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Linking the management of urban watersheds with the impacts on the receiving water bodies: the use of flow duration curves

Relier la gestion des bassins versants urbains avec les impacts sur les milieux récepteurs : l'usage des courbes des débits classés

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RÉSUMÉ

Il est de plus en plus reconnu que le changement du comportement hydrologique courant des bassins versants suite à l'urbanisation est l'une des causes principales de la dégradation des milieux aquatiques récepteurs. Cependant, les débits courants sont rarement pris en compte dans les études concernant la gestion des eaux pluviales urbaines, plus centrées sur les débits extrêmes. Dans cet article, nous suggérons qu'il est possible d'intégrer des considérations sur le milieu récepteur avec des modifications relativement mineures dans les pratiques courantes de modélisation des eaux pluviales urbaines, grâce à l'utilisation des courbes des débits classées (FDC, selon l'acronyme anglais). Nous présentons les avantages de l'utilisation des FDC ainsi que les conditions pour les intégrer dans les études hydrologiques. Enfin, nous présentons un exemple d'application où nous comparons des réglementations de contrôle à la source sur un bassin versant urbanisé (178 ha) à Nantes.

ABSTRACT

There is growing evidence that changes in the current hydrological behaviour of urbanizing catchments are a major source of impacts on the downstream water bodies. However, current flow-rates are rarely considered in studies on urban stormwater management, usually focused on extreme flow-rates. We argue that taking into account receiving water-bodies is possible with relatively small modifications in current practices of urban stormwater modelling, through the use of Flow-Duration Curves (FDCs). In this communication we discuss advantages and requirements of the use of FDCs. Then, we present an example of application comparing source control regulations over an urbanized catchment (178 ha) in Nantes, France.

KEYWORDS

Combined sewer overflows, Erosion, flow-duration curves, Model calibration, Modeling, Receiving water body, Uban hydrology

1 INTRODUCTION

A growing concern for urban stormwater management is related to its impact on the receiving water bodies. Impacts can range from acute or chronic pollution to streams' erosion or lakes' eutrophication, with severe consequences on both the possible uses of water bodies (e.g. water supply, fishing, recreational activities) and their environmental value. (Walsh et al., 2005b)

The necessity to account for these impacts when planning or managing urban stormwater systems is widely recognized by scientists, technicians and decision-makers. However, this recognition is much more theoretical than practical: in current practices of urban hydrological studies, receiving water bodies are often treated as a secondary point and superficially, if they are treated at all.

We can illustrate this point using the example of stormwater source control. Source control (also called Low Impact Development or Water Sensitive Urban Design) mainly consists in the implementation of small-scale stormwater facilities (often called Best Management Practices, or BMPs) over an urban catchment's area, upstream of the drainage system. One main principle of source control is to mimic the natural (i.e. pre-development) behaviour of the catchment, thus minimising the impacts of urbanization on the downstream environment (Booth and Jackson, 1997, Roesner et al., 2001). This strategy is mainly implemented through *source control regulations*, demanding to include BMPs in any new urban development project. (Balascio and Lucas, 2009)

A recent study on source control regulations (Petrucci, 2012; Petrucci et al., 2012), showed that the preservation of downstream water bodies is a commonly stated objective of local authorities adopting these regulations. Still, when technical studies are done to define the regulations, in most cases the only indicators considered are the peak flow-rates for extreme rainfall events (e.g. with return periods $T \geq 10$ years). This attention on extreme flow-rates is the signal of the general persistence of a conventional approach, in which the only objective is to minimize sewer overflows and flooding, without regard to downstream water bodies (Petrucci, 2013).

On the basis of two observations – the first about current modelling practices in urban stormwater management (section 1.1), the second about the link between catchment's urbanization, its hydrological behaviour and the impact on receiving water bodies (section 1.2) – we propose, in this paper, a practical approach to integrate the receiving water bodies into current modelling practices, recurring to flow-duration curves (FDC). This proposal is described in section 2, and an example about source control regulations' analysis is given in section 3.

1.1 Current trends in modelling of urban stormwater systems and their impacts on receiving water bodies

Today, there are three main modelling trends in urban hydrology studies that, ordered by growing complexity and integration of receiving water bodies are: flow-rate modelling, quality modelling, integrated modelling.

