Total volatile solids may aid in trophic state assessment in subtropical reservoirs

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ABSTRACT

Brazilian artificial reservoirs are multi-purpose systems of great importance for the community since they are used for drinking water supply, energy generation and agricultural irrigation. Anthropogenic eutrophication is an environmental problem of special concern because it can restrict water use due to aquatic systems deterioration. Therefore, trophic state prediction is an important tool for the rapid detection of water quality decrease and the identification of priority areas where action is needed. Within this context, the aim of this research was to assess the role of TVS (total volatile solids) in predicting the trophic status of subtropical reservoirs. To achieve this goal, four stations in the Itupararanga Reservoir (São Paulo State, Brazil) were sampled during dry, intermediate and rainy periods to determine total suspended solids concentrations in different depths of the water column, in addition to other variables (e.g. phosphorus, nitrogen, chlorophyll-a). Through a linear regression between TSI (trophic state index) and the TVS concentrations, an equation relating these two variables was generated ($R^2 = 0.67$). New TSI values (named $TS_{calc}$) were calculated and analyzed against the observed ones (TSI$_{obs}$, determined through the total phosphorus and chlorophyll-a concentrations). The results suggested that TVS may be considered an interesting variable to predict the trophic state of subtropical reservoirs.

Key words | eutrophication, total suspended solids, water resources management, watershed monitoring

INTRODUCTION

Background

The prediction of the trophic state of an aquatic system has become an area of great interest in recent years since eutrophication can affect the multiple uses of water resources, thus playing a negative role not only in the environment, but also in the community and the economy. Therefore, water monitoring programs must include practical plans and suitable sampling schemes for the reliable assessment of the eutrophication process within the studied aquatic system and for the rapid detection of priority areas where action is needed.

Some research has focused on identifying trophic state seasonal patterns, ranking eutrophication driving factors and building models for explaining the process dynamics (e.g. Jones et al. (2003) for South Korean reservoirs; Fragoso et al. (2008) for a Brazilian lake; Tavernini et al. (2009) for Italian lakes; Wu et al. (2009) for a Chinese reservoir; Karadzic et al. (2010) for Serbian reservoirs). An & Park (2003) showed that the use of trophic state indices (TSIs) whose calculation is performed only with nutrients may overestimate the trophic conditions. Nevertheless, there is a need to find trophic state indicators with some desirable attributes such as easy quantification, rapid determination and, of course, a direct correlation with the trophic level of the aquatic environment. This is extremely important especially for developing countries, which typically have a lack of financial means for the environmental monitoring of reservoirs.

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Suspended solids (SS) may be related to water quality deterioration (Kronvang et al. 2003; Owens et al. 2005; Bilotta & Brazier 2008). Increasing SS concentrations normally imply social, economic and environmental problems such as: absorption and subsequent release of contaminants to the water column; decrease of storage capacity volume of reservoirs (e.g. due to siltation – increased concentration of suspended sediments and their undesirable accumulation at the bottom of the water column); ecological degradation; and increase in costs of water treatment.

The aim of this research was to analyze the compartmentalization of the Itupararanga Reservoir in relation to some water quality variables and assess the role of total suspended solids (TSS) concentrations and the volatile (TVS) and fixed or non-volatile (TFS) fractions for predicting the trophic state of subtropical aquatic systems. This was possible through the study of some eutrophication-related water variables in the Itupararanga Reservoir (São Paulo State, Brazil), which was assessed as the case study, and their relation and coupling with the solids concentrations in the water column.

The case study: the Itupararanga Reservoir (Brazil)

The Itupararanga reservoir is located in Sorocaba River Basin and its catchment drains eight cities, all of them in the São Paulo State, Brazil (Figure 1). The reservoir was built to produce hydroelectric power and is owned by the energy company Votorantim Energia. The geographic coordinates of the dam are 23°36’55”S and 47°23’25”W, characterizing a subtropical climate with dry winters and wet summers.

