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# Relative importance of dust inputs and aquatic biological production as sources of lake sediments in an oligotrophic lake in a semi-arid area

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ABSTRACT: The dustfall (DF) and mass sedimentation rate (MSR) in Lake Alchichica, Central Mexico, were studied from June 2006 to June 2008. DF ranged between 0·11–0·93 g $m^{-2}$ $d^{-1}$ in the warm and rainy season and 0·54–1·21 g $m^{-2}$ $d^{-1}$ in the cold and dry season. MSR varied from 0·52–2·40 g $m^{-2}$ $d^{-1}$ in the stratification season to 1·14–5·07 g $m^{-2}$ $d^{-1}$ in the circulation season. The timing of the highest fluxes of DF and MSR is most likely a product of several factors coinciding during the cold and dry season: (a) availability of dust sources and the presence of strong winds (>7·5 m $s^{-1}$) in the DF case, and (b) the circulation period of the lake and the availability of nutrients in the MSR case. As expected, the DF in Alchichica was high and similar to that found in other arid and semi-arid areas. However, the MSR was higher than that reported for other oligotrophic lakes. Particles captured in the aerial traps consisted mainly of detrital minerals; in contrast, particles found in the water traps were mostly biogenic and, to a lesser extent, detrital minerals. The MSR was one to seven times higher than the DF. In spite of the oligotrophic status of Lake Alchichica, the large size of the settled phytoplankton (autochthonous, waterborne) is what leads to the high MSR, which surpasses the DF (allochthonous, airborne) derived from whirlwinds originating in easily eroded terrains that are characteristic of arid/semi-arid areas. Our results indicate that caution must be taken in considering that the DF amount measured through DF collectors located at the lake shore does actually represent the DF entering into the lake. Copyright © 2010 John Wiley & Sons, Ltd.

KEYWORDS: dustfall; mass sedimentation rate; phytoplankton; warm monomictic lake; tropical lake; Mexico; Puebla

## Introduction

Mass sedimentation rate (MSR) is defined as the amount of organic and inorganic matter exported from the water column to the sediments. The measure of MSR is an important factor for understanding the physical regime as well as the biological and chemical budgets of aquatic ecosystems. Sources of particulate matter entering lakes may include allochthonous inputs (Psenner, 1999), autochthonous production (Legendre, 1999) and resuspended sediment (Pierson and Weyhenmeyer, 1994; Weyhenmeyer, 1997). The importance of each depends on the characteristics of the aquatic body and the climatic conditions of the region.

Investigations dealing with particulate matter in lakes usually distinguish between deposition of particular matter produced in the water column and deposition of aolian dust (e.g. Ganor *et al.*, 2003) to elucidate aquatic ecosystem processes. Autochthonous matter in lakes is primarily organic produced mainly by phytoplankton, although considerable amounts of inorganic particles could come from precipitation of calcium carbonate in supersaturated systems (Stabel, 1986). Generally, the more productive the lake is, the more important is the autochthonous contribution. In lakes where particulate matter is mainly autochthonous, the seasonal changes in MSR are governed by changes in the standing crop of phytoplankton such as phytoplankton blooms (Bloesch and Bürgi, 1989).

The sources of allochthonous material in lakes are tributaries and dustfall (DF). DF comprises all solid particles in the air that fall to the ground under the influence of gravity and rain. In arid and semi-arid regions, which have been identified as particularly important dust sources, DF is considered to be a major contributor of particulate matter entering lakes (Dentener *et al.*, 1996). In some cases (e.g. Lake Kinneret, Israel – Foner *et al.*, 2009), bulk deposition (i.e. DF + rain + gases) is the major source of various chemical species entering lakes. This condition is in contrast to temperate climates, where minor deposition of particulate matter would be expected (Owens and Slaymaker, 1997). Seasonal variation in DF is highly sensitive to a wide range of factors, including soil composition, the moisture content, the condition of the surface (especially the degree of disturbance) and wind velocity and direction over source regions (Prospero *et al*., 2002).

Insufficient information has been published on the effects of DF on lakes. Dust particles deposited in the lakes not only introduce essential nutrients that stimulate primary productivity, but also become incorporated into organic aggregates that form high density particles, leading to the "ballast effect", which increases sedimentation rates (Psenner, 1999; Foner *et al*., 2009). In contrast, numerous studies have considered MSR in lakes (e.g. Callieri *et al*., 1986; Weyhenmeyer and Bloesch 2001; Pilskaln, 2004). DF and MSR studies have been carried out in temperate climates, whereas tropical inland waters in arid or semi-arid areas remain virtually unexamined by this approach.

Surprisingly, no studies have evaluated both DF and MSR at the same time for the same lake. In this study, we estimated both DF rate and MSR in a lake in a tropical, semi-arid region of central Mexico. We further analysed our findings in comparison with: (a) DF rates from other lakes in arid/semi-arid areas and (b) MSRs from other oligotrophic lakes.

