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Lacustrine particle dynamics in high-altitude Estany Redó (Spain) - a high resolution sediment trap study

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ABSTRACT

Particle fluxes were measured from 2000 to 2001 with 3 integrating open traps (O-traps) and a sequencing trap (S-trap) in the 73-m deep, oligotrophic, high-mountain Estany (Lake) Redó (2240 m a.s.l.) over a period of 558 days. O-traps were deployed at 26, 46, and 66 m water depth to measure overall sedimentation rates, while the S-trap was deployed at 66 m water depth to detect dynamics of seasonal particle fluxes with a resolution of 4 days (during ice break-up, summer, ice formation) to 21 days (during ice cover). Our results show a high degree of seasonal variability in particle dynamics. Total particle fluxes vary from almost zero to more than 600 mg m^{-2} d^{-1}. The highest fluxes occur during short time windows after ice-break-up (minerogenic particles), during spring (planktonic biomass), and during fall overturn (chrysophycean cysts). Particle fluxes also differed markedly from year to year in absolute values (2000: 644 mg m^{-2} d^{-1}, 2001: 370 mg m^{-2} d^{-1}) as well as in average values (2000: 76 mg m^{-2} d^{-1}, 2001: 44 mg m^{-2} d^{-1}). Annual and seasonal meteorological changes and events have a clear influence on the lake system and on the amount and composition of particles. C/N ratios during April and May increased significantly from 2000 (6-14) to 2001 (>28), reflecting the more intense soil erosion and transport of terrestrial plant remains into the lake caused by heavy precipitation in 2001. Air temperature strongly influences the timing of the occurrence of the main bio-productivity peak. Strong wind events shorten the period of ice cover. Our investigation shows that sediment trap studies lasting more than one limnological cycle are useful in studying the effects of short-term meteorological changes and weather events on high mountain lakes. However, long-term particle flux measurements would be necessary to determine amplitudes of natural seasonal cycles and for the interpretation of the decadal-scale environmental changes occurring in such lakes.

Key words: sediment trap, high-resolution particle flux, high mountain lake, seasonality, bio-productivity

1. INTRODUCTION

Predicting the frequency and amplitude of future climate changes, as well as supplying a precise answer to the question of how ecosystems might respond to these changes, are difficult problems to solve. The main reasons for this difficulty are, on the one hand, the inherent complexity and variability of nature, and, on the other hand, the influence of human activities, which is often strong enough to mask natural variability. Remote mountain lakes are often influenced by direct atmospheric deposition and by input from a generally small catchment area, and are not subject to significant influence from local human activities. In addition, global environmental changes tend to leave strongly amplified signals in high-elevation regions (Beniston *et al*. 1997). Remote mountain lakes are thus thought to be excellent sensors of past environmental changes, the signatures of which are archived in the lake sediment (Sturm *et al*. 2003). Moreover, many processes can affect the transfer of climatic and environmental signals, from the atmosphere and the catchment area, through the water column and into the sediment. Even regularly laminated sediments mask the heterogeneity of short-term particle fluxes that may occur within a year. High-resolution sediment trap studies can reveal this otherwise lacking information.

Sediment traps have been used widely in lakes since the 1950s (Bloesch & Burns 1980). A knowledge of the quantity and quality of sedimenting particles and of the timing of their formation is crucial a better understanding of dynamic sedimentation processes and proxy climate data (Rathke *et al*. 1981; Sturm *et al*. 1982; Ohlendorf & Sturm 2001; Wehenmeyer & Bloesch 2001; Müller *et al*. 2005; Rose & Monteith 2005). However, only automated, high-resolution sequencing traps can detect short-term flux events, caused by floodings, algal blooms, calcite precipitation etc. (Bloesch & Sturm 1986; Ryves *et al.* 2003; Sturm *et al*. 2003).

The geography, limnology and ecology of Estany Redó have been investigated since the 1980s. Snow and ice development during wintertime, as well as other physical properties, have been studied to examine the coupling of physical and biological processes (Catalan 1988, 1989; Ventura *et al*. 2000). The lake came into the focus of biological studies because it is oligotrophic and remote, with little anthropogenic influence (Catalan & Camarero 1991; Catalan *et al.* 2002b). These authors investigated biological processes to detect their potential as proxy data for weather and climate variability. In

