AN ANALYTICAL PROBABILISTIC APPROACH TO SIZE INFILTRATION BASINS

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ABSTRACT

In recent decades, Best Management Practices (BMPs) for runoffs and water pollution control have gained considerable recognition and acceptance. In addition to downstream runoff control by detention storages source control with infiltration basins has proved to be very effective in reducing the risk of drainage network overload and of polluted spills in receiving water bodies. Infiltration basins collect runoffs from impermeable surfaces like roofs, parking lots, streets and temporarily store rainwater volume to allows its infiltration into the soil even under conditions of low permeability. A key aspect for infiltration basins design is sizing the storage volume. Traditional approaches are based on the resolution of the continuity equation, which represents the balance of inflows and outflows from the filter medium, coupled with the Darcy's law to estimate the infiltration capacity. Despite these methods are quite robust, they can lead to underestimation of the probability of failure because they are generally based on design storm and neglect the stochastic rainfall process. The overflow risk depends on the chance of having a large single event when the basin is empty, or a sequential event during the draining process. This can last several days in relation to soil characteristics and may increase in absence of proper maintenance.

This paper proposes an analytical probabilistic approach to size infiltration basin; it results function of the probability distribution of the three fundamental hydrological parameters (rainfall height, rainfall duration and inter event time), of reliability and of soil infiltration capacity and of catchment surface. Two different runoff control rules are taken into account in the resulting formula. It has been tested by an application to a case study based on rainfall intensities recorded in Milano.

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1. INTRODUCTION

Many studies have revealed that the traditional approach in stormwater drainage has sometimes increased flooding and stream erosion, affected the balance of a water body, and created shock loads of pollutants to the receiving waters (Athayde 1976). In response to increasing concerns, many cities have encouraged the applications of local disposal of stormwater at its source of runoff.

Induced infiltration of urban stormwater into the ground is used as an alternative to its direct discharge to streams (Pitt et al., 1999; Dechesne, 2002; Fischer et al., 2003). Rainwater infiltration basins are expected to compensate for reduced groundwater recharge caused by the sealing of the urban landscape and are designed to promote the retention and degradation of contaminants in the soil (Chocat, 1997; Fujita, 1997; Mason et al., 1999). For a small catchment such as a parking lot, roof top, or depressed area, storm water quality and quantity control can be achieved by infiltration detention basins.

In practice, infiltration basins are used for rainwater temporary storage purposes. The stored runoff then infiltrates through the basin bottom into the surrounding soil. The challenge in the design of infiltration facilities is to assure that the basin site will sustain the design storage volume and infiltrating rate. Design procedures of an infiltration basin include the surface hydrologic study to size the detention storage volume, and the subsurface hydrologic study to assure the availability of an adequate groundwater conductivity. Selection of the basin size is a trade-off between costs and overflow risk. From the stormwater quality control point of view, the larger the infiltration basin, the less the overflow risk. However, from the cost point of view, the smaller, the better. Under such a trade-off, an infiltration basin is often designed to serve as an outfall device for a small and paved catchment (< 4 ha) such as a roof. Design parameters include rainwater storage volume, soil infiltration rate on the land surface, seepage rate through the soil medium between the basin, water mounding effects on the local ground-water table, and overflow risk between storm events (Guo 1998, 2001).

In current practice, some general guidelines on the minimum subsurface geometry are available, such as a maximum ponding depth and ponding time (Shaver 1986) and a minimum of 4 ft between the bottom of the basin and the ground-water table (Shaver 1986; Urbonas and Stahre 1990), but they do not provide a realistic basis for estimating the subsurface geometry required to sustain an efficient infiltration operation.

Infiltration basins are often filled with granular material, with the system designed to infiltrate surface water into the ground. The critical issue for infiltration systems is the rate of infiltration into the subsurface material. Clay-like soils allow very little infiltration whereas a sandy soil allows high levels of infiltration. Infiltration rates normally range from 5×10^{-4} mm/s for a soil with marginal infiltration capacity to 1×10^{-2} mm/s for a soil with a relatively good infiltration capacity.

One of main concern with infiltration basins is clogging: there are two ways to cope with clogging: prevention and restoration. The first priority to prevent clogging is the adaptation of a structure with a sedimentation area with a device to shut off the inflow of sediment. The sediment trapped by these devices must be regularly removed and the frequency of cleaning of infiltration facilities varies greatly depending on the location.

Traditional approaches are based on the resolution of the continuity equation, which represents the balance of inflow and outflow flow from the filter medium, coupled with Darcy's law to estimate the infiltration capacity; the basin storage volume was then achieved by maximizing the volume difference with respect to the design storm duration.

