On site flotation for recovering polluted aquatic systems: is it a feasible solution for a Brazilian urban river?

D. G. F. Cunha, D. Grull, M. Damato, J. R. C. Blum, J. E. I. Lutti, S. Eiger and P. C. S. Mancuso

ABSTRACT

Pinheiros River (Brazil) plays a pivotal role in supplying water to Billings Reservoir, which presents multiple uses (human drinking, energy generation, irrigation, navigation, fishing and leisure). An intense monitoring program was performed during the years 2007 and 2008 to find out whether on site flotation is a feasible solution or not for improving the water quality of this urban river, attenuating the pollutants load caused by the water pumping to the reservoir (approximately 10 $m^3 s^{-1}$). The monitoring of 18 variables (13,429 laboratorial analysis during the period of 490 days), suggested that despite the convenience of the on site approach for water treatment, especially for rivers located in fully urbanized areas, the flotation system is not enough itself to recover Pinheiros River water quality, given the several constraints that apply. Total phosphorus removal was high in percentage terms (about 90%), although the remaining concentrations were not so low (mean of 0.05 $mg L^{-1}$). The removal efficiency of some variables was insufficient, leading to high final mean concentrations of metals [e.g. aluminium (0.29 $mg L^{-1}$), chromium (0.02 $mg L^{-1}$) and iron (1.1 $mg L^{-1}$)] as well as nitrogen-ammonia (25.8 $mg L^{-1}$) and total suspended solids (18 $mg L^{-1}$) in the treated water.

Key words | environmental monitoring, on site treatment, urban rivers, water flotation, water resources management

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INTRODUCTION

Urban rivers in developing countries frequently are rectified channels with significant levels of degradation as a result of high concentrations of pollutants and pathogens, aerobic life absence, unpleasant odor and deteriorated aspect. The environmental reclamation of such aquatic systems and the contiguous terrestrial area should therefore be included in the agenda of public authorities. Urban rivers revitalization may be used as a tool for environmental awareness of city dwellers, so that reasonable levels of ecological health and acceptable conditions in both water quantitative and qualitative aspects could be achieved.

Big cities like São Paulo (Metropolitan Region of São Paulo has almost 20 million inhabitants) present challenging environmental problems, whose solutions are difficult to be reached. Factors like urban swelling, high population density and even lack of territorial space to install sanitation and treatment facilities, for instance, are progressively driving such cities to chaos in environmental, social and economic terms.

In this context, the selection of soil, air and water treatment methods must be oriented to achieve cost-effectiveness and satisfactory environmental performance. These elements in turn are totally dependent on specific characteristics of the country and the peculiarities of the target area (Hamby 1996; Rivett *et al.* 2002). Given the advanced stage of degradation of Pinheiros River in Brazil,

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the recovery technique tested by this research could be considered a remediation process rather than a treatment technology itself. In this case, the "on site approach" seemed to be the most appropriate alternative because of the following reasons: i) lack of space and available areas to build off site treatment structures; ii) presence of land owners interests and conflicts in the surrounding area; iii) technology availability; iv) public authorities incentive to programs that are oriented to polluted rivers and reservoirs remediation.

Concerning this situation, this research aimed to assess the feasibility of using on site flotation to recover a severely polluted river in São Paulo city, making possible and less prejudicial the pumping of the treated water into Billings Reservoir, a multiple purpose aquatic system. In order to achieve this goal, a comprehensive monitoring program was designed to evaluate the efficiency of the flotation system on removing pollutants from Pinheiros River water, including metals, nutrients and pathogens.

Flotation refers to a widespread technology for different applications (Figure 1), such as industrial uses as well as water and wastewater treatment (Rubio *et al.* 2002). Dispersed air flotation encompasses arrangements that employ bigger air bubbles (from 0.3 mm to 2.0 mm) and may be divided into two groups: froth flotation and foam flotation. The former is common in the mining industry to separate the mineral of interest from the gangue. More information about froth flotation use in this area is presented by Rubio & Tessele (1997), Allan & Woodcock (2001) and Ogunniyi & Vermaak (2009). Foam flotation in turn has wide application for metals removal from zeolites of ion exchange and on chemical oxygen demand (COD) reduction of industrial wastewater, for instance (Zouboulis *et al.* 1991; Lin & Lo 1996).

