Integrated solutions for urban runoff pollution control in Brazilian metropolitan regions

ABSTRACT
One of the most important causes for poor water quality in urban rivers in Brazil is the low collection efficiency of the sewer system due to unforeseen interconnections with the stormwater drainage system. Since the beginning of the 20th century, Brazilian cities have adopted separate systems for sanitary sewers and stormwater runoff. Gradually these two systems became interconnected. A major challenge faced today by water managers in Brazil is to find efficient and low cost solutions to deal with this mixed system. The current situation poses an important threat to the improvement of the water quality in urban rivers and lakes. This article presents an evaluation of the water quality parameters and the diffuse pollution loads during rain events in the Pinheiros River, a tributary of the Tietê River in São Paulo. It also presents different types of integrated solutions for reducing the pollution impact of combined systems, based on the European experience in urban water management. An evaluation of their performance and a comparison with the separate system used in most Brazilian cities is also presented. The study is based on an extensive water quality monitoring program that was developed for a special investigation in the Pinheiros River and lasted 2.5 years. Samples were collected on a daily basis and water quality variables were analyzed on a daily, weekly or monthly basis. Two hundred water quality variables were monitored at 53 sampling points. During rain events, additional monitoring was carried out using an automated sampler. Pinheiros River is one of the most important rivers in the São Paulo Metropolitan Region and it is also a heavily polluted one.

Key words | combined systems, diffuse pollution, separated systems, stormwater systems, urban water management, water quality

INTRODUCTION
The first sanitation systems in Brazil were implemented in the 19th century in the cities of Rio de Janeiro and São Paulo. Due to the topography and climate conditions with intense rainfall events, separate systems for sanitary sewer and stormwater runoff were considered more adequate. In 1912, the Brazilian government decided that the separate system should be adopted in all cities of the country. Unfortunately, the cities grew much faster than the capacity for investing in proper infrastructure for sewage collection and treatment. The result is that, even today, only 50% of Brazilian residences are connected to a sanitary sewer system and only 38% of the sewage is treated (Instituto Trata Brasil 2012). The fact that the growth of the urban areas was not properly followed with the same rate of sewer infrastructure expansion, created a disorganized system, with some areas having both sewage collection and stormwater systems and some areas with just one of them, but used for both purposes. This problem is difficult to solve but it must be corrected in order to reach a more appropriate level of pollution control.

The sanitary sewer collection efficiency is low, as part of the sewage is being dumped into stormwater networks that flow directly into the rivers (Yazaki et al. 2007). Consequently, despite the investments made in recent years to expand collection and treatment systems, the urban water bodies still show very high levels of contamination. The stormwater systems, in addition to urban diffuse pollution, also carry the ‘unexpected’ dumped sewage. Another
problem is that diffuse pollution control is still not being considered in the water quality restoration plans in Brazil.

It will be very costly, and have very low technical feasibility, to use the traditional approach to separate completely both systems again in all Brazilian cities. Large cities, like the São Paulo Metropolitan Region, with almost 20 million inhabitants, will not be able to reorganize and to remodel the two systems in the former separated manner over its more than 2,000 km² of urban sprawl.

This article discusses some integrated solutions for the improvement of water pollution control in such conditions, based on the European experience in urban water management. It evaluates the performance of different arrangements of sewers and stormwater systems, comparing them to the traditional separate systems.

**METHODS**

**Water quality monitoring program of Pinheiros and Tietê Rivers**

A daily monitoring program of the Pinheiros and Tietê Rivers was carried out over 2.5 years. The objective was to provide information to a special study on the performance of a tentative flotation system to reduce contamination in the Pinheiros River (FCTH 2010). Pinheiros and Tietê are the main rivers in the São Paulo Metropolitan Region (SPMR). This monitoring program was the largest water quality data collection program ever held in the Brazil, with over 200,000 water quality lab analyses (FCTH 2010). It included the evaluation of 200 water quality variables in 5,668 samples, collected at 53 different points (Figure 1). Depending on the variable, the sampling was carried out on a daily basis, or weekly or monthly intervals, both during the dry and the rainy season. During rain events, an automatic sampler was used to collect additional samples in the Pinheiros River. The mean annual rainfall in São Paulo is approximately 1,400 mm. The rainy season in São Paulo is from October to March, with approximately 75% of the total annual rainfall.

