E-proceedings of the 38th IAHR World Congress
September 1-6, 2019, Panama City, Panama
doi:10.3850/38WC092019-1675

MEASURE AND MODELING VERTICAL MIXING IN TROPICAL STRATIFIED LAKES

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ABSTRACT

Lake's mixing regime affects physical, chemical and biological processes. Each time the vertical stratification is broken an upward velocity is created. But is this velocity strong enough to re-suspend bed material and affect water turbidity? This is a key question in water quality studies, once that turbidity is an important index in those evaluations and bed material could include heavy metals, high load of nutrients or even pesticides, all harmful for the environmental. To respond this question turbidity measures and tools of environmental evaluation are needed.

In this subject, two stratified tropical lakes, located in São Paulo - BR were used as study sites. Aiming to measure variations on the water turbidity due mixing events and evaluate them according to the temperatures profiles, also assess a model 3D capacity to represent the vertical velocities due to mixing events on the lake. The first lake is called Billings, it is bigger and deeper, than the second site, Hedberg reservoir, different sizes of lakes were chosen to be able to include the size effects on the lakes' mixing regime. Both lakes had their temperature profile and the relative turbidity measured in campaigns that were performed for more than a month and with 1min and 1s time steps, respectively.

With the data collected the information were plotted and evaluated looking into specifics moments when the water column mix, and then the lakes were modeled in Delft3D which provided calculated vertical velocities. The measures on the field shows that the relative turbidity, that is, the difference between previous and current turbidity, increase when mixing events begin to happen, proving those events can re-suspend deposited materials. When the same period is modeled in Delft3D the higher vertical velocities are found at same time that turbidity peak occurs, evidencing the efficient of a calibrated model in represent physical conditions and relations in the lake.

Keywords: vertical velocity, lake modeling, turbidity, water quality, hydrodynamics modeling.

1 INTRODUCTION

Water quality is an integrated response of several hydrodynamic processes, which control the transport of algae, nutrients and dissolved oxygen in a water body (Ji, 2008) (Sperling, 2007). Stratified hydric bodies can have three layers different across the water column: the epilimnion, which is the superior layer where the temperature is usually stable, followed by the metalimnion, where occur the maximum temperature gradient, and the hypolimnion that extends itself until the bottom of the lake. But the circulation creates variation in the heights of the layers and can mix the mass vertically (Imberger, 1998) (Ji, 2008) (MacIntyre, & Melack, 2009) (Martins, 2017).

The greater effect of the stratification is the mass transport limitation across the water column, this includes the nutrients dispersion, that will affect the biota increase or decrease its development and also the oxygen vertical profile (Martins, 2017). Although when the energy provided by the wind breaks the stratification and mix the water column a re-suspension from the material at the bottom may occur (Kullemberg, 1976) (MacIntyre, & Melack, 2009) (Amorim, Martins, Vinçon-Leite & Lemaire, 2017) (Jalil, et al., 2017).

This phenomenon can perform significantly effects on the water quality, once the transport limitation is broken all the substances that were attached to the sediment can be bring back to the surface and became available for the biota again. In a healthy environmental this would not be a problem, but in urban waters that are having a pollution increasing, unbalancing the production and consumption of nutrients, this situation can lead to transform the urban lakes in eutrophics systems (Elc¸i, 2008) (Chung, Bombardelli, & Schladow, 2009) (Jalil, et al., 2017).

The eutrophication of the systems is mostly caused by the wastewater and diffusive loads input in the lakes and reservoirs, this increase the nutrients availability, providing more food the algal development and creating a bloom. In those situations, a superficial film is formed blocking the light entrance in the water column and impairing all the exchanges between the surface layer and the atmosphere, which lead to serious harmful consequences for the ecosystem. Some eutrophication consequences are the low rate of dissolved oxygen in the deeper layers, decrease in aquatic life, added odor, taste and toxicity to the water; and impossibility to the public distribution, recreation and fishing (Sperling, 2007) (Elc¸i, 2008) (Chung, Bombardelli, & Schladow, 2009).

Some indicators are used to evaluate the water clarity and the presence of those organism in it, aiming to correlate the water physical aspect to its quality. In this research the index chosen was the turbidity, which measures the difficult the light has to pass through the water, its values are influenced by the water color and for the presence of organic or inorganic Carbon. The high turbidity causes are the particle matter in suspension on the water, organic and inorganic matter, phyto and zooplankton, its consequences includes the stimulus to stratification phenomena (Elc¸i, 2008) (Jalil, et al., 2017).

To represent this phenomenon through mathematical models the water column turbulence needs to be calculated, what implies in use of full 3D or *quasi*-3D models. The turbulent flow is irregular random velocity fluctuation that can transfer mass through the eddied generated. In lakes and reservoirs vertical mixing is generally induced by the wind, as discussed before, and the amount of vertical mixing is controlled by the density stratification, once strong vertical stratification inhibits the mixing. In the numerical models vertical and horizontal turbulent dispersion are used, through the Vertical Eddy Viscosity (VEV) and Vertical Eddy Diffusivity (VED) to characterize this movement (Ji, 2008) (Chapra, 2008) (DELTARES, 2014) (Martins, 2017).

