Assessment of treatment systems for highway runoff pollution control

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ABSTRACT

Treatment systems for highway runoff pollution control are now common structures for environmental impacts reduction in Portugal. Such systems must be monitored and its performance periodically assessed, in order to understand if they are accomplishing the targets for environmental protection. Wise management decisions must incorporated the soundness of a project, the construction and maintenance costs, and the ability of the system to reduce the pollution to the level required for environmental protection.

To gather, organize and analyse all the existing information concerning the constructed treatment systems, their operation, maintenance and efficiency were understood as a priority by the Portuguese Roads’ Institute. The authors of this article were responsible for this study that will finalize in May 2008. A total of 27 different systems, corresponding to 13 different project types, located in different places in Portugal have been characterized and evaluated. Several conclusions could be drawn from the evaluation and the recommendations produced will certainly contribute to improve the future practice in Portugal.

KEYWORDS

Assessment; cost; effectiveness; highway runoff; Portugal; treatment systems

INTRODUCTION

Road runoff pollution and impacts

Road runoff is a linear diffuse source of pollution, being the pollutants characteristics and the mode of discharge in the environment very specific for this pollution source. It has been neglected for several decades, due to the fact that road runoff transports low concentrations of pollutants in huge volumes of water. The USA much earlier than Europe assessed that from 4 to 11% of impacts in the water quality were caused by stormwater. The USA-EPA (in Wanielista and Yousef, 1993) stated that diffuse sources were responsible for 70% of the presence of chemical oxygen demand (COD), oil and zinc; 90% of the presence of total Kjeldahl nitrogen and faecal coliform, and 95% of the load in iron.

It is interesting to notice that two recent studies on road runoff in Portugal (Barbosa et al., 2006a; Antunes and Barbosa, 2005) showed values of total suspended solids (TSS) and COD that surpass the permitted level for discharge of point effluents (Annex XVIII of the Portuguese law, Dec.-Lei n.º 236/98) in 15% and 50% of the samples, respectively, for COD, and in 62% of the samples for TSS.
To protect water resources from road runoff pollutants it is important to know how and when to implement treatment systems. Structural Best Management Practices (BMP) consist in systems constructed to treat stormwater at the origin or near the discharge into the receiving waters, or into the urban rain sewer system. They operate by trapping and detaining runoff until unwanted pollutants settle out or are filtered. Examples of these systems are: extended detention ponds, wet ponds, infiltration trenches, infiltration basins, sand filters, grassed swales, constructed wetlands, etc.

The concept of best management decision imposes the need for a correct balance between a sound project with reasonable construction and maintenance costs, able to reduce the pollution to the level required for environmental protection.

**Assessment of Structural Best Management Practices**

Assessing the efficiency of a specific BMP means to compute in an integrated way the performance of the system, the potential side impacts of the operations and also the construction, operation and monitoring costs. Taylor and Barret (1999) evaluated for the Caltrans BMP Retrofit Pilot Program, in California, 37 BMP at 33 sites, with 9 types of technology. The authors included in their evaluation both costs and effectiveness. Table 1, based on data by Taylor and Barret (1999), shows relative costs and average annual maintenance hours needed for several BMP.

**Table 1.** Relative construction and maintenance costs of treatment systems for road runoff in California, USA. Based in Taylor and Barret (1999).

<table>
<thead>
<tr>
<th>Type of system</th>
<th>Cost (^{(1)})/m(^3) of the design storm</th>
<th>Average annual maintenance (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand filter</td>
<td>10.0</td>
<td>49</td>
</tr>
<tr>
<td>Multi-chambered treatment train</td>
<td>8.1</td>
<td>220</td>
</tr>
<tr>
<td>Wet basins</td>
<td>7.5</td>
<td>500</td>
</tr>
<tr>
<td>Extended detention</td>
<td>1.0</td>
<td>80</td>
</tr>
<tr>
<td>Detention basins</td>
<td>2.5</td>
<td>80</td>
</tr>
<tr>
<td>Swales</td>
<td>2.0</td>
<td>116</td>
</tr>
<tr>
<td>Infiltration basins</td>
<td>1.8</td>
<td>89</td>
</tr>
</tbody>
</table>

\(^{(1)}\) The costs in USA dollars have been converted into relative costs, in order to compare the different systems.

