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RESEARCH ARTICLE

Sediment resuspension in two adjacent shallow coastal lakes: controlling factors and consequences on phosphate dynamics

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Abstract A combination of field measurements, modelling and laboratory experiments was used to evaluate the potential impact of sediment resuspension on phosphorus (P) dynamics. The study was carried out in two adjacent shallow coastal lakes (Lake Honda and Lake Nueva) which, due to their geographic proximity (only 200 m apart), are subject to equal meteorological forcing and represent ideal systems to study how morphometry and sediment properties relate to wind events. The focusing factors (a measure of the fluxes of sediment into the water column through resuspension) estimated by comparing settling fluxes measured in surface sediment traps with those measured in bottom traps, were significantly larger (approximately 34% larger) in Lake Honda (LH; 1.18) than in Lake Nueva (LN; 0.88). Our model estimates of resuspension fluxes (*E*) were also ca. 40% larger in LH than in LN, in agreement with the observed focusing factors. The larger resuspension fluxes encountered in LH, in comparison with LN, can mainly be explained by differences in lake morphometry. Still, they could arise from differences in grain size distribution or in benthic algae concentration encountered in the lake sediments. By means of adsorption experiments in the laboratory, we show that resuspension events will have different effects on P-dynamics in LH and LN. While the resuspended material from LH tends to adsorb phosphate (PO_4^{3-}), removing it from the water column, in LN the resuspended sediments tend to increase the availability of PO_4^{3-} in solution. These differences arise from (1) higher concentrations of PO_4^{3-} in water in LH compared to LN; and (2) larger PO_4^{3-}adsorption capacity of the LH sediments as a result of the more abundant iron oxyhydroxides and clay.

Keywords Resuspension · Shallow lakes · Phosphate · Wind action · Sediment

Introduction

The chemistry of the bottom boundary layer in lakes and reservoirs is intricately linked to that of the bed sediments through a wide range of physical, chemical and biological processes that lead to exchange of particulate and dissolved substances across the water–sediment interface. The importance of such exchange processes in determining the overall biogeochemistry of lake ecosystems and their nature decreases with the depth of the lake (Nõges et al. 1999). In shallow lakes, for example, the sediments are often subject to the continuous physical action of wind waves that may cause erosion and resuspension of particulate matter (e.g. Weyhenmeyer and Bloesch 2001). Sediment resuspension can significantly modify the biogeochemical behaviour of such shallow aquatic ecosystems, as documented by many others (e.g., Kristensen et al. 1992; Evans1994; Bloesch 1995; Weyhenmeyer et al. 1995; Scheffer 1998; Golterman 2004). As a consequence of resuspension, the concentration of particulate matter in the water column increases, leading to reduced light penetration that can ultimately promote

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biological adjustments. In particular, changes in the light climate in shallow lakes can potentially lead to shifts in the biological communities, which evolve from being macrophyte-dominated to being plankton-dominated (Scheffer 1998). A reduction in the abundance of macrophytes in the lake will further increase resuspension rates. Large populations of submerged macrophytes, in turn, will reduce the resuspension rates by slowing down the currents and reducing turbulent motions in the water column (Madsen et al. 2001; Horppila and Nurminen 2003). There exists, therefore, a subtle interplay between physical processes leading to resuspension and turbidity in the water column and the growth of macrophytes in shallow lakes. As a consequence of such an interplay, the ecosystem structure in shallow lakes could be of an oscillatory nature (Scheffer 1998). Nutrient recycling in shallow lakes can also be increased in response to resuspension processes. Sediment-associated particulate and dissolved nutrients are brought back into the water column where then can be released, altering the lake trophic status (Peters and Cattaneo 1984). The theory proposed by Mortimer (1941), in which the exchange of phosphate (PO_4^{3-}) through the sediment–water interface occurs through chemical mechanisms in Fe-controlled systems, needs to be extended and adapted in shallow environments to include other physical (i.e. resuspension, diffusion, gas ebullition) and biological mechanisms (i.e. rooted aquatic plants, attached algae) that affect the flux of sedimentary material. Even more recently, Gächter and Müller (2003) pointed out the need to consider apart from oxic or anoxic conditions, the molar ratio of the available reactive $Fe(II):S^{2-}:PO_4^{3-}$ in the anoxic sediment for predicting the PO_4^{3-} retention in lake sediments.

In shallow lakes, wind-driven wave motions at the water–sediment interface are the primary mechanism of resuspension. The occurrence of resuspension in response to wind-waves depends on a subtle balance of forces (e.g. Kristensen et al. 1992; Nõges et al. 1999; Weyhenmeyer and Bloesch 2001) in which the shear stress induced by the wave motion on the sediment–water interface provides the necessary energy to bring the sediment particle into the water column, and the sediment weight and cohesiveness represent stabilizing forces. Several factors (physical, biological and chemical) are involved in this balance. These include the magnitude of the wind stress, its direction, the shape and particular bathymetry of the basin, and the type of sediment. In open systems, the concentration of suspended sediments in the water column can also be influenced by the occurrence of large inflow events that inject energy in the system, in the form of currents, which can erode and resuspend sediment particles into the water column (e.g. Teeter et al. 2001). Moreover, in lacustrine environments, benthic communities could stabilize and bioturbate the bed depending on the level of anoxia on the bottom, hence significantly modifying the amount of energy required to induce resuspension. The relationship between the energy available for mixing and resuspension in the water column (turbulence) and nutrient fluxes across the sediment–water interface is further complicated by interactions between turbulence and oxygen levels in the water column, which determine the form in which phosphorus (P) is present. As shown by Søndergaard et al. (1992) and Scheffer (1998), turbulence can either inhibit or increase phosphorus fluxes across the sediment–water interface. At low turbulence, oxygen supply to the sediment surface is insufficient to balance uptake by bacteria and the resulting anaerobic conditions cause a high P release. At higher turbulence, the sediment surface becomes oxygenated and P is immobilized by iron (see Gerhardt and Schink 2005, for example). However, a further increase in turbulence slightly enhances diffusion of P from the sediment until a critical turbulence is exceeded and the top layer of the sediment is resuspended. The final effect of resuspension events on PO_4^{3-} availability depends on the particular properties of the lake water (i.e. PO_4^{3-} concentrations) and the sediments, and is therefore lake-specific to some extent (Søndergaard et al. 1992). Sediment resuspension and nutrient fluxes across the sediment–water interface, therefore, are complex processes which can be influenced by a multiplicity of factors.