Turbulence process play a critical role in vertical mixing and in water bodies it can be generated ate the bottom or surface. To calculate the vertical turbulent mixing coefficients in the momentum and mass transport equations a turbulence model is necessary, these are two-equation turbulence closure models with turbulence variables, such as turbulence kinetics energy and diffusivity (k-ε model) or turbulence kinetics energy and turbulence length scale (k-l). The turbulence closure scheme calculates vertical turbulent momentum diffusion (Av) and mass diffusion (Ab) coefficients, the models correlated them with the vertical turbulence intensity (q), turbulence length scale (l) and Richardson number (Rq) (Ji, 2008) (Chapra, 2008) (DELTARES, 2014) (Martins, 2017).

$$A_v = \frac{(1+8R_q)ql}{(1+36R_q)(1+6R_q)} \quad \text{(Eq.1)}$$

$$A_b = \frac{0.5ql}{(1+36R_q)} \quad \text{(Eq.2)}$$

$$R_q = -\frac{gH\frac{\partial b}{\partial \sigma}}{q^2}\left(\frac{l^2}{H^2}\right) \quad \text{(Eq.3)}$$

Aiming to correlate variations on the water turbidity due mixing events and also assess the 3D model capacity to represent the vertical velocities caused by those mixing events on the lake, this research performed monitoring campaigns and computational simulations for two different lakes and analyzed its results.

2 METHODS AND MATERIAL

2.1 Study areas

Two Brazilian lakes with very different sizes were chosen to perform this assessment, both located in the state of Sao Paulo – Brazil, in the transitional tropical climate zone. The Hedberg lake is located in a protected area and the nearest town is 10 km far (Smith et al., 2013), meanwhile the Billings reservoir is situated right in the state capital, São Paulo, with very different surroundings then the first (JESUS, 2006) (Wengrat & Bicudo, 2011).

Hedberg lake is placed over the preserved area of Ipanema National Forest enclosing a catchment area of 235 km². The main river is Ipanema River and the land use mixes urban and rural areas. It is located in the tropical zone, with a temperature ranging between 18 and 22 °C (ICMBio, 2008) (IBAMA, 2012). The lake has 0.26 km² of surface area, a mean depth of 4.5 m and a polymictic behavior presenting several events of stratification and mixing along the year. Water quality evaluation showed problems with excess of nutrients, especially phosphorus (ICMBio, 2008) (IBAMA, 2012) (Smith et al., 2013).

Billings reservoir is situated in the Serra do Mar region (23°47'S 46°40'W), being 747 m above sea level. This area has a tropical humidity climate with a rugged topographic, lowland areas and valley bottoms (Wengrat & Bicudo, 2011) (Martins, Vinçon-Leite, Soulignac, & Lemaire, 2014). The reservoir is located at the Upper Tietê River basin that begins between the cities of Salesópolis and Paraibuna and ends in the Rasgão Dam. The flow direction is from East to West draining 5.775 km² and involving 40 municipalities. This is the Brazilian most urbanized area with 10% of the country population (FUSP, 2009).

The Billings system is the biggest of São Paulo metropolitan region, with the total capacity of a billion and two hundred millions of cubic meters, a total surface area of 127 km² and a perimeter of 90 km. It has a central body with many ramifications, which drains an area of 560 km², a maximum depth of 18 m and a detention time of 392 days (JESUS, 2006) (Wengrat & Bicudo, 2011).

2.2 Monitoring system

To study the vertical velocity and its capacity to re-suspend bed material a monitoring system was applied to the intervenient variables. The climate variables (solar radiation, wind speed and direction, gusts, air temperature and precipitation) were monitored by a weather station with a frequency of 5 min and positioned on the lakes' proximity. Water physical variables were also recorded, specifically water temperature profile (30s interval) and water level (1h interval).

The transparency index, water turbidity, was measure by an optical sensor which was developed by the Technological Center for Hydraulics at the University of Sao Paulo. It is based on the water transparency variation, what means that the sensor emits a light each minute and based on the its reflection measure the quantity of suspend material in the water. The data are recorded on a SD card along with time and date.

Measurements campaigns were performed for all cited variables in both lakes, being July and August for Hedberg lake and October for Billings reservoir, both on 2018.

2.3 Modeling vertical velocities

The second phase of this study was to verify if 3D models can represent this upward vertical velocity, so both lakes were simulated using Delft3D model. This is a mathematic model based on the resolution of the Navier-Stokes equations, using the finite difference method. The main reasons to this choice was the model capacity of a quasi tri-dimensional modelling, which applies to the research objective, the wide spread and knowing reliability of the software and the fact that is an open source system. Still there are also some disadvantages on using Delft3D model, among them is the processing time (DELTARES, 2014).

The hydrodynamics simulations were performed in the FLOW module of Delft3D. Hedberg lake area was represented by a non-orthogonal grid, with 13x13 m cells, the vertical discretization has 30 layers with 0.20 m of thickness in the z-model. Boundary conditions were defined by the rating curve and the data collected in the monitoring.

Billings' reservoir area was reproduced in the model by an orthogonal grid with cells of 50 x 50 m and vertically the system has 11 layers with 1.68 m thickness. Unlike the Hedberg reservoir model, here the σ-model was used to a boundary and morphology better representation, since there are significant differences along the reservoir. Boundary conditions was the flow input by each affluent and its thermal characteristics.

After calibrated and validated the model by means of flow and water temperature profile, the turbidity data was checked with the modeled vertical velocity.

3 RESULTS

In a polymitic lake two different situation can be founded, one in which the water column is segregate in layers with different density and another one in which the water column became a homogenous mass, mixing the former layers and enable the vertical transport. In this research was investigated those mixing episodes and evaluated its effects through the water turbidity, considering the proportionally high velocities on the bottom layer can create an upward flux capable to re-suspend bed material and increase the water turbidity.

Water column thermal condition varies according to external driving forces, essentially solar radiation, wind gusts and incoming flow. As can be demonstrated in Figure 1, periods (10/07/2018, 01/08/2018 and 27/08/2018) with increase of wind velocities, reduction of solar radiation or high volume of incoming flow mixes the previously segregated column.

On the bigger lake, Billings reservoir, the analyzed period has no significant changes in the water column thermal condition (Figure 2), there was only a small event of stratification (10/10/2018) that occurs when the wind velocities reduces severely, but it does not stays for a long time.

