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

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ABSTRACT

There is growing evidence that changes in the current hydrological behaviour of urbanising 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 paper, we discuss advantages and requirements of the use of FDCs. Then, we present an example of application comparing source control regulations over an urbanised catchment (178 ha) in Nantes, France.

Key words | flow duration curves, model calibration, source control, stormwater management, urban hydrology

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 or contamination, with severe consequences on both the possible uses of water bodies and their environmental value (Walsh et al. 2005b; Jung et al. 2008).

The necessity to account for these impacts when planning or managing urban stormwater systems is widely recognised 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 poorly considered.

This point could be illustrated using the example of stormwater source control. Source control (also called low impact development) mainly consists of the implementation of small-scale stormwater facilities (best management practices, or BMPs) over an urban catchment, upstream of the drainage system. One principle of source control is to mimic the pre-development behaviour of the catchment, thus minimising the impacts of urbanisation on the downstream environment (Booth & Jackson 1997). This strategy is mainly implemented through source control regulations, demanding to include BMPs in any new urban development project (Balascio & Lucas 2009).

A study on source control regulations (Petrucci 2012; Petrucci et al. 2015), 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 regulations, in most cases the only indicators considered are the peak flow-rates for extreme rainfall events (e.g. return periods $T \geq 10$ years). This attention on extreme flow-rates indicates the persistence of a conventional approach, in which the only objective is to minimise sewer overflows and flooding, regardless of downstream water bodies.

In this paper are analysed the current modelling practices in urban stormwater management and their capability to describe the effects of urbanisation on the downstream environment. On this basis, a viable approach
is proposed to integrate downstream environment considerations into current modelling practices, using flow duration curves (FDCs). This proposal is then discussed and illustrated by an example about source control regulations.

**Current trends in modelling urban stormwater systems**

There are three main modelling approaches in current urban hydrology studies: flow-rate modelling, quality modelling and integrated modelling.

Flow-rate modelling is the most classical approach: it consists of modelling the urban watershed and the drainage system in order to simulate water flows. This approach has a long tradition, and nowadays is mainly represented by distributed, detailed models (e.g. SWMM 5, MIKE URBAN). Many local authorities have implemented this kind of model for the urban areas they administer. They are used to determine interventions on the sewer system (Gironàs et al. 2009), or for more sophisticated purposes like real-time control (Schütze et al. 2004). The main limit in the current use of these models for integrating downstream water bodies is that these traditional models, despite their large possibilities, are often used in a narrow way. Often, they are calibrated on a few rain events and applied just to simulate single events or short time series supposed to benchmark the functioning of the sewer system. In general, nothing inside these models constrains their application to important rain events: their structure is able to simulate low flows as well as high and current behaviours of the catchment as well as extreme. Most current models are able to simulate long time series instead of single rain events (Elliott & Trowsdale 2007).

The second approach is water quality modelling. It allows simulation of the flow of pollutants from the urban area. 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 include water-quality simulation capabilities. However, because of a frequent lack of data, measurement uncertainties, questions on relevant physical and chemical processes, and, in general, minor experience of this type of modelling compared to flow-rate modelling, water quality models have a smaller predictive reliability than flow-rate models (Bertrand-Krajewski 2007). Uncertainties are amplified by a delicate modelling process, requiring significant efforts and know-how.

The third approach is ‘integrated modelling’. This term defines the coupling of several models, each one representing a part of a complex system. Several modelling attempts belonging to this approach focus on the coupling between sewer systems and receiving water bodies. For example, Silva et al. (2013) modelled algal blooms in an urban lake as a consequence of changes in the upstream urban drainage. This type of modelling is still the object of single case-specific research, and cannot be considered as a common practice for stormwater management purposes.

Among the three approaches, the most current and solid is flow-rate modelling. However, this approach is extremely focused on sewer overflows (peak flow-rates) and does not take into account the effects downstream or those which occur due to smaller but more frequent flow disturbance. The development of other models to a level of ease of use and reliability suitable for widespread use by local authorities will probably take years. To increase the sustainability of urban water systems it is necessary to find practical and viable solutions to improve the accounting for impacts of decision-making on receiving water bodies (Ashley & Hopkinson 2002). For this reason, in this paper, we propose appropriate tools within the existing flow-rate modelling approach, and demonstrate their potential for application to downstream effects of urban stormwater management.

**Impact of urbanisation on downstream water bodies**

The most evident effect of urbanisation on catchment hydrology, recognised for several decades, is an increase in peak flow-rates. This phenomenon was particularly noticed for large rain events, when floods or rapid stream erosion were observed. The efforts in stormwater management were thus oriented, for a long time, to control this kind of high-flow event. Typical measures in the USA (Balascio & Lucas 2009) or in the UK (Faulkner 1999) address events with return periods higher than 1 or 2 years. In France, most stormwater systems are sized for a return period of 10 years (Petrucci et al. 2013). This long-lasting practice of focusing only on relatively uncommon events persists in a large majority of urban hydrological studies.

