

## Sediment resuspension by wind in a shallow lake of *Esteros del Iberá* (Argentina): a model based on turbidimetry

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### Abstract

A model based on empirical relationships is used to study frequency and magnitude of the sediment resuspension by wind-induced waves. The model has been developed for Laguna Galarza, a mesotrophic round-shaped shallow lake located in *Esteros del Iberá* wetland. Given the logistic and accessibility difficulties of this macrosystem, the installation of automated field stations facilitated continuous data acquisition. Using the wave theory, a daily spatial model of resuspension was built from simultaneous time series of hourly measurements of infrared nephelometric turbidity, wind speed and wind direction. The model was used to predict total suspended solids in another lake of the wetland (Laguna Iberá) showing a good agreement with observed field values, even although Laguna Iberá has a more irregular contour and a eutrophic state. Finally, we apply the model to discuss the ecological impacts of resuspension on the distribution of the littoral communities and to characterize the composition of the particulate suspended matter of the limnetic ecosystem. The model was useful to simulate the possible implications of the recent alterations of the wetland water level on the resuspension regime of the open water bodies.

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**Keywords:** Shallow lakes; Wind resuspension; Nephelometric turbidity; Suspended particulate matter

### 1. Introduction

Resuspension of lake sediments is a function of the bottom shear stress as the result of fluid motion and the local sediment characteristics (e.g. Håkanson

and Jansson, 1983). Several hydrodynamic processes can intervene on sediment resuspension, although wind-induced waves are usually the dominant process in shallow lakes (e.g. Leuttich et al., 1990; Weyhenmeyer et al., 1997; Douglas and Rippey, 2000). The wind surface stress induces an energetic wave-affected layer in which both large-scale orbital movements and the dissipated turbulent energy are important. The closeness of the surface and

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### Nomenclature

$D$	water depth (m)
$F$	fetch (m)
$L_w$	wavelength of the swell (m)
$S_R$	resuspended solids, daily mean (mg/L)
$S_0$	background concentration of suspended solids, daily mean (mg/L)
TSS	total suspended solids, daily mean (mg/L)
TT	total turbidity, daily mean (NTU)
$T_R$	turbidity by resuspension, daily mean (NTU)
$T_0$	background turbidity, daily mean (NTU)
$W$	estimation of the daily wind speed (m/s)
$W_{\max}$	maximum daily wind speed (m/s)
$W_{\text{med}}$	mean daily wind speed (m/s)
$W_0$	theoretical wind speed that starts the resuspension (m/s)

### Greek letters

$\alpha$	intercept of the potential equation linking TT and $W$
$\beta$	exponent of the potential equation linking TT and $W$

bottom boundaries in shallow lakes often generates a completely mixed water column during the resuspension events. In contrast with the surface or density boundaries, the bottom boundary is rigid, and the wind-induced current speed vanishes at the water–bottom interface, through the turbulent dissipation of energy and the subsequent vertical mixing (Grant and Madsen, 1986). A two-layer vertical structure of horizontal circulation is unlike to form during these events in shallow lakes (Webster, 1990) and the bottom shear stresses associated with the horizontal currents are generally too small to influence suspended solids concentration (Leutlich et al., 1990). The main effect of the horizontal advection would be to smear of the horizontal distribution of solids resuspended by the energetic wave-affected layer (Bailey and Hamilton, 1997), thereby having a secondary role on the resuspension process. Therefore, the modelling of the resuspension phenomenon in shallow lakes could

be simplified by focusing on the wave orbital motion and the associated turbulence.

As the air–water and water–bottom interfaces create bottlenecks for the energy exchange that involve complex processes, the mechanistic modelling of the resuspension process depends on multiple factors that are difficult to estimate (e.g. wind drag coefficient, vertical mixing speed). Using the dependence of the depth of the energetic wave-affected layer on wavelength, a practical spatial analysis of the susceptibility to resuspension can be performed in shallow lakes (Carper and Bachmann, 1984; Scheffer, 1998; Nagid et al., 2001). For specific sediment conditions, the resuspension regime of a certain lake may be characterized using an empirical correlation between the concentration of suspended solids and the wind speed if enough data are available (Scheffer, 1998). In this way, sediment traps and filtering of water samples are common methods to study the resuspended particles flux in the water column (Evans, 1994). However, while these methods can provide valuable information on the characterization of the suspended material, they have a limited usefulness in the study of the sudden temporal variations of the resuspended solids concentration. The inaccessibility of the studied wetland (*Esteros del Iberá*) hampers an appropriate periodicity of sample collection with these methods during periods of severe storms. In this work, the building of the resuspension model was based on hourly time series obtained by an infrared nephelometric turbidimeter, which simplified the data acquisition.

The ecological effects of the resuspension could be summarized at three fundamental levels. Firstly, the resuspension works directly on the nutrients and pollutants dynamics. The sedimentation process transforms the lake bottom into a store of nutrients, toxic metals and organic pollutants. In spite of the intermittence of the resuspension process, an order-of-magnitude estimate of the contribution of resuspended material to the total flux of particulate suspended matter in the shallow lakes is about 80–90% (Evans, 1994). Thus, the sediment resuspension conditions the availability and the final fate of all biologically active particulate matter (e.g. Cotner et al., 2000). On the other hand, the resuspension modifies the release rates of regenerated dissolved nutrients from the sediment (e.g. Ogilvie and Mitchell, 1998). Secondly, the resuspension events modify significantly both attenuation and temporal fluctuation of

light in the water column. Helleström (1991) calculated that this effect would be sufficient to reduce primary productivity in a shallow Swedish lake by about 85%. Thirdly, the wind is considered one of the strongest factors influencing the zonation of aquatic vegetation. Even moderate wave heights (0.1–0.15 m) may cause negative effects on plants with morphology that may be tolerant of the wave activity, such as long ribbon-like leaves (Doyle, 2001). Both wave energy and sediment remobilization have shown dramatic impacts in the vegetal colonization of the lakes (Galinato and van der Valk, 1986; Foote and Kadlec, 1988).

