A novel integrated concept of urban water management in a megalopolis from Latin America (São Paulo, Brazil): risk or opportunity?

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Abstract

Urban water management is a challenge for developing countries because population increase is not accompanied by sanitation improvement. We assessed the feasibility study of an *in situ* flotation pilot system ($10 m^3/s$) in a polluted river in São Paulo (the treated water was pumped to a multipurpose reservoir). We quantified 148 water variables (>200,000 analyses) in 11 sites (Aug/07-Mar/10). The study was favored by the high treated flow and laboratory data availability, but operational interruptions for maintenance occurred. Quantitatively speaking, the water pumped to the reservoir supported energy generation and human supply. However, the water quality was affected by the affluent treated water. Our project is an interesting approach because: *in situ* technologies are adequate for areas with no space for *ex situ* treatment facilities; the integrated concept attempts to explore urban waters as resources for human activities; further research may find alternatives to solve the detected inefficiencies.

Keywords

Developing countries; management; *in situ* treatment; urban areas; water quality.

INTRODUCTION

Urban water management is a challenge task worldwide and especially in developing countries, which are normally characterized by rapid population increase and sudden shifts in land use, lack of sanitation infrastructure facilities and inadequate disposal of wastewater. Monitoring, management, remediation and revitalization of urban waters are necessary as the impacts over the quantitative and qualitative aspects of the aquatic systems and the conflicts among water users are more likely to occur in such areas (MISERENDINO et al. 2008, VERMONDEN et al. 2009, MISRA 2011). The sustainable development of urban territories thus requires a multidisciplinary approach to explore the urban systems as resources for the anthropogenic activities and needs (i.e. drinking supply, energy generation, irrigation, recreation) and to minimize the risks to the human health and the ecosystems balance.

The selection of water treatment methods must be associated with the specific characteristics of the target area (RIVETT et al., 2002), considering factors related to space and technology availability,

waste management, energy demand and eventual conflicts among land owners, water users and the government sector. Taking into account that the Metropolitan Region of São Paulo (Brazil) has about 20 million inhabitants and high population density, *in situ* water treatment alternatives seemed to be convenient due to the lack of available areas to install off site facilities (CUNHA et al., 2010). Dissolved Air Flotation (DAF) is a widespread technology for water and wastewater treatment (RUBIO et al., 2002) with many specific applications (e.g. treatment of high heavy metals waters and emulsified oil wastes – ZOUBOLIS et al., 2000). The impurities are moved to the upper layers of the water column by tinny air bubbles, with posterior sludge removal. Coagulation (e.g. with ferric chloride or aluminium sulphate) and flocculation are required precedent steps and the overall efficiency of the flotation system depends upon the optimization of such processes (YAN et al., 2008).

We aimed to assess the feasibility of the *in situ* flotation treatment (pilot scale system: 10 m^3/s) of the Pinheiros River, a polluted urban aquatic system located in São Paulo (Brazil), and posterior pumping of the treated water to the Billings Reservoir, a contiguous multipurpose water body. This is a novel approach because: i) to our knowledge, there is no similar system in the world (considering the average treated flow and the integrated concept of the prototype itself); ii) the pumping of the river treated water to the reservoir aimed to enhance the multiple water uses in the latter aquatic system, like energy generation and drinking supply. We conducted a comprehensive monitoring program during 32 months to evaluate the efficiency of the flotation treatment and to analyze eventual impacts over the reservoir water quality in relation to nutrients, organic compounds, metals and pathogens.

MATERIAL & METHODS

Study area

Billings and Guarapiranga Reservoirs are important water sources for the human activities in the Metropolitan Region of São Paulo, Southeastern Brazil (Figure 1). Billings Reservoir was built in 1927 and covers an area of approximately 127 km^2, with the following geographic coordinates: 23º 47’ S e 46º e 40’ W. The main water uses in Billings are drinking (around 1.8 million citizens are supplied) and energy generation (Henry Borden Power Plant; 880 MW is the installed capacity). Accelerated artificial eutrophication and water quality degradation has been described in the recent years, with increasing densities of potentially toxic Cyanobacteria like *Microcystis aeruginosa* (MOSCHINI-CARLOS et al. 2009).

In situ flotation

We assessed a pilot-scale *in situ* flotation system treating the Pinheiros River water (10 m^3/s; the final project would treat 50 m^3/s). The process occurred on the river channel itself through two flotation stations separated by 4 km (Zavuvuz and Pedreira, Figures 1 and 2). Ferric chloride was used as the coagulant (dosages varied between 50 and 400 mg/L; the rapid mixing time was about 30 s) and the flocculation step (slow mixing time ~ 0.5 h) preceded the flotation (whose recycle flow was about 8-10% of the affluent flow). The air bubbles on upward movement joined the colloidal particles of impurities, carrying them to the surface (as sludge). Rotating blades were used for dredging this material accumulated in the upper layers of the water column. A controlled landfill was the sludge final destination.

