A simplified approach for the design of infiltration trenches

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ABSTRACT

The use of infiltration trenches has proven to be useful to reduce runoff in urban surfaces. The design of these structures is based on the continuity equation taking into account inflow, outflow and detention water volumes. Basic procedures evaluate entering flow rates and relative volumes directly as a function of rain event characteristics, without taking into account rain-runoff processes occurring in the watershed. An improved simplified procedure, based on the kinematic model for the description of rain-runoff processes, has been developed here using a dimensionless approach. The procedure and the relative applicative design graphs are presented and discussed.

Key words | best management practices, design, dimensionless approach, infiltration trenches

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INTRODUCTION

As is well known, urban development strongly affects the hydrology of natural environments. The replacement of vegetation with paved areas causes an increase in runoff volumes, as well as a change in runoff hydrographs with increasing peak flow rates and decreasing times of concentration (Metropolitan Council 2001). These phenomena are due to the reduction in infiltration processes and the growth of runoff velocities over paved areas with respect to vegetated surfaces (Maryland 1998).

The change in the hydrological behaviour of a site can cause the occurrence of exceedingly high flow rates in drainage systems and, then, of sewer surcharge and urban flooding. Various approaches have been followed for the control of rain waters in urban areas (Urbonas 1999; Lanza 2006). The traditional approach to rain water control is aimed at quick runoff collection and convection to receiving water bodies. However, the accomplishment of this approach can result cost ineffective since it requires the construction of larger and larger channels in order to follow the development of urban areas. In the last decades, a lumped approach based on the construction of large site-specific capacities has been adopted in order to store rain waters temporarily and discharge them to drainage systems in an attenuated way. More recently, a new cost effective and sustainable approach is also adopted. This approach, usually named as Best Management Practices (BMPs) (Metropolitan Council 2001), is aimed at limiting inflows to drainage systems by the construction of small storage and/or infiltration structures in a distributed way in urban watersheds.

Infiltration structures are built in order to store part of the runoff volume and to release it into the surrounding soil during and after rain events. Their operation enables a quantitative and qualitative control of rain waters (Fujita 1997). Among the various infiltration structures, infiltration trenches are shallow linear excavations that are implemented at the ground surface to intercept overland flows.

DESIGN OF INFILTRATION TRENCHES

The design of infiltration trenches is based on the balance of inflow, outflow and detention water volumes; this balance assumes the following differential form:

$$\frac{dW_t}{dt} = Q_{in} - Q_{out}, \tag{1}$$

where W_t (m^3) is the trench detention volume, Q_{in} (m^3/s) is the trench inflow rate; Q_{out} (m^3/s) is the trench outflow rate given by $Q_{out} = Q_{inf} + Q_{overflow}$, where Q_{inf} (m^3/s) is the infiltration flow rate and $Q_{overflow}$ (m^3/s) is the overflow from the trench.

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The inflow rate Q_{in} (m^3/s) depends on the rain event and on the watershed characteristics upstream from the trench. The infiltration flow rate Q_{inf} (m^3/s) depends on the infiltration processes in the surrounding soil and can be evaluated by the following relationship:

$$Q_{inf} = k A_{inf}, \qquad (2)$$

where A_{inf} (m^2) and k (m/s) are the infiltration area and capacity, respectively. In particular, A_{inf} is the area of the trench structure where infiltration is assumed to occur; in the literature, authors usually evaluate it as a function of the bottom and side areas of the trench (PSA 1977; Bettess 1996; Freni *et al.* 2004, 2009). The infiltration capacity can be considered to be constant during the infiltration process (Bettess 1996) or variable according to Green & Ampt (1911), Richards (1931) or Horton (1940) models. The infiltration rate Q_{inf} can also be evaluated by means of more complex surface-to-subsurface 2D models (Guo 1998).

Procedures based on Equation (1) need the determination of the critical rain event duration that yields the maximum difference between trench inflow and outflow volumes. Moreover, the maximum flow rate value that can be discharged into the downstream drainage system is also required (Maryland Department of Natural Resources 1984). In basic procedures, the entering flow rates and the relative volumes are directly evaluated from the rain event characteristics (height and duration), without taking into account rain-runoff processes occurring in the watershed. These procedures would benefit from considering rain-runoff models for an improved evaluation of the trench inflow.

