Infiltration of runoff at the plot-scale is increasingly considered as an effective tool to improve urban water management. As a consequence, authorities in different countries adopt regulations prescribing the infiltration of stormwater in new developments. Here we apply a simple sizing procedure for plot-scale infiltration facilities to examine the consequences, in terms of implementation, of typical regulation standards. Considering the relevance of different parameters in the sizing of infiltration facilities, local hydraulic conductivity emerges as the most relevant factor. Because of the importance of local infiltration capacity, current regulation standards based on a single constraint applied everywhere can require from developers highly different compliance efforts and can prove ineffective for stormwater management. We argue that regulations fixing constraints according to plot-scale soil characteristics are feasible and more effective.

**Introduction**

In the last forty years, decentralized facilities to store, infiltrate, evapotranspire stormwater have become one of the main tools for urban stormwater management. These facilities are often called, as a whole, Best Management Practices (BMP) or Low Impact Development (LID; Fletcher et al. (2014)). Initially, distributed storage (rainwater is locally stored and released at a given flow rate to the sewer; Roesner et al. (2001)) was the mainstream solution because it was simple to realize in almost every urban context and was able to reduce peak discharge. More recently, attention shifted to infiltration and evapotranspiration structures, like infiltration ponds or green roofs, as the net reduction of urban runoff volume is now considered necessary to achieve a more sustainable water management (Sage et al. 2015). In particular plot-scale infiltration facilities, like rain gardens, small infiltration basins or some bioretention systems (CIRIA 2015), are considered an effective way to restore pre-development water fluxes and to limit the impacts of urbanization on the water cycle.

However, this growing interest in runoff volume reduction is not followed by an effective and systematic implementation in the field. Green roofs and infiltration facilities are less present in cities than expected. The effectiveness of local policies promoting BMP implementation is the result of a complex set of factors, including financial incentives and technical support provided by local authorities, but also political and societal level of commitment for “green solutions” (Brown et al. 2016). Moreover, this effectiveness should not only be assessed in terms of the number of BMP realized, but also in relation to the global stormwater system, for example in terms of coordination between BMP and drainage system. As a consequence, a general framework to analyse local BMP policies is difficult to define.

Nevertheless, the core of most policies consists in the adoption by local authorities of specific regulations prescribing to build BMP in all new developments. Regulations are particularly important because they are applied systematically to all new developments, while other instruments (incentives, technical support) are used on a case-by-case basis. Regulations are thus likely to have a stronger impact on the water cycle than other components of local BMP policies. Even if local authorities modulate the enforcement of regulations through other instruments like incentives, a well-conceived regulation is essential to achieve the expected results. Commonly-used regulations have been developed for classical storage BMP and are not well suited for innovative ones. Versini et al. (2014), for example, studied the compliance of green roofs with some standard regulations. They found that green roofs cannot guarantee the compliance with fixed discharges because of their sensitivity to moisture conditions, and they concluded that regulations providing flexibility in the discharge prescribed (e.g. compliance required for 90% of the rain events) would be more adapted to the development of green roofs. Aiming at the promotion of better urban stormwater regulations in the future, this study analyses the sizing of infiltration BMP and discusses the effectiveness of common infiltration regulations.

Infiltration regulations are often represented by an “infiltration map”, defining areas where infiltration BMP can be installed. This “yes or no” zoning is often completed by the definition of the amount of water to infiltrate where infiltration is possible. These regulations take two general forms (see Table 1 for examples): “rainfall from an x-year return period event has to be infiltrated”,

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**ABSTRACT**

Infiltration of runoff at the plot-scale is increasingly considered as an effective tool to improve urban water management. As a consequence, authorities in different countries adopt regulations prescribing the infiltration of stormwater in new developments. Here we apply a simple sizing procedure for plot-scale infiltration facilities to examine the consequences, in terms of implementation, of typical regulation standards. Considering the relevance of different parameters in the sizing of infiltration facilities, local hydraulic conductivity emerges as the most relevant factor. Because of the importance of local infiltration capacity, current regulation standards based on a single constraint applied everywhere can require from developers highly different compliance efforts and can prove ineffective for stormwater management. We argue that regulations fixing constraints according to plot-scale soil characteristics are feasible and more effective.

