Experimental Analysis and Modeling of a Stormwater Perlite Filter

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Abstract

This paper presents the study of a mixed porous media, composed of expanded perlite (EP) and nonwoven needle punched geotextile, used to remove suspended solids (SS) in urban runoff before it is infiltrated. Several laboratory procedures were designed to quantify the most important variables that characterize the performance of this filter media: SS removal efficiency (R) and the variation in time of filtration rate (Q). Different grain size distributions of EP, diverse SS concentrations, and different hydraulic and geometric conditions were tested in order to determine the most effective filter media in terms of the maximization of R and Q. A dimensionless parameter, the "global performance index" (GPI), was developed to reach this objective. Measured data were also used to build a dimensional model to represent the performance of the filter media mathematically. The theory, assumptions, derivation and performance of this model are presented, and then compared to an existent empirical model. The dimensional model better reproduces the observations, becoming a useful tool for the design, operation and evaluation of commercial porous media filters.

Introduction

Stormwater infiltration is a common technique used in Best Management Practices (BMP's) for urban stormwater drainage control. This technique reduces runoff discharges and volumes, and promotes groundwater recharge. However, there are also some negative impacts associated with infiltration, such as the risk of groundwater contamination and the reduction of the infiltration rate through time due to infiltration surface clogging (Urbonas, 1999; Raimbault et al., 2000). Filter devices have proven to be useful in reducing the suspended solids (SS) load and concentration before stormwater reaches the infiltration areas (Urbonas and Stahre, 1993; Urbonas, 1999).

It is expected for any solution to be easy to implement, operate and maintain. In the case of a modular stormwater filter device, it must be easy to install, clean and renew, its size must be reduced and it has to be built based on standardized elements, which allows the achievement of different design criteria by minimum changes or additions. In order to accomplish these objectives, the filter media must be carefully selected.

This article presents a preliminary investigation of the expanded perlite (EP) as an alternative porous media to be used in stormwater filter devices, to reduce SS loads and concentrations in urban stormwater. Both experimental measurement and modeling are discussed as well as the main variables that characterize the performance of this material.

Filter media selection

Several materials have been reported as filter media in the literature. Clark and Pitt (1999) summarize the most widely currently used media, including sand, activated carbon and peat moss. Each one has its advantages and limitations, and the selection depends on the desired pollutant removal performance and the associated conditions, such as land use (Clark and Pitt, 1999). Most of these filters must be built in-situ because of the amount of material needed to reach a good performance and the large concrete structures involved in the construction.

Another approach can be the design of small, easy to install filter devices that do not require a complicated building process or much maintenance, which are used to treat smaller areas. A filter device should be designed to achieve high filtration rates and removal efficiency. From that point of view, it is very important to select a filter media that meets the following properties: (1) high specific surface; (2) low specific weight, allowing an easy installation and transportation of the filter; and (3) structural resistance to handle typical installation and operational loads.

A material that satisfies these characteristics is expanded perlite (EP). EP has already been used and studied as a filter media (Uluatam, 1991; Joseph and Rodier, 1994; Wigginton and de Ridder, 1999; Dogan et al., 2004). Perlite is a natural siliceous rock that, when heated to a suitable point in its softening range (760 – 1100 °C), expands four to twenty times its original volume, reaching an extremely light weight and a high specific area (Purchas, 1997). Figure 1 presents the different states for perlite, meanwhile Figure 2 shows the very complex porous microstructure of EP.

Other uses of this material are related to the construction industry, agriculture, food, beverage, medical and chemical industries (Uluatam, 1991).

Figure 1: Natural and EP (Copyright 2003–www.perlite.net & Redco II)