## Case Study

This case study exemplifies a common situation found in arid and semi-arid regions where lakes are mostly groundwater fed. Differing from the temperate zones, tropical arid and semi-arid regions are influenced by a monsoon-type regime of summer rains and dry winters, with the latter influencing the timing of dust source availability. In addition to the lack of research that integrates DF and MSR, the above combination of environmental factors has not been properly studied in relation to sources of particulate matter.

Alchichica is an oligotrophic, tropical crater lake located in the semi-arid Oriental basin, central Mexico, where DF (allochthonous source) was anticipated to be the main contributor to the deposition of particulate matter in the lake. Elmore *et al*. (2008) found that shallow groundwater dynamics can both positively and negatively affect dust generation and can, in extreme cases, lead to desertification in semi-arid systems. The large playa lakes in the central portion of the Oriental basin have already become dry or episodic as a consequence of overexploitation of the aquifer (Alcocer *et al*., 1998). Hence, large dry lake-bed areas are exposed, leading to the increased frequency and severity of whirlwinds. It has also been found that the entire central area of the Oriental basin is going under high aeolian erosion, conditions that favour dust whirlwinds (SEMARNAT, 2009).

However, a recent study showed that, contrary to findings in other oligotrophic water bodies (i.e. those poor in plant nutrient minerals and organisms), both inland and marine, the phytoplankton of Lake Alchichica is dominated by large diatoms (≈50 μm) (Adame *et al*., 2008). Large phytoplankton has high exportation rates and low rates of consumption by zooplanktonic grazers, suggesting that phytoplankton might be an important contributor to the particulate matter settling to the bottom of the lake.

For the reasons mentioned earlier, Lake Alchichica provides a unique opportunity to compare both sources of particulate matter and to better understand the factors that decide which particulate matter source prevails, regarding external and internal factors.

## Study Area

Alchichica crater lake is in the central part [19° 24·7′ N; 97° 24·0′ W, 2345 m above sea level (a.s.l.)] of the endorheic Oriental basin (4982 km$^2$) (Figure 1). It is almost circular with an area of 2·3 km$^2$, and a maximum depth of 62 m. The lake is

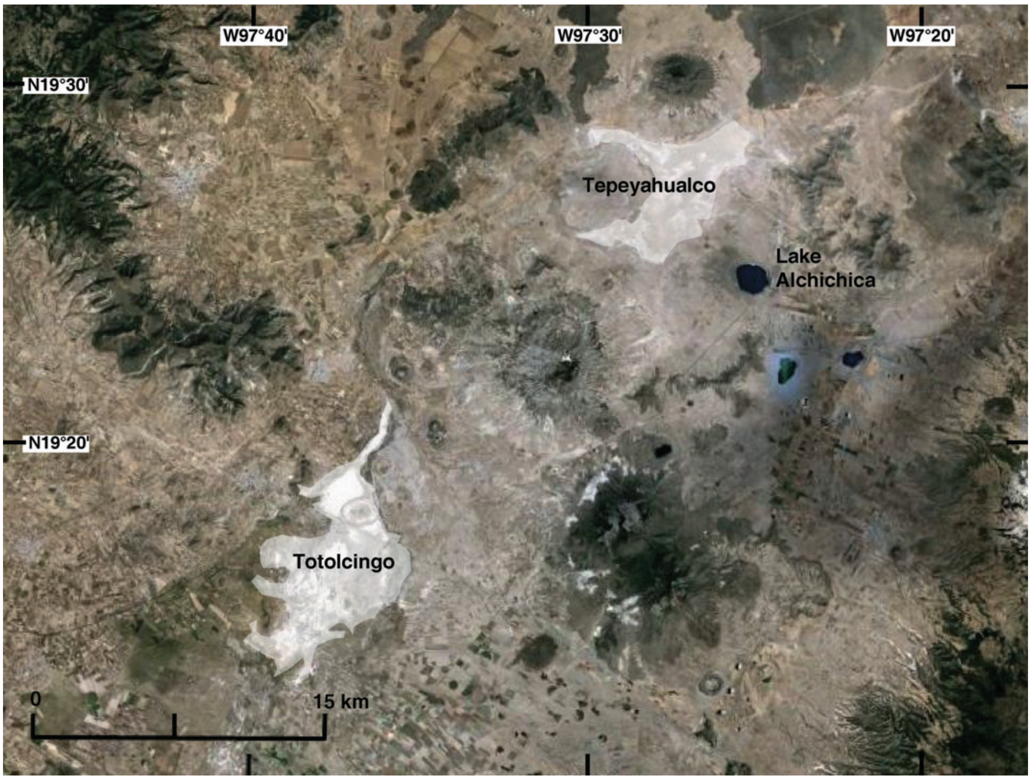


**Figure 1.** Studied area. Lake Alchichica as well as Totolcingo and Tepeyahualco dry playa lakes are indicated. (Modified from Google Earth). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

 