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or an equivalent formulation based on rainfall frequency; “x mm of rainfall have to be infiltrated”. Another common type of regulation exists, different from the preceding ones as it is more a statement of principle than a precise rule: “where infiltration is possible, stormwater must be infiltrated; else, stormwater must be released at limited discharge”. This regulation type is common as “large-scale” regulation (e.g. national). For example, the British Department for environment affairs adopted it in its standards for sustainable drainage (DEFRA 2014) while previous standards in the UK were focused on storage (Faulkner 1999). The effectiveness of these regulations is strongly dependent on the enforcement procedure. Some local authorities report that many developers prefer to ignore the infiltration principle and focus on storage when they have this possibility. The reason is that no clear guidance is provided for infiltration while sizing rules are well established for storage, and developers prefer to avoid complex assessments (Petrucci and Bompard 2015). Although meaningful, these regulations have hardly predictable effects, suggesting that quantified regulations could be preferable. Similarly, these regulations are not analysed here because their implementation cannot be a priori assessed.

### Methodology

We use a simple sizing method to analyze the relationship between regulations and the actual sizing of storage/infiltration facilities. Among the many methods available, we adopt the “rainfall method”, used in France and other countries for storage units since the 1970s (CERTU 2003), or Canton Ticino regulation in Table 1. This method uses Intensity-Duration-Frequency (IDF) curves to compute the required specific volume \( v \) (mm) as a function of return period \( T \) (years) and of emptying discharge \( q \) (L/s/ha). A graphical explanation of the method is provided in Figure 1 and an analytical description is in the Appendix.

The method relies on two main hypotheses: (1) all the rainfall falling on the contributing area is instantaneously routed to the retention unit; (2) discharge \( q \) is constant. Hypothesis 1 is acceptable only for small impervious areas. This is the case in the present application, as regulations are applied at the plot-scale. Hypothesis 2 can be acceptable for storage units but not necessarily for infiltration and other highly variable physical processes. However, if infiltration is computed as a function of saturated hydraulic conductivity, \( k_s \), the minimum value of discharge is considered and results are precautionary, well-adapted to regulation-setting. Moreover, if infiltration facilities are small in comparison to the contributing areas, and rainfall events considered are intense, the soil saturates rapidly and most of the infiltration occurs in saturated conditions.

Here we develop an application using IDF curves for the city of Brussels (Brouyaux and Tricot 2006) interpolated using the Montana model (Appendix; Garcia-Marin et al. 2013) and a
constant evapotranspiration rate of 1 mm/day. Results are only valid for Brussels, but the orders of magnitudes stand for most cities affected by northern European oceanic climate, while the general considerations and the method can be seen as more general. To evaluate this assertion, the method was tested on the case of Baltimore, USA (results not shown), using data from NOAA (www.nws.noaa.gov). Baltimore has a higher yearly average precipitation than Brussels (about 1 m vs 0.8 m) and higher rainfall depth (e.g. a 10-year 2-hour event is 64 mm vs 27 mm). Because of this diversity, we consider Baltimore as an appropriate benchmark.

To size a simple storage, the method requires two variables ($T$ and $q$). Conversely, for infiltration the discharge $q$ depends, at least, on the soil hydraulic conductivity $k_s$ (m/s) and on the area used for infiltration $A_{inf}$ (m$^2$), assuming both as constant. Moreover, the volume to be retained for infiltration depends on the area connected to the infiltration facility $A_{imp}$ (m$^2$). We can simplify the problem by considering the ratio between $A_{inf}$ and $A_{imp}$ as a variable. The sizing will thus be completely determined by $T$, $k_s$, and $A_{inf}/A_{imp}$ (details are provided in the Appendix).