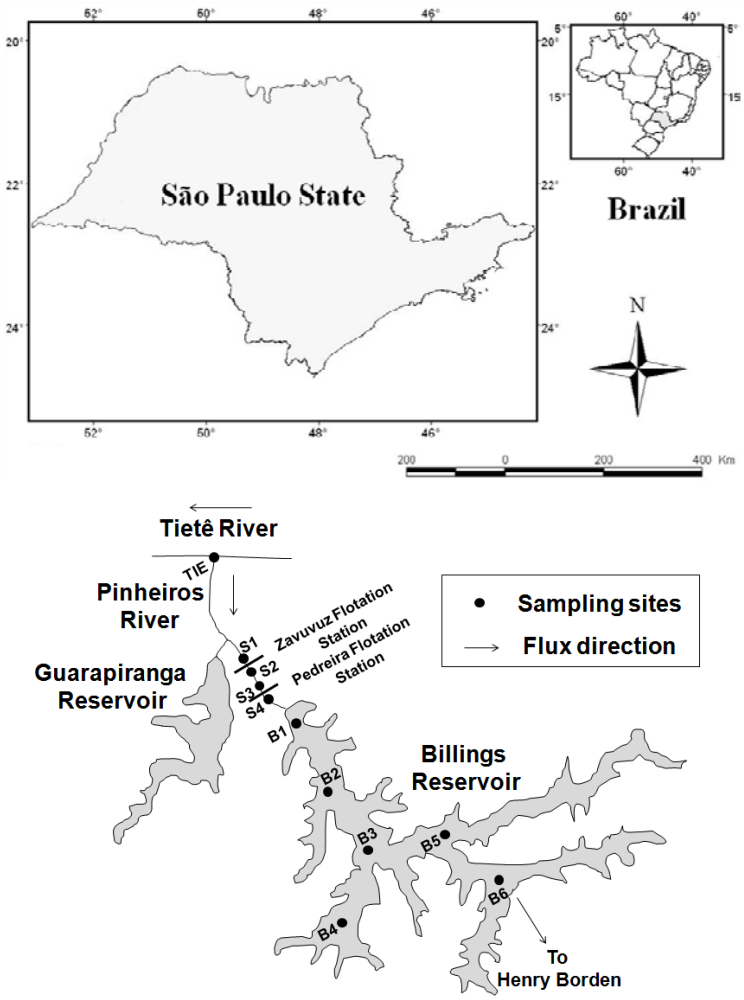

Figure 1: São Paulo State (Southeastern Brazil) and a scheme with Pinheiros River, Guarapiranga Reservoir and Billings Reservoir, including the approximate location of the monitoring sites

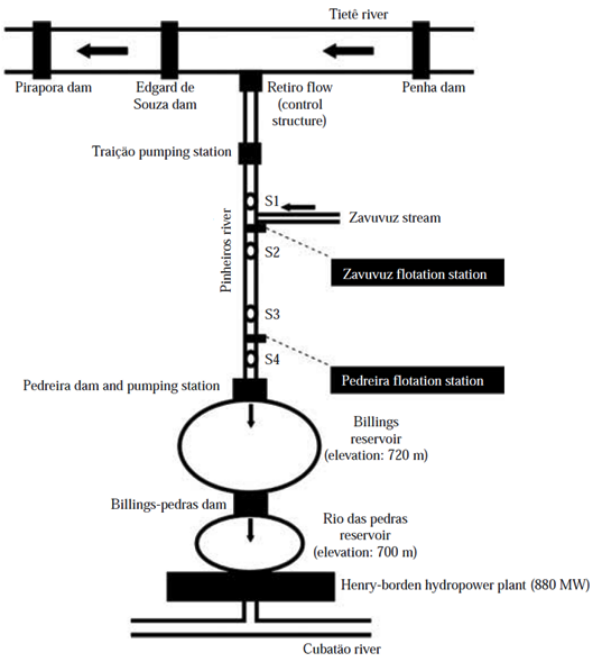

Figure 2: Scheme of the flotation stations in Pinheiros River (Zavuvuz and Pedreira), including the approximate location of the monitoring sites upstream (S1 and S3) and downstream (S2 and S4). Adapted from CUNHA et al. (2010)