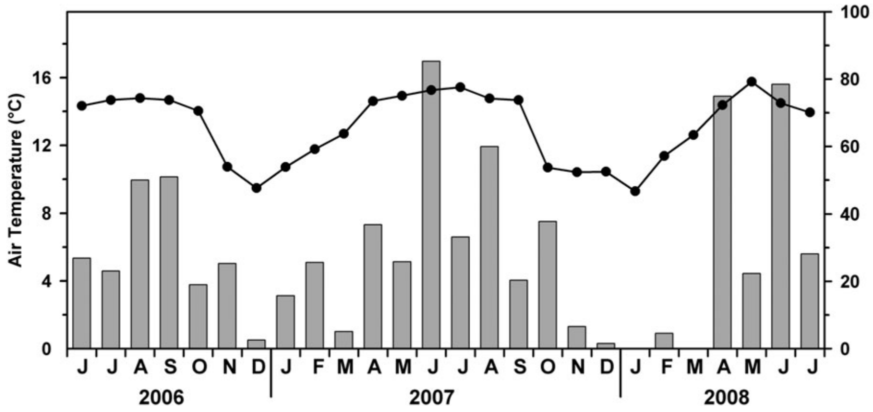


**Figure 2.** Mean air temperature (black line) and precipitation (grey bars) in Lake Alchichica, Mexico.

groundwater-fed with no influents (Filonov *et al.*, 2006). Alchichica behaves as a warm monomictic lake; mixing takes place from the end of December or the beginning of January until the onset of the stratification period, by the end of March or beginning of April (Alcocer *et al.*, 2000).

According to Adame *et al.* (2008), in Lake Alchichica the chlorophyll *a* concentration, a phytoplankton biomass proxy, averages 4·2 ± 4·2 µg $l^{-1}$, indicating oligotrophic conditions for a continental water body. In addition, the overall nutrient concentrations in the mixing layer of Lake Alchichica (<4 µmol $l^{-1}$), as well as the wide (15–35 m) euphotic zone, confirm the oligotrophic status suggested by the chlorophyll *a* concentration (Oliva *et al.*, 2001; Ramírez-Olvera *et al.*, 2009).

Lake Alchichica is close to two dry saline playa lakes that are potential dust sources. These lakes are at the central portion of the basin and have a total area of approximately 290 $km^2$ (Alcocer *et al.*, 1998). Tepeyahualco is roughly 7 km to the northwest of Alchichica, whereas Totolcingo is nearly 25 km to the west-southwest (Figure 1).

## Methods

Meteorological data, recorded every hour with a Davis GroWeather station, were as follows: air temperature with a platinum wire thermistor, precipitation through a tipping bucket with magnetic reed switch, wind speed by means of wind cups and magnetic switch, and wind direction with a wind vane and a potentiometer (http://www.davisnet.com). The station was installed on the east coast of the lake, a few metres from the edge and 4 m above the water level.

We sampled particulate matter on a monthly basis over two years (June 2006 through June 2008). The DF collectors (aerial traps) were placed near the shore (≈70 m). The collectors consisted of four PVC pipes sealed at one end; the aspect ratio of the aerial traps was six (height 50·0 cm; diameter 8·3 cm). These collectors are similar to those recommended by the ASTM (Anon, 1982). The traps were attached vertically to a square metal rack, one at each corner, and 10 m above the ground to avoid human and animal interference. The deposited matter from the traps was recovered by using deionized water.

Cylindrical sediment traps were used to collect the settling material in the lake. The aspect ratio of the sediment traps was six (height 45·0 cm; diameter 7·4 cm), suitable for water bodies of low current velocities and turbulence (Blomquist and Kofoed, 1981; Bloesch, 1994). The mooring system consisted of an anchor, cotton rope, a sediment trap station (four tubes each) and a surface buoy. The traps were located 3 m above the floor of the lake (59 m) to prevent overcatching (Bloesch, 1994).

On each sampling date, profiles of photosynthetically active radiation (PAR) were measured with a PNF-300 fluorometer (Biospherical Instruments); PAR is the spectral range or wave band of solar radiation from 400 to 700 nm that phytoplankton are able to use in the process of photosynthesis. Temperature and dissolved oxygen (DO) were measured with a DataSonde 4 (Hydrolab Corporation), and their profiles were interpolated to obtain depth–time diagrams (Surfer 6, Golden Software, USA).

After retrieval, the material from the traps was sieved (100 µm pore size) to remove leaves and insects captured by the aerial traps (McGowan *et al.*, 1996) and large copepods (Lee *et al.*, 1988) from the water traps. The particulate matter trapped in three tubes at each station (water and aerial) was filtered through weighed, pre-combusted (550 °C for four hours) GF/F Whatman filters (diameter 47 mm, 0·7 µm). Dry weight was determined gravimetrically after filter desiccation (60 °C for 24 hours) with a Mass Comparator Balance (Mettler Toledo). The content of the fourth trap (water and aerial) was used to identify the components of the particles with an inverted microscope (Leica DMIRB). Individual lithogenic particles were analysed by scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS, JOEL 5600) to obtain the semi-quantitative chemical composition. A preliminary investigation showed that analysis of 10 particles would give a representative sample (the standard deviation of the mean remained constant independently of the number of particles analysed) for aerial and water traps. The number of particles analysed in the present study is twice those usually analysed in other studies (e.g. Kulbe *et al.*, 2006). To characterize the lithogenic particles, we calculated the average composition of 10 particles each month for both the water traps and the aerial traps. Hence, 500 particles were analysed.

