



## Taking advantage of storm and waste water retention basins as part of water use minimization in industrial sites

Karla Patricia Oliveira-Esquerre<sup>a</sup>, Asher Kiperstok<sup>b,\*</sup>, Mario Cezar Mattos<sup>b</sup>, Eduardo Cohim<sup>b</sup>, Ricardo Kalid<sup>a</sup>, Emerson Andrade Sales<sup>c</sup>, Victor Matta Pires<sup>d</sup>

<sup>a</sup> Federal University of Bahia (UFBA), School of Engineering, Department of Chemical Engineering, Rua Aristides Novis, 02 Federação, 40210-630 Salvador, Bahia, Brazil

<sup>b</sup> Federal University of Bahia (UFBA), School of Engineering, Department of Environmental Engineering, Clean Technology Network of Bahia (TECLIM), Rua Aristides Novis, 02, Federação, 40210-630 Salvador, Bahia, Brazil

<sup>c</sup> Federal University of Bahia (UFBA), Institute of Chemistry, Department of Physical Chemistry, Campus de Ondina, 40170-290 Salvador, Bahia, Brazil

<sup>d</sup> Braskem's Raw Materials Unit (UNIB), Rua Eteno, 1561 Pólo Industrial de Camaçari, Camaçari, Bahia, Brazil

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### ABSTRACT

A methodology for water use minimization has been developed by the Clean Technology Network of Bahia over a 10 year period in joint cooperative programs with the chemical, petrochemical and copper metallurgy industries located in the largest Industrial Complex in Latin America, in Camaçari, Bahia, Brazil. The methodology comprises a set of tools including reconciled aqueous stream balances, database of aqueous streams; large scale training leading to the identification of water minimization alternatives in the processes, water reuse optimization approaches; geographical information systems as well as, consideration of the region's hydro and hydro-geological characteristics. The results of a study carried out to assess the possibility of using storm and wastewaters for industrial use is presented in this paper. The inorganic system is composed by three water reservoirs (basins) receiving stormwater contaminated with inorganic effluents, and occasionally with organics. These basins have been operated to control water flow inputs according to the capacity of the pumping outlet systems before their discharge to a submarine outfall. A mass balance was performed with historical updated data to assess water availability from the basins based on the daily volume variation and flow rate of inorganic effluent from 2001 to 2007. The study identified the possibility of recovering about 1140 m<sup>3</sup>/h of the overall 5400 m<sup>3</sup>/h consumed by the Industrial Complex at the moment. Organizational changes in the present effluent disposal and stormwater harvest systems will be required in order to maximize water recovery for industrial use.

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## 1. Introduction

As a result of both the absence of adequate water resource planning and management and the tendency in the water supply sector of constructing systems structured to provide clean water abundantly and inexpensively, human and industrial water use conflicts have been instigated (Tambo, 2003). Furthermore, problems with effluent discharges from industrial sources into the environment have been historically addressed by the use of end of pipe technologies.

\* Corresponding author at: UFBA, Escola Politécnica, Departamento de Engenharia Ambiental, Clean Technology Network of Bahia (TECLIM), Rua Aristides Novis, 02, Federação, 40210-630 Salvador, Bahia, Brazil. Tel.: +55 71 3235 4436; fax: +55 71 3283 9892.

E-mail addresses: [karla@gmail.com](mailto:karla@gmail.com) (K.P. Oliveira-Esquerre), [asher@ufba.br](mailto:asher@ufba.br) (A. Kiperstok), [mariocezarmattos@yahoo.com.br](mailto:mariocezarmattos@yahoo.com.br) (M.C. Mattos), [ecohim@ufba.br](mailto:ecohim@ufba.br) (E. Cohim), [kalid@ufba.br](mailto:kalid@ufba.br) (R. Kalid), [eas@ufba.br](mailto:eas@ufba.br) (E.A. Sales), [victor.mattapires@braskem.com.br](mailto:victor.mattapires@braskem.com.br) (V.M. Pires).

Today there is an ever-increasing recognition of the need to minimize water use and wastewater generation mainly because of the strict environmental regulations, economic considerations, environmental issues and restrictions on the expansion of water use at many sites (Gwehenberger and Narodslawsky, 2008; Goldblatt et al., 1993). Growing water demands have required either time averaging of runoff measures, attained by large capacity dams in upstream areas, or sparse averaging of runoff measures, by water transference to other basins (Tambo, 2003). An integrated industrial water cycle management (water supply, wastewater and stormwater) is needed to avoid or, at least minimize, environmental deterioration. In this sense, a better understanding of the benefits of water and wastewater reductions on industrial sites may be gained from considering the hydrological and hydro geological characteristics of the region.

Most industrial water minimization programs have focused on water and wastewater while stormwater usage practices have been considered mainly in urban water conservation programs (Hatt et al., 2006; Philippi et al., 2006). Irrigation and non-potable domes-

tic uses are the main types of end-use for these resources and no survey of general recycling practices has been carried out on a wide scale (Hatt et al., 2006). Even though stormwater is usually of better quality than industrial discharges (Mitchell et al., 2002), few cases of industrial use for stormwater have been reported in the literature (Thomas et al., 2002) and the most deals with roof water harvesting (Ajit, 2010; Georgia Rainwater Harvesting Guidelines, 2010; Silva, 2007; Sivanappan, 2006). With water use approaching and in some cases exceeding the limits of sustainability in many locations, stormwater for non-potable requirements including industrial uses must be considered. Water and wastewater minimization techniques have been widely studied, developed and applied to process industry (Lens et al., 2002; Mann and Liu, 1999). Rosain (1993) and Zver and Glavic (2005) have considered water minimization procedures based on the systematic approach for water reuse proposed by the Center for Waste Reduction Technologies (Byers et al., 1995) and on their experience in industrial plants. One of the tools for water use minimization is the maximization of water reuse and the identification of regeneration opportunities (Smith et al., 1994). Case studies in chemical (Rosain, 1993), petrochemical/refinery (Bagajewicz, 2000; Zbontar and Glavic, 2000), textile (Deul, 2002; Alvarez et al., 2004; Ujang et al., 2002), metallurgic (Bravo and Kiperstok, 2005), citrus (Thevendiraraj et al., 2005), sugar/distillery (Saha et al., 2005; Zver and Glavic, 2005) and thermal power (Mohsen, 2004) plants are reported in the literature. Water use surveys on industrial sites have also been applied (A1-Muzaini, 1998; Féres et al., 2008; Kiperstok et al., 2006).