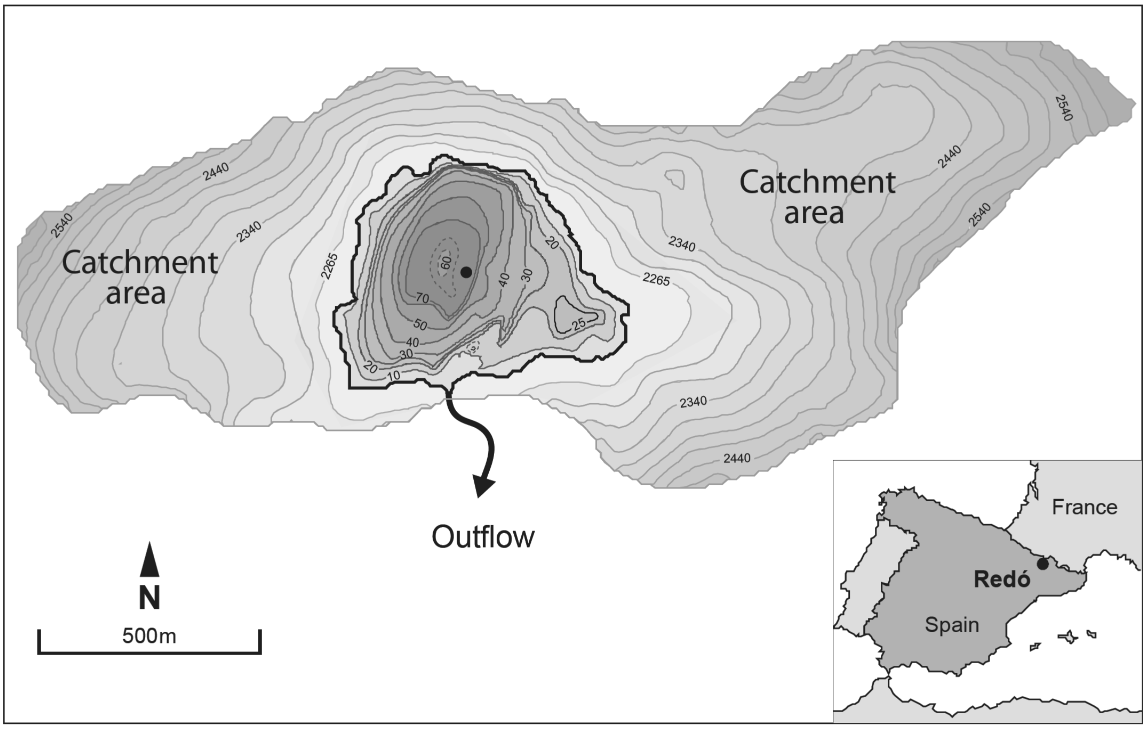

Fig. 1. Estany Redó, showing location (inset), catchment area, and bathymetry. The location of the sediment trap mooring in the centre of the lake is shown as a black dot. The dashed contour lines near the mooring indicate a small rise in the lake floor of up to 8 m.

addition, Estany Redó was used to study the effect of atmospheric pollution and acid rain on remote lake sites (Camarero & Catalan 1993, 1998; Camarero *et al.* 2004).

Here we present high-resolution sediment trap data collected from 15 April 2000 until 25 October 2001 in Estany Redó. The study aims to test if differences in the seasonal weather pattern lead to high seasonal ecosystem variability within the lake, and to investigate the influence of the catchment on the particles of the lake. In comparison and combination with almost 20-year old "trap-like" data (Felip & Catalan 2000), we set out to show the potential of perennial trap studies, that recover inter-annual variability, to contribute to climate change research. There are the first published results from a study, which uses automated, high-resolution sediment traps to determine particle dynamics in a remote high mountain lake.

2. THE SITE

Estany Redó is located at an elevation of 2240 m a.s.l. in the Spanish central Pyrenees (42°38'N, 0°46'E) and was carved into granodiorite bedrock (Ventura *et al.* 2000; Catalan *et al.* 2002b). Estany Redó is a glacial cirque lake (655 m × 565 m) with steep slopes and a maximum depth of 73 m. The lake covers 16% (0.24 km^2) of the 1.5 km^2 catchment area (Fig. 1). The rest of the catchment area consists of bare rock (25%) and alpine meadows covering a poorly developed soil about 35 cm thick (59%) (Camarero *et al.* 1999). The period of ice cover can last up to 6 months starting in November/December (Ventura *et al.* 2000; Catalan *et al.* 2002b). Estany Redó is fed mainly by precipitation-periods (snowmelt and rain), via non-permanent streams that dry up in summer. A permanent outflow stream exists on the southern shore of the lake (Fig. 1, Catalan 1988). Estany Redó is a dimictic lake and the water has a residence time of ~4 y. Electrical conductivity is very low (~12 $\mu S\ cm^{-1}$). The annual mean air temperature is 3.6 °C, and the annual mean precipitation is 1328 mm y^{-1} (Appleby 2000; Ventura *et al.* 2000).

3. METHODS

3.1. Mooring design and trap setting

To assess the particle dynamics in Estany Redó, a sediment trap mooring with three integrating Eawag-130 open traps (henceforth O-traps: Ohlendorf & Sturm 2001) and one TECHNICAP® PPS5/2 sequencing trap (henceforth S-trap) was deployed in April 2000 (Fig. 2). The S-trap, which had 24 sampling cups and an active area of 5000 cm^2, was used to measure short-term, seasonal fluxes. The rotation times of each of the sampling cups were programmed individually by a microprocessor, which allowed sampling to be conducted over any given time interval. The sampling cups consist of PVC and each cup has a volume of 250 ml. The O-traps have an active area of twice 130 cm^2 and an aspect ratio of 1:9. Total fluxes measured by O-traps were used to crosscheck sequencing fluxes of the S-trap. An "I-type" mooring string was used to deploy the traps in Estany Redó (Fig. 2, Sturm *et al.* 1982; Bloesch & Sturm 1986). The mooring consisted of a 50 kg anchor weight, a pre-stretched plastic rope 10 mm in diameter, and several buoys at the upper end of the rope to provide the required buoyancy. The S-trap was deployed at 66 m water depth, 5 m above the sediment-water interface to avoid the effects of resuspension. Three O-traps were attached to the mooring rope at water depths of 26 m (below the epilimnion), 46 m and 66 m. In order to avoid damage by ice and loss of buoyancy because of large changes in lake level, the buoys were deployed more than 2 m below the water surface. The mooring was deployed from the lake ice in early spring 2000 in order to obtain samples during ice-break up. The longest exposure period included the winter period of 2000/2001 and thus included a second stage of ice coverage.

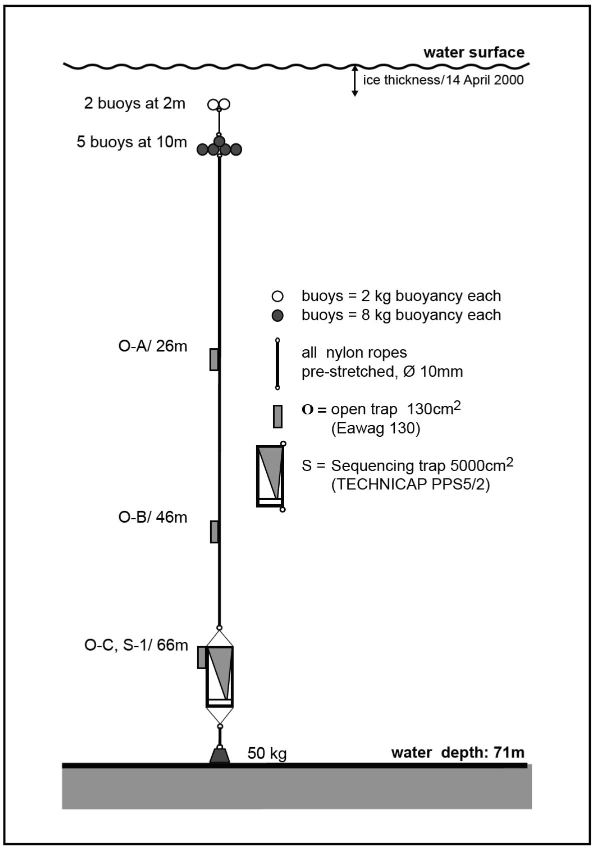

Fig. 2. Detailed sketch map of the trap mooring in Estany Redó in its winter setting showing the buoys 2 m under the water surface. In summer the uppermost buoys are at the water surface.