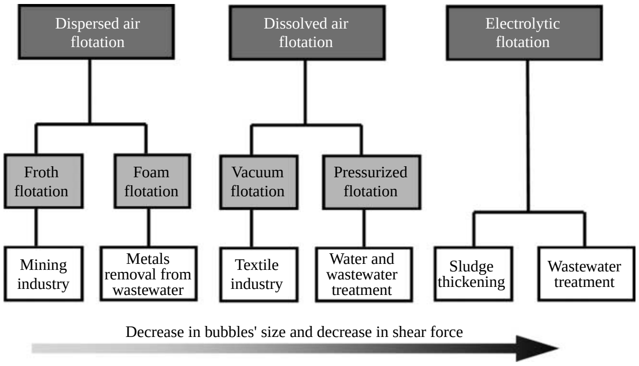

Figure 1 | Different arrangements of flotation technique and some of their main applications.

Electrolytic flotation or electro-flotation is the generation of micro bubbles of oxygen and hydrogen inside the liquid to be treated by applying an electric current between pairs of electrodes placed on the bottom of the reactor. Thus, the bubbles are formed just by water electrolysis and this process has various uses for wastewater treatment and sludge thickening and dewatering (e.g. Murugananthan *et al.* 2004; Gao *et al.* 2008).

Dissolved Air Flotation (DAF) process is based on the release of gas bubbles that are obtained by releasing a portion of the gas previously dissolved in the liquid mass due to an abrupt drop in the pressure to which this fluid is submitted. According to the mechanism to decrease the pressure, there are two possible ways of DAF: Vacuum and Pressurized flotation. The latter, specifically, has been strongly used for water and wastewater treatment for many decades (e.g. Lovett & Travers 1986 for abattoir wastewater; Heinänen *et al.* 1995 for potable water treatment; Zouboulis & Avranas 2000 for oil-in-water emulsions). DAF is also the technology employed by the prototype studied by the present research.

DAF involves coagulation and flocculation steps before the flotation itself. Regarding the coagulation, improving and optimizing this process has been an issue of special concern for some years (e.g. Klute *et al.* 1995; Wang *et al.* 2002; Yan *et al.* 2008). Factors like coagulant selection (e.g. ferric chloride or aluminium sulfate), rapid mixing times and gradients and also polymers application play an important role on water and wastewater treatment systems' overall efficiency. Flocculation step in turn must be carefully designed to favor the generation of flocs with adequate size and resistance, depending on the subsequent unit operation (either flotation or sedimentation, for instance). In addition, flocs rupture is not desirable and may compromise the final effluent quality.

STUDY AREA

Pinheiros river and billings reservoir

Pinheiros River and Billings Reservoir are located in São Paulo state (SP), Brazil (Figure 2). The former, whose

Figure 2 | São Paulo state, Brazil, where Pinheiros River and Billings Reservoir are located.

length is about 30 km, links Tietê River, the most important aquatic system of the basin, to Billings Reservoir. The latter in turn has 1,560 km^2 of drainage area and an estimated storage volume of 995 million m^3.

One relevant anthropogenic negative influence on Billings Reservoir refers to irregular occupation of its perimeter. It is estimated that more than one million people are living in the catchment's area. The continuous decrease in water quality and availability of this source is a problem of great concern for local authorities. Recently, "Billings Reservoir Law" (São Paulo state Law Number 13,579–July 13th 2009) came into effect as an attempt to stop (or slow, at least) the degradation of this environmental patrimony. Billings Reservoir water is currently used for multiple purposes, including human drinking, energy generation, leisure and navigation.

On site flotation system

The on site flotation, as the name denotes, occurs on the river bed itself. The pilot-scale flotation system was installed in the river channel using a metallic bridge over the river, supporting the coagulant injection devices (tubes) and the air-pressurized water flow injection. All the tubes were temporarily suspended (removed from the water) whenever a flood occurred. Two Flotation Stations (FS), separated by approximately 4 km, were part of the system: Zavuvuz FS and Pedreira FS.

Some important operational parameters and variables of the proposed DAF system are shown in Table 1. Ferric chloride was used as coagulant and the applied dosages were significantly high and variable because the pilot-scale system had a testing character. Rapid mixing occurred through the bubbling of the river water, through a coagulation time of approximately 0.5 min and with 800 s^{-1} as the associated velocity gradient. Flocculation in turn took place with higher periods of time (27 min as the mean slow mixing time) and, obviously, smaller velocity gradients (about 60 s^{-1}). The respective hydraulic loading rate for the pilot system was about 18 $m^3\,m^{-2}\,day^{-1}$.