Nowadays, the reservoir has multiple purposes since recreational uses and exploitation of this resource for irrigation and human consumption take place within the aquatic system. The main land uses within the area influenced by the reservoir are horticulture, pasture and urban agglomerations (Queiroz & Imai 2007). The São Paulo State Environmental Agency, CETESB (2008), has reported water quality deterioration in recent years mainly due to the lack of adequate domestic wastewater treatment.

The stations monitored in this study (Figure 1) were chosen because they represent the reservoir spatial dynamics as described by Thornton et al. (1990). According to these authors, the main ecosystem processes (e.g. transport, sedimentation and biological production) produce gradients in physical, chemical and biological variables within three general regions in reservoirs: the Riverine Zone, Transitional Zone and Lacustrine Zone. The general characteristics and also the geographic coordinates of each station are presented in Table 1.

Due to the fact that the system is a multiple use reservoir, its morphometric features and the main water uses are described as these characteristics control many ecological and physical characteristics of the system, thus directly affecting physical, chemical and biological water variables (Table 2).

MATERIAL AND METHODS

The samplings in the Itupararanga Reservoir were performed in August, October and December 2009, which were dry (D), intermediate (I) and rainy (R) periods with 57, 135 and 259 mm of rainfall, respectively. The water level in the year 2009 begun at 821.5 m in January, with a peak in April of 824.0 m, and in the sampled months the levels were 823.7 m in August, 823.1 m in October and 823.7 m in December.

Samples were collected in August (10th to 13th), October (19th to 22nd) and December (15th to 17th) at different depths of the water column through a van Dorn sampler, corresponding to subsurface, 75, 50, 25 and 1% of PAR (photosynthetically active radiation), in addition to the aphotic zone. Water temperature (T) and dissolved oxygen (DO) were determined at these same depths through a Multiparameter Water Quality Probe (YSI 556®). PAR was measured through a radiometer (Quantameter Ly-Cor®). TSS, total volatile solids (TVS), total fixed solids (TFS), total phosphorus (TP), total nitrogen (TN) and nitrate (NO₃) were determined through the methods described by APHA (2005). Chlorophyll-a (Chl-a) determination in turn followed the recommendations of Nusch (1980), through ethanol extraction.

Specifically regarding the determination of TSS, the procedure was conducted through the following steps. First, a known volume (between 200 and 500 mL) of the sample (v)
was filtered in a GFC Whatman® glass-fiber filter (whose mass had been previously measured, named ‘\( P_0 \)’). Then, the filter mass was determined again (\( P_1 \)) after a period of 1 hour in an oven (100 °C). Finally, the filter was ignited for 15 min in a furnace (550 °C) and the respective mass was measured one more time (\( P_2 \)). The concentrations of TSS, TFS and TVS were calculated with Equations (1)–(3), respectively.

\[
\text{TSS} = \frac{P_1 - P_0}{\nu}
\]

(1)

Figure 1 | Location of the study area: Brazil, São Paulo State, the most important cities, the Itupararanga Reservoir and the sampled sites (S1, S2, S3 and S4). Adapted from Marciano (2001).
TFS = \frac{P_2 - P_0}{v} \quad (2)

TVS = TSS - TFS \quad (3)

TSI (TI_{obs} - the subscript ‘obs’ means ‘observed’) was determined for each water sample with TP and Chl_a concentrations, following Equation (4), proposed by Carlson (1977) and modified by Lamparelli (2004) for subtropical reservoirs. According to the TSI result, the water trophic level was classified as (Lamparelli 2004): ultraoligotrophic (TSI < 47), oligotrophic (47 < TSI < 52), mesotrophic (52 < TSI < 59), eutrophic (59 < TSI < 63), supereutrophic (63 < TSI < 67) or hypereutrophic (TSI > 67).

\[
TSI = \frac{TI(Chl_a) + TI(TP)}{2} \quad (4)
\]

where:

\[
TI(Chl_a) = 10 \left[ 6 - \frac{0.92 - 0.34 \ln Chl_a}{\ln 2} \right]
\]

\[
TI(TP) = 10 \left[ 6 - \frac{1.77 - 0.42 \ln TP}{\ln 2} \right]
\]

TP: total phosphorus concentration (μg L⁻¹), Chl_a: chlorophyll-a concentration (μg L⁻¹).

