# Stormwater infiltration trenches: a conceptual modelling approach

Gabriele Freni, Giorgio Mannina and Gaspare Viviani


## ABSTRACT

In recent years, limitations linked to traditional urban drainage schemes have been pointed out and new approaches are developing introducing more natural methods for retaining and/or disposing of stormwater. These mitigation measures are generally called Best Management Practices or Sustainable Urban Drainage System and they include practices such as infiltration and storage tanks in order to reduce the peak flow and retain part of the polluting components. The introduction of such practices in urban drainage systems entails an upgrade of existing modelling frameworks in order to evaluate their efficiency in mitigating the impact of urban drainage systems on receiving water bodies. While storage tank modelling approaches are quite well documented in literature, some gaps are still present about infiltration facilities mainly dependent on the complexity of the involved physical processes. In this study, a simplified conceptual modelling approach for the simulation of the infiltration trenches is presented. The model enables to assess the performance of infiltration trenches. The main goal is to develop a model that can be employed for the assessment of the mitigation efficiency of infiltration trenches in an integrated urban drainage context. Particular care was given to the simulation of infiltration structures considering the performance reduction due to clogging phenomena. The proposed model has been compared with other simplified modelling approaches and with a physically based model adopted as benchmark. The model performed better compared to other approaches considering both unclogged facilities and the effect of clogging. On the basis of a long-term simulation of six years of rain data, the performance and the effectiveness of an infiltration trench measure are assessed. The study confirmed the important role played by the clogging phenomenon on such infiltration structures.


**Key words** | catchment-scale model, infiltration structure modelling, integrated urban drainage management, stormwater quality

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## NOMENCLATURE

| Description | Symbol (Unit) |
|---|---|
| Infiltration structure bottom area | $A$ (m$^2$) |
| Regression coefficient in Equation (10) | $a$ (m$^{2\ (1-b)}$) |
| Antecedent dry weather period | $ADWP$ (d) |
| Effective infiltration area in clogged conditions | $A_{eff}$ (m$^2$) |
| Effective infiltration area in clean structure conditions | $A_{eff,0}$ (m$^2$) |
| Width of infiltration trench | $B$ (m) |
| Regression exponent in Equation (10) | $b$ (–) |
| Regression coefficient in Equation (11) | $c$ (–) |
| Inflow suspended solid concentration | $C_{in}$ (mg/L) |
| Overflow suspended solid concentration | $C_w$ (mg/L) |
| Regression exponent in Equation (11) | $d$ (m$^{-1}$) |
| Sediment mean diameter | $d_{50}$ (–) |
| Cumulative infiltration volume | $F$ (–) |
| Gravity acceleration | $g$ (m/s$^2$) |

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| | |
|---|---|
| Height of the weir above the trench bottom | $h_0$ (m) |
| Sediment depth | $h_{SED}$ (m) |
| Water level in the infiltration trench | $h_w$ (m) |
| Effective water level | $h_{weff}$ (M) |
| Saturated conductivity | $k_s$ (m/s) |
| Length of infiltration trench | $L$ (m) |
| Mass of sediments trapped by the trench | $M_{sed}$ (kg) |
| Mass inflow from the catchment | $M_{sed,in}$ (kg) |
| Mass outflow to the sewer | $M_{sed,out}$ (kg) |
| Filling material porosity | $n$ (−) |
| Inflow infiltration trench discharge | $Q_{in}$ (m$^3$/s) |
| Infiltration flow | $Q_{inf}$ (m$^3$/s) |
| Outflow from the weir | $Q_w$ (m$^3$/s) |
| Square correlation coefficient | $R^2$ (−) |
| Time since the start of the rainfall event | $T$ (s) |
| Total suspended solids | $TSS$ (mg/L) |
| Volume stored in the structure | $V$ (m$^3$) |
| Input water volume from the catchment | $V_{in}$ (m$^3$) |
| Output water volume to the sewer | $V_{out}$ (m$^3$) |
| Total rain volume | $V_{rain}$ (m$^3$) |
| Mass captured inside the structure during a rain event | $\Delta M_{sed}$ (kg) |
| Infiltration structure water efficiency | $\eta_Q$ (−) |
| Infiltration structure total suspended solids efficiency | $\eta_{TSS}$ (−) |
| Average runoff reduction efficiency | $\bar{\eta}_Q$ (−) |
| Average sediments removal efficiency | $\bar{\eta}_{TSS}$ (−) |
| Capillary suction | $\psi$ (−) |
| Weir coefficient | $\mu_w$ (−) |
| Sediment density | $P$ (kg/ m$^3$) |
| Initial moisture contents | $\theta_0$ (−) |
| Saturated moisture contents | $\theta_s$ (−) |

## INTRODUCTION

The need for stormwater impact mitigation is presented in the EU Water Framework Directive 60/2000 that proposes a water-quality oriented view of the whole system and entails new sustainable approaches for disposing of stormwater (Chave 2001). The innovative trend of minimum impact in the design of new drainage systems and in retrofitting the existing ones led to the introduction of infiltration and local storage as more 'natural' measures for managing stormwater in urban areas (Fujita 1994; Urbonas 1994; Freni *et al.* 2002; Dechesne *et al.* 2005). According to this approach, many stormwater management measures may be distributed over the catchment. However, decisional problems may be connected to the efficiency evaluation of complex plans involving several stormwater management measures and some issues about the estimation of their maintenance needs may rise (WEF/ASCE 1998).

These considerations suggested the development of mathematical models for the analysis of these structures considering their inclusion in integrated urban drainage models, i.e. models that analyse jointly the sewer systems, the wastewater treatment plants and the receiving water bodies (Freni *et al.* 2009; Rauch *et al.* 2002). While the analysis of local storage is generally straightforward, the analysis of infiltration measures is hampered by the complexity of the infiltration process. More specifically, during the filling and the emptying of the infiltration structure and along with soil saturation, wide modifications of the infiltration phenomenon can be observed making the process very complex to be fully interpreted and then formulated by means of mathematical models (Mikkelsen *et al.* 1996; Guo 2001). Indeed, the real phenomenon is generally characterized by:

- tri-dimensional flow (basically in the unsaturated zone);
- infiltration from both the bottom and the sides depending on the construction technology and on soil saturation process;
- infiltration structure clogging (i.e. the permanent accumulation of solids in the infiltration structure after they are washed-off from the catchment surface).