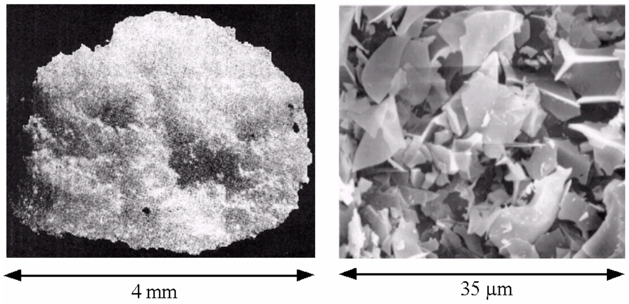


Figure 2: Microstructure of the expanded perlite

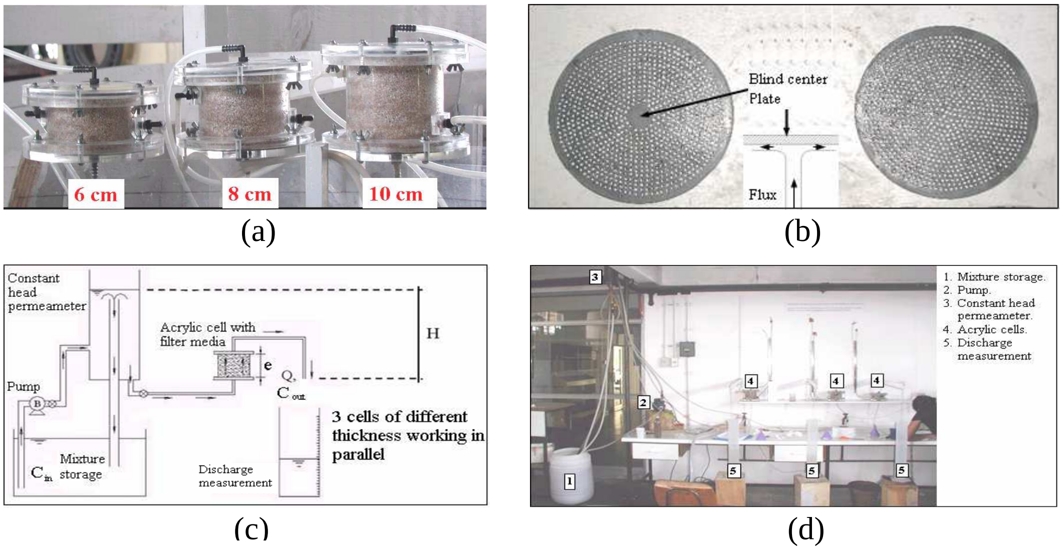
The main chemical components of EP are SiO_2 (74.70%), Al_2O_3 (13.20%), K_2O (5.08%), and Na_2O (4.40%). The more important physical properties that make EP a good filter media are its specific gravity (2.2–2.4), bulk density (32-400 Kg/m^3, loose weight), the saturation porosity (84.93% for a mean diameter of 0.5-1 mm), and its specific area (0.72 m^2/gr or 806.4 cm^2/cm^3 for a mean diameter of 0.5-1 mm).

Experimental Measurements and results analysis

An experimental method was developed to study the behavior of a mixed filter media composed of a main layer of EP and a nonwoven needle punched geotextile located downstream to remove fine particles not retained by the EP. The laboratory procedures were designed to quantify the most important variables involved: SS efficiency removal (R) and filtration rate variation in time (Q). Different grain size distributions of EP, different SS concentrations, and diverse hydraulic and geometric conditions were tested to represent the typical conditions at which a stormwater filter would operate.

1. Experimental set-up

A constant head permeameter was used to supply mixtures of water and SS at different concentrations through diffuser plates to three acrylic cells, which have filter media samples of 6, 8 and 10 cm of thickness. Figure 3 shows the experimental setup.



(a) (b)

(c) (d)

Figure 3: Experimental set-up: (a) Acrylic cells with different filter media thickness, (b) diffuser plates, (c) schematic representation, and (d) laboratory set-up

An additional objective was to determine the most effective filter media of the three tested, in terms of removal capacity and maximization of the filtration flow rate. To reach this goal, a dimensionless parameter, which couples quality and quantity characteristics, was developed to compare different experiments.

2. Filter media

Three types of EP were used: A-4, A-6 and A-5, the last one being a combination of 50% of the first two classes. The bulk densities are 0.17, 0.13 and 0.15 respectively, and the particle size distribution for each type of EP is presented in Figure 4. The main characteristics of the nonwoven needle punched geotextiles used are: Mass/unit area = 150 gr/m^2, porosity O_{90} = 170 µm, thickness = 2.5 mm, and permissivity = 2 s^{-1}.

3. Concentration of suspended solids

The particle size distribution for the SS used in the water samples (see Figure 5) is similar to those presented by RMC (2002). Turbidity measures were used to estimate the concentration of SS using a fitted curve relating turbidity and concentration.

