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Abstract Stormwater source control is becoming a common strategy for urban stormwater management in many countries. It relies on regulations or other policy instruments compelling or inciting to implement, for each new urban development, small-scale facilities to locally store and manage stormwater. Local authorities that pioneered source control since the 1980s have already observed that small-scale facilities systematically implemented over a catchment are able to influence its hydrological behaviour. This capability is the main strength of source control, as it allows compensation for the negative effects of urbanization. Yet, it also represents its main risk: if initial decision-making is not sufficiently accurate, source control can produce long term negative effects. Because of its current spreading, source control will acquire an increasing role as a driver of hydrological changes in urban catchments, and the directions of these changes depend on current policy-making practices. This paper presents an analysis and a critical discussion of the main objectives that policy-makers attribute to stormwater source control. The investigation is based on a sample of French case studies, completed by a literature review for international comparison. It identifies four main objectives, some typical of urban stormwater management and some more innovative: flood reduction, receiving waters protection, sustainable development, costs reduction. The discussion focuses on how current policy-making practices are able to translate these objectives in concrete policy instruments, and on which knowledge and tools could improve this process. It is shown that for some objectives, basic knowledge is available, but the creation of policy instruments effective at the catchment scale and adapted to local conditions is still problematic. For others, substantial lacks of knowledge exist, casting doubts on long term effectiveness of current policy instruments. Research directions are identified to improve source control policies and thus the future hydrologic behaviour of many urban catchments.

Key words stormwater management, urban areas, source control, policy-making

INTRODUCTION

Urbanization is probably the human activity most impacting the hydrology of natural catchments. For decades the basic mechanisms of this impact are understood (e.g. Leopold 1964): the creation of large impervious, non-vegetated areas associated to urbanization reduces infiltration and evapotranspiration processes, increasing the volume of surface runoff; the efficiency of artificial drainage systems reduces concentration times during rainfall and concurs, with the increased runoff volumes, to increase peak flow-rates. But the extent and consequences of these relatively simple processes are still object of research (Walsh *et al*. 2005, Braud *et al*. 2013).

The hydrological consequences of urbanization, and particularly the increased frequency and magnitude of floods and sewer overflows, drove to the development of source control, a stormwater management strategy aiming at controlling runoff upstream of the drainage system, compensating the negative effects of urbanization. This strategy, mainly activated through local regulations and policies, consists in the dissemination over an urban catchment of small-scale facilities to store and manage stormwater through retention (e.g. storage ponds), infiltration (e.g. rain gardens), evapotranspiration (e.g. green roofs) or rainwater use (e.g. for gardening or toilet flushing). These facilities (and the policies prescribing them) were rare and experimental in the 1980s and 1990s, but since 2000 they started to become increasingly common and widespread in many countries (US, UK, Australia, France, etc.). In the absence of databases of local stormwater regulations in most countries, it is difficult to exactly quantify this diffusion of source control, but it is possible to appreciate it by consulting the proceedings of the International Conference on Urban Drainage (ICUD), or those of the Novatech conference, mainly dedicated to this topic. Several institutions around the world (for example, the US EPA or some French river basin authorities) invite (or require) local authorities to implement source control regulations, suggesting that in the future they will become systematically applied over large territories.

The application of source control regulations over a catchment follows the rhythm of urban growth and renovation. Local authorities that pioneered this strategy since the 1980s already observe that small-scale facilities systematically implemented on a catchment are able to influence its hydrological behaviour. An example is provided by the Paris region, where the SIAAP (Greater Paris Sanitation Authority) observes that, after a rain event, the time required to the flows to get back to the dry-weather level is growing longer. Another example is provided by Meierdiercks *et al*. (2010) showing that a catchment urbanized under source control regulations has an intermediate hydrological regime between a classical urbanized one and a non-urbanized one.

This capability of influencing the hydrology of a catchment through small-scale facilities is the main strength of source control, as it allows compensation of the negative effects of urbanization. Yet, it also represents its main risk: if source control regulations are not well established, and their hydrological consequences are not well understood by policy-makers, source control can miss its objectives and even produce long term negative effects. The increased duration of the saturation of treatment plants observed by SIAAP in Paris is the consequence of regulations mainly focused on peak-flow reduction (i.e. to reduce sewer overflows; Petrucci 2012), and it reduces the effectiveness of the treatment. The analysis of Meierdiercks *et al.* (2010) illustrated that the "source controlled" catchment has an annual runoff coefficient close to that of a natural catchment, but that the seasonality of runoff typical of vegetated areas is not maintained.