Flow-rate modelling is the most current modelling approach: it consists in modelling the urban watershed and the drainage system, in order to simulate flow-rates in the sewer system. This modelling has a long history and tradition, and today is mainly represented by distributed, detailed models (e.g. SWMM 5, MIKE URBAN, InfoWorks, etc.). Many local authorities have already developed this kind of model for the urban areas they administer. Often they use them to determine interventions on the sewer system, or for more sophisticated uses like real-time control. The main limit in the current use of these models for integrating downstream water bodies, is the one we already noticed: these traditional models, although they have large possibilities, are often used in a traditional, narrow way. Often, they are calibrated on one or some important rain events, and they are applied just to simulate single events or short time series supposed to benchmark the functioning of the sewer system. It is worth to notice that, in general, nothing inside these models constrains to work on important rain-events: their structure is able to simulate low flow-rates as well as high, and current behaviours of the catchment as well as extreme ones. Moreover, most currently used models are able to simulate long, continuous time series instead of single rain events (Elliott and Trowsdale, 2007).

The second modelling option is water quality modelling. This approach allows simulating the flow of pollutants from the urban area to the outlet. In principle, this type of modelling is extremely important to assess the impact on downstream water bodies, and its diffusion is an encouraging trend. Also because of legal constraints on stormwater quality, most flow-rate models now includes some water-quality simulation capability. However, because of a frequent lack of calibration data, high measurement uncertainties, open questions on relevant physical and chemical processes, and in general a minor hindsight on this type of modelling compared to flow-rate modelling, water quality models have a smaller predictive capacity and reliability than flow-rate models. Uncertainties in predictions are amplified by a delicate modelling process, requiring significant efforts and know-how.

The third modelling option is integrated modelling. This term, defining the coupling of several models of different components of a system, is inclusive of many different modelling attempts in urban hydrology. The coupling between sewer systems and receiving water bodies is investigated, for example, by Silva et al. (2013), modelling algal blooms in a urban lake as a consequence of changes in the upstream urban drainage. This type of modelling, today, is still the object of single case-specific researches, and cannot be considered as a common practice for stormwater management purposes.

In summary, the most current and solid approach is, today, flow-rate modelling. However, this approach is extremely focused on sewer overflows, and do not take into account downstream effects. The development of other models to a level of easiness of use and reliability sufficient for a wide use by local authorities will probably take years. Because the purpose of this paper is to find a practical and viable solution to improve the accounting for impacts on the receiving water bodies, we will search it in the framework of flow-rate modelling approach, exploring their unexploited potential;

1.2 The impact of urbanization on downstream water bodies

The most evident effect of urbanization on catchment hydrology, recognized since several decades (e.g. Leopold, 1968), is an increase in peak flow-rates. This phenomenon was particularly noticed for large rain events, when downstream floods or rapid stream erosion were observed. The efforts in stormwater management were thus directed, for a long time, to control this kind of high-flow events. Typical measures in the US (Roesner et al.,2001, Balascio and Lucas, 2009) or in the UK (Faulkner, 1999) address rain events with return periods higher than 1 or 2 years. In France (Petrucci et al., 2012) most stormwater systems (sewers, but also BMPs and large retention basins) are dimensioned for a return period of 10 years. This long-lasting practice of focusing only on relatively uncommon events is what we still find in a large majority of urban hydrological studies.

Even if high-flow uncommon events surely have an impact on the receiving water bodies, since the 90's a consistent literature (summarized by Walsh et al., 2005b) started to reconsider their importance, in comparison with more current events. In terms of *channel erosion*, for example, it has been shown that erosive flow-rates are small enough to be exceeded even by small and frequent rain events (Hunt and Tillinghast, 2011). The latter, thus, are likely to have a stronger effect, on the long term, than large uncommon events (Booth and Jackson, 1997). The same analysis on the increased frequency of exceedance of a "disturbance threshold" because of small rain events is suggested for the *biological conditions* of streams (Booth et al., 2004, Roy et al., 2005). In terms of *water quality*, two effects should be mentioned: the first, described by Walsh et al. (2005a) is the production of runoff, not occurring in natural catchments, for rain events of a few millimetres. This frequent runoff, even if hydraulically negligible, may constitute a relevant and in some cases chronic intake of pollutants (and heat). The second effect is the increase in combined sewer overflows.

In summary, there is a growing recognition of the importance of low and medium flow-rates. The behaviour of an urban catchment during extreme rain events is significant in terms of urban flooding, thus representing a point of view focused on what happens *inside* the urban area. If we are interested in what happens *downstream*, we should look at the current behaviour of the urban catchment.