Complementarily, tiny air bubbles were produced in the bottom of the river channel. This was possible through the saturation of a certain flow of water (the recycle flow was about 8% to 10% of the total affluent flow) with air. The final pressure in the pressurized tank was about 4 atm to 5 atm. Then, the air-saturated water flow was distributed along the channel of the river through valves that were placed to drop the pressure down. This process of sudden pressure decrease released numerous air microbubbles into the water column. The upward movement of these bubbles was able to bring up the colloidal particles and the destabilized mass of impurities to the surface, where there were equipments to remove the sludge. Rotating blades were used for this purpose, promoting the dredging of the sludge accumulated in the water surface. In order to

Table 1 | General information about the pilot-scale DAF system, including some operational parameter and variables

Operational parameter/variable	Value/range
Recycle flow ($m^3\,s^{-1}$)	0.8 to 1.0
Saturation pressure (atm)*	4 to 5
Hydraulic loading rate ($m^3\,m^{-2}\,day^{-1}$)†	18
Hydraulic detention time (min)‡	25 to 30
Cross flow velocity ($m\,s^{-1}$)	0.3
Coagulant (ferric chloride) dosages ($mg\,L^{-1}$)	50 to 400
Rapid mixing time (min)	0.5
Rapid mixing velocity gradient (s^{-1})	800
Slow mixing time (min)	27
Slow mixing velocity gradient (s^{-1})	60
Sludge production per FS ($m^3\,day^{-1}$)	75
Solids content in the sludge (%)§	1 to 2 and 20
Energy consumption ($kWh\,day^{-1}$)‖	42,000

*In the saturation tank.
†In the separation zone of the pilot system.
‡In the contact zone of the pilot system.
§Before and after centrifugation, respectively.
‖Overall mean for all steps in both FS's.

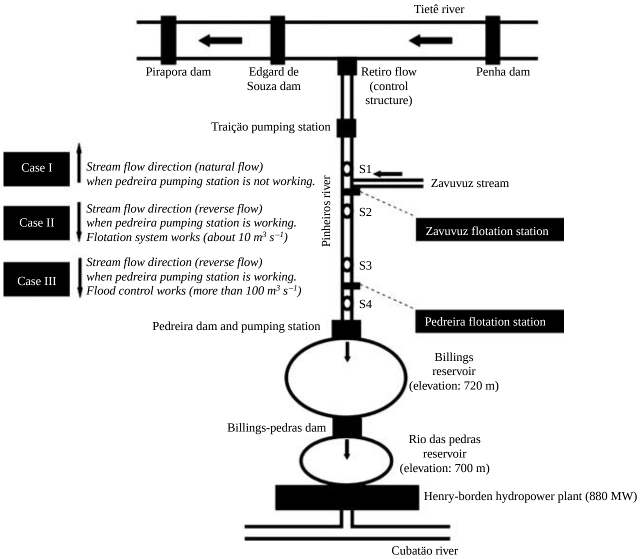

Figure 3 | Pilot-scale flotation system concept: Case I, Case II and Case III. S1, S2, S3 and S4 are sampling stations for water quality monitoring.

increase the solids content in the sludge, the material was dehydrated by a centrifugation process and the final solids percentage was about 20%. Controlled landfill was the final destination of the sludge, whose average daily production, under regular operational conditions, was about 150 m^3 (for both FS's).

There was an important particularity of the system (Figure 3), since three mechanisms were possible depending on operational and weather conditions:

- Case I "Natural condition"–when both flotation system and flood control were not working, the natural channel flow occurred (i.e. Pinheiros River feeds Tietê River);
- Case II "Flotation Works"–the on site flotation pilot-scale system operated through the pumping of about 10 $m^3 s^{-1}$ to Billings Reservoir (by reversing Pinheiros River waters), including Zavuvuz FS and Pedreira FS;
- Case III "Flood Control Works"–under significant rainfall events in the region, the operation of the flotation system was suspended and the flood control mechanism took effect. This was possible through the pumping of more than 50 $m^3 s^{-1}$ (reaching in some occasions almost 400 $m^3 s^{-1}$) of Pinheiros River water into Billings Reservoir, without any previous treatment, to avoid overflow of Pinheiros River. This practice is supported by state laws and resolutions.

