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***In situ* Remediation Technologies Associated with Sanitation Improvement: An Opportunity for Water Quality Recovering in Developing Countries**

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1. Introduction

The access to safe water is of great importance to reduce the spread of diseases caused by water-related pathogens and to assure the life quality to the human-beings. According to the World Health Organization (WHO, 2011), diarrhea, for example, is responsible for two million deaths every year, mainly among children under the age of five. The environmental effects of some pollutants (e.g. endocrine disruptors, organic compounds) remain unclear and the harmful consequences of the exposure to contaminated water are certainly an important issue for the next decades. Moreover, many research have linked water quality to health problems, such as cancer (Rodrigues et al., 2003; Han et al., 2009), insufficient uptake of nutrients and trace-metals (Lind & Glynn 1999), diabetes, cerebrovascular and kidney disease (Meliker et al., 2007).

The costs and benefits of water quality have been the topic of stimulating discussion in the scientific community (Isaac, 1998; Hajkowicz et al., 2008; Saz-Salazar et al., 2009) because water quality decrease implies not only loss of lives, but also economic damages. The costs of the anthropogenic eutrophication reach US\$2.2 billion in the United States (Dodds et al., 2009) and US\$187.2 million in England and Wales every year (Pretty et al. 2002). The reduction of nutrient loading to the aquatic systems worldwide is the cornerstone of artificial eutrophication control (Smith et al., 1999), with repercussions in other fields like public health and economics.

The anthropogenic impacts on the quality of urban water bodies in developing countries are frequently exacerbated by poor levels of sanitation and inadequate water and wastewater management. Pressure from urban areas on the water quality was reported in Argentina (Almeida et al., 2007), Brazil (Jordão et al., 2007), India (Suthar et al., 2010) and Mexico (Bravo-Inclan et al., 2008). Rapid shifts in the land use patterns, unplanned urbanization and inefficient resources allocation are further aggravating environmental problems in such

nations. Restrictions to the water uses are increasing as the pollution of rivers and lakes is offering more risks to the human health and to the maintenance of the ecological balance.

Within this context, the water resources management plays an important role in the conciliation of the water uses and the long-term sustainability. The *in situ* remediation of rivers, lakes and reservoirs is a decentralized alternative that may be convenient in some cases in comparison to off-site solutions. The main advantages of the *in situ* approach are, besides the relative small period of time required to its implementation, the suitability of the *in situ* facilities to the regions with lack of available areas to build off-site treatment plants (e.g. highly urbanized areas) and the lower expenses with pumping structures. Although it takes more time and requires more investments, the implementation of sanitation infrastructure is also necessary.

With the increase of the negative environmental impacts induced by the anthropogenic activities, the remediation of aquatic systems became an alternative to restore the ecological functions of the ecosystems and accelerate their recovery. The first and most important step in a remediation project is to define the remedial action aims to be accomplished at the site, involving the desirable mechanisms of treatment – biological (e.g. phytoremediation), physical and/or chemical (e.g. oxidation, air stripping, ion exchange, precipitation). Most of the current technologies for aquatic systems remediation were adapted from unitary processes used for drinking water production, industrial purposes or wastewater treatment. The flotation, for example, has been used in mining activities to separate the mineral of interest from the gangue since 1893 (Hoover, 1912). The technology was then adapted to treat water and wastewater through dissolved air flotation (e.g. Heinänen et al., 1995). Ultrafiltration membranes in turn have been mainly used for drinking water production (2 million m³/day worldwide according to Laine et al., 2000). According to the same authors, the oldest water industry with ultrafiltration plant started to operate in 1988 in France. The membranes are becoming cheaper over the years and the technology is more attractive for remediation of surface waters at the present time.

2. Water management in developing countries: Long and short term actions

The water management in developing countries would benefit from a well-weighted balance between long and short term actions (Fig. 1). The former actions should consider sanitation planning and infrastructure, whereas the latter ones should focus on the solutions for remediating the aquatic systems or attenuating their degradation level.

The main issues involved in both long and short term actions for water resources management are:

- i. **Political commitment.** Sanitation and environmental recovery programs usually do not receive the same amount of investments in comparison to other areas (Varis et al., 2006). Local authorities willingness and specific government policies are necessary for meeting the health and environmental goals;
- ii. **Institutional framework.** The effectiveness of the water management policies would be at risk with no solid institutions and skilled professionals. The technical and social challenges will just be overcome with trained planners, sector professionals and decision-makers;

- iii. **Financing.** This is a complicated question because water quality recovery brings benefits to the health and to the environment, making it a public good. However, at the same time, water is also a private good (at the level of households);
- iv. **Technology development and Innovation.** Sanitation and remediation of aquatic systems depend upon technology development, under a cost-benefit analysis. Moreover, the technology has to be adapted and optimized to the local peculiarities. In the case of the developing countries, technology transfer from developed countries might be necessary;
- v. **Monitoring.** Monitoring programs play a pivotal role in assessing if the targets were met. Such programs must be able to provide feedback to improve the monitored system with a view to increasing efficiency and reducing costs;
- vi. **Social acceptance.** It is desirable that people get involved with the decision-making process, increasing the chances of social acceptance of the water resources management policies or programs.

According to Calijuri et al. (2010), the water resources sustainability can be defined as a state of dynamic equilibrium between the disturbances imposed to the water bodies by the anthropogenic activities and the aquatic systems ability to self-regulation (i.e. their elasticity in response to a certain impact). When the impact is strong enough to prevent the self-recovery of the original condition, actions towards remediation, including palliative/temporary solutions, are required to avoid critical levels of degradation and severe impairment of different water uses.

