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Multicriteria evaluation for urban storm drainage

Baptista M.*, Nascimento N., Castro L. M. A. and Fernandes W.

Departamento de Engenharia Hidráulica e Recursos Hídricos - Escola de Engenharia da UFMG
Av. Contorno, 842 - 80 Andar 30110.060 - Belo Horizonte - MG – Brazil

Barraud, S. and Moura, P.

** URGC - INSA Lyon
Bâtiment J.C.A. Coulomb 34, avenue des Arts - 69621 Villeurbanne Cedex – France

Abstract
The process of conceiving stormwater systems, within the framework of the best management practices, became more complex, involving not only the technical and cost aspects, but also the environmental, social and sanitary ones. Different types of BMPs can be selected for a particular stormwater system and can be used individually or in a combined way, leading to different possibilities of arrangements that can be implemented in a particular area. Each alternative can deal with the drainage problems in a different level, according to diverse purposes. Due to the complexity of the conception considering all these aspects, a multicriteria analysis, based on a set of indicators, seems clearly convenient as a decision making tool. This is the aim of the present paper, to describe and discuss results of several steps of a decision making tool development, based on a multicriteria procedure allowing the *a priori* evaluation of stormwater systems by the aggregation of economic-financial indicators with performance indicators. Based on this methodology, a decision aid tool (*AvDren*) was created to allow the choice of convenient projects alternatives.

Keywords: urban drainage, indicators, multicriteria analysis

1 Introduction

In the last decades, an intense process of urbanization took place, a current worldwide phenomenon leading to significant environmental impacts in urban areas. These impacts are related to quality and quantity variables of the hydrologic cycle. According to US-EPA (1999), the main impacts of the urbanization on the hydrologic cycle are due to modifications on the impervious area, which changes processes as evapotranspiration, runoff and the shallow and deep infiltration. Also the quality of receiving waters is affected, due to the wastewater contamination (e.g.: combined system overflow, illicit cross connection) and stormwater discharges (diffuse pollution). Stormwater is usually heavily polluted due to pollution sources as vehicles circulation, industry pollution, animal dejects, solid

* Corresponding Author: marbapt@ehr.ufmg.br

wastes inadequate disposal, atmospheric pollution and contamination by pathogenic organisms. These impacts cause frequent operational failures on conventional stormwater drainage systems.

In the 1970's, a new concept urban stormwater management emerged, focused on compensatory or alternative solutions, usually designated as Best Management Practices – BMPs. These solutions, firstly adopted in Europe and North America, aim at compensating the effects of the progressive urbanisation over hydrological processes, without restraining the urbanisation. BMPs are based on storage and infiltration of stormwater by means of devices like trenches, swales, retention/infiltration basins, roof storage, porous pavements, etc. Also, purposes such as environmental preservation and quality of life enhancement are taken into account.

Different arrangements of BMPs can be conceived for a particular urban area, frequently allowing an adequate integration of central purposes of runoff and water quality control with the urban and landscape development project. Nevertheless, according to Barraud et al. (2004a), in spite of being rich in possibilities, sometimes these technologies are not employed, or are used in the wrong way, due to difficulties in choosing the best arrangement that fits to each area. The conception of new stormwater systems incorporating BMPs may be highly complex, involving not only technical and cost aspects, but also environmental, social and sanitary concerns. In this complex decisional environment, a multicriteria analysis, based on a set of indicators, seems a relevant and convenient tool to support the decision making in face of different alternatives.

The present paper describes the main results of several steps in developing a decision-aid tool that focus on a multicriteria procedure allowing the *a priori* evaluation of stormwater systems by the aggregation of economic-financial indicators with performance indicators, to the choice of adequate projects alternatives. The methodology presented here focus on the evaluation phase. The proposed methodology takes into account the conception and design processes of urban stormwater systems incorporating BMPs, which usually involves two different phases: (i) the elimination of techniques that are not feasible or adequate due to physical, hydrological, geotechnical, structural and environmental local restrictions; and (ii) the assessment of scenarios combining different arrangements of a variety of BMPs that could meet the stormwater management and urban development purposes.