Therefore, the pilot-scale flotation system was inserted in a complex operation routine that primarily depended on weather conditions. When pilot-scale flotation system worked, the pumped flow was near 10 $m^3 s^{-1}$, quite bigger than other similar treatment stations in Brazil (0.05 $m^3 s^{-1}$ described by Lopes & Oliveira 1999; 0.15 $m^3 s^{-1}$ by Oliveira *et al.* 2000; 0.75 $m^3 s^{-1}$ by Coutinho & von Sperling 2007–all three researches presented in national conferences), what characterizes this prototype as a pioneer structure and, thus, a challenging one.

METHODS

Monitoring stations were placed at four strategic points in Pinheiros River (Table 2, Figure 3): S1 and S2, respectively upstream and downstream of Zavuvuz FS; S3 and S4, respectively upstream and downstream of Pedreira FS. Therefore, 'S1' denotes Sampling Station 1, 'S2' means Sampling Station 2 and so on. 'Zavuvuz' and 'Pedreira' are just the names of the flotation station units. The configuration of this monitoring program allowed the assessment of the efficiency of each facility and also a global effect derived from both. It is important to stress that station S4 represented the final water quality, that is, the water that was pumped into Billings Reservoir.

Sampling surveys were performed during 17 months, from August 2007 to December 2008, through the quantification of 18 biological, chemical and physical variables in the water (Table 3), according to APHA (2005) methods.

These variables were chosen because they are relevant with respect to sanitary and environmental aspects. Laboratório Ambiental and Ecolabor, both certified by ABNT–the Brazilian Association of Technical Norms, were in charge of all the analysis. It is important to state that the frequency of each laboratorial analysis varied from variable

Table 2 | Geographic coordinates of monitoring stations in Pinheiros River

Sampling station	Geographic coordinates	
S1	23° 40′ 43.09″ S	46° 42′ 02.15″ W
S2	23° 40′ 47.74″ S	46° 42′ 03.72″ W
S3	23° 42′ 04.09″ S	46° 40′ 59.61″ W
S4	23° 42′ 11.73″ S	46° 40′ 32.18″ W

Table 3 | Total number of data available for each variable and case

Variable	**Case I** **"Natural condition"**	**Case II** **"Flotation works"**	**Case III** **"Flood control works"**	**Total**
Aluminium (soluble)	35	59	6	100
Apparent Color	422	632	143	1,197
Cadmium	26	43	4	73
Chromium hexavalent	26	43	4	73
COD	426	633	143	1,202
Thermotolerant Coliforms	191	430	45	666
Conductivity	360	607	133	1,100
Copper	35	59	5	99
Cryptosporidium sp.	35	72	3	110
Dissolved Oxygen	481	862	159	1,502
Giardia sp.	35	72	3	110
Iron (soluble)	267	469	83	819
Lead	116	112	49	277
Nitrogen-ammonia	479	890	134	1,503
Total phosphorus	426	626	133	1,185
TSS	548	893	173	1,614
Turbidity	483	875	163	1,521
Vanadium	119	110	49	278
Total	4,510	7,487	1,432	13,429
Number of days of cases occurrence	182 (37% of the time)	241 (49% of the time)	67 (14% of the time)	490 days

to variable (e.g. daily, weekly, biweekly, monthly), but the total number of data available for the four sampling stations was 13,429.

Data available for the period when the flotation system worked were submitted to statistical analysis to verify the existence of significant differences between the results for all the monitoring stations, through two softwares: Statistica 6.0® and Systat 10®. These statistical procedures were conducted, through analysis of variance (ANOVA), for all the measured variables, in order to verify the differences among the four sampling stations, considering a significance level of 95% ($p < 0.05$). The analyses followed the recommendations of Johnson & Wichern (2007).

RESULTS AND DISCUSSION

Monitoring results are presented for the maximum (max), minimum (min) and mean values for each case (natural condition, flotation works and flood control works) for all variables (Table 4). These data are complemented by Table 5, which shows the mean removal efficiency of both Zavuvuz and Pedreira FS's for all variables, as well as a statistical analysis that was able to suggest significant removal ($p < 0.05$) or not ($p > 0.05$) for a given variable.

First, an important result refers to the absence of *Cryptosporidium sp.* and *Giardia sp.* for all sampling stations in Pinheiros River for the whole period during which this research was conducted.