3.2. Meteorological data

Meteorological data were recovered from an automatic weather station, which was installed ca. 30 m next to the southern shore (Fig. 1). The sensors for the meteorological variables (e.g. air temperature, precipitation, wind speed) were attached to a mast *ca* 6-10 m above the ground, which is 36-40 m above the lake level. For a more detailed description see Ventura *et al.* (2000).

3.3. Sample preparation and measurements

After recovering the mooring, the supernatant water from the S-trap samples was decanted for chemical analysis to check for dissolution within the sampling cups. The samples were then transferred to the laboratory in cooling boxes and subsequently freeze dried. After determining the total dry-weight, the freeze-dried trap material from both the O-traps and S-traps was analyzed for inorganic carbon (C_{inorg}) using a coulometer (Coulometrix Inc. 5011 CO_2-Coulometer). Total carbon (C_{tot}) and nitrogen (N_{tot}) was measured with a Carlo Erba CHNS Elemental Analyzer (EA 1108). Organic carbon (C_{org}) was calculated as $C_{tot} - C_{inorg}$. Detailed particle analyses of the trap samples were performed with a Phillips XL30 scanning electron microscope (SEM) with an attached energy dispersive spectroscopy system (EDS). 12 mg of a sample were placed in a test-tube with 4 ml of ethanol. This suspension was then sonicated for 2 minutes and sprayed onto the targets using a spray gun (Bollmann *et al.* 1999). In the SEM, images were made at magnifications of 50×, 250×, and 1000×. Three analysis fields per image were chosen to measure their concentrations of Na, Mg, Al, Si, Cl, S, P, K, Ca, Fe, and Mn by SEM-EDS. To account for sample inhomogenities and to assess analytical precision, the average values of these measurements were used (Schloz 2000). Concentrations are given in atom-% as determined by SEM-EDS with respect to reference material.

4. RESULTS

4.1. Trap results and particle dynamics

4.1.1. O-traps

Particle fluxes were measured over a period of 558 days, from 15 April 2000 to 25 October 2001. This period was split up into 4 intervals, i.e. 3 exchanges of the traps:

- 1) 15.04.2000 – 13.08.2000: 120 days
- 2) 13.08.2000 – 19.11.2000: 98 days
- 3) 19.11.2000 – 15.06.2001: 208 days
- 4) 15.06.2001 – 25.10.2001: 132 days

Particle fluxes were determined separately for each of these periods and are shown in figure 3. Except for the lowest O-trap during period 4, total sediment fluxes increased with water depth (Fig. 3). Total particle fluxes were lowest during ice cover (58-82 mg m^{-2} d^{-1}), and were 2 – 4 times higher than this under open water conditions. The highest total sediment fluxes - up to 278 mg m^{-2} d^{-1} - were recorded in the lowermost O-traps during ice break up. The average particle flux within the expo-

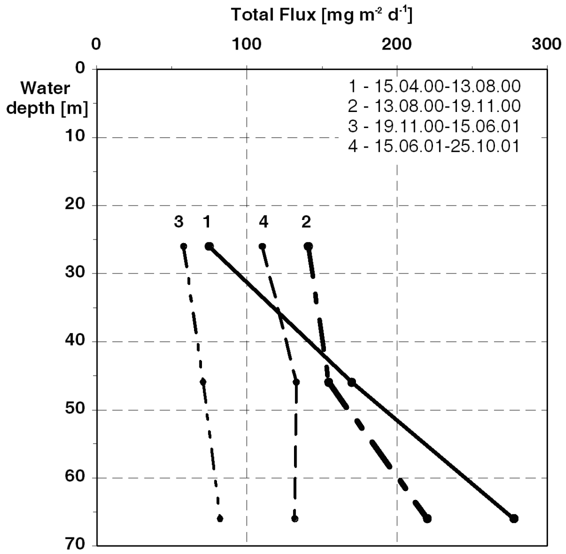

Fig. 3. Particle fluxes of O-traps in 26 m, 46 m, and 66 m water depth during the four exposure periods.