Despite the significant role of resuspended particles in determining geochemical, toxicological and biological processes in the water column of shallow lakes, there have been few publications in which the factors controlling resuspension, its quantitative significance, and its impact on lake metabolism are analyzed systematically (Bloesch 1994; Evans 1994; Weyhenmeyer 1998). Our goal in this work is to identify both the controlling factors and the main consequences of wind-induced resuspension in determining one important aspect of the metabolism of lakes: P dynamics. This analysis was conducted in two adjacent shallow coastal lakes, which, due to their geographic proximity (c.a. 200 m apart), are subject to equal meteorological forcing. Hence, these two lakes represent ideal systems to study how morphometry and sediment properties interact with wind forcing in determining resuspension fluxes and P dynamics in shallow ecosystems. Both field data and the results from laboratory experiments are used to understand the link between resuspension and P-dynamics in these two adjacent lakes. This is in contrast with previously published studies on sediment resuspension which are exclusively based on either field measurements (e.g. Cózar et al. 2005) or on laboratory experiments (e.g. Li et al. 2006). The measurement of resuspension in the field is difficult at best (Bloesch 1994; Evans 1994), and several qualitative and quantitative (direct or indirect) approaches have been proposed in the literature to study resuspension in field conditions (e.g. Bloesch 1994). Many studies have been based on the application of statistical methods (correlation analysis) to describe the relationship between wind velocity and total suspended solids. This approach, however, has limitations when applied at long-time scales (longer than several days, as was the case in our study) to eutrophic lakes. In these lakes the high contribution of algal biomass (chlorophyll *a*) to suspended solids in the water column can ultimately mask the expected correlation. Another possible approach to estimate resuspension fluxes relies on collecting sediment by a vertical series of sediment traps and comparing the sedimentation fluxes in traps close to the lake bottom with those measured in traps deployed in the water column (Gardner 1977; Gálvez and Niell 1992; Bloesch 1995; Kleeberg 2002). The ratio between sedimentation fluxes measured in traps exposed close to the lake bottom S_B and in the upper layers is referred to in the literature as the focusing factor (ff) (Kleeberg 2002). The quantification of resuspension using sediment traps in shallow lakes is also limited because the upper traps may also be affected by resuspended matter at certain times, which reveals the inherent difficulties in identifying an appropriate reference level (Bloesch 1994). But still, sediment traps are one of the most common methods to measure sediment resuspension (e.g. Weyhenmeyer 1998), and consequently, it was the method adopted in our study. Resuspension fluxes estimated from sediment traps in the two coastal lagoons were compared and the differences analyzed within the modelling framework proposed by Luettich et al. (1990) to represent sediment resuspension in lakes (see also Mian and Yanful 2004). In our work, the use of the model was not intended to predict accurately the space–time variability of resuspension fluxes or the evolution of particulate matter in the water column, but rather to investigate the effect of basin morphology as a plausible explanation of the differences in resuspension fluxes between lakes. Hence, we deemed unnecessary the use of more sophisticated two or three-dimensional models available in the literature (e.g. Holthuijsen et al. 1989).

Materials and methods

Study site, lake morphometry and meteorological observations

Albufera de Adra, composed of two small shallow coastal lakes, Honda (LH) and Nueva (LN), is one of the most important wetlands in south-eastern Spain (Fig. 1). Despite the ecological significance of the wetland, high external (1.73 and 0.03 g P m^{-2} $year^{-1}$ to LH and LN, respectively) and internal P loadings have promoted eutrophication in both lakes, especially in LH (Table 1). External load is mainly composed of episodic run-off sources in the case of LH, as a consequence of the large catchment area: lake area ratio, while point-sources (irrigation channels) are the only surface water input to LN (de Vicente et al. 2006).

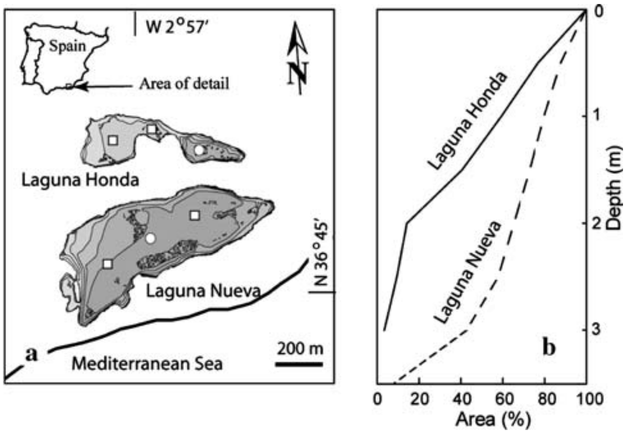

Fig. 1 **a** Geographic location and bathymetry of study sites: Laguna Honda and Laguna Nueva in Albufera de Adra. Isobaths in bathymetry map are shown every 0.5 m. *Squares* and *circles* represent sampling stations for the study. Sediments were sampled at all sampling stations. Sediment traps were deployed at the sites shown by *circles*. **b** Hypsographic curves of the study sites