Accordingly, a simplified procedure for the design of infiltration trenches based on the rain-runoff kinematic model has been developed following a dimensionless approach. The procedure and the relative applicative design graphs are here presented.

THE PROPOSED DIMENSIONLESS PROCEDURE

The analyzed system is made up of a watershed and an infiltration trench located at its outlet (Figure 1(a)). The watershed has the following characteristics: area A_c (ha), time of concentration t_c (hour) and linear area-time curve (Figure 1(b)) in the form:

$$A = A_c \frac{t}{t_c} \quad \text{for } \frac{t}{t_c} \le 1; \qquad A = A_c \quad \text{for } \frac{t}{t_c} \ge 1, \qquad (3)$$

in which A (ha) = contributing area at time t (hour) after it starts to rain.

A rain event with duration t_r (h) and constant intensity i_r (mm/h) (Figure 1(c)) calculated by the following Intensity–Duration–Frequency (IDF) curve

$$i_r = a t_r^{n-1} \qquad (4)$$

is determined for the analyzed system for fixed return period. In particular, the IDF curve parameters a and n are functions of the return period chosen for trench design and can be evaluated on the basis of historical series of annual maximum rainfall heights of different durations. According to the kinematic model, the peak flow rate Q_c (m^3/s) from the watershed is obtained for a rain duration equal to t_c and is equal to:

$$Q_c = 0.0028\, \varphi\, i_c\, A_c, \qquad (5)$$

in which φ is the runoff coefficient and i_c (mm/h) is the rain intensity obtained from the IDF formula (Equation (4)) in correspondence to the time of concentration.

The dimensionless runoff hydrograph Q/Q_c coming from the watershed and entering the infiltration trench as

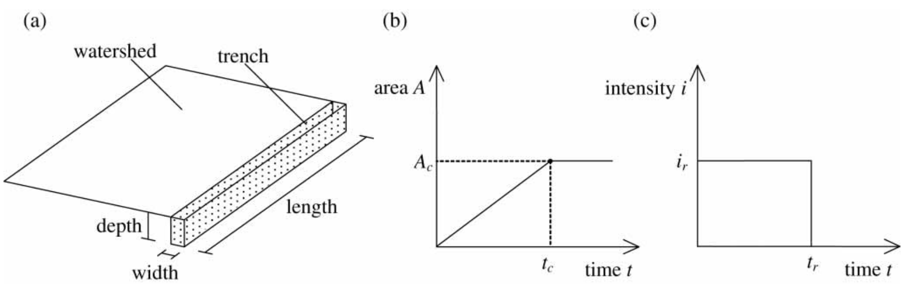

Figure 1 | (a) Sketch of the analyzed system; (b) area-time curve for the watershed; (c) design rain event.

a function of the dimensionless time t/t_c has the well known trapezoidal shape (Figure 2), characterised by the dimensionless flow rate value Q_r/Q_c. The flow rate value Q_r (m^3/s) relative to rain duration t_r can be calculated as:

$$Q_r = 0.0028\,\varphi\;\;i_r\,A \qquad \text{for } \frac{t_r}{t_c} \le 1$$
$$Q_r = 0.0028\,\varphi\;\;i_r\,A_c \qquad \text{for } \frac{t_r}{t_c} \ge 1 \tag{6}$$

Moreover, the following rain volumes can be defined: W (m^3) = cumulative rain volume entering the infiltration trench at time t; W_c (m^3) = 3600 Q_c t_c = cumulative rain volume for $t = t_c$.

