A methodology to assess sustainability of urban stormwater management

Guido Petrucci*

* Leesu, Université Paris Est – AgroParisTech, UMR MA-102, 6-8 avenue Blaise Pascal,
77455 Champs sur Marne cedex 2
(E-mail: guido.petrucci@cereve.enpc.fr)

Abstract

Urban stormwater management (USWM) in developed countries is undergoing a significant evolution. Centralized systems are giving place to distributed facilities, mainly to cope with flooding caused by fast urban growth and with water bodies' quality degradation. This evolution has to face inertias from existing structures, but it relies on the idea that new strategies are more sustainable than old ones. We assume that USWM is strongly dependent on local conditions and objectives, and thus its sustainability has to be evaluated at a local scale.

Although no global solution can be found, it is worth defining a general method to assess if an USWM strategy is sustainable on a specific site. In this paper we propose and discuss a methodology of this kind, mainly based on hydrological models. The methodology is made of three phases: definition of sustainability; modelling and analysis of several case studies; generalization procedure.

Keywords

Urban stormwater management; source control; hydrological models; sustainability; Best Management Practices.

INTRODUCTION

Urban stormwater management (USWM) is undergoing a significant evolution. While in the last 150 years the main strategy was to centralize and evacuate as fast as possible urban stormwater through combined or separate sewers, in the last two decades the interest in source control has grown (Niemczynowicz, 1999; Novotny and Brown, 2007).

The two main drivers of this evolution, at least in countries where traditional sewers are diffused, are (i) the awareness that urban stormwater contributes significantly to water bodies' pollution, (ii) the inertia of traditional structures (i.e. both sewer systems and their management institutions) to adapt to new needs. In particular, increases in runoff due to fast urban growth are often impossible to manage without extremely expensive renovations of existing structures. Among the authors pointing out these problems, see for example Chocat et al., 2007.

The basic principles of source control are in opposition to the traditional one: stormwater must be managed, and eventually reused, as close as possible to its falling site, to do not aggravate the situation elsewhere; natural fluxes must be preserved and restored, particularly toward groundwater; runoff must be slowed down. Another principle often stated is to keep water on surface, integrated to urban systems, in order to improve social awareness and to provide urban amenities.

These principles are realized through a wide set of usually small technical solutions, like retention tanks, vegetated strips, infiltration basins, ponds, etc. Two examples are shown in figure 1. These solutions are collectively addressed, especially in U.S. literature, as Best Management Practices (BMPs). Other denominations exist, referring to the same principles but putting the accent on different aspects, like SUDS (Sustainable Urban Drainage Systems) or LID (Low Impact Development).

Source control is generally considered “greener” and more sustainable than traditional USWM, and researches on it are oriented to assess more its effectiveness in reducing runoff and pollutants than its overall performance. But, as discussed below (Discussion Section), sustainability of a particular USWM system is strongly dependent on its context, and it can not be affirmed in a general way. Therefore, under which conditions source control is “better” than centralized sewers?

Figure 1 – Two examples of BMPs in France: a rainwater harvesting tank at the parcel scale in Champigny (Val-de-Marne), and an infiltration/overflow basin for a block of houses in Noisy-Le-Grand (Seine-St-Denis)

Moreover, most of the applications of source control techniques are still confined to small experimental areas. In a scenario of large diffusion of source control, does it have to replace completely traditional systems, or just to be complementary to them? To what extent? In which cases? At which scale it has to be managed?

To answer these questions about global impacts of source control, both in specific and general cases, a methodology is necessary to assess the sustainability of alternative USWM options. The purpose of this paper is to propose a methodology of this kind.

After a brief overview on Material and Methods, we discuss the main issues (Results and Discussion) posed by a similar assessment. Then, we finally propose a methodology made of three phases: first, a definition of sustainability; second, a modelling and analysis of several case studies; third, a generalization procedure.

MATERIAL & METHODS

The proposed methodology uses hydrological and hydraulic integrated models in its second and third phase, as described below. Many models are available, both commercial and research-oriented, with different characteristics. For each application one suitable model should be selected *a priori* or after a comparison with others. For the second phase, the author uses SWMM 5 (Rossmann, 2004) and STORM (IPS, 2008), that have complementary capacities. To realize the automation part of the third phase, our intention is to use Matlab programming.

RESULTS AND DISCUSSION

General sustainability assessment: main issues

In this section we shortly describe the main issues that have to be taken into account by a comprehensive methodology for USWM sustainability assessment.