## Results

### Weather conditions

The mean annual temperature was 12·9 °C and the annual precipitation 327 mm during the study period. We recognized a monsoon-type climate with two main seasons throughout the year: (1) a cold and dry season from January to March, characterized by the lowest environmental temperature (≈9 °C), and a monthly precipitation less than 26 mm, and (2) a warm and rainy season from April to December, with an average environmental temperature of 16 °C and a total precipitation of 301 mm (Figure 2).

The weather station recorded wind speeds >7·5 m $s^{-1}$ all year round. However, the direction of the strong winds differed

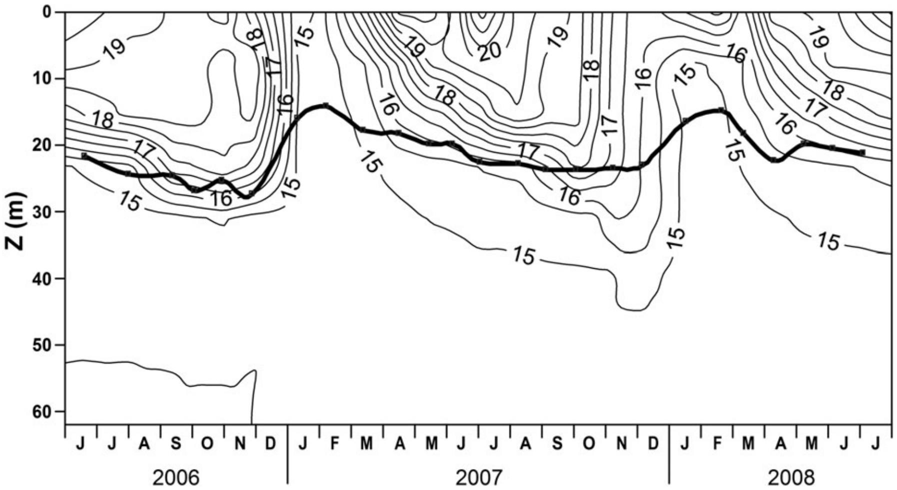

**Figure 3.** Depth–time diagram of isotherms (in degrees Celsius) in Lake Alchichica, Mexico. The bold line indicates the euphotic zone (≥1% surface PAR).

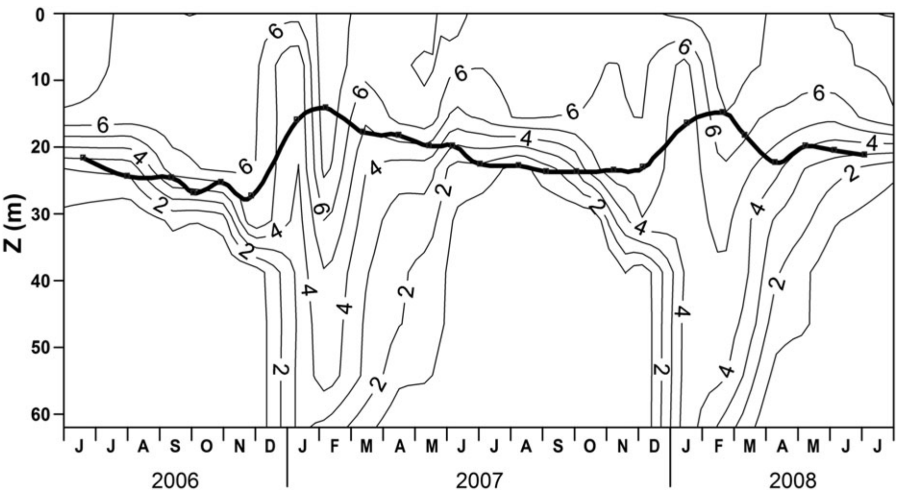

**Figure 4.** Depth–time diagram of the isopleths of DO (in mg $l^{-1}$) in Lake Alchichica, Mexico. The bold line indicates the euphotic zone (≥1% surface PAR).

between seasons: throughout the warm and rainy season winds from the northeast-southwest (NE-SW) and north-northeast-south-southwest (NNE-SSW) are predominant; in contrast, during the dry and cold season, strong winds from the west-southwest (WSW) and west (W), where the main dust sources (e.g. Totolcingo) are located (Figure 1).

## Water column

Water column temperature (Figure 3) averaged 16 ± 1·7 °C for the entire period. Temperatures were lower during the mixing period (14·9 ± 0·3 °C) throughout the dry winter (January–March), and higher during the well established stratification (water column 16·3 ± 1·8 °C) throughout the rainy summer (July–September). The top of the thermocline was at ≈10 m during the early stratification (dry spring, April–June), it progressively deepened to 18–30 m during the well-established stratification, and went down to 40 m in the late stratification (post-rainy autumn, October–December).

