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Wave dynamics and resuspension in Lake Guaíba (Brazil) with implications on points of water abstraction for human supply

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ABSTRACT

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This research examines the characteristics of Lake Guaíba's waves with regard to their main parameters; significant wave height (Hs), period (T), direction of wave propagation and its connections with the ressuspension of sediments at the bottom. To this end, SWAN (Simulating Waves Nearshore) a type of software using mathematical modeling techniques, has been validated and applied, with its main inputs being the lake's bathymetry, direction, wind speed and frequency in the region (between 1996 and 1997) in addition to currents, water level, density, and maximum and minimum frequencies, among others. The highest waves modeled reached 0.55 m in a few points of the lake, particularly when winds were blowing from the S and SE quadrants with an intensity of over 7 m/sec. Generally speaking, waves follow wind intensity and direction patterns, and reach maximum values in about 1 to 2 hours after wind speed peaks. Whenever winds were stronger, waves took some 2 hours to reach 0.10 m, but with weak to moderate winds, they took around 3 hours. In addition to speed and direction, wind regularity proved relevant in generating and propagating waves on Lake Guaíba. The lake's sediment environments were mapped and rated as follows: 1) Depositional Environment (51% of the lake); 2) Transitional Environment (41%); and 3) Erosional or Non-Depositional Environment (8%). As a contribution to the region's environmental management, subsidies have been created with relation to the concentration of particulate suspended matter. This potential has been defined as a percentage of time, throughout the year, in which the wave-created ressuspension of environment sediments can increase the pollution levels at places where water is currently captured for public supply in the Porto Alegre area.

ADDITIONAL INDEX WORDS: WAVE MODEL, SWAN, LAKE'S SEDIMENT ENVIRONMENTS.

INTRODUCTION

Set in the lowlands at the border of the Crystal Shield with the Rio Grande do Sul Coastal Plains is Lake Guaíba (which in Tupy-Guarany language means *bay of all waters*), with its 496 km^2 area. The Lake receives the outflow of eight sub-basins stretching out through the center and northeast of Rio Grande do Sul state, covering an area of 84,763.5 km^2 which includes more than 250 municipalities. This is the state's most densely populated region, with some 6.5 million inhabitants, who account for almost 70% of the state's GDP. This includes the state capital Porto Alegre, which uses water from the Lake for public supply (Fig. 1).

Specific physical and chemical properties of fine sediments tend to attract certain contaminants. These sediments can be carrying agents that remove water contaminants. When deposited, sediments contaminated with heavy metals that are slow to degrade may become a source of contaminants waiting for extreme events or human activity to be remobilized and return to the food chain (Martin & McCutcheon, 1999).

One of the purposes of this paper is to contribute with the necessary inputs to define water abstraction points for human supply in the Porto Alegre metropolitan region, brought by the knowledge of the Lake Guaíba waves and their interactions with the resuspension of sediments deposited in its floor.

To this end, mathematical modeling techniques have been used to predict waves (using SWAN software), in addition to the tools available in the Geographic Information Systems (GIS). The purpose is to describe Lake Guaíba's wave patterns, both in terms of time and of space, identifying the places more subject to wave action and/or prone to lakebed sediment resuspension. To this end, the following parameters were analyzed: significant wave height, direction of wave propagation, average and peak wave period, and orbital motion near lakebed.

Lake dynamics

The first studies on Guaíba sedimentation were conducted by Cunha (1971) who described morphological, mineral, and textural features of the Lake. Roughly speaking, one can say that land drained by the Rio Grande do Sul Southeast Basin, formed by plutonic, volcanic, and sedimentary rocks, form the highlands, which account for a remarkable volume of sediments that are carried into the Guaíba, mainly by Jacuí, Sinos, Taquari, and Gravataí Rivers (Toldo, 1994).

The outflow from the tributaries loses its carrying ability when it enters the wide depositional Guaíba basin, where coarse sediments are retained, and giving rise to the Jacuí River Delta (Fig. 1). Fine sediment enters the lake as plumes of suspended material.

The intense sedimentation of Lake Guaíba can be measured by the long-term sedimentation rates recorded by Toldo *et al* (2000), in the lagoonal basin, with an average volume of 0.52mm/year. However, short-term sedimentation rates obtained by the 210Pb method indicate values between 3.5 and 8.3 mm/year over the last 150 years (Martins *et al*, 1989), which reflects human activity, particularly farming, in areas influenced by the drainage basin.