Based on cleaner production concepts, a methodology for water use minimization has been developed by the Clean Technology Network of Bahia. This method has evolved over a 10-year period in joint cooperative programs with chemical, petrochemical and copper metallurgy industries located in Camacari's Industrial Complex in Brazil. The methodological tools are described in Section 2 and include reconciled aqueous stream balances, database of aqueous streams; large scale training leading to the identification of water minimization alternatives in the processes, water reuse optimization approaches; geographical information systems and the consideration of the region's hydro and hydro-geological characteristics. This paper briefly describes this methodology and presents the results of a study carried out to recommend organizational changes in the actual effluent disposal and stormwater harvest systems in order to maximize water recovery for industrial use at this industrial complex. This study is part of a joint research program called EcoBraskem which has been going on between Braskem and Teclim Network since 2002 and has promoted water use optimization as a result of the use of a cleaner production approach.

## 2. Clean Technology Network of Bahia (TECLIM)

### 2.1. Background and objectives

As mentioned by various authors (Deul, 2002; Rosain, 1993; Smith and Petela, 1992; Zver and Glavic, 2005), waste minimization practices are sustained by both behavioral and technological components. By bringing together industrial operators and academic institutions in cooperative research projects, a wider number of options can be considered. On the one hand, operators are under pressure to deliver short term results, while on the other, academics have the responsibility of thinking in the long term, of sustainable patterns of production. These considerations were paramount in the setting up of the Clean Technology Network of Bahia in 1998 (Kiperstok, 2000; Nascimento and Kiperstok, 2003).

**Table 1**  
Characteristics and diagnoses of industrial water usage.

Characteristics	Diagnose
Geographic location	Water is still seen as an abundant resource. The understanding of the hydrological and hydro geological characteristics of the region allows a better comprehension of the pros and cons of water and wastewater reductions in industrial sites
Cultural	Prevails the concept of water and waste water and the logistic still considers water as process input and waste water as output. Water is not classified considering its quality for different uses
Technological	Although water use and waste water generation minimization tools are well known, lack of data of enough quality in current plants, limits the contribution that these techniques may offer. Real plant improvements have to deal with complex decision taking processes that involve different personnel levels and company's priorities
Cost/Management	The low price paid for water and waste water treatment does not stimulate water metering and implementation of investments in this sense. Companies keep postponing investments on water metering in their annual plans due to other more profitable options
Legislation	Environmental regulations focus on waste water discharge. Water uses and energetic contents are not considered in the regulations

In order to attract industry professionals back to university to discuss cleaner production practices a post-graduation course was set up in 1998 and has been held on an annual basis with evening classes. So far more than 289 people have participated in the course and another 80 have opted to study further to master's level. Class exercises and final short research projects undertaken in the course have reviewed industrial and non industrial environmental problems, seeking cleaner production oriented solutions. Final course projects and dissertations may be found at [www.teclim.ufba.br](http://www.teclim.ufba.br), in Portuguese. Professionals from Bahia's environmental agency and even from the state Public Attorney's Office have also taken part in this course. This has enabled the development and spread of newer environmental attitudes such as 'at source practices'.

As a clear result of this interaction between industry, public offices and the university, cleaner production attitudes have been widely recognized in the Camaçari Industrial Complex. This has stimulated the setting up of cooperative research projects to optimize water and energy use on industrial sites. A further and decisive factor that supported these initiatives was the help of so-called Research and Development Sectorial Funds from the Brazilian Ministry of Science and Technology. These funds have stimulated cooperation between academic and research institutions to fulfill the national demand for applied research and innovation. In this institutional environment, several cooperative projects have been carried out by the Teclim Network. EcoBraskem is the most durable of these, having lasted about 5 years since 2002 (Fontana et al., 2005; Kiperstok, 2001, 2006, 2008).

### 2.2. Water use methodology and water minimization issues

Table 1 summarizes the status of the industrial water management identified during the research activities. Obviously, the presence of some professionals from the industry on the course could not account for an overall redirection of their environmental practices from end of pipe to more environmental preventive approaches. However, these professionals have helped to create the internal conditions within the industries to promote collaborative efforts towards these attitudes, by means of cooperative research projects.

The initial technical proposal was to introduce waste minimization practices using mass exchange network (MEN) synthesis, either using generalized optimization approaches (El-Halwagi and Manousiouthakis, 1989; Papalexandri et al., 1994; Sharatti and Kiperstok, 1996) or the water pinch approach as presented by Alva-Argáez et al. (2007), Smith and Petela (1992), Wang and Smith (1994). During the initial stages, contact between research groups directed the optimization efforts towards the use of the source diagram procedure (Queiroz and Pessoa, 2006). One of the reasons for this was ease of understanding and passing on this method to plant engineers.

As water is still quite a cheap utility in the region, poor measurement or rather lack of water measurement is a constant inside the industrial plants. To take this situation into account water mass balances have been built with assumed values. To reduce the level of uncertainties, reconciliation techniques have been used. As a result the few good quality measurements devices can propagate their quality of information throughout the whole water balance (Kong et al., 2004; Placido, 1995; Narasimhan and Jordache, 2000). These techniques, as well as the whole method used, have been presented elsewhere (Fontana et al., 2005; Kiperstok et al., 2001, 2006, 2008).

Reconciliation techniques came as the natural step after the difficulties of getting quality data were identified. Lack of information related to flow and quality of aqueous streams was initially overcome by getting available data from process flow sheets, experience and feeling of operators, expedite measurements, etc. To allow this data to be properly considered a quality of information record was attached to each of the values considered in the data bases (Martins et al., 2010).

When the issue of water conservation is raised inside industrial sites, several ideas from both operation and supervision levels emerge. To allow these to evolve and to stimulate further ideas and help them to be considered at decision taking moments, a Water and Energy Optimization Ideas Databank is set up on line in the company's internal information system. It may also be accessed through the webpage of Teclim and periodically ideas are surveyed by Teclim researchers, analyzed and improved.

Short 12-hour courses are delivered to all operational levels to instigate cleaner production practices. In these, a reduced version of the Unep/Unido Cleaner Production methodology (Luken and Navratil, 2004; UNEP, 2008) is shown. Participants are required to apply the methodology to generate waste minimization proposals which are stored in the Ideas Database to be further analyzed.

Chemical and thermodynamic requirements are insufficient to support decision making on water reuse, the logistics of stream transportation have to be considered together with safety, operability and control requirements. The integrated management of industrial water cycle supply, wastewater and stormwater also requires the use of tools that consider the location of water sources and consumers and it is here that Geographical Information Systems have been used.

While water conservation practices are partially applied, two alternative centralized water reuse options have been investigated. Harvesting stormwater from wastewater reservoirs built to operate as accumulation basins for pumping inorganic effluents and rain water into a submarine outfall is one of the options and is presented in this paper. Another option considers reusing the contaminated groundwater removed by a pump-and-treat system operated in the Industrial Complex and designed to protect both the São Sebastião Aquifer and surface water sources. This system is composed of 14 wells strategic located and screened at different levels to extract groundwater contaminated with organic effluents. By developing a systematic statistical analysis of recorded data, the study identified the possibility of reusing 50–120 m<sup>3</sup>/h of contaminated groundwater.