To cope with the aforementioned complexity of the physical phenomena, detailed physically based models and simplified conceptual approaches have been built up. In particular, detailed physically based models are generally stand-alone models that consider soil saturation and structure clogging. However, most of these models are too complex in terms of their effective applicability in the case of extensive applications at catchment scale. On the other hand, simplified approaches are frequently based on restrictive working hypotheses and they do not take into account structure clogging. More specifically, in the case that one dimension of the infiltration structure is much longer than the others, infiltration can be considered as a 2D phenomenon (Duchene *et al.* 1994; Akan 2002). If the soil is homogeneous for a sufficient depth, infiltration paths become sensibly linear and vertical at some distance from the bottom of the trench. Following these considerations, several simplified modelling and design approaches use 1D infiltration models that are easier to be handled than 2D and 3D ones. These approaches are generally based on either a constant infiltration rate (Jonasson 1984; Pratt & Powell 1993; Wong *et al.* 2001; Argue & Pezzaniti 2003) or they consider dynamic conditions assuming infiltration rates that are variable with time and depend on soil saturation (Barraud *et al.* 2002; Freni *et al.* 2004; Dechesne *et al.* 2005; Browne *et al.* 2008).

As aforementioned, clogging is a relevant phenomenon that should be considered in infiltration facility modelling because it affects its efficiency over time. Clogging is due to the presence of sediments in the runoff entering in the infiltration structure, accumulating and therefore reducing its mitigation capacity and its effective volume. Clogging depends on hydrological factors, catchment characteristics, structure geometry and soil properties. In particular, at the beginning of the infiltration trench life cycle, when the structure is still new, infiltration takes place both through the bottom and the sides. Over time, due to the fact that sediments accumulate both in the bottom and along the structure sides, the clogging phenomenon takes place causing progressive waterproofing of the structure bottom and sides and consequently it reduces the effective infiltration area. Research about how sedimentation and clogging affect infiltration structure performance has been piecemeal, consisting mainly of individual case-studies from monitoring programs in North America, Europe, Australia and Japan (Kronaveter *et al.* 2001; Imbe *et al.* 2002; Markus *et al.* 2002; DAYWATER 2003; Siriwardene *et al.* 2007). Dechesne *et al.* (2005) proposed a stormwater infiltration basin model suitable for simulating events in large basins with a well established clogging layer. The model was calibrated with reasonable success for a number of well established infiltration basins in France. However, the study demonstrated the importance of antecedent soil moisture conditions, which were assumed to be constant for a site. Similarly, Schluter *et al.* (2007) presented a model for infiltration trenches that is aimed to be integrated in the new version of Infoworks for a catchment scale wide approach. The model is based on the Darcy's law and the finite volume method. Although the model provided an excellent prediction of the outflow flow from the infiltration trench system, it neglects infiltration rates variability in time, clogging phenomenon and in general it does not take quality aspects into account. Recently Furumai *et al.* (2005) considered a catchment wide approach for assessing the effect of mitigation measures on the reduction of the stormwater. In particular, Furumai *et al.* (2005) consider Infoworks CS for modelling the infiltration facilities employing two different methods. One of those methods, taking clogging phenomenon into account, provided better results in terms of capability of fitting the measured data. The authors concluded that the clogging phenomenon has to be taken into account for a correct simulation of infiltration facilities. Accordingly, Freni & Oliveri (2005) considered an application of infiltration mitigation measures implementing it in the EPA SWMM urban drainage model: only quantity aspects have been modelled neglecting any reduction of the mitigation measures efficiency during its life span.

From the literature review, it may be concluded that most available models of stormwater infiltration systems are either very simple purpose-built infiltration models or complex general unsaturated soil flow models that could be very accurate but are relatively difficult to adopt and therefore are rarely used (Browne *et al.* 2008).

The present study presents a simplified infiltration trench model able to simulate the main relevant processes that control the whole phenomenon during both single events and long term analysis. The main goal is to fill a gap present in infiltration structures modelling where simplified approaches are still marginally able to take into account physical phenomena that reduce stormwater mitigation efficiency during trench life cycle. The employed parsimonious approach, enabled the model to carry out long term simulations in order to assess the main infiltration processes and efficiency reduction during the structure life span. Indeed, such analysis is generally hampered by extensive computational resources, especially when dealing with water quality analyses (Vaes & Berlamont 1999; Vaes & Berlamont 2004). In the paper, the analysis was limited to infiltration trenches, although an analogous approach can be used for other underground infiltration structures. The proposed model has been benchmarked using literature infiltration models and applying them to a hypothetical trench located in the experimental catchment of Parco d'Orlèans (Palermo, Italy).

## METHODS

### The proposed model

The proposed model specifically addresses the simulation of the clogging phenomenon as it reduces both the effective structure volume (depending on sediment depositions) and its infiltration capacity (because of fine material that progressively seals soil voids). The research is aimed to provide a useful and reliable tool for stormwater management that can be implemented in integrated urban drainage models. Furthermore, this tool is not computationally demanding and, at the same time, it is able to analyze the most relevant phenomena affecting trench infiltration during its life cycle.

The proposed model simulates the water quantity aspects of infiltration structures hypothesising that it operates as a non-linear reservoir, equipped with a weir that simulates the overflows to the drainage system and a non-linear infiltration discharge to the soil. Referring to Figure 1, the continuity equation can be written as follows:

$$Q_{in} - Q_w - Q_{inf} = \frac{dV}{dt} \quad (1)$$

where $V$ is the volume stored in the structure, $Q_{in}$ is the inflow from the contributing catchment, $Q_{inf}$ is the infiltration flow and $Q_w$ is the outflow from the weir.

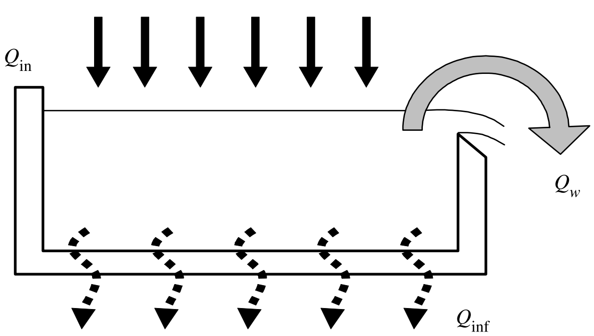


**Figure 1** | Proposed model conceptual scheme.

The outflow discharge $Q_w$ is evaluated considering a simple rectangular weir having the same width B of the infiltration structure. Discharge can be computed with the following formula:

$$Q_w = \mu_W B(h_W - h_0)\sqrt{2g(h_W - h_0)} \quad (2)$$

where $B$ is the width of the infiltration trench, $h_w$ is the water level inside the structure, $g$ is the gravity acceleration, $h_0$ is the height of the weir above the trench bottom and $\mu_w$ is the weir coefficient. This latter has been considered equal to 0.4 according to common values from literature (Marchi & Rubatta 1981).

The infiltration flow $Q_{inf}$ is evaluated using the Green-Ampt Equation (Green & Ampt 1911):

$$Q_{inf} = \min\left(Q_{in};\quad k_s\left(1 - \frac{\psi(\vartheta_s - \vartheta_0)}{F}\right)A_{eff}\right) \quad (3)$$

where $\vartheta_s$ and $\vartheta_0$ are respectively the saturated and the initial moisture contents, $\psi$ is the capillary suction, $F$ is the cumulative infiltration volume, $k_s$ is the saturated conductivity and the other symbols have the definitions given above. $A_{eff}$ here is defined as "effective infiltration area"; it is the horizontal area below the structure bottom where the infiltration paths start to be linear and vertical parallel. According to this definition, the infiltration phenomena can be analyzed using a one-dimensional approach.