High-flow events surely have an impact on the receiving water bodies. However, since the 1990s a consistent literature (summarised by Walsh et al. 2009b) started to reconsider their relevance, increasing the importance attributed to current events. In terms of channel erosion it has been shown that erosive flow-rates are small
enough to be exceeded even by frequent rain events (Hunt & Tillinghast 2011). These are likely to have a stronger effect, on the long term, than large uncommon events (Booth & 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 is the production of runoff, not occurring in natural catchments, for rain events of a few millimetres (Walsh et al. 2005a). This frequent runoff, even if hydraulically negligible, may constitute a relevant intake of pollutants (and heat). The second effect is the increase in combined sewer overflows (CSOs).

In conclusion, there is a growing interest for low 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.

**CONSTRUCTION AND USE OF FDCS**

Consequent to the growing interest for current catchments behaviour, some authors suggested hydrologic metrics linked to downstream effects. Booth et al. (2004) suggested using the annual fraction of days in which the daily mean discharge exceeds the annual mean discharge \(T_{Q\text{mean}}\). This indicator can distinguish catchments having a ‘flashy’ response from others with gradually varying flow regimes. However, the information given by such specific indicators is difficult to generalise to other geographic, climatic and urban conditions from that where the indicators were developed. That is why several researchers (Fennessey et al. 2001; Rohrer et al. 2006) used a more general way to characterise catchments’ current behaviours, using FDCs.

A FDC represents the fraction of time during which a given level of flow-rate is matched or exceeded. 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 & Fennessey 1995). Starting from a flow-rate time series, the simplest way of constructing a FDC is to order data by decreasing flow-rates, and to plot the result in frequency–flow-rate axes. 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:

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

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

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

The work of these authors addresses also the strong dependence of FDCs on the period used for calculation, a potential weakness of this instrument. 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 & Fennessey (1994) is, for time series spanning several years, to calculate several annual FDCs instead of a unique FDC for the whole recording period. Starting from annual FDCs, they calculate a median annual FDC and its confidence intervals. This method generates both more reliable FDCs and an estimation of the inter-annual variability of the hydrological regime.

Another point, useful for the following discussion, is that, starting from a time series recorded at a given time-step (e.g. 5 min), it is straightforward to construct series with longer time-steps (10 min, 1 hour, 1 day), by averaging subsequent records. Thus, starting from a time series, it is possible to obtain FDCs with several time-steps. Starting from a time series, it is also possible to construct curves other than FDCs but with similar construction procedures and meaning (Fennessey et al. 2001).

**Use and interpretation of FDCs in urban hydrology**

As mentioned in the introduction, most 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 (Fennessey et al. 2001), providing in a single view a comparison of the hydrologic regime under each scenario.
When the comparison involves many alternatives, and/or some case-specific objective is set, it is possible to define indicators on the FDC. To facilitate comparisons, one can use generic indicators (Braud et al. 2013) like the flow-rates exceeded for given fractions of the year or the intersections between FDCs and the axes. Figure 1 represents a sample FDC of an urban catchment, with its confidence intervals. In the figure $Q_{0.1\%}, Q_{1\%}$, and $Q_{10\%}$ are indicators corresponding to the values of the FDC for frequencies of exceedance of, respectively, 0.1, 1 and 10%, while $f_0$ is the intersection between the FDC and the $x$ axis.

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 $T_{Q_{\text{mean}}}$ proposed by Booth et al. (2004) as explanatory of the downstream biological status can be computed from FDCs. If some ‘disturbance thresholds’ can be estimated, their frequency of exceedance can be compared for different scenarios. In the same way, the frequency of CSOs can be estimated if the overflow threshold is known. Also $f_0$, defined above, describing the annual frequency of runoff, can be a significant indicator of water quality and biological disturbance (Walsh et al. 2005a, b). In general, which urban impacts are relevant in each specific case highly depends on local characteristics and on the relative dimension of the urban area to the receiving water body, demanding the defining of case-by-case indicators.

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 short time-steps (5–10 min) to finely describe the hydraulic system. A similar time-step can be appropriate for computing CSOs or other hydraulic-related processes, but a coarser time-step (hourly, daily) can be more adapted to describe impacts on systems having longer response-time.

**Required changes in modelling 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 few real or synthetic rainfall events, while for long-term simulations, representative inputs are necessary. However, this requirement can be easily fulfilled thanks to the rain gauge networks that have been in place for many years in most urban areas.