Local dependency on physical and social context

If stormwater management can be necessary in every urban setting, it has to be implemented differently in each one. Stormwater regime is dictated by climatic conditions; rainfall-runoff transformation depends on topography, geology and land use; available management alternatives are based on urban form and pre-existing structures, etc (Pitt and Clark, 2008). Furthermore, the social context where the USWM is developed affects the objectives that have to be aimed by the system and their priority. Thus, there is neither a general formulation nor a general solution to sustainable urban stormwater problem.

The main implication of this local dependency of USWM is that it is not possible (or at least not logically correct) to assess the sustainability of a solution *in general*, but only *in a specific context*. The definition of durability proposed later in this paper, will take into account this characteristic.

Variety of alternatives

In a traditional approach to USWM, the alternative solutions to a problem are generally a few “big” structures, with some alternative locations and with an optimisation to be done for dimensioning and eventually operation. In a source control approach to the same problem, the number of independent structures (*a priori* of different typologies) can be huge, the location becomes a territorial distribution and the dimensioning must be done for each one.

The definition of alternatives to be considered in the analysis is then a delicate issue and, although computer and algorithm innovations offer potential solutions, traditional optimisation instruments have to be reviewed (Pitt and Clark, 2008).

Complexity of involved physical phenomena

Shifting the interest from pipes flow capacity to open surfaces potential to infiltrate and stock water, we shift the emphasis from hydraulics to hydrology. The problem is that hydrology does not dispose, nowadays, of specifically developed instruments for urban areas. The traditional approach of this discipline is focused on much bigger scales (typically river watersheds), and the transposition to smaller ones is not always satisfying (Niemczynowicz, 1999). Indeed, also if elementary phenomena can be the same, intrinsic dishomogeneity of urban environment greatly increases the complexity of flow paths. Moreover, as in urban settings we usually consider a much smaller scale, the requested accuracy in flow estimations is often 2-3 orders of magnitude bigger (e.g. l/s instead of m^3/s).

While waiting for a new approach to urban water processes, we can use and adapt classical hydrological models, but we have to accurately validate hypothesis and parameters and to carefully handle results.

Non-technical complexity

USWM system, as part of an urban context, is integrated to many others (technical or not). Thus, its correct implementation and operation depends upon a wide set of exogenous variables. For example, a same technical solution can perform well or not according to citizens' collaboration. Another example is that it can be impossible inside an administrative area to set an hydrologically-sound variable policy, because of the economic inequality it generates.

This kind of complexity appears typically when studying real cases (e.g. Maytraud et al., 1995), or when trying to apply theoretical results to real systems. In some cases, such difficulties can be important enough to turn a good theoretical alternative into an inapplicable or inefficient one.

Behaviour evolution over time

Little knowledge is available and trustful about how source control systems get old. Well-planned maintenance can prevent most dysfunctions of a system and keep it efficient, but maintenance is difficult to assure (Guillon et al., 2008). Moreover, phenomena like soil compaction or pollutant accumulation are hardly avoidable and poorly known (see for example the results of Emerson and Traver, 2008). Even less is known about long term maintenance: after how many years a source control element has to be completely renovated?

The behaviour evolution over time is a good example of lack of knowledge about source control. Its solution would require years of empirical researches and therefore exceeds the purpose of this paper. Nevertheless, we have to take this uncertainty into account in our methodology: it imposes to consider different ageing and dysfunction scenarios while estimating the long-term efficacy of a source control system.

Sustainability evaluation: methodology proposal

The methodology we propose to evaluate USWM tries to cope with the described issues, and it is composed by three main parts:

- a general framework to define sustainability, declinable for any specific case;
- the analysis of a set of real specific cases, in order to validate the sustainability definition, assess models' validity and create a casuistic of contexts;
- an attempt to generalize results using models.

Actually, at LEESU, the review and validation of the first part is in progress, and the second one has started.

First phase: a general framework to define sustainability

The concept of sustainable development, thanks to its generality, is used in many contexts with different meanings. Its most known definition is the one from the 'Brundtland Report' (United Nations, 1987): "[development] *which meets the needs of the present without compromising the ability of future generations to meet their own needs*". This extremely synthetic definition, although effective, is not directly operational and needs to be transposed to each specific field of application. This can be done by declining for each object the economic, environmental and social values. The underlying idea is that, while economic value decreases in time and the far future monetary values are irrelevant, social and environmental values should take into account the future as much as the present, satisfying in this way the Brundtland's definition.