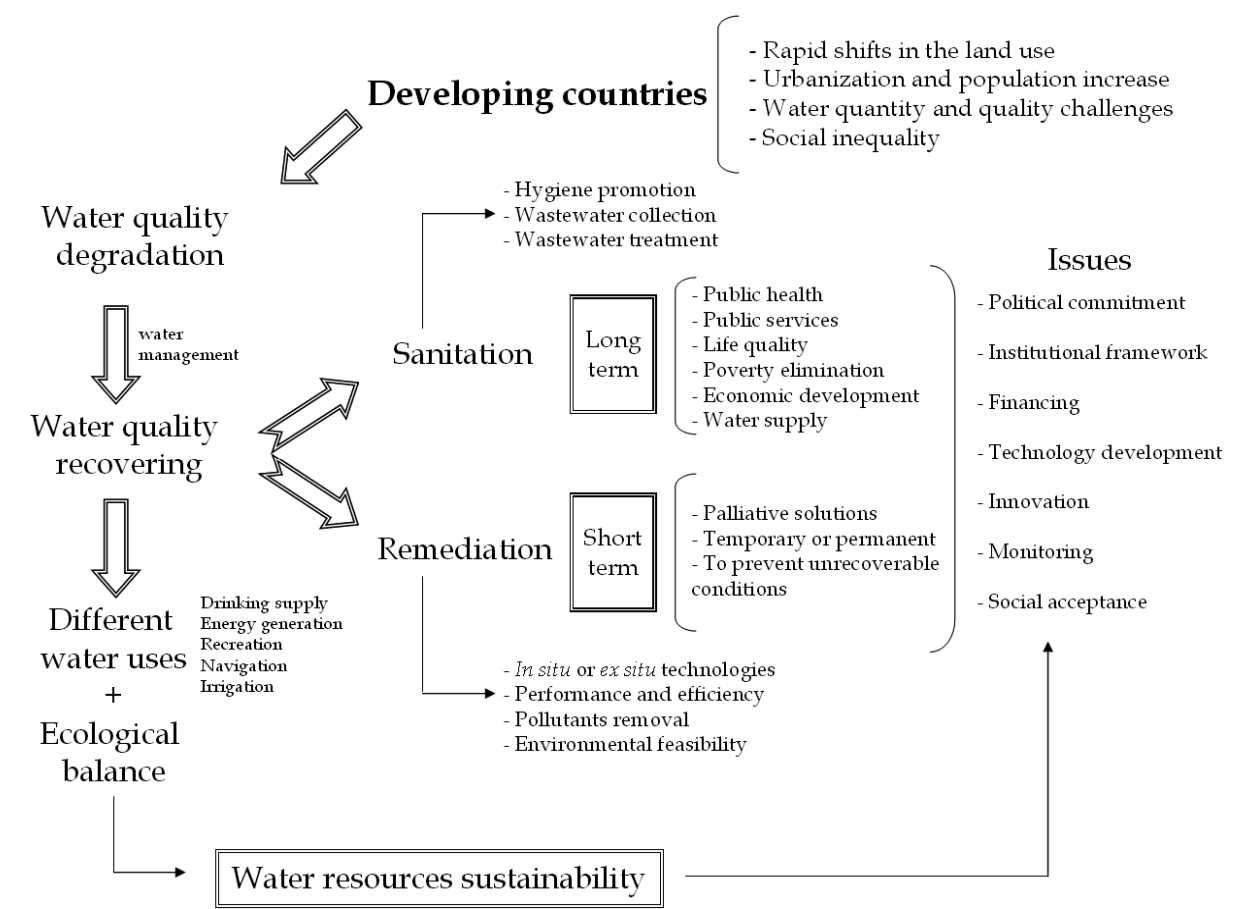


Fig. 1. Scheme of the desirable water quality management approach for developing countries, including the short term and the long term actions description.

2.1 Sanitation infrastructure

Approximately 1.1 billion people in the world do not have access to improved water supply sources and 2.4 billion people do not have access to any type of improved sanitation at all (WHO, 2011). It is clear that there is a need for additional water and sanitation services from government in partnership with other actors worldwide and especially in the megacities from the developing countries (Biswas et al., 2004). The implementation of sanitation infrastructure is a long term action that has to be continuously monitored and updated. Solid waste collection and disposal, water distribution and water and wastewater treatment are the main components of the sanitation in a country. Such items are related to life quality promotion, poverty elimination and economic development. The temporal evolution of sewage, water supply and solid waste collection services in Brazil is shown in Fig. 2.