Figure 2 reports the hydrographs relative to $t_r/t_c \le 1$ and $t_r/t_c \ge 1$. The hydrograph for $t_r/t_c = 1$ can be easily obtained as limit case of both the previous conditions. The hydrographs can be divided into three parts (growing, peak and decreasing) in which the following relationships are valid in the case of $t_r/t_c \le 1$:

$$\frac{Q}{Q_c} = \frac{t}{t_c}\left(\frac{t_r}{t_c}\right)^{n-1} \qquad \text{for } 0 \le \frac{t}{t_c} \le \frac{t_r}{t_c} \tag{7}$$
$$\frac{W}{W_c} = \frac{1}{2}\left(\frac{t}{t_c}\right)^2\left(\frac{t_r}{t_c}\right)^{n-1}$$

$$\frac{Q}{Q_c} = \left(\frac{t_r}{t_c}\right)^{n} \qquad \text{for } \frac{t_r}{t_c} \le \frac{t}{t_c} \le 1 \tag{8}$$
$$\frac{W}{W_c} = \left(\frac{t}{t_c} - \frac{1}{2}\frac{t_r}{t_c}\right)\cdot\left(\frac{t_r}{t_c}\right)^{n}$$

$$\frac{Q}{Q_c} = \left(\frac{t_r}{t_c} + 1 - \frac{t}{t_c}\right)\cdot\left(\frac{t_r}{t_c}\right)^{n-1} \qquad \text{for } 1 \le \frac{t}{t_c} \le \frac{t_r}{t_c} + 1 \tag{9}$$
$$\frac{W}{W_c} = \left(\frac{t_r}{t_c}\right)^{n} - \frac{1}{2}\left(\frac{t_r}{t_c}\right)^{n-1}\left(\frac{t_r}{t_c} + 1 - \frac{t}{t_c}\right)^2$$

and in the case of $t_r/t_c \ge 1$:

$$\frac{Q}{Q_c} = \frac{t}{t_c}\left(\frac{t_r}{t_c}\right)^{n-1} \qquad \text{for } 0 \le \frac{t}{t_c} \le 1 \tag{10}$$
$$\frac{W}{W_c} = \frac{1}{2}\left(\frac{t}{t_c}\right)^2\left(\frac{t_r}{t_c}\right)^{n-1}$$

$$\frac{Q}{Q_c} = \left(\frac{t_r}{t_c}\right)^{n-1} \qquad \text{for } 1 \le \frac{t}{t_c} \le \frac{t_r}{t_c} \tag{11}$$
$$\frac{W}{W_c} = \left(\frac{t}{t_c} - \frac{1}{2}\right)\cdot\left(\frac{t_r}{t_c}\right)^{n-1}$$

$$\frac{Q}{Q_c} = \left(\frac{t_r}{t_c} + 1 - \frac{t}{t_c}\right)\cdot\left(\frac{t_r}{t_c}\right)^{n-1} \qquad \text{for } \frac{t_r}{t_c} \le \frac{t}{t_c} \le \frac{t_r}{t_c} + 1 \tag{12}$$
$$\frac{W}{W_c} = \left(\frac{t_r}{t_c}\right)^{n} - \frac{1}{2}\left(\frac{t_r}{t_c}\right)^{n-1}\left(\frac{t_r}{t_c} + 1 - \frac{t}{t_c}\right)^2$$

If one neglects the infiltration processes through the device bottom and walls during the rain, the outflow attenuation at full trench due to an overflow device and the rain volume directly falling on the trench, Equations (7)–(12) enable the derivation of the graphs reported in Figures 3–6, relative to different values of the parameter n of the IDF curve.

The use of the graphs in Figures 3–6 enables the estimation of the behaviour of the trench for rain events with various durations. These graphs, in fact, report the ratio Q/Q_c of the overflow Q from the device to Q_c as a function of the ratio t_r/t_c of the rain duration t_r to the time t_c of

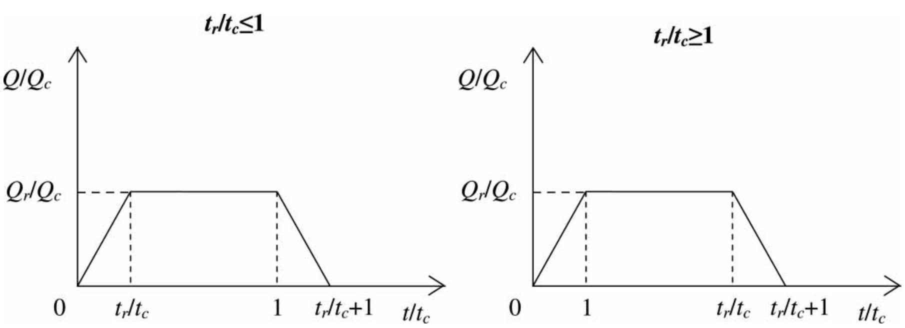

Figure 2 | Hydrographs of flow rates entering the infiltration trench.