At the onset of the circulation period, the anoxic water of the hypolimnion mixes with the oxic waters of the epilimnion. At this time, the DO concentrations diminished throughout the entire water column (4 mg $l^{-1}$, ≈60% saturation). However, soon after this decline, DO concentration increased to close to the saturation point (6 mg $l^{-1}$, ≈90%) throughout the water column. During the stratification period, DO concentrations (Figure 4) ranged from a maximum saturation of ≈108% (7 mg $l^{-1}$) at the surface, down to anoxia. Supersaturation values are due to active growing phytoplankton that reaches high rates of photosynthesis; DO is a by-product of this photosynthesis and is freed to the water during the process. Conversely, oxidation of the organic matter deposited on the lake bottom, depletes DO until anoxia is reached during the stratification. Anoxia started at the bottom around March and eventually extended in July to the whole hypolimnion and remained so throughout the rest of the stratification period.

The mixing layer ($Z_{MIX}$) comprised the entire water column throughout the circulation period. The $Z_{MIX}$ reached 15 m during the well established stratification period and went deeper (down to 26 m) by the late stratification period (Figure 3). The euphotic zone ($Z_{EU}$ ≥ 1% surface PAR) varied from 15 to 28 m (Figure 3). Two phases can be described based on $Z_{EU}$: the turbid-water phase during the circulation period ($Z_{EU}$ = 16·7 ± 1·6 m) and the clear-water phase during the stratification period ($Z_{EU}$ = 23·3 ± 2·5 m).

## Aerial traps

Dust deposition over the sampling period ranged from 0·11 to 1·21 g $m^{-2}$ $d^{-1}$, averaging 0·60 ± 0·30 g $m^{-2}$ $d^{-1}$ for the whole two-year period (Table I). The DF seasonal variation (Figure 5) was characterized by significant temporal changes ($p < 0·05$). The highest fluxes reached up to 1·21 ± 0·14 g $m^{-2}$ $d^{-1}$ and were found in the cold and dry winter (January–March). However, the lowest fluxes (0·11 ± 0·03 g $m^{-2}$ $d^{-1}$) were mea-

 

**Table I.** For each time period, particle fluxes (in g m$^{-2}$ d$^{-1}$) for DF (aerial traps) in Lake Alchichica, Mexico are shown as mean ± standard deviation (SD) and cumulative rates (in g m$^{-2}$)

| Period | Total | Particle fluxes Season Cold–dry | Particle fluxes Season Warm–rainy | Cumulative rates |
|---|---|---|---|---|
| June 2006–May 2008 | 0·60 ± 0·30 | 0·78 ± 0·29 | 0·54 ± 0·28 | 438 |
| June 2006–May 2007 | 0·58 ± 0·34 | 0·80 ± 0·34 | 0·50 ± 0·30 | 218 |
| June 2007–May 2008 | 0·61 ± 0·28 | 0·76 ± 0·27 | 0·55 ± 0·26 | 220 |

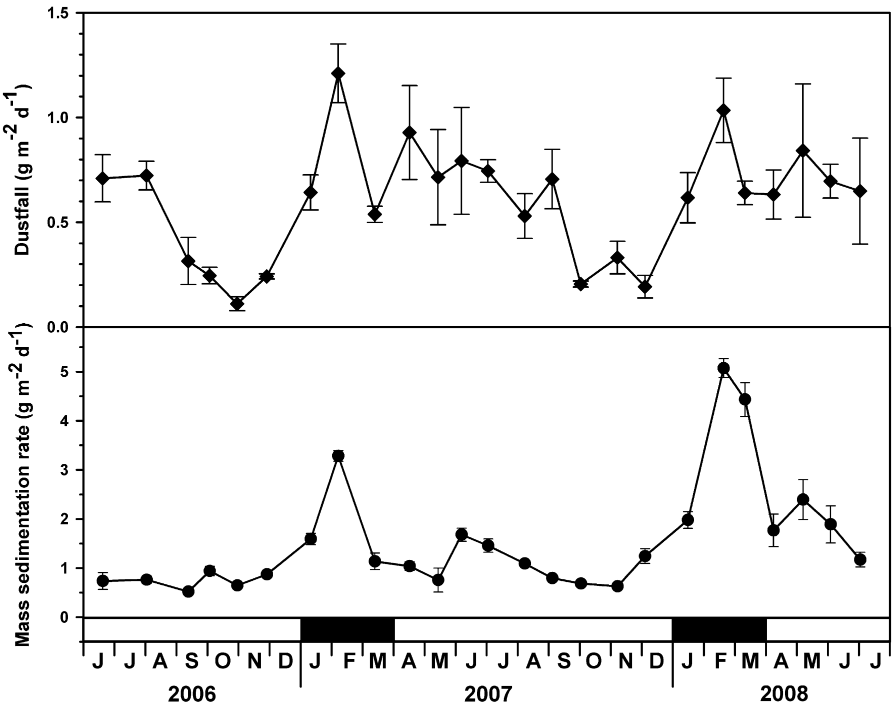


**Figure 5.** DF (top) and MSR (bottom) in Lake Alchichica, Mexico. (Black bars indicate the mixing periods; white bars indicate the stratification periods.)