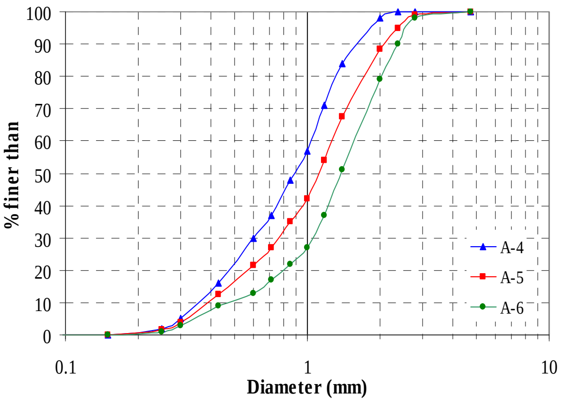


Figure 4: Particle size distribution for the 3 types of expanded perlite

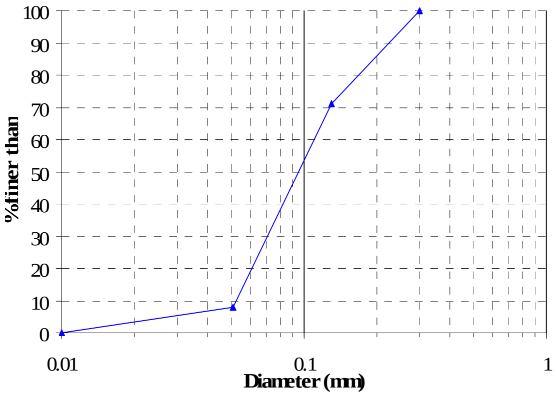


Figure 5: Particle size distribution for the suspended solids

4. Methods and results

Forty-six filtration processes were simulated for different concentrations (from 50 to 1200 mg/L), constant heads (35 and 80 cm), durations (from 4.55 to 10 h), types of EP (A-4, A-6 and A-5) and layer thicknesses (6, 8 and 10 cm). The variables measured in each experiment were input turbidity (every 30 minutes), output turbidity (every 5 minutes), and filtration volume, measured every time it reached 2 L. Using this information, the input and output concentrations (C_{inp} and C_{out}) and the filtration rates (Q) were computed. Additionally, other important variables were calculated, such as the input and removed mass, and the removal efficiency (R).

A dimensionless parameter (see Eq. 1) called Global Performance Index (GPI), was developed to compare different experiments. This parameter couples quality and quantity characteristics and is used to determine the most effective filter media in terms of removal capacity and maximization of the filtration rate, permitting the selection of the thickness and the type of EP for the filter. The main assumption is that the filtration rate is linearly proportional to the head H, which is well observed in reality. From Eq. (1) it is seen that H is in the denominator, implying that the filtered volumes $\forall$ are somehow standardized, allowing the evaluation of different samples.

$$GPI = \frac{\forall'}{H} \cdot NR \tag{1}$$

Where $\forall$' is the specific filtered volume at $t=T^*$ (m³/m²), H is the head (m), T^* is the reference filtration time (h), and NR is a value depicting the performance of the filter media in terms of the average efficiency removal, ($\overline{R}$), according to the following:

$$\text{NR} = \begin{cases} 0 \quad \text{if} \quad \overline{R} < 0.30 & 3 \quad \text{if} \quad 0.50 < \overline{R} < 0.60 \\ 1 \quad \text{if} \quad 0.30 < \overline{R} < 0.40 & 4 \quad \text{if} \quad 0.60 < \overline{R} < 0.70 \\ 2 \quad \text{if} \quad 0.40 < \overline{R} < 0.50 & 5 \quad \text{if} \quad \overline{R} > 0.70 \end{cases}$$

T^* must be as large as possible so the filter performance at different stages throughout the operation can be evaluated, which implies more certainty in computing the GPI. For the cases presented here, T^* must be a minimum of 5 hours, after this time the filtration rate decays exponentially. Therefore T^* = 6 hours was selected, since this was the duration of most of the experiments.

An exponential model given by $Q = a \cdot e^{-b \cdot t}$ was used when the duration of the experiment was less than 6 hours. Here, a and b are parameters to be calibrated, where a is the initial discharge, Q_{ini}.

The specific filtered volume, $\forall$', was computed by integrating Q through time.

$$\forall' = \int_0^{T^*} Q \cdot dt = Q_{ini} \cdot \int_0^{T^*} e^{-b \cdot t} \cdot dt = \frac{Q_{ini}}{b} \cdot \left(1 - e^{-b \cdot T^*}\right) \tag{2}$$

Table 1 presents the main statistics for GPI obtained in each one of the 46 experiments, given by the average μ, the standard deviation σ, and the coefficient of variance CV for different combinations of EP and layer thickness. The best two filter medias are the EP A4 with either 8 or 10 cm of layer thickness, since both have the best averages and the minimum coefficients of variance. Similar results were obtained when low concentrations were studied (C<200 mg/L).

