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Contribution of sediment focusing to heterogeneity of organic carbon and phosphorus burial in small lakes

Eleanor B Mackay[1,2], Ian D Jones[1], Andrew M Folkard[2] and Philip Barker[2]

[1]Lake Ecosystem Group, Centre for Ecology & Hydrology, Bailrigg, Lancaster LA1 4AP, United Kingdom

[2]Catchment & Aquatic Processes Group, Lancaster Environment Centre, Lancaster University, Lancaster LA1 4YQ, United Kingdom

Corresponding author

Eleanor Mackay,

email: e.mackay@lancaster.ac.uk

Telephone: +44(0)1524 595852

Fax:+44(0)1524 61536

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Summary

1. Sediment distributions within lakes are typically heterogeneous. Much of our understanding comes from the study of large and/ or shallow lakes, where wave mixing is the dominant sediment focusing mechanism.

2. We elucidated the heterogeneity of surface sediment distribution in a small lake, Esthwaite Water (UK). We considered multiple focusing mechanisms (downslope gravitational transport, waves, and wind-driven currents) and their effect on multiple sediment variables (water content, organic content, total phosphorus and benthic diatom taxon richness). In particular, we investigated the implications of different focusing processes for calculations of burial rates of organic carbon and total phosphorus. We used a new, high-resolution bathymetric survey of the lake in our calculations and compared the results to those from an earlier low-resolution bathymetric survey.

4. Wave-driven focusing and downslope gravitational transport were not significant in Esthwaite Water. However, calculated wind-induced current speeds were sufficient to mobilise small particles at all depths of the lake and therefore could potentially be an important resuspension process in small lakes.

5. We calculated that approximately half of the phosphorus entering the lake is retained in the sediments. This has important implications for the ability of the lake to recover from eutrophication because of the prolonged internal phosphorus loading capability.

6. Differences in calculated burial rates due to sediment heterogeneity were much larger than those due to the difference in bathymetric resolution. Ignoring sediment heterogeneity when calculating flux-to-lake bed rates for organic carbon and total

phosphorus can lead to large inaccuracies, with implications for burial rate and budget studies.

Introduction

Calculating the store of carbon, phosphorus or other particulates in lake sediments is problematic due to an uneven input of sediment and subsequent reworking within the lake. Lake sediment distribution is widely regarded to be heterogeneous, especially in large lakes, and is determined by several sediment transport, deposition and re-suspension processes, which vary spatially (e.g. Hilton & Gibbs, 1984; Cyr, 1998) and whose effects vary according to the effective sediment particle size and density (Hilton, Lishman & Allen, 1986; Rowan, Kalff & Rasmussen, 1992).

This paper is concerned with understanding sediment heterogeneity for the calculation of burial rates of nutrients and organic matter, for which sediments may be active sources or sinks (e.g. Baudo *et al.*, 1989; Søndergaard, Jensen & Jeppesen, 2003; Trolle *et al.*, 2008). While spatial heterogeneity in sediment is widely recognised, the estimation of burial rates or lake-wide fluxes of materials such as organic carbon do not often reflect this (e.g. Downing *et al.*, 2008; Anderson, D'Andrea & Fritz, 2009; Finlay *et al.*, 2010). Similarly, the general applicability of existing models used to explain this spatial heterogeneity still needs to be demonstrated, particularly in the case of small lakes.

Central to the study of sediment distribution in lakes is the concept of 'sediment focusing', a term used to describe the tendency of fine-grained sediments to be concentrated in deeper parts of the lake. Focusing occurs because the dominant sediment resuspension and transportation processes tend to be strongest near the water surface, and to decay in strength with depth. Thus sediments will tend to be resuspended and transported out of shallower areas until they reach a sufficient depth that these processes no longer affect them significantly. Therefore, this spatial process can be related to near-shore zones of re-suspension and transportation and deep-water zones of accumulation (Håkanson & Jansson, 1983; Blais & Kalff, 1995). The spatial extent of these zones depends on factors relating to the size and depth of the lake (e.g. fetch, wind speed, water depth and lake slope), which govern the physical processes (waves, currents, gravitational slope failure) controlling resuspension.

In addition to these physical processes, bioturbation of sediments by animals enhances or causes resuspension in some shallow lakes where benthivorous fish populations are high (Breukelaar *et al.*, 1994; Carvalho & Moss, 1995; Moss, Carvalho & Plewes, 2002; Tarvainen *et al.*, 2005; Jackson *et al.*, 2010). Lower rates of decomposition in deeper water may also contribute to the sediment distribution patterns of organic matter, however this is likely to be superimposed on the physical focusing processes, rather than an alternative to it (Jones, 1980; Wetzel, 1983).

One cause of sediment focussing is gravity-driven bed slope failures, whose effect is largely governed by the gradient of the lake bed. Slumping, sliding and turbidity currents are the main processes of this kind (Håkanson & Jansson, 1983). Very little active movement due to these processes is expected on slopes with a gradient of <4%, while little accumulation is anticipated for slopes >14% (Håkanson, 1977). Therefore mean basin slope has been used to categorise sediment focusing patterns among lakes, where lakes with lower basin slopes are anticipated to have larger sediment accumulation areas (Blais & Kalff, 1995). While this provides a means for comparing between lakes, it does not give a clear indication of the within-lake processes, as site slope and mean basin slope between contours have not been found to be significant indicators of the accumulation area (Blais & Kalff, 1995). It is reasonable to assume that increased accuracy in lake bathymetry will lead to increased accuracy in predictions of slope-generated resuspension and focussing.

Wave mixing has been suggested to be the dominant process causing sediment focusing for many lakes (Håkanson, 1977; Rowan *et al.*, 1992). Wind-induced surface waves have their energy confined to a near-surface layer, whose depth is approximately a half of their wavelength, known as the 'wave mixed layer' (Smith & Sinclair, 1972). When the mixing caused by wave motion in this layer interacts with the lake bed, it can resuspend particles. Wave-induced resuspension is important in large lakes where waves are large and energetic, creating deep wave-mixed layers (Håkanson, 1977; Rowan *et al.*, 1992; Cyr, 2009) and in shallow lakes where wave-mixed layers frequently reach the lake bed (Hamilton & Mitchell, 1997; Spears & Jones, 2010). However, very few studies have considered whether wave mixing is important in small, deep lakes (on the order of 1 km^2 or less), where fetches are relatively short and thus wave-mixed layer depths relatively shallow. Furthermore, accurate prediction of wave mixing requires detailed knowledge of the wind. As frictional drag over the water surface is sufficiently different from that over land, effective predictions of wave-mixing will require wind speed measurements taken over the lake itself.

Few studies examining sediment focusing have considered whether wind-induced currents might be important for sediment resuspension and focusing, particularly for small lakes. These currents are directly related to the strength of the wind blowing over the lake surface (Smith, 1979). At a simplified level, during isothermal conditions, current speed declines exponentially with depth and, as described by the law of the conservation of mass, a return current is generated in the opposing direction (Smith, 1979). These currents cause resuspension below the wave-mixed layer and are important in the offshore transport of sediments in large lakes (Lemmin & Imboden, 1987; Hawley *et al.*, 1996; Hawley & Lee, 1999). Under stratified conditions, currents and mixing below the thermocline are likely to be strongly suppressed (Wüest & Lorke, 2003). Seiching has however been found to resuspend sediments, either by breaking against the lake side, or as a 'burst-like' motion at the lake bottom in more central locations (Gloor, Wüest & Munnich, 1994; Shteinman *et al.*, 1997).