The use of the Green-Ampt equation entails a better estimation of effective infiltration area that cannot be simply defined as a part of the physical infiltration structure surface. The use of the Green–Ampt equation allows for connecting infiltration model parameters to physical soil properties that can be estimated by the analysis of soil samples.

According to the proposed approach, $A_{eff}$ becomes the fundamental model parameter. Indeed, two functional relationships have to be found in order to assess this parameter depending on the geometry and maintenance state of the infiltration structure:

1. a correlation between the effective infiltration area in clean structure condition $A_{eff,0}$ and the geometrical trench bottom area $A$;
2. a correlation between the sediment level in the infiltration structure and the effective infiltration area in clogged conditions $A_{eff}$ in order to evaluate the change of $A_{eff}$ during the structure life span.

In the present study, the correlations are investigated by means of the VSF-MODFLOW 2000 physically based model described in the following (McDonald & Harbaugh 1988; Thoms *et al.* 2006).

Once defined $A_{\mathrm{eff}}$, the proposed model simulates the clogging processes inside the infiltration structure considering the mass balance for suspended solids:

$$C_w(t)\cdot V(t) = M_{\mathrm{sed,in}}(t) - M_{\mathrm{sed,out}}(t) = \int_0^t Q_{\mathrm{in}}(\tau)\cdot C_{\mathrm{in}}(\tau)\mathrm{d}\tau - \int_0^t Q_w(\tau)\cdot C_w(\tau)\mathrm{d}\tau \quad (4)$$

$C_w$ is equal to the outflow concentration by the weir considering a fully mixed system, t is the time and $\tau$ is an integration variable. The variation of the mass captured inside the structure, $\Delta M_{\mathrm{sed}}$, is evaluated at the end of each rainfall event as the product of the retained water volume ($V$) and the correspondent concentration ($C_W$). $\Delta M_{\mathrm{sed}}$ is supposed not to resuspend in following events. The distribution of solids on the bottom area in the infiltration structure is considered uniform. This assumption neglects the solid accumulation on the wall and it is supported by the fact that such solids, which come from the catchment wash-off, are not cohesive (Ashley *et al.* 2006). Moreover according to model conceptualization, the effect of sediments on infiltration is totally deputed to the estimation of effective area $A_{\mathrm{eff}}$ thus globally taking into account both the resistance effect on the trench bottom and on the side walls.

## The literature models adopted for comparison

As aforementioned, in order to assess the reliability and the limits of the proposed model, three different types of models with progressive higher complexity have been considered:

- Conceptual models considering constant infiltration rates (usually saturated soil conditions);
- Conceptual models that assume variable infiltration rates during the rainfall events;
- Physically based detailed models.

The first type of model neglects soil saturating conditions during rainfall events and clogging phenomena that reduce the structure infiltration capacity during its life cycle. With these hypotheses, infiltrated discharge varies in time only by means of water level variations inside the trench and soil infiltration capacity does not depend on time. The first model considered in this study is the one developed by Construction Industry Research and Information Association (CIRIA) (Bettess 1996). The CIRIA model has been developed for standardizing infiltration structure design. The CIRIA infiltration model assumes that infiltration takes place only through part of the sides of the structure (Figure 2); this hypothesis gives an implicit safety factor by assuming that the structure bottom is sealed with fine particles and it does not contribute to stormwater infiltration.

The main hypotheses of the CIRIA model are:

1. the trench bottom is impervious and infiltration is considered only via a half of the perimeter;
2. soil is in a saturated condition;
3. infiltration is analyzed using the Darcy equation with horizontal infiltration paths.

Assuming the application of the Darcy law and the limitations of infiltration surface, infiltrated flow rate is evaluated by the following equation:

$$Q_{\mathrm{inf}} = (B+L)\cdot \frac{h_w}{2}\cdot k_s \quad (5)$$

where $L$ is the length of the infiltration trench and the other symbols have the definitions given above.

The second type of model, which assumes infiltration rates are variable in time, usually entails an estimation of more parameters that can be assessed by means of

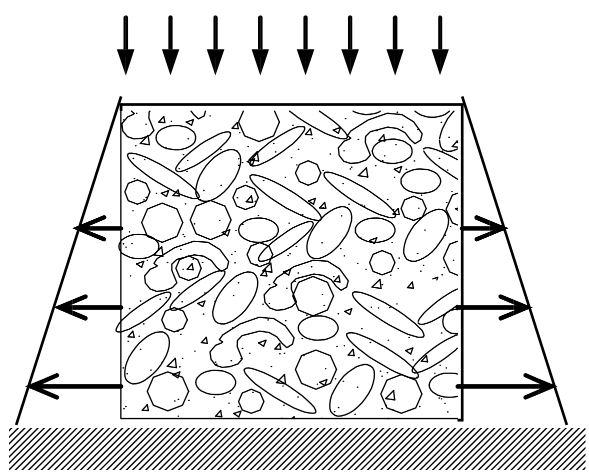

**Figure 2** | CIRIA model schematization.

experimental data. The use of conceptual infiltration models, such as Horton's law or equivalent resistance models, generally requires the monitoring of pilot structures (Guo 1998; Todorovic *et al.* 1999). A model, which belongs to this second type, is the one proposed by Todorovic *et al.* (1999). Its main hypotheses are:

1. infiltration through the front and back sides is neglected;
2. the trench bottom is impervious;
3. the horizontal filtration equation is used;
4. clogging occurs only at the bottom of the trench.

The model assumes a simple formula derived for the case of horizontal infiltration through the sides of the trench with the steep wetting front and constant water level in the trench (Pokrajac 1998). According to these assumptions the infiltration flow is estimated as:

$$Q_{\text{inf}} = \frac{4}{3} L h_{\text{weff}}^{3/2} \sqrt{\frac{k_s \cdot n}{2T}} \quad (6)$$

where $T$ is the time since the start of the rainfall event, $h_{\text{weff}}$ is the effective water level, i.e. considering the presence of sediments, $n$ is the trench filling material porosity and the other symbols have the definitions given above.

The effective water level $h_{\text{weff}}$ is given by the following expression:

$$h_{\text{weff}} = h_w - h_{\text{SED}} = h_w - \frac{M_{\text{sed}}}{\rho \cdot n \cdot A} \quad (7)$$

where $h_{\text{SED}}$ is the sediment depth, $M_{\text{sed}}$ is the total mass of sediments trapped by the trench, $\rho$ is the sediment density, $A$ is the infiltration structure bottom area and the other symbols have the definitions given above.