2 CONSTRUCTION AND USE OF FLOW DURATION CURVES

As a consequence of the growing interest for current urban catchments behaviour, some authors suggested hydrologic metrics linked to downstream effects. Booth et al. (2004), for instance, suggested using the fraction of days, on an annual basis, when the daily mean discharge exceed the annual mean discharge (T_{Qmean}). This indicator can distinguish catchments that have more "flashy" response (low T_{Qmean}) from other with gradually varying flow regimes (high T_{Qmean}). However, the information given by so specific indicators is difficult to generalize to other geographic, climatic and urban conditions from that where the indicators were developed and tested. That is why several researchers (e.g. Fennessey et al., 2001; Roesner and Bledsoe, 2002; Rohrer et al., 2006) used a more general way to characterise catchments' current behaviours, using Flow Duration Curves (FDC).

A FDC represents the fraction of time during which a given level of flow-rate is equalled or exceeded at a point of the drainage network (Vogel and Fennessey, 1994). This kind of representation has been largely employed in water management, because of its capacity to represent a huge quantity of hydrological information on a single view (Vogel and Fennessey; 1995). Considering the observations made on section 1.2, we can compare the effect of urbanization as observed on a hypothetic hydrograph plot and on a FDC (figure 1). In the hydrograph (left) one can spot the increase in peak flow-rate, in runoff volume (area under the curve) and in the response "flashiness" (shorter ascending and descending limbs of the hydrograph). On the FDC (right) it is possible to observe:

- the increase in high flow-rates. The intersection of the FDC with the y-axis represents the highest flow-rate measured during the observation period (or a similar statistic, according to the procedure followed for the construction of the curve – see next section);
- the increase in the runoff frequency. The intersection with the x-axis represents the fraction of time the catchment produces some runoff;
- the generalized increase of the frequency of exceedance for each flow-rate;
- indirectly, the increase in runoff volume, because it is proportional to the area under the FDC.

In substance, together with some elements on extreme behaviours of the catchment, this kind of representation provides much more information about the impacts on the downstream water bodies.

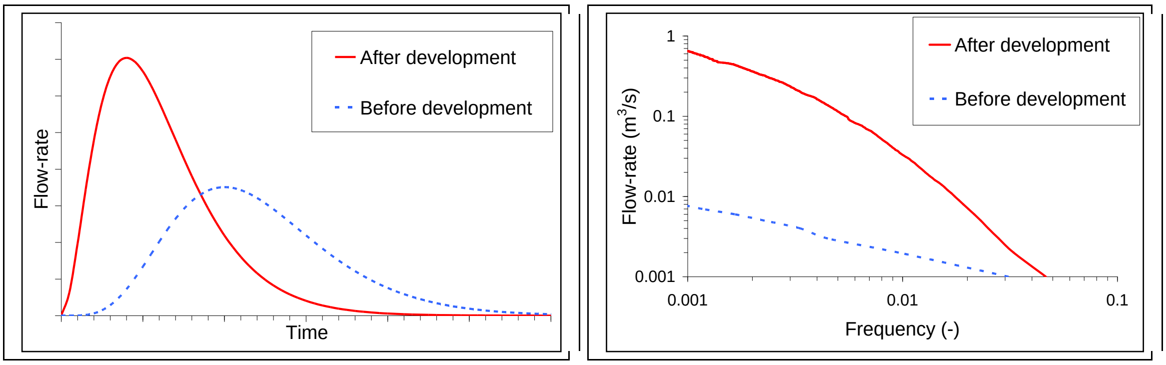

Figure 1 - Effects of the catchment's urbanization on flow-rate. Left: for a single rain event (hydrograph). Right: for a long measurement period (flow duration curve). Plots do not correspond to a real case.

2.1 Construction of the flow duration curves

Starting from a flow-rate time series, the simplest way of constructing a FDC is to order the measurements by decreasing flow-rates, and to plot the result in frequency-flow-rate axes. More formally, starting from a series of n ordered flow-rates $q_{(i)}$, where $i = 1,\ldots,n$, the value of the FDC Q_p, for the frequency p, is:

$$Q_p = q_{(i)} \qquad \text{if } i = [(n+1)p]$$

$$Q_p = q_{(i+1)} \qquad \text{if } i < [(n+1)p]$$

where $[(n+1)p]$ is the integer part of $(n+1)p$. This formalism, as well as more sophisticated and statistically robust method to calculate the FDC can be found in Vogel and Fennessey (1994).