Table 1: Main statistics for GPI for different combinations of EP and thickness

	A5-10	**A5-8**	**A5-6**	**A4-10**	**A4-8**	**A4-6**	**A6-10**	**A6-8**	**A6-6**
μ	98.2	102.2	71.0	***115.8***	***114.1***	92.2	90.4	66.0	58.1
σ	27.5	35.2	39.7	***28.5***	***25.9***	43.4	44.9	51.7	38.3
CV	0.28	0.34	0.56	***0.25***	***0.23***	0.47	0.50	0.78	0.66
N	8	8	5	***7***	***7***	5	2	2	2

In general the results are consistent with what was expected, considering the physical processes involved in filtration. It was anticipated that larger thickness for the filter media would imply a reduction in filtration rate, Q and an increase in $\overline{R}$. Likely explanations for cases where this behavior did not occur were the possible existence of preferential fluxes and the clogging of fine layers of EP, which would reduce the hydraulic capacity quickly. It was also expected that the type of EP would influence the results since larger grains imply more flux tubes, which means reductions in $\overline{R}$. This behavior took place as was expected. The expected effects of the hydraulic head, *H*, in Q and $\overline{R}$ were also observed. When H was changed from 35 to 80 cm, there was an increase in Q and a reduction in $\overline{R}$. Finally, the effects of changing the average input concentration, $\overline{C}_{inp}$ in Q and $\overline{R}$ were also evaluated ($\overline{C}_{inp}$ was computed as the ratio between the cumulative removed mass during the experiment and the total filtered volume pondered by $\overline{R}$). As it was expected, larger concentrations reduce *Q*, however, there were also reductions in $\overline{R}$, which was not expected due to the reasons previously presented. A possible explanation for this is the presence of particles already captured by the filter but afterward released and measured in the output concentration.

Modeling the performance of the filtration mixed media

Building a model to explain the filtration process is very complex. There are various mechanisms to be considered depending on how the removal of the particle occurs. A dimensional model was developed in order to estimate the removal efficiency and the filtration rate based on dimensionless variables describing the processes. Results are compared to those obtained by a model proposed by Urbonas (1999), referred to here as the *empirical model*.

1. Empirical model

This model describes the filtration rate as a function of the cumulative mass removed by the filter. It assumes that $\overline{R}$ is constant and equal to 95%, and it can be used for any filter media. The model is given by:

$$q = ki \cdot Lm^{-c} \tag{3}$$

$$Lm = \int_0^T \left(C_{inp} - C_{out}\right) \cdot q \cdot dt \tag{4}$$

Where *q* is the filtration rate per unit of surface (m/s), C_{inp} is the input concentration (gr/m³), C_{out} is the output concentration (gr/m³) given by $\left(1-\overline{R}\right)\cdot C_{inp}$, *Lm* is the cumulative mass removed per unit of surface (gr/m²), *t* is the time (s), and *ki* and *c* are parameters to be calibrated.

Values of *ki* and *c* are calibrated for each experiment with identical conditions (same type of EP, hydraulic head and thickness) using the laboratory results. The model is used to estimate the filtration flow rate through the time. Figure 6 summarizes the performance of the model by comparing the observed and modeled filtration rates.

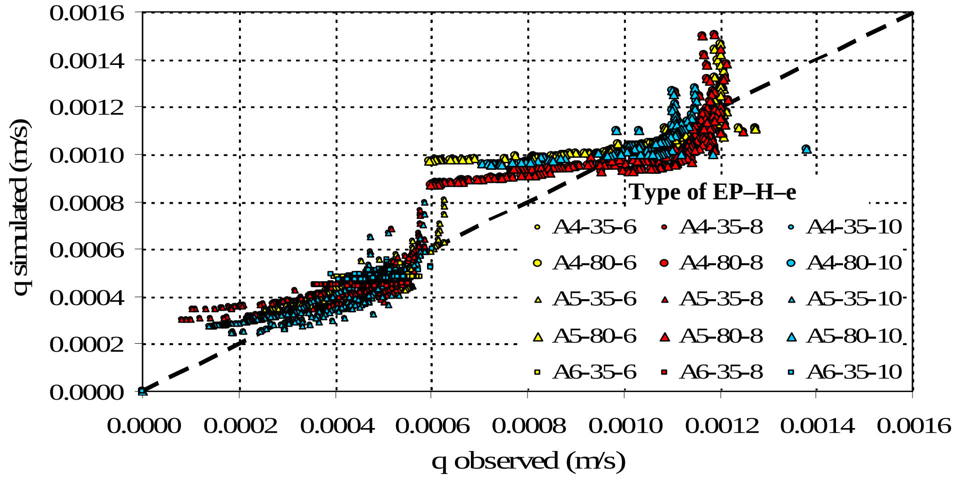


Figure 6: Global performance of the empirical model

2. Dimensional model

A dimensional analysis was performed in order to determine a relationship among dimensionless parameter to describe all the experiments grouped by similar geometric and hydraulic conditions. Table 2 shows all the variables used in the analysis.