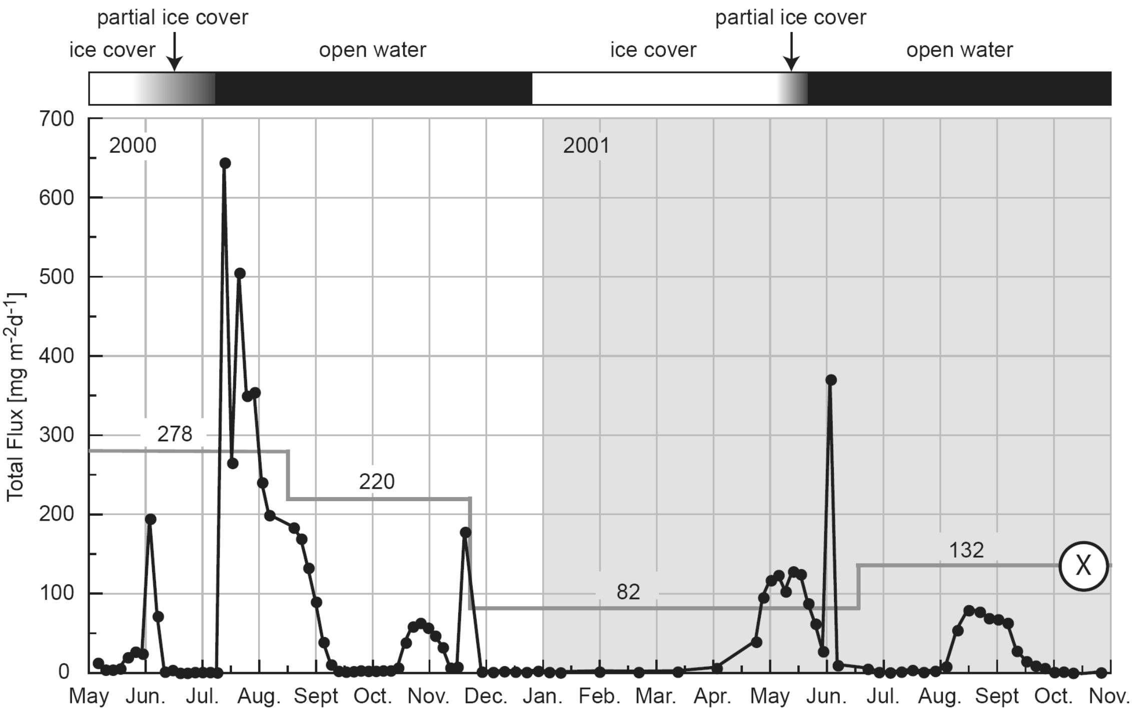

Fig. 4. Seasonal particle fluxes in Estany Redó from 14 April 2000 to 25 October 2001 revealed by the S-trap in 66 m water depth. X: mean sediment flux determined by O-trap at 66 m water depth during the four exposure periods.

sure period was half as high in the 26 m O-trap (89 mg m^{-2} d^{-1}) than in the lowest O-trap, at 71 m water depth (160 mg m^{-2} d^{-1}).

4.1.2. S-trap sediment fluxes and particle composition

The sediment fluxes measured by the S-trap were highly variable during the period of investigation (Fig. 4). The fluxes varied from almost zero during the periods of ice cover to more than 600 mg m^{-2} d^{-1} during the open water period. Five periods of high sediment accumulation were observed (Fig. 4).

Ice breakup normally begins in May/June (Catalan 1988, 1992; Ventura *et al*. 2000) on the eastern shore, where the main inflow enters the lake. In the very first

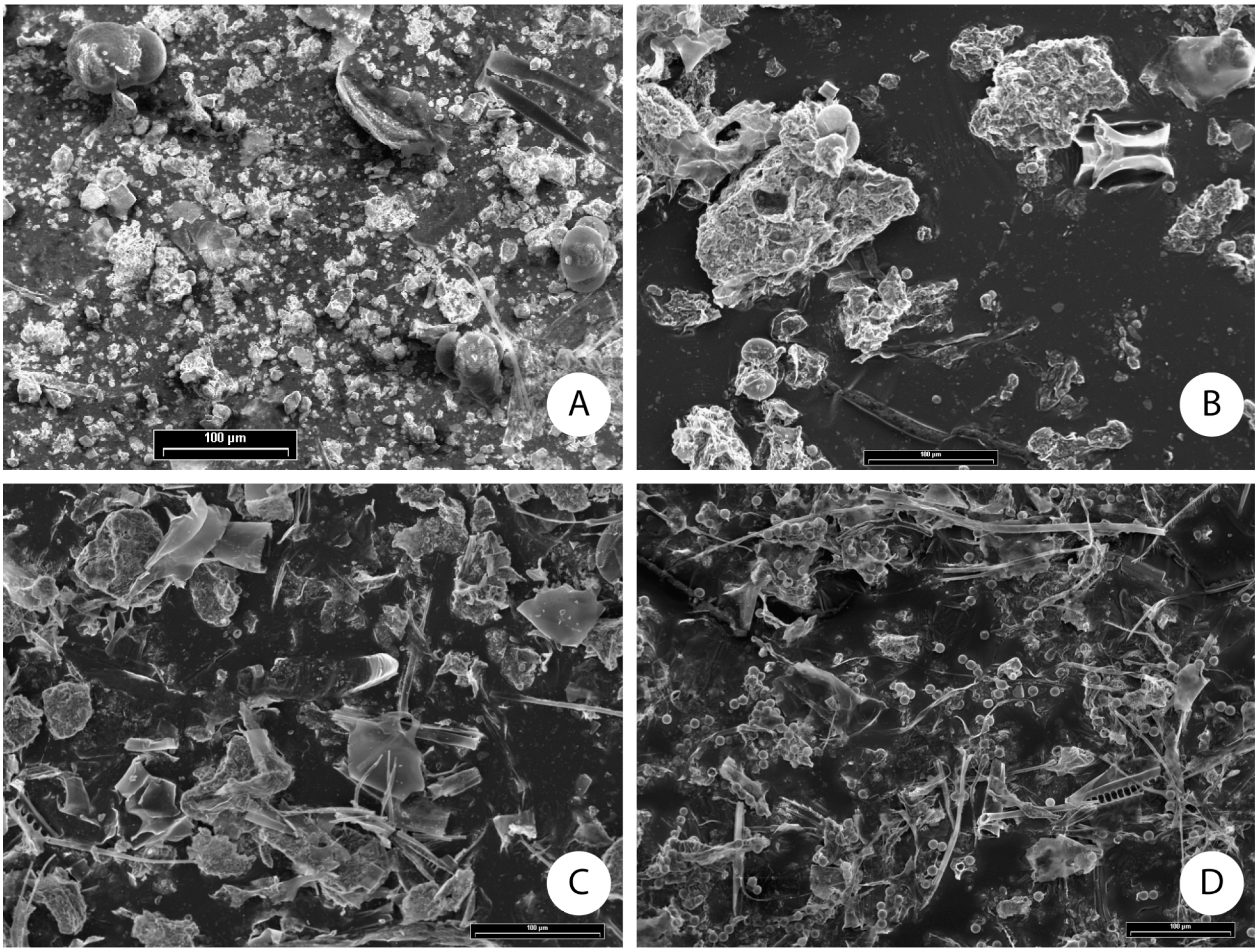

Fig. 5. SEM images. (**A**) Initial phase of ice break-up, June 2000: detrital minerals and pollen. (**B**) Beginning of open-water period, July 2000: large organic aggregates. (**C**) End of the high flux period, August 2000: more zooplankton remains less amounts of organic aggregates. (**D**) October 2000: chrysophycean cysts, zooplankton remains, and organic aggregates. The scale bars are each 100 µm in length.