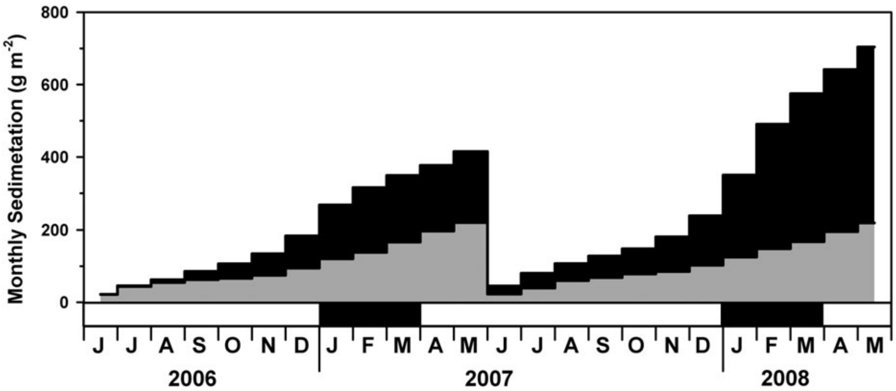


**Figure 6.** Accumulated DF (grey) and MSR (black) in Lake Alchichica, Mexico.

sured in the post-rainy autumn (October–December). There were no significant differences ($p > 0·05$) between dust deposition peaks of February 2007 and February 2008 (Figure 5(top)).

The total DF cumulative sedimentation was 218 g m$^{-2}$ and 220 g m$^{-2}$ for the first and the second years, respectively (Figure 6), attaining 438 g m$^{-2}$ over the entire period. Approximately one-third (30% and 33% for the first and the second years, respectively) of the total yearly DF was deposited during the cold and dry season (January–March).

The particles captured in the aerial traps consisted mostly of detrital minerals with an annual average of 92 ± 17%. The chemical composition of these particles (Table II) showed a dominance of silicon (Si) (32%) and aluminium (Al) (8%).

**Table II.** Average chemical composition of the particulate matter captured in the aerial and water traps in Lake Alchichica, Mexico

| Traps | Si | Al | K | Fe | Ca | Cl | Mg | S | P | Na |
|---|---|---|---|---|---|---|---|---|---|---|
| Aerial | 32 | 8 | 5 | 5 | 4 | 2 | 1 | 1 | 1 | <1 |
| Water | 34 | 9 | 6 | 4 | 3 | 2 | 1 | 1 | 1 | <1 |

Note: Values are given in atom% as determined by SEM-EDS.

Samples also contained minor concentrations of potassium (K), iron (Fe), calcium (Ca) and other elements. Minor quantities of amorphous particles such as organic matter (4 ± 6%), obsidian and other volcanic glass (3 ± 4%), were also

**Table III.** For each time period, particle fluxes (in g $m^{-2}$ $d^{-1}$) for MSR (water traps) in Lake Alchichica, Mexico are shown as mean ± standard deviation (SD) and cumulative rates (in g $m^{-2}$)

| Period | Total | Particle fluxes Season Circulation | Particle fluxes Season Stratification | Cumulative rates |
|---|---|---|---|---|
| June 2006–May 2008 | 1·54 ± 1·16 | 2·92 ± 1·52 | 1·11 ± 0·52 | 1119 |
| June 2006–May 2007 | 1·12 ± 0·76 | 2·00 ± 0·99 | 0·78 ± 0·19 | 415 |
| June 2007–May 2008 | 1·94 ± 1·40 | 3·83 ± 1·43 | 1·31 ± 0·58 | 704 |

**Table IV.** Average DF (in g $m^{-2}$ $d^{-1}$) in different climatic settings

| Location | Environmental setting | DF | Reference |
|---|---|---|---|
| Crete, Greece | Arid source area | 0·15 | Pye (1992) |
| Negev Desert, Israel | Arid, sparsely vegetated desert | 0·57 | Offer and Goossens (2001) |
| Lake Alchichica, Mexico | Semi-arid, rain shadow effects | 0·60 | This study |
| Lake Tekapo, New Zealand | Semi-arid, rain shadow effects | 0·71 | McGowan *et al.* (1996) |
| Lake Kinneret, Israel | Semi-arid | 2·36[a] | Ganor *et al.* (2003) |

[a]Greatly influenced by dust storms from the Sahara.

recorded throughout the study, as well as pine tree pollen grains at the beginning of the year (<1%).