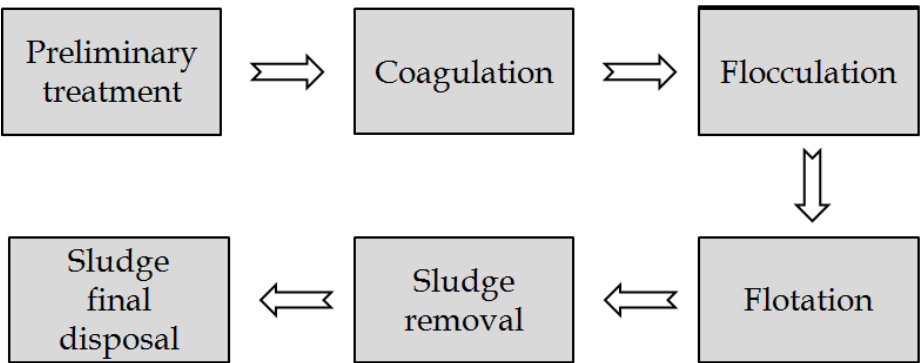
According to the Brazilian Institute of Geography and Statistics (IBGE, 2011), there was an increase in the availability of the sewage system (i.e. wastewater collection) in the urban areas of the country from 1992 (46%) to 2009 (59%). Similar increase was observed for the availability of the solid waste collection services (62% in 1992 and 82% in 2009). The situation was worse in the rural areas, where the figures for sewage system and water supply systems reached only 5% and 33% in 2009, respectively (Fig. 2). In the year 2000, only 20% of the Brazilian municipalities treated the domestic wastewater (IBGE, 2000). The remaining loads ended up in the water bodies, contributing to water quality degradation (e.g. by increasing organic matter content and decreasing dissolved oxygen concentrations).

As shown for Brazil, the sanitation conditions in other developing countries are similar: higher levels of drinking water and sewage systems in urban areas, as compared to rural ones (Massoud et al., 2009). According to the WHO (2010), people living in low-income nations are least likely to have access to adequate sanitation infrastructure. The absence of sanitation and the access to unsafe water are therefore risk factors that are linked with increased mortality and morbidity worldwide.

2.2 *In situ* remediation technologies

Dissolved Air Flotation (DAF), Ultrafiltration Membranes (UM) and Enhanced Biological Removal (EBR) are examples of *in situ* technologies for water or wastewater treatment (Table 1). Such technologies can be used either individually or in association (Geraldes et al., 2008).

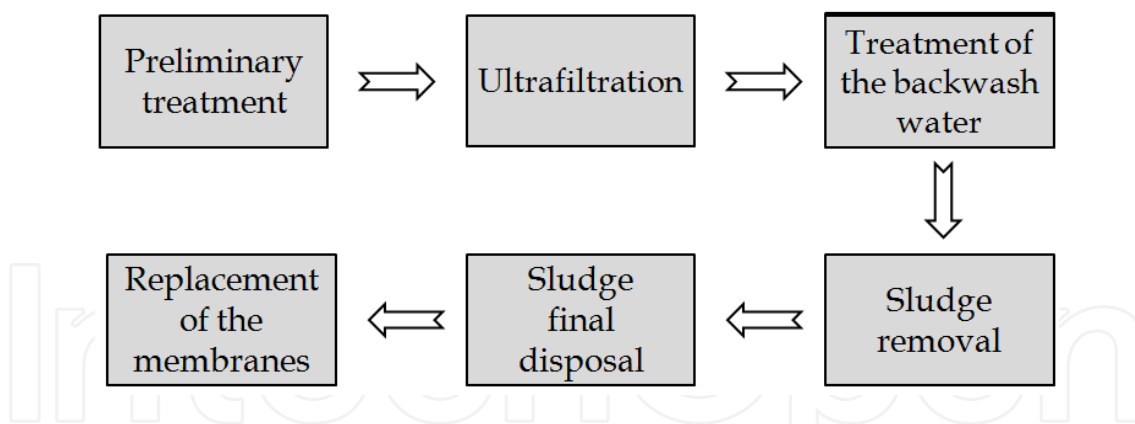
The DAF consists of the following steps:



- i. **Preliminary treatment** – barriers are installed in the river channel to remove coarse material;
- ii. **Coagulation** – chemical compounds are added to the water to promote the coagulation (e.g. ferric chloride or aluminium hydroxide). Specific coagulation time and velocity gradients are needed;
- iii. **Flocculation** – through certain flocculation time and velocity gradient, flakes are formed by aggregation of colloids;
- iv. **Flotation** – small air bubbles are produced in the bottom of the river channel and their upward movement is able to bring the colloidal and particulate matter to the water surface, as a sludge;
- v. **Sludge removal** – the sludge is removed from surface water through rotating blades or other mechanical device;
- vi. **Sludge final disposal.**

The operation costs of a DAF system vary between 0.10 and US\$0.20/m³. One of the biggest concerns in the DAF plants is the significant consumption of chemicals for aggregation and flocculation of colloids and consequently the high production of sludge. Different processes have been used for thickening and dewatering the sludge produced by DAF (i.e. increasing the solids content) and reducing its volume (Dockko et al., 2006). However, the feasibility of the alternative for final sludge disposal (e.g. application in the agriculture or disposal in a landfill) depends upon its toxicity due to the presence of metals and other persistent pollutants (Mantis et al., 2005; Luz et al., 2009).

The treatment process with UM is based in the following steps:



- i. **Preliminary treatment** – removal of coarse material and sand;
- ii. **Ultrafiltration** – the water passes through semipermeable membranes;
- iii. **Treatment of the backwash water** – the contaminants rejected by the membranes accumulate on the membranes forming a fouling layer and requiring a periodical backwash to remove the debris. The water used for backwash has to be treated as it contains high concentrations of pollutants;
- iv. **Sludge removal from backwash water;**
- v. **Sludge final disposal;**
- vi. **Replacement of the membranes** – the replacement must be achieved according to the membrane life, usually estimated as 5 to 8 years.