More in detail, it is accepted that for a sustainable decision making it is necessary, although not sufficient, to explicit all objectives involved in the decision, including environmental and social ones. Following this approach, we adapt the criteria-tree from the Daywater project (explained below) in order to base our definition of sustainability.

Daywater and Daywater 2 are projects aiming to create an Adaptive Decision Support System (ADSS) to solve problems of stormwater management recurring to BMPs (Thévenot, 2008). One of the elements developed in the ADSS is the criteria-tree: for six criteria (technical, operation & maintenance, environmental, social & urban community benefits, economic, legal & urban planning) a nearly exhaustive structure of sub-criteria and suggested indicators is given. It is a set of evaluation criteria and methods general enough to fit (through an adaptation process) a large extent of specific cases (Deutsch and Deroubaix, 2008). In table 1 an example for the Technical criteria is presented.

Table 1 – Technical criteria tree from the Daywater ADSS (http://daywater.in2p3.fr/EN/)

Criteria	Sub-criteria		Indicators
Technical	Flood Control	Storage and flood control	Design storm return interval storage volume (m3/ha)
			Response rate for superimposed critical storm durations (m3/ha/hr)
			Ratio of storage to contributing drainage area (ratio)
			Number of floods per year within catchment (1...n)
			Overflow frequency and duration (1...n)
			Discharge or throttle rate (m3/s)
			Uniform flow distribution (H/M/L)
			Length of antecedent dry periods ()
	Pollution Control	Water quality treatment	Pollutant concentration probability exceedance for given target levels (% exceedance for given target level)
			First-flush capture potential (10/15mm effective runoff treatment for all storms) (mm runoff/av storm event)
			%age pollution capture for given RI storms and retention times (% capture for given RI or retention time)
	System flexibility & potential for retrofitting	Capability for change over time	Design freeboard for storage and water quality change (%; m3/lifetime)
			Ease of retrofitting and modification (H/M/L)
			Costs of retrofitting and add-on structures/features (Euro (av.cost))
			Potential to recycle system components/waste (H/M/L)
			Reliability (H/M/L)
			Durability (H/M/L)
	Impact on drainage system	Integration with existing system	Flow reduction to STP and CSOs (%; m3)
			Reduction in stormwater flows (%; m3/ha)
		Design life	Operational lifetime (Years)
			Sedimentation rates and storage volume (m3/yr; % reduction in storage volume/yr)

We can consider that the six criteria are general enough to be mostly universal (i.e.: they are pursued, in some degree, by each USWM system). To fit a specific case we have to move upward the tree: we have (i) to choose the sub-criteria that best represent the specific issues to be solved and the existent constraints, discarding the non-relevant aspects. Then, (ii) for each chosen sub-criterion, we have to take one or more relevant indicator and, (iii) for each indicator we have to define an evaluation procedure (expert estimation, modelling, etc). For our purpose, i.e. to well define case-specific sustainability, if the fitting procedure is done well, the resulting set of indicators can be considered an exhaustive description of the problem, explicitly setting all its local aspects.

One expected result of the testing work in progress is a completion of the criteria-tree with a suggested method for measuring and assessment for each indicator proposed. In the Daywater ADSS such methods are listed but not linked to specific indicators.

It is necessary to point out that, even if many aspects are common and can be shared, the sustainability assessment can not be considered a decision support procedure. In fact, some key divergences subsist. For example no stakeholder is involved in the assessment, so the indicators represent a description of reality made by the analyst and not, as in decision making, the interests of parts. Another example is that neither preference aggregation nor negotiation procedures are comprised in our assessment.

Second phase: empiric evaluation on case studies

The purpose of this phase is threefold: validating the framework; finding indicators’ estimation methods – especially models; create the support for the generalization attempt.

In the analysis we insist on modelling, for two practical reasons: (i) most of the objectives of USWM can be assessed through a hydrologic/hydraulic model; (ii) if the model is trustful (and this will be verified through the validation), it is an optimal way to carry out the generalization.