stage of break-up in 2000, an initial input of allochthonous particles was observed, from 18.05. – 06.06. The particles consisted mostly of detrital minerals, a few pollen grains, and zooplankton remains (Fig. 5a). Detrital minerals and pollen grains were probably released by melting lake ice and transported from the catchment by snowmelt runoff. SEM images of particles that entered the S-trap during the thawing of the ice show that biological productivity was still limited in the lake at that time. This kind of particle input in the very first stage of ice break-up did not appear in 2001.

The highest particle fluxes occurred when the lake became completely ice-free; commencement of the open-water period was characterized by large autochthonous organic aggregates (Fig. 5b). Minor components included a few diatoms and pollen grains. This high productivity peaks occured in 2000 from 09.07. – 07.09. (61 days) and in 2001 from 03.04. – 29.05. (57 days). Towards the end of the high flux period, the large organic aggregates became less abundant (Fig. 5c).

During summer, a second period of high particle accumulation occurred. In 2000 it lasted 36 days from 14.10. – 18.11. and the particles were dominated by zooplankton remains. In contrast to 2001, there were many chrysophycean cysts and few organic aggregates (Fig. 5d). In 2001, organic aggregates and zooplankton remains dominated the particle composition during the high flux period from 28.07. – 10.09. (45 days). Minor components included chrysophycean cysts, as well as very few pollen grains and diatoms. The final stage of the open-water period (very low particle fluxes, no peaks) was characterized by a few organic aggregates and zooplankton remains, and a few chrysophycean cysts, pollen grains, and diatoms (Fig. 5d).

From May to October 2000, the overall sediment accumulation in the S-trap (7500 mg) was approximately 2.5 times higher than the amount that accumulated during the same time period in 2001 (3200 mg), and the mean sediment flux (91 mg m^{-2} d^{-1}) was more than twice as high as in 2001 (44 mg m^{-2} d^{-1}). The

Tab. 1. Selected information on fluxes based on the S-trap material. Note that the sampling intervals in 2000 (15 April - 31 December) and 2001 (1 January - 25 October) differ. *The value in parentheses was calculated after excluding the exceptionally high values measured from 2 April - 6 June 2001.

	Total flux [mg m^{-2} d^{-1}]		C_{org} flux [mg m^{-2} d^{-1}]		N flux [mg m^{-2} d^{-1}]		C/N ratio	
	2000	2001	2000	2001	2000	2001	2000	2001
Min.	0.1	0.2	0.0	0	0.1	0.0	6.1	5.5
Max.	644	370.4	79.4	51.4	7.4	2.3	13.7	60.8
Mean	75.6	43.7	13.5	7.6	1.9	0.4	8.7	27.3 (*12.4)

Tab. 2. Mean, minimum, and maximum values of chemical composition of the 96 S-trap sediment samples calculated for the period from May 2000 to November 2001. Values are given in atom % as determined by SEM-EDS.

	Si	Al	S	Na	Fe	Ca	P	K	Mg	Mn	Cl
Minimum	14.8	3.4	2.4	0.0	2.4	0.7	1.0	0.8	0.7	0.0	0.0
Maximum	72.4	22.1	19.7	16.1	9.1	22.6	7.5	5.1	5.3	5.4	13.2
Mean	52.8	11.4	7.2	6.8	5.1	5.0	3.0	2.7	2.5	2.0	1.6

maximum particle fluxes of the S-traps were approximately twice as high (644 mg m^{-2} d^{-1}) in 2000 (measured from 8. – 12. July) as in 2001, with only 370 mg m^{-2} d^{-1} in 2001 (measured from 29 May to 2 June; Fig. 4, Tab. 1).

As summarized in table 1 and figure 4, the highest fluxes of C_{org} (79 mg m^{-2} d^{-1}) and N_{tot} (7.4 mg m^{-2} d^{-1}) occurred from 8 – 20 July in 2000, coinciding with the period of maximum total particle flux. In 2001, the maximum flux (51 mg m^{-2} d^{-1}) occured simultaneously with the maximum flux of 29 May – 2 June 2001, within the first productivity period. However, the highest input of nitrogen occurred within the second period of high productivity in August (2.3 mg m^{-2} d^{-1}). Minimum values of the C/N ratio of the trap material were ~6 in both 2000 and 2001. For the period April to May 2000 the C/N ratios found (6 -14) were substantially lower than those found in 2001 (32 - 61). Excluding this time period from the statistics, the mean C/N ratio was 9 in 2000 and 12 in 2001, indicating autochthonous source material (Wetzel 1983; Leenheer 1988).

4.1.3. Chemical composition of particles

The semi-quantitative chemical composition measured by SEM-EDS of the trap particles is shown in table 2. The mean values are typical for bedrock dominated by crystalline rocks in the catchment of the lake. Si and Al dominated the element composition. The samples also contained some S, Na, Fe, and Ca whereas P, K, Mg, Mn, and Cl showed the lowest values.