The flotation system effect on some variables was negligible, since there was no significant relative variation in relation neither to the natural condition nor to flood control events. That was the case of chromium hexavalent, conductivity, dissolved oxygen, nitrogen-ammonia and vanadium. Nitrogen-ammonia concentrations, especially, showed to be not affected at all by flotation system treatment, presenting high mean concentrations in all

Table 4 | Main results (maximum, minimum and mean values) for 18 variables monitored from August 2007 to December 2008 in four sampling stations (S1, S2, S3 and S4) in Pinheiros River, Brazil. Data are individually showed for the three cases previously mentioned

		Case I "Natural condition"				**Case II "Flotation works"**				**Case III "Flood control works"**			
		S1	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**
Aluminium (soluble, $mg\,L^{-1}$)	Max	0.50	0.30	0.10	3.46	0.40	0.31	0.39	1.92	*	0.70	0.50	0.20
	Min	0.10	0.30	0.10	0.05	0.08	0.05	0.05	0.04	*	0.70	0.50	0.10
	Mean	0.27	0.28	0.05	0.37	0.24	0.20	0.19	0.29	*	0.70	0.50	0.10
Apparent color (CU)	Max	2,580	1,360	915	1,290	1,500	1,360	960	1,150	1,010	480	666	1,130
	Min	20	27	16	12	28	14	18	4	56	57	24	14
	Mean	478	365	284	239	418	217	266	194	324	254	331	355
Cadmium ($mg\,L^{-1}$)	Max	0.0005	0.0005	0.0005	0.0025	0.005	0.001	0.001	0.005	*	0.0005	0.0005	0.0005
	Min	0.0001	0.0005	0.0005	0.0001	0.0001	0.0005	0.0005	0.0001	*	0.0005	0.0005	0.0005
	Mean	0.0004	0.0005	0.0005	0.0006	0.0009	0.0007	0.0006	0.0007	*	0.0005	0.0005	0.0005
Chromium hexavalent ($mg\,L^{-1}$)	Max	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	*	0.03	0.03	0.03
	Min	0.01	0.03	0.03	0.01	0.01	0.03	0.03	0.01	*	0.03	0.03	0.03
	Mean	0.02	0.03	0.03	0.02	0.02	0.03	0.03	0.02	*	0.03	0.03	0.03
COD ($mg\,L^{-1}$)	Max	614	163	146	297	375	508	262	222	544	258	245	209
	Min	24	26	10	3	20	16	9	3	22	43	28	13
	Mean	108	85	67	54	128	75	73	60	98	92	91	75
Thermotolerant coliforms (MPN $100\,mL^{-1}$)	Max	1.2×10^7	3.8×10^5	4.8×10^5	2.8×10^6	7.7×10^6	1.5×10^5	2.4×10^5	1.2×10^6	5.2×10^6	4.6×10^2	2.4×10^4	6.9×10^5
	Min	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Absent
	Mean	3.4×10^5	1.1×10^5	1.5×10^5	6.4×10^4	3.5×10^5	3.7×10^4	6.8×10^4	1.9×10^4	4.3×10^5	1.7×10^2	8.1×10^3	1.3×10^5
Conductivity ($\mu S\,cm^{-1}$)	Max	1,350	1,490	1,540	980	1,510	1,640	1,510	1,510	1,070	536	566	985
	Min	215	207	194	201	262	105	63	284	173	225	234	184
	Mean	526	576	523	393	521	581	558	566	372	374	392	355
Copper ($mg\,L^{-1}$)	Max	0.019	0.008	0.003	0.019	0.041	0.021	0.013	0.020	*	0.006	0.003	0.045
	Min	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	*	0.006	0.003	0.012
	Mean	0.011	0.005	0.003	0.006	0.015	0.013	0.007	0.006	*	0.006	0.003	0.030
Cryptosporidium sp.	Absence	100%	*	*	100%	100%	*	*	100%	100%	*	*	100%
	Presence	0%	*	*	0%	0%	*	*	0%	0%	*	*	0%
Dissolved oxygen ($mg\,L^{-1}$)	Max	4.8	7.4	7.7	6.6	6.0	8.3	7.2	7.7	4.9	3.3	3.7	5.0
	Min	0.1	0.1	0.1	0.6	0.0	0.3	0.0	0.4	0.1	0.7	0.6	0.6
	Mean	1.3	1.7	2.2	2.6	1.6	2.7	2.1	2.6	1.9	1.9	1.9	2.3
Giardia sp.	Absence	100%	*	*	100%	100%	*	*	100%	100%	*	*	100%
	Presence	0%	*	*	0%	0%	*	*	0%	0%	*	*	0%
Iron (soluble, $mg\,L^{-1}$)	Max	17.2	7.14	1.15	21.5	14.3	9.9	6.9	12.3	11.4	0.37	0.22	10.3
	Min	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.06	0.08	0.05	0.03
	Mean	3.1	1.1	0.3	1.2	1.6	1.3	1.0	1.1	2.2	0.2	0.1	1.1
Lead ($\mu g\,L^{-1}$)	Max	0.011	0.040	0.005	0.72	0.05	0.02	0.03	0.05	*	0.005	0.005	0.094
	Min	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	*	0.005	0.005	0.005
	Mean	0.006	0.023	0.005	0.015	0.011	0.009	0.012	0.007	*	0.005	0.005	0.008