The use of a multicriteria approach is mainly justified by the following reasons:

- Multicriteria approaches allow the simultaneous evaluation of a vast number of criteria, including those that may indicate the causes and the consequences in a particular process;
- Multicriteria approaches may contribute to a better understanding of possible conflicts between multiple objectives and the degree of compromise among them that will certainly be required during the decision making process;
- Multicriteria approaches can lead to the best solution to a particular problem provided that criteria involved in the multicriteria decision-making procedure are adequately formulated.

2 Methodology

The methodology employed in this research is based on the definition of a global performance and a cost indicator. The performance index is based on technical, environmental, sanitary and social aspects. It is aggregated to an economical index, by means of a multicriteria procedure, allowing the comparison of possible alternatives to help in the choice of the appropriate alternative.

2.1 The Performance Indicator

As mentioned before, the performance indicator represents technical efficiency as well as environmental and social aspects. Three aspects guided its formulation:

- “design objectives” corresponding to the suitability of a drainage system to meet initial design requirements in terms of runoff control and protection against flooding;
- “impacts” of drainage systems on downstream flow conditions, on water quality, on aquifer recharge, and on human health;
- “integration” regarding ecological aspects, landscape and social acceptance.

Indicators formulation was preferentially based on mathematical expressions. However, for some of them, a more subjective assessment was employed founded on the decision team experience and knowledge. In any case, a common numerical base was employed for all of them. The complete formulation of each indicator is presented in Castro (2002) and the main aspects evaluated by each one of them can be found in Castro and Baptista (2004).

The statement of the relative importance between indicators was the next step, after their formulation. The relative importance of each particular aspect was assessed with the help of interviews with representatives of technical municipal services (TMS), designers of urban stormwater systems (DSS), environmental regulatory bodies (ERB) and researchers (RSC). The results of the interviews were treated by tendency analysis, leading to relative indicator weights to be used in the devised methodology (see Table 1). Differences on weights ascribed to the indicators, when classified according to the groups of interviews (e.g.: TMS, ERB, …), reveal specialist differences and preferences on evaluating the various aspects considered (see Baptista et al, 2005) for a comprehensive discussion of this point).

Table 1. Weights of the different partial indicators in the global performance indicator

Criterion	Indicator	Weight (%)
Objective	Ability of the system to drain an area in safe conditions - low flooding (*Io*)	10,0
Impacts	Hydrologic impacts to the downstream flow (I_{H1})	14,1
	Aquifer recharge (I_{H2})	4,9
	Sanitary impacts on the possibility of disease transmission (I_{S1})	8,1
	Sanitary impacts on the possibility of insects’ proliferation (I_{S2})	7,9
	Impact on surface water quality (I_{Q1})	10,9
	Impact on groundwater quality (I_{Q2})	7,7
Insertion	Environmental integration by habitat development and preservation (I_{A1})	9,4
	Environmental integration by landscape enhancement (I_{A2})	5,9
	Social indicator regarding the development of leisure and recreation areas (I_{SC1})	6,2
	Social indicator of impacts on the traffic conditions (I_{SC3})	5,1
	Social indicator related with the possibility of using the drainage technique to other technical functions (I_{SC3})	4,2
	Social indicator of expropriating areas (I_{SC4})	5,6

In the present study a single performance indicator, *Ip*, has been developed (Equation 1) according to a multicriteria approach that allows the combination of all the criteria previously listed (Table 1). For each project alternative, the higher the *Ip* value the better the alternative regarding performance.

$$Ip = \frac{\sum_{i=1}^{n} I_i\ w_i}{\sum_{j=1}^{j=m} \left(\sum_{i=1}^{n} I_i w_i\right)_j / m} \qquad (1)$$

where:

Ip: global performance indicator;
I_i: the performance indicator for the scenario *i*;
w_i: the weight of the indicator *i*;
n: number of performance indicators;
m: number of scenarios.

2.2 The cost indicator

To evaluate the costs of project alternatives, an indicator based on the drainage system Net Present Value (NPV) costs, including construction, operation and maintenance costs, was defined. The NPV is calculated over thirty years, a time spell usually adopted as the average lifetime of conventional urban drainage structures. However, in the case of BMPs, lifetime may be shorter (see Table 2), implying in higher refurbishing costs, a situation that has been considered in the present evaluation.