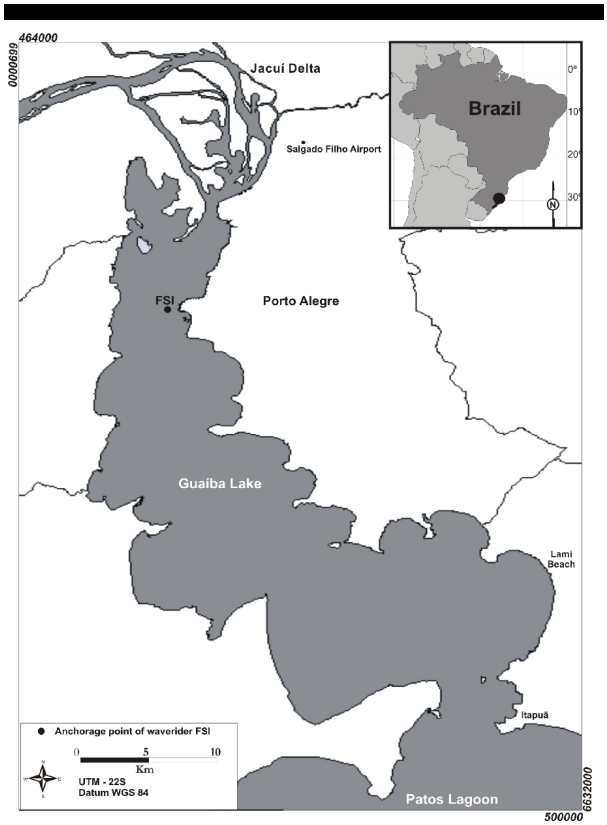

Figure 1:Study area location map. The black «FSI» point stands for the mooring place of the waverider buoy used for validating the wave model and measuring currents.

Fine sediments are preferably deposited as of the 3 m isobath. Between the shoreline and the 3 m isobath, the lakebed typically displays sandy sediment uncovered by fine sediment (Bachi *et al,* 2000). This absence of fine sediment is explained by wave action which resuspends the sediment through turbulence caused in the water column, making particle destination also dependent on the action of currents and length of the turbulent flow.

The lagoonal hydrodynamic regime, of which Lake Guaíba is part, is complex both in high-water and dry seasons. The cause and effect relationship among the several factors that play a role in the Guaíba outflow, particularly the strong influence of winds, show that the lake is not just an extension channel of its tributaries, but a kind of reservoir, closely linked to the Patos Lagoon.

The daily oscillations of the Guaíba are caused by wind speed variations, and are relatively regular, while wind direction, the Coriolis Effect, and the tide in Rio Grande (a city located near the Patos Lagoon estuary) are secondary factors that increase or decrease these oscillations. During high-water season, level variations are less affected by wind speed. In normal or dry seasons, winds of about 7 $m.s^{-1}$ may produce oscillations of over 50 cm.

METHODS AND RESULTS

For the analysis proposed in this study the following steps were taken: **a)** preparation of a bathymetric model of the Lake; **b)** wind data analysis; **c)** mathematical wave modeling; **d)** analysis of the potential resuspension of sediments in the water column; **e)** results relation with the points of water abstraction for human supply in Porto Alegre.

Preparation of a bathymetric model of the Lake

This model has been created by compiling pre-existing data from the following sources: a) Physical map from the Porto Alegre Environmental Atlas, created by Irgang e*t al.* (1997); b) Database of the «Sedimentation of the Guaíba River Complex» Project (CECO, 1999 and Bachi, *et al*, 2000), and c) Data obtained from 14 topographic profiles developed for the Itapuã State Park beaches, located south of the Lake (Nicolodi, 2002 and Nicolodi & Toldo, 2003).

Data interpolation was done on SURFER 8.0 software with a 2 m spatial resolution, using the Kriging method, which is a locally adjusted statistical interpolator. The interpolations were done in small sectors scanned by quadrant, preferably in the NW-SE direction, due to Lake direction and contour features.

This model was validated by comparison with interpolated profiles measured in the field with a recording ecobathymeter in the course of the «Mechanics of Lake Guaíba Currents» project (DNAEE, 1983). The methodology followed was that described by Plan *et al*. (2002), which had already been applied in Rio Grande do Sul in studies on shoreface delimitation on the Tramandaí continental platform – Rio Grande do Sul (Gruber & Nicolodi, 1998).