The TSI was calculated for each sampled depth and for all the sampling stations. Correlation matrices were built with Excel for Windows® to verify the correlation strength between the indices [TSI, TSI (TP), TSI (Chl_a)] and the solids (TSS, TVS and TFS). The mean TSI values were used to verify the relationship significance between them and the volatile solids concentrations. Thereafter, the mean values of TSI and TVS were plotted in a dispersion graph because these variables together presented high correlation coefficients and a regression equation was determined. Finally a classification of trophic status according to TVS concentrations was proposed for the Itupararanga Reservoir through the upper limits for each level.
RESULTS

Spatial heterogeneity and temporal variability were observed in the Itupararanga Reservoir. Water temperature oscillated according to the seasons of the year and was lower in the winter and higher in the summer. Moreover, DO concentrations increased from S1 to S4 (e.g. in December 2009, the concentrations ranged from 1.4 to 6.5 mg L\(^{-1}\)) and presented temporal variation as well, since the maximum values were found in August 2009 (Table 3).

The TSS concentrations presented a pattern of decrease from S1 to S4, varying between 7.8–9.7 mg L\(^{-1}\) (S1) and 3.7–5.6 mg L\(^{-1}\) (S4). In general, nutrient concentrations (TP, TN and NO\(_3\)) were also higher at S1 (e.g. TP: 72.7, 73.4 and 77.8 μg L\(^{-1}\), respectively in the dry, intermediate and rainy periods) than at S4 (e.g. TP: 35.6, 21.2 and 25.4 μg L\(^{-1}\), respectively). Chl\(_a\) concentrations in turn were higher at S1 than at the other stations in August (mean of 31.8 μg L\(^{-1}\) at S1), although this pattern was the opposite in the intermediate and rainy periods (Table 3).

The correlation matrices between the TSIs and the solids concentrations in August, October and December 2009 suggested that the relationship between TSI\(_{\text{obs}}\) and TSS, for example, was higher in the dry period (0.63) than in the other samplings. As a general rule for the three samplings in the Itupararanga Reservoir, the best relationship was found between TSI\(_{\text{obs}}\) and the TVS (0.73, 0.57 and 0.40, respectively for August, October and December).

The values of TSI\(_{\text{obs}}\) were plotted against the TVS concentrations and a linear regression for correlation was obtained (Figure 2), presenting a reasonable R\(^2\) of 0.67. This correlation resulted in an equation of TSI\(_{\text{calc}}\) as a function of TVS, which was used to calculate TSI\(_{\text{calc}}\).

In Figure 3, both TSI\(_{\text{obs}}\) and TSI\(_{\text{calc}}\) were plotted for each station in the three analyzed periods (dry, intermediate and rainy). In general, the reservoir presented a mesotrophic level, with peaks of eutrophic level (TSI higher than 59) in S1 and S4 during the dry season, according to TSI\(_{\text{obs}}\). Also during the dry season, the TSI\(_{\text{obs}}\) increase from S2 to S4 may be partially explained by the agricultural runoff and the associated nutrient inputs to the water body.

Considering that TSI\(_{\text{calc}}\) presented a desirable prediction capacity, a trophic classification could be determined according to the TVS concentrations. Due to the relative low capacity to indicate the extreme TSI values, the ultraoligotrophic, oligotrophic and mesotrophic levels were grouped in the same TVS interval, as observed in Table 4.

Therefore, TVS concentrations lower than 4.4 mg L\(^{-1}\) reflected a condition of ultraoligotrophy, oligotrophy or mesotrophy. In addition, the other levels were associated with higher concentrations and the respective upper limits for eutrophic and supereutrophic status were 7.4 and 10.4 mg L\(^{-1}\).

