Long-term monitoring and proposed diffuse pollution control of a tropical reservoir

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Abstract This paper presents the results of 30 years of water quality monitoring in a tropical water supply reservoir (Vargem das Flores, Brazil). This water body is subjected to eutrophication problems caused by point sources (discharge of untreated sewage) and diffuse pollution (agricultural use in the drainage basin). Emphasis is given here on the estimation of nutrient loads and on the study of the N/P ratio in the water body. In spite of the prevalence of high N/P values, there is a clear trend in the dominance of cyanobacteria in the phytoplankton, which contradicts results from research in temperate aquatic environments. Some restoration measures for Vargem das Flores Reservoir are currently being implemented: construction of wastewater treatment plants, control of recreational activities, erosion control by hydroseeding and use of natural wetlands. Finally some management strategies in order to prevent algae input in the water abstraction system are discussed. Examples of these techniques are the installation of plastic barriers and the construction of an air curtain device.

Keywords Diffuse pollution; monitoring; N/P relationship; restoration measures; tropical reservoirs

Introduction

Long-term monitoring of aquatic systems forms the basis for the knowledge of their structure and function and for the implementation of corresponding restoration measures. However most of the published papers regarding tropical lentic systems cover only short periods of monitoring, hence restricting a desirable generalization of the results. Due to high water temperatures, these aquatic systems present quite specific characteristics, such as an enhanced dynamics in all metabolical processes. Moreover most tropical lakes and reservoirs are situated in developing countries, where there is a chronic lack of financial resources for the establishment of consistent monitoring programs. This paper describes the results of three decades of water quality monitoring in a Brazilian tropic reservoir, with emphasis on the implementation of preventive and corrective restoration measures in order to combat diffuse pollution.

Research about spatial and temporal variables developed in Brazilian aquatic systems is still very restricted and is directed to quite particular situations. In tropical climates, whose characteristics do not follow well defined criteria, natural resources are rather controlled by pulses than by regular variations. Brazilian dams, mostly constructed for water supply and energy generation, present quite typical trophic variables, which depend on operational factors and on the occupation of the drainage basin. Nevertheless it is absolutely necessary to know the functioning of the system. The availability of data and practical resources led to the choice of Vargem das Flores Reservoir as the object of this research.

Characteristics of tropical reservoirs

The main characteristics of tropical lakes are summarized below (von Sperling, 1996):

- Intense solar radiation and high water temperatures accelerate nutrient uptake by the algae

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Phytoplanktonic population peaks are less frequent in comparison with temperate aquatic environments. High nutrient assimilation capacity, associated with high recycling rates, lead to the prevalence of an intense degree of productivity. Nutrient concentrations are generally low; as a consequence many water bodies can be classified as oligotrophic in spite of their high productivity. There is a frequent occurrence of low phytoplankton densities, which are however associated with high growth rates. High mineralization rates lead to an accelerated oxygen depletion and to the formation of sediments that are poor in organic matter; consequently there is no direct connection between hypolimnetic oxygen deficit or content of organic matter in the sediment and the productivity of the water body.

Methods
Vargem das Flores Reservoir is located close to the city of Belo Horizonte, Brazil. It has a surface area of 5.5 km², a volume of 0.044 km³ and a maximum depth of 23 m. The main uses of the water body are human and industrial supply, as well as recreational activities.

Since the filling of the reservoir, in the year 1973, a broad monitoring program (monthly frequency, eight sampling points, three depths) has been carried out, covering over 30 parameters. The evaluation of the water quality in the period 1973–2003 was the subject of PhD research conducted at the Department of Sanitary and Environmental Engineering of the Federal University of Minas Gerais.

Local climate presents two well defined periods: rainy season (October to March) and dry season (April to September), with an average yearly precipitation of 1500 mm. Air relative humidity ranges from 65% (August and September) to 80% (December), with an insolation average value of 2600 hours/year.

Figure 1 depicts the watershed of the reservoir and the location of the eight sampling points. The main morphometric features of the water body are presented in Table 1. Some information about the functioning of the aquatic system can be extracted from the morphometric data (Håkanson, 1981). Since the relative depth (ratio between maximum depth and mean diameter, i.e. diameter of a circle that has the same area as the...
lake) is low, vertical circulations of the water body can be performed without further difficulties, hence indicating the holomitic character of the reservoir. The high value of the shoreline development (ratio between shoreline length and the perimeter of a circle that has the same area as the lake) points out the morphometric irregularity of the reservoir, which is consistently dendritic. The volume development (ratio between lake volume and the volume of a cone whose area corresponds to lake area and whose height is equal to maximum depth) close to the unity indicates a V-shape of the reservoir. Finally the areal ratio (relationship between area of drainage basin and lake area) is relatively low, which theoretically should minimize the potential effects of diffuse pollution.