Because of its current success, source control is acquiring an increasing role as a driver of hydrological changes in urban catchments. Whether these changes will be beneficial or not depends on how policy-making practices are able to include hydrological considerations. In the beginning of the IAHS decade on Change in Hydrology and Society (Panta Rhei), we consider the importance of to initiating a discussion on how urban policies shape hydrology, and how hydrological sciences can contribute to policy-making. For this reason, we present in this communication an analysis of the objectives that policy-makers attribute to source control policies, and a short discussion of how they are supported (or not) by current scientific knowledge. This research has been conducted between 2008 and 2012 on a sample of French local authorities and institutions, but several observations can be adapted to other contexts. We hope that this contribution will foster a debate on this important topic and inspire future research.

METHODOLOGY OUTLINE

The purpose of this research is to identify and discuss the reasons of local authorities to adopt source control policies, and the objectives and rationalities leading the policy-making process in this field. The preparatory phase of this study consisted of a generalized collection of information about the adoption of stormwater source control policies in France, and resulted in a list of 44 local authorities or institutions (Petrucci 2012). Among this population, a sample of six authorities was selected for further analysis. To find a sample representative of the different rationalities at play, several criteria were applied. For instance, the sample involves authorities with different types of policies (e.g. regulations demanding to limit peak flow-rate and others demanding to infiltrate a given amount of rainfall) and spatial scales (from a municipal scale of few km^2 to a river basin scale of thousands of km^2), suggesting different rationalities.

For each authority of the sample, a survey was conducted based on official documents and semi-structured interviews (Quivy and Van Campenhoudt 1995) of technical staff. The purpose of the surveys was to reconstruct the local evolution of source control policies. The focus was on the policies' objectives, the relations to territorial characteristics and the technical framing. The various written sources were collected in order to construct, for each case, an initial "factual framework" of source control policy evolution. The interviews, cross-checked and compared with the available data, were treated like witnesses' accounts: they allowed filling the factual frameworks with the arguments and motivations that driven source control evolution. Starting from the historical reconstructions, the explicit and implicit objectives attributed to source control were elicited. The detailed results on the sample were then compared with international literature on source control in order to distinguish between French specificities and more global results.

RESULTS AND DISCUSSION

The analysis allowed identification of four main objectives attributed to source control: flood reduction, receiving waters protection, sustainable development and costs reduction.

Flood reduction is the main traditional objective of urban stormwater management, and it appears to be the main reason for the first developments of source control in France (e.g. in

Bordeaux; Bourgogne 2010).

The protection of receiving waters, including both water quantity and quality considerations, is also a common objective of stormwater management, often imposed to local authorities by large scale environmental regulations (e.g. the Water Framework Directive and its national implementations in Europe, the Clean Water Act and the NPDES permit program in the US). The diffusion of upstream water management facilities, in this context, is generally considered as one of the best tool to reduce non-point source pollution from urban areas (Ellis 2000).

The concept of sustainable development is, since the end of the 1990s, strongly linked to source control: in the UK, for example, source control techniques are usually called Sustainable Urban Drainage Systems (SUDS). In practice, this large concept is used to re-group all the positive effects of source control that are difficult to quantify and represents a strong political argument for the implementation of source control strategies.

Costs reduction is one of the main reasons of the development of source control: a too fast urbanization makes economically unfeasible to maintain the level of service of water management with traditional sewer infrastructures. In this perspective, and often without an explicit recognition by practitioners, source control represents a repartition of costs and responsibilities of water management between the public and private sectors.

The following paragraphs discuss, for each of these objectives, how they are included in current policy-making practices, and some of the main questions that they raise.

Flood reduction

Being the most classical objective of source control, flood reduction has been also the most discussed in hydrological literature. There is a general acceptance of the positive effect of source control – both water retention alone, reducing peak flow rates, and other techniques reducing runoff volume – on flooding for what concerns sewer overflows or, more in general, small scale floods. When considering a larger scale, however, this positive effect is less clear: in particular, several hydrologists argued that water retention alone, while reducing flow rate immediately downstream of the storage facility, can actually increase it farer downstream, by increasing the duration of maximum flow rates and thus the probability of superposition of peaks originated from different sub-catchments (McCuen 1979, Urbonas and Glidden 1983, Goff and Gentry 2006, Fang *et al*. 2010).