Monitoring

We selected 11 monitoring sites (Figures 1 and 2) to evaluate the studied concept of urban water management (one in Tietê River: TIE – the tributary of Pinheiros River; four in Pinheiros River: S1, S2, S3 and S4 – upstream and downstream the flotation stations; six in Billings Reservoir: B1, B2, B3, B4, B5 and B6 – covering the riverine, transitional and lacustrine regions). Altogether, 148 water variables were quantified from August 2007 to March 2010 with different frequencies (e.g. daily, weekly or monthly), following APHA (2005) methods. All the analyzed variables are important in relation to sanitary, environmental and health aspects, including metals (aluminium, cadmium, copper, iron, lead), biological indicators (biochemical oxygen demand, thermotolerant coliforms, *Cryptosporidium sp.*, *Giardia sp.*), nutrients (total phosphorus and nitrogen, nitrate, nitrogen-ammonia), organic compounds (aldrin+dieldrin, 1.2-diphenylhydrazine, 2.4.6-trichlorophenol, endosulfan, endrin, 4.4-DDD, fluoranthene) and other physical and chemical variables (apparent color, conductivity, dissolved oxygen, total suspended solids, turbidity). The full list of all the quantified variables may be found at the website of the São Paulo State Attorney (MP-SP): <http://www.mp.sp.gov.br/portal/page/portal/Billings>.

RESULTS AND DISCUSSION

The *in situ* flotation system seemed to be a convenient approach for the Metropolitan Region of São Paulo. Considering aspects like lack of space to build off site structures, technology availability and incentive from the public authorities to the remediation of local polluted urban rivers, the prototype we tested was considered feasible. However, several constraints related to the low/insufficient efficiency for the removal of some variables (and the potential impacts to the Billings Reservoir), operational procedures and high chemical products consumption, sludge and solid waste production must be carefully examined. The approach itself represented an opportunity for recovering the water quality of a severely polluted river in São Paulo, but some inefficiencies we detected must be solved not to offer risks to the public health and to the multiple uses of the Billings Reservoir water.

Considering space restrictions, we present the results for some water variables and sampling sites. Data for all the parameters may be found at <http://www.mp.sp.gov.br/portal/page/portal/Billings>. The system efficiency for total phosphorus removal (90%) and dissolved oxygen increment (63%) in Pinheiros River water was relatively high. Some authors assessing the efficiency of other *in situ* flotation systems in Brazil, although quite smaller, reported higher removal efficiencies for total suspended solids (94%, treated flow: 0.15 m^3/s, OLIVEIRA et al. 2000), biochemical oxygen demand (98%) and fecal coliforms (99.99%, treated flow: 0.05 m^3/s, LOPES et al. 1999). Our removal efficiency for total suspended solids was 40%, lower than the percentage we were expecting. The high treated flow (10 m^3/s) generates a more difficult condition to control the system. Moreover, the sludge removal was impaired due to the magnitude of flow and flux velocity, what certainly contributed for a worse final water quality.

Nitrogen-ammonia reduction percentage was almost zero (2%). By analyzing the average concentrations of some of the assessed variables in the Billings Reservoir (from B1 to B6), the impact over the water quality could be visualized. There was a trend of water quality improvement from B1 to B6 (B1 was submitted to the influence of the Pinheiros River treated water). Average concentrations of dissolved oxygen, for example, increased from 4.4 mg/L (B1) to 7.0 mg/L (B6) and the nitrogen-ammonia concentrations decreased from 6.4 mg/L (B1) to 0.3 mg/L (B6), what may be associated with the assimilation capacity of the aquatic system. Despite of the significant

percentage efficiency for phosphorus removal, the remaining average concentration was still high in B1 (0.11 mg/L), contributing for the eutrophication of the headwaters of the Billings Reservoir.

TABLE 1: Overall removal or increment efficiency (%) achieved by the flotation system (S1 vs. S4) for some water variables in the sampling sites in the Pinheiros River and average concentrations in the Billings Reservoir (B1-B6)

Variable	Removal efficiency*	B1	B2	B3	B4	B5	B6
Dissolved oxygen (mg/L)	63% (increment)	4.4	5.9	5.8	6.7	6.9	7.0
Iron (soluble, mg/L)	31%	0.11	0.05	0.04	0.04	0.03	0.05
Nitrogen-ammonia (mg/L)	2%	6.4	1.9	0.7	0.5	0.6	0.3
Total phosphorus (mg/L)	90%	0.11	0.04	0.05	0.04	0.03	0.03
Total suspended solids (mg/L)	40%	13	8	7	6	7	8

*** CUNHA et al. (2010)**

The iron concentrations in the water (0.11 mg/L in B1) suggested the impact of inappropriate operational procedures, like high consumption of chemicals during the coagulation step (ferric chloride). Therefore, we observed evidence of possible lack of criteria in the application of the coagulant, possibly as a result of the dosage changes, that were frequent in a process that was being tested. Although the tendency of iron is to form insoluble compounds and be immobilized in the sediment of the reservoir, it is advisable to review the dosages of coagulants to detect eventual hyper dosages.