### Water traps

The MSR for the entire period averaged 1·54 ± 1·16 g $m^{-2}$ $d^{-1}$ (0·52–5·07 g $m^{-2}$ $d^{-1}$) (Table III). The highest MSR (Figure 5(bottom)) reached up to 5·07 ± 0·19 g $m^{-2}$ $d^{-1}$ during the cold, dry winter (January–March), when the lake was circulating. The lowest MSRs (0·52 ± 0·04 g $m^{-2}$ $d^{-1}$) were observed from July to December, corresponding to the well established (rainy summer) and late stratification (post-rainy autumn) periods. In between, smaller peaks of MSR were detected during the early stratification (dry spring, April–June). There were significant differences ($p < 0{\cdot}05$) between MSR peaks of February 2007 and February 2008 during the circulation period; nevertheless, there were no significant differences ($p > 0{\cdot}05$) between MSR peaks observed in June 2007 and May 2008 (Figure 5(bottom)).

There was approximately 75% more accumulated particulate matter (Figure 6) during the second year (704 g $m^{-2}$) than the first year (415 g $m^{-2}$). The MSR during the circulation period accounted for 40% and 48% of the total accumulated particulate matter for the first and the second years, respectively.

The particles in the water traps were mostly of biogenic origin composed of large diatom cells (mostly *Cyclotella alchichicana*) with annual average of 21 ± 23%, and their empty frustules (the hard and porous cell wall or external layer of diatoms composed of almost pure opal) which contributed 54 ± 52% on annual average. *C. alchichicana* was found throughout the year with higher abundance during the circulation period. The cyanobacterium *Nodularia spumigena* and amorphous organic matter contributed an annual average of 9 ± 6% and 8 ± 5%, respectively. The lithogenic material (detrital minerals) represented on average less than 3% of the particles caught in the traps. The chemical composition of the lithogenic particles captured in the water traps was similar to that of the lithogenic particles found in the aerial traps (Table II). Consequently, the lithogenic material captured in the water traps was most likely from DF. There were also minor quantities of plant debris (3 ± 2%) and pine tree pollen (2 ± 2 %).

## Discussion

### Aerial traps

The DF measured in Lake Alchichica was similar to the values observed for other arid and semi-arid locations, except Lake Kinneret (Table IV). The very high DF in Lake Kinneret is related to the irregular surges in particulate matter inputs coming from Sahara dust storms (Ganor *et al.*, 2003), whereas the minor depositions in the other sites are influenced by local dust sources. Arid and semi-arid sites have large agricultural areas that remain uncovered (i.e. unvegetated) after harvesting, thus creating sources for potential dust storms and whirlwinds. In addition, the Oriental basin where Lake Alchichica is located has been largely affected by an active volcanism (Carrasco-Núñez *et al.*, 2007), a well known source of nutrients in croplands and aqueous environments (Frogner *et al.*, 2001; Staudigel *et al.*, 1995). Ash inputs could result in fertilization and further eutrophication of water bodies (Jones and Gislason, 2008).

The dry lake beds of Tepeyahualco and Totolcingo are covered by unconsolidated silt deposits without vegetation and have become some of the main dust sources in the area. The chemical composition captured in aerial traps is similar to the soil type (dominated by crystalline rocks) found in the dry playa lake beds in the Mojave Desert, USA (Reynolds *et al.*, 2007), a place with conditions comparable to the Oriental basin. The magnitude of wind speed (>7 m $s^{-1}$) in those areas could be considered strong enough to sweep away dust particles, thus favouring dust whirlwinds (McGowan *et al.*, 1996; Brazel, 1989). Similar situations have previously been described in other arid and semi-arid places (e.g. Ebinur Lake, China by Bao *et al.*, 2006; playa lakes, Mojave Desert, USA by Reynolds *et al.*, 2007).

During the cold and dry season, strong winds from the WSW and W blow more frequently across the Totolcingo dry lake bed, heading directly to Lake Alchichica and gathering a large dust load and natural fertilizers (i.e. phosphorus-rich volcanic ashes). Additionally, the agricultural land surrounding the lake remains uncovered during this period, becoming another source of particles and probably pollutants (e.g. herbicides, insecticides). During the warm and rainy season, the strong winds blow from a different direction (NE-SW and NNE-SSW),

 

**Table V.** Average MSR (in g $m^{-2}$ $d^{-1}$) in various lakes

| Lake | Trophic state | MSR | Reference |
|---|---|---|---|
| Malawi, East Africa | Oligotrophic | 0·23 | Pilskaln (2004) |
| Mergozzo, Italy | Meso-oligotrophic | 0·61 | Callieri *et al*. (1986) |
| Maggiore, Italy | Meso-oligotrophic | 1·32 | Callieri (1997) |
| Alchichica, Mexico | Oligotrophic | 1·54 | This study |
| Kinneret, Israel | Oligotrophic | 4·65[a] | Eckert *et al*. (2003) |

[a]Mostly resuspension of littoral organic matter.

away from the major dust sources, so DF remains low. Moreover, before sowing time (May–November), the agricultural soils around the lake are covered with crops.

The cumulative DF in the lake was quite similar for both years. This is most likely derived from the similar weather conditions observed during the two years of the study.