The case studies constitute the main support of all the methodology: they provide knowledge about involved phenomena and they define the validity limits of framework and models. Thus, *a priori*, the greater is the number of case studies considered, the better will be the understanding of phenomena and the generality of the conclusions. On the other hand, the number of treatable case studies is limited by available resources. In order to obtain the better result, it is important to carefully choose the cases to analyse. The most important characteristics for this choice are: variety of territorial scales (from the block to the district or to the city), variety of contexts (climate, hydrogeology, urban structure, objectives, etc), variety of applied BMPs, availability of hydrologic measures and feedbacks on performances, possibility of collaboration with local experts.

After a case study is selected, the analysis procedure follows these points:

1. Framework fitting to define local sustainability, together with assessment methods for each indicator.
2. Hydrologic/hydraulic model fitting. The “situation”, pre- or post-BMPs installation, to use in the fitting phase depends mostly on measures availability.
3. Validation of the fitted model, with additional measures in the same “situation”.
4. Test of the fitted model with/without applied BMPs (i.e. the “situation” not considered for fitting).
5. Assessment of all the indicators for the two “situations”, recurring to long time-series, eventually synthetic. Calculation of indicators’ variations.

6. Eventually, simulation of significant USWM alternatives other than the two already considered.
7. Analysis of results and retrofitting to framework, model and other assessment procedures.

Remarks on the procedure:

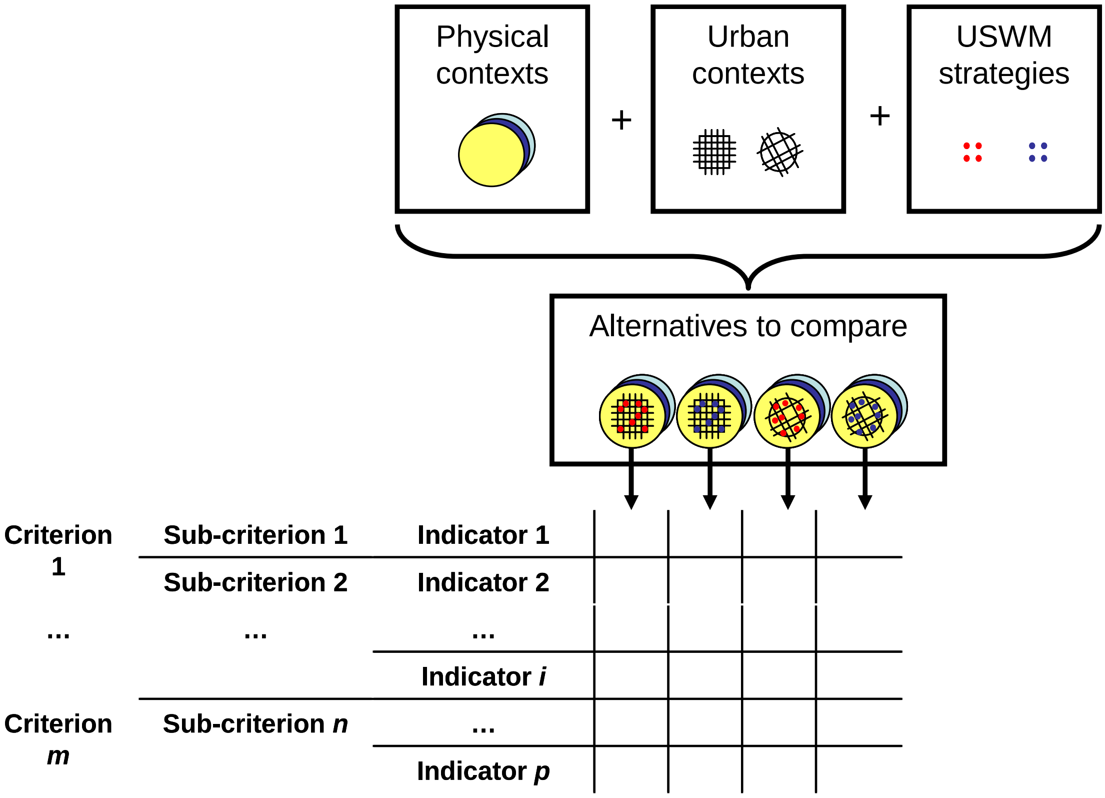
- Model fitting phase, which can be carried out with suitable algorithms (e.g.: Franchini et al., 1998), helps to verify if literature's hydrological standard parameters (e.g. those presented in Appendix A of Rossmann, 2004) are able to describe urban setting, or if they need corrections. We refer here to the issue "complexity of involved physical phenomena" described above.
- Although a specific phase of global retrofitting is explicit in the procedure, partial retrofits can be done at any point and for any object (framework, indicators, etc), especially when, for the first case studies, the methodology in itself is tested. Moreover, in these first tests, many indicators and models can be tried in parallel and compared.