Table 2. Lifetime of different drainage techniques, in years (based on CERTU, 1998; US-DT, 2003; WSDE, 2001; MWCG, 1992 and interviews with Brazilian technicians)

Technique	Detention basins		Infiltration basins	Swales	Porous pavements
	concrete	Earth or vegetated			
Lifetime (years)	30	10-15	5-10	5-15	10-25

Equation 2 allows the cost indicator, *Ic*, calculation, here proposed. The rationale concerning this indicator is: the higher *Ic* value the lower the cost for the alternative under evaluation in respect to the average cost of all the alternatives considered.

$$Ic = \frac{\overline{C}}{C_i} \qquad (2)$$

where:
I_c: cost indicator for the alternative *i*;
$\overline{C}$: average global cost (NPV) of the different alternatives;
C_i: global cost (NPV) of the alternative *i*.

2.3 Integration of cost and performance indicators

The next part of the methodology here proposed is to aggregate the two main indicators, *Ip* and *Ic*. This aggregation is also done by a multicriteria procedure, leading to the performance-cost analysis. The procedure is based on a “Pareto chart”, allowing the visualization of dominant and dominated alternatives. Uncertainties associated to both indicators are also plotted in the chart, showing eventual indifference between the alternatives. The use of the Pareto chart provides the decision-maker with information about the best performance-cost alternative as well as about other relevant solutions among those that are not dominated.

3 The AvDren Software

The proposed decision-making methodology can be applied with the help of the *AvDren* software, specially developed for this purpose. *AvDren*, a computer program written in the Microsoft Visual Basic 6.0 language, runs in the MS Windows environment, making its use easy and friendly.

AvDren makes possible and straightforward to perform comparative analysis of the partial indicators incorporated to the global performance indicator with the help of a performance graphs. This toll makes easy the identification and elimination of alternatives with unacceptable level of functionality. After removing these alternatives, the feasible alternatives can be compared according to the results obtained for their global performance and cost indicator. The software offers also the possibility for the analyst to enter unitary costs data into a database as well as to adopt different Internal Return Rates and uncertainties for NPV estimations. These features can be relevant so that all the proposed alternatives have their costs calculated with the same basic data. *AvDren* is a free-software and can be downloaded from www.ehr.ufmg.br.

4 Case Study

In order to exemplify the use of the described methodology, a real case study has been selected for application. This case study refers to an area in southwestern France, a new service and industrial development, called Technopolis, for what a wide range of stormwater management alternatives has been devised. Its total drainage surface is nearly 23 ha, with about 6 ha occupied by buildings and others 6 ha corresponding to streets and car parks (Baptista & Barraud, 2001). Three drainage scenarios were evaluated and compared with the help of *AvDren*: scenario I (a conventional pipe system, without any restriction in terms of maximum downstream flow); scenario II (an intermediate system, with the incorporation of a detention basin downstream of a conventional pipe system, in order to respect a fixed downstream flow limit); and scenario III (an alternative system, with the use of porous pavements, ditches and a detention basin, respecting the fixed downstream flow limit).

The technical solution for each one of these scenarios was simulated considering three return periods (10, 30 and 100 years) and with the help of the *CANOE* software. The hydrological, environmental and social characteristics related to the three scenarios were introduced in the *AvDren* software to calculate the *Ip* indicator Building costs were calculated with data from a previous study (Baptista & Barraud, 2001). Maintenance costs were calculated using the *AvDren* database.

Figure 1 shows the performance of each scenario according to each criterion. It is a representation of partial indicators used in the global performance indicator assessment. The chart analysis allows eliminating some alternatives, then simplifying the costs analysis phase. Nevertheless, in the present case, all the alternatives were considered and the global analysis results are presented in Table 3 and Figure 2. The same uncertainty level was adopted for all the evaluations.