*Figure 1 | Examples of indicators defined on an annual median FDC. Grey lines represent 90% confidence intervals (15 years of simulation at 5-minute time-step). Source: Petrucci (2012).*
The second requirement 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 times.

The third and more problematic requirement is that the model should be reliable when simulating a catchment’s current behaviours. Today this is not always the case: even if flow-rate models are able to simulate the whole hydrologic regime, in practice they are often calibrated on a few high flow-rate events. This procedure focused on peaks does not guarantee the reliability of the model for low flow-rate events and for the parts of the hydrologic response other than peaks (ascending and descending limbs of the hydrograph). 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. It requires calibrating the model on low flows as well as on high flows, and considering the whole hydrograph shape and not just the peak position and amplitude. Further, event-based calibration is not sufficient: time series of input (rainfall) and output (flow-rate) are necessary. Although rain data are easily available, flow-rate time series are less common. Calibration of flow-rate models is also complex because typical models can involve hundreds 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 is necessary (Gupta et al. 2005). Technical analyses of urban stormwater management should start to include automatic calibration methods, quite diffused in hydrologic research but scarcely applied in practice.

Another potential difficulty in the use of FDCs can be mentioned. In most situations, the reference case for scenario comparison can be the actual state of the system. However, when the objective is to restore the ‘natural’ behaviour of a catchment, a pre-development FDC is necessary. Defining this curve can be difficult in the absence of suitable data or of a nearby reference catchment.

**EXAMPLE OF APPLICATION IN URBAN HYDROLOGY**

**Methodology**

We propose the application of FDC analysis to the comparison of different source control regulation scenarios. This example (detailed in Petrucci 2012) is intended here to show the better insight given by FDCs on the catchments’ behaviour.

We considered the ‘Gohards’ urban catchment, in Nantes, France (Figure S1, supplementary material, available online at http://www.iwaponline.com/wst/070/206.pdf, already studied and described by Rodriguez et al. (2008). This catchment (178 ha) is covered by a mixed land-use (residential, commercial, industrial and agricultural), giving an impervious cover of 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 of the sewer system (1999–2003), and 10 years of rainfall measurements at two rain gauges inside the catchment (1999–2008). Both time series have a 5-minute time-step. This catchment was chosen for this study because of the long available observation period.

The model used is SWMM5, with typical methods for subcatchments’ delineation and parameters’ estimation (Gironàs et al. 2009). The only particular feature of the modelling setup is that we distinguished, in each subcatchment, roof, road and green areas, in order to prepare the simulation of source control regulation scenarios (Petrucci et al. 2013).

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 minimise the changes from current modelling practices.

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 optimisation algorithm largely applied in hydrology (Savic & Khu 2005). Optimisation consisted of maximising the commonly used Nash criterion to keep the example as simple as possible; multi-objective optimisation on metrics based on the FDC could be, however, a significant alternative (Krause et al. 2005). For calibration we used 1 month of the available rainfall/runoff data (October/November 2000), to keep the computational requirements low. The period was selected for data quality (no gaps) and for the variety of rainfall events that occurred. Validation was performed calculating the Nash criterion for each season of the remaining data (nine periods of 4 months without long gaps were identified), in order to
verify that the choice of a single month, in autumn, for
calibration, was not reducing the performances in other
periods of the year.

Scenarios

The scenarios compared are of two types: specific flow-rate
regulations, demanding to implement BMPs to store storm-
water and 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. These regu-
lations are the most common in France, and are used in
other countries (Faulkner 1999; Balascio & Lucas 2009).
For more details on their modelling, see Petrucci et al.
(2013). In this example, we consider regulations with several
values of specific flow-rate and volume chosen according to
French current practices and applied systematically all over
the catchment. However, the same procedure can be applied
to more complex scenarios, with partial applications of
source control.

Specific flow-rate regulations were modelled by instal-
ling a reservoir downstream of the impervious areas of
each subcatchment. Each reservoir has a volume and an
outfall sized as a function of $q^*$, according to regula-

tory local sizing procedure. Volume regulations are
modelled as a pervious filter strip downstream of each
impervious area. The storage of the strip is sized as a
function of $i^*$.

Each scenario was simulated on a 10-year period with a
5-minute time-step in order to compute median annual
FDCs. 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 indicator to
FDC analysis.

Results and discussion

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 S2, supple-
mental material, available online at http://www.iwaponline.com/
wst/070/206.pdf). In validation, the Nash criterion values for
the available data not used in calibration ranged between
0.72 and 0.89 (median: 0.85), without evident seasonal biases.