Table 4 | *(continued)*

		Case I "Natural condition"				Case II "Flotation works"				Case III "Flood control works"			
		S1	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**	**S1**	**S2**	**S3**	**S4**
Nitrogen-ammonia (mg L^{-1})	Max	117.0	72.5	59.0	71.5	81.0	79.0	62.5	70.0	54.2	42.0	38.9	45.0
	Min	0.5	1.5	0.4	0.1	0.7	1.1	0.1	8.0	3.0	6.5	5.6	4.4
	Mean	27.2	26.0	21.5	19.5	26.2	25.9	26.0	25.8	18.4	20.8	18.8	20.1
Total phosphorus (mg L^{-1})	Max	4.6	2.0	1.8	0.39	3.10	2.00	2.60	1.00	5.4	0.47	0.58	0.49
	Min	0.001	0.002	0.002	0.001	0.001	0.001	0.001	0.001	0.006	0.023	0.006	0.001
	Mean	0.57	0.37	0.30	0.08	0.52	0.27	0.31	0.05	0.74	0.18	0.28	0.15
TSS (mg L^{-1})	Max	544	108	114	112	152	577	172	115	340	353	224	121
	Min	5	5	5	5	5	5	5	5	5	5	5	5
	Mean	41	30	25	24	30	21	20	18	57	65	61	47
Turbidity (NTU)	Max	356	196	206	192	217	196	140	149	126	110	149	162
	Min	5	2	2	1	5	2	1	1	6	7	3	2
	Mean	65	67	57	36	54	34	43	28	41	55	65	43
Vanadium (mg L^{-1})	Max	0.028	0.010	0.005	0.032	0.050	0.005	0.005	0.05	*	0.005	0.005	0.021
	Min	0.005	0.005	0.005	0.002	0.002	0.002	0.002	0.002	*	0.005	0.005	0.005
	Mean	0.010	0.008	0.005	0.007	0.010	0.004	0.004	0.007	*	0.005	0.005	0.005

*Unavailable data; COD, chemical oxygen demand; TSS, total suspended solids.

sampling stations, i.e. 26.2 mg L^{-1} (S1), 25.9 mg L^{-1} (S2), 26.0 mg L^{-1} (S3) and 25.8 mg L^{-1} (S4). The pumping of the water to Billings Reservoir thus might contribute to the enrichment of this aquatic system and to the increase of its trophic state, depending on the existing phytoplanktonic community.

Another important comment refers to the low removal efficiencies for TSS (30% in Zavuvuz FS and 10% in Pedreira FS), resulting in only 40% of overall reduction. This percentage is lower than that normally expected for varied DAF systems associated with previous coagulation (e.g. more than 95% of TSS removal from chemical mechanical polishing wastewater by Tsai *et al.* 2007; 85% of TSS removal from personal care products wastewater by El-Gohary *et al.* 2010; 79% turbidity removal from landfill leachate by Palaniandy *et al.* 2010). So, the low efficiencies by Zavuvuz and Pedreira FS's were probably linked with three main factors:

i. The on site regime–the on site scheme itself hampers the treatment system control. For example, the river was submitted to rain events and therefore to suspended solids loads into the channel by runoff. Also, the contribution of resuspended sediments from the bottom of the channel in such rain and high river flow events was probably not negligible.
ii. The sludge removal system–the inefficiency of the sludge scraping equipment frequently caused the break of the flocs and thus the decrease of the TSS overall removal;
iii. The preferential flow lines–also as a consequence of the on site regime, preferential flow lines in the water flow were probably formed. This certainly caused a low level of homogeneity in the distribution of the coagulant, which may have caused efficiency decrease as well.