Table 3. Performance and Cost indicators (Technopolis)

Scenario I			Scenario II			Scenario III		
Return period	*Ip*	*Ic*	Return period	*Ip*	*Ic*	Return period	*Ip*	*Ic*
I-10	0.651	1.339	II-10	1.011	1.001	III-10	1.178	1.326
I-30	0.669	1.109	II-30	1.104	0.936	III-30	1.364	1.128
I-100	0.742	0.920	II-100	1.429	0.786	III-100	2.258	0.778

The results obtained are clearly in favour of the scenarios including BMPs, with the possible choice of the scenario III-100, which was exactly the implemented alternative.

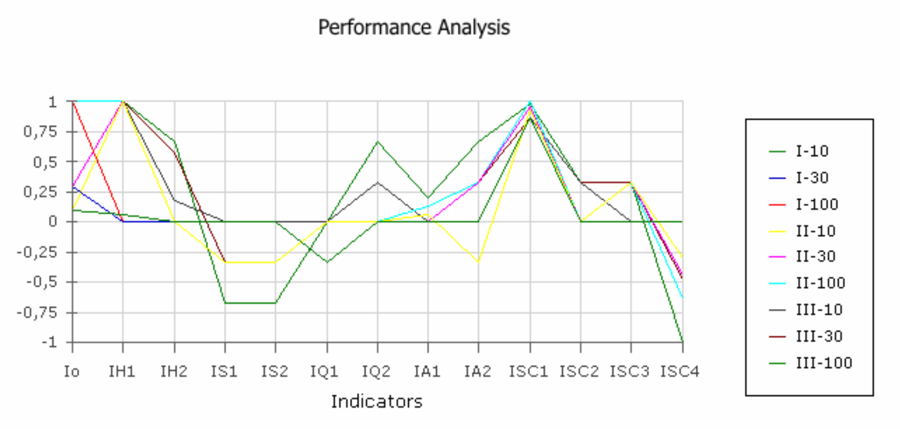

Figure 1. Performance chart (Technopolis)

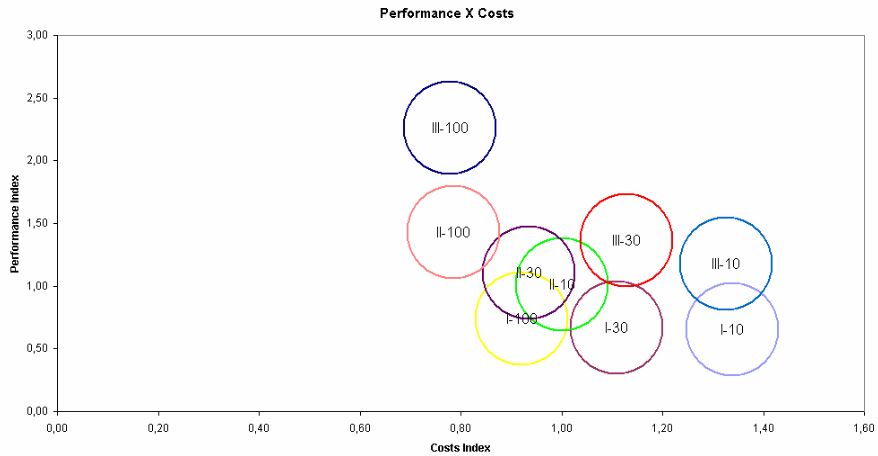

Figure 2 – Pareto Chart - Technopolis

5 Critical Analysis of the Set of Indicators

Decision support systems are nowadays applied to diverse domains. However, few researches and studies deal with quality and credibility assessment of the issues so obtained (Barraud et al., 2004b), despite the existence of diverse methods employing different approaches. The quality of the decision aid process depends on the quality of individual indicators, of the global set of indicators and of on the method used to select, rank or sort good solutions. Some criteria may be employed in assessing indicators' quality, e.g.: accessibility (is the indicator easy to calculate and are the data for the calculation available?); objectivity: (aren't indicators ambiguous? can they be evaluated in the same way by different appraisers?); relevance (are the performance criteria relevant?); robustness (do indicators give stable results according to the variation of uncertain parameters?); sensitivity (do they discriminate different strategies?) and fidelity (can they be estimated with a constant bias?).