Concerning the detailed model, MODFLOW 2000 (McDonald & Harbaugh 1988; Thoms *et al.* 2006) was employed for the simulation of the infiltration trench behaviour, and developed by the United States Geological Survey. The model enables the simulation of steady and non-steady flow in a irregularly shaped system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined. Unsteady flow from external sources can be simulated. Hydraulic conductivity or transmissivity for any layer may differ spatially and be anisotropic (restricted to having the principal direction aligned with the grid axes), and the storage coefficient may be heterogeneous. The model integrates the 3D Richards equations by means of a finite volume approach. The Variably Saturated Flow (VSF) module simulates three dimensional variably saturated flow in porous media. The saturated ground-water flow equation is expanded to include unsaturated flow using Richards' Equation and solved using a finite-difference approximation similar to the one solved by MODFLOW 2000.

The two simplified models and the proposed one have been compared with MODFLOW 2000 that has been considered as a benchmark.

## The simplified urban drainage model

Inflow $Q_{\text{in}}$ and suspended solid concentration $C_{\text{in}}$ are evaluated with a lumped conceptual model flow and sediment loads from the catchment (Mannina 2005). The model is able to simulate the main phenomena that take place both in the catchment and in the sewer network during storm events. It is divided into two independent modules: a hydrological and hydraulic module, which calculates the hydrographs at the outlet of the surface catchment and at the outlet of the sewer system, and a solid transport module, which calculates the pollutographs for different pollutants (TSS, BOD and COD). The hydrological module evaluates the net rainfall, considering a loss function (initial and continuous). From the net rainfall, the hydraulic module simulates the rainfall-runoff process and the flow propagation with a cascade of two different reservoirs.

The solid transport module reproduces the accumulation and propagation of solids in the catchment and in the sewer network. The main phenomena simulated are: build-up and wash-off of pollutants from catchment surfaces, and sedimentation and resuspension of pollutants in the sewers (Bertrand–Krajewski *et al.* 1993).

To simulate the build-up on the catchment surfaces, an exponential function was adopted (Alley & Smith 1981). In order to simulate the solid wash-off caused by overland flow during a storm event, the formulation proposed by Jewell & Adrian (1978) is adopted.

The particle size that can be found on impervious surfaces can range from very fine to coarse and the median diameter can vary between 30 μm and 500 μm

**Table 1** | Particle classes adopted in the model

| Class of particles | 1 | 2 |
|---|---|---|
| Diameter (μm) | 50 | 500 |
| Bulk density (kg/m$^3$) | 1,600 | 2,000 |
| Specific gravity | 1.6 | 2 |

(Deletic *et al.* 1997). Rainfall and overland flow are able to lift into suspension only fine particles; particularly it was observed that the median diameter of suspended solids in overland flow is about 80–100 μm (Chebbo *et al.* 1990). In the present study, two particle classes are adopted in order to properly simulate different types of sediment transport in impervious area runoff and in the sewer network (Table 1); each class is present as the 50% of the total suspended solids mass. In relation to the characteristic of the hydraulic conditions, the fine ones ($d_{50} = 50\ \mu m$) are transported as suspended load while the coarse ones ($d_{50} = 500\ \mu m$) are mainly transported as bed load.

Model calibration was performed in a previous study (Mannina *et al.* 2004) and it has been omitted in the present paper for the sake of conciseness. The calibration has been carried out by means of water quantity and quality registrations carried out in the experimental catchment during a two month campaign. The discharge in the sewer system has been measured with a time step equal to 30 seconds while TSS, BOD and COD have been measured with a 24 bottles sampler started at the beginning of rainfall events. Calibration has been performed on catchment hydrological and hydraulic parameters and on wash-off and build-up parameters according to the Alley-Smith approach (1981).

However, in the present study, only overland rainfall-runoff phenomena are considered because the infiltration trench is considered directly fed by surface runoff.

As discussed before, the proposed model and the two literature approaches (CIRIA and Todorovic) have been compared with MODFLOW. The analysis has been carried out considering four different soils, described in the following paragraph, and a specific volume of $40\ m^3/ha_{imp}$. These parameters were selected in order to analyze the effect of clogging on infiltration structure efficiency in the long term. In fact, such process has a major role not only in terms of runoff reduction efficiency but also on structure durability and maintenance of acceptable efficiencies during its life cycle (DAYWATER 2003). The following structure characteristics were considered: trench specific volume equal to $40\ m^3$ per hectare of connected impervious area; filling material void ratio equal to 0.5, trench cross-sectional area equal to 2 m by 2 m; trench length was computed according to the connected impervious area and to the design specific volume.

In order to allow the comparison between the CIRIA model, Todorovic model, and the proposed one, $h_{weff}$ is calculated considering the progressive build up of sediments in the trench according to Equation (3) even if this option was not originally implemented in the CIRIA model.

In order to evaluate the infiltration structure behaviour at rainfall event scale, the stormwater volume reduction efficiency and the solid mass interception efficiency $\eta_{TSS}$, were estimated as in the following:

$$\eta_Q = \frac{V_{in} - V_{out}}{V_{in}} \qquad (8)$$

$$\eta_{TSS} = \frac{M_{sed,in} - M_{sed,out}}{M_{sed,in}} \qquad (9)$$

where $V_{in}$ is the input water volume from the catchment, $V_{out}$ is the output water volume to the sewer and the other symbols have the definitions given above.

## THE MODEL APPLICATION

In order to evaluate, on one hand, the proposed model reliability and, on the other hand, long term infiltration structure efficiency, an application has been carried out on an experimental catchment in Palermo (Italy), called Parco d'Orlèans.

The Parco d'Orlèans experimental urban catchment is located in the University Campus of Palermo, Italy (Figure 3). Its total drainage surface is 12.8 ha with 68% of impervious area, and the drainage network is made by circular and egg-shaped concrete conduits.

Rainfall data has been collected since 1994 with a tipping bucket raingauge and data logger at a maximum time resolution of one second (Aronica & Cannarozzo 2000). Discharge data has been collected since the same year with an ultrasonic flow meter installed at the basin outlet.

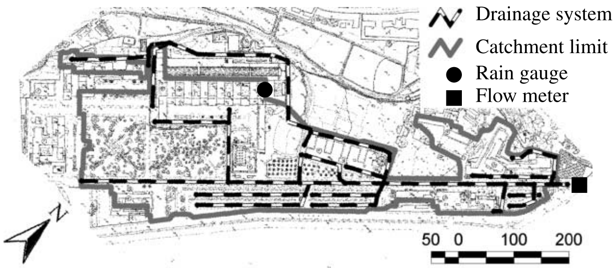


**Figure 3** | The experimental catchment of Parco d'Orlèans (Palermo, Italy).

From this archive, a 6-year continuous rainfall series was extracted and used for the simulations (Table 2).

This choice was driven by considerations about the life cycle of such structure that, although it is extremely variable depending on installation conditions, ranges between five and ten years (DAYWATER 2003).