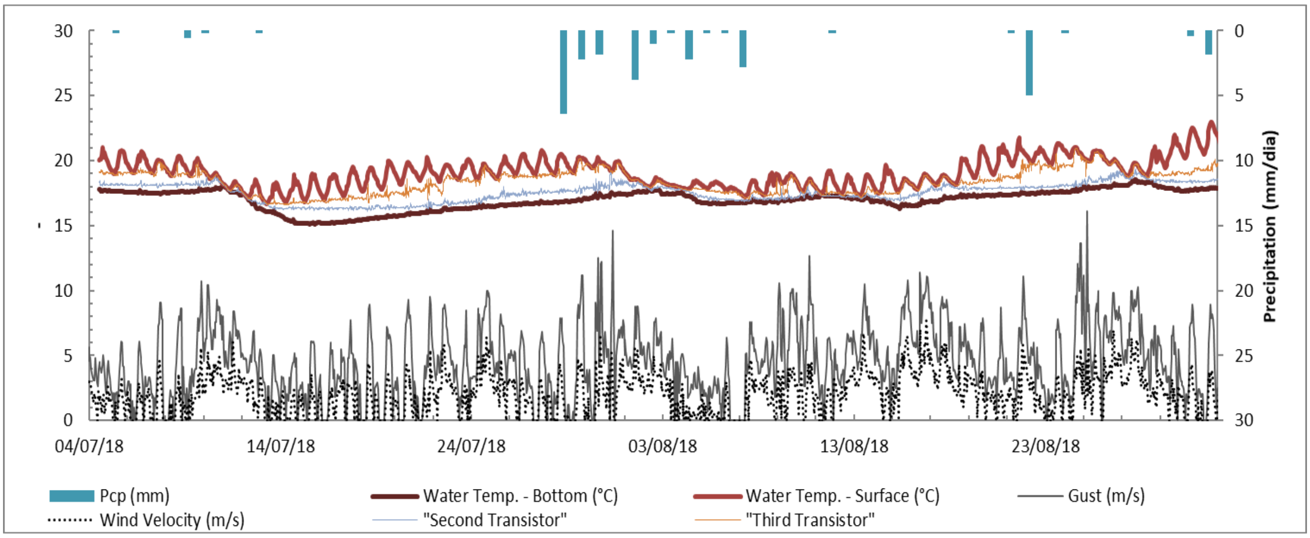

Figure 1. Climate data from Hedberg's monitoring station on the campaign period.

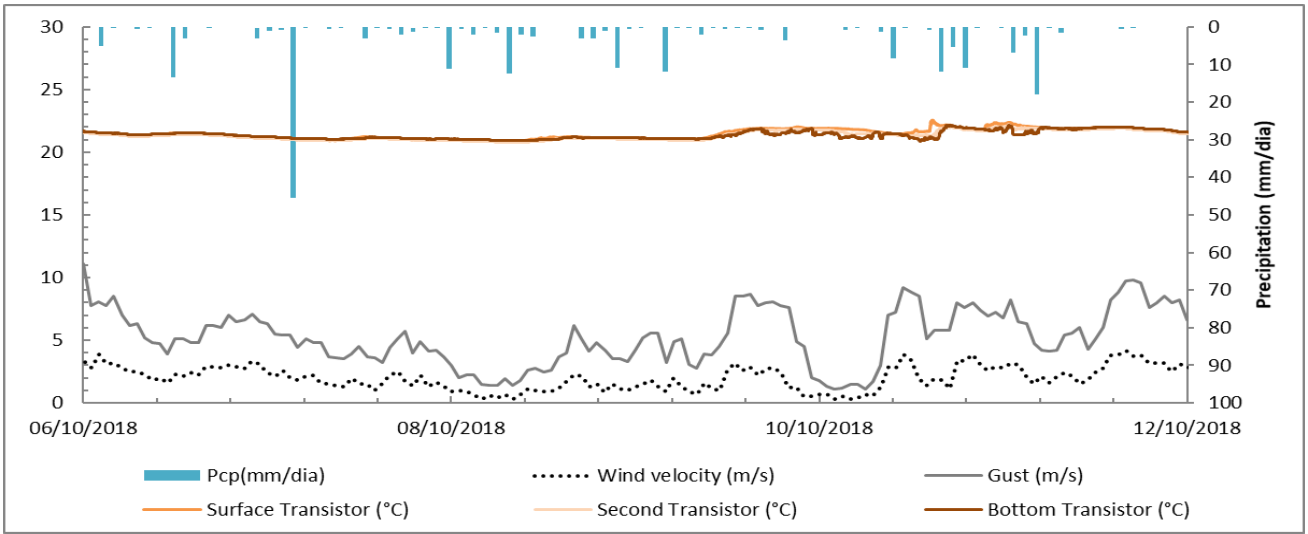

Figure 2. Climate data from Billings' monitoring station on the campaign period.

Crossing the turbidity data with the water temperatures measures it's possible to observe its behavior on to the mixing moments. In Figure 3 is easy to notice a big change on the relative turbidity when the turnover event begin to happen, after a long period of a stratified and stable water column, with a decreasing in turbidity measures, they rises up rapidly, when the external conditions initiates the break in the stability condition.