It is well reported that a water level change in shallow lakes can cause large and rapid ecosystem shifts. Sediment resuspension is often involved in the internal mechanisms causing such alterations. A drop in the lake water level usually contributes to an increase in resuspended sediments which lead to a higher trophic state and lake turbidity. This has been well reported in shallow ecosystems such as in Lake Chapala, Mexico (de Anda et al., 2001) or Lake Newman, Florida (Nagid et al., 2001). Likewise, the rise of the water level can promote undesirable changes in the shore vegetation and the state of the lake. Engel and Nichols (1994) reported how, in the early 1970s, during a high water period of Rice Lake (WI, USA), waves damaged the littoral marsh vegetation and eroded the bottom. The lack of vegetation and the resulting softer sediment altered the dynamics of the lake causing higher turbidity. Once the water level returned to normal, the littoral vegetation continued to be excluded for at least a decade and the turbid conditions remained due mainly to wind resuspension.

Sediment resuspension as an environmental perturbation plays a significant role in geochemical, toxicological and biological processes. Due to its multiple effects on the ecosystem, the quantitative modelling of the resuspension process is important to understand shallow lakes functioning. In this work, we attempted to model the spatial variability of the resuspension process of a particular shallow lake of *Esteros del Iberá* wetland (Laguna Galarza). The integration of physical models and ecological results help to build a better predictive framework. In the last section, we illustrate the applicability of the resuspension model on the littoral and limnetic ecosystems, paying attention to the potential effects of the water level variation in *Esteros del Iberá* wetland.

## 2. Study site

The study has been focused in *Esteros del Iberá*, one of the most pristine and largest wetlands of South America (13,000 km<sup>2</sup>). This subtropical wetland is located between 27°36′–28°57′S and 58°00′–57°30′W (northeast Argentina). The macrosystem consists of a mosaic of marshes, swamps and open water bodies. The wind-induced resuspension plays a relevant role in the dynamics of the wetland lakes because of their shallowness. The larger lakes of the macrosystem have an average depth about 2.5 m. Most of the lakes remain permanently flooded with a small seasonal variation of the water level. However the inhabitants of the region have reported rises of the water level in the last years, a fact which highlights the need to study this poorly known ecosystem. Thanks to the existence of a nearby small village (*Colonia Pellegrini*), a series of water level data from 1968 is available for Laguna Iberá. The analysis of this register revealed a sudden increase of 80 cm of the average water level cm in 1989 (Ferrati and Canziani, 2005). *Esteros del Iberá* is mainly fed by rain. However, data analysis suggests that a possible cause of this water level increase is related to a change in ground water flux associated to the construction of the Yacyretá hydroelectric dam on the River Paraná (Ferrati and Canziani, 2005). The Yacyretá reservoir is located at the north of *Esteros del Iberá*, separated by a thin strip of land (4–12 km wide). The wetland drains only through River Corriente in the south. The drainage is slow due to the very flat slope and the huge amount of vegetation accumulated in the basin. At the present, the wetland has maintained the elevated water level that resulted from 1989.

The present modelling effort has been mainly addressed to Laguna Galarza (16 km<sup>2</sup>, mean depth 1.9 m), a mesotrophic round-shaped lake located in the oriental border of the Ibera macrosystem. A small stream (Yacaré) that originates in the vast marsh area to the northeast feeds the lake, while the lake outlet is a small stream (Isirí) that connects with another shallow lake (Laguna Luna). The water level of Laguna Galarza varies about 0.4 m throughout the year. The validity of the model was also examined in Laguna Iberá (58 km<sup>2</sup>, mean depth 3.2 m), which has a more irregular morphology and a eutrophic status. This lake is divided into two basins by a narrow passage that acts as a barrier reducing the interchange of wave energy and water

masses. A small river (Río Miriñay) feeds the southern basin. The bottom of both lakes is quite flat and homogeneous. It is dominated by silt-clay, with fractions of very fine sand and high percentage of organic matter (Varela and Bechara, 1981). Macrophytes cover was scant (usually below 5% lake area), and practically absent in the open waters. The vegetation of the marsh areas is dominated by emergent macrophytes such as *Typha latifolia*, *Scirpus californicus*, *Hymenachne amplexicaulis* and *Echinochloa helodes*. The shoreline has vegetation that usually varies from coast to coast but often concludes in extensive floating mats of vegetation and organic matter called “embalsados”.

### 3. Methods

The bathymetry of the lakes was outlined with small portable equipment consisting of a global positioning system (GPS) and an echosounder. The surveys were performed during June 1999 in Laguna Galarza and during February 1999 in Laguna Iberá. Over 30 transects in each lake were run to outline the structure of the isobaths (Fig. 1).

Two meteorological stations, one in each lake, and one hydrological station were used for autonomous monitoring. All sensors were connected to data loggers that received energy supply from a battery connected to a solar panel. Sensors of Vector Instruments were used to measure wind speed (model A100R) and direction (model W200P). Both variables were registered with an hourly frequency. The hydrological station (Hydro-lab Datasonda 2) equipped with a turbidimeter was anchored in a mid-lake site (2.2 m depth) of Laguna Galarza. The installed turbidimeter is a nephelometric detector at 90° from an infrared light source of 880 nm. Infrared nephelometric turbidity is closely related to the scattering coefficient due to particulate matter (Kirk, 1994). The sensor measures the responses when the light source is on and when it is off. The difference is used to eliminate the effects of ambient light. If the light environment saturates the sensor the data are removed. A second sensor measures and normalizes the light source output to correct its possible variations. Each measurement was repeated three times and an average value was used. The calibration was performed using standard formazine solution. The turbidimeter was submerged few centimeters under

the water surface. Thus, the sensor only registers resuspension events that involve mixing of the whole water column, intervening in the light attenuation of the superficial layer. Since the resuspended particles have a relatively high sinking velocity (e.g. Kristensen et al., 1992; Ogilvie and Mitchell, 1998), once wind has stopped, these particles fall out of the surface layer and are not registered by the sensor. In this way, the sensor does not register the settling particles due to the resuspension by previous events.