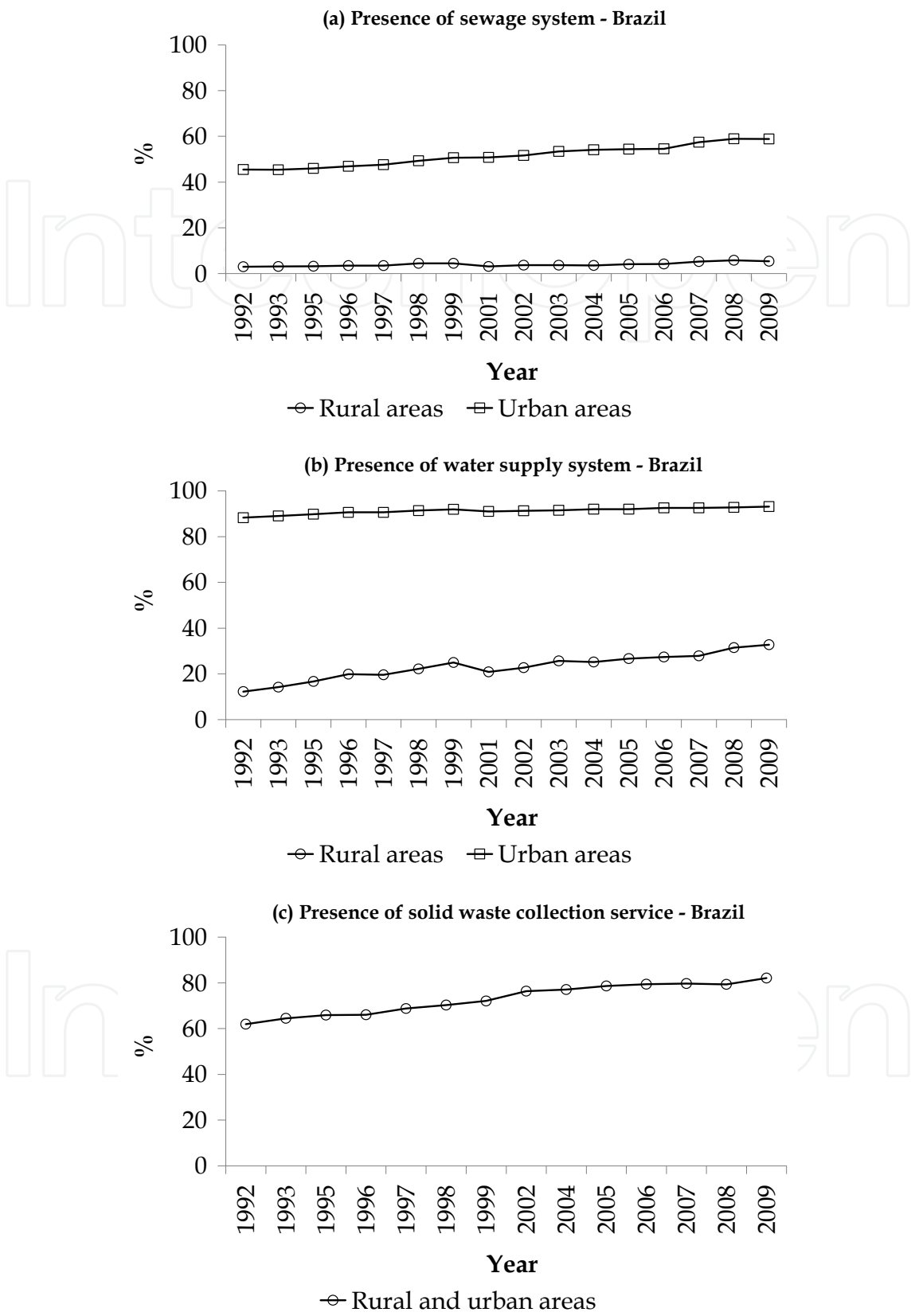


Fig. 2. Evolution (%) of the availability of the (a) sewage, (b) drinking water supply systems and (c) solid waste collection services in Brazil from 1992 to 2009. Reference: IBGE (2011).

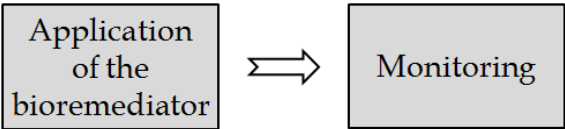
In situ technology	Brief description	Total operating costs (US\$/m ³)	Benefits	Limitations
Dissolved Air Flotation (DAF)	Small air bubbles carry the impurities to the surface (as sludge) after previous coagulation and flocculation	0.10 – 0.20	- High efficiency for the removal of some nutrients (e.g. phosphorus), hydrocarbons and surfactants	- Significant amount of sludge to be managed - Chemicals consumption for coagulation and flocculation
Ultrafiltration Membranes (UM)	The water is forced against a semipermeable membrane	0.03 – 0.25	- No addition of chemicals - The membranes may be fed with the water course own pressure - Smaller footprint	- Preliminary treatment is required to remove coarse and sand material (to protect the membranes) - Treatment of the backwash water is necessary
Enhanced Biological Removal (EBR)	The growth of certain types of bacteria and the biological conversion are stimulated with the addition of specific enzymes or inoculums (commercially available: see Table 2).	0.01 – 0.15	- Minimum infrastructure is required - Some added reagents increase gas transfer rates and dissolved oxygen concentrations - Degradation of toxics - Rapid odor elimination	- Acceptability of the addition of inoculums to the aquatic systems, especially if they are exogenous and if the surface water is used for drinking water production

Table 1. Brief description of some *in situ* technologies: Dissolved Air Flotation, Ultrafiltration Membranes and Enhanced Biological Removal; comparison of their operating costs, efficiency and performance criteria.