Roesner (1974) and others (Goforth et al., 1983; Padmanabhan and Delleur, 1978) also developed deterministic and stochastic relationships among overflow, infiltration rate and size of facilities. The concept of first flush volume, or water-quality capture volume, leads to a storage volume of approximately 30% of a 2-year, 1-h storm runoff depth (Guo and Urbonas 1996). When a 2-year or larger event is chosen, the volume-based method can be used to maximize the runoff detention volume by choosing a proper rainfall duration (Guo 1999a).

The draining process of an infiltration basin is usually as long as 2–3 days. During such a long and slow releasing process, the chance for the basin to be overwhelmed by the next rainfall event is a concern. The overflow risk depends on the chance to have a large single event when the basin is empty, or the sequential event during the draining process. This paper proposes an analytical probabilistic approach to size infiltration basin that takes into account the possibility of overflows.

Spills can be discharged into the urban drainage system at different rate depending on downstream availability. Storage volume is related to the reliability of the infiltration basin systems, considering overflows.

Resulting formula is function of the probability distribution of the three fundamental hydrological parameters (rainfall height, rainfall duration and inter event time), of reliability and of soil infiltration capacity and catchment surface. The possibility of bypassing first flush and storing only cleaner rainfall water is considered. An application to a case study based on rainfall intensities recorded in Milano is also presented.

2. INFILTRATIN BASIN VOLUME

Let consider an infiltration basin that collects rainwater from an impermeable surface and infiltrates it into the soil. Based on drainage catchment (roofs, parking, courty), first flush can be bypassed and discharged in the urban drainage system. To analyze the dynamics of stored volume in an infiltration basin, a simplified scheme has been adopted, based on the following hypothesis:

- outflow from infiltration basin has been considered constant and equal to the infiltration capacity at saturation;
- rainfall-runoff transformation has been neglected, considering rainfall intensities instead of water discharges (as small surface are considered, discharges may be assumed approximately proportional to rainfall intensities);
- the duration of the runoff event has been assumed equal the duration of the runoff event; to simplify modelling in applications, first flush runoff and Initial Abstraction are averaged over the duration of the storm (Figure 1).

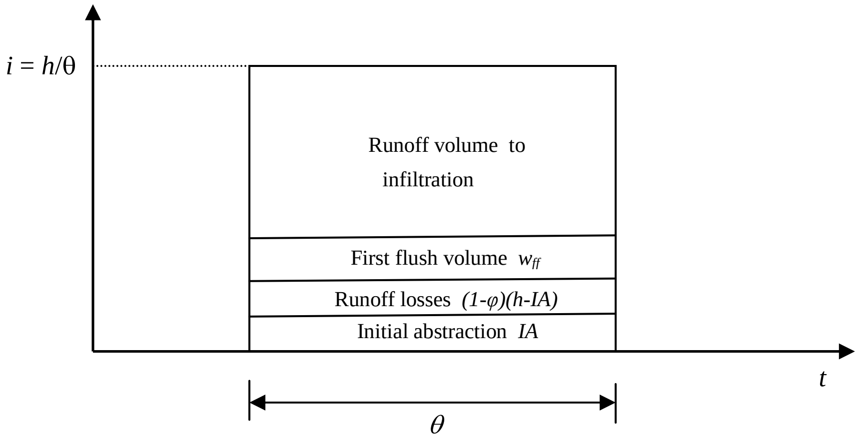

Figure 1 - Schematization of rainfall event components.

- rainfall intensities have been considered constant in time (if inflow are always greater than the constant outflow for all the storm duration, the final stored volumes are independent from hydrograph pattern and rectangular events may be used);
- carryover have been assumed to be due to the previous storm only, so that a couple of storms at a time has been considered.

Two different runoff control management rule have been considered:

- all rainwater collected from the roof is stored in the infiltration basin; some impermeable surfaces (as roofs) can be assumed little polluted and all runoff can be intercepted and disposed through infiltration and percolation.
- rainwater runoff is intercepted after a preset runoff has occurred, that is first flush volume (usually equal to 3-5 mm) is collected to the sewer and the remainder runoff is intercepted by the infiltration basin. It happens when stormwater washes very

polluted surfaces as like parking lots or when roof is made of metal. Furthermore this rule may have utility in a real time control of a storm sewer system where the storm sewer capacity of the downstream watershed is optimized by rapidly conveying away the initial runoff before the flow from upstream

A generic load/use cycle can be schematized as follows (Figure 2):