### Table 3

<table>
<thead>
<tr>
<th>Period</th>
<th>Station</th>
<th>(T) (°C)</th>
<th>DO (mg L(^{-1}))</th>
<th>TSS (mg L(^{-1}))</th>
<th>TP (μg L(^{-1}))</th>
<th>TN (mg L(^{-1}))</th>
<th>NO(_3) (mg L(^{-1}))</th>
<th>Chl (_a) (μg L(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>August 2009</strong></td>
<td>S1</td>
<td>18.56 ± 0.38</td>
<td>6.33 ± 1.60</td>
<td>9.29 ± 2.51</td>
<td>73.83 ± 14.59</td>
<td>0.05 ± 0.09</td>
<td>0.84 ± 0.01</td>
<td>31.8 ± 16.12</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>17.61 ± 0.39</td>
<td>7.14 ± 1.75</td>
<td>3.62 ± 0.81</td>
<td>44.41 ± 12.92</td>
<td>0.10 ± 0.10</td>
<td>0.60 ± 0.01</td>
<td>15.3 ± 6.59</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>17.72 ± 0.25</td>
<td>7.83 ± 1.47</td>
<td>3.50 ± 0.30</td>
<td>44.71 ± 20.11</td>
<td>0.06 ± 0.09</td>
<td>0.44 ± 0.02</td>
<td>17.3 ± 2.77</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>17.90 ± 0.31</td>
<td>8.57 ± 0.78</td>
<td>3.92 ± 0.80</td>
<td>33.62 ± 10.79</td>
<td>0.01 ± 0.10</td>
<td>0.42 ± 0.01</td>
<td>29.8 ± 8.73</td>
</tr>
<tr>
<td><strong>October 2009</strong></td>
<td>S1</td>
<td>19.96 ± 0.01</td>
<td>1.79 ± 0.14</td>
<td>9.74 ± 0.50</td>
<td>73.44 ± 1.68</td>
<td>0.04 ± 0.05</td>
<td>0.90 ± 0.04</td>
<td>1.8 ± 0.44</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>20.38 ± 0.67</td>
<td>7.86 ± 1.93</td>
<td>4.69 ± 0.63</td>
<td>22.32 ± 3.12</td>
<td>0.04 ± 0.05</td>
<td>0.55 ± 0.01</td>
<td>17.5 ± 3.22</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>20.28 ± 0.62</td>
<td>7.42 ± 2.47</td>
<td>2.78 ± 0.38</td>
<td>24.92 ± 6.39</td>
<td>0.03 ± 0.03</td>
<td>0.48 ± 0.02</td>
<td>8.8 ± 1.70</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>20.22 ± 0.37</td>
<td>7.63 ± 1.22</td>
<td>5.65 ± 0.25</td>
<td>21.38 ± 3.80</td>
<td>0.02 ± 0.04</td>
<td>0.44 ± 0.02</td>
<td>14.8 ± 1.51</td>
</tr>
<tr>
<td><strong>December 2009</strong></td>
<td>S1</td>
<td>21.39 ± 0.13</td>
<td>1.42 ± 0.39</td>
<td>7.80 ± 0.38</td>
<td>77.85 ± 14.64</td>
<td>0.07 ± 0.03</td>
<td>0.67 ± 0.34</td>
<td>7.3 ± 0.39</td>
</tr>
<tr>
<td></td>
<td>S2</td>
<td>23.23 ± 0.22</td>
<td>5.66 ± 2.04</td>
<td>4.63 ± 0.34</td>
<td>38.78 ± 7.50</td>
<td>0.05 ± 0.03</td>
<td>0.70 ± 0.01</td>
<td>14.1 ± 3.76</td>
</tr>
<tr>
<td></td>
<td>S3</td>
<td>23.28 ± 0.56</td>
<td>5.40 ± 1.84</td>
<td>2.88 ± 0.22</td>
<td>29.92 ± 11.09</td>
<td>0.02 ± 0.04</td>
<td>0.60 ± 0.10</td>
<td>15.5 ± 2.97</td>
</tr>
<tr>
<td></td>
<td>S4</td>
<td>23.44 ± 0.81</td>
<td>6.53 ± 1.95</td>
<td>4.28 ± 0.42</td>
<td>25.41 ± 7.58</td>
<td>0.06 ± 0.05</td>
<td>0.86 ± 0.94</td>
<td>15.8 ± 1.87</td>
</tr>
</tbody>
</table>
DISCUSSION