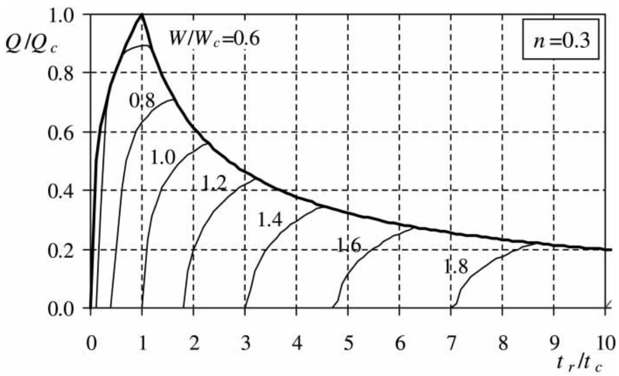

Figure 3 | Dimensionless outflow from the infiltration trench as a function of the dimensionless rain duration for various values of the dimensionless trench net volume ($n = 0.3$).

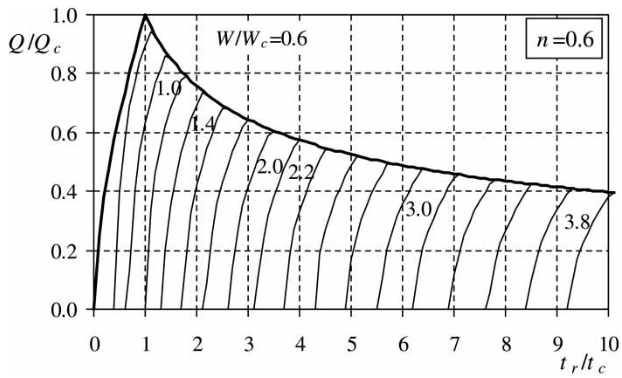

Figure 6 | Dimensionless outflow from the infiltration trench as a function of the dimensionless rain duration for various values of the dimensionless trench net volume ($n = 0.6$).

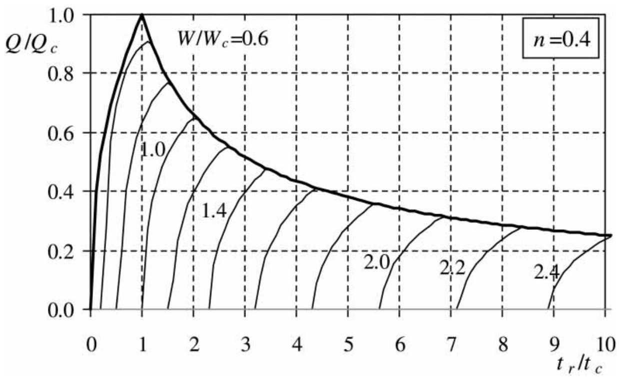

Figure 4 | Dimensionless outflow from the infiltration trench as a function of the dimensionless rain duration for various values of the dimensionless trench net volume ($n = 0.4$).

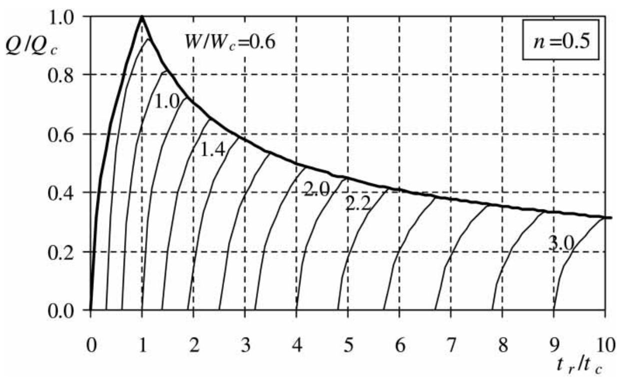

Figure 5 | Dimensionless outflow from the infiltration trench as a function of the dimensionless rain duration for various values of the dimensionless trench net volume ($n = 0.5$).