In pure numerical terms, the flotation system was able to reduce the apparent color of the water from 418 CU (mean, S1) to 217 CU (mean, S2) by the action of Zavuvuz FS and from 266 CU (mean, S3) to 194 CU (mean, S4) by Pedreira FS. The dynamic of this variable in the monitoring stations during episodes of Natural Condition also showed a tendency of decreasing from stations S1 to S4, although maximum values had been higher (e.g. peaks of 2,580 CU

Table 5 | Removal efficiency and statistical difference for all variables (exception for dissolved oxygen, to which increment efficiency is presented) by Zavuvuz FS (S1 vs. S2), Pedreira FS (S3 vs. S4) and the overall effect caused by both (S1 vs. S4)

	Zavuvuz FS (S1 vs. S2)		**Pedreira FS (S3 vs. S4)**		**Overall effect (S1 vs. S4)**	
Variable	**Removal efficiency**	**Statistical difference**	**Removal efficiency**	**Statistical difference**	**Removal efficiency**	**Statistical difference**
Aluminium (soluble)	17%	No ($p = 0.684$)	Null	No ($p = 0.314$)	Null	No ($p = 0.344$)
Apparent color	48%	Yes ($p < 0.05$)	27%	No ($p = 0.461$)	54%	Yes ($p < 0.05$)
Cadmium	22%	No ($p = 0.135$)	17%	No ($p = 0.708$)	22%	No ($p = 0.411$)
Chromium hexavalent	Null	No ($p = 0.545$)	33%	No ($p = 0.549$)	Null	No ($p = 0.803$)
COD	41%	Yes ($p < 0.05$)	18%	No ($p = 0.556$)	53%	Yes ($p < 0.05$)
Thermotolerant coliforms	89%	No ($p = 0.079$)	72%	Yes ($p < 0.05$)	95%	Yes ($p < 0.05$)
Conductivity	Null	No ($p = 0.319$)	Null	No ($p = 0.987$)	Null	No ($p = 0.288$)
Copper	13%	No ($p = 0.844$)	14%	No ($p = 0.698$)	60%	No ($p = 0.108$)
Dissolved oxygen	69%	No ($p = 0.997$)	24%	No ($p = 0.141$)	63%	No ($p = 0.101$)
Iron (soluble)	19%	No ($p = 1.000$)	Null	No ($p = 0.383$)	31%	No ($p = 0.138$)
Lead	18%	No ($p = 0.501$)	42%	No ($p = 0.123$)	36%	No ($p = 0.282$)
Nitrogen-ammonia	1%	No ($p = 0.617$)	1%	No ($p = 0.200$)	2%	No ($p = 0.635$)
Total phosphorus	48%	No ($p = 0.312$)	84%	Yes ($p < 0.05$)	90%	Yes ($p < 0.05$)
TSS	30%	Yes ($p < 0.05$)	10%	No ($p = 0.855$)	40%	No ($p = 0.063$)
Turbidity	37%	Yes ($p < 0.05$)	35%	No ($p = 0.571$)	48%	Yes ($p < 0.05$)
Vanadium	60%	No ($p = 0.545$)	Null	No ($p = 0.503$)	30%	No ($p = 0.418$)

COD, chemical oxygen demand; TSS, total suspended solids.

and 1,290 CU in SI and S4, respectively). On the other hand, Case III showed the worst situation for apparent color, since mean values were situated in the approximated range of 250 CU to 350 CU for all monitoring stations. Statistical procedures showed that mean removal of apparent color was 54% (S1 vs. S4), besides statistically significant. Other beneficial effects derived from the flotation system could be detected for the following variables: COD ($p < 0.05$ and reduction of 53% comparing S1 to S4), thermotolerant coliforms ($p < 0.05$ and overall removal efficiency of 95%), total phosphorus ($p < 0.05$ and 90% reduction between S1 and S4) and, finally, turbidity ($p < 0.05$ and overall removal of 48%). Numerically, the noteworthy phosphorus removal represented a reduction from $0.52\,\mathrm{mg\,L^{-1}}$ in the inflow water to $0.05\,\mathrm{mg\,L^{-1}}$ in the treated water.