Scenario simulation

In Figure 2 are plotted the median annual FDCs for flow-rate
and volume regulations. The reference value (black line) is
the FDC calculated by the model with no regulation applied.
As discussed before, starting from time-series, it is possible
to compute confidence intervals and other statistics on
FDC. In this example, we limit to the median FDCs to
keep a good readability of results.

The two sets of FDCs show immediately a significant
difference of behaviours between the two types of source con-
trol regulations: while specific flow-rate regulations reduce the
frequencies of high flow-rates but increase those of small ones,
volume regulations systematically reduce frequencies.

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 fre-
quencies of the reference case. The effect of specific flow-
rate regulations can be summarised by a flattening of the
hydrological behaviour of the catchment. The atypical
behaviour of the $q^* = 0.5$ l/(s·ha) curve is because of the
sizing procedure, which uses rainfall statistics (maximal

![Figure 2](https://iwaponline.com/wst/article-pdf/70/1/127/471011/127.pdf)

**Figure 2** Median annual FDCs for flow-rate (left) and volume (right) regulations. FDCs are computed over 10 years of simulation with a 5-minute time-step.
intensities) for durations up to 4 days. This is not adapted for long emptying times of a reservoir: with so low an outlet flow, emptying can require 1 week, causing spills for subsequent rain events. This sizing problem cannot be identified by single-event simulations, but easily appears with long-term simulations.

Volume regulations, in contrast, reduce flow-rates for each frequency. Small values of $i^*$ significantly reduce high-frequency flow-rates but are poorly effective at reducing low-frequency ones. Stricter regulations (higher $i^*$) are able to significantly reduce both.

If the comparison of FDCs allows the identifying of global trends, it is possible to show that FDC-based indicators can help decision-making. In Figure 3 are plotted the indicators $Q_{10\text{years}}$, corresponding to the peak flow-rate for a 10-year design rainfall (26.8 mm in 1 hour), and $Q_{1\text{year}}$, representing the flow-rate exceeded 10% of the year (36.5 days).

The first graph, representing a classical indicator for stormwater management, shows a linear reduction of peak flow-rates decreasing $q^*$. Because classical stormwater management practices aim to reduce peak flow-rate indicators in order to prevent sewer overflows, this reduction 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, and the fewer the sewer overflows and other nuisances.

The second graph, issued from the frequency analysis of long-term simulations, presents a different behaviour of flow-rate regulations: the indicator has a significant increase for low values of $q^*$. If there was a constraint on downstream flow-rates, like an erosive threshold for a downstream creek or the activation threshold for a CSO 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 downstream conditions.

More generally, this example shows that protecting the environment downstream of an 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 the point here is that similar observations are impossible if only single-event, peak flow-rate 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.

As the example shows, FDCs are not alternative but complementary to classical peak flow-rate and other analyses. On one side, the concern for water bodies’ protection is growing, but the first purpose of urban stormwater systems remains the protection of people and goods from flooding and other nuisances. FDC analysis, in this context, is just a tool to facilitate the search for a better compromise between different objectives. On the other side, FDCs can provide information on low flows, but they do not preserve temporal patterns: environmental processes depending on the stability of a given level of flow or on high/low flow successions cannot be described by FDC analysis (Sánchez Navarro et al. 2007).

**CONCLUSIONS**

In this paper, we presented the value of analysing urban stormwater management by the means of FDCs. An analysis of the current modelling practices in urban hydrology and of the literature on the impacts of urban areas on the downstream environment demonstrated that current approaches based on peak flow-rates are not satisfactory. They are not able to inform decision-makers of the impact of their choices on the environment. In this context, we argued that FDCs are a promising tool: they provide a good insight on the impacts on downstream water bodies without...
requiring significant changes in the way urban water studies are done today. FDCs, rarely used today in urban hydrology, represent a practical approach to improve the protection of water bodies.

To illustrate the use of FDCs, we presented an example of application to source control regulations in an urban catchment in France. The case-study demonstrates how FDC analysis can modify the conclusions on the impact of different types of regulation: while a typical peak-flows analysis would conclude on the appropriateness of flow-rate regulations, the FDCs show their potential negative impacts on the environment, suggesting that volume regulations can be more appropriate. Beside source control, FDCs can be used for almost any situation where flow-rate modelling can be applied, including decisions on new infrastructures, new operation rules or new urban developments.

We discussed in general the advantage and requirements of the use of FDCs in urban hydrology, but it should be remembered that information provided by FDCs has to be interpreted according to the specific context. A wise use of FDCs requires an understanding of which changes in the hydrological behaviour are more harmful (or positive) to the specific downstream environment. Local knowledge on water bodies remains necessary to better manage them.

**ACKNOWLEDGEMENT**

We thank Nantes Métropole for providing geographical data about the catchment.

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First received 12 September 2013; accepted in revised form 15 April 2014. Available online 29 April 2014