The more stringent regulations regarding water quality associated with the reduction of costs of the ultrafiltration membranes have made this technology more attractive in the last years. UM can be used for drinking water production (Lainé et al., 2000; Xia et al., 2005) and river water treatment (Konieczny et al., 2009). The lower level of energy requirements and the lower consumption of chemicals are the main advantages of the UM systems. The need for frequent backwash preventing membrane fouling, especially when the organic matter content in the raw water is high, is an important issue to be managed.

However, the addition of a preliminary step with coagulation [e.g. with FeCl_3 , $\text{Fe}_2(\text{SO}_4)_3$ or $\text{Al}_2(\text{SO}_4)_3$] and flocculation may increase the efficiency of the system and avoid too rapid membrane fouling (Konieczny et al., 2006; Babel & Takizawa, 2011; Bergamasco et al., 2011). The treatment of the backwash water is also an issue because the effluent from the backwash contains significant concentrations of the pollutants previously accumulated on the membranes. The backwash water is normally sent to a thickening tank, where the suspended matter settles to the bottom (as sludge). The clear water on top is then pumped to the upstream part of the treatment plant. Some recent studies consider the recycling of the backwash water as an interesting alternative, e.g. through a blending of 10% of backwash water and 90% of raw water (Gora & Walsh, 2011). The operating costs of the UM are expected to approximately range between 0.03 and US\$0.25/m³ and the main factors influencing the costs are the quality of the water to be treated, labor, energy and chemicals (if any) consumption as well as membrane replacement.

The EBR in turn is based in a single step, the **application of bioremediators** (Table 2) in the river or reservoir to be treated and subsequent monitoring of their efficiency in relation to the targeted pollutants.



The bioremediators, which can be microorganisms (e.g. bacteria) or enzymes, are able to increase biodegradation and gas transfer rates. There is a considerable variety of products available in the market. Some examples are shown in Table 2 with the commercial name of the bioremediators, their definition, main applications and highlights according to their manufacturer. The bioremediators are expected to perform the removal, transformation or detoxification of pollutants from the aquatic environment into a less toxic form (Whiteley & Lee, 2006). The effect of the bioremediators is normally based in the combination of several processes, like solubilization (physical), oxidation (chemical) and catalysis (biological). Some recent studies have recognized the effectiveness of enzymatic processes of water remediation, mainly when associated with established technologies (Demarche, in press). However, some factors like costs and stability of the biocatalysts require further investigation.

There are two broad types of remediation through microorganisms: biostimulation (stimulation of the growth of indigenous microorganisms) and bioaugmentation (introduction of specific microorganisms to the local population). In both cases, predation, competition, adaptation to the environmental matrix (water, wastewater), possible adsorption on available solids as well as survival strategies play an important role in determining the overall efficiency of the remediation (Fantroussi & Agathos, 2005). The use of immersed biofilms (e.g. artificial plastic substrates) is also an alternative to perform water treatment taking advantage of the nutrient uptake by algae (Jarvi et al. 2002) or the organic matter degradation by bacteria (Bishop, 2007). Although biofilms are usually unwanted in drinking water treatment stations due to the biofouling, they may be useful for water remediation and biodegradation of persistent compounds. Ammonia-nitrogen concentrations removal, for example, may be considerably improved with the growth of nitrifying bacteria (Jiao et al., 2011).

Company / Product	Definition	Highlights
Bio-Organic Catalyst™	“Fermentation supernatant derived from plants and minerals, which is blended synergistically in combination with a non-ionic surfactant to create a broad spectrum bio-organic catalyst”	- Dissolved oxygen levels increase - Biological nitrogen removal is enhanced - Solubilization rates of insoluble fats, oils and grease increase
Advanced BioCatalytics Corporation/ Accell3 Green™	“Refined, fermentation-derived, bioactive stress proteins that are formulated with surfactants”	- Bacterial metabolism is enhanced to accelerate the breakdown of organic material by oxidation - Organic contaminants are digested more rapidly and more completely to carbon dioxide and water
Enzilimp™	“Facultative bacteria are added to boost the nitrogen cycle and accelerate the organic matter degradation”	- Odors elimination - Reduction of Total and Fecal Coliforms, Biochemical and Chemical Oxygen Demand
Bioplus Biol2000™	“Facultative bacteria that are able to promote the degradation of organic compounds from industrial effluents”	- Biochemical and Chemical Oxygen Demand reduction - Phosphorus and nitrogen concentrations decrease
BioTC™ Rinenbac/Rinenzim	“Specific bacteria to stimulate degradation of fats and organic matter”	- Odors elimination - Reduction of Coliforms and Biochemical Oxygen Demand
Realco™ Realzyme	“Enzymes that are able to transform biofilms into water-soluble organic residues”	- Avoid the contamination from a biofilm

Table 2. Examples of some bioremediators available in the market, including their definition and major benefits, according to their manufacturer.

3. Case study with DAF: The Pinheiros River (São Paulo State, Brazil)

The Pinheiros River (23°42’S; 46°40’W) is located in the Southeast Region of Brazil (Fig. 3) in an extremely urbanized area in the Metropolitan Region of São Paulo, whose population is approximately 19.7 million inhabitants. This river links the Tietê River to the Billings Reservoir (storage volume: 995 million m³; residence time: 30 months), a multipurpose water system used for drinking supply, energy generation (through Henry Borden Power Plant), navigation and recreation.