Beholding more specific the major mixing event on the Hedberg lake, the

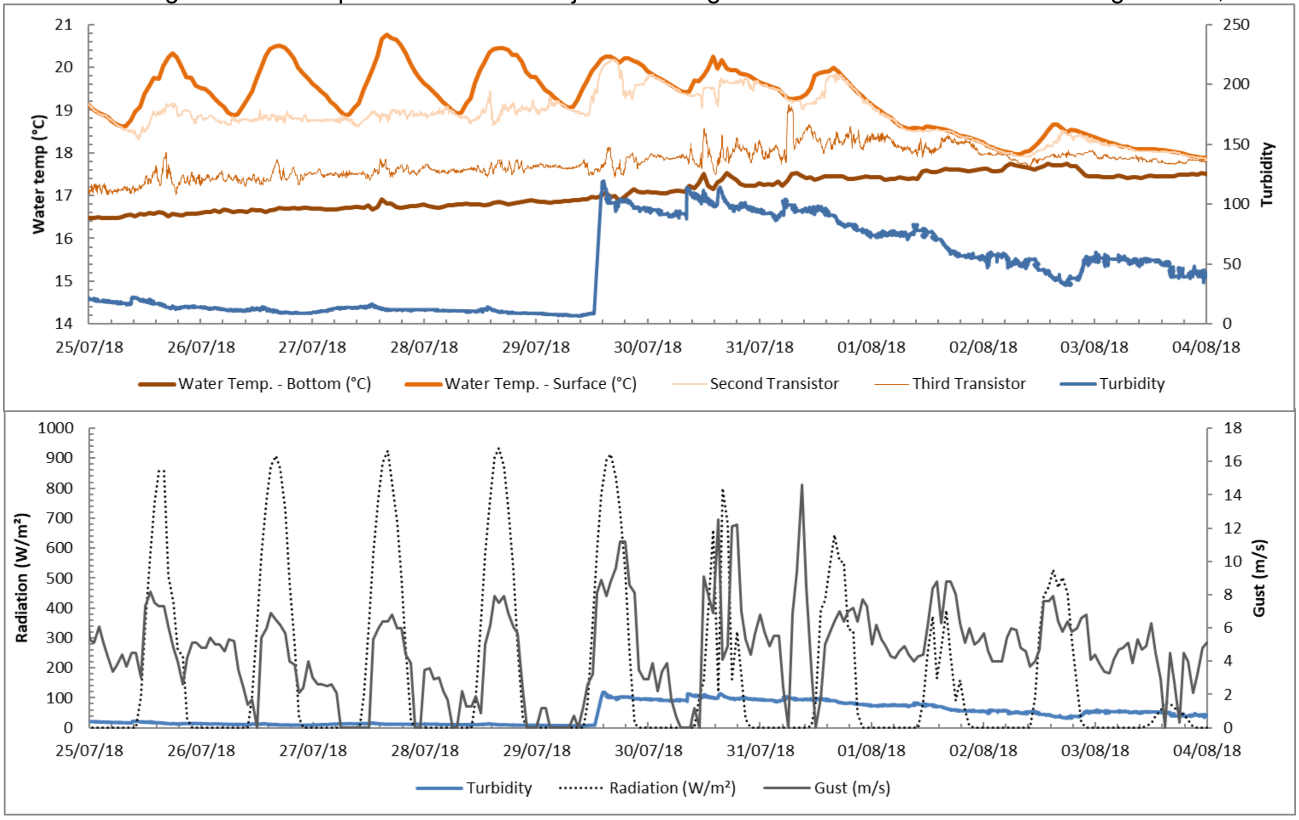

Figure ***4*** shows that the instant of the higher variance between wind speed measures, combined with the posterior decrease of the solar radiation, provide the condition to the accumulated energy of the stratification transforms itself in upward vertical velocity and re-suspend bed material. The first sign of mixing between two uppers layers matches with to moment of the turbidity peak.

In Hedberg's mixing events, the turbidity peak can represent a difference of about 100 units, meanwhile values of very different scales of variations are observed in Billings reservoir measures (Figure 5). No significant events of stratifications mean that were no accumulation of energy on the water column, forbidding the energy release that create the upward vertical velocity.

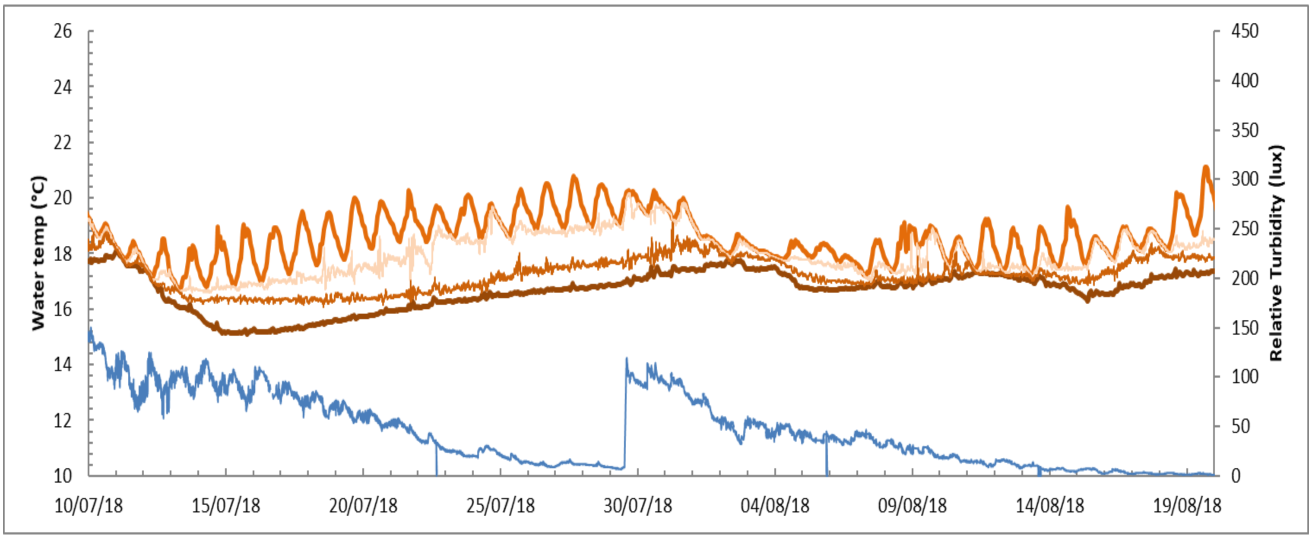

Figure 3. Time series of Hedberg's turbidity and water temperature measures.