Simultaneously to the monitoring period (March 1999–August 2000), a general limnological study (nine samplings dates; Secchi depth, chlorophyll a concentration, plankton composition) was carried out to obtain a biological characterization of the studied lakes (Cózar et al., 2003). During the periods of higher phytoplankton biomass, the long-term use of the turbidimeter without continuous cleaning resulted in algal growth on the turbidimeter window. The blockage of the window occurred even by simple deposition of filamentous branches. This fact prevented the use of the turbidimeter in the eutrophic Laguna Iberá, since it was observed that intense biological growth occurred around the sensor cage. In order to develop a consistent wind-turbidity correlation, a significant problem was the difficulty to discriminate between the turbidity due to the wind-induced resuspension and that due to biological activity or other physical process (e.g. rain). During the monitoring period in Laguna Galarza, we acquired four simultaneous turbidity-wind registers of approximately 2–3 weeks duration. Only one register (1–20 September 1999) showed a temporal series of turbidity driven almost exclusively by wind. The remainder showed clear biological control of the temporal variability of the turbidity or abnormal sensor drifts by the bio-fouling problem.

Suk et al. (1998) analyzed the feasibility of using the infrared nephelometric turbidimeter to quantify suspended solids concentration in a coastal wetland, with a sediment composition very similar to the Ibera wetland lakes. The particles size distribution covered the range from clay to very fine sand, with mean sizes within the silt category and high percentage of organic matter. As in the Ibera wetland lakes, the origin of the organic matter in the sediment was the mobilization of the litter from the marsh vegetation. Suk and co-workers used standard formazine solution to calibrate the sensor. They found a consistent

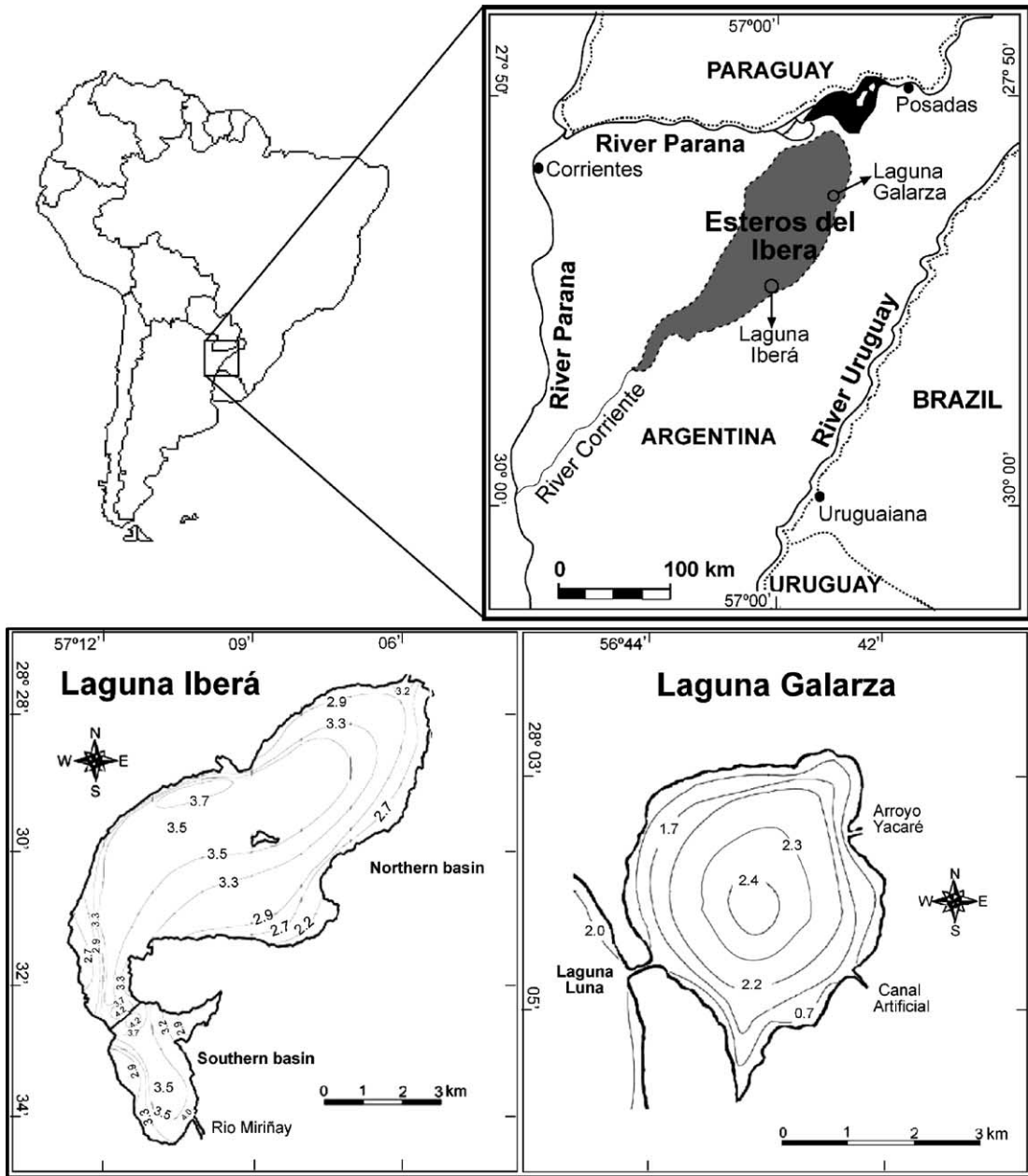


Fig. 1. Location of *Esteros del Iberá* wetland in South America and bathymetry and location of the studied lakes, Laguna Iberá and Laguna Galarza.

linear correlation ( $R=0.827$ ) analyzing 593 samples during a period of 6 months including periods of severe storms. The relation between turbidity and concentration of suspended solids showed a slope of 1.584 mg/L

per nephelometric turbidity units (NTU). We have initially used the results from this study to transform the turbidity data to concentration of suspended solids.