By analyzing the water quality results in the Itupararanga Reservoir, clear compartmentalization among the sampling stations was observed, since gradients for these variables applied from the riverine to the lacustrine zone. The TSS spatial dynamics, for example, were probably related with the sedimentation process, more intense in the headwater of the reservoir, as observed by Figueiredo & Bianchini Jr. (2008) in a Brazilian reservoir.
The reasonable $R$-squared derived from the linear regression between TSI$_{obs}$ and TVS may be explained because the TVS concentrations are directly linked with the biomass growth and the phytoplankton community structure, which are in turn the main indicators of trophic state in aquatic environments. Xu et al. (2009) studied the seasonal variation of SS in a Chinese subtropical reservoir (Three-Gorges Reservoir). The authors concluded that the water residence time (a hydrological feature) played an important role in the seasonal patterns of TSS and TVS concentrations within the reservoir central axis (mainstream). Nevertheless, within a branch of this Chinese reservoir, TVS concentrations presented a stronger correlation with algal biomass, reflecting a more autochthonous system than the mainstream.

In the case of the Itupararanga Reservoir, the correlation matrices analysis suggested that TVS concentrations, rather than the TFS, would be useful indicators and predictors of the trophic state. This indicated that internal processes are probably more important than hydrological features in the studied system regarding the solids dynamics. For this reason, the focus of this research was to perform further explorations of the relationship between these two variables, TSI$_{obs}$ and TVS.

Comparing the values plotted in Figure 3 (TSI$_{obs}$ and TSI$_{calc}$), the TSI$_{calc}$ did not indicate the peak in S4_D although it presented approximate values for the other stations and periods. The TSI$_{calc}$ showed a relevant potential to predict the trophic level of the Itupararanga reservoir, although some restrictions for predicting the highest variations in TSI apply. As was expected for a linear regression, the curve for TSI$_{calc}$ was smoother than that for TSI$_{obs}$.

The determination of local boundaries for TVS concentrations seemed to be useful for rapid trophic state assessment of the Itupararanga Reservoir. Our study indicates that it is possible to predict (with almost 70% certainty) the trophic state of the studied aquatic ecosystem based on TVS concentrations, which are easy and simple to determine. The next steps should focus on applying this methodology to other aquatic systems within the watershed and trying to build a regional classification of trophic status based on volatile solids concentrations.

**CONCLUSIONS**

TVS may be considered an interesting variable to predict the trophic state of subtropical reservoirs. This was verified in the Itupararanga Reservoir, since the linear regression highlighted the significant relationship between TVS concentrations and the TSI. The agreement involving the solids concentrations and the trophic level reflected the influence of land use patterns over the eutrophication-related water variables. In the case of the Itupararanga Reservoir, the tributary rivers contribution (point source) as well as the role of agricultural runoff certainly induced the spatial heterogeneity and the temporal variation of the studied water variables and the consequent response in terms of trophic state.

The trophic state may be reasonably assessed with TVS concentrations. This may be particularly interesting in regions where TP and Chl$\alpha$ analyses are difficult to perform. The next steps and further research should include the assessment of these relationships in other aquatic systems, not only in subtropical but also in temperate ones.

Moreover, establishing TVS boundaries for trophic state in a regional context (e.g. for the watershed management unit) would certainly contribute to monitoring the water resources and detecting areas of special concern in terms of water quality and vulnerability to eutrophication. The methodology proposed by this research is available for this purpose.

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