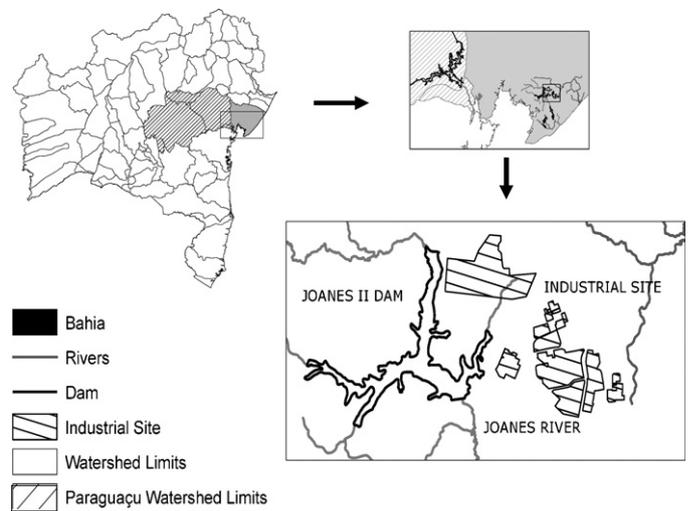


Fig. 1. Location of Camaçari Industrial Complex with respect to Salvador City.

### 3. Case study

#### 3.1. Camaçari Industrial Complex

The State of Bahia (Fig. 1) is the largest state in the north-east of Brazil, with a population of 13 million inhabitants and an area covering over half a million km<sup>2</sup> (PERH-Ba, 2004). Water demand with respect to the total availability is not so high but water resources are unevenly distributed in both time and location. The Central and North regions of the State are characterized by scarce and highly irregular rainfall in contrast to a plentiful water supply and greater rainfall in the West, South and coastal regions. The most densely occupied areas of the State include the metropolitan region of Salvador and the Camaçari Industrial Complex (Fig. 1). About 40% of the population of the State of Bahia live in the metropolitan region of Salvador, demanding on average 43,200 m<sup>3</sup>/h of water whereas the Industrial Complex requires approximately 5700 m<sup>3</sup>/h to produce more than 11.5 million tons of primary, intermediate and final chemical and petrochemical products per year. Such levels of production supplies more than half of the country's chemical/petrochemical market demand and approximately 35% of the total worldwide export volume from the State of Bahia.

The majority of the companies at the Complex are connected through a pipe network to Braskem's Raw Materials Unit (UNIB). The largest company at the Camaçari Industrial Complex and one of the five major private enterprises in the country, Braskem/UNIB, receives petroleum-by-products, mainly naphtha, from Petrobrás and processes them into primary olefins (mainly ethylene) and aromatics. Its utility facilities also include water treatment units which produce clarified, drinking and demineralized water for internal use and for almost all the other companies at the Industrial Complex.

Increasing environmental concern as regards water use minimization has been observed at the Industrial Complex since its installation in the late 1970s. At that time, petrochemical production required *c.a.* 5400 m<sup>3</sup>/h of water for a production of 380,000 t/year of ethylene, its main petrochemical product. In 1989, the duplication of the Industrial Complex boosted a significant number of water disposal regulations in terms of quality and quantity, and this forced the industries to treat or reduce its pollutants within its plants and to adopt new policies of pollution control and water reuse (Marinho and Kiperstok, 2001). Since then, the production of ethylene has increased by 178%, from 460,000 t/year to

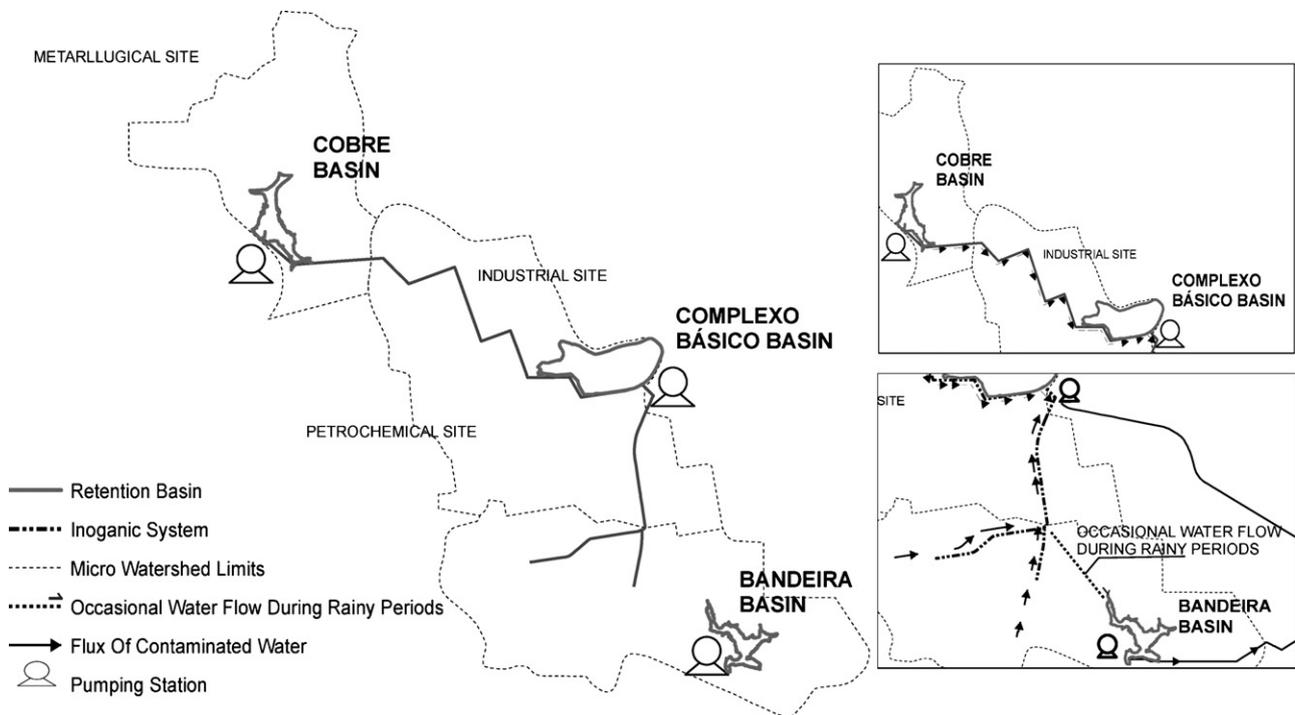


Fig. 2. Schematic sketch of the inorganic effluent drainage system (PS, pumping station). Source: Cetrel – Environmental Protection Industry (2002).

1,280,000 t/year, while water consumption has increased by 12%, from 4800 m<sup>3</sup>/h and 5400 m<sup>3</sup>/h.