As stated before, using MODFLOW simulations, the two above discussed correlations were investigated for the considered soil types. The first empirical correlation was obtained in order to link $A_{eff,0}$ to the bottom area of the real structure, A, for each type of soil. A power law relationship was assumed to fit to the present study (Figure 4a):

$$A_{eff,0} = aA^b \tag{10}$$

where $a$ and $b$ are curve parameters and $A_{eff,0}$ and $A$ are expressed in [m$^2$]. Equation 10 has been obtained considering that the trench is completely filled by water and it is not dependent on $h_w$ because the duration of the filling process is much faster than the variation of $A_{eff}$. These results are physically reasonable and they have been confirmed by MODFLOW. Figure 5a shows the agreement between the infiltration flow computed by MODFLOW and by the simplified model in these steady-state runs adopted for obtaining regression curves. Data points have been obtained by analysing infiltration structures with variable bottom area $A$ according to the two modelling approaches and comparing results (Freni *et al.* 2004).

A similar approach was used in order to estimate the variation of the effective infiltration area because of the clogging. In order to simulate clogging, sediments captured during each rainfall event were considered to progressively deposit on the structure bottom. Thus, increasing sediment level was considered in the physically based simulations while the clogging process is taking part. Figures 5b–d show the agreement between MODFLOW and the simplified model at three sediment levels used as examples.

The clogged layer infiltration capacity is obviously very poor and depends on the dimensional characteristics of captured sediments. The results are well interpolated by the following exponential law (Figure 4b):

$$\frac{A_{eff}}{A_{eff,0}} = ce^{-d \cdot h_{SED}} \tag{11}$$

where $h_{SED}$ is the depth of sediments on the structure bottom computed by a mass balance routine at the end of each event simulated by MODFLOW.

In Table 3 the main characteristics of the four different soil types considered (Rawls & Brakensiek 1983) and the coefficients of the two proposed equations for the different soils are reported. The coefficient values show that a proportionally stronger reduction of the effective area takes place for the more permeable soils (gravel) and, as a consequence, structure infiltration flow rates are largely affected by clogging phenomena. This fact is well justified

**Table 2** | Characteristics of the adopted rainfall time series

| | 1994* | 1995 | 1996 | 1997 | 1998 | 1999 |
|---|---|---|---|---|---|---|
| Rainfall depth (mm) | 285 | 552 | 655 | 602 | 634 | 582 |
| N° Events ($V_{rain} > 2$ mm) | 22 | 56 | 63 | 73 | 66 | 57 |
| Average ADWP (days) | 5.5 | 4.5 | 3.8 | 4.3 | 4.1 | 4.6 |
| Average rainfall intensity (mm/h) | 7.2 | 8.5 | 9.7 | 7.7 | 5.8 | 6.2 |
| Maximum 5 min rainfall intensity (mm/h) | 37.8 | 42.2 | 57.8 | 36.5 | 40.2 | 42.8 |
| Maximum 10 min rainfall intensity (mm/h) | 27.3 | 28.5 | 34.3 | 22.4 | 33.6 | 29.2 |
| Maximum 15 min rainfall intensity (mm/h) | 22.1 | 23.2 | 25.6 | 19.8 | 22.7 | 24.2 |

*6 months.

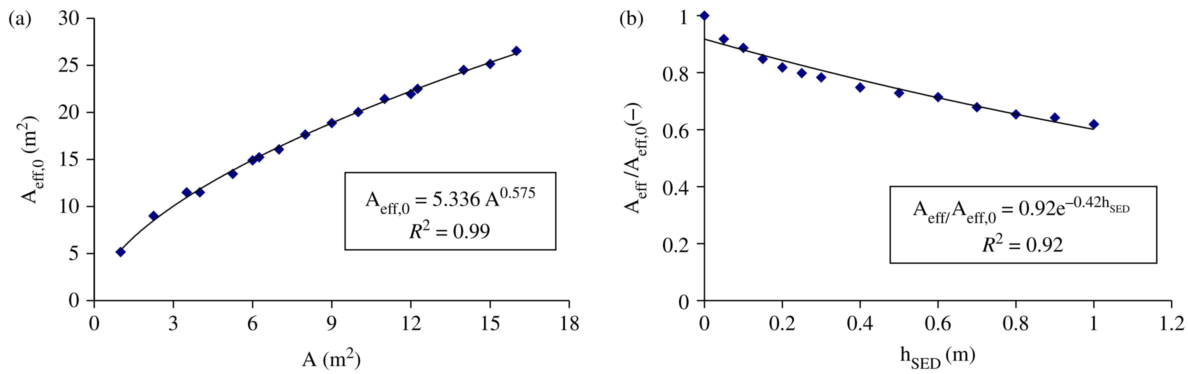


**Figure 4** | Correlation curves between (a) effective infiltration area $A_{eff,0}$ and geometric infiltration trench bottom area, in clean structure conditions and (b) effective infiltration area $A_{eff}$ and sediment height, in clogging condition; curves are referred to sandy-loam.