Wind data analysis

As to local winds, twelve-month data were used between 1996 and 1997, obtained from Salgado Filho Airport (Fig. 1), measured daily at the standard height of 10 m with one hour intervals.

The predominant winds in the Porto Alegre region blew from SE and E quadrants, in 29% and 22% of the records, followed by S, NW, N, and W winds, in 12%, 10%, 8.8% and 7%. The least frequent winds came from NE and SW quadrants with 4.1% and 4.3% of the records analyzed. As to velocity, the average was 2.52 $m.s^{-1}$ and maximum of 13 $m.s^{-1}$. Calm atmospheric conditions and unrecorded data account for 13.7% of the data.

Wave modeling

SWAN (Simulating WAves Nearshore) is a numerical model for wave spectrum analyses in coastal zones, lakes, and estuaries. Studies such as those of Lin *et al.* (1998) and Jin & Ji (2001) determined SWAN could be applied in sheltered

environments (Chesapeake Bay and Lake Okeechobee, respectively) when compared with other models and data measured in the field, with satisfactory results.

Cartesian coordinates were used, as well as the Mercator projection system, and nautical convention for wind and wave directions. The spatial grid was made up of a rectangular grid with a 200 m resolution, where any figure equal or higher than zero was considered null. The contours of Lake Guaíba (Jacuí River Delta and Patos Lagoon entrance) were considered closed.

The wave model was validated through a correlation of the data obtained with the data measured by an FSI3D waverider buoy produced by Falmouth Scientific, Inc., and moored near Jangadeiros Club, in the southern area of Porto Alegre (UTM 22S 474233 and 6667179) between June and August, 2005 (Fig. 1). The results were considered within expectations, and the correlation obtained likens most of the studies consulted in literature and deemed satisfactory (Ris *et al.,* 1999, Gorman & Nielson, 1999, Wood *et al,* 2001, Shan-Hwei Ou *et al.,* 2002, Pires-Silva *et al,* 2002, Rusu *et al.,* 2002, Ou *et al,* 2002, Rogers *et al*., 2003, Hsu *et al.,* 2005).

Waves on the Guaíba follow wind intensity and direction patterns, and reach maximum values about 1 and 2 hours after wind speed peaks. In situations when winds blew more intensely, waves took about 2 hours to reach 0.10 m, and wind direction did not remain constant at all times. With weaker winds, this time practically doubled. Both situations with shorter response times coincided with those when wind intensity was lower than 4 m/s. Wave increase was higher with wind speeds above 7 m/s.

The definition of wave behavior patterns includes Lake Guaíba's general NW-SE geographical direction, which favors wave generation and propagation driven by certain types of winds, and the wave refraction process, which causes a wave breaking zone alignment that tends to be parallel to the shoreline.

Analysis of sediment resuspension potential in the water column

The relation between wave energy and the start of bottom sediment motion is then a key component to be analyzed. This evaluation consists of two main procedures: a) orbital speed (U_m) and b) shear stress (τo). While significantly different from each other in terms of methodology, they have a common wave orbital motion parameter, which is determined from height (H) and period (T) of the surface wave. In this manner, the wave effectiveness in starting sediment motion is a function of the orbital motion near the bottom and its frequency (1/T).

The interaction between water and bottom surface involves friction forces that act within a boundary layer. In shallow water environments, this layer may occupy a significant portion of total depth, and under certain conditions the boundary layer may contain almost the entire water column, as in shallow waters where waves break.

The area covered by the boundary layer has more energy in its dynamics, when compared with other natural systems, and this significantly affects resuspension and carriage of sediments. It is therefore a modeling agent of shallow water topography (Swift *et al.; apud* Toldo, 1994).

Calculations were made to define the percentage of time for wave orbital motion to reach the minimum limit to start moving silt and very fine sand (15 $cm.s^{-1}$) fractions of sediment by cross-checking information on wind frequency as a consequence of speed intervals and directions with the results relative to orbital motion (U_m)). The result can be seen in the figure 2, which corresponds to the percentage of time with a wave action potential to resuspend silt and fine sand.

Based on the systematized information on sedimentary distribution, which are typical of incident waves, orbital motion, boundary layer, and the beginning of a turbulent flow, three sedimentation environments have been determined in Lake Guaíba (Fig. 3). The environments identified as (1) Depositional Environment, (2) Transitional Environment e (3) Erosional Environment have a spatial distribution strongly conditioned by the Lake's geometry and bathymetry.