concentration, for various values of the ratio W/W_c (the entering rain volume W corresponds to the design net volume of the trench, i.e. the geometrical volume of the trench times the porosity of the trench filling material). In particular, in all the graphs the thick curve corresponds to the no-trench condition. Each line with parameter W/W_c intersects both the axis t_r/t_c and the no-trench curve; for dimensionless rain durations shorter than the value associated with the intersection of the W/W_c curve and the t_r/t_c axis, the trench with dimensionless net volume equal to W/W_c is able to intercept the whole runoff volume. In this case the dimensionless outflow Q/Q_c from the device is equal to zero. For dimensionless rain durations t_r/t_c longer than the value associated with the intersection of the W/W_c curve and the no-trench line, the trench with dimensionless net volume equal to W/W_c determines no reduction in the peak flow Q/Q_c with respect to the no-trench condition; for intermediate value of t_r/t_c, the trench with dimensionless net volume equal to W/W_c enables a reduction in the peak flow Q/Q_c.

Globally the graphs in Figures 3–6 show that the presence of the trench always determines an increase in the duration t_r of the critical event (in terms of Q/Q_c) and a decrease in the peak outflow with respect to the no-trench critical event with duration t_c and outflow Q_c, as the parameter W/W_c and then the trench net volume W increase. From the graphs in Figures 3–6 it is also possible to derive the graph in Figure 7 by taking into account the maximum value Q_{max}/Q_c of the ratio Q/Q_c for each value of W/W_c. This graph can be used for the design of infiltration trenches according to the following steps:

- characterisation of the watershed area A_c (ha), time t_c (hour) of concentration and runoff coefficient φ and determination of the parameters a and n of the IDF curve;

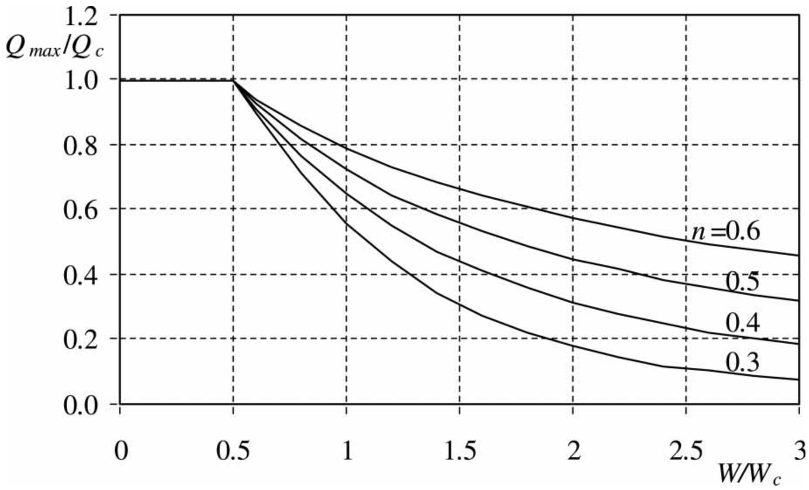

Figure 7 | Maximum dimensionless outflow from the infiltration trench as a function of the dimensionless trench net volume for various values of *n*.

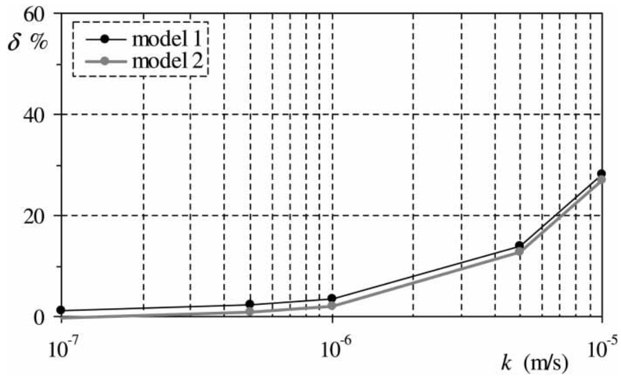

Figure 8 | Percentage differences δ between maximum outflows of models 1 and 2 with respect to the simplified procedure for various values of the soil infiltration capacity.

- evaluation of Q_c (m^3/s) and W_c (m^3);
- determination of the net volume W (m^3) to assign to the infiltration trench in order that the maximum outflow Q_{max} (m^3/s) from the device is acceptable for the downstream drainage system.