The environmental protection programs at the Industrial Complex are managed by Cetrel – an Environmental Protection Company and include treatment and disposal of liquid effluents, disposal of solid waste, incineration of hazardous waste, air monitoring and water resource management. About 2500 m<sup>3</sup>/h of inorganic and organic effluent are produced by the Complex, and through two separate wastewater systems the organic effluent is directed to an activated sludge treatment system and then to a submarine outfall. This outfall also receives the inorganic effluents. This end-of-pipe approach has reduced the direct release of several pollutants to achieve regulatory compliance.

### 3.2. The inorganic system

The inorganic effluent drainage system at the Industrial Complex is composed of a 30 km network of collecting open channels, three basins (each with pumping stations) and a main channel that conducts the inorganic effluents to a submarine outfall 4.8 km inside off shore in the ocean. A schematic outline of this system is shown in Fig. 2.

The attenuation basins (Complexo Básico, Cobre and Bandeira) were designed to accumulate rain water contaminated with inorganic effluents, and occasionally with organics, during intense rain events common in tropical areas. To reduce the risk of contaminated material reaching Jacuípe and Joanes rivers, these basins are operated at <30% of their capacity under normal operation conditions. A close view of the flows during drought and rainy periods is

also shown in Fig. 2; contaminated water stored in the Cobre and Bandeira basins is also pumped to the main channel. Some specific characteristics of these basins are shown in Table 2.

Note that the actual capacity of the main basin is lower than the original one because in the early stages of the Industrial Complex construction and operation, significant soil removing occurred, resulting in soil erosion and deposition in lower areas.

After 30 years of operation of the Industrial Complex the environmental practices in industries have generally been improved. As a result, inadequate discharges into these basins have been notably reduced making it possible to consider the waters in them as alternative water sources for industrial use.

### 4. The mass balance of the inorganic waste water system basins

The water balance of each basin was determined by calculating the inputs, outputs, and storage changes of the stored water volumes using recorded data from a 7-year period. As the basins had been designed to work as attenuation reservoirs, an increase in the pump flow rate follows, and sometimes antecedes, the increase in the water volume in order to keep the basin with at least 70% of its capacity free. A close view of this phenomenon for the Complexo Básico basin is shown in Fig. 3.

The averaged total flow rate of inorganic effluent drained through the inorganic system are *c.a.* 1000 m<sup>3</sup>/h and lower than 10 m<sup>3</sup>/h, in dry weather operational conditions. Therefore, the increase in pumping during heavy rainfall shows that water of good quality has been discharged. Eq. (1) describes the water balance in

Table 2  
Attenuation basins characteristics at the Industrial Complex.

Basin	Original capacity (m <sup>3</sup> ) <sup>a</sup>	Actual capacity (m <sup>3</sup> )	Pumping station capacity (m <sup>3</sup> /h)	Potential overflow risk
Complexo Básico	2,021,000	1,600,000 <sup>b</sup>	12,000	Jacuípe River
Cobre	808,000	– <sup>c</sup>	4500	Joanes River
Bandeira	412,000	– <sup>c</sup>	2500	

Sources: <sup>a</sup>EIA/RIMA (1989); <sup>b</sup>Cetrel – Environmental Protection Industry (1999). <sup>c</sup>Not known.

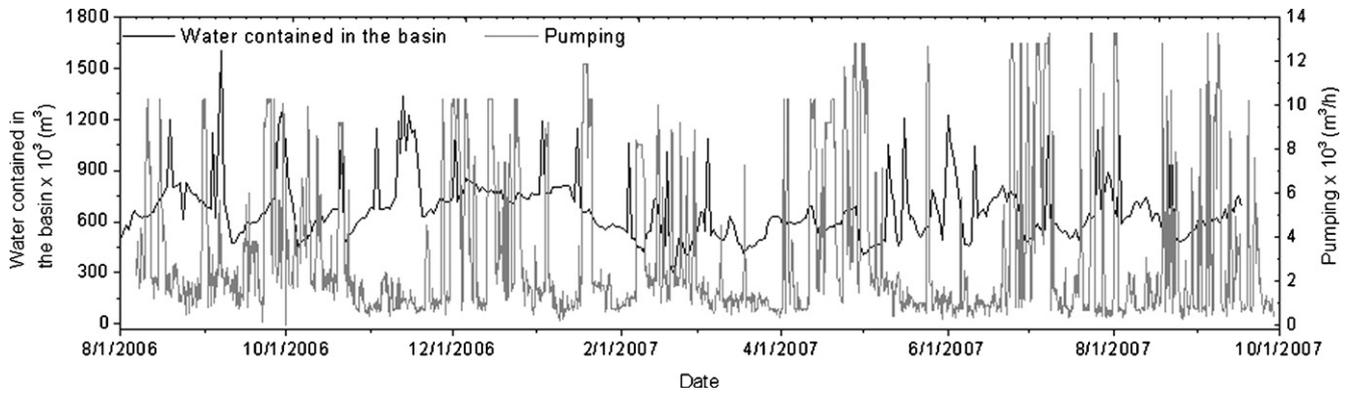


Fig. 3. Water contained in the Complexo Básico basin and pumped flow rate (2006 and 2007).