Depositional Environment: this corresponds to 51% of the lake area. These are low hydrodynamic environments which favor the deposition of fine sediments. These deposits are located in deeper lake areas, near the navigation channel, and are sheltered from the main resuspension forces, which can be generated by winds from quadrants E and SE.

Transitional Environment: this corresponds to 41% of the lake area. These are mostly low energy environments, their substrate basically formed by sand and silt, remobilized in certain situations linked to waves generated by winds of 11 $m.s^{-1}$ or above. In weaker wind situations, erosion may occur in shallow areas.

Erosional Environment: this corresponds to 8% of the lake area. These are environments where erosion or non-deposition of fine sediments prevails due to wave action with orbital motion above 15 $cm.s^{-1}$ for at least 50% of the time. A characteristic of these environments is a lakebed formed by sand, since fine sediments are constantly remobilized and thrown into the water column.

Relation of results with the points of water abstraction for human supply in Porto Alegre.

After obtaining data on the Lake Guaíba resuspension potential, the data were cross-checked with the Porto Alegre points of water abstraction for human supply (Fig 2 e 3) with the purpose of finding the relationship of these points with the lakebed sediment carrying dynamics. Abstraction points installed in places with a high resuspension potential, even if only for a few days a year, are not recommended, unless supported by a well-founded study on horizontal currents.

The results of this analysis are presented on chart 1, which shows the relationship between abstraction points and the sediment resuspension potential in the context of its sedimentation environment. Moreover, the main features of the water treatment stations (WTS) for water abstraction and destination have been inserted.

The points were identified according to their conditions as follows: Bad (inadequate site for water abstraction); Reasonable (pending further viability studies on water abstraction) and Good (adequate site for water abstraction).

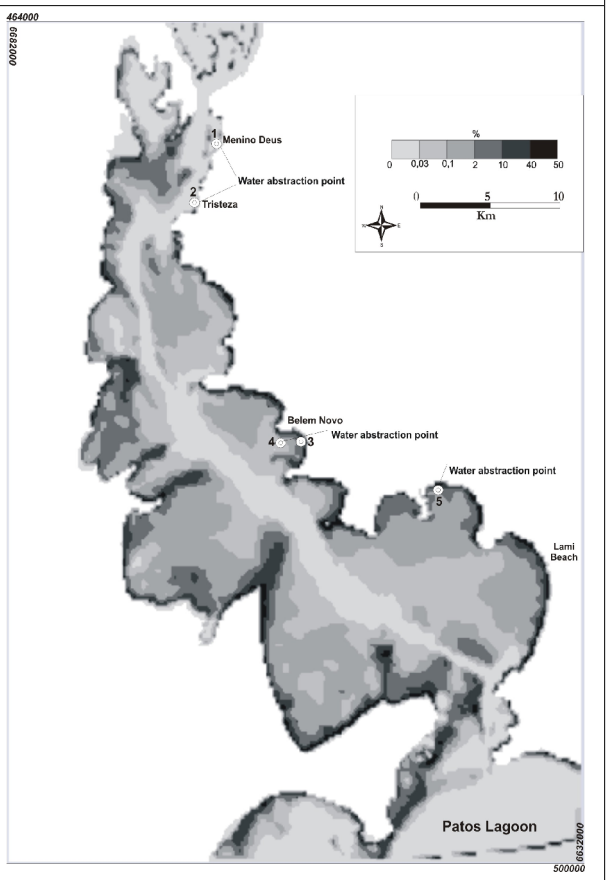

Figure 2: Map of time percentage with a potential to resuspend silt and very fine sand through wave action in Lake Guaíba.

CONCLUSIONS

The knowledge of hydrodynamics and morphology of bodies of water is a basic prerequisite for the management of water basins. At this point, the action of waves in the upper layer of lake and lagoon bottoms may lead to sediment resuspension and a reintroduction of pollutants into the water column.

As a general rule, waves followed wind intensity and direction patterns, and reached maximum values between 1 and 2 hours after their speed peaks. Whenever winds blew more intensely in the first hours, waves took about 2 hours to reach . 10 m. Wave increase was higher with wind speeds above 7 m.s-1. Factors such as Lake geometry and geomorphology were also important, particularly when there were sandy spits, which partly reduce wave energy, resulting in decreased H values, even in significant fetch situations.