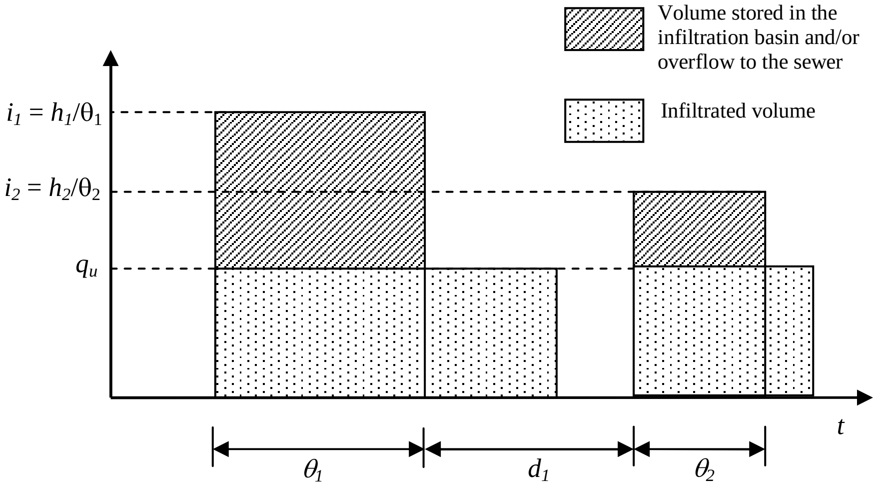

Figure 2 - Schematization of a load/use cycle

To identify independent events from the storm stochastic process a minimum dry period, the so called InterEvent Time Definition, IETD (USEPA, 1986) has to be defined. It is well recognized that the conventional flood frequency approaches developed for extreme events are no long applicable to analyze a complete rainfall data series. Among others, the one–parameter exponential function has been recommended to model the probability distribution of a rainfall data series (Chow 1964; Wanielista and Yousef 1993). The probability distribution functions are:

$$f_h = \xi e^{-\xi h}$$
$$f_\theta = \lambda e^{-\lambda\theta}$$
$$f_d = \psi e^{-\psi(d - IETD)}$$

where $\xi = 1/\mu_h$, $\lambda = 1/\mu_\theta$, $\psi = 1/(\mu_d - IETD)$, μ_x = expected value of variable x.

For an adequate design, overflow volume w_{sf} must be lower or equal to the volume that can be accepted from the downstream drainage system w_{s0}. If the stored water at the end of the first event is supposed to be lower than the basin volume, the overflow volume is equal to

$$w_{sf} = \begin{cases} h - IA - w_{ff} - q_u\theta - w_o \\ \qquad \text{if } \{h - IA - w_{ff} - q_u\theta > 0\} U \{h - IA - w_{ff} - q_u\theta - q_u d \leq 0\} \\ 2(h - IA - w_{ff} - q_u\theta) - q_u d - w_o \\ \qquad \text{if } \{2(h - IA - w_{ff} - q_u\theta) - q_u d > 0\} U \{h - IA - w_{ff} - q_u(\theta - d) > 0\} \end{cases} \tag{1}$$

where :

w_{sf} = overflow unit volume (depth)
w_o = basin unit volume (depth)
w_{ff} = first flush unit volume (depth)
h = rainfall depth
IA = initial abstraction
θ = rainfall duration
d = interevent duration
q_u = basin unit outflow = $\frac{fS_o}{\varphi S}$
f = infiltration rate
φ = runoff coefficient
S = drainage area
S_o = infiltration basin area

Unit volumes have the same units of the rainfall depth, that is are expressed as volumes per effective drainage area φ*S*. Combining the above relationships with the associated conditional constrains, the probability of having an overflow volume w_{sf} greater than w_{so}, results:

$$P(w_{sf} > w_{s0}) = \frac{\beta_1}{1+q^*} e^{-\xi(IA+w_{ff}) + \psi IETD - \frac{\xi}{\beta_1}(w_o+w_{so})} + \frac{e^{-\xi(IA+w_{ff})}}{1+q^*}\left[\beta_2 e^{\psi IETD - \frac{\xi}{\beta_1}(w_o+w_{so})} - e^{-\xi(w_o+w_{so})} + \right.$$
$$\left. + 2(1-\beta_2) e^{-\frac{\xi}{2}(w_o+w_{so}) - \frac{\lambda}{2} IETD q^*}\right] \tag{2}$$

with

$$q^* = \frac{\xi q_u}{\lambda}\ , \qquad \beta_1 = \frac{\xi q_u}{\xi q_u + \psi}\ , \qquad \beta_2 = \frac{\xi q_u}{\xi q_u + 2\psi}$$

Equation (2) may be solved to estimate the basin volume w_o needed to have an overflow volume lower than or equal to w_{so} with an assigned probability. The general condition $(w_o - w_{so})/q_u > IETD$ for the possibility of pre-filling has also to be taken into account.

3. APPLICATION

Relationship to estimate infiltration basin volume has been applied to a case study, using the rainfall series recorded in Milano, Italy, from 1971 to 1991 (series with a time resolution of 1 minute and a depth resolution of 0.2 mm). An IETD= 6 hours has been selected to identify independent rainfall events (Adams et al., 1986). The total number of storms in the series for IETD=6 hours is equal to 979. Mean and standard deviation of rainfall characteristics are shown in table 1, while the correlation coefficients among them are shown in table 2.