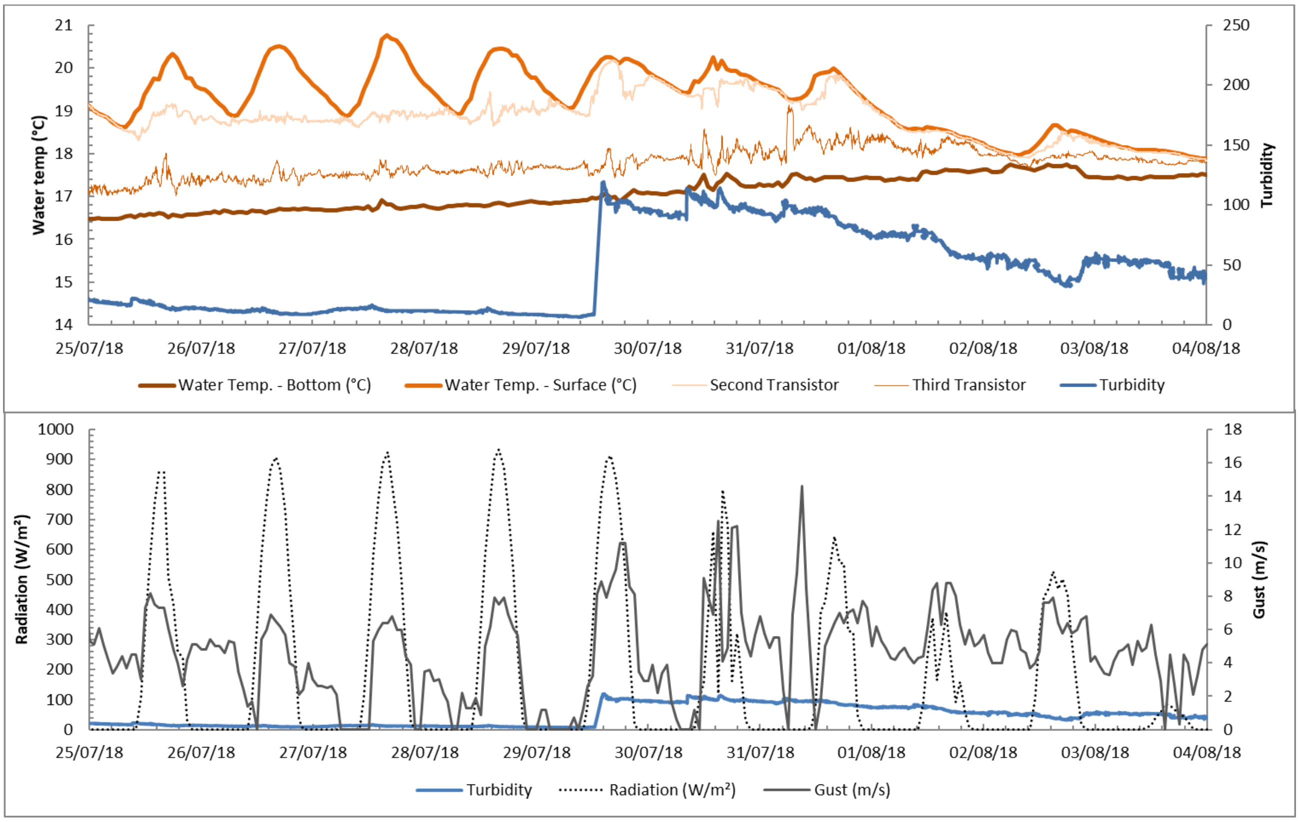

Figure 4. Hedberg's turbidity behavior detail during turnover moments.

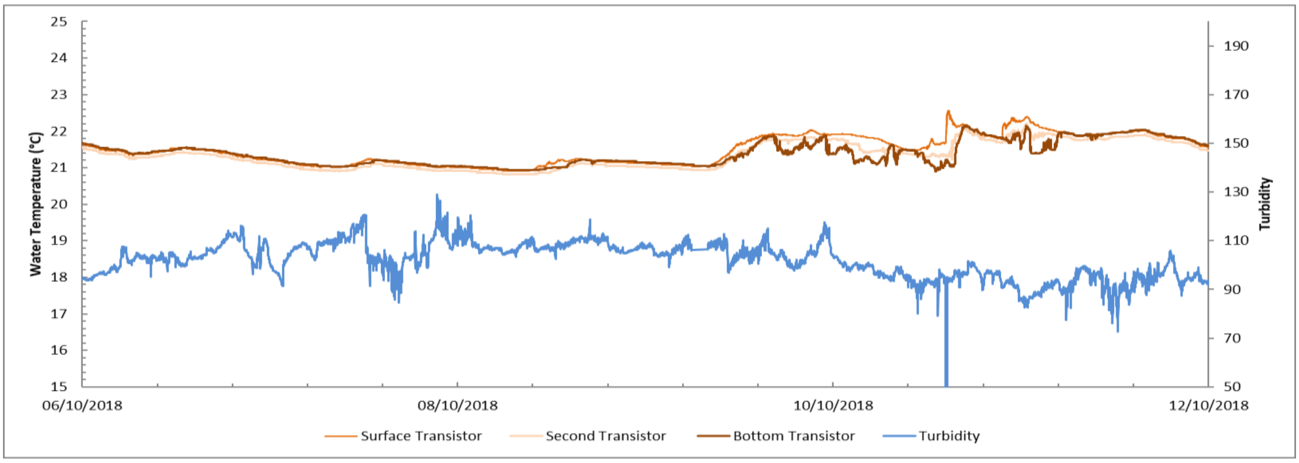

Figure 5. Billings' turbidity and water temperature measures.