Taylor and Barret (1999) concluded that biofiltration swales and strips are the best choices, for being relatively inexpensive, having a comparable effectiveness for many runoff constituents and requiring no specialized maintenance. These are followed by the extended detention basins, due to their moderate cost, flexible sitting, moderate performance and low maintenance. Two types of systems have been rated in the third place: infiltration devices and sand filters. The first ones have moderate cost and are highly effective, although presenting significant sitting constraints and potential groundwater impacts. On the other hand, sand filters have high cost, are highly effective, have significant head requirements and moderate maintenance.

One relevant conclusion from this study conducted at California is that there are various structural BMP systems commonly used, but hardly ever monitored. This is the case of infiltration swales, infiltration ponds and biofilters. The reason for it is linked to the difficulty in sampling at the inlet and outlet of the system, in such a way that it is possible to calculate the percentage of pollutants removal. It was observed that the most original and innovative BMP systems are also seldom monitored (Taylor and Barret, 1999). Studies such as this one
provide precious information to improve the practice and enhance the benefit/cost ratio at a given country or region.

**Structural Best Management Practices in Portugal**

The very first system for highway runoff treatment in Portugal was built in 1990 at the major national highway, A1: a large detention pond was constructed approximately 136 km from Lisbon, to the North, intended to protect the underground water. Since this date, many other treatment systems for highway runoff control have been constructed, presenting different types of layouts. For several reasons, some of them have not been built, and many of the constructed ones have not been monitored which makes difficult to assess the soundness of the project and the construction. It was felt the need to gather and organize all the existing information concerning the constructed treatment systems, their operation, maintenance and efficiency. To analyse these data and provide conclusions able to enhance national best management practices were understood as a priority by the Portuguese Roads’ Institute (E.P.E.).

This communication presents results from a study that has been requested to LNEC by the Portuguese Roads’ Institute in 2005, and will be finalised in May 2008. It should be referred that the study comprises, as well, other environmental mitigation measures, concerning the fauna, noise and the state of water resources in areas crossed by roads.

**STUDY OBJECTIVES AND METHODS**

Summarizing, the study objectives and activities concerning the structural BMP in Portugal, may be described as follows:

i. Study and characterization of all the projects ever produced in Portugal for the purpose of road runoff treatment and the results of the monitoring studies produced;

ii. Conception of a database to store the information concerning the roads and the treatment systems;

iii. Insertion of the information on the designed database;

iv. Evaluation, in situ, of the constructed infrastructure and of the level of similarity to the project design;

v. Evaluation of the methods used for monitoring the systems’ performance and analysis of their results and conclusions;

vi. Production of a report on the causes for failure of efficiency of the treatment systems.

It was also asked that the study should take into account the construction and operation costs, and try to relate them with the efficiency of the systems.

The treatment systems project documents and drawings were available at the E.P.E. archives, consulted between May 2005 and November 2006. The data was screened, and the most important information previously defined by the project team, collected and inserted in a MS Access® database, designed and tested to fit the purpose. It was noticed a lack of relevant information regarding the project and/or the treatment operation(s), the targeted efficiency and the objectives for environmental protection. For some cases there was not even a specific project document, with a memory and technical drawings, but a couple of pages with short descriptions of the planned system.

The monitoring information regarding the performance of the systems was obtained from different sources. On the one hand, the road operating companies have a legal obligation to
implement monitoring plans that have to be approved both by the E.P.E and the Water Institute (e.g.: Santos and Aguileira, 2004). These documents were available at the E.P.E. library. On the other hand, treatment systems have been chosen as the subject for several academic research studies (e.g.: Albuquerque, 2006; Barbosa, 1999; Barbosa et al. 2006; Leitão et al., 2005), some of these had contributions from the LNEC team, and all these documents were considered for the purposes of the present study.