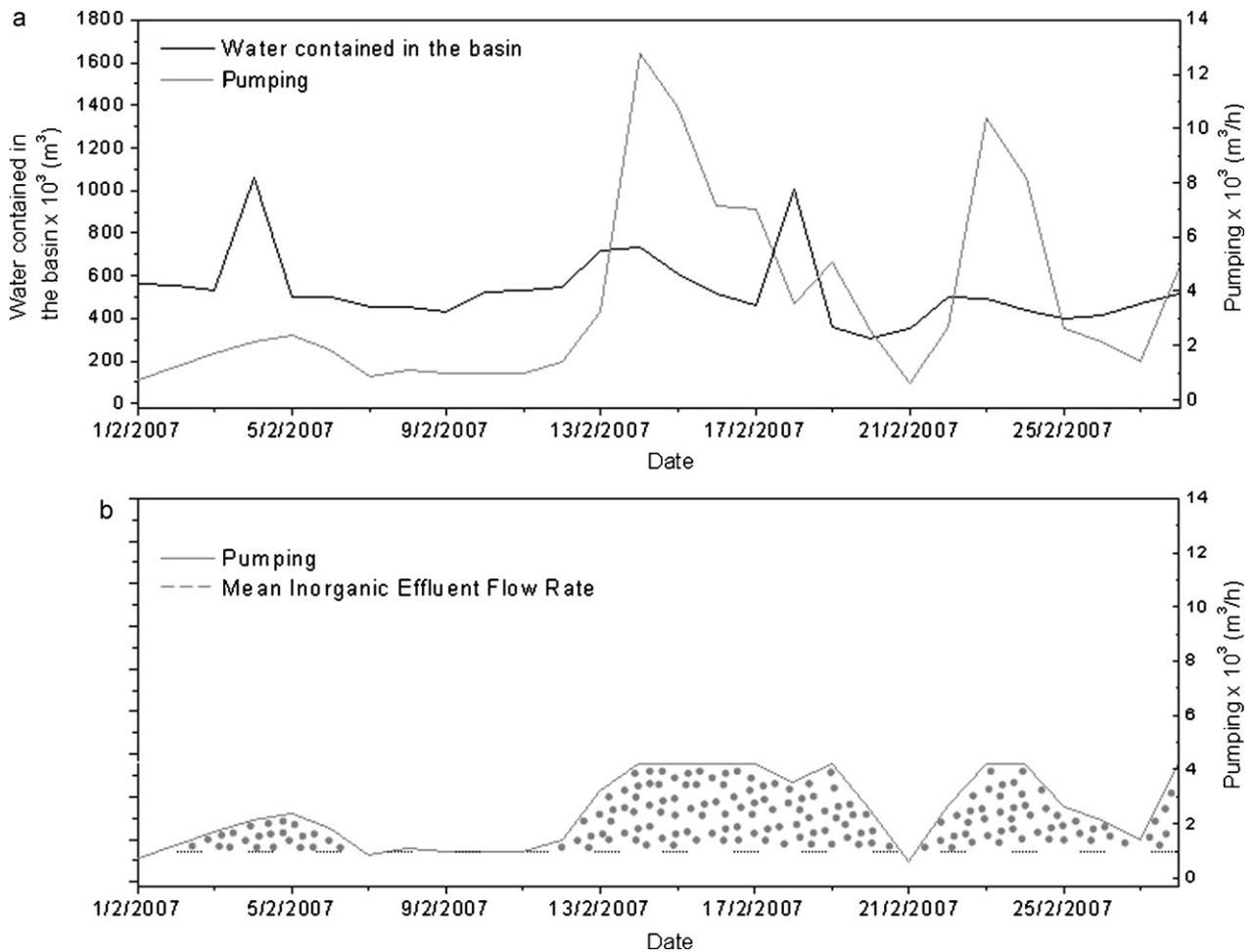


Fig. 4. Water contained in the Complexo Básico basin and pumped flow rate (February 2007).

the basin:

$$V_A = \frac{\Delta V}{\Delta t} + Q_P - Q_I \quad (1)$$

where  $V_A$  represents the rainwater volume plus the possible natural flow of superficial groundwater that reaches the basin,  $\Delta V/\Delta t$  is the change in stored water volume over one-day period,  $Q_P$  is the volume of contaminated water pumped from the basin and  $Q_I$  is the mean volume of inorganic effluent produced in the Industrial Complex reaching the basin.

This research considers  $V_A$  the daily volume of water available for use. This value cannot exceed the current water treatment

capacity of Braskem/UNIB<sup>1</sup> which is equivalent to 3200 m<sup>3</sup>/h. Therefore, as shown in Fig. 4(a) and (b), the area below the pumping curve of 4200 m<sup>3</sup>/h and above the mean inorganic effluent, reaching the Complexo Básico basin, the flow rate of 1000 m<sup>3</sup>/h represents the majority of the actual volume available for industrial use.

<sup>1</sup> The actual Braskem/UNIB's water clarification capacity is 3200 m<sup>3</sup>/h. Since this unit is intended to receive the water to be produced from the attenuation basins, drinking water production is planned to be removed from this unit.

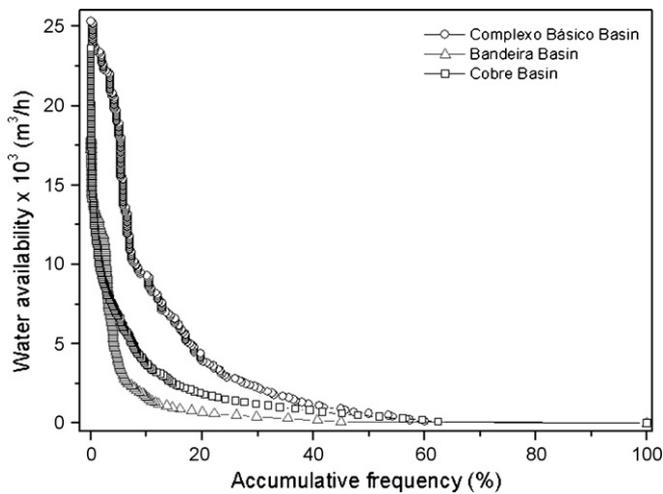


Fig. 5. Water availability in each basin.

Table 3

Annually averaged flow rates of water available for industrial usage and estimated reduction of the actual industrial water pumped from Joanes River.

Basins	Annually averaged flow rate (m <sup>3</sup> /h)	Estimated reduction on the actual water harvest (%) <sup>a</sup>
Complexo Básico	1140	20
Cobre	870	15
Bandeira	440	8

<sup>a</sup> The total reduction is lower than the sum of the individual one because the Complexo Básico basin receives water from Cobre basin, mainly during raining periods.

## 5. Modeling results

### 5.1. Water availability

Fig. 5 shows the water availability from each of the three basins obtained by picturing the accumulative frequency. Table 3 presents the annually averaged flow rates of water available for industrial use from these basins. The impact of changing the actual water pumped from Joanes River to UNIB's water treatment plant is also highlighted in Table 3.

The use of water accumulated in the attenuation basins means the decentralization of industrial surface water withdrawn at the Industrial Complex. By reducing water demand from the regional sources, the need for the transposition of water resources from the semi-arid region of Paraguaçu to Salvador's metropolitan region is also reduced. Through changing some operational procedures in the inorganic system, the basin may further operate as an accumulation basin and, consequently, increase the amount of available water.

### 5.2. Stormwater withdraw

In terms of supply continuity, the Complexo Básico basin is the main water source because it has the greatest storage capacity and receives water from the other basins during rainy periods. The necessary measures to implement the proposed water withdrawal from the Complexo Básico basin are quite simple. These include the installation of an overflow gate at the end of the main channel of the inorganic system, with the objective of diverting dry time contribution (mainly inorganic effluents) from reaching the basins. A floating withdrawal has been suggested to install inside the basin to pump water to the treatment facility. Furthermore, normal operation at over 30% of the basin's capacity can also be suggested as the quality of possible overflows from the basins will be improved, as commented on in the following section.

As mentioned, while the above technological measures will lead to an improvement in the stored water quality, inorganic effluents with low dilution will be pumped to a submarine outfall. This will not represent a real constraint because this effluent is composed of an overwhelming quantity of inorganic and by rain-washing diluted organics that will suffer rapid dilution and dispersion in the ocean.