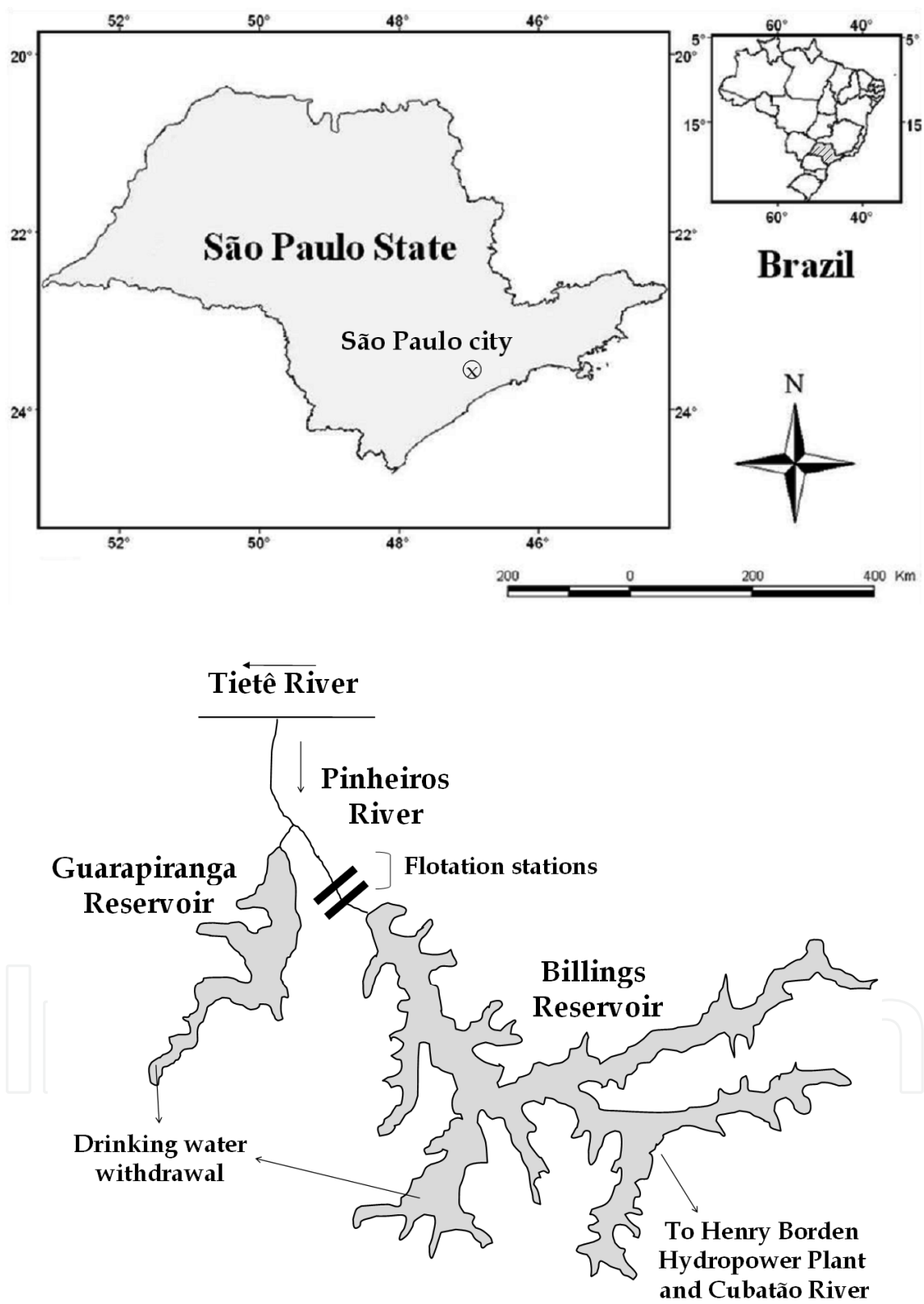


Fig. 3. Map of the São Paulo State, located in the Southeast Region of Brazil, and a scheme of the Tietê and Pinheiros Rivers and the Billings and Guarapiranga Reservoirs, two important multipurpose reservoirs in the area.

Considering the technology availability and the need for recovering the Pinheiros River water quality to assure no impacts to the Billings Reservoir, the DAF was tested. The *in situ* DAF pilot-scale system, composed by two treatment plants (Zavuvuz - 23°40'44''S; 46°41'53''W and Pedreira - 23°42'01''S; 46°40'56''W), was installed in the Pinheiros River channel to treat 10 m³/s (Table 3) with subsequent pumping of the water to the Billings Reservoir (Fig. 4). Previous coarse material removal was necessary. Coagulation with ferric chloride and flocculation were followed by the flotation step (i.e. the production of tiny air bubbles in the bottom of the river). The upward movement of such bubbles was responsible for bringing the impurities to the surface, where they were collected through rotating blades for sludge removal. The treated flow (10 m³/s) of the system installed in the Pinheiros River is significantly bigger than other similar treatment stations in Brazil: 0.05 m³/s reported by Lopes & Oliveira (1999), 0.15 m³/s (Oliveira et al., 2000) and 0.75 m³/s (Coutinho & von Sperling, 2007).