Third phase: generalization

This last phase has the purpose of comparing alternative USWM solutions for a wide range of conditions and sustainability definitions. Although its contents will greatly repose on the preceding phase, it is possible to define its development under some reasonable hypothesis.

The main activities will be (i) to create a set of alternative scenarios, each composed by a context and a sustainability definition, (ii), to cross them with a set of alternative USWM systems, (iii) to fit and run models and (iv) to assess indicators. A simplified schema is presented in figure 2.

Figure 2 – Schema of the generalization phase



The first problem to solve is the creation of fictive contexts: each one has to be described by a set of significant "key-variables" that drive USWM performances. The choice of this set of pertinent key-variables is not obvious, as they have to satisfy many requirements. In facts, these variables must (i) describe quite in detail the urban and physical context (climate, hydrogeology), (ii) allow discrimination between different USWM systems, (iii) be easily transposable to the model and (iv) their number must be as small as possible. The choice of this set of key-variables has to be done on the basis of the experience from case studies, but also in function of the model employed.

Once the key-variables are selected, together with their range and possible values, it is possible to generate scenarios through variables combination. Basically, the exhaustive set of available scenarios can be obtained by Cartesian product of all the definition-sets of the key-variables. To obtain a finite set of scenarios it will be necessary to discretize continue definition-sets, and to bound infinite ones. The approach to use for each variable has to be decided case by case.

The opportunity of an exhaustive or a selected review of the set of scenarios will depend on their number and on the time requested to analyse each one. *A priori*, the big number of expected scenarios (for n variables with 10 values each, the total number of scenarios is 10^n) suggests that a selection will have to be done, on a basis of pertinence and significance of scenarios. The use of typical climate, urban forms and topographies from specific world areas or, eventually, of a research algorithm, could simplify the exploration of the scenarios' set.

Also for sustainability definitions, a combinatory approach can be used: as we consider that sustainability estimation is a subset of the whole set of indicators considered, it is possible to extract all the subsets and to assess them on all scenarios. In this case too, the exhaustive approach seems pointless, as many resulting definitions have limited interest. Thus, a selection strategy has to be defined to discard unrealistic definitions.

As described in the issues' paragraph of this paper, one sensible point of this methodology is the procedure to define USWM alternatives to be considered. This point is still object of research. The main difficulty is that, as such procedure cannot be exhaustive (as discussed above, we have to cope with a series of spatial distribution) and it has to be automatic (to allow the treatment of a large number of scenarios), we need to find an algorithm capable to efficiently select a small number of good alternatives in a high dimensional space. A possible solution is to create an expert system trained over case studies and researchers' experience.

In conclusion, it is necessary to remember that any result obtained in this phase, independently from the chosen procedure, pass through the model and the objectives' assessment. Therefore, any result can be considered valid and trustful only in the validity field of the model. Also if the presented methodology is theoretically valid, practically the fictive scenarios will have to be chosen in "neighbourhoods" of the case studies.

CONCLUSIONS

This paper proposes a methodology to solve the problem of sustainability assessment for USWM systems using source control, both in specific and general cases. The methodology is articulated in three phases.

The first phase is the setting of a sustainability definition. We adopt a general criteria-tree and a method to apply it to site-specific problems.

The second phase is the sustainability assessment for a series of case studies. For each one a specific definition of sustainability is given, and measured through existing data and modelling. A validation of the framework, of the models and of the assessment procedure is done.

The third phase consists in a generalization of the results obtained. A set of theoretical scenarios is constructed and modelled, in order to assess the sustainability of USWM systems in a wide range of conditions.

The methodology described can cope with many issues inherent to the complexity of USWM systems although, due to these issues, the validity of the general results obtained will be strongly dependent on the case studies considered. Moreover, some described task which has not yet been performed is still to define in detail, and can bring unexpected difficulties. In particular, the study of real cases can always bring unpredicted new elements to the analysis, and the third phase includes some innovative and non-straightforward practical, technical and mathematical operations. We can expect that, at least at the beginning, the scope of the methodology will have to be reduced, for example to a restrained set of significant indicators. The general formulation proposed stands anyway as a valid theoretical reference and, if the first tests will give adequate results, as the methodology permits feedbacks and further extensions, oriented improvements can be foreseen.

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