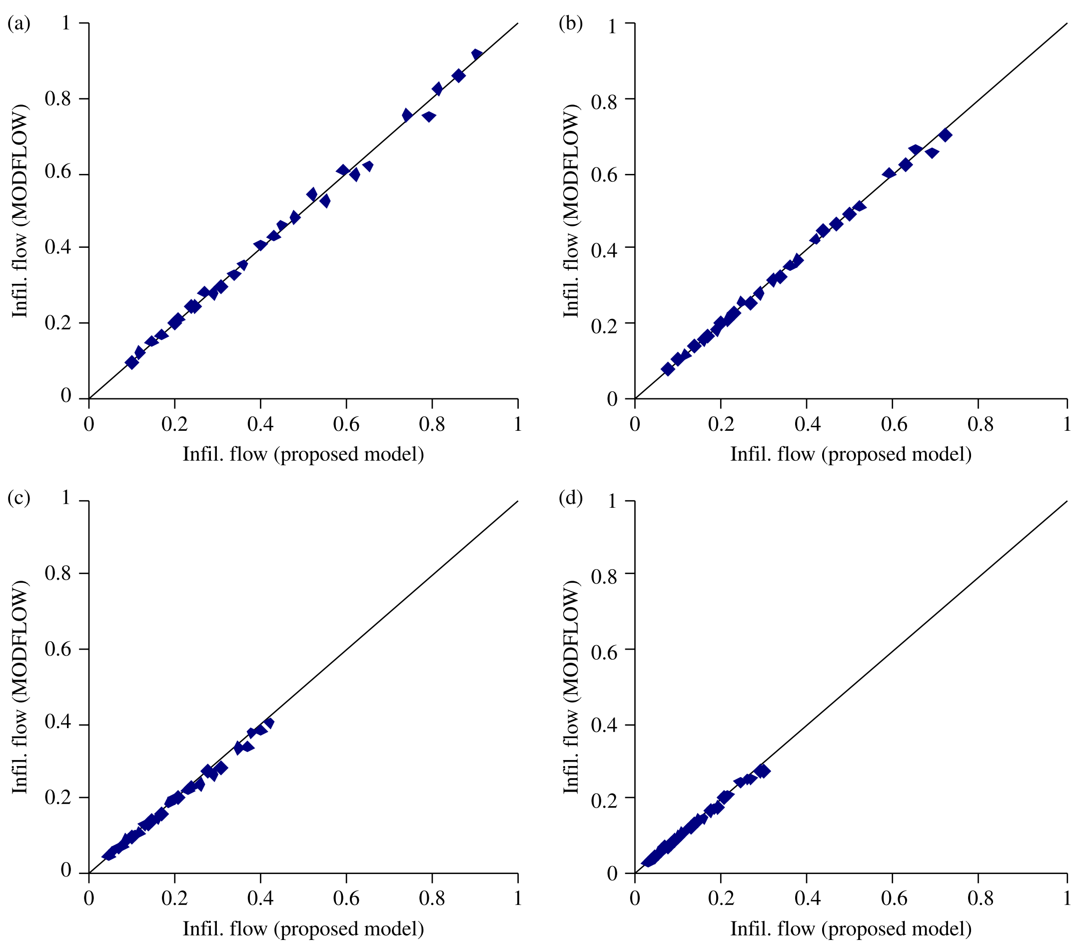


**Figure 5** | Calibration of the regression curves for the clean infiltration structure (a) and for three sediment levels: $h_{SED} = 0.1$ m (b); $h_{SED} = 0.3$ m (c); $h_{SED} = 0.5$ m (d). Curves are referred to sandy-loam and infiltration flow expressed in L/s.

**Table 3** | Soil characteristics and parameters comparing in Equation (10) and (11)

| | Parameter | Type of soil Sandy-Loam | Loamy-Sand | Sand | Gravel | Unit |
|---|---|---|---|---|---|---|
| Soil characteristics | $\theta_s$ | 0.45 | 0.43 | 0.44 | 0.55 | – |
| | $\theta_0$ | 0.05 | 0.04 | 0.02 | 0.01 | – |
| | $\psi$ | 0.11 | 0.10 | 0.09 | 0.08 | m |
| | $k_s$ | 6.10 | 17.00 | 65.00 | 100.0 | $10^{-6}$ m/s |
| Equation (10) | $A$ | 5.34 | 9.35 | 21.15 | 38.12 | – |
| | $B$ | 0.57 | 0.45 | 0.34 | 0.23 | – |
| | $R^2$ | 0.99 | 0.99 | 0.99 | 0.97 | – |
| Equation (11) | $C$ | 0.92 | 0.88 | 0.72 | 0.55 | – |
| | $D$ | 0.42 | 0.57 | 0.68 | 0.74 | $m^{-1}$ |
| | $R^2$ | 0.82 | 0.99 | 0.99 | 0.99 | – |

due to the greater area around the structure that is interested by infiltration phenomena and that is consequently reduced when clogging takes part.

## ANALYSIS AND DISCUSSION OF RESULTS

In the following section some rainfall events are analyzed for comparing the proposed model with the two literature examples. Figures 6 and 7 show computed hydrographs and pollutographs coming from the catchment for two recorded events, respectively, the event of 13/02/1994 and the event of 22/09/1999. These events have been selected as examples in order to evaluate the model behaviour during the whole rainfall event simulation at the beginning of the infiltration structure life cycle and after a 5-year period. The first event has been selected as the first relevant rainfall in the analysed period. The event is characterised by rainfall volume of around 5 mm in about 40 minutes and the infiltration structure may be considered clean thus allowing to compare modelling results without the effect of clogging. The second selected event is a double peaked rainfall that may provide some additional modelling difficult if infiltration is not properly analysed. Moreover, the second event has been taken at the end of the analysed period thus showing how the models simulate clogged infiltration structures.

The benchmark simulation performed with the MODFLOW model was introduced for the sake of comparison with the proposed model and the other two simplified approaches.

Figures 8 and 9 show the infiltration flow from the structure according to the different simplified models and to the reference MODFLOW simulation.

The analysis of the first event (Figure 8) shows different model behaviours for the two soil types.

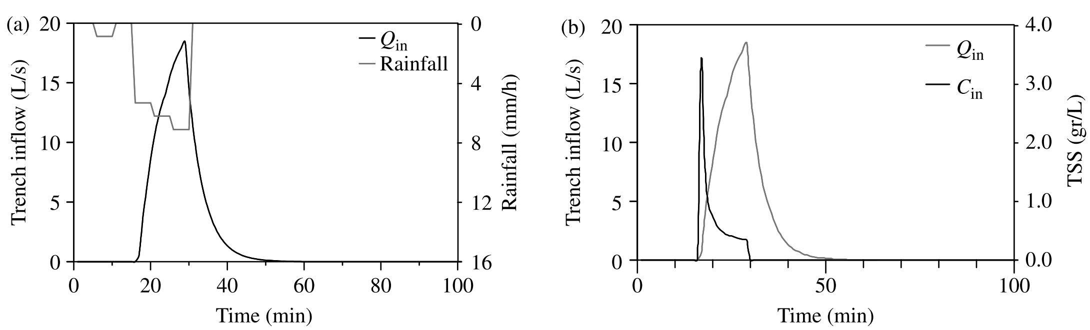


**Figure 6** | Quantity and quality characteristics of the event 13/02/1994.

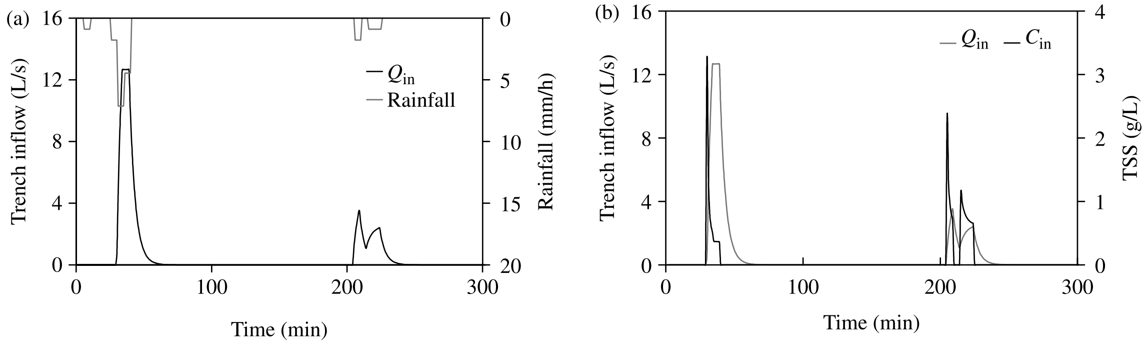


**Figure 7** | Quantity and quality characteristics of the event 22/09/1999.

For the sandy-loam soil (Figure 8a), a good agreement has been found both for the proposed model and the Todorovic model; the CIRIA model is characterized by larger underestimation of infiltration peak flow. Figure 8b, representing infiltration flow for the gravel soil, shows a small overestimation of the infiltration flow rate for the proposed model and significant underestimation for the other two simplified models.