Table 1 - Mean and standard deviation of rainfall characteristics in the Milano series.

Variable	*Mean*	*Std. deviation*	$1/\mu_x$
Rainfall depth h [mm]	*12.89*	*19.09*	$\xi = 0.078$
Rainfall duration θ *[hour]*	*8.712*	*11.21*	$\psi = 0.010$
Interevent duration d [hour]	*104.97*	*152.86*	$\lambda = 0.115$

Table 2 - Correlation coefficient among rainfall characteristics in the Milano series.

Variables	*P*
h [mm]- θ *[hour]*	*0.740*
h [mm] - d [hour]	*0.047*
d [hour]- θ *[hour]*	*0.032*

As can be observed, while the other characteristics are only weakly correlated, rainfall depths and durations are not independent random variables as assumed. More, also the hypothesis of exponential CDFs for all three rainfall characteristics is not well suited to the samples of recorded values. Both results are not unexpected, since they were observed for rainfalls in the Alpine catchments in previous studies (Bacchi et al., 1994, 2004, 2008), but these hypotheses have been held anyway to avoid a considerable increase in the complexity of relationships.

Infiltration basin volume is estimated for a roof surface of S=300 m^2 with runoff coefficient φ=1 and a basin infiltration surface of S_o = 5 m^2. Initial Abstraction *IA* for evaporation and water retained in surface depression has been assumed equal to 2.0 mm. First flush volume has been set equal to zero.

Infiltration rates *f* = 5, 10, 15 mm/hour have been assumed (q_u = 0.08, 0.17, 0.25). Results are shown in Figure 3 for an assumed overflow unit volume of 5 mm.

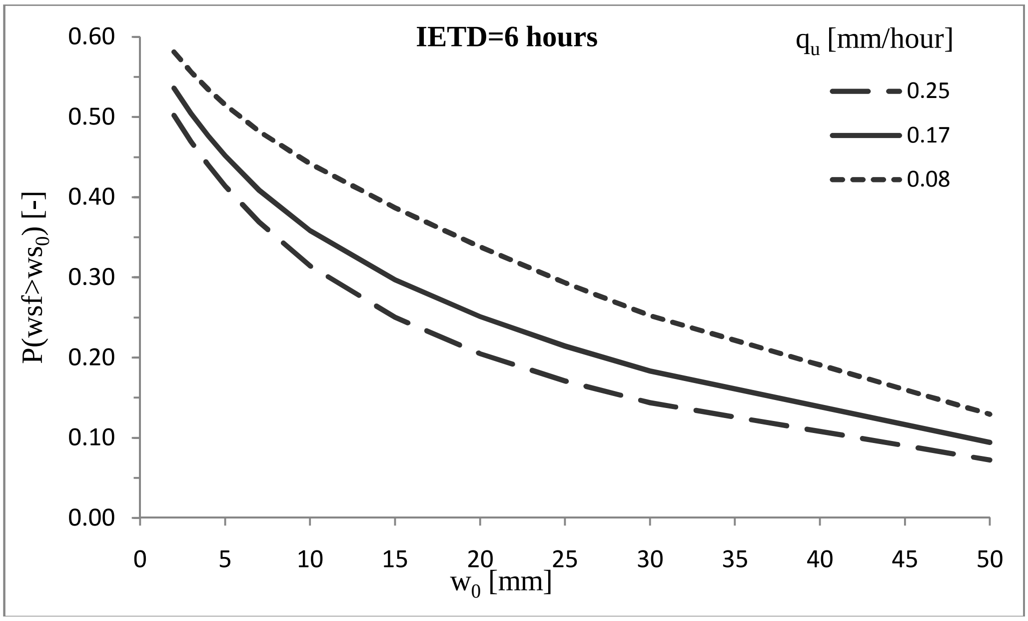

Figure 3 - Relationship between infiltration basin volume w_o and the probability to have an overflow volume greater than w_{so} = 5 mm for values of infiltration rates f = 5, 10, 15 mm/hour (q_u = 0.08, 0.17, 0.25 mm/hour)

4. CONCLUSIONS

A probabilistic approach for the design of an infiltration basin was presented. Design is based on the probability of an overflow to the stormwater sewer greater than an assigned value. This probability has been evaluated considering the effect of the previous rainfall event, that is assuming that the basin may not be empty at the beginning of the rain storm.

An equation for overflow probability is proposed, in terms of means of the rainfall characteristics. Possibility to prevent infiltration of first flush was considered. This equation may be solved to estimate the basin volume according to an assumed level of overflow risk and for assigned values of drainage area, basin infiltration area and ground infiltration rates.

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