Resuspension potential is also related closely to particle size and composition; smaller and less dense particles are more readily entrained into the water column (Miller, McCave & Komar, 1977; Gloor *et al.*, 1994). Understanding the fate of small particles within lake systems is important because they are often associated with heavy metal contaminants and phosphorus (Williams, Jaquet & Thomas, 1976; Schorer, 1997; Andrieux-Loyer & Aminot, 2001). The cohesive properties of sediments, such as the behaviour of colloidal particles and the tendency of organic material to form aggregates (Alldredge & McGillivary, 1991), can result in an increase in effective grain size, thereby increasing the critical shear required for resuspension (Håkanson & Jansson, 1983).

In the past, the definition of sediment accumulation zones has been based on the distribution of a single sediment variable such as water content as a proxy for grain size (e.g. Håkanson, 1977; Rowan *et al.*, 1992; Blais & Kalff, 1995). The transition from the zones of re-suspension and transport to that of accumulation has then been assumed to be identified by an abrupt change in the depth profile of this variable (Blais & Kalff, 1995; Anderson *et al.*, 2008). Here, we hypothesise that these single variable-based focusing models used to predict areas of accumulation do not explain the depth distribution of all sediment variables, particularly those associated with small particle sizes. Furthermore, our understanding of sediment distribution is dominated by results from large and shallow systems. Much less is known in this respect about small, deep lakes, yet their ubiquity (e.g. Downing *et al.*, 2006) makes them important components in global biogeochemical cycles.

In this study, we examined the extent to which estimates of different sediment distribution processes (slope failures, wave mixing and wind-induced current shear) accounted for the heterogeneity observed within the surface sediments of a small lake by testing the adequacy of focusing models. In order to predict wave-mixed depths and wind-induced currents we used continuously monitored wind data measured by a buoy on the lake. To assess the effect of slope processes we used a far more detailed bathymetry of the lake than previously existed. Burial rate and whole lake flux-to-bed rates of organic carbon and total phosphorus were calculated using three methods. The first used the established method of a single site in the deepest part of the lake, the second used the predictions provided by each sediment distribution process, and the third was a depth-integrated measure (taken to be the true estimate). We compared the results of the first two methods to that of the depth-integrated measure to calculate the errors in these predictions and contrasted these errors with the differences between values calculated using two different resolution bathymetries. The work expanded on a previous study of Hilton *et al.* (1986), by providing a directly quantitative approach to elucidating the processes responsible for the distribution patterns of different sediment variables. The total phosphorus burial rate was also compared with previous phosphorus budget measures to examine the lake’s capacity for phosphorus retention.

Methods

Study site

Esthwaite Water (54º21'N, 3º0'W) is a lake of glacial origin, forming a part of the larger Windermere catchment within the southeastern area of the English Lake District. Based on a new bathymetry of the lake (see below), it has a surface area of 0.96 km^2, a total volume of 6.7×10^6 m^3, and an average depth of 6.9 m (Fig. 1 and Table 1). Esthwaite Water contains three basins, which are separated by sills. The northernmost basin is the largest (0.54 km^2) and deepest (maximum depth 16 m) and was where the sampling for this study took place.

The biological, chemical and physical characteristics of the lake have been previously described (Mortimer, 1941; Sutcliffe *et al.*, 1982; Talling & Heaney, 1988; George *et al.*, 1990; George, 2000). High-resolution meteorological data were provided by the UK Centre for Ecology and Hydrology (CEH) Automatic Water Quality Monitoring Station (AWQMS) in the north basin of the lake and a meteorological station on the shore (see Rouen, George & Hewitt, 2001; Madgwick *et al.*, 2006 for more details), from which data have been collected with hourly resolution from 2005.

Field and laboratory methods

A bathymetric survey of the lake was undertaken on 21 May 2009 using a BioSonics DT-X echo sounder (Biosonics Inc, Seattle, USA) with a 200 kHz split-beam vertical transducer of beam angle 6.5°. The data threshold was set at –70 dB, the pulse rate at 5 pulses s^{-1}, pulse width at 0.4 m and data recorded at a range of 2 m from the transducer. Navigation along 39 transects was undertaken with a Garmin GPSMAP 60CSx GPS (Global Positioning System) (www.garmin.com) with an accuracy to less than 10 m, while a JRC Model DGPS212 GPS (www.jrc.co.jp) with an accuracy to less than 5 m inputted location data directly to the hydroacoustic system to provide spatial position for the data. The detection of the depth of the lake bottom was undertaken using Sonar5-Pro Version 5.9.6 software (Lindem Data Acquisition, Oslo, Norway, www.fys.uio.no/~hbalk/sonar4_5). The lake bottom data were imported into ESRI ArcMap (www.esri.com) where Triangulated Irregular Network (TIN) and raster surfaces were created with the data and contours calculated from the raster surface. This survey represents a much higher resolution and more accurate bathymetry than a previous study by Ramsbottom (1976) undertaken in the 1930s, with an increase of two and half times in the number of transects surveyed.

Sediment cores were collected at 29 sites during the spring and summer of 2009 using a Jenkin corer (Jenkin & Mortimer, 1938) for deep sites and manually pushing a core tube into the sediment at very shallow sites. Sites were selected both to cover a wide range of water depths and to provide good spatial coverage of the basin. To avoid discrepancies in accumulation caused by the presence of the stratification, the summer samples were taken only from depths within the epilimnion. The top 2 cm of sediment from the cores were extruded, sliced and then frozen on the day of sampling for later analysis. Water depths were recorded with a Plastimo Echotest II (Southampton, Hampshire, UK) echo sounder in deeper water and a weighted graduated line in shallow water.

Water content for the samples was determined by pre- and post-weighing of well mixed sub-samples dried at 60˚C for 24 hours. Organic content was determined as loss-on-ignition (LOI) then by ashing at 550˚C for three hours. Total phosphorus concentration was determined using the molybdenum blue reaction on a SEAL AQ2 auto analyser (Seal Analytical Ltd., Fareham, Hampshire, UK) following a two hour hot sulphuric acid-hydrogen peroxide digestion (Rowland & Grimshaw, 1985).

Particle size analysis was carried out on a Malvern Mastersizer 2000 (Malvern Instruments Limited, Malvern, Worcestershire, UK) after heating for three hours in hydrogen peroxide to remove organic material and passing through a 2 mm sieve. Diatom slides were prepared following Battarbee (1986). Counts up to 200 frustules were made on each slide to species or genus level to provide a measure of taxon richness as a simple indicator of the dispersal of benthic (littoral) taxa across the lake.