The work of these authors on FDC is particularly interesting because it addresses a major inconvenient of this instrument: the strong dependence on the period used for calculation. In particular, the extremes of the curve are highly dependent on the extreme values of the time series, and they are poorly reliable. The solution suggested by Vogel and Fennessey (1994) is, for time series spanning over several years, to calculate several annual FDCs instead of a unique FDC for the whole recording period. Starting from the annual FDCs, they suggest calculating a median annual FDC, together with its confidence intervals. This method generates both more reliable FDCs and an estimation of the inter-annual variability of the hydrological regime of the catchment.

Another point, useful for the following discussion, is that, starting from a time series recorded at a given time-step (e.g. 5 minutes) it is straightforward to construct time series with time-steps multiple of the original one (e.g. 10 minutes, 1 hour, 1 day), by averaging subsequent records. Thus, starting from a time series at a given time-step, it is possible to obtain FDCs at different, longer, time-steps. Starting from a time series, it is possible also to construct curves other than FDCs but with similar construction procedures and meaning: for example, Fennessey et al., 2001 build a quasi-FDC starting from a time series of the peak flow-rates for a series of rain events.

2.2 The use and the interpretation of FDC in urban hydrology

As observed in section 1.1, most currently used flow-rate models can perform continuous simulations over long periods of time. Thus, for any scenario of stormwater management that can be described by these models, it is possible to obtain long-term simulated time series and, consequently, the corresponding FDC. Scenarios can include new infrastructures (e.g. reservoirs), new operation rules (e.g. activation rules for pumps), new regulations (e.g. source control) and new urban developments.

FDCs can then be used to compare alternative scenarios. This can be done directly on the FDCs themselves (e.g. Fennessey et al., 2001; Konrad and Burges, 2001), providing in a single view a comparison of the changes of the hydrologic regime consequent to the adoption of each alternative.

When the comparison involves many alternatives, and/or some case-specific objective is set and quantified, it is possible to define indicators on the FDC. To facilitate comparisons, one can use generic indicators (Petrucci, 2012) like, for example, the flow-rates exceeded for given fractions of the year ($Q_{0.1\%}$, $Q_{1\%}$ and $Q_{10\%}$ in figure 2), or the intersections between FDCs and the axes (f_0 in figure 2).

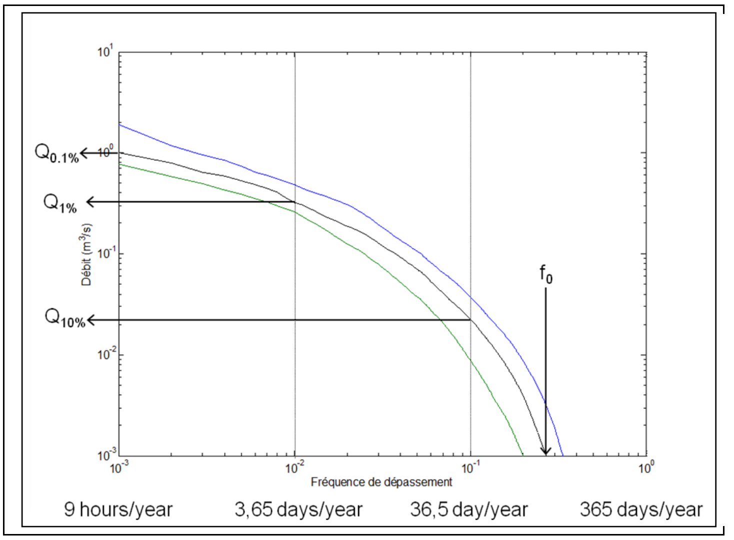

Figure 2 - Examples of indicators defined on an annual median FDC. Blue and green lines represent the confidence intervals at 90% (15 years of simulation at 5' time-step). Source: Petrucci (2012).

The most interesting application of FDC indicators, however, lies in the possibility to define parameters linked to receiving water status on a specific case-study. The indicator T_{Qmean} proposed by Booth et al. (2004) as explanatory of the downstream biological status can easily be computed from FDCs. If an “erosive threshold” can be estimated (Hunt and Tillinghast, 2011), its frequency of exceedance can be compared for different scenarios. In the same way, the frequency (and the volume, through some supplementary consideration) of combined sewer overflows can be estimated if the overflow threshold is known. Also the f_0 indicator defined above, describing the annual frequency of runoff generated by the catchment, can be a significant indicator of water quality and biological disturbance according to Walsh et al. (2005a,b).