A total of 27 different treatment systems, corresponding to a total of 13 different project typologies, have been evaluated in this study, either by collecting data already existing or by direct observation of the system at the field and meetings with the road operation staff. Many of the evaluated systems have the same layout and operations, belonging to the same road. Figure 1 shows that the systems are spread up across the country, with some concentration in the Northern region and at the South coast. Although not being a very large country, Portugal presents a large variation in rainfall pattern along the territory, and from West to East due to the influence of the Ocean. Being precipitation the process of transportation of pollution, the hydrological differences must be analysed and special attention given to the design size.

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**Figure 1.** Roads with treatment systems (Number of treatment systems within brackets).

**DESCRIPTION OF THE TREATMENT SYSTEMS STUDIED**

**Types of technology**

During this study, different types of technologies and combination of operations have been observed. They may be pointed out as follows:

i. Detention basin/pond;
ii. Wastewater treatment plant, with different physical and chemical operations, including the addition of FeCl₃;
iii. Retention pond;
iv. Sedimentation pond + infiltration basin;

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v. Sedimentation pond + infiltration bed;
vi. Oil separator + decantation pond;
vii. Oil separator + detention basin;
viii. Multifunction basin (detention basin + oil separator located inside an inspection chamber before the outlet);
ix. Grassed swale;
x. System for control of accidental spillages (oil separator chamber).

Figure 2 illustrates the diversity of the systems types. Although systems to control accidental spillages on the road are not classified as treatment systems, they act, at the end, as a sediment trap therefore contributing to some pollutants removal. For these reason some systems of this kind have been included in the analysis.

Evaluation methodologies
In the framework of this project, the evaluation was done through the study of the project, the visual inspection at the site, meetings with the operating companies to gather empirical information like the construction and operation/maintenance costs and results of the monitoring reports. With this range of information, the systems could be grouped in four different levels of assessment, which may be described, from the less information level as:
Group 1 - Study of the project, visual inspection at the site, 1 measurement with water probe when there is water, information from the operating companies; Group 2 - Monitoring in more than 1 occasion, including grab sampling of water and/or sediment/soil from the bottom of the systems and analysis at the laboratory; Group 3 - Evaluation performed in the course of a Master Thesis dissertation (Albuquerque, 2006); and Group 4 - Evaluation performed in the course of a Ph.D. Thesis dissertation (Barbosa, 1999).

Despite of the level of assessment, all systems were visited within the project activities, during March, May and July 2007. During the visits to the systems, when there was water present, measurements of pH, salinity and total dissolved solids, among others, have been done with a water quality probe, in order to have additional indicators for the evaluation.

RESULTS AND DISCUSSION

Construction and maintenance of the systems
During the visits to the systems, the authors identified several changes made at some stage in the original project. The most common change is the increase or decrease of the number of constructed systems, compared to the planned. Unfortunately, not always these changes have been reported or justified, and the final drawings of the constructed systems are not available at the E.P.E. archives, as they should be. This situation led to some confusion about the locations of the systems, for a given highway, that could only be explained by the information detained by the operating companies.

Half of the systems in this analysis have been constructed after the year 2002 so there is not yet much maintenance experience. It was observed during the field work, the high level of sediment accumulation below the inlet pipe at the majority of the most recent systems. The need for rehabilitation and adaptation works due to some errors in the design project was noticeable for some cases. A positive example is the 3 systems at A23, constructed in 2005, that have been rehabilitated recently (summer of 2007), after the recommendations from Albuquerque (2006) Master Thesis.
Concerning the older systems, some like the detention pond at the A1 highway, have been the subject of proper maintenance care but, in several cases, the systems need urgent conservation actions. The worst situation occurs at the road IP4, where presently the vegetation covers the 3 systems, constructed in 1996, making them extremely difficult to locate, contributing to a bad performance, and placing at danger the local groundwater resources as identified by Barbosa (1999).

**Suitability of treatment operations and size**

For most of the treatment systems, the choice of the type of operation was according to the targets proposed in the environmental impact study. It was noted that several studies did not present a clear objective for pollutants removal at the designed system, which is thought to be a relevant lack of information, for the measured efficiency must be compared to the proposed efficiency. This is the procedure to determine if the objectives are, or not, being accomplished. It is considered that the most suitable solution is a natural and simple system.
with as less maintenance needs as possible – and offering good possibilities for monitoring the performance.