Wind speed was measured at 2.9 m above the lake’s surface with a Vector A100L2-WR cup anemometer with optical rotation sensing (Vector Instruments, Rhyl, Wales) obtained as hourly averages from the AWQMS buoy in the north basin of the lake. As the buoy is a rotating platform, wind direction data were obtained as hourly averages from a Vector W200P-WR wind vane (Vector Instruments, Rhyl, Wales) measured at 4.9 m above the water surface at an unsheltered location on the shore of the north basin of the lake.

Data analysis and statistical methods

The influence of particle size and density on the distribution pattern of different sediment characteristics was examined for a representative range of sediment variables. Water content was taken to characterize typical whole sediment bulk density measures, organic content (as LOI) provided a measure of low-density sediment comprising a range of grain sizes and the distribution of total phosphorus and benthic diatom taxon richness were taken as independent measures of small particle sizes. Phosphorus is often associated with small particles (e.g. Pacini & Gächter, 1999) reflecting their large surface area to volume for binding sites (Froelich, 1988). In Esthwaite Water, approximately 83% of total phosphorus is labile, reductant-soluble and metal oxide-adsorbed phosphorus (Spears, unpublished data). In a study of Lake Võrtsjärv (Nõges & Kisand, 1999), these forms of phosphorus were most associated with finer, soft sediments. Benthic diatoms, are also representative of small size fractions (<40 μm) (e.g. Kelly *et al.*, 2005). They will grow actively only in the photic zone, which extends to ≈2.5 m depth in Esthwaite Water (Maberly *et al.*, 2006). High diatom diversity in this shallow water is associated with the large number of habitat niches present (e.g. epipelic, epilithic, epipsammic and epiphytic) (Round, Crawford & Mann, 1990). Occurrence of these benthic taxa in deeper water was therefore interpreted as a tracer of resuspension and transport of the diatom frustules.

Three focusing models and direct measurements of slope were tested to examine whether they can account for the heterogeneity in the surface sediment characteristics of the four variables defined above (water content, organic content, total phosphorus concentration and benthic diatom taxon richness). These are divided into lake bed gradient and wave-mixing models. In addition, the resuspension potential for wind-induced currents was assessed.

Lake bed gradient

Bed slope was calculated at each sampling site from the lake bathymetry using the Spatial Analyst slope analysis function in ESRI ArcMap. In addition, the mean basin slope α'_p (%) was calculated as (Blais & Kalff, 1995):

$$\alpha'_p = (l_0/2 + l_1 + l_2 + _{\dots} + \ l_{n-1} + \ l_n/2) Z_{max}/10nA_L \ , \qquad (1)$$

where l_0 is the length of the shoreline (km), l_i and n are the lengths (km) and number of the contour lines respectively, Z_{max} is the maximum lake depth (m) and A_L is the lake surface area (km^2). This was used to predict the percentage of the lake bed surface occupied by the accumulation area (*%ZA*) using:

$$\%ZA = 49.92(\pm 3.73) - 2.50(\pm 0.31)\alpha'_p \ , \qquad (2)$$

from Blais & Kalff (1995). To estimate the average depth of the transition to the accumulation zone, *%ZA* was compared to the hypsometric curve of the lake calculated from the bathymetric data. The calculation of *%ZA* was also carried out using the bracketed standard error estimates in Equation (2) to give a predicted error for the transition estimate.

Wave mixing

Wind data from 2008 were used for all wave mixing and wind-induced current calculations; it was representative of a recent five-year period 2005 – 2009 (average and average maximum wind speeds 2.3 m s^{-1} and 13 m s^{-1}). Wave theory was used to predict wave-mixed-layer depth, Z_c (m), as a function of the maximum wind speed and effective fetch across a lake (Smith & Sinclair, 1972). To calculate Z_c, an effective fetch, F_e (m), for each coring site and for sites forming a 100 m grid across the lake was calculated in ESRI ArcMap using the USGS Wind Fetch Model (Finlayson, 2005; Rohweder *et al.*, 2008). For a given wind direction, *D*, F_e represents the weighted average fetch measured along radials centred about *D*, to account for short-term variability in the wind field (Håkanson, 1977). Each measured wind direction was binned into one of 16 classes (N, NNE, NE, ENE, E etc.) and F_e for each site was calculated for each class. Z_c was then calculated as a function of F_e based on Smith & Sinclair (1972) following Spears & Jones (2010):

$$Z_c = 0.0062 F_e^{0.56} W_8^{0.88}, \quad (3)$$

where W_8 is maximum wind speed for 2008 (m s^{-1}) at a height of 8m above the water surface. As wind speed data over Esthwaite Water is measured at a height of 2.9 m above the water surface, the height correction used by Spears & Jones (2010) was applied to the data:

$$W_8 = W_{2.9} \frac{\ln(8/z_0)}{\ln(2.9/z_0)}, \quad (4)$$

where a surface roughness length (z_0) of 3.2×10^{-5} m was used, based on the neutral value of the transfer coefficient (C_d) suggested by MacIntyre *et al.* (2002). The 100 m grid of sites were used to generate an interpolated raster surface of Z_c using inverse distance weighting within ArcMap.

In addition to the calculation of Z_c, the depth at which surface waves cease to resuspend bed sediments can be identified as the depth where there is a transition in the nature of bed sediment from coarse to fine particles: known as the mud energy boundary depth *EBD* (m) (Rowan *et al.*, 1992). The predicted *EBD* was calculated as a function of the maximum fetch for each site F_m (km) following Rowan *et al*. (1992):

$$EBD = 3.076 F_m^{0.549}. \quad (5)$$

EBD is valid for sites whose depths (h) satisfy the condition required for the application of deepwater wave theory (Rowan *et al.*, 1992):

$$h > 1.660F_m^{0.5} . \quad (6)$$

Thus, *EBD* was calculated for 26 of the 29 sediment sites in this study, since the other three sites were too shallow for this condition to apply. The depths predicted by Z_c and *EBD* were used to delineate the depth of the transition from zones of sediment resuspension and transport to zones of accumulation.

Wind-induced currents

Indicative wind-induced current speeds were calculated from 2008 wind data, using the method of Smith (1979) where surface current speed U_s (m s^{-1}) is assumed to be 3% of the wind speed W (m s^{-1}) and current speed U_z (m s^{-1}) at depth z (m) is calculated as:

$$U_z = U_s\, e^{-kz}, \quad (7)$$

where $k = 6/W^{1.84}$ is a decay coefficient inversely related to wind speed in temperate latitudes.

This exponential decay in current speeds below the lake surface generates a gradient return current of mean velocity $\bar{U}_g$ to ensure the conservation of mass of the water body under isothermal conditions. $\bar{U}_g$ (m s^{-1}) is given by:

$$\bar{U}_g = M_d/Z, \quad (8)$$

where Z is the depth of the water column (m) and M_d is the quantity of water transported by the gradient current:

$$M_d = \frac{U_s}{k} \left(1 - e^{-k(D-b)}\right) , \qquad (9)$$

where $b = 0.033W^{1.63}$ is the thickness of the bottom boundary layer (m). The resultant current speed $U_L = U_z - \bar{U}_g$, represents an average speed at that depth, because channelling and boundaries have not been taken into account. The spatial influence of these effects will result in lower or higher speeds in different areas of the lake, for example, boundaries have been shown to increase return current speeds (Falconer, George & Hall, 1991).