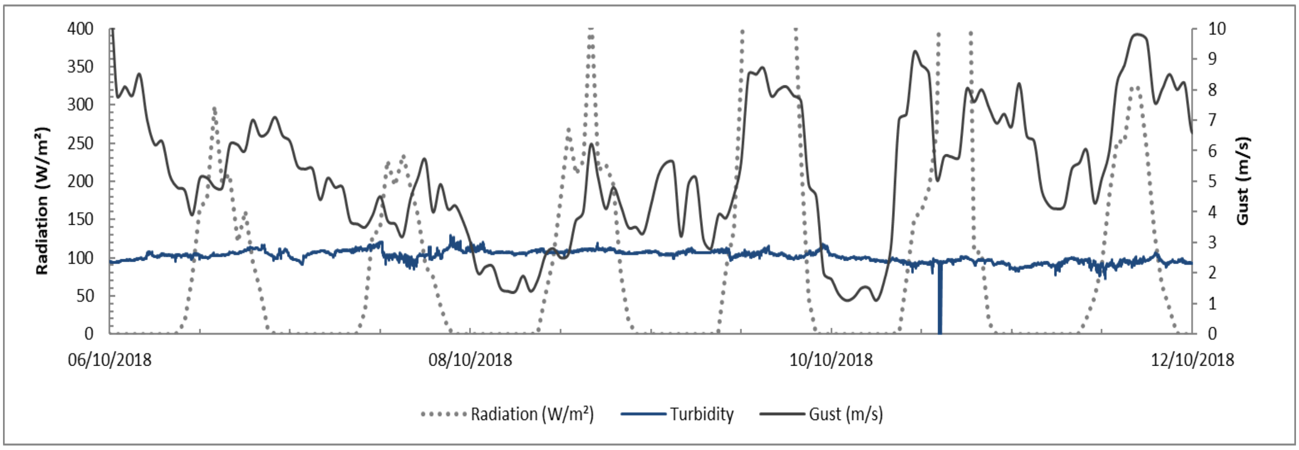

Figure 6. Billings' turbidity and climate variables behavior.

3.1 Delft3D vertical velocity simulations

After observe the correlation between the mixing events and increase of water turbidity on the filed the 3D model capacity of represent the re-suspension phenomena was evaluated. During the calibration and validation, the model showed that it can reproduce with high accuracy the water column thermal condition, then its capacity to represent the effects of those events were analyzed by the calculated vertical velocity.

For the Hedberg reservoir simulation (Figure 7 and Figure 8), peaks of $6x10^{-4}$ m s^{-1} and several events with the magnitude between $4x10^{-4}$ and $2x10^{-4}$ m.s^{-1} were founded, while Billings' peaks were of $2x10^{-4}$ m.s^{-1}, showing the difference of energy release by the mixing events on those cases. When compared with the sedimentation rate on those places, the vertical velocity is about 10 times smaller.

Studies, i.e. (R.A. Luettich, Harleman, Somlyody, & Koncsos, 1993) (Jalil, et al., 2017), says that velocities of 4x10-4 m s-1 begin to move bed material, so the model results implied that mixing events could be powerful enough to -suspend what were accumulated on the lake bottom.

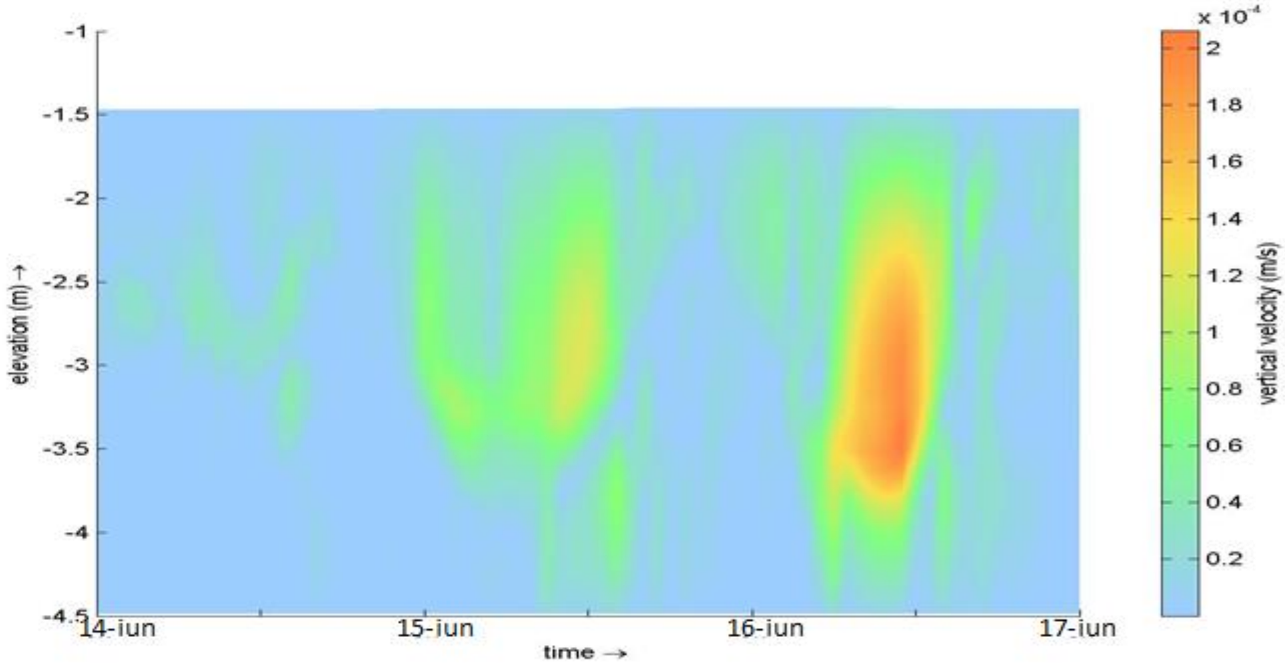

Figure 7. Hedberg's modeled vertical velocity.