Table 1 Main morphometric features of the investigated lakes (modified from de Vicente et al. 2006) min–max (average)

	Honda	Nueva
Morphometric features		
Age of the lake (years)[a]	≈480	≈80
Lake area (10^3 m^2)	94	271
Volume (10^3 m^3)	118	627
Mean depth (m)	1.2	2.3
Maximum depth (m)	3.2	3.8
Maximum length (m)	586	759
Catchment area (10^5 m^2)	137.2	5.0
Chemistry of the water column		
TP (μg L^{-1})	98–529 (290)	22–245 (95)
P–PO_4^{3-} (μg L^{-1})	0–287 (75)	0–33 (4)
Chl *a* (μg L^{-1})	2–409 (124)	4–136 (51)
TSS (mg L^{-1})	1.5–124.2 (36.2)	5.0–80.0 (23.8)
Secchi depth (m)	0.10–2.14 (0.62)	0.35–1.40 (0.80)
Settling rates		
DW (g DW m^{-2} day^{-1})	1.72–35.12 (10.45)	1.83–15.16 (6.32)
TP (mg TP m^{-2} day^{-1})	3.9–115.2 (31.2)	2.9–37.3 (14.4)
TN (g TN m^{-2} day^{-1})	0.13–0.35 (0.26)	0.05–0.27 (0.12)
TC (g TC m^{-2} day^{-1})	1.24–3.54 (2.18)	0.37–2.17 (0.96)

These values were estimated from bi-weekly samples from July 2000 to August 2001

TSS total suspended solids. Settling rates were estimated by using sedimentation traps

[a] Paracuellos (2006)

Notwithstanding their proximity, LH and LN exhibit clear differences in their water quality owing to their age, morphometry, hydrologic regime and nutrient loading (de Vicente et al. 2003, 2006). LH has the larger contributing watershed which results in a continuous silting process and in a lower dilution capacity. As a consequence, submerged macrophytes are currently absent from LH due to the high nutrient loading and subsequent increase in turbidity. In LN, in turn, macrophyte patches commonly develop in the littoral zone (Ortega et al. 2004).

Meteorological information was provided by the Regional Environmental Agency (Consejería de Medio Ambiente) who installed and maintained a meteorological station near the lakes (4 km) during the study period. The wind sensors were located 7 m above the ground level on top of a building in the city of Adra, far (at least 100 m) from any obstacles, and provided information every two hours. Morphometric information for LH and LN was derived from existing bathymetric maps of the lakes (Cruz-Pizarro et al. 1992).

Sediment analysis

Surface sediment samples (0–5 cm) were collected monthly, from July 2000 to August 2001 (study period), at three different sampling stations located along a longitudinal transect in both study lakes, using an Ekman dredge (Fig. 1). In the laboratory, interstitial water was separated from the sediment particles with a centrifuge (10 min, 8,944*g*). After filtration (Whatman GF/C), PO_4^{3-} concentration in the interstitial water was measured as molybdate reactive phosphorus (Murphy and Riley 1962). The wet sediments were analysed for total phosphorus (TP) and for iron oxyhydroxides (FeOOH). TP was measured by spectrophotometry (Murphy and Riley 1962) after acid digestion (Golterman 1996). FeOOH was first extracted in CaEDTA (0.05 M) and later quantified using the *o*-phenanthroline method (Golterman et al. 1978). Organic matter and chlorophyll *a* concentrations were estimated by loss on ignition (550°C, 3 h) and by using acetone (90%) to extract algal pigments (Lorenzen 1967), respectively. The particle size distribution of the surface sediment layer was determined using the method proposed by Robinson (1922). In this method, the different fractions of the sediment are separated by letting a homogeneous suspension settle down and then collecting aliquots of the suspension at different times and at the same height of the flask.

Sedimentation and resuspension fluxes

In our study, a pair of sediment traps, plexiglass cylinders with an aspect ratio (height:diameter = 40:6.4 cm) greater than 6 (Bloesch and Burns 1980) were deployed at three different depths (50, 135 and 260 cm) at the deepest site of each lake (Fig. 1). The particulate matter in the traps, collected every two weeks during the study period (June 2000–August 2001), was dried (104°C for 24 h) and weighed. These weights divided by the trap surface area and the time between consecutive visits to the lake to collect the material provides an estimate of the settling fluxes (g dry weight m^{-2} day^{-1}). For each period between two consecutive visits and for each lake, we calculated settling fluxes (S) at each depth, which we refer to as S_B, S_M and S_T (for the lowest, middle and upper trap). From those estimates two possible measures of the resuspension fluxes (or focusing factor) could be obtained for each lake: S_B/S_M and S_B/S_T. In the entrapped matter, TP concentration was measured, after acid digestion by following Murphy and Riley (1962). Total carbon (TC) and total nitrogen (TN) concentrations were quantified by CNH Elemental Analyser (Perkin Elmer 2400).