Rather than generate a predicted depth for the transition to an accumulation area for the wind-induced current mechanism, the potential for current-induced resuspension was assessed through the comparison of Reynolds number Re^* calculated using particle size as the characteristic length scale, and the relative shear stress θ required to resuspend specific-sized particles, following Gloor *et al*. (1994). Estimates of U_L 1 m above the lake bed were calculated for the range of observed wind conditions from 2008. These theoretical current speeds allowed the calculation of the friction velocity at this location u* (m s^{-1}):

$$u^* = (C_{1m} \, U_L^2)^{1/2} , \qquad (10)$$

assuming a bottom drag coefficient C_{1m} of 1.5×10^{-3} (Elliott, 1984), which was then used to calculate Re^* as:

$$Re^* = u_* D_p / v, \tag{11}$$

where D_p is particle diameter (m) and v is kinematic viscosity at 5˚C (1.5×10^{-6}) (m^2 s^{-1}). The relative shear stress θ was calculated as:

$$\theta = \frac{\rho u_*^2}{(\rho_p - \rho) g D_p}, \tag{12}$$

where ρ is the density of water (kg m^{-3}), ρ_p is the density of the suspended particles (kg m^{-3}) and g is acceleration due to gravity (9.8 m s^{-2}). Values of Re* and θ were calculated for different particle sizes and densities, these values were used to compare critical thresholds of resuspension based on the modified Shields diagram (Gloor *et al.*, 1994). Current-induced resuspension was predicted to occur when the critical values of Re* and θ were exceeded.

Sediment burial rate

Sediment burial rate, *BR*, (g $m^{-2}yr^{-1}$) for carbon and total phosphorus were calculated using:

$$BR_i = AR_i * D_i * C_i, \tag{13}$$

where AR_i is the accumulation rate (m yr^{-1}) for each site i based on the ArcMap inverse distance-weighted interpolation of accumulation rates calculated by Hilton *et al.* (1986), D_i is the sediment dry bulk density (g m^{-3}) for each site calculated according to Rausch & Heinemann (1984) and C_i is the concentration of organic carbon or total phosphorus (g g^{-1}) . Organic carbon was estimated to be 50% of the weight LOI based on previous analyses of these sediments (Pennington, 1974). Predictions of whole lake flux-to-bed rates (tonnes yr^{-1}) were calculated for each of the focusing models (mean basin slope α'_p , mud energy boundary depth *EBD*, wave mixed layer depth Z_c), a single burial rate value from the deepest site and a fully depth integrated measure (representing the true sediment heterogeneity in the lake) using the new bathymetric data. The depth integrated measure was calculated as the total sum of the mean *BR* at 1 m depth intervals multiplied by the area of the lake bed at each corresponding depth interval. For the focusing models with a predicted transition depth to the accumulation zone, the value of *BR* from the deepest site was applied to the lake area below the transition depth, thus assuming a constant burial rate across the accumulation zone. The single-site burial rate value was obtained by multiplying the rate by the whole lake area, following the approach taken in many burial rate studies. This enabled an assessment of the prediction error for the single site and focusing processes compared to the depth-integrated value. The whole lake flux-to-bed rate calculations and the α'_p model were then repeated using the original bathymetric data from Ramsbottom (1976) to assess the effect on the results of using high- and low-resolution bathymetric data. Linear and piecewise regression analysis were conducted in the R statistical package using the base and segmented packages (Ihaka & Gentleman, 1996; Muggeo, 2008).

Results

Surface sediment characteristics

Across the sampling sites, there were different degrees of variability in the surface sediment characteristics (Table 2). The highest variability (coefficient of variation) between all sites was for the sand particle size fraction, benthic diatom taxon richness and total phosphorus concentrations. Water and silt content were the least variable. The water depth distributions of the four sediment variables of particular interest were very different. The bulk measures of water content and organic content increased approximately linearly at shallower depths, but had a constant value in deeper water (Fig. 2). Piecewise linear regression of these plots showed that the correlation was maximised by a breakpoint between regression line segments at 5 - 6 m ($r^2 = 0.50$, $P<0.05$). The distributions of the benthic diatom taxon richness and total phosphorus (the variables associated with smaller particle size fractions) had clear linear relationships with water depth. The former has a significant, negative linear relationship with depth ($r^2 = 0.60$, $P<0.01$) throughout the whole water column (Fig. 3a), while the latter exhibited a similarly consistent significant positive linear relationship with depth ($r^2 = 0.82$, $P<0.01$) (Fig. 3b).

Focusing processes

Lake bed gradient

Using the new bathymetry, the mean basin slope for the lake was calculated using Equation (1) as 2.33% which, using Equation (2), gives an accumulation zone of 44% (range of 41% to 47% based on the standard error from the equation) of the lake area. This implies that the transition to the accumulation zone occurs at 8.0 m (±0.5 m) depth, based on the high-resolution bathymetric data. The corresponding results using the old bathymetry were a mean basin slope of 3.2%, an accumulation zone of 42%

and a transition depth of 8.0 m (±0.5 m). Site-specific slope measurements for the new bathymetry ranged from 1° - 13° (0˚ - 10˚ for the old bathymetry). No significant correlations were found between site-specific slope and any of the sediment variables in Table 2 (P>0.05), either for specific depth ranges or using the whole dataset, indicating that local slope was not important in determining sediment characteristics in any section of the lake.

Wave mixing

The average and maximum wind speeds of 2.4 m s^{-1} and 13.4 m s^{-1} in 2008, prevailingly from the south (Fig. 4) are typical of wind conditions measured over the lake. These winds resulted in a clear gradient in the wave mixed-layer depth, Z_c, across the lake from the interpolated grid data (Fig. 5a). Z_c was greatest along the northeastern shorelines and lower in more wind-sheltered bay areas. The average and maximum Z_c for 2008 were 1.6 m and 3.7 m respectively. This map of Z_c (Fig. 5a) was compared with the lake bathymetry to identify the area where wave-induced resuspension was likely to occur (Fig. 5b), demonstrating that the effect of wave-induced resuspension of bed sediments was predicted to be restricted to a narrow nearshore zone. The *EBD* values calculated at the 26 sites applicable to deepwater wave theory varied between 2.4 and 3.5 m, averaging 3.1 m.

Wind-induced currents

Using the method of Smith (1979), a theoretical profile of wind-induced current speed with water depth was generated for different wind speeds (Fig. 6). Theoretical wind-induced current speeds calculated at 1m above the lake bed in the deepest part of the lake were up to 0.07 m s^{-1}, with wind speeds of 7 m s^{-1} capable of generating currents speeds at this depth of 0.05 m s^{-1}. Using Equation (10) these currents represent u* values of 2.7×10^{-3} m s^{-1} and 1.9×10^{-3} m s^{-1} respectively. According to the revised Shields diagram of Gloor *et al.* (1994), resuspension of 20-μm diameter organic particles is possible at current speeds of 0.05 m s^{-1} ($\theta = 0.38$, Re* = 0.026), while 0.07 m s^{-1} speeds are sufficient to resuspend quartz grains of 2 μm diameter ($\theta = 0.23$, Re* = 3.6×10^{-3}). This suggests resuspension driven by these currents is sufficient to resuspend these small particles at all depths in the lake, especially as most particles have lower densities than quartz.