### 5.3. Water quality

About 90 quality parameters for the inorganic effluent, generated and disposed of by the industries, are monitored by Cetrel at the main pumping station. Time series plots of some parameters considering daily values of the last 6 months are shown in Fig. 6.

Conductivity which measures water's ability to conduct an electric current and is directly related to the amount of dissolved salts

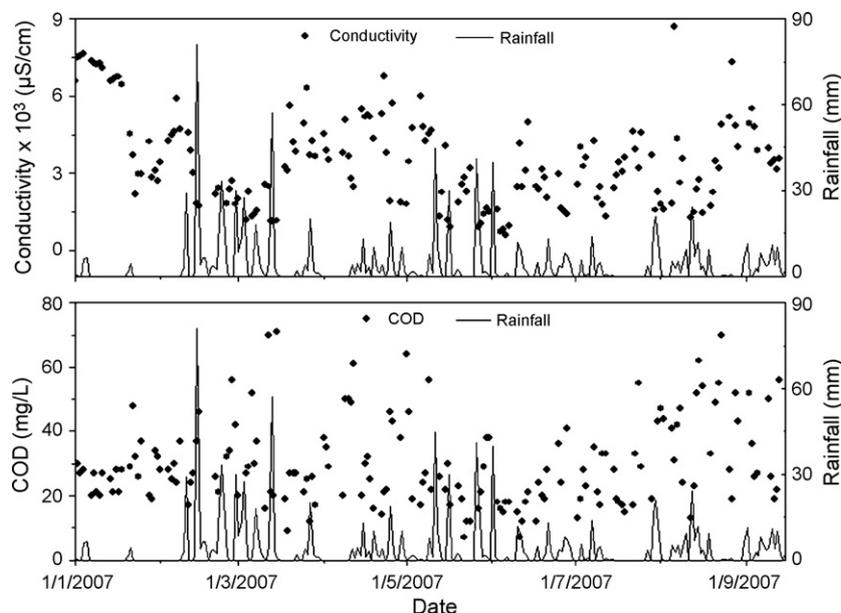


Fig. 6. Quality parameters of the contaminated water at the main pump station.

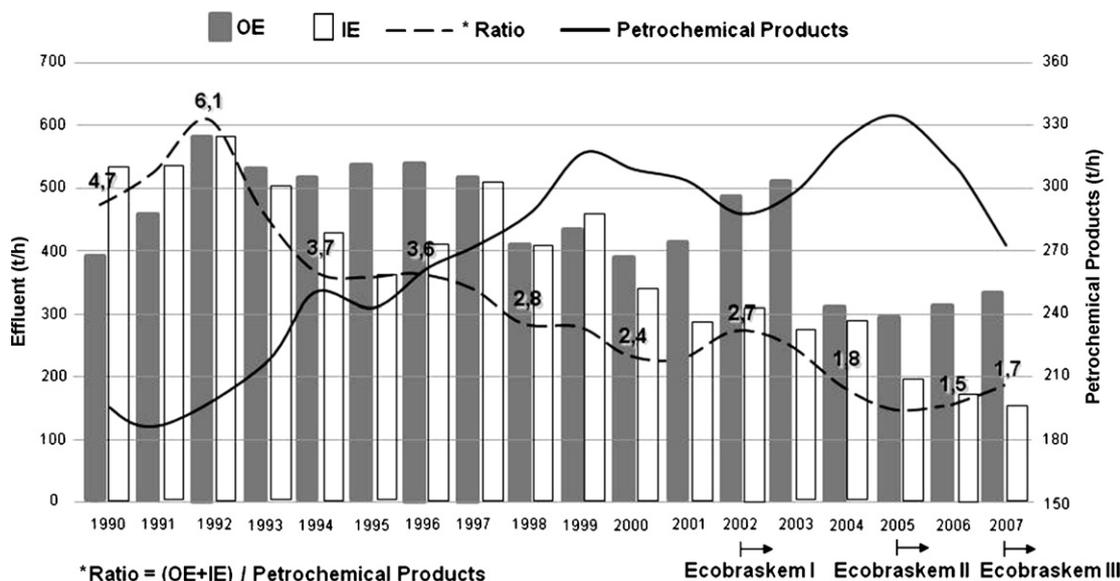


Fig. 7. Effluent generation and petrochemical production by Braskem/UNIB.

(ions); therefore, this parameter can be used as an indirect indication of the amount of inorganic compounds. As seen in the graph conductivity is lower on rainy days as it affects the concentration of salts in industrial discharges.<sup>2</sup> Chemical oxygen demand (COD) test is commonly used to indirectly measure the amount of organic compounds in water. COD increases during rainy periods due to the washing of organics deposited on the soil which reach the inorganic system.

Water use/reuse operations are represented by the maximum inlet and outlet contaminant concentration which are dictated by equipment corrosion, fouling limitations, minimum mass transfer driving forces and limiting water flow rate through an operation (Thevendiraraj et al., 2003). Therefore, the first initiatives indicate considering the use of the stored water as cooling water or after conventional treatment at Braskem/UNIB's facility. For the former, the definition of both the chemical treatment and cycles of concentration are the main issues. You et al. (1999) and Strauss and Paul (1984) suggest some upper water quality for chemical treatment of cooling water, e.g. 6000  $\mu\text{S}/\text{cm}$  of conductivity.

An exploratory study of the stored water quality has been carried out. Seven sampling campaigns in the Complexo Básico and Cobre basins were conducted during drought and rainy periods over a 2-year period. Clorets, sulfate, salinity, conductivity, total suspended solids, pH, alkalinity, metals, nitrogen compounds, biological oxygen demand (BOD<sub>5</sub>) and chemical oxygen demand (COD) are some of the parameters analyzed in the stored water. Contaminant values are compatible with the treatment capacity of the existing water treatment plant. It is expected that they will be lower in the water pumped from the basin, as proposed in the previous section.

## 6. Environmental impacts of Ecobraskem research program

Water is an abundant resource in Brazil as a whole but not in the Northeast region of the country. In fact, the immediate region of the Industrial Complex, the metropolitan region of Salvador, although

very humid (above 1900 mm of rain per year) is still home to large water resources that have not been fully developed. Nevertheless, because of obvious "poor planning" about two thirds of region's urban and industrial water demand is supplied by importing water from Paraguaçu watershed, located in a semi arid region of the State of Bahia with 400–800 mm of rain per year, using a 100 km long pipeline.