As anticipated, it is possible to adapt the FDC time-step to the time-scales of the system studied. Models of urban stormwater systems often use considerably short time-steps (5’-10’) in order to finely describe the hydraulic system. A similar time-step can be appropriate for computing, for example, combined sewer overflows, but a coarser time-step (hourly, daily) can be more adapted to describe impacts on systems (e.g. urban lakes) having longer response-time.

2.3 Required changes in current modeling practices

If, in general, each scenario that can be tested in terms of peak flow-rate can be tested in terms of FDC, three main requirements have to be satisfied.

The first is the availability of local rainfall data over long periods: peak flow-rate analyses could be based on a few (or even just one) real or synthetic rainfall events, while for long term simulations, representative input data is necessary. However, this requirement can be easily fulfilled thanks to the raingage networks that are in place since many years in most countries, particularly for urban areas.

The second is the calculation capability necessary to run long term simulations. Still, with the exception of very large and complex urban catchments, requiring specific solutions, present calculation resources can in most cases run hydrologic simulations in reasonable computation times.

The third and, by our point of view, more problematic requirement is that the model should be reliable when simulating catchment's current behaviours. Today this is not always the case, because, even if flow-rate models are able to simulate the whole hydrologic regime of a catchment, in practice they are often calibrated on a few high flow-rate events for which measurements are available. This procedure focused on peak flow-rate does not guarantee the reliability of the model (i) for low flow-rate events and (ii) for the parts of the hydrologic response different from the peak (i.e. ascending and descending limbs of the hydrograph). Now, the reliability of the model in these terms is a primary condition for the reliability of the FDCs obtained.

The solution to this reliability issue demands the probably most important evolution in current modelling practices. In facts, it requires to calibrate the model on low flows as well as on high flows, and considering the whole hydrograph shape and not only the peak position and amplitude. Further, an event-based calibration is not sufficient: time series of input (rainfall) and output (flow-rate) are necessary. While rain data are easily available, flow-rate time series are less common. Further, calibration of flow-rate models is complex because typical urban catchments' models can involve hundreds to thousands of parameters, often difficult to estimate *a priori*. To calibrate just on some peaks, manual calibration of a few parameters can often be satisfactory, but to fit the model for the whole catchment's response, a better procedure should be find. Technical analyses of urban stormwater management should start to include automatic calibration methods, quite diffused in hydrologic research, but barely applied in practice.

3 AN EXAMPLE OF THE APPLICATION OF FDC IN URBAN HYDROLOGY

3.1 Methodology

We propose the application of FDC analysis to the comparison of different source control regulation scenarios. This example is intended to show the better insight given by FDCs on the catchments' behavior.

We considered the urban catchment of "les Gohards", in Nantes, France (figure 3), already studied by Rodriguez et al. (2003). This catchment (178 ha) is covered by a mixed land-use (residential, commercial, industrial, agricultural), giving an impervious cover of about 0.38. The sewer system is separated (14.8 km); its average slope is 0.79%. Available data include 5 years of flow-rate measurements at the outfall (1999-2003), and 10 years of rainfall measurements at two raingages inside the catchment (1999-2008). Both time series have a 5' time-step.

The model of the catchment is realized in SWMM 5 (Rossman, 2004), using typical methods for subcatchments' delineation and parameters' estimation (e.g. Gironàs et al., 2009). The only particular feature of the modeling setup is that we distinguished, in each "real" subcatchment, roof, road and green areas, in order to prepare the simulation of source control regulation scenarios. Details on this procedure are given in Petrucci et al., 2012.

After setup, the model was calibrated and validated. As for the model setup, all choices in the calibration/validation procedure were a compromise between accuracy and simplicity: the purpose was to reach our aim using the most current options in hydrological literature, in order to minimize the changes from current modeling practices.

For calibration, we used only one month of the available rainfall/runoff data, to keep the computational requirements low. The period was selected for data quality (no gaps) and for the variety of rainfall events occurred. Calibration parameters were nine global parameters (roughness of pipes and surfaces, infiltration, initial losses, etc.) and one shape parameter (length of the overland flow path) for each subcatchment, for a total of 101 parameters. To cope with so many parameters, calibration was performed using a genetic algorithm, an automatic optimization algorithm largely applied in hydrology in the last 20 years (Savic and Khu, 2005). Optimization consisted in maximizing the Nash criterion (Nash and Sutcliffe, 1970).