In some occasions, mainly for metals, the less critical situation in S4 was observed in Case III (Flood Control Works), which may be associated with the dilution process that occurs in such periods and with the inefficiency of flotation system to remove these substances from the water. This situation was found for aluminium (soluble), cadmium and vanadium, with the lowest mean concentrations detected for Case III: $0.1\,\mathrm{mg\,L^{-1}}$, $0.0005\,\mathrm{mg\,L^{-1}}$, $1.1\,\mathrm{mg\,L^{-1}}$ and $0.005\,\mathrm{mg\,L^{-1}}$, respectively. Among all the metals studied, the best performance of flotation system on their removal was obtained for copper (60% of reduction between S1 and S4, although statistically insignificant).

Another important comment concerns the different percentages of reduction and even different statistical significance of removal by comparing the performance of Zavuvuz FS and Pedreira FS. The former was able to consistently remove four variables in statistical terms: apparent color, COD, TSS and turbidity. Nevertheless, the latter was able to significantly reduce only two variables, thermotolerant coliforms and total phosphorus. Therefore, this performance disagreement could be linked with the fact that the first FS presented greater chance of variable's removal, since the upstream concentrations were higher. The second FS in turn had to deal with lower concentrations and values, probably of difficult further decrease. Anyway, overall effect was considered statistically representative for apparent color, COD, thermotolerant coliforms, total phosphorus and turbidity.

CONCLUSIONS

At this initial stage of development, the on site flotation technology seemed to be not feasible for recovering the water quality of Pinheiros River (Brazil) regarding its use, since the system presented insufficient efficiency for some key variables. However, the intense water monitoring program performed during the years 2007 and 2008 in this river enabled the authors to point the following main conclusions and directions.

i. In light of the results and comments previously mentioned, the tested DAF pilot system showed not to be a convenient solution for Pinheiros River water reclamation. Factors such as low removal efficiency for some variables, high required coagulant dosages, deficiency on sludge removal equipment and also the high amount of sludge production negatively affected the system feasibility. However, mainly in developing countries, without prejudice to the sanitary systems implementation (that requires a longer time and much more investments), on site alternatives for water and wastewater treatment, not specifically the one considered by this research, might be a convenient solution for big cities. In many cases, even land availability to build treatment structures is a problem, so the on site approach might be appropriate. Therefore, current research on water quality recovering must consider such technologies in the range of management possibilities, focusing on performance improvement, cost reduction, accordance and commitment with environmental standards and regulations;

ii. The flotation system showed significant efficiency in the removal of thermotolerant coliforms and total phosphorus. The turbidity, apparent color and COD removal efficiencies ranged from 48% to 54% when considering the overall effect of the two flotation stations in series. Poor or null removal was found for some metals, TSS and also for nitrogen-ammonia, which represents a threat to the Billings Reservoir, considering its vulnerability to eutrophication, also depending on phosphorus concentrations and phytoplanktonic community structure;

iii. The monitoring results for Flood Control events showed that this situation was not as critical to station S4 (Pinheiros River) in water quality terms as expected. The concentrations of some variables (e.g. aluminium, cadmium, conductivity, nitrogen-ammonia, thermotolerant coliforms and vanadium) were even lower in this case in comparison with the other cases. On the other hand, the opposite was found for some variables deeply linked with rainy events, like apparent color, total suspended solids and turbidity, and also for copper. For such variables, Flood Control mechanism offered an impact on water quality;

iv. Considering that the monitoring has continued during subsequent years, including other water quality variables, future research and scientific investigations about flotation treatment in Pinheiros River should focus on the following topics: optimization of coagulation and flocculation processes (e.g. coagulants dosage, velocity gradients control) so that the overall pollutants removal could be enhanced; improving metals removal (e.g. by the optimization of rapid and slow mixing parameters and by testing other coagulants–polyelectrolytes like aluminium polychloride–it is expected that efficiency on metals reduction would be boosted. Also, there is the expectation that more stringent control over the industrial effluents released into the river will also contribute in the medium term to a decrease in the metal concentrations in the water body); still concerning the coagulation step, there is a need to decrease the coagulant consumption as much as possible, given the significant economic burden derived from the large use of such chemical compounds; designing clear operational rules for pumping of Pinheiros River waters depending on weather conditions, considering the possibility of flotation or flood control; sludge treatment and destination alternatives.

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