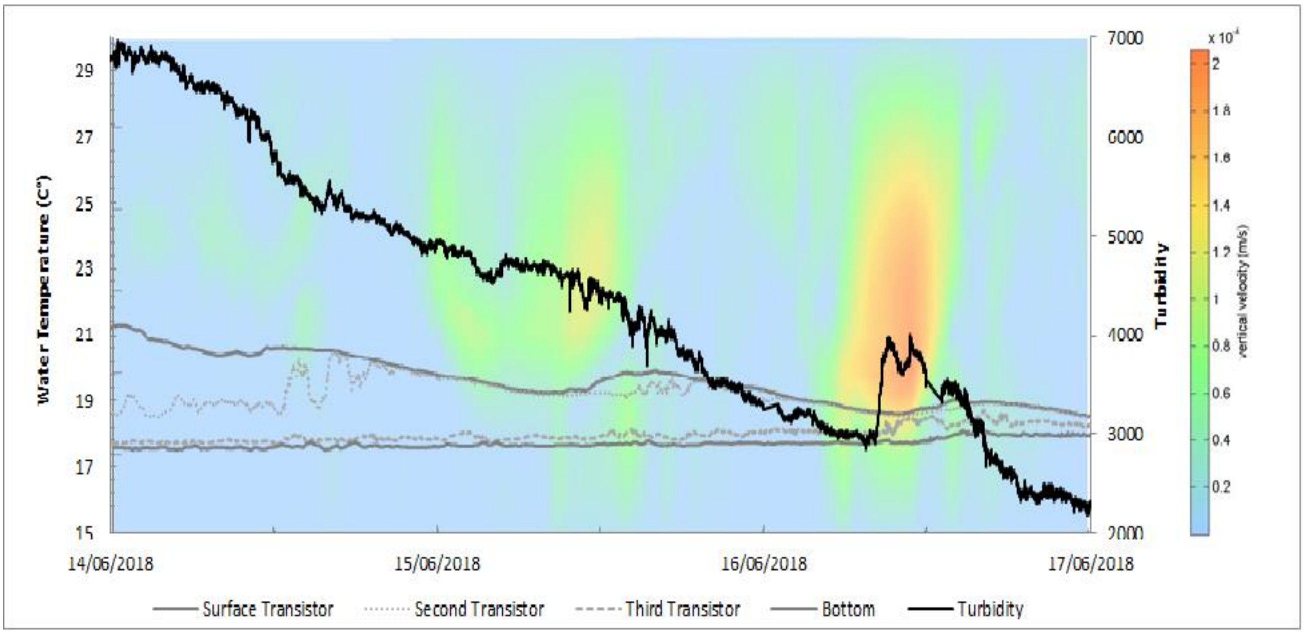

Figure 8. Hedberg's turbidity measures related to the modeled vertical velocity and water temperature profile.

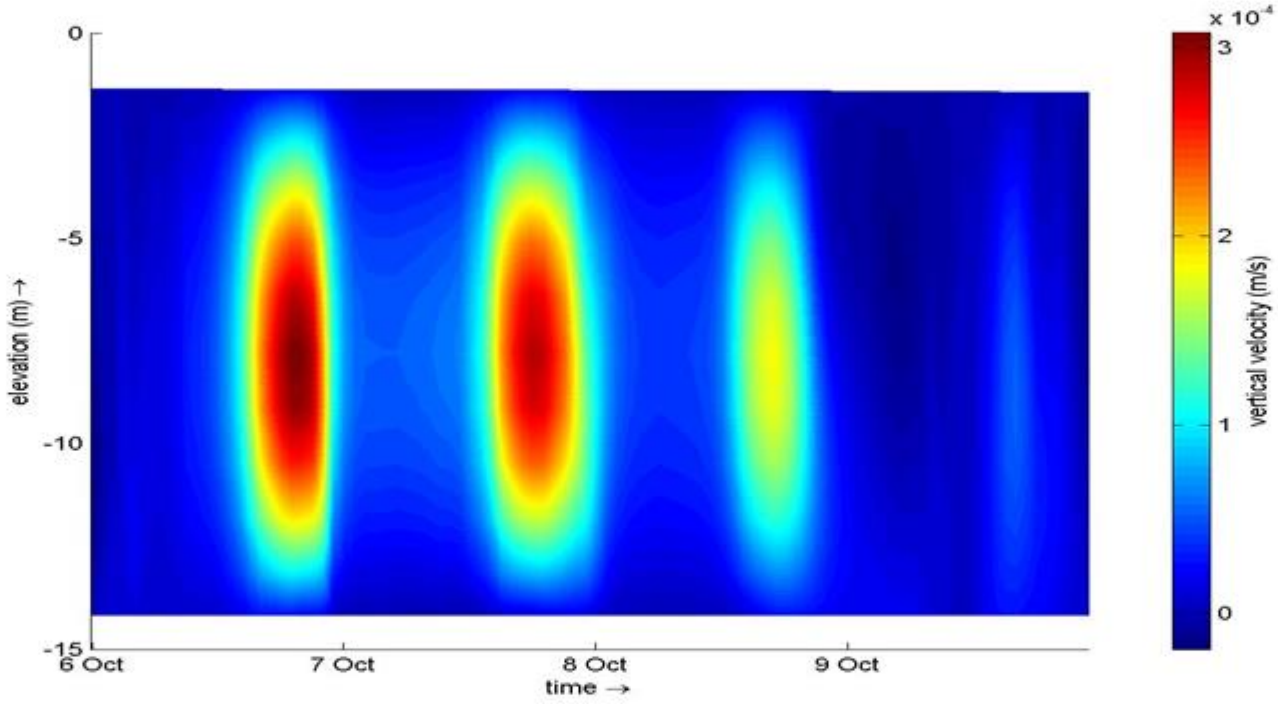

Figure 9. Billings' modeled vertical velocity.