Validation was performed calculating the Nash criterion for each season (4 months) of the remaining data, in order to verify that the choice of a single month, in autumn, for calibration, was not reducing its performances in other periods of the year.

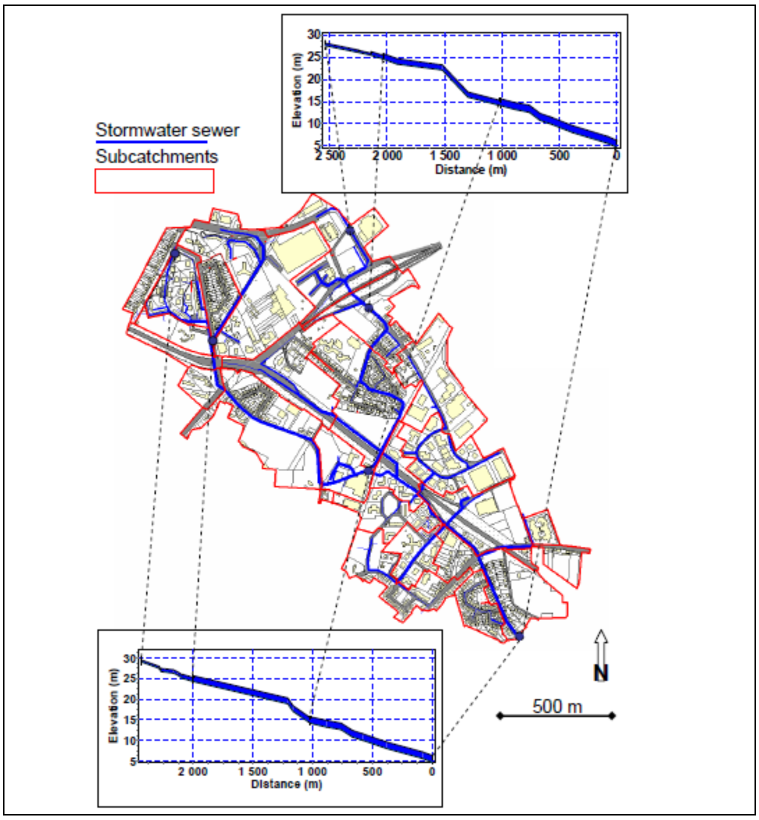

Figure 3 - The Gohards catchment. Source: Petrucci, 2012.

3.2 Scenarios

The scenarios compared are of two types: specific flow-rate regulations, demanding to store stormwater and to release it at a limited specific flow-rate *q** (l/s/ha), and volume regulations, demanding to store and infiltrate a given volume *i** (mm) of stormwater. For more details on this kind of regulations and their modeling, see Petrucci et al. (2012). In this example, we consider source control regulations applied systematically and homogeneously all over the catchment. However, the same procedure can be applied to more realistic scenarios, with partial or non homogeneous applications of source control.

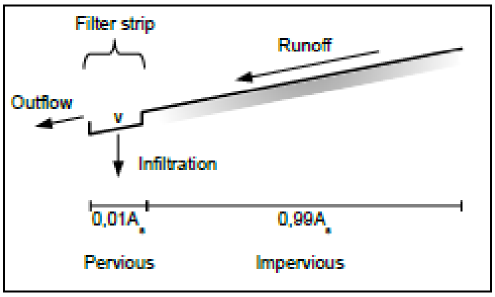

Figure 4 - Scheme used for volume regulations' modeling. Source: Petrucci et al., 2012.

Specific flow-rate regulations were modeled by installing a reservoir downstream of the roof and road areas of each subcatchment. Each reservoir has a volume and an outfall sized as a function of *q**, according to French "rainfall-based" sizing procedure. Volume regulations are modeled as a pervious filter strips downstream of each impervious area (figure 4). The storage of the strip is sized as a function of *i**.

Each scenario was simulated on a 10 years period with a 5' time-step. We also simulated a synthetic rainfall having a return period of 10 years (triangular, 1-hour duration), in order to compare a classical peak flow-rate approach to FDCs.

3.3 Results and discussion

3.3.1 Calibration and validation

The calibration procedure provided a high value of the Nash criterion (0.91), meaning a good accuracy of the model. Visual verification was also satisfactory (figure 5). In validation, we calculated the Nash criterion for nine seasons with available data, obtaining values ranging between 0.72 and 0.89 (median: 0.85), without evident seasonal biases.