A modelling framework to analyze differences in resuspension

Resuspension fluxes estimated from sediment traps in both lakes were compared and the differences analyzed within the modelling framework proposed by Luettich et al. (1990) to represent sediment resuspension in lakes. Consistent with many other lake sediment models (e.g. Carper and Bachmann 1984; Hawley and Lesht 1992; Hamilton and Mitchell 1996 and references there in), Luettich et al.'s (1990) model presumes that resuspension is primarily driven by wave generated stresses at the lake bottom. The resuspension flux E at a given location within the lake is calculated through the expression (see also Sanford and Maa 2001)

$$E = \begin{cases} 0 & \tau < \tau_c \\ K_r \left(\frac{\tau - \tau_c}{\tau_{ref}} \right)^{\eta} & \tau \geq \tau_c \end{cases} \qquad (1)$$

Here, K_r is an empirical constant (with dimensions of flux), η a non-dimensional exponent, τ the bottom shear stress due to fluid motion, τ_{ref} a unit stress to make the term in parentheses dimensionless and τ_c the critical shear stress for commencement of sediment erosion. It is through the critical shear stress that the sediment characteristics influence resuspension fluxes. Lavelle and Mofjeld (1987), however, argued, via a review of previous work, that critical shear stress should be set to zero, given the highly subjective way in which critical stresses have been determined in laboratory experiments, the stochastic nature of bottom stresses and particle movement, and the fact that previous experimental results, which were originally interpreted with a non-zero critical shear stress, can also be represented with $\tau_c = 0$ (see Luettich et al. 1990). Not having sufficient information to infer differences in τ_c between lakes, we adopted a constant reference value for τ_c in Eq. 1. Any differences in E between lakes are then a function of bottom shear stress, and are mainly determined by the lake morphometry and wind forcing. The bottom shear stress was estimated as in Luettich et al. (1990) (see also Mian and Yanful 2004)

$$\tau = H_s \rho \frac{\sqrt{v(2\pi/T)^3}}{2\sinh(2\pi h/L)}. \tag{2}$$

Here, h is the depth of the water column, H_s the significant wave height, T the wave period, v the viscosity of water and L the wave length. Wave height H_s and period T were estimated using empirical equations proposed by Luettich et al. (1990) and reported also by Mian and Yanful (2004), in which wave properties are predicted in terms of wind speed u measured at 10 m height, the effective fetch F (the distance to the shoreline from any given location measured upwind), and the average depth along the fetch. The effective fetch was calculated as in CERC (1984) and solely depends, for a given location within the lake, on the shape of the basin and the wind direction. The wave length L was estimated from the wave period T using the following approximation (see CERC 1984)

$$L = \frac{gT^2}{2\pi}\sqrt{\tanh\left(\frac{4\pi^2}{T^2}\frac{h}{g}\right)} \tag{3}$$

where g is the acceleration of gravity. The resuspension model was fed with bi-hourly averaged wind data. This time interval (2 h) was considered appropriate for our modelling purposes, given that the time interval for waves to equilibrate to an applied wind force is 1 h, or even less, in lakes of small to medium size (e.g. Smith 1979 as reported in Hamilton and Mitchell 1996). The wind speed records, measured 7 m above sea level, were adjusted to 10 m using the approach of Amorocho and De Vries (1980).

Estimates of area-averaged resuspension flux E_{av} at each lake were obtained at bi-hourly time steps by (1) deriving wave characteristics from wind speed and direction records (Fig. 3a, b) at each cell in a discretized bathymetry; (2) getting point estimates of bottom shear stress at each cell from Eq. 2; (3) getting point estimates of E at each cell from Eq. 1; and (4) averaging in space the spatially variable estimates of E. The discretized bathymetry was constructed by overlaying a regular grid (of 1 × 1 m) on top of the bathymetry map and interpolating the depth information to the centre of each grid cell. The fetch F for each cell was then estimated for each wind direction, ranging from 1 to 360° with a 1° interval. The constant η in Eq. 1 was set to 1 following Bailey and Hamilton (1997). The critical shear stress for entrainment was also set to a reference constant value (=0.01 Pa), equal in both lakes, given the lack of adequate in situ data for its evaluation. This reference value for τ_c is of the same order of magnitude as values reported by others in the literature. Mian and Yanful (2004), for example, report values for τ_c of ca. 0.06 Pa. Mantz (1977) and Miller et al. (1977) (as reported by Luettich et al. 1990) also suggest values for τ_c of ca. 0.05 Pa. The bi-hourly resuspension fluxes E_{av} were made non-dimensional by dividing by the maximum resuspension flux estimated through Eq. 1 during the study period in Lake Honda. Note that by making non-dimensional estimates, the actual value of the empirical constant K_r in Eq. 1 becomes irrelevant.

We used average resuspension fluxes E_{av}, rather than point estimates of E, as a basis of comparison between the two lakes because our study sites are so small that they will be rapidly homogenized in response to wind forcing. If we accept the analytical solution of Heaps (1984) as a plausible description of the velocity field in the study lakes, one expects maximum velocities (at the surface) of $O(10^{-1})$ ms^{-1} in response to wind speeds of $O(10)$ ms^{-1} and eddy viscosities of $O(10^{-3})$ ms^{-1}. With those currents a lake of 700 m long (LN) would be homogenized in approximately 2 h. Under these conditions, the material collected in a given sediment trap (from which we estimate resuspension fluxes) will come from resuspended material from all locations within the lake.