In terms of policy-making, the French cases showed that flood reduction is the first objective usually taken into account and, often, the only one object of a quantitative analysis. However, the quantitative analysis is usually extremely simplistic: it generally consists in determining the critical flow rate at one or several critical points of the sewer system, and by calculating the admitted flow from upstream parcels by an inversion of the rational formula (Petrucci *et al*. 2013).

In contrast to French current regulations, prescribing a given flow rate all over a catchment, the regulation approach mainly followed in the United States (Balascio and Lucas 2009) and in other countries is to demand to who increases the soil's impervious cover, to preserve pre-development flow rates on a case-by-case basis. From a hydrologic point of view, this choice seems more pertinent, because the case by case (i.e. parcel by parcel) determination of flow rates automatically takes into account the hydrologic features of the catchment and of its different parts. However, this type of no-aggravation regulation does not provide coordination of stormwater management at the catchment scale, raising two issues. The first is the problem of peaks superposition described above. The second is the fact that, even if the probability of flooding does not increase, the simple fact of urbanizing an area increases the damage caused by flooding: considering the flood risk as the combination of probability of occurrence and damage, the no-aggravation principle appears to be only partial.

In general, and with few exceptions, no specific modelling is realized to simulate consequences of source control regulations at the catchment scale. Urban hydrologic models available today (e.g. the US EPA SWMM model; Rossmann 2004) are able to support design of source control facilities on small scales, but to consider different urbanization scenarios under different stormwater management strategies at a large scale they require significant adaptations (Petrucci *et al*. 2013, Versini *et al*. 2013). Most local authorities do not have the resources to autonomously develop similar analyses: despite the understanding of source control that hydrologists may have, it is difficult to translate it in practice.

Receiving waters protection

Two types of benefits are expected by stormwater source control in terms of downstream environment protection. The first is an improvement of stormwater runoff quality provided by several processes like sedimentation of suspended solids in retention systems, filtration by the ground, pollutants' degradation by vegetation and associated microorganism. The second is associated with the reduction of runoff volumes and flow rates: positive effects include the reduction of urbanization-induced physical degradation of streams (e.g. bank erosion, channel incision; Walsh *et al*. 2005) and the reduction of polluted water flows to receiving waters (e.g. combined sewer overflows, CSO).

Even if this objective is globally recognized by local authorities, its inclusion in decision-making processes is extremely poor: in most cases, positive effects of source control are described, but no assessment is done. Thus, it is impossible to compare alternative regulations to find which ones are satisfactory and which ones are not. In the few cases where assessments were done, results significantly influenced final decisions: for example, the city of Paris analysed the impacts of different source control regulations on CSO volume to the Seine River and found that typical flow rate regulations could actually produce negative impacts (Mouy *et al*. 2007). The city finally adopted a regulation prescribing stormwater infiltration or evapotranspiration through green roofs.

In comparison with the case of flood reduction, the reasons for this poor integration of receiving waters in decision-making appear more complex. Surely, the lack of models and tools to easily analyse catchment scale impacts of source control on specific urban areas is a relevant problem. CSO and similar issues can be simulated and studied with existing models but, as for flood reduction, the application to source control regulations is still too complex for a generalized use by local authorities. For stream erosion quantification and linking to source control, methods exist (e.g. Tillinghast *et al*. 2011), but they are still confined to research.

For runoff quality, lots of research focuses on the effectiveness of small scale facilities in reducing pollutant loads. For example, the International Stormwater BMP Database (www.bmpdatabase.org) collects performance analysis from more than 500 source control facilities. However, this type of study is limited to single facilities or, at most, to the neighbourhood scale (e.g. Bressy 2010), and the upscaling to the city level is difficult because of the complex and poorly characterized processes occurring in the sewer system, in the ground, etc. Almost no measurement is available, to our knowledge, on the impact of source control on water quality at the city scale. Measurement campaigns comparing different contexts and source control implementation at a city-relevant scale appears to be a priority to support decision-making and achieve more pertinent regulations in the future.