EXAMPLE OF APPLICATION AND COMPARISON WITH OTHER EXISTING DESIGN PROCEDURES

An example is provided here to illustrate the application of the procedure described above. A rectangular watershed with unitary width, length $= 50$ m, time of concentration $t_c = 0.14$ h and runoff coefficient $\varphi = 0.9$ is considered. Finally, the coefficients a and n of the IDF curve are assumed to be equal to 30 and 0.40 mm/h^n, respectively.

Simple elaborations yield $Q_c = 0.0012$ m^3/s and $W_c = 0.62$ m^3. Under the assumption that the flow rate handled by the downstream drainage system $Q_{max} = 0.31 \cdot Q_c = 0.00038$ m^3/s, the observation of the graph in Figure 7 provides $W/W_c = 2$, i.e. an available net volume $W = 1.22$ m^3 to be assigned to the trench for unitary length. Considering a soil porosity $p = 0.4$, the width and the depth of the trench can be set equal to 2.05 and 1.50 m, respectively.

From the graph in Figure 4, it is possible to derive the rain duration $t_r = 6.9 \cdot t_c = 0.97$ h associated with Q_{max}. The graph in Figure 4 also shows that the trench is able to intercept the whole runoff volume and to reduce the outflow Q to zero for rain duration shorter than 5.6 $t_c = 0.78$ h; for rain duration longer than $t_r = 0.97$ h, the trench is completely full and does not enable the reduction in the incoming flow rate peak. Nevertheless, these flow rates are always lower than the prefixed value $0.31 \cdot Q_c$ since rain durations are longer than the critical value.

In order to verify the validity of the assumptions made in the development of the procedure (infiltration processes and outflow attenuation at full trench neglected), the results of the application of the dimensionless procedure were then compared with the results of two more complete models (Freni *et al.* 2004) based on the numerical solution of eq. (1). In particular, in the two models, inflows are calculated considering a constant rain intensity and a linear area-time curve as in the proposed dimensionless procedure but, unlike the procedure, flows infiltrating in the surrounding soil during the rain event are taken into account. Infiltration flow rates, in fact, are evaluated by using Equation (2) and considering the wetted area of the side and bottom surfaces of the trench as infiltration area. The difference between the two more complete models lies in the modelling of the overflows from the trench: in the first model all flows approaching the full trench go immediately out without any reduction, as assumed in the proposed dimensionless procedure; in the second model, instead, the operation of a broad crested weir with the same length as the trench and with an outflow coefficient equal to 0.385 is considered. The application of the models to the previous example, considering various values of the soil infiltration capacity k (within the range 10^{-7}–10^{-5} m/s), enables the search for the rain duration that maximises the peak outflow rate Q_{max} from the trench after the device complete filling of the structure. Percentage differences δ between the maximum outflows provided by models 1 and 2 and the maximum outflow obtained by means of the proposed procedure were then calculated for various values of k and reported in the graph in Figure 8.

The graph in Figure 8 shows, as was expected, that δ grows as k increases, infiltration processes during the rain event being neglected in the proposed simplified procedure. However, the differences due to the use of the proposed procedure are lower than 3% for values of $k < 10^{-6}$, becoming appreciable only for high values of k (new trenches in sandy/gravel soils). Additionally, Figure 8 shows that models 1 and 2 perform similarly pointing out small differences due to the introduction of the weir. Accordingly, the correctness of the hypothesis (assumed in the proposed procedure) of neglecting the outflow attenuation due to overflow device results confirmed.

CONCLUSIONS

A simplified procedure for the design of infiltration trenches based on the kinematic model for the description of rain-runoff processes on the watershed was developed. Simplifications consisted in neglecting infiltration processes within the trench during the rain, the outflow attenuation due to the overflow device and the rain volume directly falling in the trench.

The procedure was developed adopting a dimensionless approach. Easily applicable graphs, enabling the design of the trench as well as the analysis of the behaviour of the device for various rain durations as a function of watershed characteristics and rain IDF curves were produced.

A comparison between the proposed simplified procedure and two more complete models requiring the numerical solution of the continuity equation showed appreciable differences only for soils with high values of infiltration capacity.

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