5. DISCUSSION

5.1. Comparison of the 2000/2001 sediment trap results with other lakes

The mean particle flux measured in the lower O-trap from 2000 to 2001 was 160 mg m^{-2} d^{-1}. Mean particle fluxes from May to September in the lowest sediment O-trap in Estany Redó differed between 251 mg m^{-2} d^{-1} (2000) and 117 mg m^{-2} d^{-1} (2001). These fluxes are within the range found in other small high mountain lakes. Lower mean annual particle fluxes of 48 mg m^{-2} d^{-1} have been measured in Gossekölleseee/Austria (EMERGE final report). Gossekölleseee is small (150 × 80 m), shallow (10 m), has a small catchment area (0.59 km^2), and is on a higher elevation (2417 m a.s.l.). Higher particle fluxes 703 mg m^{-2} d^{-1} (average over 2.5 y) have been observed in Hagelseewli/Switzerland (corrected after Ohlendorf & Sturm 2001). This lake is 250 × 150 m in size, 19 m deep, has a very small catchment of 0.3 km^2 and is located at an elevation of 2339 m a.s.l. Larger high mountain lakes like Silvaplanasee/Switzerland located at 1791 m a.s.l. show much higher mean particle fluxes of 3900 mg m^{-2} d^{-1} (Troxler 2005; Bluszcz *et al.*, submitted). Silvaplanasee is 77 m deep, but in contrast to Estany Redó, Gossekölleseee, and Hagelseewli it differs very much in size (3100 m × 1400 m) and catchment area (129 km^2) and represents a proglacial lake.

Wehenmeyer & Bloesch (2001) investigated 11 Swedish and 9 Swiss lakes of different sizes, water depth and topographical settings, but all on a much lower elevation. They measured particle fluxes of 400 – 7900 mg m^{-2} d^{-1} in generally shallow Swedish lakes (<21 m water depth), some of whichare influenced by re-suspension, sediment sliding and eutrophication. In Swiss lakes they reported particle fluxes of 1500 – 4800 mg m^{-2} d^{-1}; however, these lakes are much larger, have prominent tributaries and are often eutrophied.

The comparatively low particle fluxes in Estany Redó as well as in other high mountain lakes are caused by their high elevation, relatively small catchment areas together with a lack of permanent inflows and low nutrient content. Additionally, the long duration of ice cover also causes a reduction of particle fluxes.

In Estany Redó, Ventura *et al.* (2000) describe maxima of *Daphnia pulicaria* during the period of ice cover, and maxima of *Daphnia cyaneus* during the

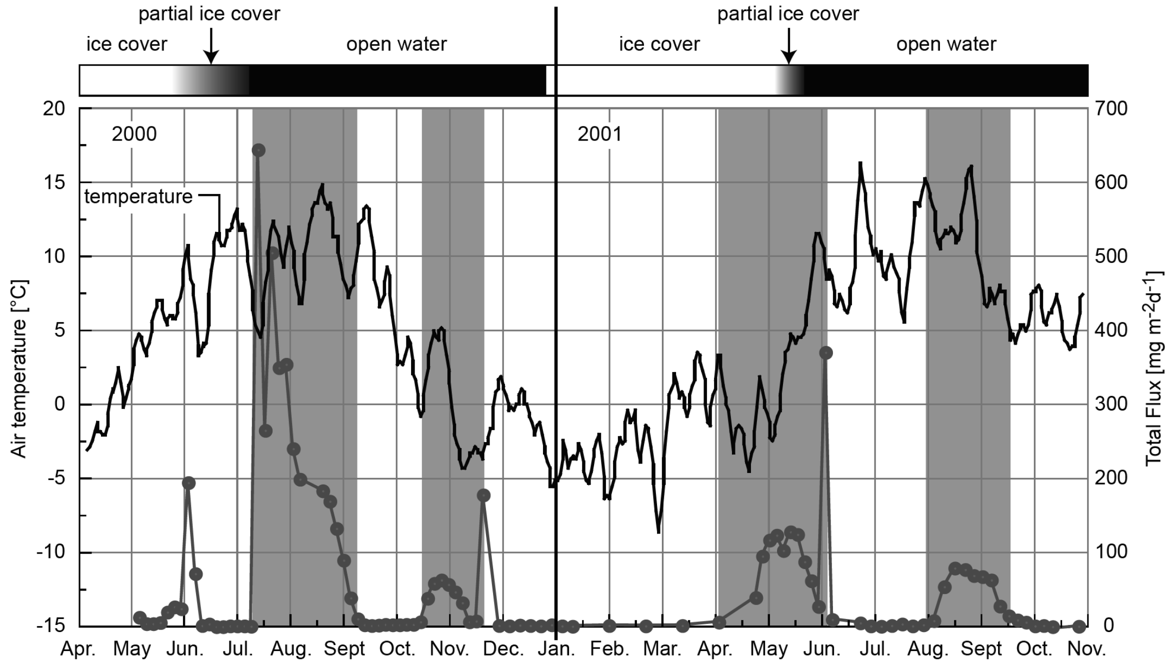

Fig. 6. Variations in total sediment flux and air temperature (7-days running mean) in 2000 and 2001. The shaded bars display periods with high autochthonous particle fluxes. The peak of June 2000 displays allochthonous material.

open-water period. This is consistent with the fact that analyses of the trapped particles in 2000 and 2001 revealed zooplankton remains and fecal pellets (Fig. 5b). Overall, particles of autochthonous organic origin dominate the particle sedimentation during that time period as well as during the end of the high flux period (Figs 5b, c). Total sediment fluxes and the flux of organic carbon are very well correlated (r^2 94.2%, p <0.001). However, the preservation of this kind of particle is limited because they decompose very easily and thus will not be preserved in the sedimentary archive. The trapped material during fall overturn agrees with the results of Felip & Catalan (2000), who reported blooms of flagellate chrysophytes in the hypolimnion. After fall overturn fecal pellets, chrysophycean cysts, zooplankton, and diatoms characterized the sedimentation during the final stage of the open-water period (Fig. 5d).

The biological cycle in Estany Redó is controlled by the availability of phosphorus (Catalan & Camarero 1991; Ventura *et al*. 2000; Catalan *et al*. 2002b), i.e. once the phosphorus pool is consumed, the food chain collapses. The sediment trap data implies that this happens after approximately 2 months of high biological productivity. As shown in figure 6, the duration of the period of high sediment fluxes during the open-water period was *ca* 2 months and was essentially the same in 2000 and 2001.

