Journal of Hydrology 522 (2015) 534–543

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A simple model of flow-rate attenuation in sewer systems. Application to urban stormwater source control

Guido Petrucci [a,*], Bruno Tassin [b]

[a] Earth System Sciences (ESSC), Vrije Universiteit Brussel, Pleinlaan, 2, 1050 Brussels, Belgium
[b] Université Paris-Est. Laboratoire Environnement Eau Systèmes Urbains (UMR MA102), UPEC, UPEMLV, ENPC, AgroParisTech. 6-8 avenue Blaise Pascal, 77455 Champs sur Marne cedex 2, France

ARTICLE INFO

Article history:
Received 6 October 2014
Received in revised form 5 January 2015
Accepted 6 January 2015
Available online 14 January 2015
This manuscript was handled by Geoff Syme, Editor-in-Chief

Keywords:
Urban hydrology
Storm drainage
Source control
Top-down modeling
Best management practices
Flow attenuation

SUMMARY

In urban stormwater management, "soft" solutions are being widely applied, including stormwater source control. However, no specific resource-effective model is available to assess their effects at the city-scale. As a consequence, source control regulations are often based on simplistic hydrologic assumptions. In this paper, we apply a top-down modeling approach to this problem, and we develop a simple model of flow-rate attenuation in the sewer system, using a numerical empirical approach. Then, we apply the model to source control regulations, assessing which type of regulation is more effective depending on relative positions in a catchment. We show that a model requiring only two types of information about a catchment (concentration time and pluviometry) can provide relevant information on source control effectiveness. This information could be helpful, for example, to define a stormwater zoning.

1. Introduction

Stormwater management in urban areas is a topic of growing complexity. Besides the increasing size and vulnerability of the urban systems themselves, which makes it more difficult to protect people and assets from flooding, new objectives are set for stormwater management in terms of protection of receiving water bodies and resource preservation. New strategies have been elaborated in the last decades, including Real-Time Control (RTC) of drainage systems, radar-based rainfall predictions, small-scale storage/infiltration facilities distributed all over a catchment (source control). The Novatech international conferences, which arrived at their 8th edition in 2013, show the evolutions of these new strategies.

Some of these strategies brought to the development and use by local authorities of advanced management and simulation models at the city scale. For example, RTC is generally associated with detailed models of sewer systems, allowing the optimization of the system's operation (Schütze et al., 2004; Labadie, 2007). However, other new strategies (in a general way, those involving "soft" infrastructures) did not produce specific modeling solutions at the catchment-scale.

Stormwater source control is a good example: this strategy consists of the implementation of stormwater management facilities (often called Best Management Practices, BMPs) like storage ponds, green roofs and porous pavements (Azzout et al., 1994; Revitt et al., 2008) at the scale of urban parcels or housing estates. The purpose is to mimic to some extent the behavior of the catchment before urbanization (Booth and Jackson, 1997; Andoh and Declerck, 1999; Walsh et al., 2005). The main instruments for local authorities to develop source control are regulations prescribing BMPs in all new urban developments or renovations (e.g. Balascio and Lucas, 2009). Source control regulations set the limit between the spatially-distributed, private management of stormwater on one side and the traditional, centralized public drainage system on the other. A proper decision-making procedure, coupling source control to other strategies of stormwater management, would be required to set this limit together with the optimization of RTC or of the other strategies applied. This procedure, requiring specific modeling tools, would allow "source control optimization" as part of a wider stormwater management optimization.

Research mainly focused on French case studies (Petrucci et al., 2013) showed that source control regulations, despite their wide use, are generally a compromise between strongly simplified technical considerations and pragmatical considerations of applicability. Local authorities in charge of large and complex sewer systems often have a detailed model of them, developed

* Corresponding author.
E-mail addresses: guido.petrucci@vub.ac.be (G. Petrucci), bruno.tassin@enpc.fr (B. Tassin).

http://dx.doi.org/10.1016/j.jhydrol.2015.01.012
0022-1694/

to support management and, in some cases, RTC. The models currently used are, for example, SWMM, Infoworks, MIKE, CANOE. Although these models can be used, in principle, to find effective source control regulations (Mouy et al., 2007), their application to this purpose is often limited. For example, it is a current practice to use models to determine the maximum acceptable discharge at "bottlenecks" in the sewers. This maximum discharge, divided by the upstream area, is then used as the regulation value and applied to every parcel (Petrucci et al., 2013). Furthermore, the adoption of source control regulations extends today to an increasing number of local authorities that do not have an already available model of their sewer system. Where no model is available, its complexity and cost (involving the modeling itself, but also data collection and upkeeping) discourage authorities from developing one.