**Comparative analysis of Pinheiros and Tietê Rivers**

In order to assess significant differences in the water quality condition of the Tietê and Pinheiros Rivers, statistical tests were used with a significance level (p-value) of 10%, as follows:

- Significance test for comparing means: a null and an alternative hypothesis for a population parameter are defined. Based on sample information, the statistical test to reject the null hypothesis in favor of the alternative hypothesis or do not reject the null hypothesis was realized. The tests considered only the p-value error, i.e., the probability of rejecting the null hypothesis being true (Martins 2001).
- Nonparametric test of the medians: the non-parametric tests do not require that data follow any specific distribution. The test gives information if two independent groups come from populations with the same median (Martins 2001).

**Surface runoff analysis**

To evaluate the surface runoff effects in the receiving water body after a rainfall event the following indicators were calculated (Brites 2005):

- **Event Mean Concentration (EMC):**

\[ \text{EMC} = \frac{M}{V} = \frac{\int_{0}^{T} C_t Q_t \, dt}{\int_{0}^{T} Q_t \, dt} \approx \frac{\sum C_t Q_t \Delta t}{\sum Q_t \Delta t} \]  

where: EMC (mg/L); \( M \) = mass of pollutant contained in the runoff event (g); \( V \) = total runoff volume during the event (m³); \( t \) = time (s); \( C_t \) = concentration at time \( t \) (mg/L); \( Q_t \) = flow at time \( t \) (m³/s); \( \Delta t \) = time interval (s).

- **Diffuse Load (DL):**

\[ DL = \int_{0}^{T} (C_t Q_t - L_{base}) \, dt \approx \sum (C_t Q_t - L_{base}) \]  

where: DL (g/s); \( L_{base} \) = pollutant load present in the river on the day just before the rainfall event.
Wash load analysis

To evaluate the wash loads a Pollutant Mass Distribution × Runoff Volume methodology, described by Gupta & Saul (1996), was used. The variability of the pollutant mass rate which is transported during a rain event in the drainage network can be described by two curves: hydrograph $Q(t)$ and pollutogram $C(t)$. If these curves, called $M(V)$ curves, have a 45° slope, a uniform distribution is admitted for the pollutant during the event. When $M(V)$ curves are above the bisector, curve $>45°$, wash load occurs. When the curves are below the bisector, curve $<45°$, the wash load does not occur (Brites 2005).

RESULTS AND DISCUSSION

Water quality data analysis

Data collected from the Pinheiros and the Tietê Rivers show a severely contaminated river, with elevated levels of biochemical oxygen demand (BOD₅) concentration. It also shows a seasonal behavior, with higher concentrations during dry periods and lower concentrations during the rainy season, as presented in Figures 2 and 3.

A major project started in 1992 (Tietê Project) aimed at the cleanup of the waters of the Tiete River basin (Projeto Tietê 2002). This was the result of a massive media campaign towards reversing the daunting water quality situation of the Tiete River. The project involves the construction of sewers, pumping stations and five new biological treatment plants.

With the implementation of the Tietê Project the region went from 70% of sewage collection to 86% in 2011 and from 24% treatment in 1992 to 66% in 2011. During this period the investment was USD 1.6 billion. The project continues and during the current phase (2009–2015) the investment will be approximately USD 1.05 billion aiming to reach 84% of treatment in the region. In the final configuration to be completed in 2023, the project will provide adequate collection and treatment for the entire population of the region, at an additional investment of USD 2.5 billion. Simulation models estimated that, at the end of the project, the BOD₅ levels will stay around 10–15 mg/L and dissolved oxygen (DO) levels around 2 mg/L in the Tietê River during dry periods.