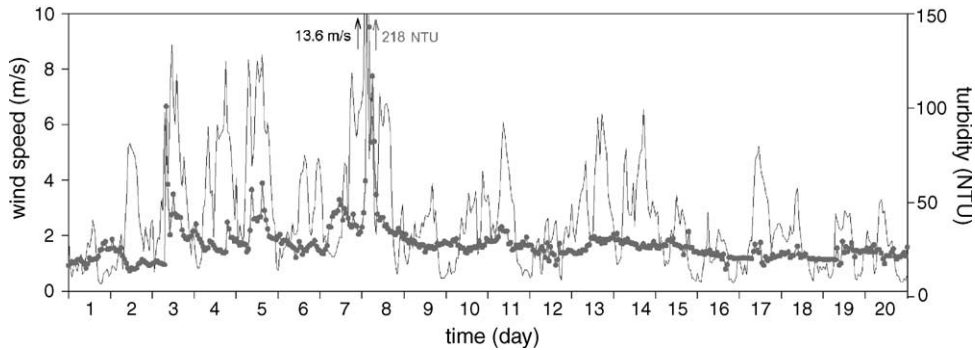


Fig. 2. Hourly temporal series of wind speed (black line) and turbidity (grey circles) from 1 to 20 of September 1999 in Laguna Galarza.

The validation of the model was carried out through extensive spatial samplings of the total suspended solids (TSS) in one resuspension event in each lake. Vertical profiles of temperature (0.5 m intervals) were performed along the fetch line. Laguna Galarza was sampled with a grid of 24 points (9 March 2000) and Laguna Iberá with a grid of 40 points (23 June 2000). Samplings lasted 4 h in Laguna Galarza and 8 h in Laguna Iberá. The water samples were collected at 0.5 m depth in polyethylene 2 L-bottles. A variable volume of sample ranging from 250 to 600 mL was immediately filtered under low vacuum pressure. Previously, the Whatman GF/F filters (47 mm-diameter) were dried (60 °C, 5 h) and weighed. The filters with the retained residue were again dried and weighed. The net weight of the residue and the filtered water volume were used to calculate the TSS concentration.

The mean sinking velocity of the resuspended sediment in the lakes was estimated through sedimentation columns (SETCOL) after Bienfang (1981). The samples for this analysis were acquired after artificial resuspension events of the superficial lake sediment (3 cm) in microcosms. Sinking velocities of the organic and inorganic matter were discriminated.

#### 4. Correlation between wind and turbidity

The continuum series from 1 to 20 September 1999 corresponded to the studied period of lowest phytoplankton biomass, and probably the lowest primary productivity (austral winter). A strong storm (peak of wind speed of 13.6 m/s) that covered the whole range

of wind of the region was registered during this period (Fig. 2). The wind blew basically from the south, coming exclusively from this direction when the hourly speeds were higher than 5 m/s. The temporal series of turbidity was driven by wind, however some days showed a smooth turbidity increment during calm periods and a fall when the wind speed increased again. This process was clearly observable twice, once during the first and second days and again during the seventh day. Both periods showed similar inverse hourly relationships between wind speed and turbidity (Fig. 3). A possible explanation for this apparent paradox could be a physical or biological accumulation of particles in the superficial layer and a subsequent dispersion when the wind begins to blow. Before the formation

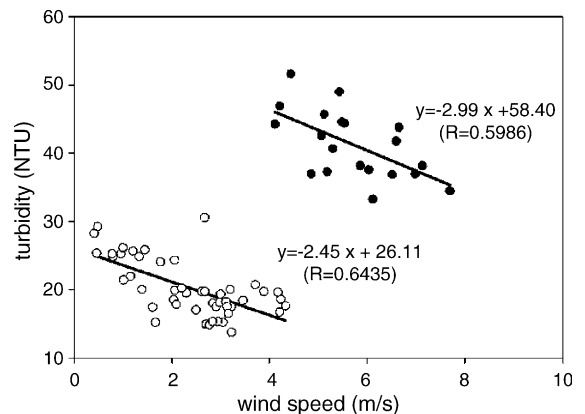


Fig. 3. Inverse hourly correlation between wind speed and turbidity. The empty circles correspond to 1 and 2 September 1999 and the solid circles to 7 September 1999.

of well-developed waves, the wind-induced motion is insufficient for sediment resuspension but not for the dispersion of the particles accumulated in the superficial layer, near the sensor. The superficial accumulation could be due to the buoyancy of some cells like *Microcystis aeruginosa* (Reynolds and Rogers, 1976), a dominant species in Laguna Galarza. Although these local increments of turbidity do not modify significantly the general wind-turbidity correlation, we have removed these days in order to obtain a more precise modelling of the resuspension phenomenon.

The acquisition of simultaneous hourly series of wind and turbidity allowed a suitable daily average for modelling. The traditional samplings of TSS make it difficult to acquire an hourly data series (Somlyody, 1982; Aalderink et al., 1985; Kristensen et al., 1992). The use of wind speed on a daily basis presents two considerable advantages. (i) The velocities of sedimentation measured in the settling columns were  $12.4 \pm 0.9$  m/day for inorganic matter and  $6.5 \pm 0.7$  m/day for the organic matter. The consequent short-residence times agree with other resuspension studies in shallow lakes (Kristensen et al., 1992; Bailey and Hamilton, 1997; Ogilvie and Mitchell, 1998). A dynamic resuspension model implies the consideration of the settling process of the particles resuspended by previous events. Nevertheless, according to these results and the lake shallowness, the resuspended particles are not likely to remain suspended in the water column for periods longer than a day. Consequently, the daily periodicity avoids the modelling of the deposition process, which complicates the modelling of the concentration of suspended solids (Bailey and Hamilton, 1997). The turbulent conditions during the resuspension event may change some initial properties of the particles, for instance, the tendency to flocculate (Lick et al., 1993). (ii) A daily averaged wind reduces the error due to generation time of a well-developed wave (with defined direction, long crests and relatively long wavelengths). For the same instantaneous measurements of wind speed and direction, the resuspension may even be different according to the development state of the waves. The time necessary for the formation of a well-developed wave is on the order of hours. Due to the day–night periodicity of the wind speed (Fig. 2), a daily average is the most suitable because it integrates the matter resuspended into single daily cycle of wind.