From all the systems, the six A2 highway runoff treatment plants are an exception at the national level. These kind of “heavy” structures are not suitable for road runoff because of the high variation in the flow, combined with huge variations in pollutants concentrations. Additionally, the introduction of chemicals was not assessed until now and should be in the future. It is questioned if the addition of FeCl$_3$ is really needed or if the amount used could be reduced. Measurements during the field work inspection identified a very basic pH (around 9.5 which is attributed to the local soils characteristics) of the runoff water at the wastewater decantation compartment. It is known that at such pH most of the heavy metals are particulated.

Several systems were projected considering high return periods, i.e., for extreme events of precipitation. This is a frequent error: systems should be projected for an average precipitation that has a return period of, for instance, 1 or 2 years. The increase in the volume of the systems corresponds to higher costs, for land acquisition, construction and even maintenance. Therefore, sizing a runoff treatment system based on rainfall with a high return period leads to an expensive - and, sometimes, ineffective - solution.

**Summary of the evaluation results**

Figure 3 summarizes the systems evaluated, the type of assessment they had and some general comments and observations.

It was noteworthy that only the A22 had comprehensive monitoring results, accomplished by the operating company, dated from 2003/2004 and presented in a proper report (Santos and Aguileira, 2004). These treatment systems are considered to be adequate and efficient, although the infiltration operation has not been assessed yet. Some core soil samples could be taken in the future for this purpose.

Previous studies already concluded that, despite the system of A1 highway reduces the pollutant concentration properly the same target could be accomplished with a much less volume basin (aprox. 14 times). A similar conclusion was verified in 1999 (Barbosa, 1999) for the IP4 systems (7 times oversized), although now the situation changed due to the lack of maintenance, and it is anticipated that the bad functioning of the ponds are endangering the quality of groundwater. During the current study, it was also understood that A23 systems are oversized.

The A2 wastewater treatment plants show a good efficiency for the removal of COD, TSS and oils, although it is not considered that this choice reached a good balance between costs and results and, as mentioned before, there is the possibility that the chemical treatment contributes with additional contaminants discharged in the environment. This side effect has not been taken into account in the project.

It was verified at the site that the four A27/IP9 systems for control of accidental spillages are totally unsuitable and inefficient.

During the field work it was observed, for several cases, a subsurface flow of water into the treatment systems. This water is thought to be non-polluted (if polluted should be from agriculture activities) and is part of the natural drainage of the basins. Future projects should include the assessment of this possibility, taking into consideration local information on the
groundwater level and base flows, because such input if can not be diverted from the treatment system, must be taken into account to size the system volume.

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Table 2. Data concerning construction and maintenance costs compared to the systems’s efficiency

<table>
<thead>
<tr>
<th>Road and treatment system</th>
<th>Construction costs (€/system)</th>
<th>Average maintenance costs (€/year/system)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2 6 water treatment plants</td>
<td>931 651</td>
<td>3333</td>
<td>Good efficiency for COD, TSS and oils removal.</td>
</tr>
<tr>
<td>A22 8 retention and treatment ponds; 1 retention pond and infiltration bed</td>
<td>170 000</td>
<td>437</td>
<td>Fair efficiency, for the retention pond treatment.</td>
</tr>
<tr>
<td>A27 4 System for control of accidental spillages</td>
<td>10 000</td>
<td>625</td>
<td>The project is unfitted for the purpose.</td>
</tr>
</tbody>
</table>

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Figure 3. Summary of the evaluation results.

Operation and maintenance costs

Unfortunately, only three of the operating companies could provide data concerning this point. It was obvious that these costs are diluted in the total cost of the infrastructure. Nevertheless it will be a recommendation from this study that, from now on, it is necessary to calculate these figures as a way of better computing the treatment systems costs vs. their efficiency. Table 2 gathers the existing information that was treated and summarized as averages, for the costs of operating and maintenance. Again, A2 is a special case with very high construction and maintenance costs, as expected.
CONCLUSIONS

Several conclusions could be drawn from the evaluation, concerning the project, the maintenance or the monitoring aspects. Table 3 presents some of the recommendations that will be produced and are presently being established. The final results from this study will be presented to E.P.E in May 2008 and it is expected that they will contribute to better future practices, concerning treatment systems project and design choices, sizing, maintenance and monitoring, and the integrated assessment of construction and maintenance costs as well.