Adsorption experiments

The flocculent layer was sampled in November 2002 at maximum depth in each lake. We used a horizontal Van Dorn sampler, which was bounced off the bottom a few times to resuspend the sediment (Doremus and Clesceri 1982). In the laboratory, the flocculent layer was concentrated by centrifugation (10 min, 8,944g). Maximum PO_4^{3-}-adsorption capacity was measured using the batch-experimental technique, based on shaking (in Erlenmeyer flasks at 150 rpm) at a constant temperature (20°C) of 0.5 g fresh sediment with different solutions (100 ml of 3 mM $NaHCO_3$ increasingly enriched with KH_2PO_4) and during different times (Table 2). The flocculent layer was also incubated for 24 h with filtered (Whatman GF/C) water taken from each lake using a Van Dorn sampler, following the same methodology described above for quantifying the maximum PO_4^{3-}-adsorption capacity. All suspensions were prepared in triplicates. Dry weight (DW) of sediment suspension was quantified (104°C, 24 h) in order to express final results in terms of DW. After shaking, suspensions were centrifuged (10 min, 8,944g) to

Table 2 Experimental conditions for the adsorption experiments performed for quantifying the maximum P–PO_4^{3-} adsorption capacity of the flocculent layer collected in November 2002

	Shaking time (h)	Initial P concentration (mg L^{-1})
Honda	2, 4, 6, 12 and 24	0.5, 1.1, 2.8, 5.9, 11.2, 27.8 and 33.3
Nueva	2, 4, 6, 12 and 24	0.5, 1.0, 2.5, 5.1, 10.6, 20.1 and 30.9

separate the supernatant, where the PO_4^{3-} concentration (C_e) was analysed following the molybdenum blue method (Murphy and Riley 1962). Finally, adsorbed PO_4^{3-}–P (q, mg g^{-1} DW) was calculated as the difference between the initial and final concentration in the supernatant. Results from isotherms were fitted to the Freundlich model using the following equation:

$$q = K_F C_e^n \quad (4)$$

where K_F is an adsorption constant and n an empirical saturation constant (0.3–0.4; Golterman 2004).

Statistical analysis

Our work compares sedimentation fluxes between lakes and analyzes correlations between variables. Statistical comparisons of variables and fluxes between basins were done using a t test student, with a significant level fixed, unless it is explicitly stated, at $P < 0.05$.

Results and discussion

Sediment composition

Surface sediments from both study sites exhibited large differences both in grain size and composition (Table 3). The solid phase of the sediment from LH is silty with lower organic matter content and high FeOOH. It also shows high PO_4^{-3} concentrations in the pore-water. By contrast, the sediment in LN has a larger fraction of sand and organic matter, and lower concentrations of FeOOH and interstitial PO_4^{-3}. Chlorophyll *a* concentrations in the sediments are also very different in the sediment of both study lakes, with larger concentrations in LN. Note (Table 3) that the fraction of clay in the sediment is larger than 24% in both lakes, which is sufficient to render the sediment behaviour as cohesive (Raudkivi 1998). Resuspension of cohesive sediments has been traditionally quantified using Eq. 1 (see for example, Mehta et al. 1982; Bloesch 1994; Huang et al. 2006).

Settling fluxes and focusing factor

Settling fluxes (S) were significantly larger (at least twice as large) in LH than in LN (Table 1). Similarly, average values for TC, TN and TP settling fluxes were up to two-fold higher in LH than in LN. The larger settling fluxes encountered in LH could be the result of greater external P load (de Vicente et al. 2003) but also it could be caused by larger resuspension fluxes.

Table 3 Surface sediment composition of the three sampling stations selected in both lakes during the study period

	Honda	Nueva
P–PO_4^{-3} (μg L^{-1})	770 ± 581	271 ± 351
TFe (mg Fe g^{-1} DW)	35.2 ± 6.4	21.5 ± 5.4
FeOOH (mg Fe g^{-1} DW)	15.6 ± 4.2	5.2 ± 2.3
FeOOH:TFe (%)	44	24
FeOOH:TP (atomic ratio)	15	8
TP (μg g^{-1} DW)	549 ± 134	340 ± 53
Chl *a* (μg g^{-1} DW)	32.7 ± 8.8	63.6 ± 33.1
O.M. (%)	5.6 ± 2.9	16.8 ± 2.1
Clay (%)	39.3 ± 3.01	24.3 ± 4.5
Silt (%)	60.3 ± 2.3	60.0 ± 14.0
Sand (%)	0.4 ± 0.3	15.7 ± 6.3

Note that clay, silt and sand are shown as a percentage of the mineral fraction. Mean ± SD ($n = 42$)

The evolution of the focusing factor estimated from bi-weekly sedimentation fluxes S measured in traps deployed at different depths is shown in Fig. 2a, b. Average values of the focusing factor estimated from bottom and middle depth traps for LH (1.05) and LN (0.95) were not significantly different (t test student; $P > 0.05$). However, the focusing factor estimated as S_B/S_T was significantly larger in LH (1.18) than in LN (0.88). During January 2001, the focusing factor in LH was 2.17, 44% larger than in LN ($S_B/S_T = 1.51$). The larger focusing factor in LH at that time could also be due to the occurrence of a strong rainfall event (see Fig. 3d), which, given the larger catchment area of LH compared to LN, resulted in larger inflows and possibly in larger sediment loads. Rainfall events in the area are, however, episodic and infrequent, which indicates that any differences in focusing factors between lakes are probably the result of differences in wind-driven resuspension fluxes. In fact, a significant and positive correlation exists between maximum wind speeds previous to the sampling date and focusing factors calculated in LH. In LN, the correlation is also positive, but not significant.