Sustainable development

Since the end of the 1990s, source control is strongly associated with sustainability of urban development. For example, in 1999 the English Construction Industry Research and Information Association (CIRIA) officialised the use of the expression SUDS to define source control facilities (Faulkner 1999). If sustainable development has been a strong argument for promoting source control, in the practice of decision-making it is often used as a "black-box" to group all the (positive) effects of source control that are not easily taken into account: for instance, the reduction of the urban heat island effect by increased evapotranspiration, the groundwater recharge by diffused infiltration, the improvements in landscape and urban ecology, etc. (e.g. Getter and Rowe 2006). Once again, the problem in decision-making is the difficulty in translating the general objective in a specific assessment of alternative regulations over a given catchment or urban area. Some attempts have been realized in the last decade (e.g. Taylor and Fletcher 2006, Thévenot 2008), but their generalization in practice is still far off.

The importance of a concrete definition of some analysis framework for sustainability in urban stormwater management is stressed by the emergence of "green-washing" practices in some contexts. In particular, the association between source control and sustainable development has grown so universally accepted that some local authorities appear to adopt source control strategies, less to address some water management need than to show involvement in sustainable development. This is not necessarily a negative fact, as source control diffusion has indeed positive effects, but if source control can also produce negative effects, a regulation established without any hydrological consideration can represent an unnecessary risk.

To this consideration on sustainability, it is possible to add a supplementary objective, sometimes expressed by French local authorities and correlated with the social dimension of sustainable development: the improvement of public awareness. This objective consists in the idea that source control regulations, demanding a significant investment from private actors, forces them to think about water management and to find optimal, locally-adapted solutions. Ideally, this increased awareness has far-reaching effects, making citizens more aware of the importance of water management and more prone to positive behaviours like water savings, reduction of pesticides use in gardening, etc. As discussed above, even if this objective is positive and realistic, if it becomes the main reason of strategies having hydrological effects, but missing a hydrological foundation, it can constitute a risk.

Costs reduction

Source control can be considered as the attribution to citizens of a share of responsibility of stormwater management; in the paradigm of centralized drainage networks the responsibility was completely in charge of the network manager. This sharing of responsibility responds to the need of guaranteeing the "economic durability" of stormwater management, whose costs increase rapidly because of fast urbanization, development of areas further from the receiving waters (i.e. requiring larger transport infrastructures) and raising legal requirements (e.g. for receiving waters protection as discussed above).

Many researchers discussed the complexity of estimating costs connected to source control (e.g. in Thévenot 2008). The main difficulties come from the large range of alternative parcel-scale solutions, the strong link with the specific context (e.g. with the land value) and the long term maintenance costs, still poorly known. But these difficulties hide, in the opinion of the authors, a major question about source control economy that is still not addressed in scientific literature. In a perspective of global stormwater management efficiency – i.e. involving source control, sewer systems, treatment plants, etc. – the cost that should be minimized is not that incurred by the network manager or the local authority, but the total cost for the society. Today, source control regulations are mainly driven by feasibility concerns: what local authorities cannot afford is demanded to citizens. Probably, in the future this approach will continue to stand as it supports the effectiveness of the system and it is relatively easy to implement. But it does not guarantee the efficiency of the system: a different repartition of costs could achieve the same results with minor expenses. If this remark is a long term perspective, because too many aspects of source control are still ignored to consider the opportunity of a realistic economic optimization, nevertheless research should proceed also in this direction, to provide factual elements to decision-makers.

CONCLUSIONS

Urban areas are a good example of how human activities can influence hydrologic systems, and urban stormwater source control shows how the recognition of negative impacts can drive changes in current practices to reduce these impacts. Understanding how hydrology was influenced by urbanization in the past appears not sufficient to forecast how urbanization will influence hydrology in the future.

In this communication are identified the four main objectives that local authorities attribute to source control policies: flood reduction, receiving waters protection, sustainable development and costs reduction. Each objective is then critically analysed to underline the difficulties in its achievement. This discussion shows how, despite several decades of applications and researches, the stormwater management strategy of source control still raises important questions that must be answered to achieve a more hydrologically sustainable urban development. The role of hydrologists in this process is surely to develop new knowledge and tools, but also to dialogue with decision-makers to understand how social drivers interact with hydrologic systems.

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