Remarks on $A_{inf}/A_{imp}$. This variable represents the surface ratio between the infiltration facility and the contributing impervious area. This may appear as a design variable that developers can freely set. However, it depends on the urban setting: in sprawl urbanization the choice of the infiltration area is almost free, but in dense urbanization, even if 10% of a plot remains pervious, it is not guaranteed that it can be fully employed for infiltration. For example, areas in close proximity of buildings can be unusable. We can assume ratios of 1% to 5% as realistic for dense urbanization, and 10% as a reasonable maximum.

Assuming $A_{inf}$ constant means that infiltration area does not change with time or with the water level in the infiltration facility. This assumption is strictly verified only if infiltration occurs at the bottom of the facility and not on its sides, but is acceptable if the lateral surface is small compared to the bottom. This case is realistic, in particular for rain gardens or other plot-scale open facilities, where excessive depths are generally avoided to grant other uses.

Remarks on $k_s$. This variable is the key parameter in most infiltration regulations. Often a permeability test is required to prove the suitability of infiltration at the plot-scale. For example, in France infiltration is usually admitted for $10^{-7}$ m/s < $k_s$ < $10^{-4}$ m/s (CERTU 2003); we use this range in the analysis). In Brussels, a minimum value of $k_s = 6 - 10^{-6}$ m/s (20 mm/h) is considered necessary (guidebatimentdurable.bruxellesenvironnement.be/), while in New York the threshold is 3.5 - $10^{-6}$ m/s (Table 1). Even if $k_s$ is considered as a sizing variable it is never used, according to our knowledge, to determine the regulation requirements (i.e. the volume of water to be infiltrated). Moreover, regulations demanding local tests take into account the spatial variability of $k_s$ but not its time-variability. Clogging is often mentioned as an issue for infiltration facilities. However, research on this point has not provided yet concluding results: while some experiments showed relevant clogging (Barraud et al. 2016), in other cases no passings from $A_{inf}/A_{imp}$ = 10% to 1% (storage quadruples in the worst case). When passing from $k_s = 10^{-4}$ m/s to $k_s = 10^{-3}$ m/s, the required storage at least quadruplicates ($A_{inf}/A_{imp}$ = 1%, $T = 100$ years) and it can increase more than 45 times ($A_{inf}/A_{imp}$ = 10%, $T = 2$ months).

To interpret results in terms of regulations, we discuss three examples.

Example 1. We consider a regulation requiring to infiltrate the volume of a 1-year event. The corresponding volume to be stored (and thus the required effort, in terms of costs and space) ranges between 3 (10%, $10^{-4}$ m/s and 58 mm (1%, $10^{-7}$ m/s). For a 100 m$^2$ building this corresponds to a pond going from 0.3 to 5.8 m$^3$. Both values are feasible, but the first can be a small depression in the garden, while the second requires the construction of a significant storage, with clearly different costs.

Example 2. Jointly with the regulation of example 1, it is required to limit the discharge for a 10-year event to 2 L/s/ha, demanding 33.9 mm of storage (dashed line in Figure 2). If local infiltration capacity is high ($k_s = 10^{-4} - 10^{-5}$ m/s) and a sufficient surface is used for infiltration, adding a similar storage is useless: a smaller volume (about 30 mm for $k_s = 10^{-4}$ and $A_{inf}/A_{imp} = 1%$) can manage a 100-year storm. In other words, for high conductivities, infiltrating a 100-year event requires a smaller volume – and thus, in principle, a smaller cost – than controlling discharge for a 10-year event.