The winds over the lakes are episodical with peak values of 15 ms^{-1} and even larger (Fig. 3a), which explain the time variability encountered in focusing factors and in the time series of modelled average resuspension fluxes E_{av}. Note that the peaks in the time series of E_{av} coincide with peaks in the times series of wind speed (Fig. 3a). The model results suggest also that resuspension fluxes are larger in LH. Note, also, that there is a time–lag between

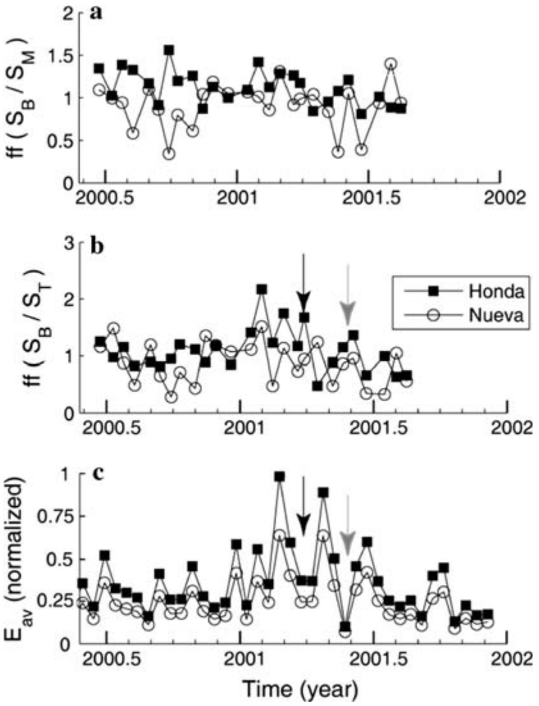

Fig. 2 Time series of focusing factors calculated from sediment trap observations (**a**, **b**), and bi-weekly time series of simulated area-averaged and non-dimensional resuspension fluxes **c**. Focusing factors in **a** are calculated as the ratio of settling fluxes measured for bottom traps (S_B) and medium traps (S_M). In frame **b** the focusing factors are estimated as the ratio of settling fluxes measured for bottom traps (S_B) and surface traps (S_T); i.e. S_B/S_T. The bi-weekly non-dimensional resuspension fluxes E_{av} **c** were obtained by first averaging in time the bi-hourly estimates of resuspension fluxes provided by the model, and then dividing by the maximum value calculated at Lake Honda. The *arrows* on frames **b** and **c** define two times (late March and late May) when peaks in the focusing factors coincide with troughs in the time series of resuspension flux calculated with Luettich's model

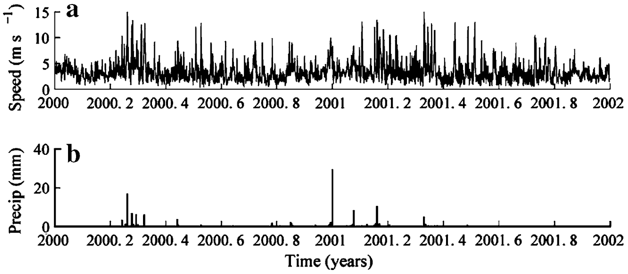

Fig. 3 Time series of **a** wind speed and **b** rainfall recorded at a nearby station (see text). Wind speed records are 6 h averages and are shown every 12 h. Rainfall data are shown on a daily basis as collected at the meteorological station

the time series of E_{av} (Fig. 2c) and that of the focusing factors (Fig. 2a, b). For example, the peak of focusing factor in late March (see also the peak in late May) occurs at the same time when the model predicts low values of E_{av}, due to lower wind speeds (see Fig. 3a, b). That lag between the time series can be explained in physical terms, if one considers that settling and resuspension do not occur simultaneously. Instead, one or the other process will dominate the sediment dynamics in different periods of time. It seems plausible, in particular, that settling in the traps will mainly occur during periods when the wind forcing is low enough not to keep the sediment particles in suspension. However, it is during those periods of low winds, when shear stress and resuspension fluxes estimated with the model will be also low. When averaged over sufficiently long periods, though, both approaches to estimate resuspension should converge. In fact, on average the ratio of the average focusing factor in LH versus the average focusing factor in LN is approximately 1.34. The ratio of E_{av} at LH vesus E_{av} at LN is close to 1.34 (ca. 1.4).

Resuspension fluxes: physical and biological mechanisms controlling differences between lakes

The differences in resuspension fluxes between lakes can be attributed to differences in their morphometry as well as to differences in their sediment properties (grain size distribution and composition). A cross-section of the bathymetry maps reveals that LN has a nearly flat bottom with a depth of 3 m, while LH is naturally divided in two basins separated by a narrow (hardly 20 m wide) strait (see Fig. 1). The easternmost basin is the smaller and deeper, with a maximum depth of 3.2 m. The westernmost basin of LH is at most 2.2 m deep. Basin wide estimates of resuspension fluxes E_{av} in LH is on average 40% times larger than in LN (see Fig. 4a). These differences in resuspension fluxes are in the same order of the differences in focusing factors (approximately 34% larger in LH than in LN) (Fig. 4b). Note that the settling fluxes estimated from the sediment traps are also two times larger in LH than in LN. This might be surprising, given the smaller size (and hence fetch) of LH. However, a large fraction of LH (>80%) is shallower than 2 m, while in LN most of the basin is deeper than 3 m (only 35% is shallower than 2 m). Furthermore, sediment resuspension in LN is also reduced (in comparison with LH) given the larger fraction of sand in the sediment (Table 3), which might result in a larger critical shear stress τ_c in Eq. 1. Hence, resulting in larger values of resuspension fluxes, given the same wave properties. Note, though, that we have ignored the differences in τ_c between lakes since we did not have sufficient in situ information to estimate appropriate values for τ_c.