To overcome the resource conservation challenge in the Industrial Complex efficient and sustainable use of water resources must be promoted. As well as guaranteeing greater protection of the water resources in the region, the reuse proposed in this research project represents a considerable reduction in both the water volume extracted from the regional water resources for industrial use and inorganic effluent disposal via the submarine outfall. The industrial use of each 1000 m<sup>3</sup>/h of stormwater would represent: reduction of 17% in the actual industrial water withdrawn from regional resources; increasing the availability of about 2% of the actual human water withdraw from regional resources, and, consequently, reducing water transmission from the semi-arid Paraguaçu watershed; reduction of the same amount of contaminated water discarded via the submarine outfall and reduction in energy consumption in pumping the same amount of contaminated water to the submarine outfall and in particular in bringing water from the Paraguaçu watershed. These results have stimulated the development of an engineering project to support the proposed changes. The project's profitability, in terms of money and public image, is another issue to be considered.

By increasing Braskem/UNIB's appreciation of the value and vulnerability of the natural resources as well as the importance of rational water use practices, this joint research program is helping to close the loop between water supply and wastewater disposal within the Industrial Complex. As presented in Fig. 7, Braskem's effluent flow rate has been falling in a reasonably constantly pattern over recent years, both in absolute and relative numbers.

People working in Braskem's facilities also have shown an increasing degree of environmental concern. The activities related to the quantification of the aqueous streams in reconciled mass balances and stimulation for the search of opportunities among the plants' collaborators may be the main reasons for the reduction in specific waste water generation by more than 40% in <2

<sup>2</sup> These are mainly the recovery of the demineralization resins in the water treatment plant and cooling towers blow down.

years. According to Smith and Petela (1992), traditional approaches to water minimization such as changing washing operations, when complemented with water pinch analysis methodology have shown to achieve 30–60% fresh water savings in industrial applications. Further work is needed to identify means to reduce the contributions to the inorganic system both at the source and outside production limits.

## 7. Economic benefits

Considering the annually averaged flow rate of at least 1000 m<sup>3</sup>/h and raw water regional cost of US\$ 0.42/m<sup>3</sup>, this water use will imply in an economic benefit of US\$ 3,350,000.00 per year. According to Braskem/UNIB, a total investment of US\$ 12,000,000.00 for a flow rate in the range of 500–800 m<sup>3</sup>/h (Furtado, 2010).

Such a low water tariffs (US\$ 0.42/m<sup>3</sup>) can, most probably, be associated to inadequate subsidies, related to poor cost attribution in the public owned water production and distribution system. Such a situation is fragile and industry knows that this is not going to last for long. Examples from other, more stressed watersheds in the south-east of the country (Féres et al., 2008) are beginning to be considered. However, as “so far so good” attitudes prevail, investments in water consumption reduction are kept on a waiting list as investments in water metering are. The implementation of a charging system would induce rational industrial water use mainly in small and medium companies which operate under more stringent financial constraints than larger ones (Féres et al., 2008). Accordingly to these authors, larger companies will easily absorb higher water rates by applying water conservation and reuse practices, such as the one proposed in this paper. As reference, we can consider that drinking water in Salvador's region is charged at a rate of US\$ 2.5/m<sup>3</sup>.

## 8. Conclusions

Improvements in environmental practices at Camaçari's Industrial Complex over the last decade have led to considering the use of the attenuation basins of the inorganic effluent system as a source of water supply for industry. The use of water from this source implies significant flow rate reduction in regional water sources. The proposal discussed here would reduce by 17% the amount of water withdrawn today by Braskem UNIB. Further developments in terms of water conservation at the source and effluent streams segregation in plants may produce greater results. Nevertheless, one can expect other indirect positive evolutions in terms of the environmental management of the industrial district as part of the industrial water cycle is closed thus increasing the pressure for more precise environmental practices and water use attitudes by industrial operators.

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## Appendix A. Abbreviations and nomenclature

BOD	Biological oxygen demand (mg/L)
COD	Chemical oxygen demand (mg/L)
V <sub>A</sub>	Rainwater volume and possible natural flow of groundwater that reaches the basin (m <sup>3</sup> )
ΔV/Δt	Change in stored water volume over one-day period (m <sup>3</sup> /h)
Q <sub>P</sub>	Volume of contaminated water pumped from the basin (m <sup>3</sup> )
Q <sub>I</sub>	Mean volume of inorganic effluent produced in the Industrial Complex reaching the basin (m <sup>3</sup> )
Teclim	Clean Technology Network of Bahia
UNIB	Braskem's raw material unity

## References

- Ajit, B.S., 2010. Water harvesting in an industry – Bangalore, India. <http://www.rainwater-toolkit.net/fileadmin/rw-material/documents/KUMAR.pdf> (accessed 07.10.2010).
- A1-Muzaini S. Industrial wastewater management in Kuwait. *Desalination* 1998;115:57–62.
- Alva-Argáez A, Kokossis AC, Smith R. The design of water-using systems in petroleum refining using a water-pinch decomposition. *Chem Eng J* 2007;128:33–46.
- Alvarez D, Garrido N, Sans R, Carreras I. Minimization–optimization of water use in the process of cleaning reactors and containers in a chemical industry. *J Cleaner Prod* 2004;12(7):781–7.
- Bagajewicz M. A review of recent design procedures for water networks in refineries and process plants. *Comput Chem Eng* 2000;24(9):2093–113.
- Byers W, Doerr W, Krishnan R, Peters D. How to implement industrial water reuse: a systematic approach. New York: Center for Waste Reduction Technologies; 1995.
- Bravo JLR, Kiperstok A. Studies on water conservation at a primary copper metallurgy. In: European Metallurgical Conference – Emc 2005; 2005.
- Deul AS. Systematic approach to water resource management in industry. In: Lens P, editor. *Water recycling and resource recovery in industry: analysis, technologies and implementation*. Netherlands: IWA Publishing; 2002. p. 252–70.
- El-Halwagi MM, Manousiouthakis V. Synthesis of mass exchange networks. *AIChE J* 1989;35(8):1233–44.
- EIA/RIMA. Estudo de Impacto Ambiental e Relatório de Impacto Ambiental para Ampliação do Complexo Petroquímico de Camaçari. Hidroconsult; 1989 [in Portuguese].
- Féres J, Reynaudb A, Thomasb A, Motta RS. Competitiveness and effectiveness concerns in water charge implementation: a case study of the Paraíba do Sul River Basin, Brazil. *Water Policy* 2008;10:595–612.
- Fontana D, Kalid R, Kiperstok A, Silva MAS. Methodology for wastewater minimization in industries in the petrochemical complex. In: Proc. 2nd Mercosur Congress on Chemical Engineering and 4th Mercosur Congress on Process Systems Engineering; 2005.
- Furtado M. Reuso de água: algumas indústrias evitam desperdício com recirculação mas poucas reusam de fato. *Química e Derivados* 2010;15–24 [in Portuguese].
- Georgia Rainwater Harvesting Guidelines, 2010. Available, <http://www.ecy.wa.gov/programs/wr/hq/pdf/GARainWaterGdlns.040209.pdf> (accessed 07.10.2010).
- Goldblatt ME, Eble KS, Feathers JE. Zero discharge: what, why and how. *Chem Eng Prog* 1993;89(4):22–7.
- Gwehenberger G, Narodslawsky M. Sustainable processes – the challenge of the 21st century for chemical engineering. *Process Safety Environ Protect* 2008., doi:10.1016/j.psep.2008.03.004.
- Hatt BE, Ana Deletic A, Fletcher TD. *J Environ Manage* 2006;79:102–13.
- Kiperstok A. Implementation of cleaner production practices with the support of a diploma course. *J Cleaner Prod* 2000;8:375–9.
- Kiperstok A, Silva M, Kalid RA, Sales EA, Pacheco Filho JGA, Oliveira SC, et al. Uma política nacional de meio ambiente focada na produção mais limpa: elementos para discussão. *Bahia - Análise & Dados* 2001;10(4):326–32 [in Portuguese].
- Kiperstok A, Kalid R, Sales E. Development of water and wastewater minimization tools for the process industry: the experience of the Clean Technology Network of Bahia, Brazil. In: Proc. Global Conf. on Sustainable Product Development and Life Cycle Engineering 4; 2006.
- Kiperstok A. O papel da universidade e da Rede TECLIM na introdução de práticas de produção limpa na Bahia. *Prata da Casa: Construindo Produção Limpa na Bahia, Bahia: Teclim/UFBA*; 2008 [in Portuguese].
- Kong M, Chen B, He X, Hu S. Gross error identification for dynamic system. *Comput Chem Eng* 2004;29:191–7.
- Lens P, Hulshof Pol L, Wilderer P, Asano T, et al. *Water recycling and resource recovery in industry: analysis, technologies and implementation*. London: IWA Publishing; 2002.
- Luken RA, Navratil J. A programmatic review of UNIDO/UNEP national cleaner production centers. *J Cleaner Prod* 2004;12:195–205.
- Marinho M, Kiperstok A. *Ecologia Industrial e Prevenção da Poluição: Uma Contribuição ao Debate Regional*. Bahia Análise & Dados 2001;10(4):271–9 [in Portuguese].
- Mann JC, Liu YA. *Industrial water reuse and wastewater minimization*. New York: McGraw Hill; 1999.
- Martins M, Souza L, Amaro C, Kiperstok A, Kalid R. New objective function to data reconciliation of water balance. *J Cleaner Prod* 2010;18(12):1184–9.