Table 2: Variables describing the filtration process

Variable	Definition	Dimensions	Type
q	Filtration rate per unit of area	LT^{-1}	Dependent
C_{inp}	Input concentration	ML^{-3}	Independent
C_{out}	Output concentration	ML^{-3}	Dependent
H	Head	L	Independent
e	Thickness of filter layer	L	Independent
d_m	Mean diameter of grains of filter media	L	Independent
CU	$CU = d_{60} / d_{10}$	–	Independent
μ	Dynamic viscosity = water viscosity	$ML^{-1}T^{-1}$	Independent
θ_0	Effective porosity of the filter media	–	Independent
θ_R	Cumulative removed effective porosity	–	Dependent
ρ_s	Specific mass of SS = 2650 kg/m^3	ML^{-3}	Independent
Se	Specific surface of filter media	L^{-1} ó L^2M^{-1}	Independent

The analysis considers two dimensionless variables to be explained given by (i) $P = C_{out}/C_{inp}$, where P is the instantaneous proportion of SS passing the filter, and (ii) $q^* = \dfrac{q}{\sqrt{2gH}} \cdot \sqrt{\dfrac{e}{H}} = \sqrt{\dfrac{e}{2g}} \cdot \dfrac{q}{H}$, which is proposed since q and H are proportional.

The main assumption in developing this model is that both q^* and P are related to θ_R which corresponds to the ratio between the volume of retained solids by the filter during a time $t = T$ and the total volume of the filter, and can be computed as follows:

$$\theta_R = \int_0^T \frac{\left(C_{inp} - C_{out}\right) \cdot q \cdot dt}{\rho_S \cdot e} \tag{5}$$

Thus, q^* and P can be expressed in terms of θ_R and the other independent variables. The expression for q^* has $n_1 = 3$ dimensional variables, it involves $r_1 = 1$ dimension and there are 4 dimensionless variables. Therefore q^* can be rewritten as function of $n_1 - r_1 + 4 = 6$ dimensionless variables. On the other hand, the expression for P has $n_2 = 4$ dimensional variables, it involves $r_2 = 1$ dimension and there are 3 dimensionless variables. Then P can be rewritten as a function of $n_2 - r_2 + 3 = 6$ dimensionless variables. Eqs. 6 and 7 show the original and the reduced expressions for q^* and P.

$$q^* = \sqrt{\frac{e}{2g}} \cdot \frac{q}{H} = f_1\left(e, d_m, CU, \theta_0, \theta_R, Se, \frac{C_{inp}}{C_{ref}}\right) = g_1\left(\frac{e}{d_m}, CU, \theta_0, \theta_R, e \cdot Se, \frac{C_{inp}}{C_{ref}}\right) \tag{6}$$

$$P = \frac{C_{out}}{C_{inp}} = f_2\left(e, H, d_m, CU, \theta_0, \theta_R, Se\right) = g_2\left(\frac{e}{H}, \frac{e}{d_m}, CU, \theta_0, \theta_R, e \cdot Se\right) \tag{7}$$

From the laboratory results, a linear relationship between q^* and θ_R was observed, given by $q^* = -a \cdot \theta_R + b$. Parameters a and b change for different experiments, grouped according to the type of EP, the range of concentration used, and the thickness of the EP layer. A similar analysis can be done to study the variable P, which also leads to linear relationships given by $P = m \cdot \theta_R + n$. In this case experiments are grouped by type of EP, thickness of the EP layer, and head. Considering all the values of each of the 4 parameters, it is possible to set typical values which are suggested for a pre-design step. Table 3 presents those values.

Table 3: Reference values for parameters of the dimensional model

Parameter	a	b	m	n
Value	0,003 – 0,004	9,5*10^{-5} – 10,5*10^{-5}	10 – 14	0,30 – 0,35

These two linear relationships can be used in (7) and solved for each time t_n using finite differences for $\theta_R^{t_n}$, q^{t_n} and $C_{out}^{t_n}$.