Operational parameter or variable (unit)	Value or range
Tietê River mean flow (m ³ /s)	120
Pinheiros River mean flow (m ³ /s)	5*
Zavuvuz Stream mean flow (m ³ /s)	0.7
Treated flow (m ³ /s)	10
Recycle flow (m ³ /s)	0.8 – 1.0
Hydraulic detention time (min)	25 – 30
Ferric chloride dosages (mg/L)	50 – 400
Rapid mixing (coagulation) time (min)	0.5
Rapid mixing velocity gradient (/s)	800
Slow mixing (flocculation) time (min)	27
Slow mixing velocity gradient (/s)	60
Sludge production in both plants (m ³ /day)	150
Solids content in the sludge after centrifugation (%)	20
Energy consumption in both plants (kWh/day)	42,000

Table 3. Major operational parameters or variables of the *in situ* DAF pilot-scale system (both plants) in the Pinheiros River, São Paulo, Brazil. * When the pilot-scale system was operating, there was a contribution from the Tietê River waters to the total flow of the Pinheiros River. Reference: adapted from Cunha et al. (2010).

The system was operated from August 2007 to March 2010. A comprehensive monitoring program (148 water variables and more than 200,000 laboratory analyses) was delineated to assess the efficiency and feasibility of the pilot-scale prototype. Detailed information about the monitoring results in the Tietê and Pinheiros Rivers and in the Billings Reservoir may be found in some recent papers (Cunha et al., 2010; Cunha et al., 2011a and Cunha et al., 2011b). The efficiency achieved by each flotation station and the overall effect for some variables is shown in Table 4. The global removal efficiency achieved by both DAF treatment stations was 90% for total phosphorus, 54% for apparent color, 53% for chemical oxygen demand, 48% for turbidity, 40% for total suspended solids, 31% for soluble iron and only 2% for nitrogen-ammonia. The prototype promoted an increment of about 60% in the dissolved oxygen concentrations.

Through the operation and performance assessment of the DAF system, some positive aspects have been observed:

- i. The technology was available and the local government was willing to promote the reclamation of the water quality of the Pinheiros River and to stimulate additional energy generation with the Billings Reservoir water. The conjunction of technology availability, environmental and economic issues (as shown in Fig. 1) proved to be important to boost actions towards effective water management;
- ii. The treated flow that was transferred to the Billings Reservoir (10 m³/s) was convenient for favouring the different water uses in the reservoir, such as energy and drinking water production;
- iii. Considering the combined effect of both treatment stations, the pilot-scale system reached a significant percentage of removal of total phosphorus, one of the targeted nutrients whose loads to the Billings Reservoir must be reduced to help preventing the artificial eutrophication.

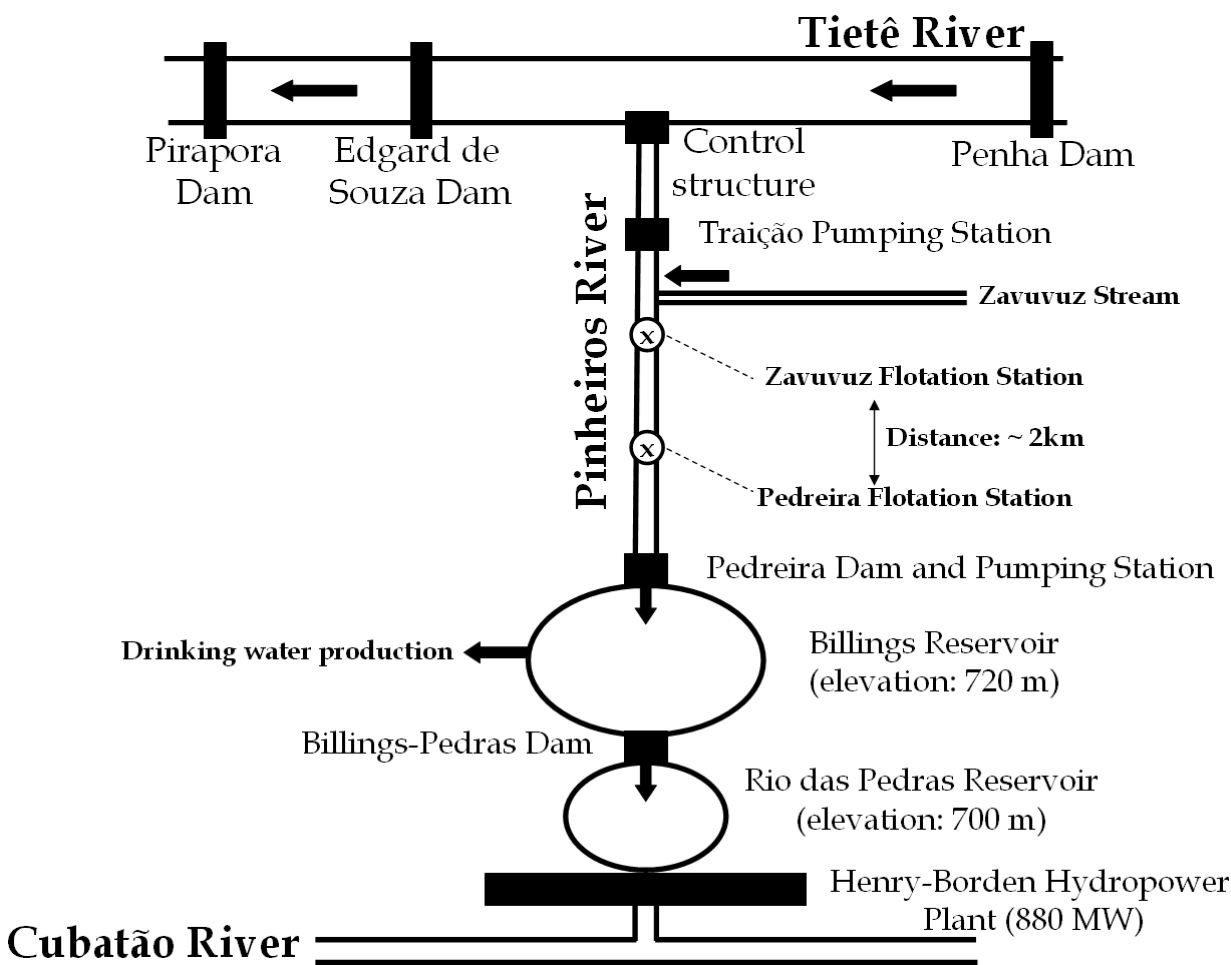


Fig. 4. Scheme of the *in situ* DAF pilot-scale systems placed in the Pinheiros River. Reference: adapted from Cunha et al. (2010).