One can say that that the Guaíba incident waves can potentially generate near-bottom turbulence in different situations. However, the maximum depth does not exceed 1.9 m for S quadrant winds and minimum speeds of 11 m.s-1. On the other hand, the boundary layer thickness where the turbulent flow begins has very low values of up to 1 cm.

Low depth places containing fine to very fine sand and silt may show excessive turbulence, and this turbulence takes up the entire water column in some places.

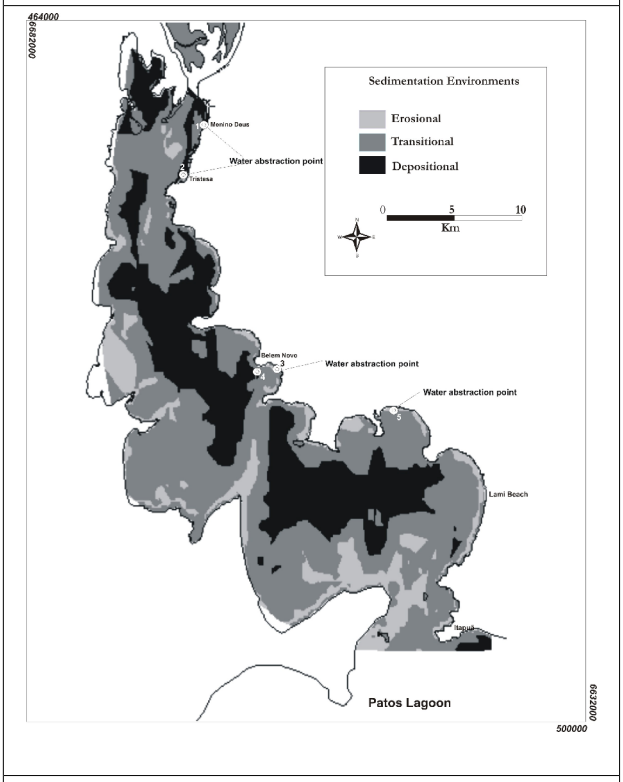

Figure 3: ap of sedimentary environments in Lake Guaíba.

Abstraction Points	WTS characteristics	Percentage of time with sediment resuspension potential	Sedimentation Environments	Situa tion
Menino Deus	Capacity: 2,000 L/s Population: 418,000	0.03 and 0.1%	Depositional Environment	Good
Tristeza	Capacity: 200 L/s Population : 49,000	< 0.1%	Depositional Environment	Good
Belém Novo A: Old point B: Current point	Capacity: 1,000 L/s Population: 48,000	A: 10-40% B: < 0.1%	A: Transitional Environment B: Depositional Environment	A: Bad B: Good
Lami	Capacity: 20 L/s Population: 1,150	10 – 40%	Erosional Environment	Bad

Chart 1: Relationship between water abstraction points and sedimentation environments in Lake Guaíba.

This condition results in erosion of the sediments deposited in the Guaíba lakebed, usually where depths are lower than 1.5 m. Deposition of material carried in the water column occurs when there is no turbulent flow, or when there is an insignificant flow near the bottom.

Based on the information system on sedimentary distribution, which are typical of incident waves, orbital

motion, boundary layer, and the beginning of a turbulent flow, three sedimentation environments have been defined on Lake Guaíba: 1) Depositional Environment; 2)Transitional Environment; and 3) Erosional or Non-Depositional Environment.

The results discussed in this paper have a direct relationship with the sedimentary patterns of Lake Guaíba. More than that, they form an intricate system where causes and effects often overlap: Bathymetry is a fundamental factor for the entire system, as it defines wave patterns, but at the same time it is defined by wave action, among other factors. The identified sedimentation environments are a result of this process, which makes them a source of inputs for the management of lagoonal environments such as, for example, those related with mining, building navigation terminals, and, more importantly, water quality.

All this technical information has a direct relationship with the quality of the water captured for treatment stations in the Porto Alegre region. These analyses permit assuming a great deal of consistency in locating the reservoirs that abstract water for human supply. The only places ranked as bad for water abstraction were the old Belém Novo point and the Lami point.

The results of this study can be used as inputs to other studies that require considering the dynamics of incident lake waves and their consequences to the sedimentary distribution and energy flows associated to this body of water.

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