The mean energy consumption of the pilot-scale flotation system was 42,000 kWh/day and the dewatered sludge production was significant (around 150 m^3/day considering both flotation stations), boosted by the high consumption of coagulants. After centrifugation, the solids content in the sludge increased from 1-2% to 20%. However, considering the high amount of sludge production and the final destination of the material (a controlled landfill close to São Paulo city), managing this solid waste is a key point for the system sustainability.

CONCLUSIONS

The most important advantages of the proposed methodology and the integrated system for recovering the water quality of the Pinheiros River (São Paulo, Brazil) were:

i) The *in situ* approach seemed to be convenient for big cities like São Paulo due to the lack of available areas to build off site treatment structures. Moreover, since the treatment occurred on the river channel itself, there were smaller expenses with pumping structures;

ii) Besides the technology availability, we observed the local government willing to 1) recover the water quality of the Pinheiros River, an environmental issue and 2) boost the energy generation in the Billings Reservoir, an economic factor;

iii) The pilot-scale system treated a relatively high flow (10 m^3/s) and the frequency of the laboratory analyses produced a significant number of monitoring data (over 200,000 results on water quality) during the 32 months the system was operating;

iv) Quantitatively speaking, the flow transferred to the Billings Reservoir after the flotation treatment (~10 m^3/s) favoured the multiple water uses in the reservoir (i.e. the additional flow was important for increasing energy generation and drinking water production);

v) The *in situ* flotation system reached satisfactory percentage removal of total phosphorus (90%) from the water, contributing to the decrease of phosphorus loads to the Billings Reservoir. The flotation stations also increased the dissolved oxygen concentrations in the water, although the increment levels were below the expected ones;

On the other hand, we could also detect some disadvantages and limitations of our system, including:

i) Interruptions occurred during the 32 months of the system operation for technical repairs and maintenance. Parameters like coagulant dosage and slow and rapid mixing gradients need adjustments to increase the overall flotation efficiency. We observed high soluble iron concentrations in the treated water, what was associated with no optimum ferric chloride dosages during the coagulation process;

ii) There were some difficulties regarding operation and maintenance of the prototype considering the influence of many external factors over an "opened" system – rainfall and other weather attributes, natural and anthropogenic-induced water quality temporal and spatial variability of the river;

iii) The treatment facility was not able to remove nitrogen-ammonia from the Pinheiros River water. High concentrations of this nutrient were observed in the riverine zone of the Billings Reservoir (B1), what could have implications for the eutrophication of the aquatic system. There is a need to find alternative/complementary units to control the nitrogen-ammonia concentrations in the water that is pumped to Billings, including biological processes;

iv) Electrolytic flotation (which does not require the use of coagulants) or membranes are technologies that should also be tested as alternatives to overcome the limitations of the *in situ* flotation system;

v) The sludge removal unit must be improved. The inefficiency of this process affected the final water quality (i.e. by increasing the total suspended solids concentrations and decreasing the overall rates of pollutants removal from the water). Also, one of our biggest concerns was the final destination of all the dewatered sludge (with 20% of solids) that was produced everyday (about 150,000 L). During the 32 months we ran the system, the sludge was sent to a controlled landfill. However, this mechanism can become costly over time. It is necessary to improve the sludge dewatering processes and to look for alternative solutions for the material disposal;

vi) The treated water effects over the Billings Reservoir water quality were negative. The monitoring program revealed that the headwaters (B1 and B2) of the reservoir were affected by the effluent of the flotation system. The monitoring results also suggested the assimilation capacity of the water body, with progressive water quality increase down the reservoir. Further studies and data analyses are necessary to assess the

temporal and spatial magnitude of the real impacts over Billings Reservoir and to estimate these impacts considering that the final project would treat 50 m^3/s.

In summary, the *in situ* flotation system may be considered an opportunity for recovering the Pinheiros River water quality and favouring the multiple water uses in the Billings Reservoir because 1) the *in situ* approach is convenient for a megalopolis like São Paulo, 2) technology is available and 3) the government incentives may be used as a source of money and as a way to involve local people in the decision-making process. Nonetheless, we detected many inefficiencies and gaps that must be overcome. At the present stage, we believe the system may offer risks to the Billings Reservoir, including water quality degradation and its interface with public health issues. In addition, the high amount of sludge has to be managed with emphasis on volume reduction and some alternative final destination. Cleaning up the river water should not mean transferring the problem to somewhere else (as solid waste). Urban waters in developing countries are such a challenging issue and our project seems to be an important contribution for the water resources management in such areas, focusing on integrative approach, technology application, environmental quality and sustainability in the long-term.

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02-WWW-YES-2011-Cunha-2011_03_31.doc