The occurrence of a second bloom in fall (Fig. 6), shorter in duration (36 and 45 days in 2000 and 2001, respectively) and with lower productivity than the first bloom in both years, is presumably the result of the remobilization of phosphorus. According to Catalan & Camarero (1991) phosphorus can be remobilized when the lower boundary of the mixed epilimnion water layer reaches phosphorus-rich fine-grained sediment layers at approximately 25 m water depth. However, the difference in the amount of biomass produced in 2000 as compared to 2001 did not necessarily reflect a difference in the phosphorus pool or in other nutrients, but was more likely the result of natural variability. Seasonal particle flux variations within a single year in Estany Redó exceeded those between years, a finding that corresponds with the work from Wehenmeyer & Bloesch (2001).

5.2. 2000/2001 sediment trap results and concurrent meteorological data

In ice-covered lakes, the main relevant factor is the timing of ice break-up, which, is both closely linked to ambient air temperature (e.g., Livingstone 1997) and a major determinant of the timing of the spring phytoplankton bloom (e.g., Wehenmeyer *et al*. 1999). In Estany Redó the ice cover started to break up in late May in 2000, and early May in 2001. Taken into account the uncertainties of an exact dating of the break up due to the remoteness of the lake and its harsh weather conditions in winter, the data agree with the meteorological information. A comparison of the meteorological data from 2000 and 2001 shows that average meteorological conditions in 2000 and 2001 were comparable (Tab. 3), although differences did occur in the timing, frequency, and amplitude of weather events (Figs 6 and 7a-c).

Tab. 3. Comparison of meteorological data measured at Estany Redó from 2 April to 1 November in 2000 and 2001. The data were measured at an automatic weather station located 30 m from the south shore of the lake. The time period chosen represents the time during which data is available for both years.

	2000	2001
Temperature [°C]		
Minimum	-6.5	-9.3
Maximum	17.0	19.1
Mean	6.6	7.0
Incident solar radiation [W m^{-2}]		
Minimum	16.5	6.3
Maximum	390.3	390.8
Mean	219.4	231.8
Wind speed [m s^{-1}]		
Minimum	1.0	0.5
Maximum	17.0	17.6
Mean	5.7	5.4
Precipitation [mm d^{-1}]		
Minimum	0.0	0.0
Maximum	76.8	56.8
Mean	4.4	4.3
Sum	930.7	911.4

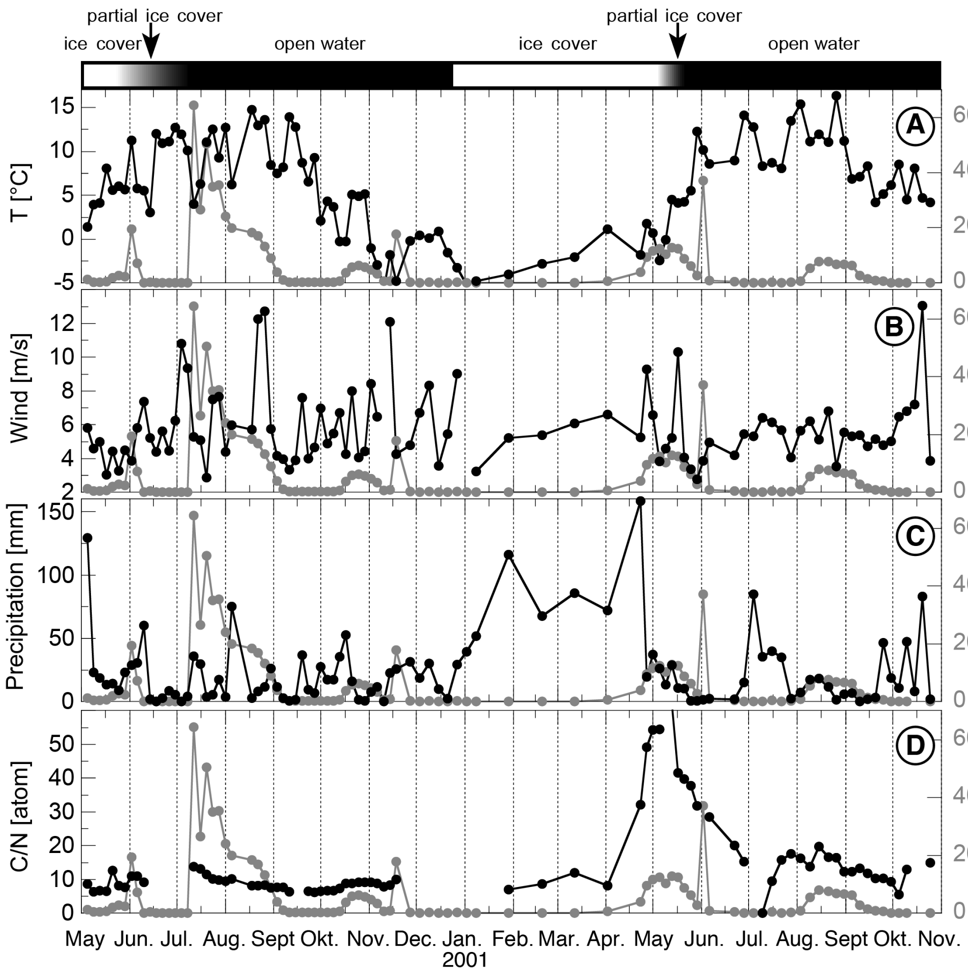

Fig. 7. Meteorological parameters (air temperature, wind speed, precipitation) and C/N-ratio (atomic) in 2000 and 2001. The meteorological data and C/N ratios are averaged over the trap exposure intervals. Total sediment flux rates (TF) are indicated in gray for comparison purposes.