The different focusing processes of slope failure, wave mixing and wind-induced current-shear produced a wide range of estimates for the depth of transition to the accumulation zone. Wave mixing predicted the shallowest transition depths (Z_c = 1.6 m and *EBD* = 3.1 m). No relationship was found between local bed slope and sediment characteristics, but using Blais & Kalff's (1995) empirical relationship to predict transition depth from mean basin slope gave a value for the transition depth of 8.0 m (±0.5 m). Wind-induced current shear was predicted to be able to resuspend sediment in the deepest part of the lake, and thus predicts no transition depth and no accumulation zone, at least for small particles. These predictions can be compared to the depth profiles of sediment variables in Figs 2 and 3. Although benthic diatom taxon richness and total phosphorus concentration show no break in their distribution that might be identified as a transition point (e.g. Blais & Kalff, 1995; Anderson *et al.*, 2008), the water content and organic content distributions suggest a transition at 5 - 6 m.

Burial rate estimates

Estimates of the net yearly flux of sediment to the bed (Table 3) were calculated for total phosphorus and organic carbon using the methods described above. The range of values calculated for total organic carbon flux to the bed was 41- 62 tonnes yr^{-1}. The different focusing models (wave mixing: *EBD*, Z_c; lake bed gradient: α'_p) and the single site-based calculation lead to over-estimates of between 27% and 54% compared to the depth-integrated true value. Calculated values for the total phosphorus flux using the single-site and focusing model methods were 40 - 110% larger than the value calculated using the depth integration method. This larger variation reflected the linear depth distribution pattern of the total phosphorus compared with the piecewise linear pattern for organic carbon. The latter pattern resulted in a larger area of the lake with similar organic carbon concentrations, reducing the difference in the flux rate estimates from the single-site and focusing models from the depth-integrated value. The difference in total fluxes resulting from the use of different bathymetries (i.e. that of Ramsbottom (1976) and the new one described above) were much smaller than the difference in values calculated using different focusing models: 5 - 11% for organic carbon and 3 - 11% for total phosphorus. Thus the effect of the improved resolution in the bathymetry was secondary to that of the choice of focusing model and transition depth to the accumulation zone.

Discussion

Sediment characteristics

Both organic content (measured as LOI) and total phosphorus concentrations in Esthwaite Water (Table 2) were comparable to those found in other lakes such as

Bassenthwaite Lake, Wastwater (15% and 25% organic content as LOI, respectively) (Bennion, Monteith & Appleby, 2000), Lake Rotoiti, New Zealand (3460 mg P kg^{-1}) (Trolle *et al.*, 2008) and Loch Leven, Scotland (2288 mg P kg^{-1}) (Spears *et al.*, 2006). Burial rates of organic carbon (Table 3) were also similar in magnitude to small (surface area <100 km^2), natural meso-eutrophic lakes (11 - 198 g C m^{-2} a^{-1}) (Mulholland & Elwood, 1982), but lower than man-made impoundments in the USA (148 - 17,000 g C m^{-2} a^{-1}) (Downing *et al.*, 2008).Water content, which is routinely assumed to be inversely proportional to sediment particle size, ranged between 75 - 92%. This would imply that the whole lake was an accumulation zone, as previous work on larger lakes suggests that the transition to an accumulation zone occurs at a depth in the lake where sediments exceed 50% water content (Håkanson & Jansson, 1983). However, the results from this study suggested that this was not the case.

The four different sediment variables examined (water content, organic content, benthic diatom taxon richness and total phosphorus concentration), each representing different characteristic densities and particle sizes, showed a different relationship with depth (Figs 2 and 3). The linear relationship with depth seen in the total phosphorus concentrations and benthic diatom taxon richness implied that they were most closely associated with resuspension all the way to the deepest waters. Hence, classifying lake sediments as accumulation areas on the basis of single or bulk variables such as water content, which do not take account of these specific particle sizes, leads to an oversimplification of the heterogeneity within the sediments.

Sediment focusing predictions

Slope-based models, both site-specific and across the lake basin, did not adequately explain sedimentation patterns in this lake, even after significant improvements to bathymetric data. The transition depth predicted by the mean basin slope calculations (approximately 8m) was closer to the depth of the transition in the piecewise linear fit of the plots of the bulk variables of water content and organic matter (5 - 6 m), but overestimated it by around 30%. These calculations did not predict the distribution of either sedimentary total phosphorus concentration or benthic diatom taxon richness very well, which suggested that the processes assumed to be acting in its calculation were not those which govern the distribution of these variables. Moreover, the site-specific measure of slope was a poor predictor of all of the sediment variables in this study, as was the case for Blais & Kalff (1995).

Although wave action is the dominant focusing process in a number of large or shallow lakes such as Lough Neagh (surface area = 383 km^2) (Douglas & Rippey, 2000), Lake Vänern (5655 km^2) (Håkanson, 1977) and a typical North American prairie lake (1.04 km^2, mean depth = 1.3 m) (Carper & Bachmann, 1984), it is clear that neither the Z_c or *EBD* models was effective at describing the sediment distribution in Esthwaite Water (Figs 2 and 3). This suggested that lake morphometry, in terms of both water depth and wind sheltering, was important in determining the influence of wave mixing. In lakes such as Esthwaite Water, where Z_c values were low compared to mean water depth, wave-induced resuspension occurred only in a small proportion of the lake. It is therefore clear that neither slope-based models nor wave mixing could account for the sedimentation pattern in Esthwaite Water.

While currents have not been directly measured in Esthwaite Water, theoretical calculations suggested wind speeds during episodic events were sufficient to resuspend small particles throughout the depth of the lake (Fig. 6). Current speeds greater than the minimum resuspension threshold values identified here (0.05 m s^{-1}) have been measured close to the lake bottom in a number of lakes, particularly during storms. Aota (2006) recorded current speeds up to 0.3 m s^{-1} and frequently above 0.06 m s^{-1} at 1.8 m above the bottom in 90 m water depth in Lake Biwa during storms (wind speeds >10 m s^{-1}), and currents >0.1 m s^{-1} were measured 1.8 m above the lake bed in 11 m of water in the Salton Sea in response to wind speeds of 10 m s^{-1} (Chung, Bombardelli & Schladow, 2009). Resuspension due solely to wind-induced currents occurs in larger lakes below the wave base, during isothermal conditions (Lemmin & Imboden, 1987; Hawley *et al.*, 1996; Hawley & Lee, 1999). These currents are important for the transport of material from nearshore areas dominated by resuspension due to wave action to the deeper parts of the lake (Hawley & Lee, 1999). Current speeds of 0.05 to 0.07 m s^{-1} have also been found to resuspend material in Lake Alpnach, a smaller lake (surface area 4.76 km^2) (Gloor *et al.*, 1994).