The scarce results of CIRIA model in terms of agreement with MODFLOW are basically due to the hypothesis of such a model (i.e. soil in saturated condition). This hypothesis is far from the reality especially at the beginning of the infiltration processes and leads to a poor agreement with MODFLOW that whereas considers the saturation process. On the other hand, Todorovic model shows a better agreement with MODFLOW in the case of sandy-loam whereas a mismatching in the case of gravel. Such a result may be justified by the consideration that infiltration paths are sensibly vertical in pervious soils and maintain sub horizontal paths in impervious ones. Todorovic model neglects vertical infiltration and for this reason the results largely underestimate infiltration flows in pervious soils and provide better adaptation to physically based model in impervious ones.

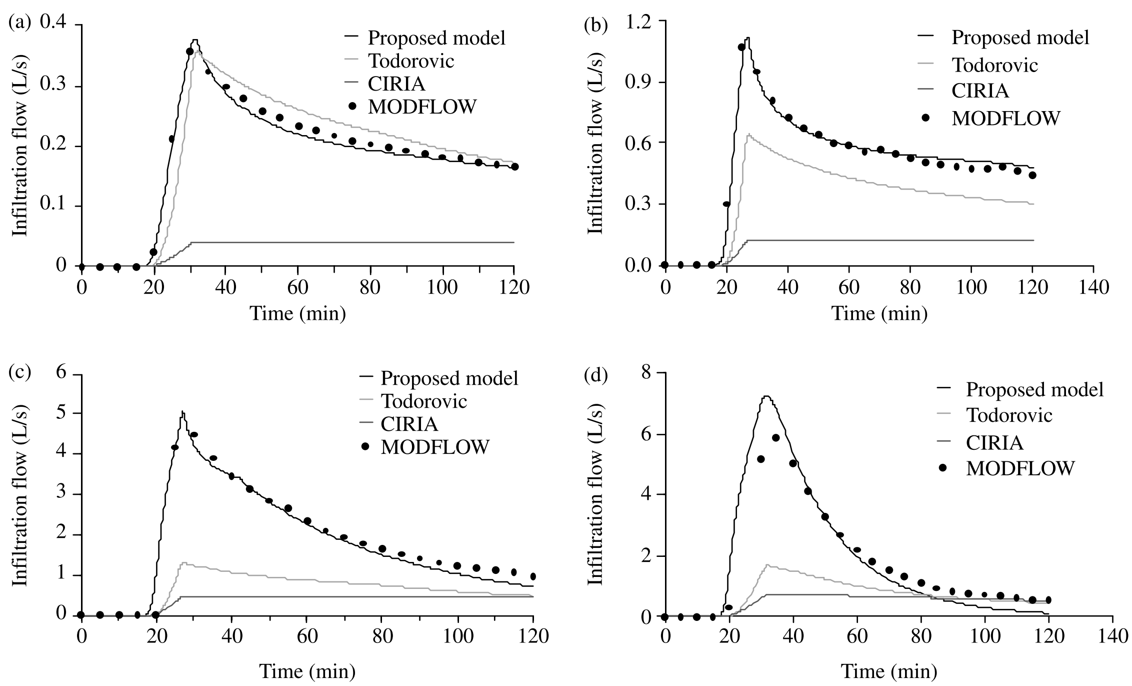


**Figure 8** | Modelling benchmark for sandy-loam (a), loamy-sand (b), sand (c) and gravel (d) considering the event 13/02/1994.

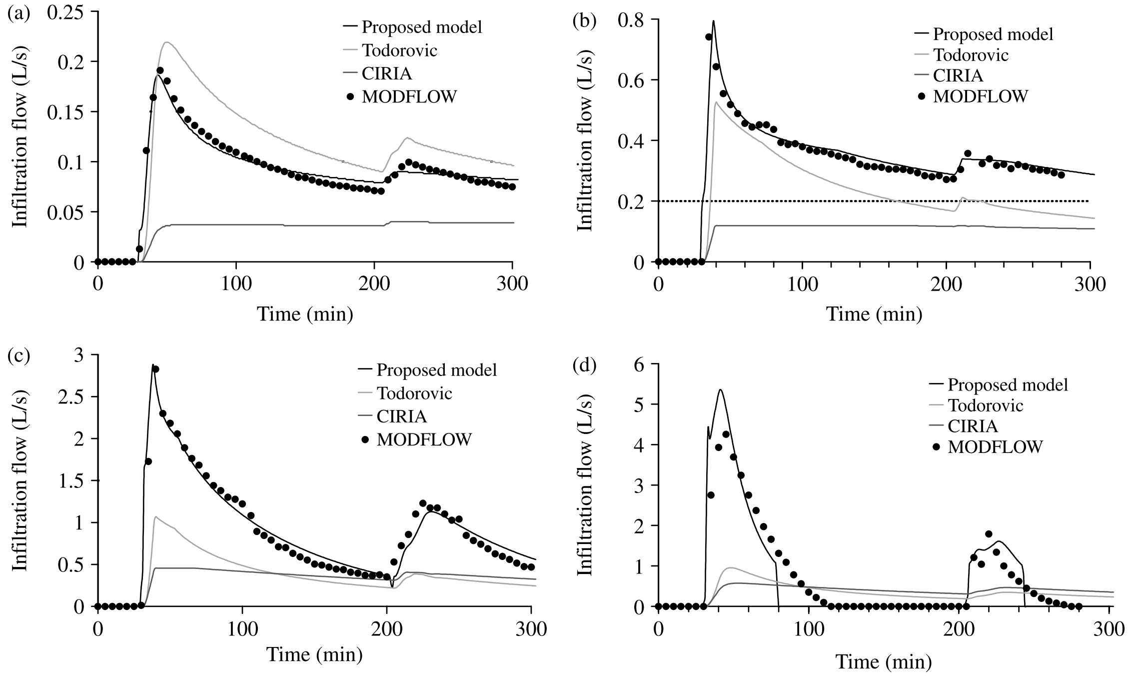


**Figure 9** | Modelling benchmark for sandy-loam (a), loamy-sand (b), sand (c) and gravel (d) considering the event 22/09/1999.

Figure 9 shows similar behaviour for the event picked at the end of the long term simulation when the clogging effect becomes more relevant. Once again, the CIRIA model demonstrates a relevant underestimation of infiltration flow that was exalted by the presence of a sealed layer at the bottom of the infiltration trench. Comparing the Todorovic model and the proposed model, they show similar results for sandy-loam soil and wide different behaviours for gravel.