Some of the issues identified coincide with the ones from the study by Taylor and Barret (1999), although the data from Portugal is rather limited concerning monitoring results. A similar conclusion concern the fact that infiltration systems are seldom monitored. This observation gave rise to the recommendation that the project of a treatment system should itself give some indications concerning monitoring the efficiency and prepare devices or structures needed for the monitoring actions. This purpose is especially important for structural BMP that do not present an open inlet and/or outlet, as is the case of infiltration systems.

Table 3. Preliminary recommendations designed to improve the Portuguese national practice in construction, operation and monitoring of systems for road runoff treatment.

<table>
<thead>
<tr>
<th>Activity</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project</td>
<td>Must have a <strong>Document</strong> with specific content requirements: reason for the implementation of the structural BMP (<em>e.g.</em>: protection of groundwater); site constraints; justification of the typology; sizing principles; objectives of each of the treatment operations; targeted efficiencies; estimation of construction and operation costs; access to the site; fencing and gate; methodology for monitoring; structures to support the monitoring activities. Must have <strong>Technical drawings</strong> following specific requirements concerning descriptions, measurements, views, scales, etc.</td>
</tr>
<tr>
<td>Construction</td>
<td>During this phase a <strong>Report</strong> must be produced, containing: any alteration made to the original project and the cause for it; total construction costs; drainage conditions observed at the site; additional recommendations for the system operation.</td>
</tr>
<tr>
<td>Operation</td>
<td>During this phase a <strong>Report should be produced on an annual basis</strong>, containing: maintenance activities, their periodicity and staff requirements; costs for maintenance activities; report any empirical data concerning the structural BMP behavior (<em>e.g.</em>: variation in the amount of solids transported to the system and consequences for the foreseen maintenance routines); report on unusual events (<em>e.g.</em>: accidents with accidental spillages of substances on the road pavement draining to the system).</td>
</tr>
<tr>
<td>Monitoring</td>
<td><strong>Report should contain</strong>: methodologies used; description of equipment; pictures of the site and equipment, procedures used to handle and conserve the samples; results; critical discussion of results, comparison with the target treatment efficiencies; recommendations for future monitoring; recommendations to rehabilitate part of the system (if needed).</td>
</tr>
</tbody>
</table>

Concerning the monitoring, several observations lead to specific recommendations, in order to improve if and avoid problems that are now common faults. It was observed, for several cases, that the quantification limits used by the analytical laboratory, for quality parameters measured in road runoff samples, were quite high. Sometimes, the concentrations measured at both the inlet and outlet samples were below these limits leading to no conclusions at all, in
spite of the investment made to obtain such results. It is of main importance to discuss detection and quantification limits with the laboratory in charged of analysis, previous to the start of the monitoring programme, giving them possible ranges for the expected concentrations.

Field observations of the different systems, some of them in their first year of operation, together with the experience of the study team, provided evidences used for recommendations. Special care should be given to the maintenance of treatment systems before the rainfall season (winter) and also, for the case of the first and second year of operation of a new road, after the first month of rainfall. In this last situation, the treatment systems are generally overloaded with solids from the construction materials accumulated at the road pavement, and from the non stabilized vegetated areas.

It was verified that most of the construction companies or consortiums do not record the construction and maintenance costs, although some could be able to make estimations of it. Such information is important to perform cost-benefit analysis, and other type of environmental vs. economical assessment that, at the end, may help to enhance the global benefits of decisions of the kind.

It is important that, in the next future, these recommendations are implemented in order to make mandatory tasks such as to compare the projected and the constructed treatment system; to assess and register the construction and operation costs, and to foresee the possible monitoring methods from the project phase, in order to design also devices or structures within the system itself that will allow performing the monitoring tasks.

It is believed that the benefits from this study results are shared between all, from E.P.E, to the managers of Portuguese national roads, to project companies, and all engineers and technical staff involved in different activities, concerning the project, maintenance, operation, and monitoring of structural BMP.

REFERENCES
Taylor, S e Barret, M, 1999 - Caltrans BMP Retrofit Program.