Results and discussion

Main physico-chemical and hydrobiological results

Vargem das Flores Reservoir is strongly stratified for most of the year with deep mixing occurring once during the middle of the cool, dry season (June to August). According to the thermal structure the reservoir is a warm monomitic aquatic system. This feature leads to the formation of an anoxic hypolimnion and to the onset of internal fertilization processes.

Average values of the most relevant water quality parameters, obtained from the 30-year monitoring program are given below:

- Secchi depth: in the range 0.8–2.3 m; higher values in the winter period (generally from July to September)
- Dissolved oxygen: higher in the winter period due to enhanced gas dissolution; epilimnion: 6–7.5 mg/L; metalimnion: 3–7 mg/L; hypolimnion: 1–4 mg/L
- pH: surface: 7–8; bottom: 6.5–7.5
- Turbidity: surface: 3–20 NTU; bottom: 3–100 NTU; seasonal variations, with lowest values in April, highest values in the rainy season (November to March); homogeneity during circulation
- COD: surface: 2–25 mg/L; bottom: 2–15 mg/L; parameter with low spatial variations
- Fe: surface: 0.1–3 mg/L; bottom: 0.1–9 mg/L (resuspension during circulation period)
- Total phosphate (PO₄): surface: 0.01–0.2 mg/L; bottom: 0.01–0.35 mg/L; resuspension during circulation; higher values in cold periods, due to reduced phytoplankton assimilation
- Ammonium nitrogen (N-NH₄): surface: 0.1–1 mg/L; bottom: 0.1–2 mg/L
- Nitrate nitrogen (N-NO₃): surface: around 0.01 mg/L; bottom: 0.05–0.4 mg/L
- Phytoplankton density: 100–4000 org/mL
- Chlorophyll a: 2–11 μg/L

Point source pollution

Contamination of Vargem das Flores Reservoir is caused, in large scale, by the discharge of untreated sewage in the tributaries of the water body. The most important corrective measure currently in course is the construction of wastewater treatment plants (activated sludge and anaerobic digestion).
Diffuse pollution

Non-point sources in Vargem das Flores Reservoir are originated from run-off of urban areas, forest coverage and agricultural use in the drainage basin. Calculations made with conventional export coefficients gave the results presented in Table 2.

It can be seen from Table 2 that the relationship between N-load and P-load ranges from 7 to 19, with an average value of 10. High nutrients concentrations are responsible for frequent algae blooms, especially from cyanobacteria, which may excrete toxic metabolites. There is a deep concern about this problem, since Brazil was the first country in the world to register human deaths caused by the ingestion of cyanoprocaryota toxins (Azevedo et al., 1996; Carmichael et al., 2001). Table 3 presents N/P ratios in 3 periods of the monitoring program: period I stretches from the time of dam construction until the implementation of local regulations concerning soil use; period II refers to the time of installation of water distribution systems in the sub-basins of direct contribution to the lake and period III, the most recent one, reflects the effects of sewer construction in the watershed.

Generally, in tropical climates eutrophic waters are N-limited while oligotrophic waters are P-limited (Ryding and Rast, 1989). Reasons for N-limitation in polluted tropical waters are sewage discharge (low N/P), denitrification (N lost from the bottom of the lake) and P-release from sediment (internal fertilization, with consequent decrease of N/P). On the other hand further processes, such as nutrient excretion by zooplankton and metabolism of algae and bacteria) can significantly change N/P values. Research carried out in a tropical urban reservoir (Pampulha Lake, Brazil) has shown a clear increase in N/P ratios proportional to the distance from sewage discharge, i.e. in this case phosphorus was becoming progressively limited. (Pinto-Coelho et al., 2003).

Some information can be obtained from Table 3: the highest N/P values are consistently registered in July (middle of the dry season, when the lake is circulating), while the lowest ones are found in March/April, following the rainy period. The limnological explanation of this pattern is probably the larger phosphorus assimilation by the algae in periods of higher water transparency, which happens in the winter time. There is also a marked increase in N/P values during phase III, indicating a stronger phosphorus assimilation over the time. The results show that, in recent times, phosphorus plays the role of a limiting nutrient. This feature should avoid the dominance of cyanobacteria, as extensively reported in the technical literature (Forsberg and Ryding, 1979; Shapiro, 1990, 1997; Cooke et al., 1993; Chorus and Bartram, 1999). However an opposite trend has been registered in Vargem das Flores Reservoir, where blooms of Microcystis aeruginosa and Cylindrospermopsis raciborskii could not be coupled with low N/P ratios. Research at Salto Grande Reservoir, Brazil (Deberdt, 2002) has also shown a reverse trend to the conventional assumption, i.e. cyanobacteria growth has been registered under conditions of high N/P. This means that other factors (grazing, sedimentation) may be involved in the complex relationship between N/P values and cyanobacterial blooms. Moreover it should be observed that high N/P values do not necessarily mean phosphorus deficiency. This could indicate high phosphorus recycling rates, which are a frequent issue in tropical aquatic systems.