Beyond the purely physical processes, there are other (biological) mechanisms which can be argued as a plausible explanation for the differences in sediment dynamics between LH and LN. In particular, we can argue that the larger resuspension fluxes encountered in LH will cause larger concentrations of total suspended solids in the water column compared to LN (Table 1). Therefore, the increased

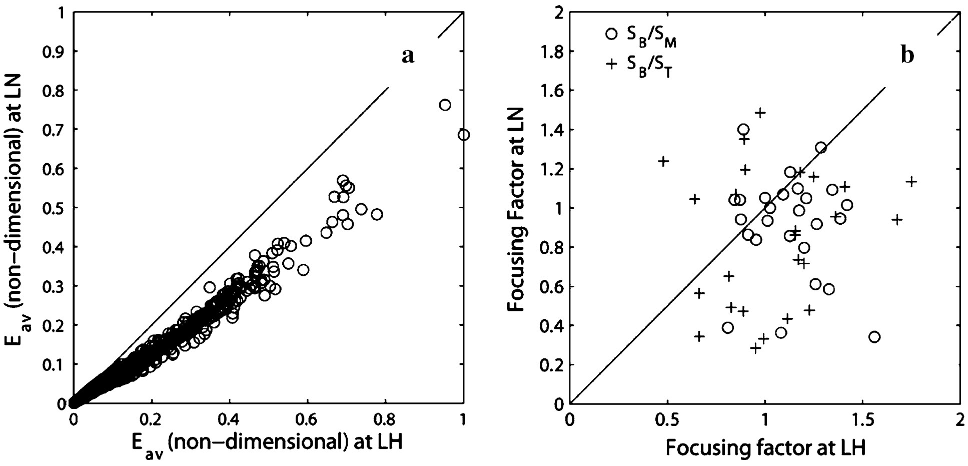

Fig. 4 **a** Bi-hourly non-dimensional resuspension fluxes in LH, as predicted by the model of Luettich et al. (1990) versus resuspension fluxes at LN. The non-dimensional fluxes are calculated by dividing the dimensional estimates by the maximum value of E_{av} for Lake Honda during the study period. **b** Focusing factors at LH versus values of focusing factors estimated from observations at LN. The *solid line* in both plots represents the line of equal values (i.e. slope 1:1). *Circles* and *crosses* below the 1:1 line suggest that resuspension in LH is larger than in LN

light attenuation prevents the development of macrophytes and benthic algae which could possibly causes sediment stabilization (Madsen et al. 2001; Horppila and Nurminen 2003). In contrast, resuspension in LN is limited by the presence of cohesive agents in the sediment, such as algal mats, which are reflected in the high concentration of chlorophyll *a* in the surface sediment (Table 3). Hence, in this lake the growth of submerged macrophytes will be stimulated by the higher light penetration reducing the resuspension fluxes.

The fact that sediment resuspension in LH is larger than in LN explains the existence of great differences in several sediment characteristics between both lakes investigated. For example, organic-matter concentrations in the surface sediment from hypertrophic LH are far lower than in LN (Table 3), presumably because of the dynamic transport of sedimentary particulate organic matter to the water column, which would stimulate its overall mineralization (Wainright and Hopkinson 1997). In addition, the C:P ratio is similar in the surface sediment (237) and in the material collected by the bottom sedimentation traps (199) in LH, which reflect the important contribution of resuspended matter to the settling particles in this lake. By contrast, LN shows major differences between chemical composition of the two materials (C:P in surface sediment: 416; C:P in bottom traps: 157; de Vicente et al. 2003) and thus reflect the minor contribution of particles from surface sediment to the settling matter. Even more, the noteworthy difference between P-sedimentation (measured by sedimentation traps and hence including both settled and resuspended matter) and P-retention rates (estimated from P mass balance) in LH may reflect the effect of resuspension episodes, reducing the net P retention in the sediment (de Vicente and Cruz-Pizarro 2003).

Resuspension and phosphate dynamics

Wind forcing in lakes may impact nutrient dynamics (P in particular) in different ways. First, it can have a direct effect on the dissolved P pool present in the sediment. To show that, we have related the maximum wind speed recorded during a 48 h period before the sampling ws_{48} and the concentration of PO_4^{-3} in the interstitial water (P_{inters}) of the surface sediments of LH and LN. Our results reveal that in both lakes there exist an inverse, but not statistically significant, relationship between ws_{48} and P_{inters}. This may reflect the importance of wind-induced turbulence for oxygenating the sediment surface and thus, precipitating the PO_4^{-3}. Another likely explanation is that exposure to wind enhances PO_4^{-3} diffusion from the interstitial to the overlying water and hence, may decrease the PO_4^{-3} availability in the pore-water. However, one needs to keep in mind the inherent difficulties in explaining the P dynamics in the pore-water by considering only the wind data. The PO_4^{-3} availability in the surface sediment is the final result of a range of biological, physical and chemical mechanisms interacting. It is important to note that maximum wind speed was recorded during the winter period, just when the organic matter mineralization was expected to be less intense and hence, could account for a lower PO_4^{-3} release from the particulate organic matter to the dissolved pool.