The situation presented in Figures 2 and 3 shows the current intermediate situation of the project implementation. BOD levels demonstrate that a large quantity of untreated sewage is still being dumped into the system. The resulting trend in BOD levels, from 50 to 60 mg/L during the monitoring period (2007–2010), is due to the fact that the collection system increased faster than the treatment capacity.

Results in Table 1 show that there is no statistically significant difference between the water quality in the Pinheiros and the Tietê Rivers. Both are located right in the center of the densely occupied urban area and are intensely impacted by pollution from point and non-point sources.

The pollutograms monitored during rain events in the Pinheiros basin allowed for important conclusions about diffuse pollution. Table 2 presents the EMC for six water quality parameters monitored during the rain events. A high EMC variability was observed in these events and a pattern was not found. This result agrees with the general

![Figure 2](https://iwaponline.com/wst/article-pdf/66/4/704/443171/704.pdf)

Figure 2 | Variation of BOD₅ concentration in the Pinheiros River.
conclusions of the NURP (National Urban Runoff Program), developed in USEPA in 1983 that stated ‘… regardless of the analytical approach taken, we are forced to conclude that, if land use category effects are present, they are eclipsed by the storm to storm variability …’ (Novotny & Olem 1994).

Diffuse pollution contributes with a substantial load to urban rivers. In sewered areas, urban diffuse sources have been identified as a major cause of pollution in surface water bodies (Novotny & Olem 1994). Table 3 and Figure 4 demonstrate that the diffuse pollution load contribution to the Pinheiros River is very expressive when compared with the total amounts that come from other sources. The BOD₅ levels in the diffuse pollution loads are very high for a separate system, indicating that part of the sewage is being discharged without treatment. Part of this discharge enters the river through the stormwater system. This fact can be easily verified in a visual inspection along the Pinheiros River.

Figure 5 shows the wash loads M(V) curves of monitored rain events for four water quality variables: total organic carbon (TOC), BOD₅, chemical oxygen demand (COD) and total suspended solids (TSS). In most events pollutant loads were not uniformly distributed along the runoff volume.

It can be observed in the wash load curves that TOC is more easily transported by the runoff as it is the water quality variable with more curves above the bisector. TSS presents the most erratic behavior indicating the complexity of the transport of the material, probably with different origins and many different interfering factors.

### Separate or combined systems?

A separate system will offer adequate protection if properly implemented and operated in a way that conveys to the treatment plant all the sewage produced in a certain urban area. When the system lacks efficiency and an important fraction of the sewage ends discharged directly into the water body without treatment, the environment can be severely degraded. A well-planned and operated combined system will offer a better level of protection than a low efficiency separate system (Paoletti & Papiri 2007). A separate system with stormwater treatment for the first flush as shown in Figure 6(c) gives a similar environmental protection to the receiving water body as the combined systems with devices to divert the most polluted portion of the urban runoff. (Figure 6(a) and (b)) (Paoletti & Papiri 2007).
Simulations done in previous studies (Yazaki et al. 2007) indicate that pollution loads can be reduced by more than 80% with the use of first flush reservoirs, as shown in Figure 6(b).

The same calculation procedures were applied here and the results are shown in Table 4 and Figure 7. Hypothetical first flush reservoirs were introduced to detain the first 5 mm (first simulation) and 10 mm (second simulation) of rain. Volumes in these reservoirs ($V_h$) were calculated by:

$$V_h = h \times A$$

where: $h = 5$ or 10 mm, equivalent to 5,000 or 10,000 m$^3$/km$^2$; $A$ = the Pinheiros River basin area = 269.68 km$^2$.

The DL reduction was calculated by:

1. The time needed to fill the reservoirs ($t_h$) is determined by:

$$V_h = \int_{0}^{t_h} Q_t dt \equiv \sum_{0}^{t_h} Q_t$$

where $Q_t$ = flow at time $t$ and $V_h$ the reservoir volume.