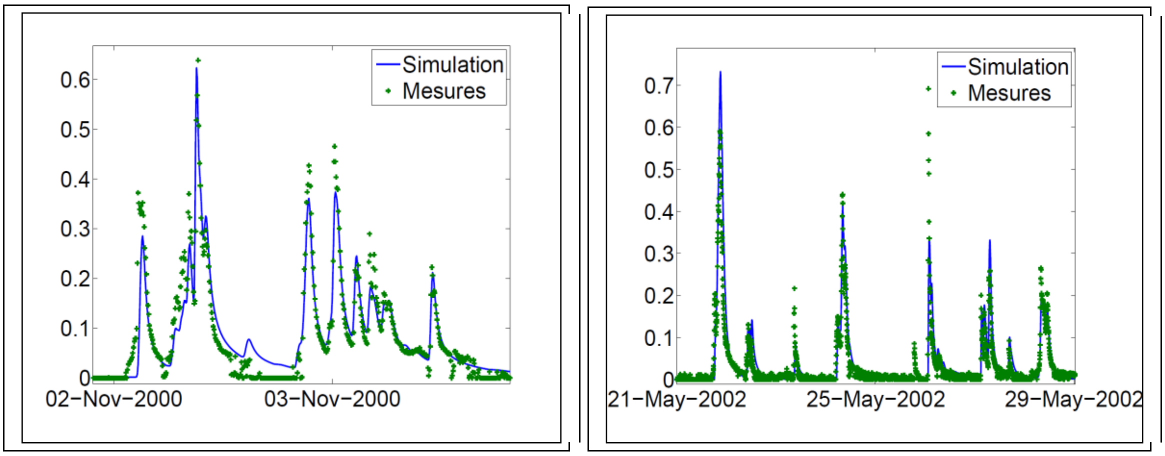

Figure 5 - Examples of results from calibration (left) and validation (right).

3.3.2 Scenarios' simulation

In figure 6 are plotted the median annual FDCs for, respectively, specific flow-rate and volume regulations. The reference value (black line) is the FDC calculated by the model with no scenario applied. The two sets of FDCs show immediately a significant difference of behaviors between the two types of source control regulations: while specific flow-rate regulations reduce the frequencies of high flow-rates, but increase those of small ones, volume regulations systematically reduce frequencies.

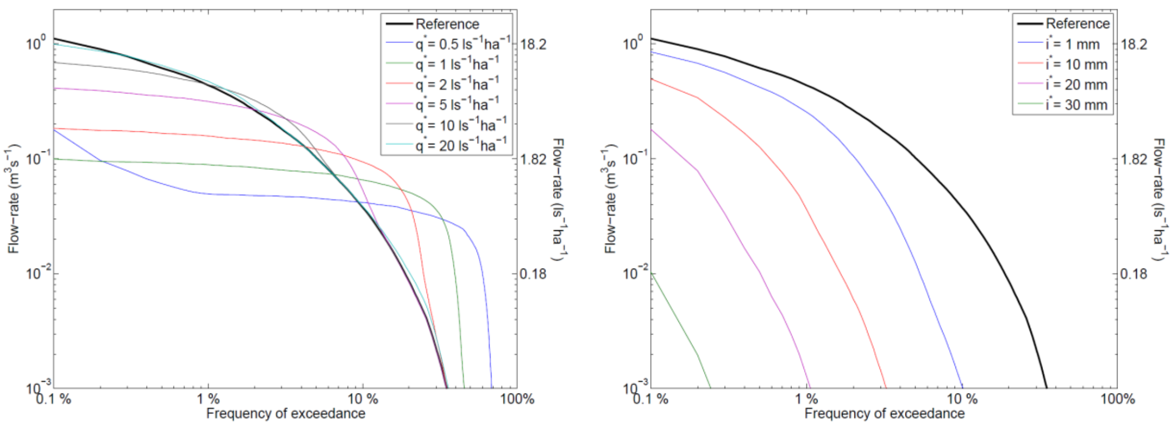

Figure 6 - Median annual FDCs for flow-rate (left) and volume (right) regulations.

When specific flow-rate regulations become stricter (i.e. smaller *q**), highest flow-rates progressively disappear, but low flow-rates are increasingly common, exceeding the frequencies of the reference case. The effect of specific flow-rate regulations can be summarized by a flattening of the hydrological behavior of the catchment. The atypical behavior of the *q**=0,5 l/s/ha curve is because of the sizing procedure, not adapted for long reservoir's emptying times: with a so low outlet flow, complete emptying can require more than one week, causing spills for subsequent rain events. A similar sizing problem cannot be spotted by single-event simulations, but easily appears with long term simulations.