As a consequence, many regulations are biased by conceptual shortcuts. For example, most regulations are fixed on the basis of a "*the more the better* axiom", assuming that a more strict regulation (i.e. prescribing to manage more water at the parcel level) is always more beneficial than a less strict one. This assumption goes to the extreme of regulations that prescribe to manage *all* the water at the parcel level (Urbonas and Jones, 2001), disregarding efficiency and potential negative effects of excessive constraints (Petrucci et al., 2013). Another recurrent shortcut is to fix regulations on a uniform basis over large catchments (i.e. in the form of a unique constraint for all new developments), neglecting geographical and topographical specificities, differences between upstream and downstream areas, and any other structural or hydrologic heterogeneity (Faulkner, 1999). More generally, the aggregation of the flow-rate contributions from the individual small-scale BMPs to the city-scale is usually realized as a linear composition, disregarding all the flow processes occurring in the drainage system, like the superposition and propagation of contributions, backwater effects, and overflows.

The way to a more effective inclusion of "soft" infrastructures in stormwater management at the city scale includes, as a necessary but probably not sufficient condition (Roy et al., 2008), the development of models having two characteristics:

- they should be able to describe the more significant processes at the right scale and for the strategy studied. These processes are not necessarily the same described by traditional sewer system models.
- they should be "efficient" (or at least "reasonable") in terms of data requirements: to study a city-scale long-term regulation, it should not be required to describe each existing or planned gutter or sidewalk.

A promising way to develop similar models is to adopt a top-down reasoning. A top-down (or downward) approach in hydrologic modeling means to "start with trying to find a distinct conceptual node directly at the level of interest (or higher) and then look for the steps that could have led to it from a lower level" (Klemeš, 1983). By contrast, the bottom-up (or upward, or reductionist) approach describes the behavior of a hydrologic system at a given scale as the aggregation of processes at lower scales. Most models, if not all, used today in urban hydrology (Elliott and Trowsdale, 2007) follow this last paradigm, describing the catchment as a combination of elementary components (subcatchments or grid meshes). The scientific debate about this opposition is long-lasting and rich (after Klemeš, 1983, for instance, Blöschl and Sivapalan (1995), Bergstrom and Graham (1998), Andréassian (2005), Sivapalan and Young (2005). The main argument of the promoters of the top-down approach is epistemological: a complex system has emerging properties that cannot be inferred by the properties of its components (Andréassian, 2005). A bottom-up approach is unable to catch these properties, while a top-down can.

From the authors' point of view, the top-down approach has another, more operational, advantage. Bottom-up models require a detailed description of a catchment to analyze its large-scale behavior, thus requiring large quantities of data to answer large-scale questions (e.g. Lee et al., 2012). Conversely, a top-down approach can provide "data-parsimonious" models, by trying to answer a large-scale question at the scale where it is asked, using only the strictly necessary data. This data-parsimony can be a significant advantage in terms of applicability of the model by local authorities, as it can reduce modeling costs.

The purpose of this paper is to illustrate the potential of top-down modeling in urban hydrology: starting from a process that is relevant at the city-scale level, but usually neglected in policy-making about source control regulations (i.e. flow-rate attenuation in the drainage system), we build a simple, data-parsimonious model. Then, we test its implications for the development of source control regulations that are more consistent at the city-scale.

1.1. Flow-rate attenuation in pipes and its impact on source control

A hydrograph measured upstream and downstream of a pipe or of a series of pipes is not just translated, but it incurs a deformation and, in particular, its maximum flow-rate is attenuated (Kovacs, 1988; Fig. 1). In the absence of backwater effects, the shape of the hydrograph at the outlet will depend on its shape at the inlet and on the characteristics of the pipes where it flows through. In terms of source control regulations, this implies that identical hydrographs entering the drainage system at different points will contribute differently to the cumulative hydrograph at the outlet of the drainage system. Intuitively, the longer the path of the hydrograph in the sewer, the greater its deformation, and the more attenuated its peak flow-rate. Thus, a new urban development far from the outlet will produce, in terms of peak flow-rate at the sewer's outlet, a smaller contribution than the one of an identical urban development closer to the outlet. Today, in many urban areas, new developments occur upstream of existing settlements, with paths in the sewer system reaching easily lengths of several kilometers. This article aims to analyze if, in conditions representative of actual urban areas and sewer systems, the effect of the attenuation process on the performances of source control regulations is significant.

With this objective, this paper is structured in two parts: the first is the development of a simple model of peak flow-rate attenuation in pipes (the *attenuation model*), based on numerical experiments on a mechanistic model of flow in pipes (the *flow model*); the second is the application of the attenuation model to source control regulations.

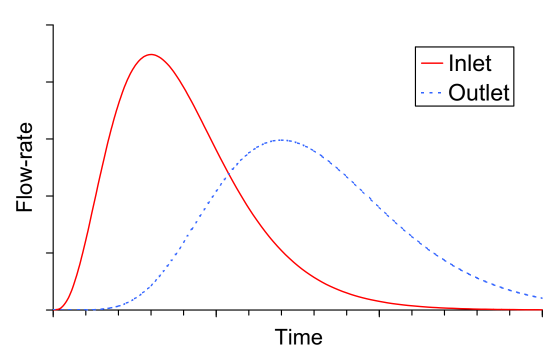

Fig. 1. Deformation of a hydrograph flowing in a pipe after Kovacs (1988).