## Water traps

There are few reports of MSR in deep oligotrophic lakes; among those available, Lake Alchichica MSRs were similar to or higher than, for example, those for Lakes Maggiore, Mergozzo and Malawi (Table V). Lake Maggiore is much larger (212·5 $km^2$), deeper ($Z_{MAX}$ = 372 m) and more productive (mesotrophic) than Alchichica; however, its small (<2 µm) phytoplankton builds large aggregates (5–250 µm), increasing its sedimentation rate (Callieri, 1997) to an extent that is similar to Alchichica.

Lake Mergozzo is oligotrophic and morphometrically comparable to Alchichica ($Z_{MAX}$ = 73 m; area = 1·81 $km^2$); however, the phytoplankton is dominated by small-sized species, as in most oligotrophic water bodies (Morabito *et al*., 2002), explaining its lower MSR. Finally, the low MSRs of Lake Malawi are surely related to its vast area (29600 $km^2$) and depth ($Z_{MAX}$ = 706 m), resulting in very low primary production.

However, MSRs in mesotrophic Lake Kinneret ranged from similar to as much as to three times those found in Lake Alchichica. The similar MSR values in Kinneret were related to the blooms of a large (≈50 µm) dinoflagellate species (*Peridinium gatunense*), while the higher MSRs were associated with resuspension of littoral organic matter (Eckert *et al*., 2003; Viner-Mozzini *et al*., 2003), phenomena that were not observed in Alchichica.

Like Lake Kinneret, Lake Alchichica is dominated by large (≈50 µm) phytoplankton. During the circulation period, nutrients released from the hypolimnion promote a diatom bloom (Oliva *et al*., 2001), which rapidly settles down to the bottom, thus accounting for the high MSR values. According to Legendre (1999), large phytoplankton cannot be consumed entirely by herbivores (either because of the size of the phytoplankton or because of their great abundance). As a result, the phytoplankton forms aggregates, which are exported to the bottom of the lake, explaining the highest deposition events in winter. The smaller peaks found in the early stratification in Alchichica were associated with the presence of a deep chlorophyll maximum developed at the metalimnion and composed mainly of *C. alchichicana*.

The higher accumulated MSR during the second sampling year was associated with a more extended and intense diatom bloom than in the first year, when the bloom was shorter and weaker. Adame *et al*. (2008) explain this behaviour as follows. The phytoplankton biomass in Lake Alchichica displays a biennial cycle, with higher concentrations in even years and lower concentrations in odd years. A higher hypolimnetic silicate concentration (SRSi) as well as a higher ratio of nitrogen to soluble reactive silica (N:Si), were detected before the circulation period. These explain the higher phytoplankton biomass in even years, and exhaustion of SRSi represents a higher sedimentation rate afterwards. However, in spite of the pH of the lake (≈9), the recently deposited diatom frustules did not dissolve as rapidly as expected for an alkaline environment (Caballero *et al*., 2003). Apparently, the total remineralization process takes two annual cycles to accumulate enough SRSi to generate a significant diatom bloom, resulting in the biennial cycle.

Fluxes of DF and MSR in Lake Alchichica are apparently contradictory because the main component of the particulate matter in the lake is not allochthonous (dust) – as was expected being located in a semi-arid area – but autochthonous (phytoplankton) – unexpected being oligotrophic – The combination of the two following phenomena explains this apparent contradiction.

(1) Even though the DF collected in the aerial traps is equivalent to or larger than that reported in the literature for other arid and semi-arid places, the DF recovered in the water traps is unexpectedly small, accounting for less than 3% of the total amount collected in the water traps. This could be explained as follows. Except for the largest, most dust whirlwinds simply 'vanish' upon reaching the edge of the lake (personal observations). As the dust whirlwind approaches the littoral area, the cold waters rapidly subtract energy from it, so the whirlwind 'disappears' and its dust load is quickly deposited in the edge of the lake. As a result, the dust barely reaches the pelagic zone.
(2) In spite of its oligotrophic status, the phytoplankton biomass in Lake Alchichica is dominated by large species. Large phytoplankton cannot be consumed by herbivores and are rapidly exported to the bottom of the lake. This explains why Lake Alchichica shows a higher MSR than those reported in the literature for other oligotrophic ecosystems.

In conclusion, most of the particulate matter deposited in the tropical Lake Alchichica is waterborne (autochthonous), composed of phytoplankton cells and their frustules, rather than dust (airborne, allochthonous). This outcome is opposite to what was expected because the lake is oligotrophic with low phytoplankton biomass and lies in a semi-arid region with major dust sources.

Our results indicate that caution must be taken in considering that the DF amount measured through DF collectors located at the lake shore does actually represent the DF entering into the lake. The real DF amount reaching the lake could only be properly evaluated through sediment traps located in the water column of the lake. However, the simultaneous evaluation of both DF and MSR is not routinely carried out for the same lake.

These findings challenge the idea that aquatic bodies in semi-arid regions are exposed to receive huge amounts of airborne dust, nutrients and other pollutants (e.g. pesticides), particularly those surrounded by phosphorus-rich volcanic terrains and/or degraded/eroded agriculture lands. Whirlwinds 'vanishing' at lake shore prevent the possible deleterious effects on the water quality and trophic status of a lake.

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