Example 3. We consider a regulation requiring to store and infiltrate a fixed amount of 20 mm. If $k_s$ is high (10$^{-5}$-10$^{-5}$ m/s), depending on the infiltration area, this volume allows to manage any event up to a 10-year return period, or even exceeding 100-year. Conversely, with low conductivity (10$^{-6}$-10$^{-7}$ m/s) even observed a strong seasonal variation in $k_s$ for two infiltration BMP in Pennsylvania, with values oscillating over one order of magnitude ($5 - 10^{-7}$ m/s to 3 - $10^{-4}$ m/s). They explain this variation as the effect of temperature on water viscosity. Because of the absence of a robust understanding of the processes influencing soil permeability, it is probably too soon to include them in regulations and, in this note, they will not be discussed further. But it is important to remember that solutions to account for infiltration variability (seasonal correction of permeability tests, good construction practices) are an open issue for infiltration regulations.
because, according to infiltration capacity, every development will infiltrate more or less water. However, this solution is difficult to coordinate with the rest of the water management sector. Drainage systems are usually sized according to a given return period; if plot-scale infiltration manages an undetermined amount of water, the same drainage system sizing will perform differently in areas with varying permeability. Even applications like real-time control of drainage systems or the prediction of future urban impacts, demanding to forecast runoff from urban catchments, will be more difficult. The unpredictability of the effects of these regulations makes them non-optimal in the global framework of urban water management.

Current regulation standards, based on volume or return periods applied homogeneously, are thus unsuited to achieve a good use of infiltration in urban water management. To improve them, it is necessary to avoid a single requirement applied everywhere and adopt regulations that depend on the local hydraulic conductivity.

Example 3 shows a possible solution to these issues. A fixed volume can be considered equitable because every new development requires the same effort, and is effective because, according to infiltration capacity, every development will infiltrate more or less water. However, this solution is difficult to coordinate with the rest of the water management sector. Drainage systems are usually sized according to a given return period; if plot-scale infiltration manages an undetermined amount of water, the same drainage system sizing will perform differently in areas with varying permeability. Even applications like real-time control of drainage systems or the prediction of future urban impacts, demanding to forecast runoff from urban catchments, will be more difficult.

The unpredictability of the effects of these regulations makes them non-optimal in the global framework of urban water management.

Figure 2. Storage volume (mm) as a function of $k_s$ and $T$, for $A_{inf}/A_{imp} = 1\%$ and $10\%$. The grey dashed line represents a simple storage rule (no infiltration) with $q = 2 \text{ L/s/ha}$. 
30 mm, or a 20-year event) is required, without any discharge control. Where conductivity is low a small infiltration volume (e.g. 3 mm) is required, together with discharge control (e.g. 2 L/s/ha for a 10-year event). A similar regulation attenuates the problems of homogeneous standards, while remaining simple and easily applicable. More complex regulations, involving more thresholds, can also be proposed if their practical feasibility is verified. In particular, the capacity to define narrow intervals of conductivity depends on the reliability of conductivity measurements.

Conclusions

Developing a regulation promoting an effective use of BMP at the city-scale is a daunting but important task. It requires determining proper city-scale objectives, forecasting future developments of urban areas and infrastructures, choosing feasible and reliable methods to perform plot-scale analyses, finding enforcement and control strategies, etc. Here, we focused on a narrow but relevant aspect of this wide process: the setting of effective regulations. Many cities develop infiltration maps, distinguishing areas where infiltration is possible from others where it is proscribed. However, an effective regulation, feasible and relying on well-established methods, can go farther than simply saying “do” or “don’t”: where the soil is adapted almost all the rainwater can be easily managed by infiltration but elsewhere, even if infiltration remains possible, only small rain events can be managed. We argue that heterogeneous regulations, setting constraints depending on plot-scale soil characteristics could be feasible and more effective by avoiding the construction of superfluous storage – reducing developers’ efforts – and by maximizing the use of the infiltration capacity of the territory – reducing stormwater runoff volume and its negative impacts. The relevance of hydraulic conductivity requires a deep investigation of the variability of this parameter, the measurement methods, etc. However, this investigation must not necessarily take place before the adoption of new regulations: it can be part of the follow-up of new rules, through a learning-by-doing approach.

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