The results of the dimensional model are summarized in Figures 7 and 8. Figure 7 shows the performance of the model predicting q, meanwhile Figure 8 shows the performance in predicting C_{out}.

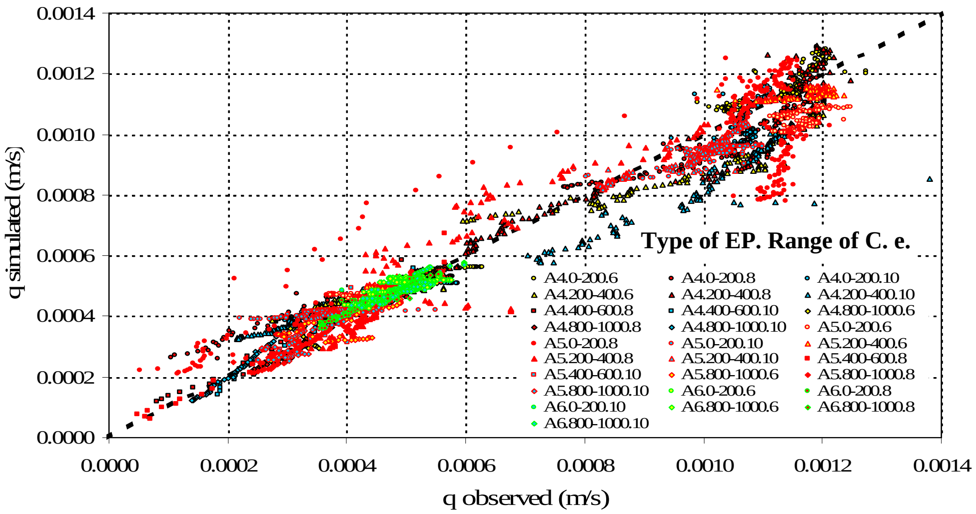


Figure 7: Global performance of the dimensional model, prediction of q

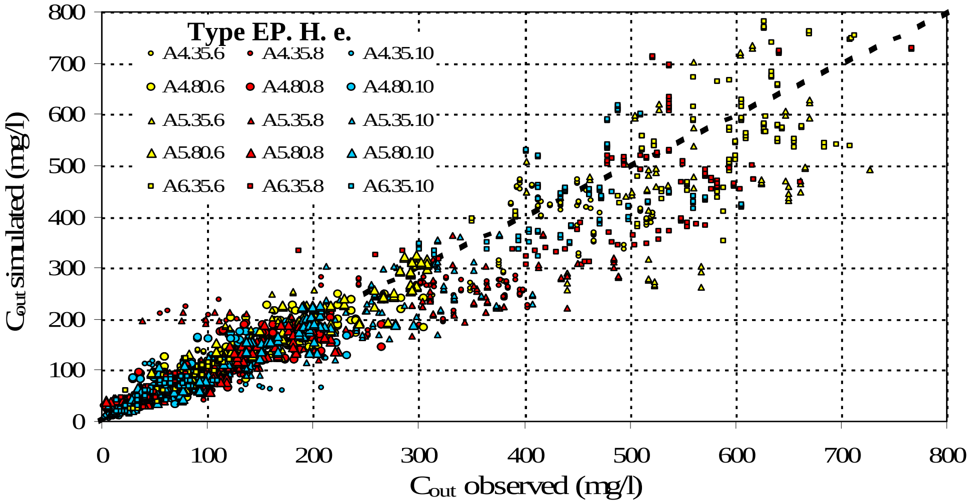


Figure 8: Global performance of the dimensional model, prediction of C_{out}

Conclusions

Expanded perlite (EP) supported by a downstream geotextile layer is an interesting combined filter media to be used in standardized filters designed to remove SS from stormwater, because of its convenient physical characteristics and its neutral chemical composition.

Laboratory experiments showed that differing thickness of EP layers does not affect the filtration rate substantially as was expected, but greatly affects the removal efficiency (*R*) since a strong proportionality between thickness and *R* was found. Results show that the 10 cm EP class A4 layer was the best combination according to the Global Performance Index (*GPI*), an index developed to evaluate the filter performance, which can be used to analyze and compare diverse filter medias and pollutants.

The dimensional model developed here reproduces the filtration rates and the output concentration better than a comparable empirical model. Additionally, the theoretical background supporting this model is more complete, making the dimensionless model a good approach to study the filtration of SS in any porous media in a filtration system not controlled by cake filtration phenomena.

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