For the quality of the global set of indicators, the number of indicators employed has to be considered. In effect, the indicators have to be exhaustive, but their number must not be excessive, because a large number of indicators can bring difficulties in the methodology application. Therefore, their independence or redundancy has to be examined. The quality of the method depends on different aspects: the weighting procedure, the way uncertainties are taken into account and at last the sensitivity of the global method and its robustness. Based on these aspects, the critical analysis was here done by means of:

- The verification of each aspect related to the quality of each indicator: accessibility, objectivity, relevance, robustness, sensibility and fidelity;
- The verification of the global quality of the set (number, potential redundancy and dependence of the different indicators);
- The verification of the quality of the methods (relevance of the weighting procedure, sensitivity and robustness of the method).

The critical analysis was here performed using the case study data. Part of this analysis, concerning the assessment of redundancy is here presented and discussed (see Castro et al, 2007, for the complete evaluation). The redundancy assessment is based on the correlation among indicators taken in pairs. Table 4 illustrates the matrix of determination coefficients for all the indicators employed. The main issue of this kind of evaluation is to suggest possibilities of combining highly correlated indicators.

Table 4 - Determination matrix of the indicators

Coefficient of Determination (R_2)												
I_O	0.000	0.034	0.290	0.290	0.018	0.034	0.412	0.290	0.392	0.000	0.290	0.404
	I_{H1}	0.088	0.360	0.360	0.526	0.095	0.325	0.360	0.217	0.333	0.360	0.328
		I_{H2}	0.179	0.179	0.002	0.878	0.173	0.179	0.010	0.263	0.179	0.181
			I_{S1}	1.000	0.324	0.137	0.958	1.000	0.596	0.120	1.000	0.961
				I_{S2}	0.324	0.137	0.958	1.000	0.596	0.120	1.000	0.961
					I_{Q1}	0.003	0.311	0.324	0.112	0.458	0.324	0.316
						I_{Q2}	0.140	0.137	0.019	0.286	0.137	0.144
							I_{A1}	0.958	0.669	0.119	0.958	0.999
								I_{A2}	0.596	0.120	1.000	0.961
									I_{SC1}	0.009	0.596	0.647
										I_{SC2}	0.120	0.128
											I_{SC3}	0.961
												I_{SC4}

A high coefficient of determination not necessarily means a redundancy between a pair of indicators, but it suggests that an evaluation on redundancy and on the possibility of indicators association must be performed. On the other hand, a low value of the R^2 directly means that the pair of indicators is not redundant. As an example, R^2 between I_{S1} and I_{S2} is equal to 1, which means that a possible redundancy exists. Analysing I_{S1} and I_{S2} formulations and the way they are calculated, one can conclude that both indicators are really redundant and can be combined. R^2 for indicators I_{S1} and I_{A2} is also equal to 1, but in this case the indicators don't depend on the same factors and since each one considers a different aspects on the global analysis, they are not redundant. For most of the indicators employed in the present methodology, R^2 is very low, then meaning a non-redundancy between them.

6 Conclusions

This paper presents and discusses a methodology based on multicriteria analysis to incorporate performance and costs indicators in a decision-aid tool for the conception of stormwater systems. The performance indicator is based on hydrological, sanitary, environmental and social criteria and the cost indicator takes the building, maintenance and operation costs into account.

In spite of the great variability of weights suggested by different decision-makers for the performance indicator, the application of the proposed methodology suggests its relatively low sensitivity to changes in indicators weights. The global results indicate the methodology robustness.

An important advantage of this methodology is its simplicity. It does not require any complex numerical decision aid methods and, at the same time, it allows a complete follow up of the calculation procedures by the decision-makers. Its flexibility for customisation and use allows dealing with a wide range of different physical and technological contexts.

The critical analysis proved to be a strong tool to validate the indicators set, checking some aspects related to their quality and redundancy. It is relevant in identifying the indicators that can be suppressed, the ones that can be combined and even some others requiring improvements on formulation and data used. The tests here performed suggest that the devised indicators are relevant to the decision-making tool, provided that the required information and date are available. Their validation to the Brazilian conditions may create opportunities to use them in other tropical developing countries without substantial modifications.

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