The measurement and modelling of wind-induced currents in lakes is complicated by their interaction with the lake morphometry. Boundaries enhance return current speed (Falconer *et al.*, 1991), as can the alignment of a lakes' major axis relative to the wind direction (Bowyer, 2001). The presence of islands or an uneven lake bed can also deflect flow (Bowyer, 2001). The theoretical calculations presented here cannot account for these effects but did show that current speeds were sufficient to resuspend small particles and therefore represent a potential mechanism for the movement of sediment in the lake. This mechanism for sediment focusing has been overlooked in many previous studies: this study suggests it is important in small lakes like Esthwaite Water. Current speeds in small lakes are likely to be lower than those found in large lakes, but the distribution of total phosphorus concentrations and benthic diatom taxon richness in Esthwaite Water suggested that current-driven resuspension and transport to deeper parts of the lake bed occurred for smaller particles, and thus the sediment variables associated with those particles.

Bioturbation of sediment by invertebrates and fish has resulted in resuspension or increased mobilisation of sediments and the release of nutrients in some shallow lakes (e.g. Moss *et al.*, 2002; Vanni, 2002; Jackson *et al.*, 2010). The daily migration of burrowing benthic invertebrates such as *Chaoborus* has been observed to disturb the sediment surface around the burrow, causing sediment mobilisation (Gosselin & Hare, 2003) and increasing the propensity of the sediment to be resuspended. There are no contemporary records on the spatial abundance of *Chaoborus* in Esthwaite Water and it is therefore difficult to assess this effect. However, data from a single site suggests that abundance is relatively low compared to other lakes (Reynoldson, 1990; Gosselin & Hare, 2003) and very few benthic invertebrates were observed in the sediment samples for this study. Benthivorous fish, particularly the common carp (*Cyprinus carpio*) and common bream (*Abramis brama*) increase turbidity at high stocking densities (Carvalho & Moss, 1995; Jackson *et al.*, 2010). Esthwaite Water is not a shallow lake and has a low benthivorous fish population, with no record of carp or bream (I.Winfield, pers comm.). It is therefore unlikely that bioturbation played a significant role in sediment resuspension in this lake. Although localised sediment mobilisation effects cannot be excluded, they are likely to be secondary to physical resuspension.

Burial rate calculations

The large overestimation in whole-lake fluxes to the sediments arising from calculations based on single sites (Table 3) was also found in a study from Kassjön, where overestimates were between 25% and 85% for different variables (Rippey *et al.*, 2008). In our study, these overestimates, due to assumptions about the distribution of sediment variables with depth, were much larger than the errors from using a low-resolution bathymetry. As many carbon burial rate studies are explicitly sampled at the deepest point in the lake or areas where sediment accumulation is most rapid (e.g. Downing *et al.*, 2008; Anderson *et al.*, 2009; Finlay *et al.*, 2010), these values should therefore be regarded as maximum burial rates and not necessarily representative of the whole lake. This qualification of organic carbon burial is important for comparing between lakes and especially when assessing the overall importance of lakes in global carbon burial (e.g. Buffam *et al.*, 2011).

The total annual phosphorus efflux from Esthwaite Water estimated from four years of routine monitoring data amounted to ~1 tonne yr^{-1}, whilst Hall *et al*. (2000) estimated an annual phosphorus influx of ~2 tonnes yr^{-1}.The importance of accurate burial rate estimates was therefore underlined by the depth-integrated method value (~1 tonne yr^{-1}: Table 3) which balanced the phosphorus budget of the lake. All other calculations would have left a large discrepancy in the budget and consequent uncertainty in appropriate management strategies. That approximately half of the phosphorus entering the lake was retained in the sediments is likely to affect the lake recovery from eutrophication because of the potential for prolonged internal loading (Jeppesen *et al.*, 2005).

The findings of this study demonstrated that different sediment variables have different distributions with water depth, and implied that this can be explained by consideration of the particle size fraction with which each variable is most closely associated. Thus, these distributions cannot be explained by measures of single sediment variables. Moreover, previously developed focusing models for wave mixing and slope processes have been found not to be relevant to Esthwaite Water and, by extension, are hypothesised to be similarly irrelevant to other small lakes. We did however find evidence for the resuspension and focusing of small particles, which was inferred to relate to bed-shearing of wind-induced currents. This has not been widely considered as a focusing mechanism in previous studies, particularly in small lakes. Our comparison of flux rate predictions demonstrated that those derived from the different focusing models or a measurement at a single, deep site, suggested that whole lake fluxes to the bed for total phosphorus are up to twice that of a depth-integrated value. Therefore, the calculation of fluxes of materials such as total phosphorus or organic carbon should routinely take into account the specific different depth distribution of these variables.

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Tables

Table 1 Summary of the bathymetry of Esthwaite Water

Depth (m)	Area enclosed by contours (m^2)	% Total area	Layer (m)	Volume (m^3)	% Volume of layer	% Cumulative volume
0	956565	100	0-1	889513.4	13.30	13.30
1	849502	88.81	1 - 2	810936.5	12.12	25.42
2	773103	80.82	2 - 3	734959.3	10.99	36.41
3	699232	73.10	3 - 4	670431.2	10.02	46.44
4	642365	67.15	4 - 5	612987.7	9.16	55.60
5	584819	61.14	5 - 6	558876.7	8.36	63.96
6	533841	55.81	6 - 7	509740.2	7.62	71.58
7	485632	50.77	7 - 8	458245.4	6.85	78.43
8	430580	45.01	8 - 9	402397.2	6.02	84.44
9	373818	39.08	9 - 10	341333.5	5.10	89.55
10	306442	32.04	10 - 11	270203.2	4.04	93.59
11	233792	24.44	11 - 12	195089.4	2.92	96.50
12	158770	16.60	12 - 13	128789.7	1.93	98.43
13	103929	10.86	13 - 14	77289.41	1.16	99.58
14	51139	5.35	14 - 15	24529.54	0.37	99.95
15	8337	0.87	15 - 16	3234.118	0.05	100.00
16	0	0				

Table 2 Summary of the characteristics of the surface sediments of Esthwaite Water

	Mean	Standard deviation	Range	Coefficient of variation %
Clay (<2 μm) (%)	1.8	0.4	1.2 - 2.7	19.4
Silt (2 - 63 μm) (%)	82.9	10.4	56.6 - 93.7	12.6
Sand (63 - 1000 μm) (%)	15.3	10.6	4.3 – 42.0	69.5
Water content (%)	86.5	4.0	75.4 - 92.1	4.6
Organic content (%)	25.5	6.0	9.9 - 34.0	23.5
Total Phosphorus (mg kg^{-1})	3139.1	1483.6	476 - 6870	47.3
Diatom plankton (%)	61.4	21.8	8.7 - 88.5	35.5
Diatom benthic (%)	38.6	21.8	11.5 - 91.3	56.5

Table 3 Estimates of burial rates and fluxes to the sediments of Esthwaite Water using different accumulation area predictions