- Mitchell VG, Mein RG, McMahon TA. Utilising stormwater and wastewater resources in urban areas. *Aust J Water Resour* 2002;6(1):31–43.
- Mohsen MS. Treatment and reuse of industrial effluents: case study of a thermal power plant. *Desalination* 2004;167:75–86.
- Nascimento LFM, Kiperstok A. Two new innovative environmental academic programs in Brazil. In: Full Paper Available at the website of World Resources Institute ([www.wri.org](http://www.wri.org)), Bell Conference; 2003.
- Narasimhan S, Jordache C. Data reconciliation and gross error detection: an intelligent use of process data. Houston, TX: Gulf Publishing Company; 2000.
- Papalexandri KP, Pistikopoulos EN, Floudas CA. Mass exchange networks for waste minimization: a simultaneous approach. *Trans IChemE/A* 1994;72:279–94.
- Plano Estadual de Recursos Hídricos (Bahia's Water Resource Management Plan), PERH-Ba, 2004 [in Portuguese].
- Philippi LS, Vaccari KP, Peters MR, Gonçalves RF. Aproveitamento da água de chuva. In: Gonçalves RF, editor. Programa de Pesquisas em Saneamento Básico PROSAB, vol. 4. Uso racional da água em edificações, Rio de Janeiro: ABES RJ; 2006. p. 73–152 [in Portuguese].
- Placido, J., 1995. Desenvolvimento e aplicação industrial da técnica de reconciliação de dados. Master dissertation. Escola Politécnica, Universidade de São Paulo, São Paulo, 244 pp. [in Portuguese].
- Queiroz EM, Pessoa FLP. Water source diagram procedure: wastewater reduction for single contaminant. In: CHISA 2006-17th International Congress of Chemical and Process Engineering, Praga. Proceedings CHISA/2006, v. T847; 2006.
- Rosain RM. Reusing water in CPI plants. *Chem Eng Prog* 1993;89(4):28–35.
- Saha NK, Balakrishnan N, Batra VS. Improving industrial water use: case study for an Indian distillery. *Resour Conserv Recycl* 2005;43:163–74.
- Silva, G., 2007. Aproveitamento de água de chuva em um prédio industrial e numa escola pública - estudo de caso. Ph. Thesis. University of Campinas (UNICAMP), Campinas – SP, Brazil [in Portuguese].
- Sivanappan RK. Rain water harvesting, conservation and management strategies for urban and rural sectors. In: National Seminar on Rainwater Harvesting and Water Management; 2006.
- Sharatti PN, Kiperstok A. Environmental optimisation of releases from industrial sites into a linear receiving body. *Comput Chem Eng* 1996;20:s1413–8.
- Smith, R., Petela, E., 1992. Water minimisation in the process industries: Parts 1/5. Chemical Engineer.
- Strauss DS, Paul RP. Cooling water treatment for control of scaling, fouling, corrosion. *Power* 1984;132(6):S1–24.
- Tambo N. Urban methabolic system of water in the 21st century, water resources and water supply in the 21st century. Japan: Hokkaido University Press; 2003.
- Thevendiraraj S, Klemes J, Paz D, Aso G, Cardenas GJ. Water and wastewater minimisation study of a citrus plant. *Resour Conserv Recycl* 2005;37:227–50.
- Thomas J-S, Le Pol J, Gillet S, Phan L. SIRRUS: evaluation software of the technical and economic profitability of rainwater on an industrial site. *Water Sci Technol* 2002;46(6–7):71–6.
- UNEP, 2008. [http://www.uneptie.org/scripts/runsearch\\_en.asp](http://www.uneptie.org/scripts/runsearch_en.asp), Understanding Cleaner Production (accessed 11.08.08).
- Ujang Z, Wong CL, Manan ZA. Industrial wastewater minimization using water pinch analysis: a case study on an old textile plant. *Water Sci Technol* 2002;46(11–12):77–84.
- Wang YP, Smith R. Wastewater minimisation. *Chem Eng Sci* 1994;49:981–1006.
- You S-H, Tseng D-H, Guo G-L, Yang J-J. The potential for the recovery and reuse of cooling water in Taiwan. *Resources. Conserv Recycl* 1999;26:53–70.
- Zbontar Z, Glavic P. Total site: wastewater minimization, wastewater reuse and regeneration reuse. *Resour Conserv Recycl* 2000;30:261–75.
- Zver ZL, Glavic P. Water minimization in process industries: case study in beet sugar plant. *Resources. Conserv Recycl* 2005;43:133–45.