Reported mathematical functions linking TSS (or total turbidity, TT) with wind speed ( $W$ ) use the following equation:  $TT = \alpha W^\beta + T_0$  (Somlyody, 1982; Aalderink et al., 1985; Kristensen et al., 1992). The  $T_0$  coefficient would correspond to the background turbidity, which does not depend on wind resuspension. The plankton, due to its mobility, buoyancy or small size, can remain in suspension making a significant part on this background turbidity. The  $\alpha$  and  $\beta$  coefficients depend on the characteristics of the process of remobilization of the particles from the bottom. Our data also followed this pattern (Fig. 4). A saturation level of resuspended particles was not observed despite the highest registered wind speed was measured during the calibration period (8 September 1999). The lack of saturation level of resuspended solids has occurred in others studies like Lake Arresø (mean depth 3 m), where up to 2 cm of the superficial sediment was resuspended in a mid-lake station (Kristensen et al., 1992). Using a particle concentration of bottom sediments from similar ecosystems (Carignan and Vaithyanathan, 1999) or from general resuspension models (Weyhenmeyer et al., 1997), the maximum registered turbidity peak would erode only 0.2–0.6 cm thick layer. Therefore, it seems probable that the lack of a saturation level is the

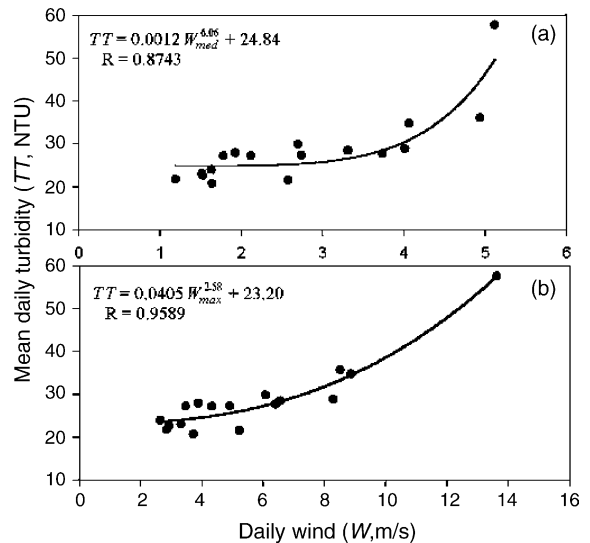


Fig. 4. Empirical correlation ( $TT = \alpha W^\beta + T_0$ ) between daily wind speed ( $W$ ) and mean daily turbidity (TT) from 1 to 20 of September 1999 in Laguna Galarza: (a)  $W$  = mean daily wind,  $W_{med}$ ; (b)  $W$  = maximum daily wind,  $W_{max}$ .

general feature of the resuspension regime in the soft sediments of Ibera wetland.

Diverse possible estimations of the daily wind were examined. The mean daily turbidity was adequately correlated with the wind through the mean daily speed ( $W_{\text{med}}$ ) and the maximum daily speed ( $W_{\text{max}}$ ). Other possible quantifications of daily wind were also explored through the combination of both  $W_{\text{med}}$  and  $W_{\text{max}}$  (e.g.  $W_{\text{max}}W_{\text{med}}$ ,  $R=0.9587$ ). The general correlation in the flat segment of the curve is probably due to the variability of the  $T_0$  when resuspension does not occur. The generally good correlations suggest a good reliability in the use of the day–night wind cycle for resuspension modelling in shallow lakes. The use of a moving 24 h-average of wind speed did not show good results.

## 5. Building of the model

The wave-affected depth depends on the wavelength, which in turn depends on wind speed and fetch line. The dependence of the energetic wave-affected layer on the fetch determines the spatial variability of wind-induced resuspension. We have used an empirical approach of the wave theory developed in coastal oceanography but widely used in the qualitative spatial analyses of the resuspension in shallow lakes (e.g. Carper and Bachmann, 1984; Scheffer, 1998; Nagid et al., 2001). The estimation of the wavelength ( $L_w$ ) links wind speed ( $W$ ) and fetch ( $F$ ) in the following form (Pond and Pickard, 1983):

$$L_w = 1.56 \left[ 0.77 W \tan h \left[ 0.077 \left( \frac{9.8F}{W^2} \right)^{0.25} \right] \right]^2 \quad (1)$$

Resuspension occurs when, at least, the energetic wave-affected layer reaches the bottom. This condition corresponds to the case in which the wavelength exceeds twice the water depth ( $L_w \geq 2D$ ). This approach has been used to make spatial estimates of the minimum wind speed necessary for resuspension in prairie shallow lakes like Little Wall Lake (Carper and Bachmann, 1984) or Lake Newman (Nagid et al., 2001). From Eq. (1) and considering the depth at the hydrological station and the fetch during the calibration period (Fig. 2), the wind speed necessary for the wave-affected layer to reach the bottom ( $W_0$ ) is

2.3 m/s. The calibration curve shows that resuspension was only registered when this wind speed value is exceeded.

The obtained empirical correlations between TT and  $W$  are only valid at the point where the hydrological station is located and for winds coming from south. Assuming a homogeneous layer of sediment in the lake, we have used the calibrated resuspension curve according to the respective value of  $W_0$  in each point and for each wind direction (from Eq. (1)). The proposed quantitative spatial model is based on the discontinuous typical response of the sediment layer to a gradual increase of the wind. In this way, the turbidity by wind resuspension ( $T_R$ ) at any point of the lake can be expressed as:

$$T_R(\text{NTU}) = \frac{2.2}{D} \alpha (W + (2.3 - W_0))^\beta \delta(W, W_0) \quad (2)$$

where “ $\alpha(W + (2.3 - W_0))^\beta$ ” determines the turbidity from  $W$  (m/s) and the resuspension curve referred to the each value of  $W_0$ ;  $\delta(W, W_0)$  a step-function that determines when the wind-induced wave begins to resuspend sediment,  $\delta=0$  if  $W < W_0$  and  $\delta=1$  if  $W \geq W_0$ ; the “2.2” factor indicates the depth (m) where the wind-turbidity relation was originally determined and  $D$  the depth (m) of the new site where it is applied.  $D$  is in the denominator because resuspended solids become more diluted when the water is deeper than 2.2 m depth.