Second, resuspended particles in the water column can also alter P dynamics in solution, as a result of mechanisms

Table 4 Results of the adsorption experiment with lake water and with solutions used for estimating the P maximum adsorption capacity

Lake water experiment		P maximum adsorption capacity		
Initial P (μg P–PO_4^{-3} L^{-1})	P_{ads} (μg g^{-1} DW)	Freundlich		
		n	K_F	r^2
Honda				
37 ± 2	+22 ± 4	0.32	1.59	0.95
Nueva				
4 ± 1	−4 ± 1	0.33	0.73	0.98

Note that $P_{ads} < 0$ indicates P desorption, while $P_{ads} > 0$ reflects P adsorption by the flocculent layer ($n = 3$)

such as adsorption or desorption. The experiments performed with lake water to simulate natural conditions showed that the sediment from LH adsorbed PO_4^{3-}, while that from LN released PO_4^{3-} (Table 4). Accordingly, in LH resuspended matter contributed to a PO_4^{3-} removal from the water column, while in LN resuspension events induce increases in the availability of PO_4^{3-}. These differences are partly a consequence of larger concentrations of PO_4^{3-} in the water column of LH, compared to LN (Tables 1, 4). We also found a much higher value for the empirical saturation constant (K_F) in the sediment from LH than in LN which indicates its high PO_4^{3-} adsorption capacity (Table 4). The study of the kinetic PO_4^{3-} adsorption revealed that for both lakes equilibrium was reached within 6 h (Fig. 5) and our results fit very well to the Freundlich adsorption model, one of the most common in the literature (Table 4). Given that the adsorbate PO_4^{3-} and the incubation conditions were exactly the same for both lakes, differences in PO_4^{3-} adsorption capacity may be explained primarily by the chemical composition of the adsorbent (resuspended material). In fact, surface sediment from LH contains much higher FeOOH concentrations than that from LN (Table 3). This compound has traditionally been considered to be among the main agents contributing to the PO_4^{3-} adsorption capacity (e.g. Lijklema 1977, 1980; Golterman 2004). Furthermore, the great proportion of clay in the sediment from LH (Table 3) may significantly increase such capacity, as many authors have pointed out (Boström et al. 1982; Istvánovics et al. 1989; López and Morguí 1993; López et al. 1996).

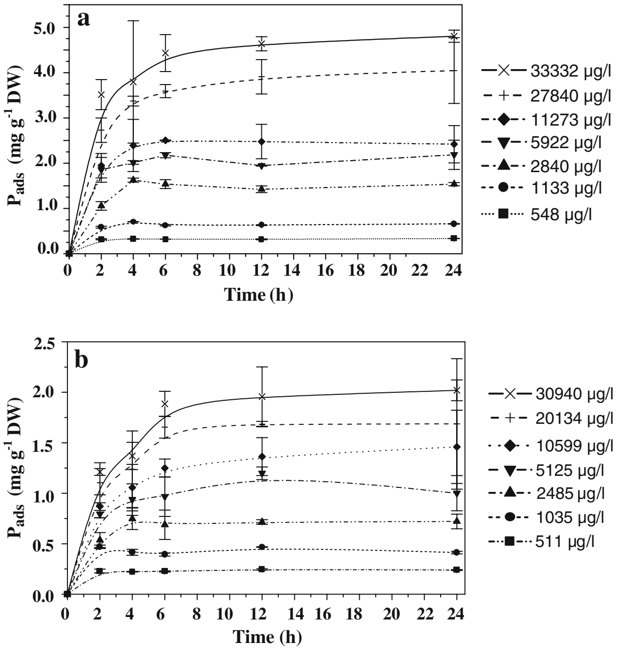

Fig. 5 Temporal development of PO_4^{3-} adsorption process of resuspended matter in LH **a** and in LN **b**. Note the different scale used for the amount of P adsorbed (P_{ads}). *Vertical bars* represent SD ($n = 3$)

Finally, PO_4^{3-} adsorption capacity also depends on the degree of saturation which in turn can be related to the Fe:P ratio and reflects the number of free adsorption sites (Jensen and Andersen 1992; Jensen et al. 1992). For calculating the Fe:P ratio, it is necessary to specify which Fe and P sedimentary forms should be considered. As FeOOH is the most important Fe sedimentary pool contributing to PO_4^{3-} adsorption capacity and all P fractions are subject to a potential mobilization, it seems reasonable to examine the atomic ratio FeOOH:TP. The twofold higher ratio in LH (15) compared to LN (8) (Table 3) confirms the high capacity of such sediments to adsorb PO_4^{3-}.

Conclusions

Our work reveals that in-lake characteristics can have a strong influence on the PO_4^{3-} dynamics of shallow lakes by controlling the magnitude of sediment resuspension. The resuspension fluxes, estimated by comparing settling fluxes measured in surface sediment traps with those measured in bottom traps, were significantly larger (34%) in LH than in LN due to its much greater lake area affected by wind-induced waves.

The differences in resuspension between the study sites were analyzed within the modelling framework proposed by Luettich et al. (1990) to represent the dynamics of suspended sediments in lakes. The model results agree with the field observations, in that resuspension fluxes predicted for LH are, on average, 40% larger than in LN. The modelling results suggest that resuspension fluxes in LN are lower mainly due to its morphometry. The presence of benthic algae or the larger grain size of LN sediment could also contribute to the reduced resuspension fluxes in LN compared with LH.

Our laboratory experiments revealed that PO_4^{3-} availability in the water column can be strongly influenced by the occurrence and magnitude of resuspension fluxes. Hence, differences in resuspension-sedimentation fluxes between lakes result in differences in the dynamics of P. While the resuspended material from LH tends to adsorb PO_4^{3-} and thus contributes to its removal from the lake water, we find the opposite tendency in LN. These differences are due to (1) larger PO_4^{3-} concentrations in the water column of LH, and (2) more PO_4^{3-} adsorption sites on the sediment particles (in particular, iron oxyhydroxides). The concentrations of PO_4^{3-} encountered in LH, in turn, are much greater than in LN as a consequence of a large external P input and an intense organic matter mineralization (see de Vicente et al. 2003). These results suggest that resuspension represents a self-control mechanism that tends to decrease PO_4^{3-} availability in the water column.

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