The ice-cover period was much shorter in 2001 than in 2000, probably because of at least two periods of high wind, which accelerated the initial ice break-up (Fig. 7b). The open water period began *ca* 50 days earlier in 2001 (end of May) in comparison to 2000 (beginning of July). The onset of the first and second phase of bio-productivity also shifted towards an earlier date in 2001 compared to 2000, by 98 and 59 days, respectively. This suggests that the onset of the main period of biological productivity may be linked to internal lake factors that are governed primarily by climate.

A comparison of the organic material with the precipitation data reveals a different picture (Fig. 7d). C/N ratios from April to May differ substantially between 2000 (6-14) and 2001 (>28). The high values in the latter case reflect the enhanced transport of particles from soil erosion and enhanced transport of the remains of higher plants to the lake (Wetzel 1983). Camarero *et al.* (1999) also suggest an external source of particulate organic matter for Estany Redó, because mobilization of allochthonous organic material is possible during ice break-up, as it is incorporated into soil material from the shore or deposited on the snow and then transported into the lake by streams of meltwater. Another reasonable explanation for higher C/N values is heavy rainfall and initial meltwater in early spring. In April 2001 (Fig. 7c, d), C/N ratios of trapped material increased parallel with higher precipitation, implying that surface runoff and erosion within the catchment area was transporting organic material from soils into the lake.

5.3. *Comparison of the years 2000-2001 with the years 1984-85*

According to Felip & Catalan (2000), dinoflagellates are the main phytoplankton species in Estany Redó. In 1984 and 1985, they analyzed water samples from different water depths in the lake and observed the first algal bloom to occur in July in both years, although differences in the amount of productivity from one year to another do occur. Felip *et al.* (1999) report highest primary-productivity during the same time in 1984 and 1985 but this peak was dominated by chrysophycean cysts and dinoflagellates.

By contrast, SEM images of sediment trap samples during this time interval (the beginning of the open water period) in 2001 do not clearly reflect this bloom. Chrysophycean cysts are very rare and the trapped material consists mainly of organic aggregates about 100 µm in size, which have a similar structure to fecal pellets, although they differ in shape (Fig. 5b).

As seen in figure 4, the open-water productivity peaks differed in terms of their shape and height at least as much from 2000 to 2001 as they had done from 1984 to 1985. For this reason, excluding the timing of the peaks, both studies document the high inter-annual environmental variability of the lake, but do not provide a clear conclusion on the issue of climatic forcing.

Catalan *et al.* (2002a) reported a warming trend in the central Pyrenees from the early 1970s onwards, especially in summer and autumn (June to November). Felip & Catalan (2000) investigated the phytoplankton community from May 1984 to August 1985, taking samples at intervals of 6-30 days from 9 different water depths. Their 20-yr-old data has been compared with our results from 2000 and 2001 to test whether the postulated warming trend has influenced the biological productivity of Estany Redó, even if the interpretation of both investigation periods is hampered by inadequate long-term data series. During both time periods, the first productivity peak occurred under the ice in spring (Fig. 4). This phenomenon has recently been observed also in other ice-covered lakes in the Alps, Scandinavia and Siberia (Marchetto *et al.* 2004; Sturm *et al.* 2005). In 1984, small first productivity peaks occurred during the open-water phase in July/August, followed by maximum productivity peaks in November/December. This succession within the year 1984 is also apparent in 2000 and 2001. However, at present, the first phase of bio-productivity is greater than the second (Fig. 4). We attribute these differences to natural variation within the lake ecosystem. There is no evidence to support the hypothesis that the productivity of Estany Redó has reacted to climate warming in the central Pyrenees.

6. CONCLUSIONS

Sedimentation in Estany Redó is dominated by autochthonous particles based on the strong correlation of total sediment fluxes and the flux of organic carbon of 94.2 (r^2, in percent, p <0.001). The elemental composition of the trapped minerogenic particle reflects the crystalline bedrock in the catchment.

The small catchment area of the lake and its lack of permanent inflows as well as a very low nutrient supply result in particle fluxes that are similar to other small high mountain lakes. From 2000-2001 the mean particle flux of high alpine Estany Redó was 160 mg m^{-2} d^{-1}. Mean fluxes from May to September differ between 251 mg m^{-2} d^{-1} (2000) and 117 mg m^{-2} d^{-1} (2001). This is an order of magnitude smaller than in lakes which are on a lower altitude, bigger in size, with a bigger catchment, and have permanent inflows.

The particle fluxes of Estany Redó show a seasonal pattern consisting of a long period with low sedimentation, when the lake is ice-covered, and short periods with high flux rates during ice break-up and during the open-water period. In 2000 a distinct particle flux of detrital minerals occurred directly after the initial ice-break-up. The highest particle fluxes consist of autochthonous material and, although the inter-annual pattern is highly comparable, the seasonal variability is high. In 2000 and 2001 two phases of enhanced bio-productivity were recorded. The first peak in both years marked the highest sedimentation period and lasted *ca* 2 months. The trapped material consisted mostly of zooplankton remains and organic aggregates (fecal pellets). The second period was comprised of the same particles but was shorter in duration. One difference between 2000 and 2001 was that much higher amounts of chrysophycean cysts were deposited in 2000. Both periods of high bioproductivity, within the year, together covered *ca* 100 days.

Estany Redó is one of the very few lakes in which detailed particle flux data from recent years can be compared with older water sample data that was collected almost 20 years ago. According to this comparison, there is no clear sign of a warming trend in the Pyrenees affecting Estany Redó over the past two decades. Our data do, however, show a link to meteorological data: the onset of the main period of biological productivity in the lake appears to be associated with air temperature, and the duration of ice cover and partial ice cover is affected by air temperature and perhaps high wind speeds. Soil erosion during periods of high precipitation is documented by changing C/N ratios in 2001. Although sediment trap data can thus be used for studies of environmental change and weather events in high mountain lakes on a very short time scale, our results strongly suggest that long-term investigations of such lakes are necessary to clarify the existence, rate, duration, and amplitude of environmental changes.

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