2. The DL retained in the reservoir ($DL_{reservoir}$) was calculated by:

$$DL_{reservoir} = \int_{0}^{t_h} (C_t Q_t - L_{base}) dt \equiv \sum_{0}^{t_h} (C_t Q_t - L_{base})$$

where $C_t$ = concentration at time $t$.

These results show that it may be interesting to pursue mixed solutions such as this. In an unplanned and disorganized urban area, like the Metropolitan Region of São Paulo, a system that joins characteristics from both separate and combined systems may be effective and less expensive than the separation attempt, in terms of investments and operational costs. As said before, a complete and effective

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**Table 2** | Event mean concentration (EMC)

<table>
<thead>
<tr>
<th>Date</th>
<th>TOC (mg/L)</th>
<th>BOD$ _5$ (mg/L)</th>
<th>COD (mg/L)</th>
<th>TP (mg/L)</th>
<th>N-NH$_3$ (mg/L)</th>
<th>TSS (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19/08/09</td>
<td>6.29</td>
<td>22.4</td>
<td>14.8</td>
<td>12.4</td>
<td>102.0</td>
<td>102.0</td>
</tr>
<tr>
<td>20/08/09</td>
<td>7.95</td>
<td>24.1</td>
<td>15.3</td>
<td>11.9</td>
<td>105.8</td>
<td>105.8</td>
</tr>
<tr>
<td>21/08/09</td>
<td>9.14</td>
<td>38.0</td>
<td>23.5</td>
<td>11.9</td>
<td>105.8</td>
<td>105.8</td>
</tr>
<tr>
<td>22/08/09</td>
<td>11.64</td>
<td>59.9</td>
<td>39.9</td>
<td>11.9</td>
<td>105.8</td>
<td>105.8</td>
</tr>
<tr>
<td>23/08/09</td>
<td>9.93</td>
<td>44.7</td>
<td>31.4</td>
<td>11.9</td>
<td>105.8</td>
<td>105.8</td>
</tr>
<tr>
<td>24/08/09</td>
<td>11.64</td>
<td>14.7</td>
<td>15.3</td>
<td>11.9</td>
<td>105.8</td>
<td>105.8</td>
</tr>
<tr>
<td>25/08/09</td>
<td>12.44</td>
<td>14.7</td>
<td>15.3</td>
<td>11.9</td>
<td>105.8</td>
<td>105.8</td>
</tr>
<tr>
<td>26/08/09</td>
<td>12.44</td>
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<td>15.3</td>
<td>11.9</td>
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</tr>
<tr>
<td>27/08/09</td>
<td>12.44</td>
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<td>15.3</td>
<td>11.9</td>
<td>105.8</td>
<td>105.8</td>
</tr>
<tr>
<td>28/08/09</td>
<td>12.44</td>
<td>14.7</td>
<td>15.3</td>
<td>11.9</td>
<td>105.8</td>
<td>105.8</td>
</tr>
</tbody>
</table>

**Table 3** | Pollutant loads calculated during the period from 21/08/2009 to 28/12/2009

<table>
<thead>
<tr>
<th>Water quality variables</th>
<th>Total load (ton/day)</th>
<th>Diffuse pollution load (%)</th>
<th>Other sources (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC</td>
<td>23</td>
<td>37</td>
<td>63</td>
</tr>
<tr>
<td>BOD$ _5$</td>
<td>106</td>
<td>36</td>
<td>64</td>
</tr>
<tr>
<td>COD</td>
<td>207</td>
<td>39</td>
<td>61</td>
</tr>
<tr>
<td>TP</td>
<td>2</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>N-NH$_3$</td>
<td>9</td>
<td>43</td>
<td>57</td>
</tr>
<tr>
<td>TSS</td>
<td>177</td>
<td>57</td>
<td>43</td>
</tr>
</tbody>
</table>
remodeling of the system to cut all existing interconnections between the two systems not only is costly, but it often comes across several technical difficulties. The decision to separate combined networks should be taken only in cases when decisive advantages can be reached or in situations where this solution is essential to protect the environment.