Method	Flux tonnes yr^{-1}	Organic Carbon Burial rate g m^{-2} yr^{-1}	Flux tonnes yr^{-1}	Total Phosphorus Burial rate g m^{-2} yr^{-1}
Depth integrated	40.5	44.3	1.0	1.2
α'_p	51.3	54.8	1.4	1.6
EBD	57.2	61.9	1.8	2.0
Z_c	58.6	63.0	2.0	2.1
One site	62.4	65.3	2.1	2.2

Figure Legends

Fig. 1 Bathymetry of Esthwaite Water, showing position of sediment sampling sites, shore weather station and AWQMS buoy

Fig. 2 Distribution with water depth (m) of % water content (diamonds) and % organic content (squares) in surface sediments of Esthwaite Water

Fig. 3 Distribution with water depth (m) of small particles in surface sediments of Esthwaite Water: (a) benthic diatom taxon richness (number of taxa) and (b) total phosphorus (mg kg^{-1})

Fig. 4 Wind speed (m s^{-1}) and direction (15° segments) over Esthwaite Water for 2008

Fig. 5 Esthwaite Water showing (a) a map of wave-mixed layer depth (m) and (b) a map of the wave-affected area from 2008 wind data

Fig. 6 Theoretical wind-induced current profiles for wind speeds of 7 m s^{-1} (dashed line) and 13.4 m s^{-1} (solid line with crosses). Dotted vertical lines denote critical resuspension threshold for organic particles (density = 1050 kg m^{-3}) of 20µm diameter.

Illustrations

Fig. 1

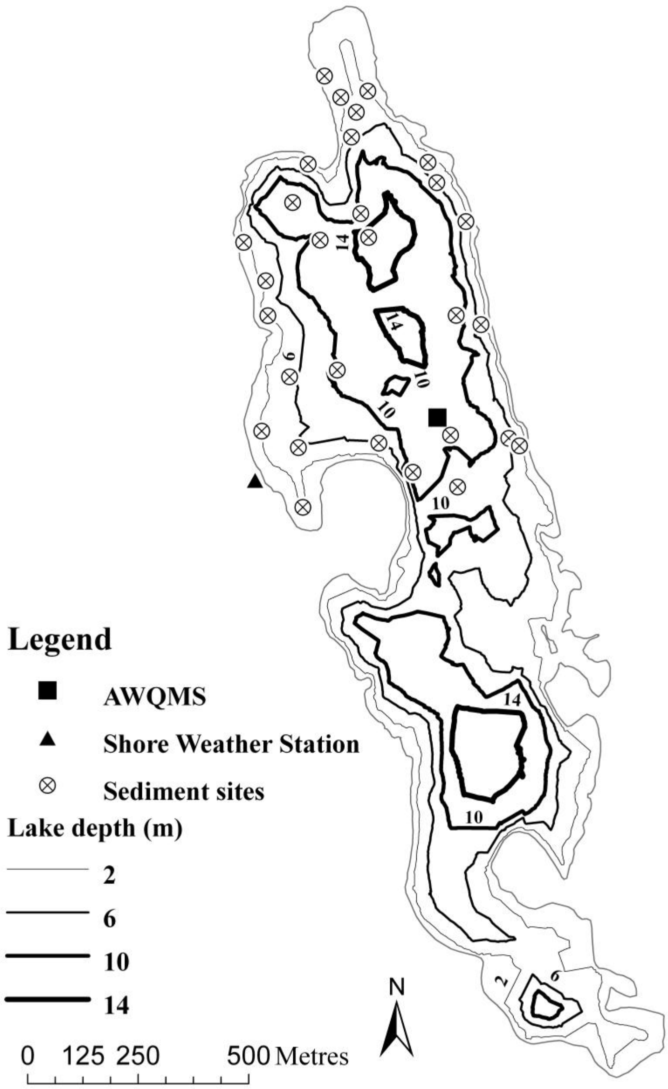

Fig. 2

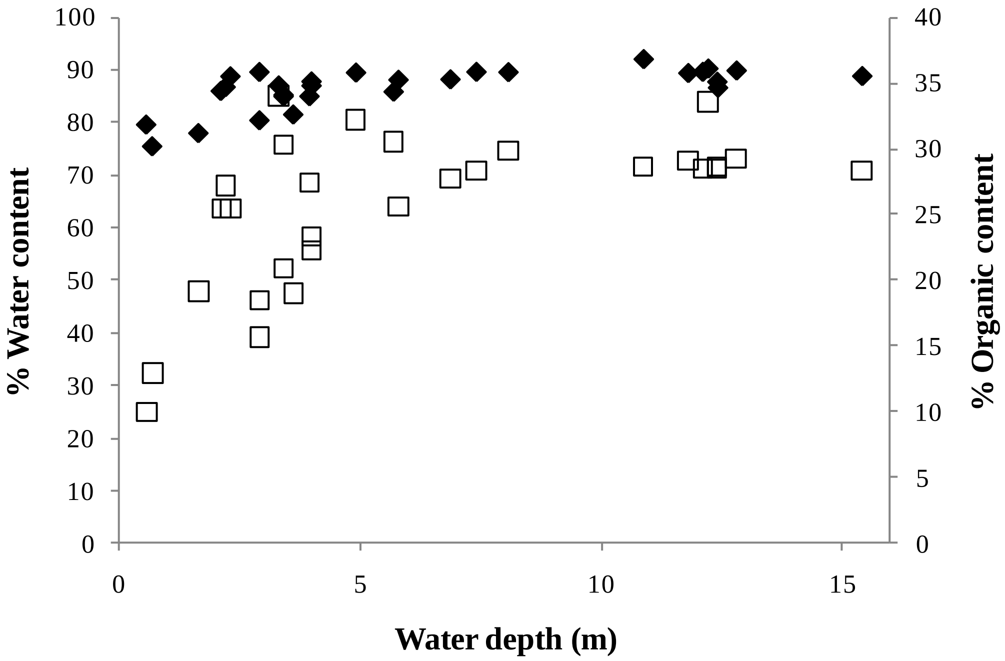
% Water content
% Organic content
Water depth (m)
0
10
20
30
40
50
60
70
80
90
100
0
5
10
15
20
25
30
35
40
0
5
10
15

