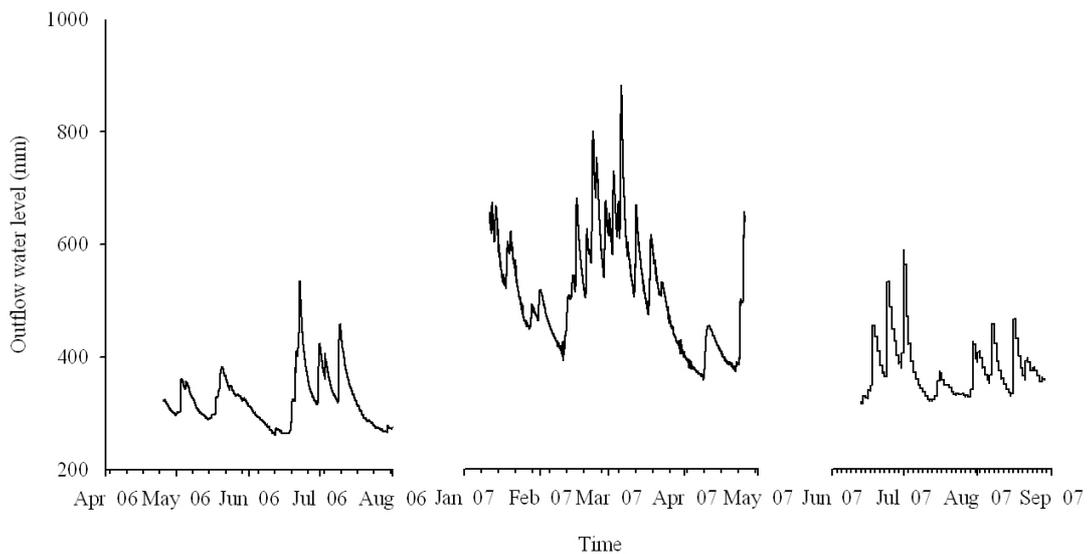


Figure 17. Variation of water level (mm) in the outflow stream from the Round Loch of Glenhead during the periods 25th April to 31st July 2006, 11th Jan to 25th April 2007 and from 13th June to 29th Aug 2007. (Note that some data are missing due to equipment failure)

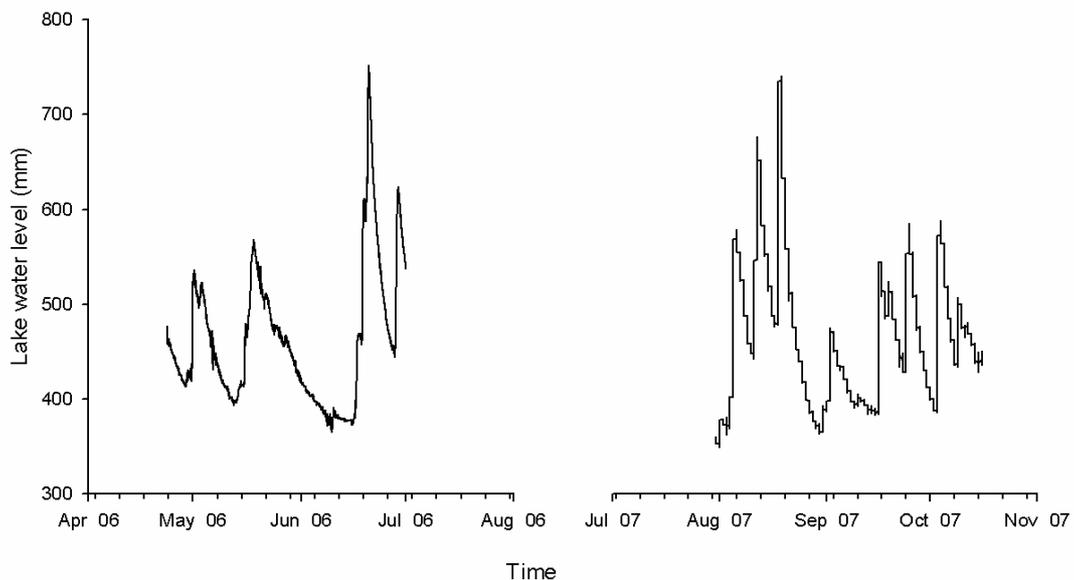


Figure 18. Variation of water level (mm) of the loch during the periods 25th April to 31st July 2006 and from 31st July to 16th Oct 2007. (Note that some data are missing due to equipment failure)

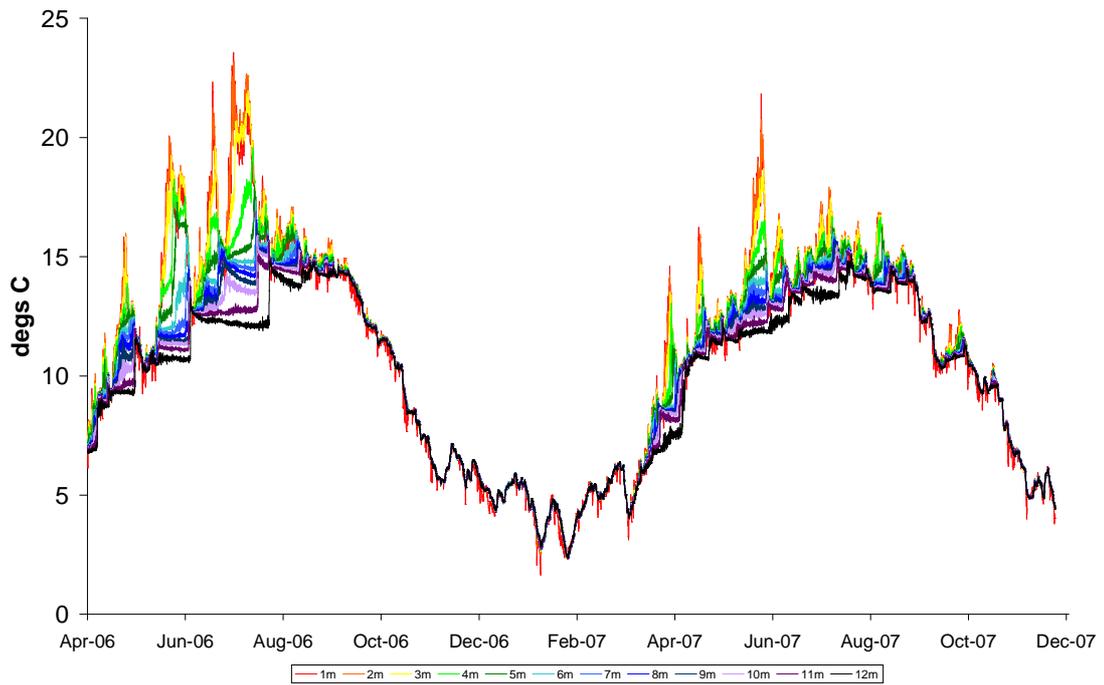


Figure 19. Water temperature traces for the period April 2006 to December 2007 recorded at 12 water depths (between 1 m to 12 m depth) in the Round Loch of Glenhead.