The total turbidity (TT) is obtained adding  $T_R$  to the background turbidity ( $T_0$ ). In the same way that the resuspension curve is displaced along the wind axis according to the  $W_0$  value, a displacement is also performed along the turbidity axis according to  $T_0$  value. The turbidity due to resuspension (Eq. (2)) can be converted into resuspended solids ( $S_R$ ) by using the empirical relation between turbidity and suspended solids (1.584 mg/L per NTU; Suk et al., 1998):

$$S_R(\text{mg/L}) = \frac{3.48}{D} \alpha (W + (2.3 - W_0))^\beta \delta(W, W_0) \quad (3)$$

## 6. Model validation

The model was validated using whole lake samplings after extended period (>48 h) of regular winds. We have assumed that the measured concentration of



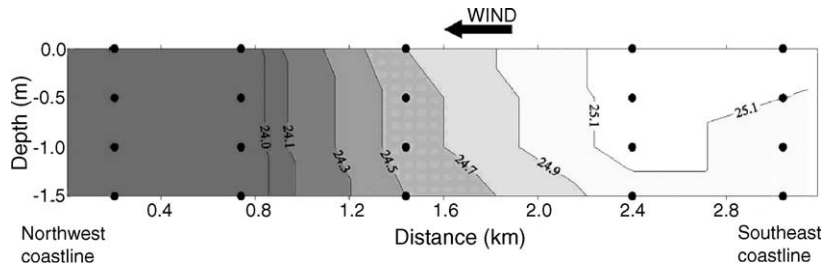


Fig. 5. Transect of water temperature ( $^{\circ}\text{C}$ ) including five vertical profiles on 9 March 2000 from the northwest coastline to the southeast coastline of Laguna Galarza (see Fig. 6).

TSS in the 2L-averaged samples at 0.5 m depth is a good estimate of the daily turbidity. The daily wind velocities were estimated 24 h prior to the sampling. The determination of the background concentration of suspended solids ( $S_0$ ) was resolved by obtaining an averaged concentration of suspended solids in the lake area that did not show resuspension. We averaged the TSS concentration of the sampling sites in which  $W_0 < 3$  m/s in order to obtain a better spatial estimation of the  $S_0$  (four sampling sites in Laguna Galarza and two sampling sites in Laguna Iberá). Measurements of the temperature profile along the fetch direction showed the tilting of the mixing depth along the wind direction. A very slight thermal stratification can be observed to the leeward side and a well-mixed water

column in the windward side (Fig. 5). The sampled resuspension events can be classified as peripheral wave attacks (Evans, 1994).

During the resuspension event of Laguna Galarza (9 March 2000), the wind blew from E–SE direction ( $112.5^{\circ}$ ). The daily mean and standard deviation of the wind speed was  $3.34 \pm 0.39$  m/s. The value of  $S_0$  was  $4.7 \pm 2.5$  mg/L ( $n=4$ ). The mean daily speed of wind ( $W_{\text{med}}$ ) was the best estimator of the daily wind for the model (Fig. 6). The modelled and empirical TSS showed a good linear correlation when the model and measured values are compared ( $\text{TSS}_{\text{measured}} = 1\text{TSS}_{\text{model}} + 0$ ),  $R=0.8945$ . The remainder estimators of the daily wind did not show acceptable modelled results, overestimating and

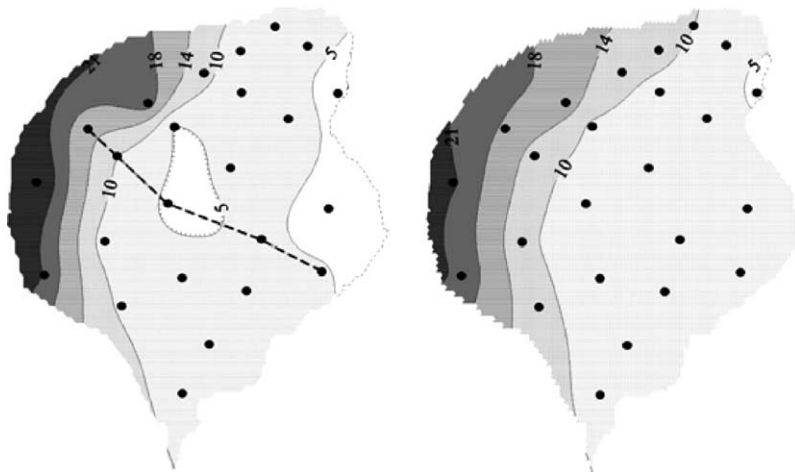


Fig. 6. Resuspension event by E–SE wind in Laguna Galarza (9 March 2000). Left: measured concentration of total suspended solids (mg/L). Right: modelled concentration of total suspended solids (mg/L). The spatial interpolation has been performed by kriging. Dash line indicates the drawn transect in Fig. 5.

underestimating TSS concentrations in calm and resuspended areas, respectively.

The model was also applied to another shallow lake in *Esteros del Iberá*, Laguna Iberá. The artificial inlet that crosses in the narrow pass of Laguna Iberá impedes the propagation of the waves between both basins. Consequently, the model was computed independently for southern and northern basins. During the resuspension event of Laguna Iberá (23 June 2000), the wind blew from E–NE ( $67.5^\circ$ ). The daily mean and standard deviation of the wind speed was  $4.62 \pm 1.32$  m/s for the northern basin and  $4.88 \pm 1.81$  m/s for the southern basin. The value of  $S_0$  was  $6.7 \pm 1.2$  mg/L ( $n=2$ ) for the northern basin and  $3.1 \pm 1.3$  mg/L ( $n=3$ ) for the southern basin. The relationship between modelled and empirical values of TSS showed also a relatively good linear correlation for the equation  $TSS_{\text{measured}} = 1TSS_{\text{model}} + 0$ ,  $R=0.7611$  (Fig. 7).

The effect of the horizontal advection seemed to cause an elongation of the area of abundant suspended solids in the NW sector of the wave attack zone in Laguna Galarza, and towards the eastern shore of the narrow pass of Laguna Iberá, which is a wind-protected area in the simulation. On the other hand, the eutrophic Laguna Iberá shows more heterogeneous distribution of plankton than Laguna Galarza. The central area of the northern basin of Ibera usually accumulates a higher concentration of plankton. These factors induce an error in the modelled spatial distribution. The coupling of a hydrodynamic model

would help to increase the accuracy of the simulation through the consideration of the redistribution of matter resuspended by the wave action.