![Figure 4](https://iwaponline.com/wst/article-pdf/66/4/704/443171/704.pdf)

**Figure 4** | Pollutant loads calculated during the period from 21/08/2009 to 28/12/2009.

![Figure 5](https://iwaponline.com/wst/article-pdf/66/4/704/443171/704.pdf)

**Figure 5** | MVV curves of four water quality variables for the monitored events.
The experience in this matter in the Metropolitan Region of São Paulo is an ongoing project called Córrego Limpo (Clean Creek). It aims to restore the water quality in small, open creeks, in order to enhance the urban landscape and to create recreational areas (Projeto Córrego Limpo 2012). The main action of this project is to eliminate the sewage discharges into the stormwater system in the contributing watersheds of those creeks. It is a very successful program that cleaned 100 creeks in 4 years. The cost was approximately USD 110 million and the area affected by the program was only 9% of the area of the city of São Paulo. The watershed areas of the restored creeks are showed in Figure 8. A total sewage flow of 1 m$^3$/s was taken from the stormwater system and discharged into the sanitary sewers. To extrapolate this program to the entire area of the metropolitan region would be economically unfeasible.

<table>
<thead>
<tr>
<th>Water quality variables</th>
<th>Without reservoir (ton/day)</th>
<th>% Reduction with reservoir for 5 mm</th>
<th>% Reduction with reservoir for 10 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOC</td>
<td>9</td>
<td>20</td>
<td>39</td>
</tr>
<tr>
<td>BOD$_5$</td>
<td>38</td>
<td>18</td>
<td>39</td>
</tr>
<tr>
<td>COD</td>
<td>80</td>
<td>19</td>
<td>39</td>
</tr>
<tr>
<td>TP</td>
<td>1</td>
<td>20</td>
<td>42</td>
</tr>
<tr>
<td>N-NH$_3$</td>
<td>4</td>
<td>27</td>
<td>53</td>
</tr>
<tr>
<td>TSS</td>
<td>101</td>
<td>12</td>
<td>28</td>
</tr>
</tbody>
</table>

Figure 6 | Different arrangements for a combined system.

Table 4 | Diffuse load reduction using 1st flush reservoir in the Pinheiros River

Figure 7 | Diffuse load depletion simulation using hypothetical 1st flush reservoir.
CONCLUSION

The analysis of the water quality data of the Pinheiros and Tietê Rivers showed severe contamination due to the discharge of untreated sewage. The Tietê Project, to be completed in 2023, will collect and treat the sewage from the Metropolitan Region of São Paulo. The data analysis also showed that an expressive load of organic matter is discharged as diffuse pollution. The water managers in São Paulo recognize that part of this organic load in the diffuse pollution is due to sewage discharge into stormwater drains. This problem is not likely to be solved by the traditional approach adopted by the Tietê Project. The project assumes that the area is serviced by a separate system, without considering the losses of sewage or the low efficiency of the collection by the current system due to the interconnections with the stormwater system. The water quality restoration will only be successful if both actions are carried out: (i) the separate system must service the entire area and it must convey the sewage to efficient wastewater treatment plants; and (ii) the sewage currently conveyed by the stormwater drains must be controlled by an approach similar to the ones used in combined sewer systems. A simplified mass balance simulation showed that the pollutant load reduction that can be achieved by this approach is very significant.

The costs of the Projeto Córrego Limpo also showed that the separation of the system is feasible in some situations, but it would be very expensive to expand that type of solution to the entire urban area.

Last, but not least, there are management and institutional complexities that will have to be faced in order to achieve the desired restoration of the water quality. Water management of mega cities in the developing world is probably the major environmental challenge of the future. Fragmented management, in which the sectors involved (water supply and sanitation, drainage, solid waste, land use) are dealt with separately, has been responsible in part for the escalating degradation of the urban ecosystem. This is the case in São Paulo Metropolitan Region and the urban water management needs to be reformed to facilitate the solution. The Projeto Córrego Limpo is a remarkable example of good results in an integrated environment as it is a very successful program run by the water utility, responsible for the sanitation system, and the municipality of São Paulo, responsible for the stormwater drainage system.

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