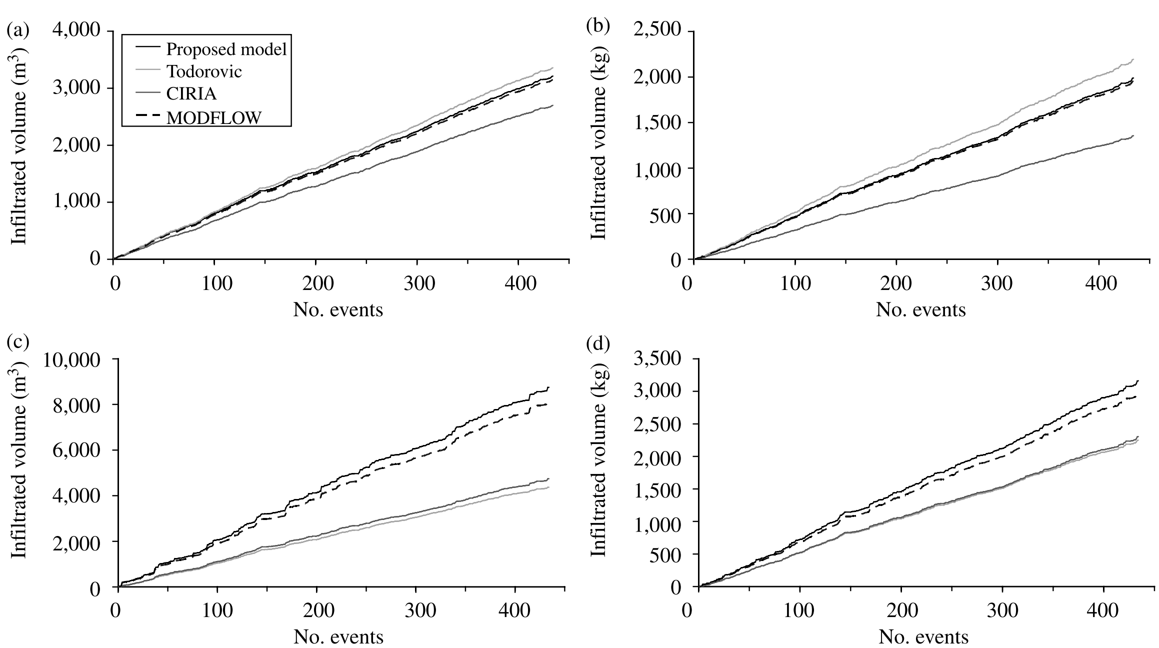


**Figure 10** | Modelling benchmark during the long term analysis: sandy-loam (a-b) and gravel (c-d).

**Table 4** | Average efficiencies for sandy-loam and gravel soil and infiltration design specific volume equal to 40 $m^3/ha_{imp}$ obtained with the different models

| | Sandy-Loam | | Loamy-Sand | | Sand | | Gravel | |
|---|---|---|---|---|---|---|---|---|
| MODEL | $\bar{\eta}_Q$ (%) | $\bar{\eta}_{TSS}$ (%) | $\bar{\eta}_Q$ (%) | $\bar{\eta}_{TSS}$ (%) | $\bar{\eta}_Q$ (%) | $\bar{\eta}_{TSS}$ (%) | $\bar{\eta}_Q$ (%) | $\bar{\eta}_{TSS}$ (%) |
| CIRIA | 28.25 | 53.24 | 34.12 | 54.33 | 38.22 | 59.99 | 44.74 | 67.88 |
| Todorovic | 30.29 | 55.99 | 35.58 | 57.22 | 36.11 | 62.11 | 41.21 | 66.25 |
| MODFLOW | 30.21 | 55.65 | 38.01 | 62.11 | 63.22 | 81.12 | 76.74 | 88.45 |
| Proposed | 30.27 | 55.81 | 38.92 | 63.74 | 65.76 | 83.38 | 80.43 | 92.08 |

The effect of clogging widened the gap between the two literature models and the proposed model that showed a better agreement to the MODFLOW benchmark simulations.

Figure 10 shows the adaptation among models on the long term for the two extreme soils (loamy sand and gravel) used as examples. The whole analysis period has been compared according to cumulated infiltration volumes and intercepted sediment mass:

- CIRIA models provided a general underestimation of infiltrated volumes and intercepted sediment mass because of the restrictive hypotheses of saturated soil conditions.
- Todorovic model overestimated infiltration flows for scarcely pervious soils (Figure 10a) and underestimates infiltration flows for pervious soils (Figure 10c). Those results reflect on intercepted masses and confirm results provided for single events.
- The proposed model generally fits the results of physically based one without sensible differences between soils types.

In Table 4 the global efficiency are reported both for the quantity ($\bar{\eta}_Q$) and for the quality ($\bar{\eta}_{TSS}$): volumes and intercepted mass have been cumulated in the whole analysed period and global efficiencies have been obtained by applying Equation 8 and Equation 9 to the cumulated variables. Concerning sandy-loam soil, comparable results have been obtained by all simplified models. This evidence can be explained considering the small relevance of the infiltrated volumes with respect to the overall runoff volume so that differences between models are appreciable at single event scale but not in the long term.

Different behaviours for the whole analysis period are instead evident when considering the gravel soil with the CIRIA and Todorovic models underestimating mitigation efficiencies and the proposed approach being more adherent to benchmark simulation. The results can be justified looking at the hypotheses adopted in the two simplified models adopted for comparison: The CIRIA model, assuming constant infiltration rates (equal to the saturated soil value), tends to underestimate the infiltrated volume because of the neglecting of soil saturating conditions during the infiltration process; the Todorovic model tries to solve the problem introducing horizontal infiltration paths but this behaviour is far from the reality when considering permeable soils where infiltration paths are horizontal only in the early stage of the process.

The proposed model shows a better adaptation to the different soil characteristic because effective infiltration area is a function of soil infiltration capacity and of clogging partially sealing the infiltration structure.

## CONCLUSIONS

A simplified infiltration trench model was presented. The model was applied to a hypothetical trench installed in an urban catchment where an urban drainage model has been successfully calibrated, both regarding stormwater quantity and quality aspects, and six years of continuous rainfall data has been recorded. The study mainly has examined three tasks:

- A benchmarking analysis between the proposed simplified model and a physically based one taken from literature.
- A comparison between the proposed model and two widely adopted simplified approaches both on single rainfall event and long term analysis.
- Infiltration trench efficiency evaluation in the long term considering both runoff volume reduction and stormwater quality mitigation.

The comparison between modelling approaches showed, especially for the gravel soil, a better agreement of the proposed model with the physically based one, both in the rising and decreasing limb of the infiltration hydrograph. Literature simplified models generally underestimate infiltration volumes and retained sediments. This underestimation is more evident considering more permeable soils and it is progressively reduced when considering loamy soils where the infiltration process is less relevant and the assumption of neglecting unsaturated soil at the beginning of the rainfall event has not a great impact on modelling analysis. The reported underestimation can be considered as an implicit safety factor for the estimation of mitigation efficiencies; in contrast, it should be considered that efficiency in sediment retention also represents a measure of the quantity of solids that are progressively clogging the infiltration trench and, especially in permeable soils, literature models tend to underestimate the clogging level on the long term overestimating the life expectancies of the structure.

The results showed that the infiltration devices are more effective for the quality rather than for the quantity control and they still maintain a good performance also considering the clogging and the absence of any pre-treatment structure.

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