Management strategies

For the restoration of Vargem das Flores Reservoir some preventive and corrective measures are currently under implementation. Since the point source pollution can be effectively controlled by one single action, i.e. the construction of wastewater treatment plants, especial attention has been dedicated to combating the more complex non-point pollution. Some of the adopted measures include limitation of agricultural use in the
### Table 2 Nutrient loads from diffuse sources

<table>
<thead>
<tr>
<th>Sub-basin</th>
<th>Area (ha)</th>
<th>Total area (ha)</th>
<th>Load (kg/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Water</td>
<td>Forest</td>
<td>Rural</td>
</tr>
<tr>
<td>Creek Betim</td>
<td>75.31</td>
<td>1.41</td>
<td>1.162.84</td>
</tr>
<tr>
<td>Creek M. Redondo</td>
<td>5.53</td>
<td>1.711.54</td>
<td>1.177.12</td>
</tr>
<tr>
<td>Creek Bela Vista</td>
<td>5.03</td>
<td>622.52</td>
<td>395.70</td>
</tr>
<tr>
<td>Creek Água Suja</td>
<td>70.94</td>
<td>1.307.90</td>
<td>699.17</td>
</tr>
<tr>
<td>Creek da Laje</td>
<td>0.32</td>
<td>196.40</td>
<td>114.38</td>
</tr>
<tr>
<td>Creek Batatal</td>
<td>0</td>
<td>125.76</td>
<td>43.65</td>
</tr>
<tr>
<td>Direct contribution</td>
<td>491.25</td>
<td>718.37</td>
<td>322.69</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>648.38</td>
<td>6.096.17</td>
<td>3.915.55</td>
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</tbody>
</table>

### Table 3 N/P ratios

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>I (1973/1992)</td>
<td>0.5 m</td>
<td>118.0</td>
<td>18.8</td>
<td>42.9</td>
<td>0.5</td>
<td>4.4</td>
<td>19.2</td>
<td>89.6</td>
<td>113.9</td>
<td>49.7</td>
<td>43.3</td>
<td>74.2</td>
<td>29.9</td>
</tr>
<tr>
<td></td>
<td>5.0 m</td>
<td>59.0</td>
<td>7.5</td>
<td>5.3</td>
<td>2.5</td>
<td>10.1</td>
<td>5.8</td>
<td>92.3</td>
<td>84.6</td>
<td>43.8</td>
<td>44.7</td>
<td>78.6</td>
<td>28.0</td>
</tr>
<tr>
<td>II (1993/1997)</td>
<td>0.5 m</td>
<td>49.0</td>
<td>42.0</td>
<td>49.8</td>
<td>12.9</td>
<td>16.7</td>
<td>70.9</td>
<td>85.3</td>
<td>77.5</td>
<td>66.8</td>
<td>64.2</td>
<td>57.6</td>
<td>49.8</td>
</tr>
<tr>
<td></td>
<td>5.0 m</td>
<td>58.0</td>
<td>40.4</td>
<td>47.1</td>
<td>43.9</td>
<td>29.1</td>
<td>26.0</td>
<td>108.5</td>
<td>76.4</td>
<td>66.8</td>
<td>110.7</td>
<td>67.5</td>
<td>55.4</td>
</tr>
<tr>
<td>III (1998/2002)</td>
<td>0.5 m</td>
<td>174.0</td>
<td>132.9</td>
<td>44.3</td>
<td>143.9</td>
<td>232.5</td>
<td>243.6</td>
<td>343.2</td>
<td>155.0</td>
<td>265.7</td>
<td>298.9</td>
<td>258.0</td>
<td>215.9</td>
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<tr>
<td></td>
<td>5.0 m</td>
<td>197.0</td>
<td>171.1</td>
<td>50.0</td>
<td>91.9</td>
<td>143.9</td>
<td>223.8</td>
<td>378.4</td>
<td>167.7</td>
<td>256.3</td>
<td>255.8</td>
<td>236.6</td>
<td>216.4</td>
</tr>
</tbody>
</table>
watershed (through the enforcement of current legal determinations), control of recreational activities (by limiting the number of visitors and by introducing a strong movement of environmental education), erosion control by hydroseeding (at the steeper slopes of the drainage basin) and use of natural wetlands. Moreover specific techniques are now being tested in order to avoid algae input in the water abstraction tower: the installation of plastic barriers, similar to those used for oil pollution control and the construction of an air curtain device, which should also prevent phytoplankton from reaching the abstraction point.

Conclusions
The results of 30 years of monitoring in Vargem das Flores Reservoir show an increased deterioration of the water quality over that time. The reasons for this behaviour can be summarized as the existence of point sources of pollution (sewage discharge), as well as diffuse sources (agricultural and recreational uses, run-off from urban areas). Cyanobacteria blooms occur frequently in the water body, leading to a serious concern about the production of toxic metabolites. The dominance of cyanobacteria is not coupled with low N/P values, as is usually assumed in the technical literature. The implementation of preventive and corrective techniques should drastically change the current situation.

References