If the comparison of FDCs allows identifying global trends, FDC-based indicators can help decision-making. In figure 7 are plotted the indicators $Q_{10years}$, corresponding to the peak flow-rate for a 10-years design rainfall (26,8 mm in 1 hour) and $Q_{10\%}$, representing the flow-rate exceeded 10% time of the year (i.e. 36,5 days).

The first graph, representing a classical indicator for stormwater management decision making shows a linear reduction of peak flow-rates (red line) increasing *q**. This justifies a general trend, among local authorities, to progressively reduce the *q** value in regulations: the stricter the rule, the smaller the flow-rates to be managed downstream, the less sewer overflows and other nuisances.

The second graph, issued from the frequency analysis of long term simulations, presents a different behavior of flow-rate regulations: the indicator has a significant increase for low values of *q**. If there was a constraint on downstream flow-rates, for example an erosive threshold for the downstream creek (or the activation threshold for a combined sewer overflow) estimated at 1 l/s/ha (about 200 l/s), the graph could show that regulations ranging from *q**=5 l/s/ha to *q**=1 l/s/ha (quite common in France) will significantly worsen the creek's erosion.

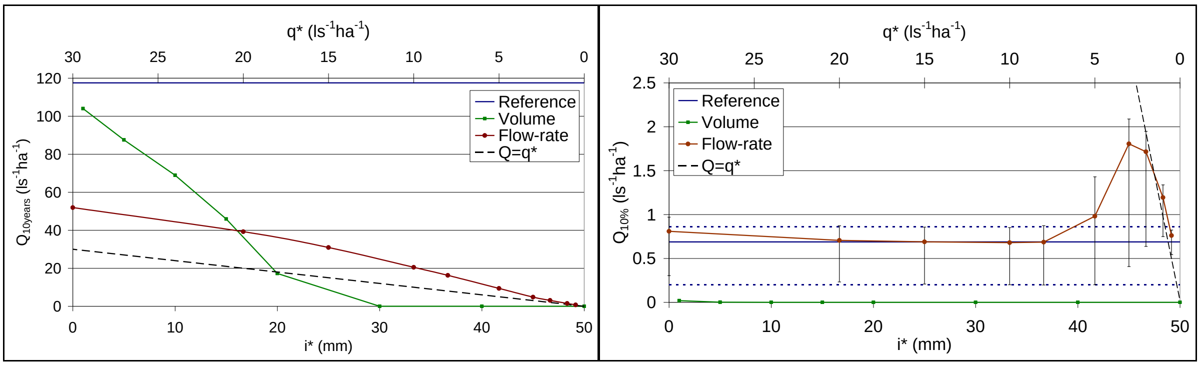

Figure 7 - $Q_{10\%}$ (left) and $Q_{10years}$ (right) indicators.

More generally, this example shows that protecting the environment downstream of a urban area can be an objective contrasting with the protection of the urban area alone. Volume regulations seem able to attain these two objectives simultaneously, but it is not possible to understand this point if only single-event, peak flow-rate based analyses are done. Taking into account downstream water bodies through FDCs can improve their protection and cast doubts on the current practices of source control regulations.

4 CONCLUSIONS

In this communication, we presented the interest of analyzing urban stormwater management by the mean of FDCs. We argued that this instrument can provide useful information on the impacts on downstream water bodies without requiring significant changes in the way urban water studies are done today. We think that FDCs represent a practical approach to improve the protection of water bodies.

Two final remarks: the first is that FDC analysis, as we showed in our example, is not alternative but complementary to classical peak flow-rate analyses on single events. The concern for water bodies' protection is growing, but the first purpose of urban stormwater systems remains the protection of people and properties from flooding and other nuisances. Decision-making in this domain is a search for a compromise between different objectives. FDC analysis, in this context, is just a tool to facilitate the search for a better compromise. The second remark is on the meaning of FDCs: if they actually provide much information on downstream impacts, this information has to be interpreted according to the specific context. A wise use of FDCs requires to understand which changes in the hydrological behavior are more harmful (or positive) to the specific downstream environment. Local researches on water-bodies are necessary to better manage them.

ACKNOWLEDGMENTS

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