Fig. 3

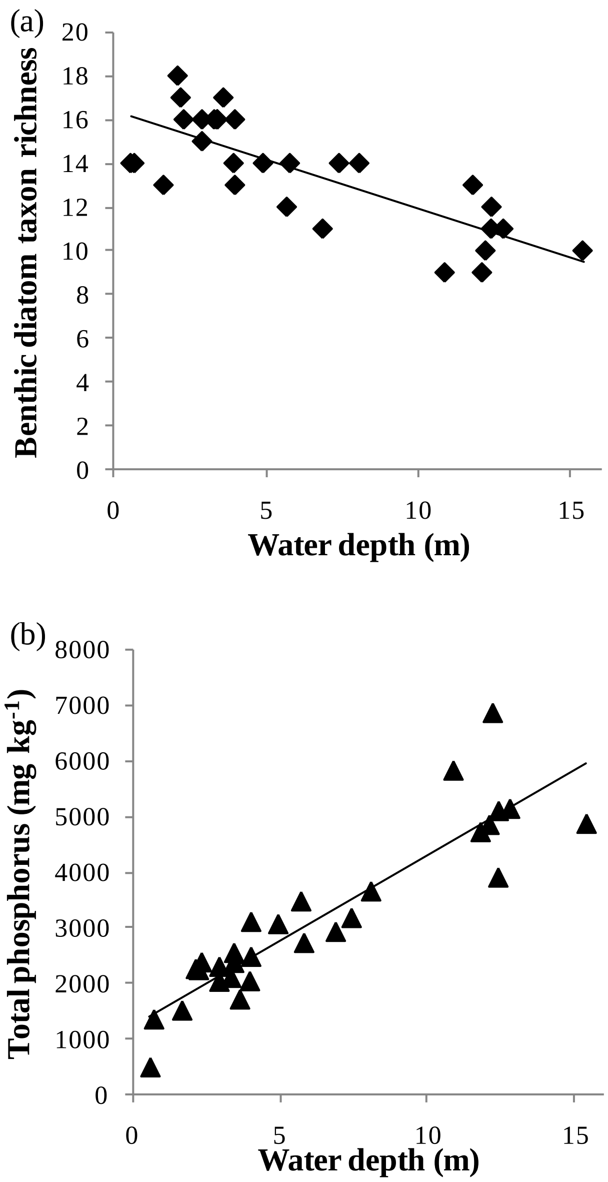
(a)
Benthic diatom taxon richness
0
2
4
6
8
10
12
14
16
18
20
0
5
10
15
Water depth (m)
(b)
Total phosphorus (mg kg-1)
0
1000
2000
3000
4000
5000
6000
7000
8000
0
5
10
15
Water depth (m)

Fig. 4

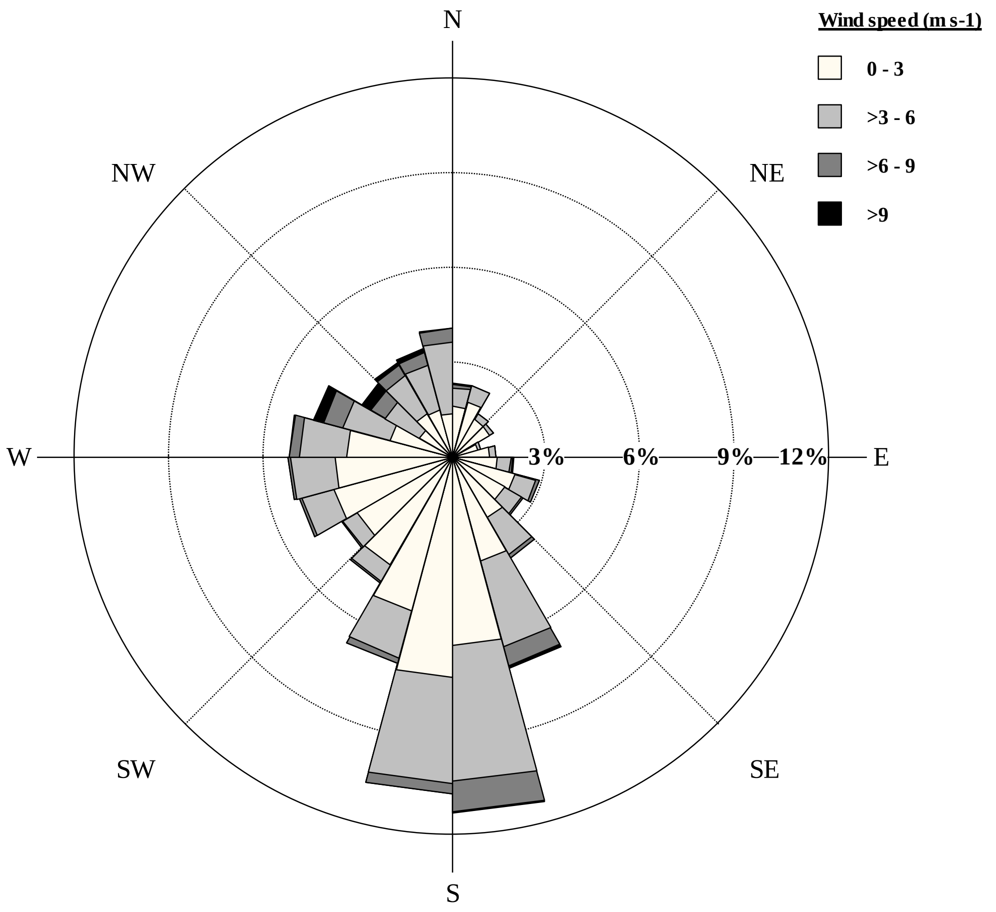

Fig. 5

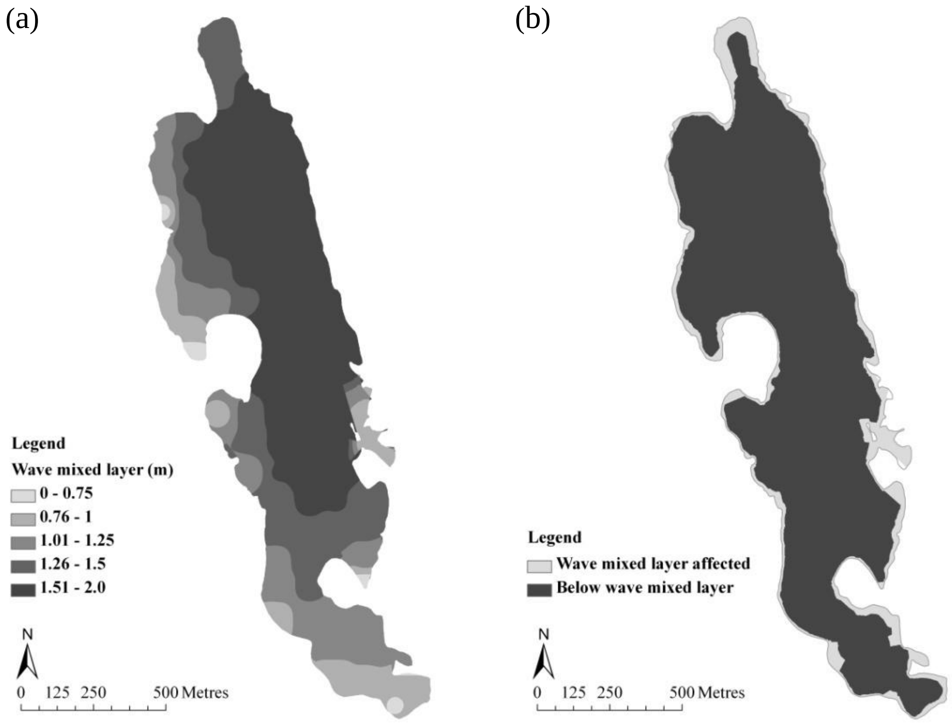
(a)
Legend
Wave mixed layer (m)
0 - 0.75
0.76 - 1
1.01 - 1.25
1.26 - 1.5
1.51 - 2.0
N
0 125 250 500 Metres
(b)
Legend
Wave mixed layer affected
Below wave mixed layer
N
0 125 250 500 Metres

Fig. 6