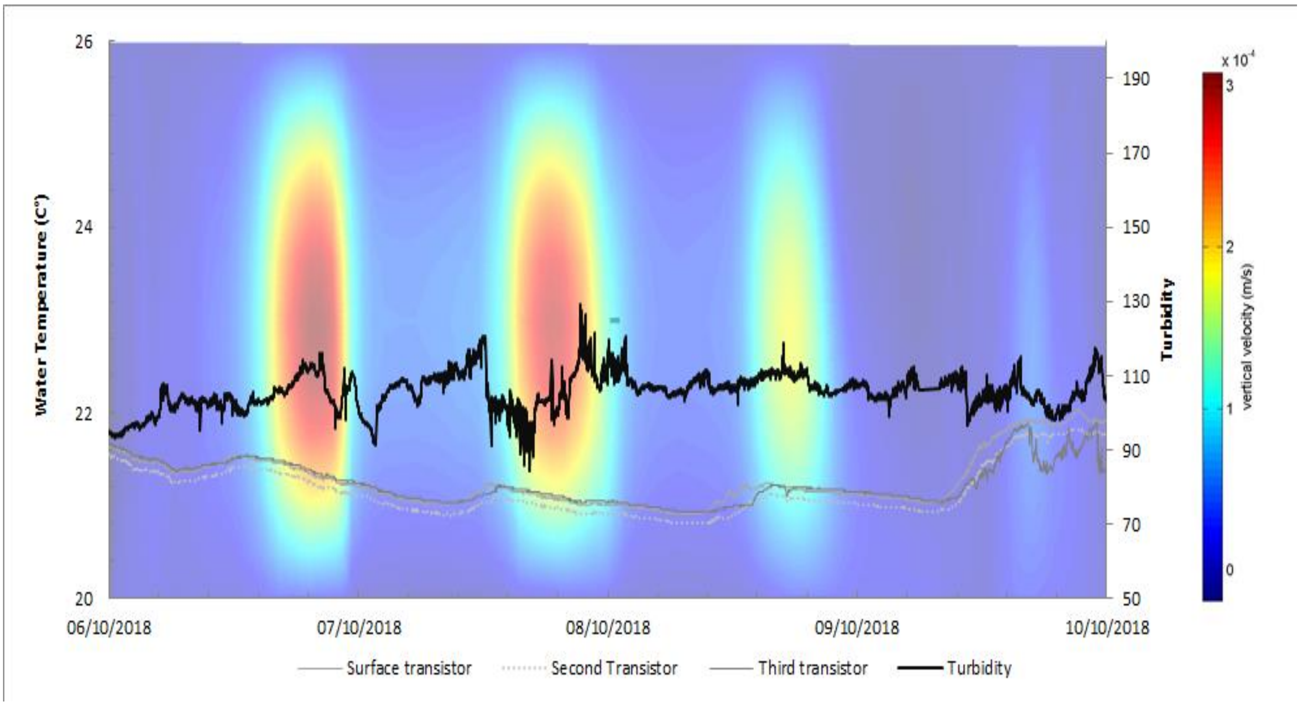

Figure 10. Billings' turbidity measures related to the modeled vertical velocity and water temperature profile.

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4 CONCLUSIONS

The goal of this research was to study the mixing episodes and evaluated its effects in the water turbidity, assuming that this velocity increment close to the bottom layer is capable to form an upward flux big enough to re-suspend bed material and increase the water turbidity. Two tropical lakes were used to investigate this hypothesis, one small and located in a preserve area and another one that is the biggest of the metropolitan region of São Paulo, Brazil.

In both lakes, climate and water physical variables were monitored, especially the water turbidity, that was used as the index to evaluate variations on the water clarity in mixing events. The turbidity data was analyzed with the water temperatures profiles measures, making possible to understand its behavior on mixing moments. Turbidity measurements showed peaks of variation when the mixing event occur and the more intense and lasting the previous stratification period was, higher is the upward velocity generated.

The hydrodynamic simulations results confirm the field observations and calculate peaks of vertical velocities matching with the mixing events. The peaks vary between 6x10-4 m.s-1 and 2x10-4 m.s-1, which according to literature is big enough to move bed materials, this means that mixing events can bring on surface all kind of materials that were accumulated on the bottom of the lakes.

Be capable of understand, forecast and prevent re-suspension episodes on polluted environmental can be crucial to maintain the water quality on reservoirs that are the used as water source for cities, avoiding algae blooming harmful events. In this field lies the main contribution of this study, that proves that water column mixing events are correlated with the increase of the water turbidity, indicating that the vertical velocity created by this phenomenon is can re-suspend bed material.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of CAPES - Agency for the improvement of Higher Level Education (Brazil) and program CAPES/ANA – National Water Agency (BRAZIL) for the support trough project MOMA)- Monitoring and Modelling Water Sources; ICMBio –Institute for Biodiversity Conservation (Brazil) and The Hydraulics Tech Center Foundation FCTH/USP.

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