## 7. Model simulation

In addition to using a homogeneous background ( $S_0$ ) and ignoring horizontal advection, other restrictions must be taken into account when using the model for simulation purposes. As the resuspension curve does not have a limit for maximum resuspended matter, the model could overestimate the concentration of  $S_R$  in very shallow waters. The minimum depth to which the model was applied in the model validation was 1.6 m. The percentage of the lake area exceeding this depth is 73% in Laguna Galarza and 94% in Laguna Iberá. Other limitations to the model simulation are the existence of a heterogeneous bottom (i.e. rock, sands) or with beds of benthic macrophytes. These effects could be modelled by assigning different resuspension calibration curves to them.

Resuspension models offer wide practical possibilities from the temporal or spatial analysis of light attenuation or amount of material that is brought into suspension. The impacts of the modifications to the lake morphology on the resuspension regime can be also described. These modifications can result from changes in the water level, alterations of the



Fig. 7. Resuspension event by E–NE wind in Laguna Iberá (27 June 2000). Left: measured concentration of total suspended solids (mg/L). Right: modelled concentration of total suspended solids (mg/L). The spatial interpolation has been performed by kriging.

lake contour or by the construction of infrastructures like the bridge foundation that actually separates the northern and southern basins of Ibera.

### 7.1. Littoral zone

A simple application is the analysis of the impacts of resuspension events on the littoral vegetation. The northwestern and southeastern shores of Laguna Galarza showed appreciable differences in their vegetation patterns (Fig. 8). The SE shore was colonized by patches of marsh vegetation, which do not occur in the NW shore. We have compared the resuspension regime in a site located in the northwestern shore (NW station) and another in the southeastern shore (SE station). Both studied sites were 1.7 m depth. The straight-line fetch for each site was computed for each octant of wind direction (north, northeast, east, etc.) and the daily evolution of the  $S_R$  was modelled with the available registers of wind for 1999 and 2000.



Fig. 8. A landsat-5 image in the infrared waveband obtained during February 1999. The location of the southeastern station and northwestern station are indicated. Differences in the vegetation on the lake coasts can be observed. The NW shoreline is composed by firmer and less vegetated *embalsados* (light grey). The white spots of the southern littoral of the lake correspond to patches of floating macrophytes, mainly water hyacinths (*Eichhornia azurea*). Some plants with ribbon-like leaves (*S. californicus*, *T. latifolia*) are also present in sparse patches along the SE littoral, although these little dense patches were not detectable by remote sensing.

The resuspension dynamics showed a relation with the situation in the lake (Fig. 9). The averaged flux of resuspended particles at NW station was  $19.6 \text{ g m}^{-2} \text{ d}^{-1}$  while at SE station was  $8.9 \text{ g m}^{-2} \text{ d}^{-1}$ . The estimation of the potential energy of the resuspended matter could be interpreted as a minimum limit of the energy used to resuspend the sediment. Assuming complete mixing of the water column, the median potential daily energy at SE station would be  $0.53 \text{ J/m}^2$ , while at NW station would be  $1.63 \text{ J/m}^2$ . Macrophytes genera that have been reported as susceptible to the wave action are found in the shoreline of Ibera wetland lakes (e.g. *Scirpus maritimus*; Foote and Kadlec, 1988). Immature developing plants are particularly sensitive and the spring growth period is considered the most vulnerable phase due to the easy unearthing of young plants (Lee and Stewart, 1981). In this sense, it can be observed that the spring (October–December) is the season of highest calm in the SE littoral area, facilitating the yearly re-colonization of this shoreline sector. A relatively calm period during spring does not occur in the NW littoral. With the actually existing conditions in Laguna Galarza, the complexity of the interaction between the positive/negative effects of the wave action on the macrophytes stands (e.g. water renewal, light attenuation, sediment erosion) leads to a reduction of the vegetal colonization of the wave-exposed littoral.

The floating mats of organic matter and vegetation (*embalsados*) that compose much of the shoreline of Laguna Galarza also show marked spatial differences. The NW shoreline is composed by firmer and less vegetated *embalsados* than the SE shoreline (Fig. 8). The *embalsados* seem to support higher erosion and stack in the NW coast by wind and waves. Obviously, the plant colonization depends on multiple factors, but the wind-induced waves seem to be an important factor in Laguna Galarza. Likewise, great differences were also observed in the densities of littoral animal populations such as the caiman. In the Galarza-Luna system, the number of caimans per coast kilometre was 2.9-fold higher in the southern coast than in the northern coast for the year 2000 (Waller, pers. commun.). Bonetto et al. (1981) pointed out that highest concentrations of fish biomass and the highest species diversity were found in the lakes sectors where macrophytes beds occur. Thus, the cascading effect of the resuspension on the ecosystem structure (macrophytes beds > benthic and fish communities) seems to

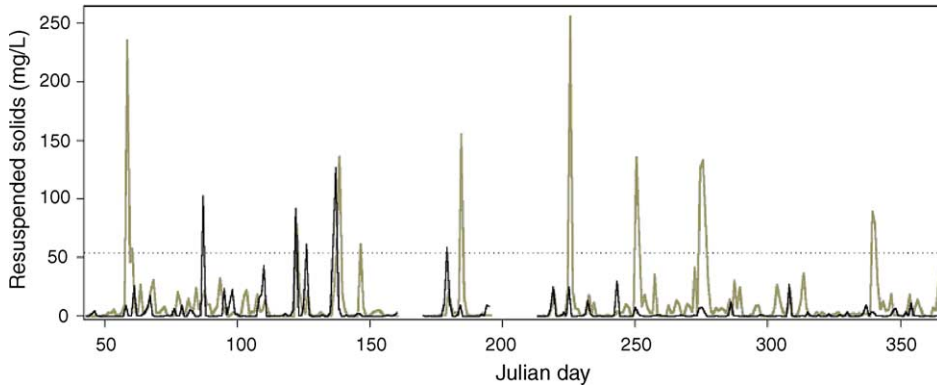


Fig. 9. Modelled daily concentrations of resuspended solids during an averaged Julian year estimated from available winds registers during 1999 and 2000. Results have been modelled for SE station (black line) and NW station (grey line) of Laguna Galarza. The dash line shows the upper limit of daily concentration of resuspended solids in the resuspension calibration curve. The peaks that exceed this limit assume the lack of a saturation level of resuspended solids.

influence the spatial distribution of a top-predator like the caiman.