However, our experience indicated the following negative factors and limitations:

- i. The operation and maintenance of an “opened system” have to consider the potential influences of external factors, like sudden changes in the water flow and quality, both natural or human-induced;
- ii. Sludge production and energy consumption were high. During the studied period, the sludge was sent to a landfill because no other alternative was considered safe due to the significant level of contamination (e.g. by heavy metals);
- iii. As expected, ammonia-nitrogen was not removed by the DAF system and we assume that the high concentrations of this nutrient in the Billings waters may contribute to water quality decrease, affecting the aquatic life. A biological component with adequate residence time would probably be necessary for removing ammonia-nitrogen. Total suspended solids and metals (aluminium, chromium and iron) concentrations were also high in the treated water.

Variable	Relative efficiency (%) of removal (–) or increase (+)		
	Zavuvuz Flotation Station	Pedreira Flotation Station	Overall effect
Aluminium (soluble)	–17	null	null
Ammonia-Nitrogen	–1	–1	–2
Apparent color	–48	–27	–54
Cadmium (total)	–22	–17	–22
Chromium hexavalent	null	–33	null
Chemical oxygen demand	–41	–18	–53
Copper (total)	–13	–14	–60
Dissolved oxygen	+69	+24	+63
Ionic conductivity	null	null	null
Iron (soluble)	–19	null	–31
Lead (total)	–18	–42	–36
Total phosphorus	–48	–84	–90
Total suspended solids	–30	–10	–40
Turbidity	–37	–35	–48

Table 4. Efficiency (%) of removal (–) or increment of the *in situ* DAF pilot-system in the Pinheiros River. Reference: adapted from Cunha et al. (2010).

The DAF system in the Pinheiros River has focused on integrative approach, technology application, environmental quality and sustainability in the long-term. Nevertheless, since some inefficiencies and gaps were detected, further studies regarding sludge management and efficiency improvement for the removal of some variables (e.g. through complementary processes like those previously described in this chapter) are necessary. Urban waters in developing countries are a challenging issue and the operation of the DAF system in the Pinheiros River was an important contribution for the water resources management.

4. Conclusion

The term “developing countries” is often used to describe nations whose inhabitants have a standard of living between “low” and “medium”, a growing industrial base and a rising Human Development Index. According to Kofi Annan (Secretary-General of the United Nations from 1997 to 2006), “developed country is one that allows all its citizens to enjoy a free and healthy life in a safe environment”.

Therefore, environmental sustainability is an important step towards the full development of the developing countries, with a view to ensuring social equity, economic strength and environmental quality. Specifically regarding the management of water resources, two main issues should be considered. Our chapter has shown that the implementation of sanitation facilities (e.g. sewage collection and treatment systems) requires significant investments with long-term returns. On the other hand, the remediation of polluted rivers and reservoirs should be seen as a short-term palliative and emergency action to prevent these aquatic systems to reach levels of irreversible degradation, before necessary wastewater collection and treatment are available. The *in situ* approach for remediation may be desirable from the environmental point of view and also economically convenient. By analyzing the main benefits and limitations of three *in situ* technologies (Dissolved Air Flotation, Ultrafiltration Membranes and Enhanced Biological Removal), our investigation has suggested that the costs of remediation of aquatic systems ranged from US\$ 0.01/m³ (the cheapest cost in the range for treatment with bioremediators) to US\$ 0.25/m³ (the most expensive cost in the value range for ultrafiltration membranes). The technologies described in this chapter can be used simultaneously (for example, the DAF associated with the biological treatment with enzymes or with biofilms) to increase the efficiency and meet environmental standards. Although further research is required to find alternatives to solve the detected inefficiencies, our experience with the operation of a pilot-scale DAF system in the Pinheiros River (São Paulo, Brazil) was positive. It has indicated that integrated concepts of water management are necessary to explore urban waters as resources (and not risks) for human activities.

A well-balanced combination of actions, policies and programs for increasing the levels of sanitation coverage and promoting the remediation of impacted aquatic systems is a great opportunity to the developing countries. Political commitment, technology development or transfer from other country, comprehensive monitoring and involvement of the local citizens are factors that can legitimate the whole process and increase the probability of economic and environmental effectiveness and public acceptability.

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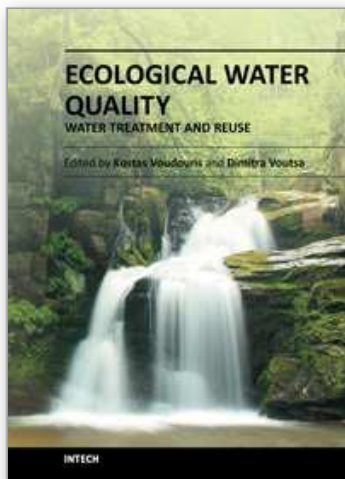
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