An interesting application in *Esteros del Iberá* is the analysis of the effect of the water level on the wind-induced resuspension. We have modelled the variability of the resuspension frequency along a water gradient. The modelling of the number of resuspension events per time unit allows the resuspension analysis in shallower waters without a possible overestimation of the resuspended matter. The difference between

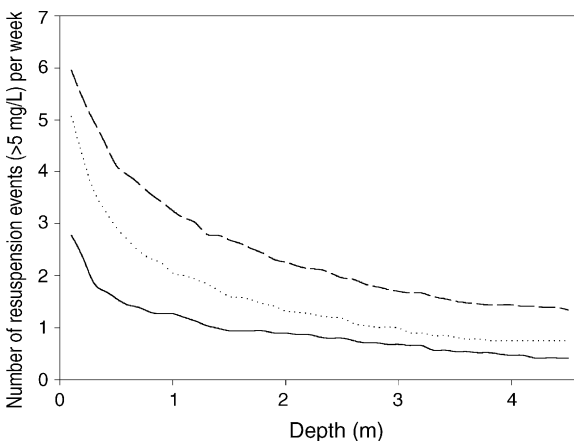


Fig. 10. Predicted number of daily events per week able to resuspend more than 5 mg/L in function of the depth of the water column. Predictions correspond to SE station (solid line), a mid-lake station (dotted line) and NW station (dashed line) of Laguna Galarza. The lines have been calculated from wind registers of 1999–2000.

the resuspension regime of the NW and SE shores increases more towards shallower waters (Fig. 10). It is interesting to note that the relation between resuspension frequency and water level is not linear. There is a sharp increase of the resuspension frequency when the water depth is lower than 1 m (typical macrophytes habitat). Thus, the negative impact of the waves on the littoral ecosystem rapidly increases when new areas are flooded (with a thin water layer). The physical damage is not the only negative impact acting in these areas. Probably, the deposition of resuspended matter above the new flooded areas plays also an important role. Galinato and van der Valk (1986) reported that the seeds may be prevented from germinating if they were covered by as little as 1 cm of sediment.

## 7.2. Limnetic area

In the limnetic area, the permanent increase in the water level registered in the wetland should also have impacts on the trophic state due to a lower mobilization of the matter accumulated in the sediment. According to Fig. 10, 63 resuspension events (>5 mg/L) per year occur with the current water level, and 90 events with a water level 1 m lower. Although historic data are not available, we would expect wind-induced increases in the trophic state with shallower waters as it has occurred in similar systems. Nagid et al. (2001) observed an increase of the total nitrogen and phosphorous concentrations in Lake Newman (Florida) with a decrease

of the water level because the particulate matter of the bottom is more frequently brought to the water column.

The background suspended particles concentration in the lakes ( $S_0$ ) would depend on the autochthonous production and the allochthonous supply, mainly through inflowing rivers and streams. The resuspension events can alter the temporal evolution of these latest processes with sudden increases of the suspended particulate matter. The contribution of the resuspension to TSS must be estimated through the daily variation of resuspended matter during the seasonal cycle. We estimate the matter that can be supplied by autochthonous production from the seasonal biovolume-size spectra of the planktonic community, from bacteria to zooplankton (Cózar et al., 2003). The dry weight can be obtained through the conversion factors proposed by Moloney and Field (1989). The particle concentration in the mouth of Arroyo Yacaré varied from 0.4 to 1.1 mg/L from winter to summer. The water drainage through the huge vegetation mass surrounding the lakes causes the natural filtering and decantation of most of the particulate matter transported towards the lakes. The allochthonous particulate matter measured in the mouth of the streams is mostly resuspended from the flux of the streams. Once the allochthonous particulate matter arrives to the open waters, it settles in a few days, adding to the potentially resuspendible matter. The majority of the particulate matter settles during  $\leq 5$  days according to the lakes depth. Considering the renewal time of the studied lakes ( $>60$  days), the allochthonous supply from streams would constitute on average less than 0.1 mg/L when considering the whole volume of the lake. The contribution of the allochthonous particulate matter to the TSS is practically negligible considering the average plankton concentration (1.7 mg/L) and the resuspension frequency during one lake renewal (more than 10 events with  $S_R > 5$  mg/L, Fig. 10). The contribution of the allochthonous particulate matter to the TSS of the whole lake represented less 3% in the studied basins. The resuspended matter in the limnetic area of Laguna Galarza represented about 72% of total suspended particulate matter (annual averaged TSS  $\sim 6.2$  mg/L). This percentage varied from 87% to 68% between the NW and SE shores, respectively. This composition of the particulate matter highlights the importance of the resuspension events on the vertical flux of particles, the light environment, or simply,

the aesthetic aspect of the lake. If the water level in Laguna Galarza were 1 m less than the present, the  $S_R$  contribution to TSS would increase 82% in the limnetic area, increasing the annual averaged TSS to 9.5 mg/L.

The differences of trophic state and morphology of Laguna Iberá lead to a different composition of the suspended matter with respect to Laguna Galarza. The  $S_R$  contribution in the limnetic area was 6% in southern basin (annual averaged TSS  $\sim 3.9$  mg/L) and 26% in northern basin (annual averaged TSS  $\sim 6.4$  mg/L). Applying a decrease in the lake water level of 1 m, the  $S_R$  contribution would increase to 8% in the southern basin (TSS  $\sim 4.0$  mg/L) and to 34% in the northern basin (TSS  $\sim 7.2$  mg/L).

## 8. Conclusion

The morphology of the southern basin of Laguna Iberá determines a relatively low concentration of resuspended particles and TSS. Despite the fact that the annual averages of TSS are similar in Laguna Galarza and in the northern basin of Ibera, a significant difference occurs with respect to the particulate composition and, consequently, the frequency of appearance of these particles. In the northern basin of Ibera, most of the particulate matter is composed by plankton (74%). Thus, the variation of suspended matter concentration shows a strong seasonal component. Laguna Galarza, on the other hand, reaches similar annual averaged TSS due to intense resuspension pulses of shorter duration.

The use of resuspension models and turbidimetry appear as a useful tool to understand particulate matter dynamics, especially in ecosystems where logistic and accessibility difficulties hamper their study. The described relations between the resuspension regime and the distribution of littoral communities, TSS concentrations, water level and lake morphology could help to improve the understanding of management actions on *Esteros del Iberá* reserve.

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